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Assessment of groundwater vulnerability by applying a modified DRASTIC model in an urban metallurgical-industrial environment: Case study in Monterrey, Mexico

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ABSTRACT

In this study, groundwater vulnerability in the "Campus UANL" aquifer was assessed by applying a modified DRASTIC model. Pollution source mapping (P) and Management of water resources (M) were added to the DRASTIC parameters. A geographical information system was used for the spatial integration of different parameter maps. The effect of parameters on the resulting vulnerability maps was determined through a single parameter sensitivity analysis. The most influential parameters identified were topography, pollution sources mapping, net recharge, and soil type. Efficiency was validated by calculating the coefficient of determination (r^2). Values for the DRASTIC-PM model were 0.63 for EC, 0.89 for Al^{3+}, and 0.64 for Co^{2+}, which improved to 0.68 for Co^{2+} after sensitivity adjustments. These validation results indicate that the modified model is more effective than the conventional DRASTIC model in identifying critical vulnerability zones within an urban metallurgical-industrial environment. The groundwater vulnerability assessed by applying the modified model revealed that the aquifer in the study has very high vulnerability. In contrast, the conventional model indicated that the aquifer exhibits high vulnerability. The results revealed a critical situation regarding groundwater quality, especially in the northeastern area. The DRASTIC-PM model proposed in this study provided a more accurate and detailed vulnerability zonation. This modified model can be implemented in zones where anthropogenic contamination is high, particularly in and around urban centers. However, the limitations of this study are related to the availability and quality of hydrogeological and geochemical data. The innovation of this study lies in the application of the DRASTIC-PM model, calibrated with metal ions and adapted to an urban-industrial setting, to assess the vulnerability of the "Campus UANL" aquifer. This approach allows for a more accurate evaluation of vulnerability in an area under high anthropogenic pressure, significantly improving the model's precision compared to conventional methods.

Keywords: groundwater, contamination, metallurgical industry, vulnerability, modified DRASTIC.

INTRODUCTION

Groundwater vulnerability assessment is vital in understanding its susceptibility to pollution and developing planning strategies for quality conservation (Shekhar et al., 2015). Safe drinking water is vital for public health, as more than 80% of diseases and nearly 50% of child deaths are linked to its deficiency. An estimated 200 million people worldwide consume water that exceeds safe contaminant thresholds (Imam, 2024), underscoring the urgent need to strengthen water quality monitoring, implement scientifically validated treatment methods, and establish effective regulatory and management frameworks (Landrigan et al., 2018; Amare, 2019; Velázquez-Chávez, 2022).

Globally, industries such as metallurgy and textiles are significantly contributing to the release of heavy metals into the environment through various pathways. In Nigeria, direct discharges from factories in small areas have increased groundwater pollution, severely affecting the quality of drinking water (Zacchaeus, 2020). In China, irrigation with industrial wastewater has been identified as the main source of hazardous pollutants (Lin et al., 2022). In Mexico, atmospheric deposition from smokestacks has infiltrated aquifers, deteriorating groundwater quality (Pérez, 2022). Case studies from San Luis Potosí, Zimapán, and Tepic illustrate how industrial and urban contamination impacts groundwater quality in the country (Aguirre-García, 2023; Covarrubias, 2017; Espinosa, 2015). This phenomenon is not limited to these regions but represents a global issue that requires urgent action to mitigate pollution and protect water resources worldwide. Multiple models exist for assessing groundwater vulnerability, including DRASTIC, GOD, AVI, SINTACS, and EPIK. These models provide a qualitative and relative assessment of vulnerability. Their primary advantage lies in their ability to assess factors that influence the movement of pollutants over large areas, making them suitable for regional-scale studies.

Over the years, groundwater vulnerability assessment in aquifers has been improved by modifying the DRASTIC model, using techniques such as sensitivity analysis, AHP (Analytic Hierarchy Process) method, and multiple linear regression to adjust factor weights. Besides, additional factors like land use and irrigation type have been incorporated to obtain better model accuracy (Kirlas et al., 2022). The effectiveness of these models is optimized by applying sensitivity analysis, which allows for maximizing the correlation coefficient (r^2) between the vulnerability index and pollution indicators, as documented in previous studies (Rehman et al., 2024).

In previous studies, the DRASTIC model has been widely used to assess aquifer vulnerability, and its accuracy has been improved by incorporating additional parameters tailored to specific contexts (Männik et al., 2023; Hamza et al., 2017). In various countries, factors such as fractured media (Hamza et al., 2017), land use (Zhang et al., 2022), anthropogenic influence (Albuquerque et al., 2021), and distance to pollution sources (Männik et al., 2023) have been included.

However, there is a gap in the application of groundwater vulnerability models in urban-industrial environments, where both pollution from industrial activities and the role of local water management are crucial factors that influence aquifer quality (Kumar et al., 2021). The main scientific problem addressed is that traditional models like DRASTIC do not account for the complexities of urban-industrial settings, making them less effective in such contexts (Zhang, 2022; Lin et al., 2022).

In this study, the pollution indicators Al^{3+} and Co^{2+} are chosen for model calibration due to their toxicity and the high concentrations of these elements originating from nearby metallurgical industries. These elevated concentrations have been reported in previous studies (Aguilar, 2010; Pabón et al., 2020; Pérez, 2022), justifying their selection to assess groundwater quality in this context.

The "UANL Campus" aquifer lies beneath the Ciudad Universitaria campus of the Universidad Autónoma de Nuevo León and forms part of the Monterrey aquifer (Figure 1b). This hydrogeological unit is located within the Metropolitan Area of Monterrey, in a zone characterized by intense metallurgical industrial activity. It is surrounded by facilities such as Ternium, Ferromex, and Internacional de Metales, among others. Previous studies have reported high concentrations of potentially toxic elements (PTEs) in groundwater (García, 2017; De León et al., 2021), to date, no study has applied an anthropogenically adapted DRASTIC model to this aquifer, representing a clear gap in the regional literature. On the other hand, Mora et al. (2018) mention that climate change could modify the hydrological cycle and affect the quantity and quality of groundwater resources. Therefore, it is necessary to conduct annual monitoring programs to identify future changes in water chemistry. Due to the history of contaminants present in the groundwater of the study area and the constant modification of the hydrologic cycle, which alters the properties and levels of groundwater, it is necessary to assess the vulnerability of the "UANL campus" aquifer to contamination.

This study aims to assess the contamination vulnerability of the "UANL Campus" aquifer using a modified DRASTIC-PM model, tailored specifically for urban-industrial contexts. The application of the improved model, which includes additional parameters such as Pollution source mapping (P) and water resources management (M), is expected to allow a more accurate assessment of groundwater vulnerability in environments with intense industrial pressure.

MATERIALS AND METHODS

Study area

The "UANL campus" aquifer is located in the MMA (Figure 1b), between the cities of San Nicolás de los Garza and Monterrey, is bordered to the east by the Ternium steel plant, to the north by the Topo Chico stream, to the west by Ferromex, and by the Niños Héroes park to the south (Figure 1). The cities of Monterrey and San Nicolás de los Garza are situated in the physiographic provinces of the Sierra Madre Oriental and the Llanura Costera el Golfo Norte (National Institute of Statistics and Geography, INEGI, for its initials in Spanish, 2024). The temperature ranges between 10 and 36 °C (Weather Spark, 2024).

The study area is located within the Hydrological Region 24 (HR 24), in the Rio Bravo subregion, San Juan River basin, where the area is drained to the North by the Pesquería River, towards the middle part of the Topo Chico and Talaverna, and to the South nearby the Santa Catarina River (CONAGUA, 2015). In Monterrey, the months with the highest precipitation are September, August, and October. The annual rainfall in Monterrey is 616 mm. July is typically the hottest month, while January is generally the coldest month (HikersBay, 2024).

Geology

The geology of Nuevo León is predominantly characterized by folded Mesozoic sedimentary rocks, which overlie a Paleozoic and Precambrian basement (Montalvo et al., 2005). In this case, the most significant physiographic feature is the bending of the Sierra Madre Oriental at Monterrey, known as the Monterrey Curvature. The stratigraphy of this mountain range is highly varied, comprising siliciclastic, carbonate, and sulfate rocks with ages ranging from the Late Triassic to the Quaternary (Rubio, 2012).

The predominant material in the Monterrey is fluvial sediments, with some outcrops of shales from the Upper Cretaceous Méndez Formation, which is composed of light greenish-brown and gray shales, as well as marls with laminated stratification. It also exhibits a high degree of fracturing. Quaternary fluvial deposits, composed of gravels, sands, silts, and clays, outcrop above this formation (Figure 2) (De León et al., 2021).

Hydrogeology

The recharge zone is located in the Monterrey curvature, whose geologic structure is of great importance within the Sierra Madre Oriental in the Monterrey hydrogeologic system. This area comprises pore and gravel aquifers, as well as fractured and karst aquifers, with groundwater depths of up to 1,200 meters. Most of the water consumed in Monterrey and its metropolitan area (2000 l/s) is extracted from the calcareous-karstic Cupido and Aurora aquifers. The discharge zone is located in the MMA valley, where comprising pore/gravel aquifer from which 250 l/s are

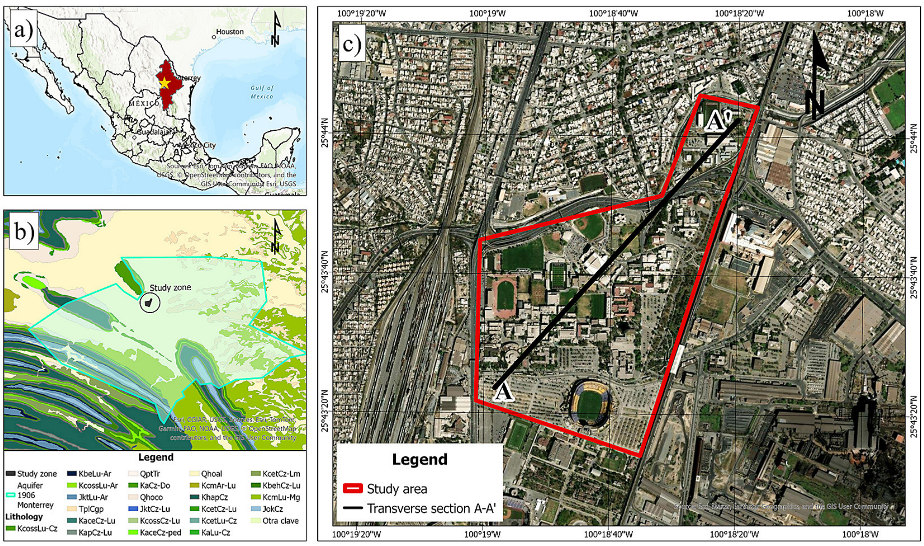

Figure 1. Study area location: (a) location of Nuevo León state, (b) aquifer of the Metropolitan Area of Monterrey, including the highlighted study area, and (c) study area boundaries (modified from the Mexican Geological Service and Google Earth, 2024)

extracted (De León et al., 2017). The aquifer in the study area belongs to the lithological pore/gravel aquifer classification. The aquifer under study is composed of lithology that includes alluvial sediments, such as gravels, sands, silts, and clays, with calcareous cementation, as well as cemented gravel channels that range in thickness from 21 to 25 m. These sediments rest on top of the Méndez Formation shale. Their matrix contains distributed cementitious cement, filling the pores between the gravels (De León et al., 2021) (Figure 2). Monitoring over the years indicates that the piezometric levels in the "UANL campus" aquifer range from 499 to 518 meters above sea level (masl), with groundwater flow directed from southwest to northeast. The piezometric gradients fluctuate between 5.4% and 8.4%, classifying the aquifer as stable and dynamic. Figure 3 illustrates the piezometry of a specific measurement, which represents the hydrogeological conditions (García, 2017).

Hydrogeochemistry

Three predominant water families exist in the Monterrey aquifer: mixed-calcic, bicarbonate-calcic, and sulfate-calcic water. The chemical composition of the mixed-calcic water family can increase the solubility and mobility of PTEs, while the presence of bicarbonate-calcic and sulfate-calcic waters suggests mixing water processes with different chemical histories and potential contamination sources, which could contribute to the dispersion of PTEs (García, 2017). High concentrations of coliform bacteria, Cl^-, SO_4^{2-}, and PTE such as Fe^{3+}, Al^{3+}, Mn^{2+}, Ba^{2+}, and Co^{2+}

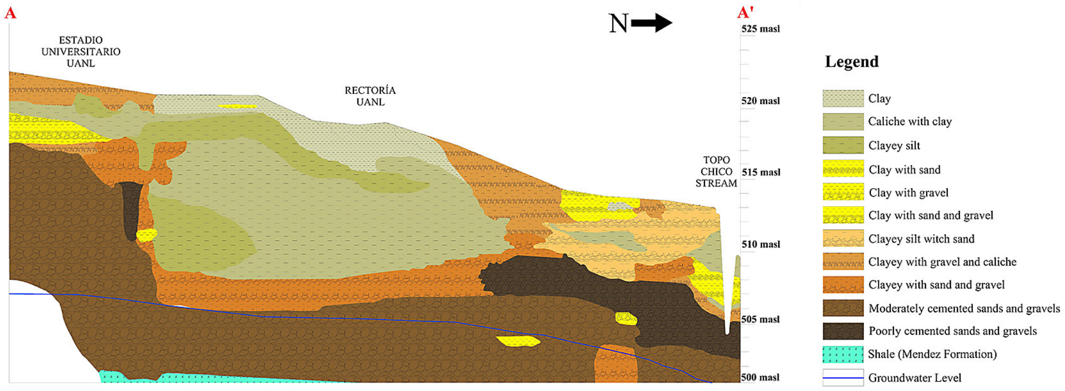

Figure 2. Hydrostratigraphic profile A-A' of the "UANL Campus" aquifer. The A-A' section is indicated on the area delimitation map (Figure 1c) (modified from Silva et al., Universidad Autónoma de Nuevo León, or unpublished data, 2015)

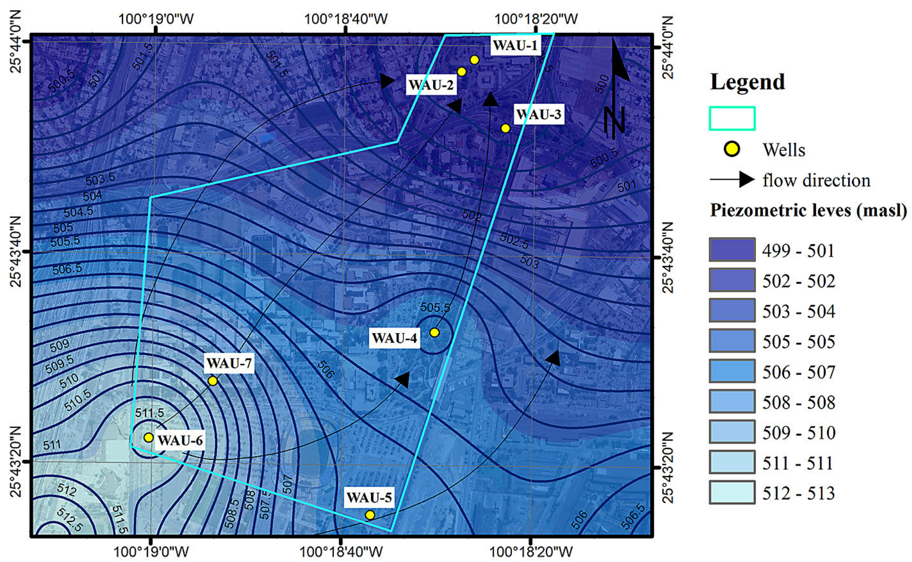

Figure 3. Piezometric map of the "UANL Campus" aquifer

have been detected exceeding the maximum permissible limits (MPL) established by national and international environmental regulations. In this way, the elevated levels of Al^{3+} and Co^{2+} could be related to the chemistry of sulfate-rich water, where acidity and the presence of sulfates enhance the dissolution and mobility of these metals (García, 2017; Pérez, 2022).

Measurement record

For the piezometric studies and sample analysis, hydraulic developments were selected during field visits, along with measurements of water temperature, pH, electrical conductivity (EC), and water table levels (Table 1). The highest temperatures and EC records were detected in the northeast of the study area. Water samples were collected under the Mexican Standard NOM-230-SSA1-2002 and analyzed through a certified laboratory "Activation Laboratories Ltd." (ActLabs/Canada), using inductively coupled plasma mass spectrometry (ICP-MS) to determine the concentrations of Al^{3+} and Co^{2+} since these PTE can be used as indicators of contamination from the metallurgical industry (Table 2).

Assessment of groundwater vulnerability

The DRASTIC model was developed to assess groundwater vulnerability to contamination by considering seven hydrogeological parameters. To obtain the model's results, each parameter is assigned a value from one to five (Table 3), with five indicating the most critical parameter. The weight for each parameter is determined based on its relative importance in contaminant propagation dynamics. To determine how each category contributes to the risk, each parameter is classified based on its impact on overall contamination risk (Al-Rawabdeh et al., 2013).

The DRASTIC model and its modification, DRASTIC-PM, assess areas vulnerable to groundwater contamination. Both models use different sets of physical parameters. To calculate the DRASTIC model, Equation 1 is used:

$$DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \tag{1}$$

where: D, R, A, S, T, I, and C represent depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity, respectively. Each parameter is evaluated based on two components: the factor rating (r), which varies according to local conditions (Table 4), and the factor weight (w), which is determined by its relevance (Table 3) (Rajput et al., 2020).

Two additional parameters are incorporated to determine the DRASTIC-PM model: pollution source mapping and water resource management. These parameters are essential to the model. To obtain results from the DRASTIC-PM model, Equation 2 is applied:

$$DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw + PrPw + MrMw \tag{2}$$

In this case, the parameters for D, R, A, S, T, I, and C are calculated as in the traditional DRASTIC. The additional parameters, Pollution source mapping (P) and Management of water resources (M), are incorporated into the model (Tables 3 and 4).

Sensitivity analysis by elimination

A sensitivity analysis by elimination was performed to evaluate the sensitivity of the DRASTIC model parameters. This analysis assesses how modifications to the input parameters impact the model's results. Sensitivity is calculated using the following formula:

$$S = \left| \frac{\frac{V}{N} - \frac{v}{n}}{V} \right| \times 100 \tag{3}$$

where: S represents the sensitivity in terms of rate of change, V corresponds to the intact vulnerability index, v to the modified vulnerability index, N is the number of parameters used to calculate V and n is the number of parameters used to calculate v (Oke, 2020).

Single parameter sensitivity analysis

A sensitivity analysis of a single parameter was carried out to evaluate the impact of each individual parameter on the vulnerability index. This was done by comparing the assigned theoretical weight with its actual effective weight. To calculate the effective weight of each parameter, the following formula was used:

$$W = \frac{PrPw}{V} \times 100 \tag{4}$$

where: W represents the effective weight of each parameter, while Pr and Pw represent the rating value and the assigned weight of each parameter, respectively. V indicates the overall vulnerability index (Ouedraogo et al., 2016).

Table 1. Field measurement register

Measurement number	Date	Well	EC (μ/cm)	Tem (°C)	P.L. (m)
1	28/06/2024	WAU-1	1450	25.6	13.37
		WAU-2	1484	25.6	14.47
		WAU-3	N/A	N/A	N/A
		WAU-4	1104	25.4	13.32
		WAU-5	903	25.0	14.56
		WAU-6	1195	25.6	13.32
		WAU-7	1098	25.3	14.56
2	21/05/2024	WAU-1	1300	25.7	15.5
		WAU-2	1391	25.7	16.44
		WAU-3	N/A	N/A	N/A
		WAU-4	941	25.4	14.28
		WAU-5	812	24.8	16.2
		WAU-6	1377	25.6	13.54
		WAU-7	1059	25.2	13.1
3	04/10/2023	WAU-1	1420	25.7	15.96
		WAU-2	1519	25.7	16.92
		WAU-3	N/A	N/A	N/A
		WAU-4	1028	25.4	14.7
		WAU-5	863	24.9	16.67
		WAU-6	1505	25.7	13.94
		WAU-7	1158	25.3	13.49
4	22/05/2023	WAU-1	1434	25.7	15.77
		WAU-2	1502	25.6	16.82
		WAU-3	N/A	N/A	N/A
		WAU-4	1009	25.3	14.47
		WAU-5	829	24.9	16.08
		WAU-6	N/A	N/A	N/A
		WAU-7	1091	25.1	13.07
5	08/02/2023	WAU-1	1498	25.5	15.69
		WAU-2	1560	25.4	16.64
		WAU-3	N/A	N/A	N/A
		WAU-4	1010	25.1	14.47
		WAU-5	840	24.5	15.06
		WAU-6	1339	25.4	13.35
		WAU-7	1085	25	13.04
6	08/11/2022	WAU-1	1512	25.5	15.54
		WAU-2	1565	25.4	16.5
		WAU-3	N/A	N/A	N/A
		WAU-4	N/A	N/A	N/A
		WAU-5	823	24.7	15.88
		WAU-6	1278	25.6	13.08
		WAU-7	1102	25	12.84

Note: N/A: Not available.

Calibration of vulnerability assessment model

The coefficient of determination (r^2) was used to assess model fit, which measures how well the model aligns with observed data (Roca et al., 2024). The formula used was:

$$r^2 = 1 - \frac{Sum\ of\ squares\ for\ regression\ (SSR)}{total\ sum\ of\ squares\ (SST)} \quad (5)$$

Table 2. Concentration of potentially toxic elements (PTE) detected in the water samples

Well	PTE	
	Al^{3+} (mg/L)	Co^{2+} (mg/L)
WAU-1	0.005	0.00021
WAU-2	0.005	0.00021
WAU-3	0.004	0.00009
WAU-4	0.002	0.00007
WAU-5	0.002	0.00009
WAU-6	0.002	0.000098
WAU-7	0.002	0.000105

Table 3. Parameters and weights applied to the two models

Parameter	DRASTIC (w)	DRASTIC-PM (w)
Depth to water	5	5
Net recharge	4	4
Aquifer media	3	3
Soil media	2	2
Topography	1	1
Impact of vadose zone	5	5
Hydraulic conductivity of the aquifer	3	3
Pollution source mapping	Not used	6
Management of water resources	Not used	7

where: *SST* measures total variability, while the *SSR* represents unexplained variability. In this study, calibration was done by evaluating the relationship between contamination indicators (EC, Al^{3+}, and Co^{2+}) and the vulnerability index calculated by the model.

RESULTS AND DISCUSSION

Vulnerability assessment of the study area was performed using the two models, DRASTIC and DRASTIC-PM, by calibrating the models with the results obtained from water sampling and water samples analysis taken from seven available wells (Figure 4). In addition, the effective weight of each parameter was calculated to determine the effective vulnerability of the DRASTIC-PM model.

Parameters and thematic maps

The thematic maps provide a clear and comprehensible visualization of the spatial distribution of each parameter for both the DRASTIC and DRASTIC-PM models. This tool was crucial in identifying areas of highest vulnerability, facilitating comparisons between the two models, and aiding in the interpretation of the results.

Depth of water (D)

Water tables were obtained from measurements taken in the studied wells and ranged from 11 to 17 m (Figure 5), thus indicating a classification of seven (Figure 6a).

Net recharge (R)

The term "net groundwater recharge" refers to the infiltrated water amount from the land surface to reach the water table (Yang and Wang, 2010). Precipitation represents a vital factor in aquifer recharge. In addition, its intensity affects the pollutants' transport and their infiltration. De León et al. (2021) reported that the net recharge of the aquifer under study fluctuates between 60 and 62 mm, according to CONAGUA records, indicating a classification of three (Figure 6b).

Aquifer media (A)

By aquifer media, we mean the consolidated or unconsolidated medium that serves as an aquifer (such as sand, gravel, or limestone) and exerts the most significant control over the route that a contaminant must follow. In general, the larger the pore size and the more fractures in the aquifer,

Table 4. Classification of parameters

Parameter	Range	Rating (r)
Depth to water (m)	0–5	10
	5–10	9
	10–30	7
	30–50	5
	50–75	3
	75–100	2
	100 <	1
Net recharge (mm/año)	> 254	9
	177.8–254	8
	101.6–177.8	6
	50.8–101.6	3
	0–50.8	1
Aquifer media	Massive shale	2
	Metamorphic/igneous	3
	Weathered metamorphic/igneous	4
	Thin bedded sandstone, limestone, shale sequences	6
	Massive sandstone	6
	Massive Limestone	6
	Sand and gravel	8
	Basalt	9
	Karst limestone	10
Soil media	Non-expansive and aggregate clay	1
	Organic soil	2
	Clay loam	3
	Silty loam	4
	Loam	5
	Sandy loam	6
	Expansive and/or aggregate clay	7
	Peat	8
	Sand	9
	Gravel	10
	Thin or absent	10
Topography (%)	0–2	10
	2–6	9
	6–12	5
	12–18	3
	> 18	1
Impact of vadose zone	Silt/clay	1
	Shale	3
	Limestone	6
	Sandstone	6
	Stratified limestone, sandstone, sandstone, shale	6
	Sand and gravel with significant silts and clays	6
	Metamorphic/igneous	4
	Sand and gravel	8
	Basalt	9
	Karst limestone	10

Hydraulic conductivity (m/day)	4.84–14.52		2
	14.52–33.89		4
	33.89–48.4		6
	48.4–96.8		8
	> 96.8		10
Pollution source mapping	Downstream of the source		10
	Source	> 0.1	8.7
		0.1–0.2	8.2
		0.2–0.3	7.7
		0.3–0.4	7.2
		0.4 >	6.7
	Upstream of the source		6
Management of water resources	Potable		10
	Domestic		9
	Irrigation		6
	Non-use		4

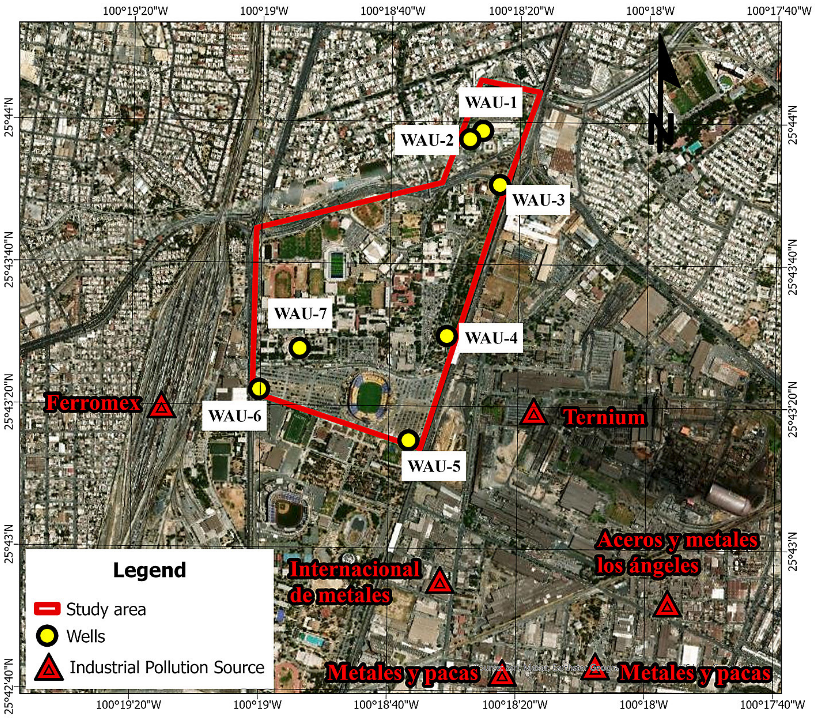

Figure 4. Location of the wells in the studied area, including nearby potentially polluting industries (edited in Google Earth, 2024)

the greater the permeability and the lower the attenuation capacity; consequently, it results in the highest contamination potential (Patel et al., 2022). This map was prepared from stratigraphic profiles (Figure 2). The aquifer media consists mainly of gravels, sands, silts, and clays; the classification of eight was assigned to the entire study area (Figure 6c).

Soil media (S)

The soil media represents the surface layer of soil, and it plays a critical role as it is the initial pathway for contaminant migration to the water table (Rehman et al., 2024). At a thickness of one meter or less, this parameter significantly impacts the amount of recharge that can infiltrate the soil, thereby affecting the ability of a contaminant to

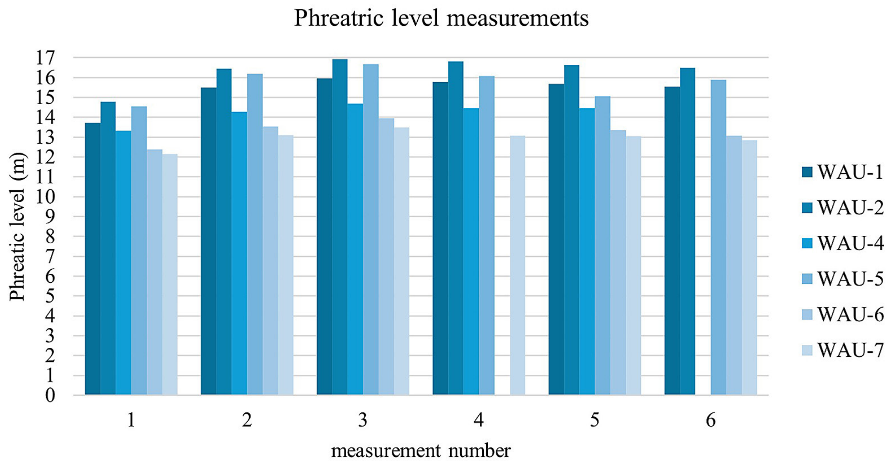

Figure 5. Recording of water table measurements

move vertically into the vadose zone (Patel et al., 2022). A rating of ten was assigned to gravel, nine to sand, and seven to clay (Figure 6d).

Topography (T)

Topography refers to the slope of the land surface, which influences the likelihood that a contaminant will runoff or remain on the surface before infiltrating. On steep slopes, infiltration and vulnerability to contamination are lower, as water tends to run off quickly. In contrast, water remains on the surface longer on gentler slopes, facilitating more significant infiltration and increasing vulnerability. The study area exhibits a slight slope (0.0004–0.28%) (de León Gómez et al., 2021), corresponding to a rating of ten (Figure 6e).

Impact of vadose zone (I)

The vadose zone is the unsaturated zone above the water table (Patel et al., 2022); the study area consists of sand and gravel with silts and clays. A rating of six is assigned according to lithology (Figure 6f).

Hydraulic conductivity (C)

Hydraulic conductivity refers to the ability of the geologic materials in the aquifer to transmit water, which in turn controls the flow rate. Hydraulic conductivity varies between 90–95 m/day, corresponding to a ten rating (Figure 6g).

Pollution source mapping (P)

The addition of a detailed map pollution sources, enabling us to pinpoint the specific locations where human activities may introduce contaminants into the aquifer. This parameter provides critical information on potential threats and helps to adjust the assessment of vulnerability based on the proximity and type of contaminant sources. Thus, a more accurate picture of the actual risk of contamination is obtained. The classifications were defined according to the distance of the sampled site from the pollution source and whether it was upstream, downstream, or at the source (Figure 6h).

To assess risk, it is essential to consider the toxicity and the amount of harmful substances coming from each contamination source. Therefore, developing a detailed inventory of potential contamination sources, including their characterization and location, is crucial. In addition, to examine the contamination exposure routes, it is necessary to create a natural vulnerability aquifer map, which illustrates the degree of protection the physical environment offers to groundwater against human activities that could cause contamination (González et al., 2018).

Management of water resources (M)

Incorporating water resource management into the analysis enables us to assess how current water use and management practices impact aquifer vulnerability. Each water use was categorized as potable, domestic, irrigation, or non-use (Figure 6i). Sustainable management of water resources is crucial for socioeconomic development, particularly in regions with limited freshwater resources. Therefore, it is essential to know the status of water sources and understand the factors that impact their reserves and quality to ensure an adequate supply for the local population (White et al., 2007; White and Falkland, 2010).

Vulnerability maps

Pollution vulnerability maps indicate the areas that are most and least vulnerable to pollution. The conventional DRASTIC index is divided into four vulnerability classes, ranging from 72 to 200 (Table 5) (Soyaslan, 2020).

For the DRASTIC model, the vulnerability indices ranged from 155 to 161. These values were used to create a pollution vulnerability map and classify high vulnerability (Figure 7a). In contrast, for DRASTIC-PM the values ranged from 268–289, are classified as very high vulnerability to pollution parameters (Figure 7b). In both cases, the zones of highest vulnerability were concentrated in hydraulic developments WAU-1, WAU-2, and WAU-3, related to the northeast zone of the study area, which the flow direction would influence.

Calibration and validation of models

The efficiency of the DRASTIC and DRASTIC-PM models was validated by calculating the determination coefficient (r^2). To calculate this coefficient, the vulnerability index was plotted against the measured values in the EC, Al^{3+}, and Co^{2+} fields. These are essential parameters since they are presented in the processes of the metallurgical industries near the study area.

Groundwater contamination by PTE such as Al^{3+}, and Co^{2+}, among others, represent one of the most significant worldwide issues; due to their

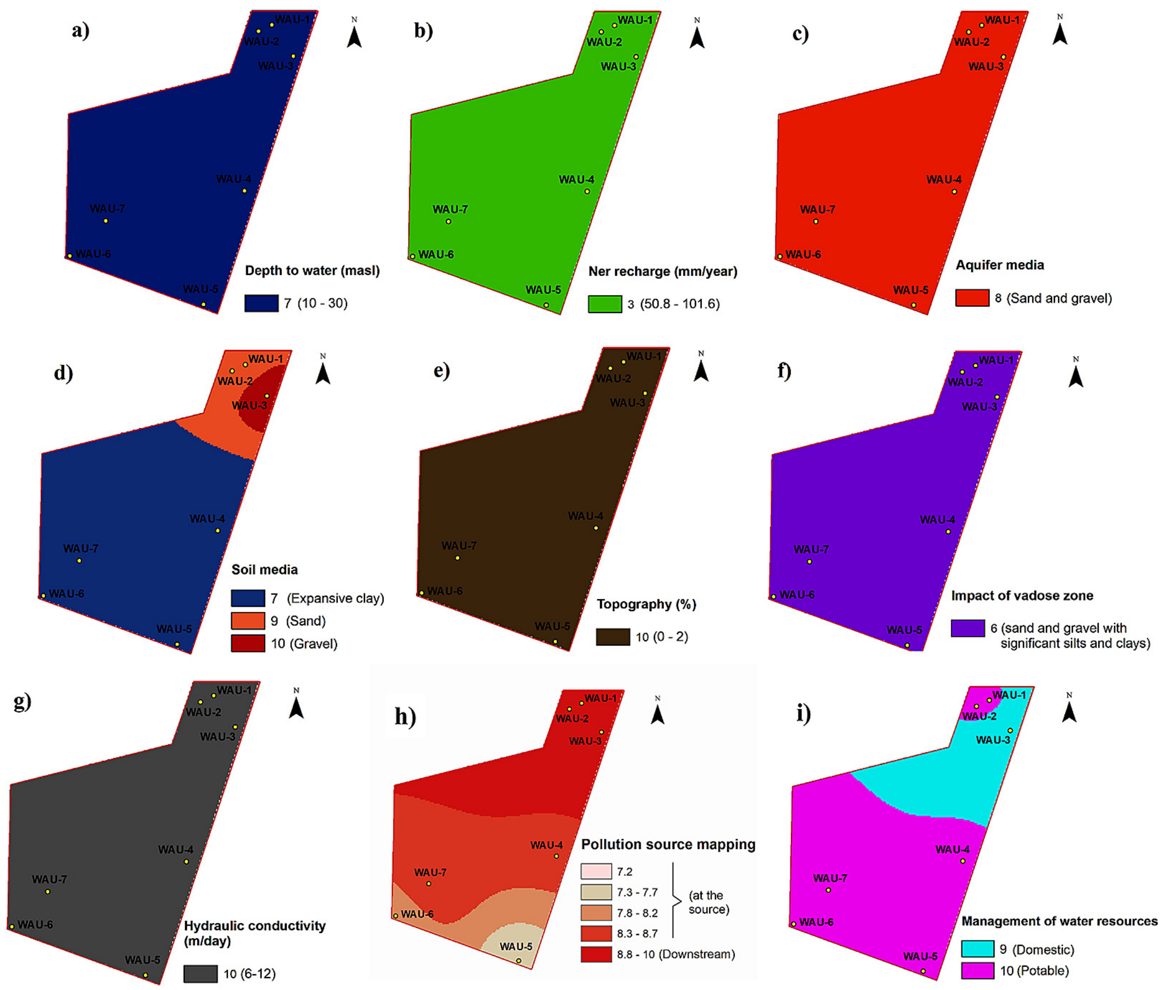

Figure 6. Classification maps (a) depth to water, (b) net recharge, (c) aquifer media, (d) soil media, (e) topography, (f) impact of the vadose zone, (g) hydraulic conductivity, (h) pollution source mapping, and i) management of water resource

Table 5. Values and classes of the DRASTIC model

Value	Class
72–100	Low
100–140	Moderate
140–200	High
200 <	Very high

toxicity, they are considered a serious population problem, especially if it is considered that the increase in the concentration of PTE in water comes from the various anthropogenic activities, also raising the potentially harmful effects on the different ecological systems and the environment in general, which are the human life support (Pabón et al., 2020).

Figure 8 shows the scatter plots comparing the DRASTIC and DRASTIC-PM vulnerability indices with CE, Al^{3+}, and Co^{2+} values. It is observed that, for the DRASTIC model, the r^2 values are 0.61 for CE, 0.78 for Al^{3+}, and 0.27 for Co^{2+} (Figure 8a). In contrast, the DRASTIC-PM model shows higher r^2 values, with 0.63 for CE, 0.89 for Al^{3+}, and 0.64 for Co^{2+} (Figure 8b). These results indicate that the DRASTIC-PM model offers superior performance, attributable to the addition of the two parameters "M" and "P" within the conventional DRASTIC model, thus improving its effectiveness in identifying vulnerable areas.

Sensitivity analysis by elimination

A sensitivity analysis was performed by sequentially eliminating one parameter at a time to evaluate the influence of each parameter on the DRASTIC-PM model, identifying which parameters are critical for the model's accuracy and effectiveness (Table 6). The results showed a high value of the index of variation (%) when eliminating topography, followed by mapping pollution sources, net recharge, and soil type, which shows that these are essential parameters in evaluating the vulnerability index. However, excluding the water resource management layer caused a significant fluctuation in the vulnerability index, resulting in a mean variation rate of 1.75%, indicating a strong association between the use of water development and the potential for contamination. This impact can be attributed to the crucial theoretical weight assigned to this parameter.

Single parameter sensitivity analysis

The effects of individual parameters on aquifer vulnerability were determined using the DRASTIC-PM model and evaluated through a single-parameter sensitivity analysis (SPSA). Table 7 provides a summary of the statistical results of this analysis. Significant differences were identified by comparing the theoretical weight with the effective weight determined by SPSA. For example, the effective weight for hydraulic conductivity was 10.76%, compared to a theoretical weight of 8.33%. Likewise, aquifer media, soil media, topography, water resource management, and pollution source mapping showed effective weights of 8.61%, 5.72%, 3.59%, 24.76%, and 18.94%, respectively. Notably, these effective weights were higher than their theoretical counterparts, suggesting that these parameters have been underestimated in vulnerability assessments. In contrast, the impacts of depth to water, net recharge, and the vadose zone were overestimated.

Table 6. Statistics of sensitivity analysis by elimination

Parameter	Variation index (%)			
	Min	Max	Mean	SD
D	0.12	0.24	0.18	0.05
R	0.83	0.87	0.85	0.02
A	0.27	0.35	0.31	0.03
S	0.51	0.76	0.67	0.10
T	0.92	0.96	0.94	0.01
I	0.01	0.09	0.05	0.04
C	0.01	0.09	0.05	0.04
P	0.62	1.25	0.98	0.25
M	1.38	1.87	1.71	0.17

Table 7. Statistics of single parameter sensitivity analysis (SPSA)

Parameter	Theoretical weight		Effective weight (%)			
	Weight	Weight (%)	Min	Max	Mean	SD
D	5	13.89	12.11	13.05	12.56	0.38
R	4	11.11	4.15	4.47	4.30	0.13
A	3	8.33	8.30	8.95	8.61	0.26
S	2	5.56	5.05	7.04	5.72	0.78
T	1	2.78	3.46	3.73	3.59	0.11
I	5	13.89	10.38	11.19	10.76	0.33
C	3	8.33	10.38	11.19	10.76	0.33
P	6	16.67	16.11	21.13	18.94	2.00
M	7	19.44	22.18	26.10	24.76	1.35

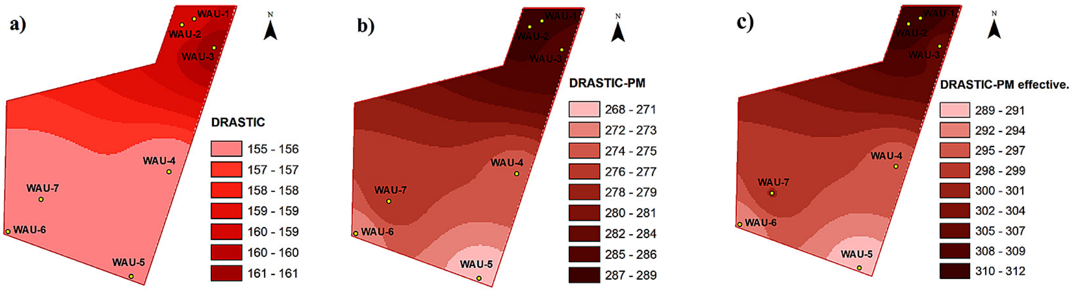

Figure 7. Vulnerability maps of the "UANL campus" aquifer, obtained by the following models: (a) DRASTIC, (b) DRASTIC-PM, and (c) DRASTIC-PM with effective weight

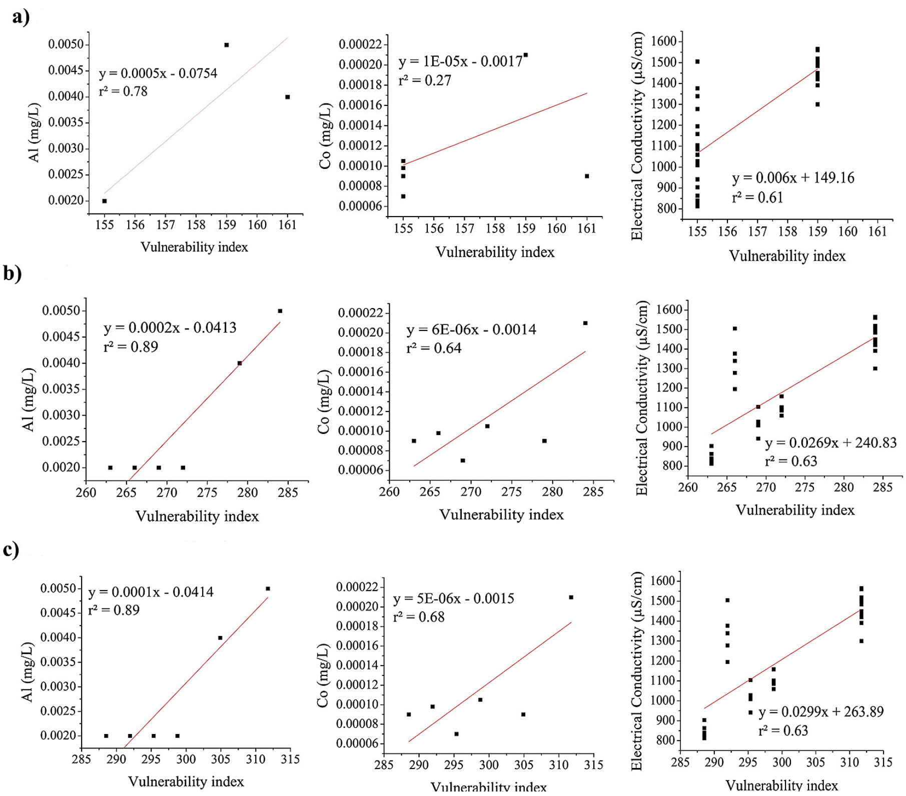

Figure 8. Scatter plots for the calibration of (a) the DRASTIC model, (b) the DRASTIC-PM model, and (c) the effective DRASTIC-PM model, showing the relationship between vulnerability indices and the concentrations of Al^{3+}, Co^{2+}, and electrical conductivity (EC)

Applying the effective weight obtained from the SPSA, the DRASTIC-PM index was recalculated, replacing the theoretical weight with the values of the calculated effective weight. This adjustment obtained the effective DRASTIC-PM indices, providing a more accurate vulnerability assessment. The effective DRASTIC-PM index values ranged from 289 to 312, reclassifying the study area as having very high vulnerability to contamination (Figure 7c). Calibration and validation of the model were performed by calculating r^2. The scatter plots revealed an improvement in correlation for Co^{2+}, with a value of 0.68, while Al^{3+} and EC kept their r^2 values (Figure 8c).

CONCLUSIONS

The assessment of groundwater vulnerability with the best possible accuracy is required for the proper utilization of the groundwater resources of the study area. Therefore, a study was carried out to assess the groundwater vulnerability of the "UANL Campus" aquifer applying the DRASTIC-PM model in the GIS environment.

The model was validated using the coefficient of determination (r^2). Regarding identifying groundwater susceptibility, DRASTIC-PM outperformed the conventional DRASTIC, reaching determination coefficients (r^2) of 0.63 for EC, 0.89 for Al^{3+}, and 0.64 for Co^{2+}.

Subsequently, through sensitivity analysis, the DRASTIC-PM model was adjusted to calculate the vulnerability indices of the refined DRASTIC-PM model. An improvement was observed in the r^2 value for Co^{2+}, reaching 0.68, while the values of Al^{3+} and CE remained unchanged.

Topography, contamination source mapping, net recharge, and soil type were highlighted as critical parameters. It was determined that the "UANL Campus" aquifer is very highly vulnerable to contamination, and its most vulnerable areas are located to the northeast.

A more accurate vulnerability assessment was obtained by incorporating the parameters of water resource management and pollution source mapping, along with the model adjustment.

This study highlights the urgent need to strengthen public policies aimed at regulating industrial pollution sources, as well as implementing real-time monitoring technologies and reactive barriers to protect urban aquifers.

Expanding the monitoring network is recommended by increasing the number of sampled wells and considering seasonal and geographical factors. It is worth noting that the analysis was conducted using publicly accessible wells, as data from private wells was not available. This aspect should be considered in future studies to achieve a more comprehensive regional understanding.

The DRASTIC-PM model can be applied in other countries, particularly in regions exposed to industrial pollution.

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