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Mapping groundwater pollution vulnerability with application in a basin in southern Brazil

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Abstract

This study presents the criteria and conditions that supported the development of a proposed vulnerability index and its application in the Córrego do Ribeirão do Feijão Basin, which is located in the central portion of the state of São Paulo, southeastern Brazil. This basin was selected, because it is representative of very large areas in the south, west, and southeast regions of Brazil, is the main source of freshwater for the municipality of São Carlos, and has been undergoing accelerated changes due to diversified anthropogenic activities, thus increasing the number of contaminant sources. The proposed index is based on a hierarchy of information that includes a total of 46 attributes categorized into groups (4 rainfall attributes, 6 point contaminant sources, 5 non-point contaminant sources, 5 unconsolidated material 1, 4 unconsolidated material 2, 4 rock substrate 1, 4 rock substrate 2, 1 relief, 6 unconsolidated material 3, 4 rock substrate 3, and 3 groundwater), which were obtained from principles and procedures of engineering geological mapping and laboratory tests. The final vulnerability index for each land unit was obtained as a percentage using the total vulnerability index, which is the sum of the partial indices (these indices are normalized eigenvectors of the unit) and the maximum value that a unit can reach, considering the classes of maximum influence in vulnerability. The basin was divided into 29 categories controlled by engineering geological units and types of land uses, resulting in 94 land units, of which 17 were classified as Class 1, with the highest vulnerability; 41, 23, and 13 were classified as Classes 2, 3, and 4, respectively, with decreasing degrees of vulnerability. The results verify that the proposed index enables an adequate subdivision of the region and classification of the units, respecting the natural variability and the anthropogenic aspects. The attributes associated with land units and the datasheet used for data treatment permit a dynamic vulnerability analysis, because it is easier to identify and characterize the anthropogenic changes (mainly related to contaminant sources) per land unit in situ and to obtain new results that will require new control or planning measures.

Keywords Groundwater vulnerability · Attributes · Vulnerability index · Ribeirão do Feijão Basin · Brazil

Introduction

Meeting the increasing need for water with sufficient physicochemical and biological quality to meet human, agricultural, livestock, and leisure demands is hampered by the decreasing availability of water sources of this quality. This decrease is partially due to anthropogenic changes that affect the infiltration and storage rates but mainly due to the increasing number of contaminants associated with the different types of land uses and the effects on environmental components. Such conditions are directly controlled by the management and technologies applied in the disposal, storage, use, and control of the amount of contaminants. Among the affected environmental components are surface water and groundwater; in this aspect, when groundwater is affected by contaminants, there is contamination of the geological materials (rocks and unconsolidated materials), and contamination of surface water through discharge zones (springs) can also occur. Contamination of the entire biological and food chain may occur, which will have a broad effect on society.

In the case of subsuperficial waters (saturated and vadose zones), some studies that highlight management and consequent planning to maintain groundwater's availability and quality stand out. The first is the assessment of the degree of alteration of these waters, the second is the estimated availability, and the third is their vulnerability to the possible

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installed and/or planned sources of contaminants, considering the foreseen uses for a given region. Moreover, vulnerability studies are essential for the analysis and estimation of possible contamination and also provide fundamental information for territorial planning, aiming at maintaining the quality of groundwater storage. Since the 1970s, studies involving vulnerability estimates have been performed in both technically and economically developed and developing countries, with dozens of methods developed for scales ranging from very small for large areas (large basins and countries) to large scales for small areas (first-order basins). However, the same procedures have been applied to conditions of very different environmental components, with some results not revealing the actual vulnerability conditions. Others are based on a reduced set of information about the environmental components involved in the contaminant flow, which can include very distinct areas in the same category.

The predictability of groundwater contamination is a complex process, because it depends on natural and anthropogenic information and contains a significant degree of uncertainty, such as contaminant sources, potential infiltration capacity, distribution of infiltrated waters, and different physical and chemical conditions of the water and geological materials. One method to assess the potential for contamination is to consider the contaminant sources and waters and to assess the vulnerability aspect by considering the characteristics of the geological environment. Groundwater vulnerability cannot be measured directly in the field, although it is possible to identify units that present different contamination conditions and, therefore, different degrees of vulnerability. This zoning can be developed via mathematical models or several types of analyses based on information that represents the system and a conceptual model.

The importance of vulnerability studies has been discussed in several publications. Recently, there have been noteworthy suggestions from several professionals regarding the importance of the topic and the need to consider data that provide a more representative index in terms of vulnerability, such as Witkowski (2016), Iván and Mádl-Szőnyi (2017) and Baalousha (2017).

A proposal and application of a vulnerability index method based on information that reflects the different natural and anthropogenic environmental components that interfere in the process of groundwater contamination was developed. The process considers the following basic assumptions: the use of logical tree resources to structure the information in a hierarchy; sequential discretization of the problem; the variability of geological materials, vadose and saturated zones, diffusion, and point contaminant sources; and terrain units delimited based on engineering geological zoning associated with land-use types.

Literature review

The estimation of groundwater contamination is a complex problem requiring data from different areas of study, scales, and magnitudes of the involved mechanisms and processes. These studies can be classified into three main categories: analyses of vulnerability before the installation of possible sources of contamination, analyses of the vulnerability of groundwater to installed contaminant sources, and analyses aimed at generating guidelines and standards for territorial and environmental planning.

The studies are complex, because predicting the extent of contamination varies over small distances, often less than a 1000 m because of the natural attenuation processes that occur in the space from the source of contamination to the considered groundwater depth associated with the flow conditions. These studies have multiplied in the last 50 years, with pioneering works by Le Grant (1964) and Albinet and Margat (1970), who coined the term groundwater vulnerability. However, the term has undergone conceptual variants, depending on the researchers, scale of analysis, country, and methods and procedures, as can be observed in the works of Rao and Alley (1993), Vrba and Zaporozec (1994), Zaporozec (2002), Gogu et al. (2003), Worrall and Kolpin (2004), and Witkowski (2016).

The most well-known concept used by the professionals involved in this subject is that of Rao and Alley (1993), which conceptualizes groundwater vulnerability as the possibility of a contaminant reaching a certain position in the saturated system (hazardous event) when a contaminant is disposed at a point topographically above the analysed point. In general terms, the vulnerability of a groundwater system, according to Gogu and Dassargues (2000), can be developed in two directions: the intrinsic condition, which is only based on geological, hydrogeological and hydrological factors without considering the possible sources of contaminants, and the specific condition, which addresses the assessment of the contaminants and their interrelationship with the aspects considered in the intrinsic condition.

These different methods and procedures can be grouped into seven categories: geological complexity and clustering methods (MODEL BASED ON REGIONAL GEOLOGIC FRAMEWORK, DIVERSITY, and GALDIT vulnerability index); methods focused on indices (DRARCH, MLPI, LPI, AVI, PI, COP, and RI); analogic methods (AlbinetandMargat, USEPA, and BRGM); parametric methods (DRASTIC,GOD, EPIK, SINTACS, FLEMISH METHOD, VULPEST, VLDA model, DRASTICA model, NEURO-FUZZY TECHNIQUES, and DRAV model); mathematical methods (MODFLOW, GLEANS, PRZN, AEM/DRASTIC, SEEPAGE, SEEP/W, and SEEPAGE);

statistical methods (PCASD, GLA, AGRIFLUX–MOD-FLOW, GERMAN METHOD, MULTIVARIATE STATISTICAL ANALYSIS, DASTI/IDRISI, and PESTANS); combined methods (CNR-GNDCI, USGS, EVARISK, and AQUIPRO); and methodologies coupling travel time estimation and rating methods (APLIE method).

Because these methods produce different results for the same area, some authors, such as Neukum and Hötzl (2006), have attempted to propose a relationship between the different results, although the variability of attributes considered in the different methods is limited. It should be noted that many of these methods have been modified for applications in specific regions with changes in attribute classes and simplifying or increasing complexity, such as the recent examples of Mishima et al. (2011), Duarte et al. (2015), Dickson-Anderson et al. (2015), Sahoo et al. (2016), Bonfanti et al. (2016), and Boufekane and Saighi (2018). Others have developed procedures to specific natural conditions, e.g., Zhou et al. (2012), Huneau et al. (2013), and Jia et al. (2014).

The methods and procedures cited above present some points in common that should be highlighted:

1. The attributes/information used in the different methods varies widely, which leads to very different results for the same area.
2. The methods do not usually separate intrinsic vulnerability from specific vulnerability.
3. The concepts of vulnerability considered in the different methods vary, even when the same method is applied in different areas and by different professionals.
4. When data about contaminant sources are used, the data do not often reflect the intensity or magnitude.
5. Most of the methods used do not consider data regarding contaminant sources and anthropogenic aspects.

Proposal and development of a vulnerability index

The main point of this work is the proposal of a set of procedures that consider the following aspects:

1. Use of the conceptually most appropriate context, which is the assessment of specific vulnerability.
2. The water of the saturated and unsaturated zones as the environmental component responsible for the maintenance and continuity of the surface channels and subsurface storage.
3. The data associated with specific data acquired in posterior studies should allow for risk analysis in the future.
4. The result should generate the classification of the land units in terms of the vulnerability grading based on the

final vulnerability index values obtained using all attributes for units relative to the reference value (maximum or minimum values of the total vulnerability index).

The proposed index is based on the following aspects of geological materials, contaminant sources, and methods to acquire the data:

1. The spatial variability of the geological materials, mainly unconsolidated materials.
2. Large extensions consisting of zones with infiltration conditions that respond on large scales.
3. Attributes that are obtained by engineering geological mapping procedures, e.g., those proposed by Zuquette, Pejon and Collares (2004), without the requirement of sophisticated equipment, although they must represent the characteristics of the environment.
4. Costs and uncertainties related to obtaining the information. The set of procedures and methods must have a reasonable cost, and the uncertainties should fit within the work scale and the data type.
5. The diversity and specific characteristics of contaminant sources.
6. The relationships between the mechanisms related to the introduction of the contaminant, transport of pollutants in porous media and natural attenuation.
7. Application at scales preferably larger than 1:50,000. The purpose of an analysis and vulnerability map is the possibility of application for different purposes, i.e., spatial or specific planning, which is possible only at scales larger than the considered magnitude.

To satisfy the previous conditions, the following aspects were considered:

1. The attributes and their classes are hierarchically ordered from the lowest to the highest influence in the context of vulnerability.
2. The degree is related to the potential magnitude of the contaminant load that would reach the depth level under analysis.
3. The contaminant load and the degree of vulnerability are functions of four major aspects of the analysis:

- The analysis of the contaminant sources according to the magnitude and contaminant types.
- Contaminant transport to the depth level under analysis.
- The natural attenuation conditions of geological materials.
- The conditions of redistribution of contaminants and biogeochemical reactions.

The main components that control the contaminant flow process in geological porous media are the following:

1. The introduction of contaminants from a source in contact with the geological materials.

   This aspect depends on the availability of contaminants in a liquid solution and the liquid volume to transport them from the contaminant source to the geological environment as well as the propagation and distribution to varying depths.

2. The propagation of contaminants in the geological environment to the analysed depth (contaminant transport).

   The propagation depends on the amount and types of liquids, the porosity and the characteristics of the voids, and the spatial distribution of the geological materials that control the variability of the hydraulic properties and flow conditions.

3. The interactions of the contaminants with the water and geological materials as well as decay reactions, degradation aspects, sorption and other processes that constitute natural attenuation.

Figure 1 shows a diagram of the relationships among the fundamental components in the groundwater vulnerability assessment with the separation of different aspects that are part of the three basic components (source of contaminants, geological materials, water, anthropogenic conditions, and water conditions—vadose and saturated) and the interactions that should be assessed in vulnerability studies.

Based on Fig. 1, it is found that the following basic conditions must be considered in the proposal of a vulnerability index:

1. Type of contaminant sources in spatial (point or diffuse) and temporal (continuous or pulse) terms.
2. Conditions for introducing water or other contaminated liquids from the surface.
3. Flow conditions in saturated and unsaturated zones.
4. Processes involved in the transport of contaminants in the geological environment (advection and hydrodynamic dispersion).
5. Aspects of sorption, desorption, fugacity, and retardation that interfere with and control natural attenuation conditions.
6. Biogeochemical reactions that result in precipitations, chemical compound releases, decays, and degradations.
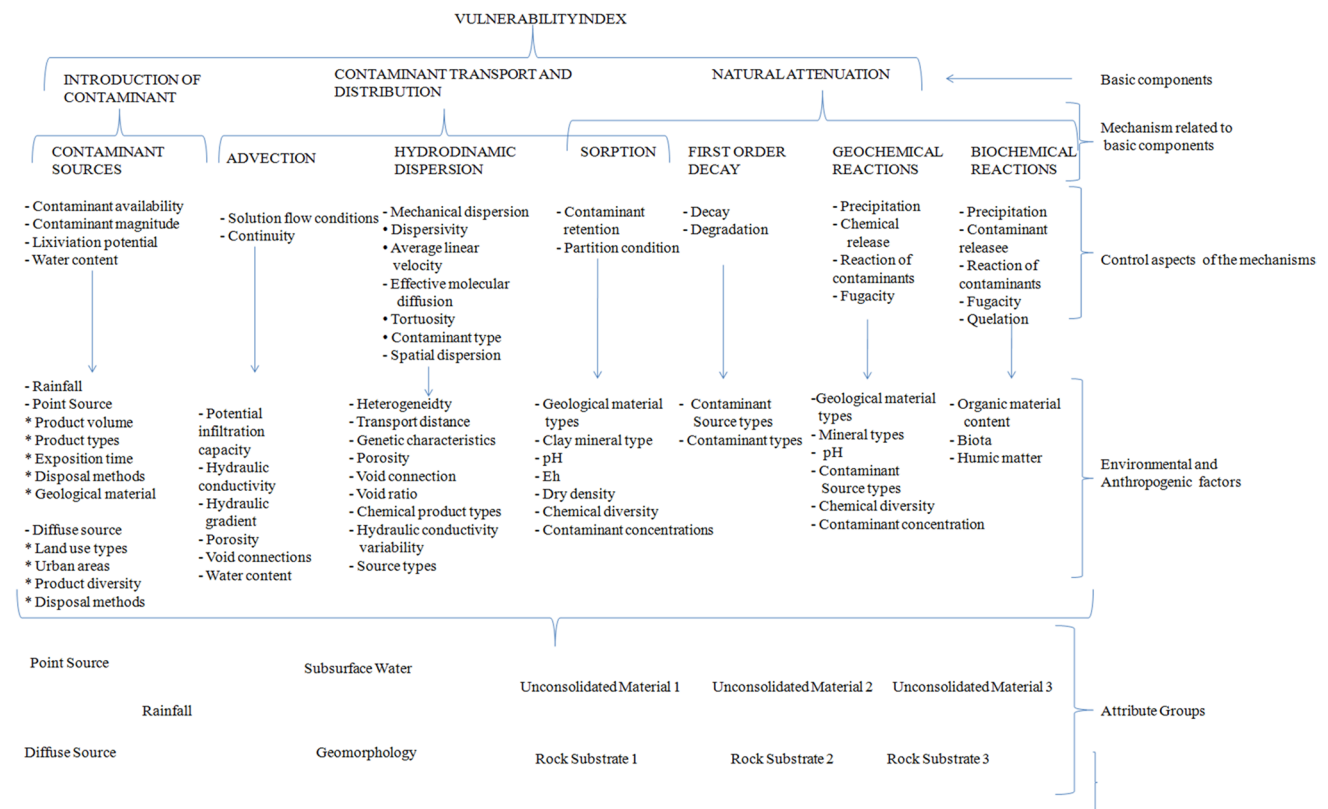

Fig. 1 Hierarchical levels and respective constituents considered to obtain the Vulnerability Index

7. The (two-dimensional)equation that governs the transport of contaminants, which incorporates the following factors: advection, contaminant sources, hydrodynamic dispersion, sorption and retardation aspects, irreversible reactions, and other reactions among the chemical components:

$$\overbrace{\left(1 + \frac{\rho_d}{\theta}\frac{\partial \bar{C}}{\partial C}\right)}^{\substack{\text{Retardation}\\\text{aspects}}} = \overbrace{\frac{\partial}{\partial xi}\left(D_{ij}\frac{\partial C}{\partial xj}\right)}^{\substack{\text{Hydrodynamic}\\\text{disperson}}} - \overbrace{\frac{\partial}{\partial x}(ViC)}^{\substack{\text{Retardation}\\\text{aspects}}} + \overbrace{\frac{qs}{\theta}Cs}^{\substack{\text{Advection}}} \quad - \overbrace{\lambda\left(C + \frac{\rho_d}{\theta}\bar{C}\right)}^{\substack{\text{Contaminant}\\\text{sources}}} + \overbrace{\left(\frac{\partial C}{\partial t}\right)\text{reac},}^{\substack{\text{Reactions}}}$$

where C—dissolved concentration; $\bar{C}$—sorbed concentration, which is a function of the dissolved concentration, C, as defined by the sorption isotherm; V_i—average linear water velocity; D_{ij}—dispersion coefficient tensor; qs—flow rate of a fluid source per unit aquifer volume; Cs—contaminant concentration of the fluid source; Θ—porosity; λ—reaction constant; ρ_d—bulk density of the porous medium; t—time; x—longitudinal direction; and React—the biological or chemical reaction of the solute (other than sorption).

8. The position of the target depth of the saturated zone in relation with the geological materials generates two conditions: the depth of the saturated zone is positioned only within the unconsolidated materials (above the top of the rock substrate) or in the rock substrate (below the top of the rock substrate), which both demand different information to obtain the vulnerability index. In the first condition, the rock materials do not interfere with the contaminant flow or the final vulnerability index. However, in the second condition, the rock and unconsolidated materials should be considered

Considering the spatial limits and the possibilities of both conditions, it is observed that the following basic data are essential:

- Saturated zone depth.
- Depth of the rock substrate.
- Type of contaminant sources and its characteristics.
- Position (depth) of release of the contaminant to the geological environment.
- Source of water (rain, introduction with the contaminant or anthropogenic not related to the contaminant).
- Characteristics of the geological materials between the base of the contaminant source and the position of the groundwater level in question.
- The need to address the understanding of the flow in the direction of interest between the contaminant source base and the point (depth in question to obtain vulnerability).

Selection of attributes

One of the major challenges in proposing an index for vulnerability estimation is the set of criteria to select the attributes that actually control the process. In this case, three basic components are needed: introduction of the contaminant from a source in contact with the geological environment, propagation of the contaminant in the geological environment to the analysed depth, and the interactions of the contaminants with the water and the geological materials between the base of the contaminant sources and the analysed position.

In the process, the relationships between the introduction of contaminants, contaminant transport, natural attenuation, characteristics of the contaminant sources, waters and geological materials (considering the mechanisms and control aspects of the mechanisms), and environmental and anthropogenic factors that affect the cited aspects and consequently the mechanisms are needed. These relationships were used to define the hierarchical levels and attribute groups in this study.

The achievement of the final vulnerability index is focused on a hierarchical chain of five levels, which were defined by the initial subdivision and the logical trees developed from hierarchical level 1 to level 5, which is related to the most detailed level. The levels are defined as follows:

Hierarchical Level 1—final vulnerability index (FVI), which is the purpose of the proposal.

Hierarchical Level 2—this is the main subdivision, i.e., the basic components composed of the mechanisms, processes, and functions that affect the migration of the contaminants in the natural porous environment (introduction of the contaminant, transport and redistribution, and natural attenuation).

Hierarchical level 3—this level represents the grouping of the aspects at a detailed level than just the basic components alone, representing a set of interrelated information (attribute groups).

Hierarchical level 4—this level includes the attributes that characterize the different groups of hierarchical level 3. The attributes should be identified and characterized based on field and laboratory studies.

Hierarchical level 5—this level brings together all classes related to the attributes that allow the characterization of an area and its classification.

The hierarchical arrangement of the information allows for different methods of data processing, such as weight methods, rating indexes, fuzzy theory, overlapping, matrices, statistics, scoring, and methods that use combinations of the above.

The attributes and definition of the respective classes were selected based on the following aspects as well as the mechanisms and processes involved in contaminant transport in natural porous media:

1. The groups of hierarchical level 3 were defined considering that they gathered attributes related to the different mechanisms, processes, and functions involved in the movement of a contaminant between the sources and the analysed depth.
2. The attributes were selected based on their importance in the process as well as their interrelationships with more than one mechanism, either directly or indirectly.
3. The classes were adopted based on the following points:

   - The amplitude of the data variations based on both the natural occurrence and anthropogenic characteristics.
   - The interference of the extreme classes for the different mechanisms, processes, and functions.
   - When adopting nominal or ordinal classes, limits or descriptions should be mapped to a scale greater than 1:50,000.
   - The classes of each attribute were defined considering the following points:

1. The maximum and minimum classes are directly related to extreme movement of contaminants in natural porous media.
2. The maximum number of classes for each attribute cannot be greater than 7 to avoid a large number of mapping units, which would make it difficult to apply the classes in regions with high spatial variability.
3. The maximum and minimum classes must be valid for the most regions in terms of their geological conditions and contaminant source types.
4. The classes should reflect the degree of sensitivity in terms of the contaminant movement and geological variability.
5. The data of the maximum and minimum classes must be easy to obtain in the laboratory or in the field.
6. The maximum and minimum class results must generate conditions for the proposal of intermediate classes with real significance.
7. The use of the maximum class values should represent a potential for groundwater contamination at the determined depth level and over short time periods, generally less than 10 years.

For the selection of the attributes and classes, logical trees were used; 46 logical trees were elaborated, one for each attribute. All aspects related to vulnerability attributes, and respective classes could be analysed. One example of logical tree is shown in Fig. 2.

From the developed relationships, we defined ten groups of attributes that aggregate different attributes and respective classes, namely, rainfall, point and diffuse sources, groundwater, unconsolidated material 1 and rock substrate 1 (advection), unconsolidated material 2 and rock substrate 2 (hydrodynamic dispersion and redistribution), and unconsolidated material 3 and rock substrate 3 (sorption, reactions, and chemical precipitations). The global procedure is organized into five hierarchical levels from the top (hierarchy level 1) to attribute classes (hierarchy level 5) with respective elements used to define the weights and obtain the eigenvector for each element of each hierarchical level, as shown in Table 1.

Definition and assignment of weights

After the development of all hierarchical levels (Table 1—cols. 1, 2, 4, and 6), the weight assignment phase was conducted for all items of each component of the hierarchical level based on the following fundamental conditions:

1. Each hierarchical level assigns weights that denote the possibility of a higher contaminant load reaching the analysed depth, i.e., toward the highest degree of contamination.
2. The weights can be assigned based on different aspects, conditions, and criteria using the following procedures, some of which yield more effective results: simple assignment, linear evaluation, relative position, direct weights, least squares, entropy, eigenvector, minimal information trade-off assessment (MITA), and minimal pair comparison (MIPAC).
3. Considering that a system consists of "*n*" data points, a set of n-1 comparison pairs is possible, which can be assessed in three different manners: direct comparison, basic comparison group, and complex comparison group.

Based on these conditions, to obtain the numerical vulnerability index, weights ranging from 1 to 9 were adopted, as proposed by Saaty (1980), for the hierarchical analysis method; these weights are associated with the following precautions:

- The weights were defined by comparisons of direct importance based on the mechanisms, phenomena and processes.
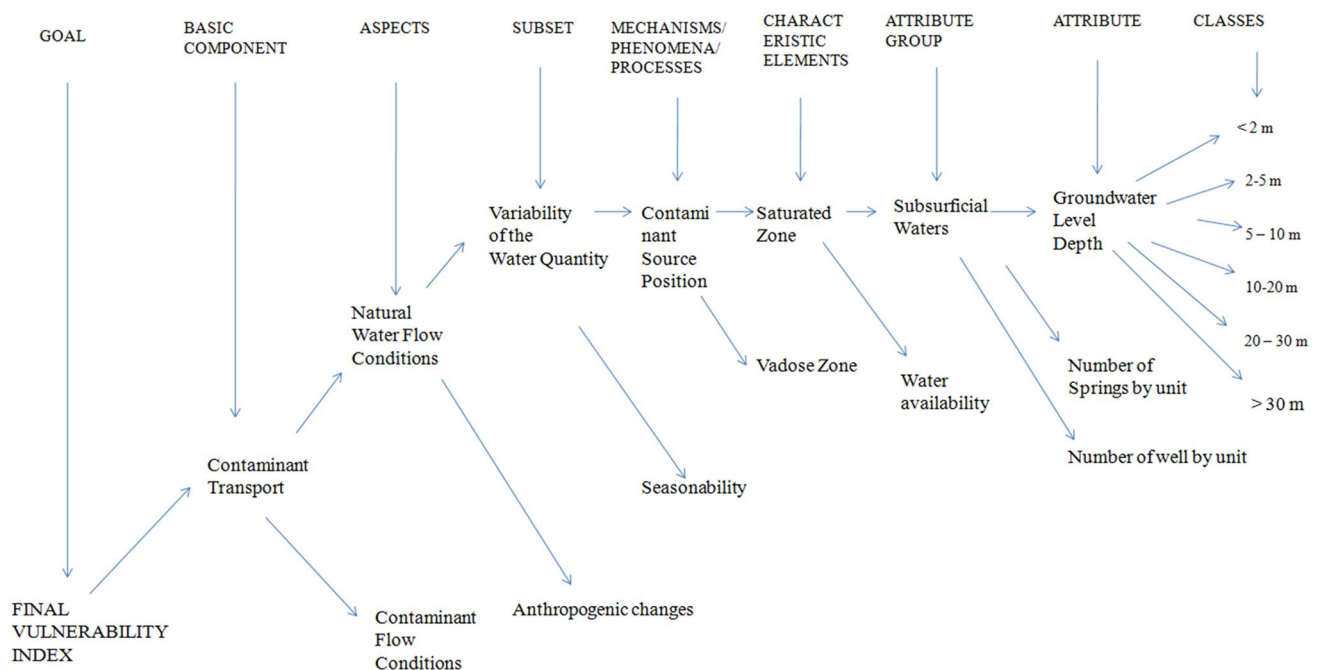
Fig. 2 Example of Logic tree developed to analyze the vulnerability conditions associated with contaminant transport considering the five hierarchic levels

- The attribution of the weights followed the complex comparison group system.
- For all information associated with each of the hierarchical levels, an eigenvector was obtained from the initial weights assigned in the previous phase.

Obtaining the final vulnerability index

Based on the matrices, with the eigenvector (partial index) values normalized and respecting the appropriate maximum eigenvalue, the consistency index and the consistency ratio, the following operations were developed:

1. A total partial index (TPI), from Table 1 (col. 8), was adopted for the different aspects relevant to the hierarchical levels, including the mapped attributes and classes. The TPI values were obtained as follows:

$$TPI = (NH2 \times NH3 \times NH4 \times NH5),$$

where NH2—partial index for hierarchical level 2; NH3—partial index for hierarchical level 3; NH4—partial index for hierarchical level 4; and NH5—partial index for hierarchical level 5.

Table 1 lists the partial indices for the different hierarchical levels and the total partial index for each class of all attributes. From this table, it is possible to apply the

vulnerability index for the two conditions (ground water level above and below the top of the rock substrate) as well as to for different regions at scales greater than 1:50,000.

2. Calculation of the total vulnerability index (TVI) for each unit, according to the following expression:

$$TVI = (TPIc - \text{introduction of contaminants}$$
$$+ TPIc - \text{transport of contaminants})$$
$$- (TPIc - \text{natural attenuation of contaminants}),$$

where TVI—total vulnerability index for the unit and TPIc—sum of total partial indices for each basic component of hierarchical level 2:

$$TPIc = \sum_{1}^{n} (TPI).$$

Here, n—number of attributes and respective classes considered part of the component; and

3. Obtaining the final vulnerability index (FVI) for each unit.

To verify the amplitude and the possibility of categorization of the units in terms of the total vulnerability index (TVI), some aspects were considered:

Table 1 Partial index for basic components

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xNH4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
	Rainfall	0.539834289	Annual total volume (mm/year)	0.4209	<900	0.0553	0.00279174
					900–1350	0.0951	0.00479745
					1250–1550	0.1564	0.00788734
					1550–2000	0.2687	0.01355212
					>2000	0.4245	0.02141235
Contaminant Introduction/0.222							
			Chemical characteristics (electrical conductivity–EC/composition)	0.1894	1—Without chemical components and EC <80 microSiemens/cm	0.113549095	0.00306356
					2—With solid particles and EC varying from 81 to 500 microSiemens/cm	0.178277564	0.00480993
					3—With solid particles. Sulfites, Acid and EC varying from 500 to 1.000 microSiemens/cm	0.300603401	0.00811028
					4—With solid particles. Sulfites, Acid and EC higher than 1.000 microSiemens/cm	0.40756994	0.01099624
			Temporal distribution (months)	0.2682	>8 months	0.1410	0.00453292
					8–6 months	0.2022	0.00650004
					6–4 months	0.2698	0.00867243
					<4 months	0.3869	0.01243561
			pH	0.1215	>7.5	0.170201759	0.00247814
					7.5–6	0.206414899	0.0030054
					6–5	0.282979824	0.00412019
					<5	0.340403518	0.00495628
	Point sources	0.163161249	Waste volume or potential contaminant material storage (m³)	0.0806	<50,000	0.046383214	0.000135393
					50,000 a 100,000	0.084483711	0.000246608
					100,000 a 250,000	0.142462728	0.000415849

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xNH4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
			Exposition time (years)	0.0679	250.000 a 500,000	0.288238542	0.000841368
					>500,000	0.438431806	0.001279782
					<5	0.094415659	0.000232168
					10–5	0.150834773	0.000370903
					20–10	0.291882556	0.000717739
					>20	0.462867012	0.00113819
			Disposal techniques	0.1456	5—Sanitary landfill	0.063753213	0.000336171
					4—Controlled sanitary landfill	0.100771208	0.000531367
					3—Disposal in simple excavation	0.189203085	0.000997668
					2—Without any kind of protection and control	0.271465296	0.001431437
					1—Disposal into erosion features and natural depressions	0.374807198	0.001976358
			Waste types/biological. chemical and physic products	0.2172	6—Organic material/sand used in industries and similar materials	0.04120603	0.000324168
					5—Civil construction wastes/food industry wastes and similar	0.063819095	0.000502065
					4—Solid and liquid urban wastes/animal wastes	0.100502513	0.000790653
					3—Industrial waste and tailing/Industrial products	0.237688442	0.001308531
					2—Solid and liquid wastes from mines/ Inorganic and organic products and tailing	0.166331658	0.001869895
					1—Hazardous wastes and products	0.390452261	0.003071688
			Geological material at the base	0.1367	Low flow types	0.035275254	0.000174648
					Lithologies of Adamantina formation	0.051843934	0.000256679

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xN-H4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
					Lithologies of Pirambóia Formation	0.086050241	0.000426035
					Basalts/diabases	0.133083912	0.000658898
					Lithologies of Botucatu formation	0.258150722	0.001278104
					High flow types	0.435595938	0.002156635
			Initial water content (%)	0.352	Dry	0.04925187	0.000627961
					<25%	0.1340399	0.001709009
					25–50%	0.27680798	0.003529302
					>50%	0.539900249	0.006883728
	Non-point Sources	0.297004461	Urban areas	0.1304	5—Less than 20 thousands inhabitants	0.06375321	0.000548086
					4—From 20 to 100 thousands inhabitants without sanitary resources. Economy based on agriculture activities	0.10077120	0.00086633
					3—From 20 to 100 thousands inhabitants without or with sanitary resources. Economy based on industrial activities	0.189203085	0.001626579
					2—From 100 to 500 thousands inhabitants with partial sanitary resources. Economy based on industrial and commercial activities	0.271465296	0.002333787
					1—Higher than 500 thousands inhabitants with partial sanitary resources. Economy based on industrial and commercial activities	0.374807198	0.003222217
			Land uses types	0.1498	Natural vegetation and reforestation	0.032949791	0.000325445
					Livestock/pastures	0.062238494	0.00061473

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xNH4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
					Roads/pipeline	0.106171548	0.001048656
					Irrigated areas/fruit and vegetable crops	0.164225941	0.00162206
					Sugar cane plantation/annual cycle crops	0.197175732	0.001947505
					Land uses with high concentration of chemical products	0.437238494	0.004318605
			Diversity of used products	0.2572	Common wastes	0.060523446	0.001026357
					Livestock and agriculture organic wastes	0.10523446	0.001784566
					Fuel products	0.180479826	0.003060577
					Inorganic products	0.192475463	0.003263999
					Organic and inorganic products	0.461286805	0.007822502
			Disposal characteristics	0.3875	Indirect manners	0.086309524	0.002205122
					Direct—solid materials	0.142857143	0.003649857
					Direct—liquid products	0.264285714	0.006752236
					In excavation direct on geological materials	0.506547619	0.012941785
			Temporal continuity	0.0752	Few days/year	0.081144191	0.000402313
					Some days/years	0.154115587	0.000764105
					Seasonal—months	0.287799183	0.001426908
					Continuous/years	0.476941039	0.002364674
			Area distribution (% of the unit)	0.0631	<5	0.040180814	0.000396223
					20 a 5	0.063787042	0.000629004
					40–20	0.102963335	0.001015321
					60–40	0.166248117	0.001639373
					80–60	0.23606228	0.00232781
					100–80	0.390758413	0.003853269
Contaminant transport/0.4450	Unconsolidated materials 1	0.3515	Macroporous	0.3085	No	0.043840178	0.002113579
					1–2%	0.080466149	0.003879353
					2–5%	0.147613762	0.007116607
					5–10%	0.285238624	0.013751639

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xNH4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
	Unconsolidated Materials 2	0.2546	Infiltration rates (mm/h)	0.1679	>10%	0.442841287	0.021349821
					<10	0.051311288	0.001432457
					10–30	0.078677309	0.002196434
					31–70	0.124857469	0.003485646
					71–100	0.265678449	0.007416945
					>100	0.479475485	0.013385517
			Hydraulic conductivity (cm/s)	0.3537	<10−7	0.040180814	0.002220994
					10−6 a 10−7	0.063787042	0.003525829
					10−5 to 10−6	0.102963335	0.005691298
					10−4 to 10−5	0.166248117	0.009189365
					10−3 to 10−4	0.23606228	0.013048343
					>10−3	0.390758413	0.021599171
			Field capacity (volumetric moisture—%)	0.1068	>0.25	0.094415659	0.001575797
					0.16–0.25	0.150834773	0.002517432
					0.12–0.16	0.291882556	0.00487152
					<0.12	0.462867012	0.00772525
			Depth distribution (m)—thickness	0.1988	<2 m	0.097810219	0.002201023
					2–5	0.131873479	0.002967549
					5–15	0.185888078	0.004183039
					15–25	0.244768856	0.005508034
					>25	0.339659367	0.007643355
			Depth distribution—material sequence	0.5545	Heterogeneous	0.051612903	0.003239535
					Gradational—increasing heterogeneity	0.093010753	0.005837913
					Gradational—decreasing the heterogeneity	0.157526882	0.009887332
					Two discontinuities	0.279032258	0.017513739
					Homogeneous	0.418817204	0.026287481
			Lateral continuity—% of the unit	0.0948	<50%	0.094415659	0.00101308
					75–50%	0.150834773	0.001618457

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xNH4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
			Porosity (%)	0.152	100–75%	0.291882556	0.0031319
					100%	0.462867012	0.004966563
					<15	0.061669325	0.001061021
					30–15	0.097288676	0.001673852
					40–30	0.160021265	0.002753166
					50–40	0.262626263	0.004518485
					>50	0.418394471	0.007198477
	Rock substrate 1	0.178	Lithologies	0.1282	Rock with porosity <5%	0.052807115	0.000535728
					Basalts/diabases	0.081156198	0.00082333
					Sandstones with fine cements	0.128960534	0.001308305
					Sandstones	0.292384658	0.002966242
					Porous sandstones with low cementation grade	0.444691495	0.004511395
			Continuity (areal distribution—% of the unit)	0.0900	<5	0.062415806	0.00044525
					20–5	0.101481814	0.000722753
					40–20	0.139649753	0.000994586
					60–40	0.178715761	0.001272814
					80–60	0.227211495	0.0016182
					100–80	0.29052537	0.002069122
			Discontinuities (frequency. aperture. continuity). Palmstrom (2005) JV classification	0.2335	Not present	0.047664442	0.000880744
					I and II (<3)	0.077216397	0.001426805
					III (3 to 10)	0.1113441373	0.00209617
					IV (10 to 30)	0.177311725	0.003276366
					V (30 to 60)	0.246425167	0.004553444
					VI (>60)	0.337940896	0.006244472
			Hydraulic conductivity (cm/s)	0.5484	$<10^{-7}$	0.040180814	0.001743807
					10^{-6} to 10^{-7}	0.063787042	0.002768294
					10^{-5} to 10^{-6}	0.102963335	0.004468506
					10^{-4} to 10^{-5}	0.166248117	0.007215002

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xNH4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
	Rock Substrate 2	0.1290	Depth distribution	0.2776	$10-3$ to $10-4$	0.23606228	0.010244867
					$<10-3$	0.390758413	0.016958524
					3 or more geological material layers with strong hydric diffraction surfaces	0.0516129303	0.000821729
					3 or more geological material layers	0.093010753	0.001480824
					2 layers—sand/basalt	0.157526882	0.002507985
					2 layers—sand/sandstones	0.279032258	0.004442473
					Homogeneous (without hydric diffraction surface)	0.418817204	0.006667989
			Lithological heterogeneity	0.1900	Heterogeneous—mass/constituents	0.1215110673	0.001324102
					Heterogeneous—mass	0.1893815	0.00206369
					Heterogeneous—constituents	0.268199234	0.002922567
					Low heterogeneity	0.420908593	0.004586641
			Porosity (%)	0.1219	<5%	0.054143646	0.000378518
					10–5%	0.084530387	0.000590952
					15–10%	0.159668508	0.001116243
					30–15%	0.243093923	0.00169947
					>30%	0.458563536	0.003205818
			Discontinuities (set. frequency. aperture. continuity)	0.4105	1—Not present	0.051518438	0.001212899
					2—Closed or infilling with low hydraulic conductivity	0.084598698	0.001991707
					3—<3 sets. >3/m. with aperture higher than 0.1 mm. continuity less than 10 m	0.169739696	0.003996182

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xN-H4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
					4—<3 sets. >3/m. with aperture higher than 0.1 mm. continuity higher than 10 m	0.261388286	0.006153864
					5—>3 sets. >3/m. with aperture higher than 0.1 mm. continuity higher than 10 m	0.432754881	0.010188348
	Geomorphology	0.0870	Declivity (%)	1	>30	0.100859599	0.003901249
					15–30	0.16217765	0.006273032
					5–15	0.267621777	0.01035161
					<5	0.469340974	0.018154109
Contaminant Attenuation/ 0.333	Unconsolidated materials 3	0.5398	Mineralogy (types/proportion—%)	0.0825	Clay minerals > 60%	0.35585157	0.0051542573
					Clay minerals between 45 and 60%	0.241198858	0.0034935942
					Clay minerals between 30 and 45%	0.147478592	0.0021361227
					Clay minerals between 15–30%	0.107992388	0.0015641931
					Clay minerals between 5 and 15%	0.072312084	0.0010473892
					Clay minerals between 5 and 15%	0.04376784	0.0006339461
					Stable minerals	0.031398668	0.0004547874
			Clay mineral types	0.3179	Smectite group	0.461368653	0.026387519
					Illite group/Vermiculites	0.247792494	0.014172244
					Kaolinite group	0.134657837	0.00770162
					Gibbsite/limonite/goethite	0.086092715	0.004923987
					Chlorites/stable minerals	0.0700883	0.00400863
			pH	0.1285	>8	0.394808004	0.009127566
					6.5 a 8	0.294213088	0.006801912
					5 a 6.5	0.186587345	0.004313713
					<5	0.124391563	0.002875809
			Cation exchange capacity (meq / 100 g)	0.1458	>50	0.427083333	0.011202823

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Atributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xN-H4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
					25–50	0.289473684	0.007593184
					10–25	0.161732456	0.004242404
					5–10	0.077850877	0.002042106
					<5	0.043859649	0.001150482
			Contaminant retention capacity (retardation aspect)	0.2654	High	0.473653396	0.022616476
					Intermediate	0.302107728	0.014425342
					Low	0.144613583	0.006905154
					Very low	0.079625293	0.003802028
			Texture	0.06	Clay	0.417197452	0.004503229
					Silt	0.261677282	0.002824545
					Sandy silte	0.159235669	0.00171879
					Clayed silty sand	0.102441614	0.001105755
					Sand	0.059447983	0.000641682
Rock Substrate 3		0.1632	Mineralogy	0.1687	Clay minerals	0.739495798	0.006785613
					Sulfite and carbonatic minerals	0.166539343	0.001528165
					Stable minerals	0.093964859	0.000862222
			Clay mineral types	0.4229	Smectite group	0.461368653	0.010612863
					Illite group	0.247792494	0.005699971
					Kaolinite group	0.134657837	0.003097534
					Gibbsite/limonite/goethite	0.086092715	0.0019080391
					Micas	0.0700883	0.001612241
			Clay mineral proportions	0.2958	Clay minerals > 50%	0.386466165	0.006218241
					Clay minerals 30–45%	0.253634085	0.004080972
					Clay minerals 15–30%	0.142857143	0.002298571
					Clay minerals 5–15%	0.101253133	0.001629163
					Clay minerals < 5%	0.072180451	0.001161383
					Not present	0.043609023	0.000701669
			Characteristics of discontinuity walls (weathering degree. Infilling types)	0.1127	Infilling with clay material	0.352028042	0.002144555

Table 1 (continued)

Basic components (Hierarchic Level 2)/Partial Index (NH2)	Attributes group (Hierarchic Level 3)	Partial index (NH 3)	Attributes (Hierarchic Level 4)	Partial index (NH 4)	Classes (Hierarchic Level 5)	Partial index (NH 5)	Total partial index (NH2xNH3xNH4xNH5)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
					Infilling with sand material	0.264396595	0.001610704
					Without infilling–high weathering degree of the walls	0.197295944	0.001201927
					Without infilling–low weathering degree of the walls	0.115172759	0.000701632
					Without infilling and weathering of the walls	0.07110666	0.000433182
	Subsurficial Waters	0.297	Groundwater level (m)	0.5717	> 30 m	0.4448	0.025172122
					20–30 m	0.232	0.013129344
					10–20	0.145066667	0.008209613
					5–10	0.084266667	0.004768819
					2–5	0.0576	0.003259699
					< 2	0.036266667	0.002052403
			Number of well within of the unit	0.2855	No present	0.420382166	0.0118806726
					1	0.25477707	0.0072004076
					2	0.161358811	0.0045602582
					3	0.101380042	0.0028651622
					> 3	0.062101911	0.0017550994
			Number of natural springs within of the unit	0.1428	0	0.486631016	0.006878529
					1	0.303030303	0.004283333
					2	0.13963161	0.001973693
					3 or more	0.070707071	0.000999444

Attribute group (hierarchic level 2—col. 1), attributes (hierarchic level 3—col. 2), attributes (hierarchic level 3—col. 2), attributes (hierarchic level 4—col. 4), classes (hierarchic level 4—col. 4), classes (hierarchic level 5—col. 6), and total partial index (col. 8)

- The maximum and minimum values that a unit can were calculated considering the maximum and minimum partial index values.
- For both the top of the saturated zone being above and below the rock substrate level, we have the following.
- Top of the saturated zone above the top level of the rock substrate:
- maximum value = 0.106216463100
- minimum value = 0.020618785200.
- Top of the saturated zone below the top level of the rock substrate:
- maximum value = 0.134887500100
- minimum value = 0.024351523200.

The possible difference between the maximum and minimum values for both conditions shows that it is possible to fit a significant range of natural and anthropogenic conditions between these limits.

The final vulnerability index (FVI) is obtained for each terrain unit and is represented by the units resulting from the combination of geological and geotechnical characteristics and land-use types. The FVI is a ratio between the total vulnerability index (TVI) and the maximum possible value for a unit considering the classes with a maximum total partial index, which result in the maximum TVI value. Then, the FVI is obtained from the following ratio:

$$FVI = TVI \text{ of the unit/maximum value of TVI (possible for specific condition).}$$

From the FVI values, all units can be compared, because the classification is based on a reference value.

4. Based on the FVI values, the vulnerability classes were defined considering the mean and standard deviation; however, other criteria can be used for class definition, depending on the amplitudes of the obtained values and the number of terrain units under analysis. Moreover, the same expression and procedures can be used to obtain the final partial indices for the three basic components (contaminant sources, contaminant transport, and natural attenuation) based on the relevant values for each situation as well as for specific group of attributes if necessary

Application

The proposed vulnerability index method was applied in the Ribeirão do Feijão Basin (RFB) located in the municipality of São Carlos, State of São Paulo, Brazil. The following aspects related to the basin supported the selection of this basin:

- The natural environmental conditions of the basin are representative of most of Brazil, mainly in the south, southeast, and west regions.
- There are large groundwater storage areas.
- The Ribeirão do Feijão Basin supplies 50% of the total drinking water in the municipality of São Carlos.
- The exploitation of surface and groundwater has increased significantly over the last 50 years due to rapid changes in land uses in the basin.
- An unconfined aquifer occupies more than 50% of the study area.
- In the study area, rainfall is seasonal, with well-defined rainy and dry periods. The surface water channels are maintained by water infiltrated during the rainy period.
- There are several types of diffuse and point sources of contaminants.

The methodology was applied following the steps shown in the flowchart (Fig. 3); some aspects are fundamental to its application, such as the selection of a topographical map compatible with the chosen scale; interpretation of aerial photography and satellite images to identify and delimit water conditions, land uses, and contaminant sources; field and laboratorial works to characterize the geological materials; elaboration of maps and charts; adoption of the partial index and the calculation of the total vulnerability index for individual units; the data processing; and obtaining the final vulnerability index and classes for individual units.

The proposed procedures associated with the predefined hierarchical levels permit the elaboration of intermediate cartographical documents and analyses to assess the results of different attribute groups. In this study, two intermediate analyses were developed: contaminant sources and natural attenuation conditions according to procedures cited in the respective topic and considering the specific attribute and class groups.

Study area

The Ribeirão do Feijão Basin (RFB) is located in the centre of São Paulo State, southeast Brazil, with an area of 243 km^2, a perimeter of 48 km, and a drainage density of 0.60 km/km^2. Figure 4a shows the study area location, main drainage channels, and geological formations.

The climate type according to the updated Köppen-Geiger classification (Peel et al. 2007) is Cwa, with rainy summers and dry winters. The average annual rainfall is 1410 mm, with minimum and maximum values of 960 mm

Fig. 3 Flowchart of the steps developed during the application in the study area
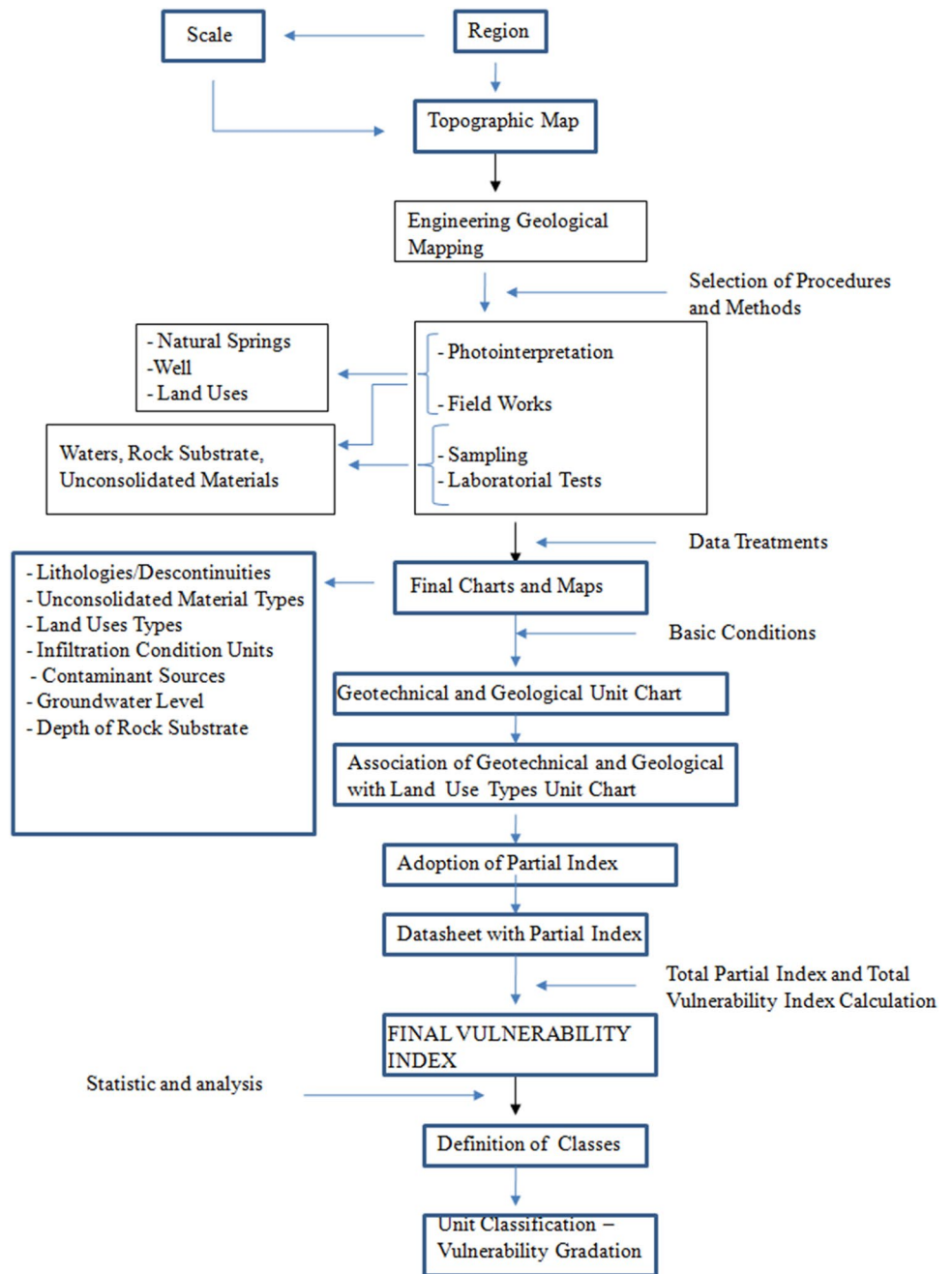
and 1660 mm. The average annual temperature is 21.2 °C, with minimum and maximum values of 5 °C and 37 °C.

Land uses are predominantly rural types, with grazing areas (semi-intensive and extensive cattle breeding) and agriculture with different types of crops (sugar cane, orange, and fruit plantations are most common). The other land uses are forestation (*Pinus* sp. and *Eucalyptus* sp.) and natural vegetation (Cerrado shrubs, semi-deciduous forests, and riparian vegetation).

The slope varies from less than 2 to 20% in most of the region; in some zones, it can exceed 100%. The altitude and relief amplitudes range from 650 m to over 1000 m and 20 to over 80 m, respectively.

Rock substrate map

Geologically, the basin is supported by different lithologies; the main characteristics are shown in Table 2. The unconsolidated materials found in the study area are mainly sandy residual and transported.
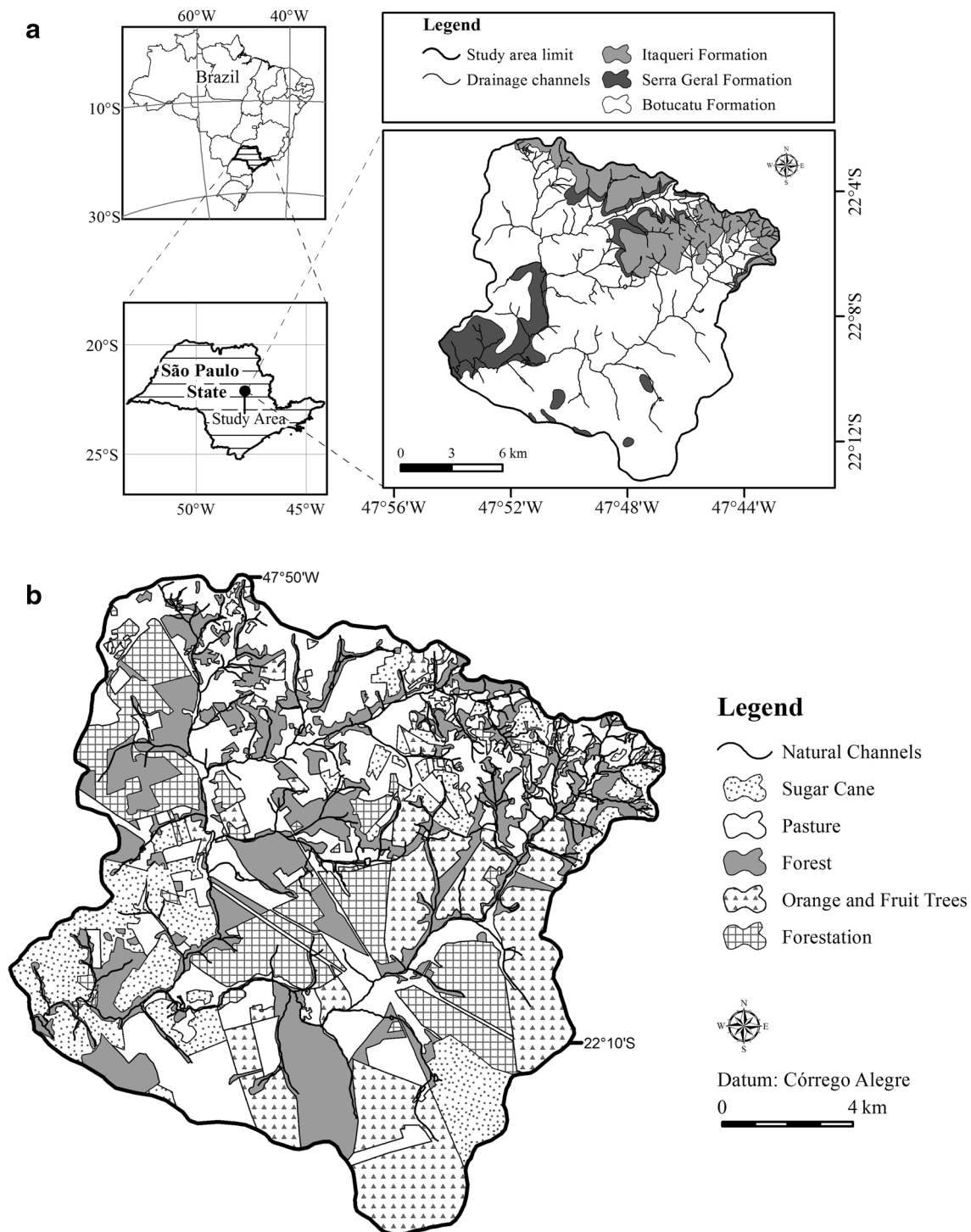
Fig. 4 **a** Ribeirão do Feijão Basin location with the drainage channels and map with geological formations. **b** Land-use map of Ribeirão do Feijão Basin. **c** Unconsolidated material unit map of Ribeirão do Fei-jão Basin. RUM is Residual Unconsolidated Material. **d** Map of the unit distribution in terms of position of groundwater level related to upper rock substrate surface

Land-use map

The land-use map is shown in Fig. 4b. The main land use is pasture (77 km^2; 32%), followed by forest (56 km^2; 23%), orange and fruit plantations (43 km^2; 17.6%), sugar cane (34 km^2; 14%), and forestation (32 km^2; 13.4%). However, the area associated with sugar cane plantations is increasing and may occupy 50% of the basin within a few years. The

c

Legend

～ Natural Channels

RUM from Itaqueri Formation

RUM from Serra Geral Formation

RUM from Botucatu Formation

Sandy Transported 1

Sandy Transported 2

Sandy Transported 3

Sandy Colluvium

Alluvium

Lateritic Concretions

Datum: Córrego Alegre

0   4 km

d

LEGEND

01 – Unit Number

Groundwater level above the upper rock substrate surface

Groundwater level below the upper rock substrate surface

0   1   2   3 km

Fig. 4 (continued)

Table 2 Geological formations, main lithologies, and basic characteristics of the study area

Formation	Era	Period	Lithologies	Basic characteristics	Characteristics of the limit between unconsolidated material and rock substrate	Fracture conditions	Heterogeneity grade	Groundwater conditions	Potential groundwater recharge
Itaqueri	Cenozoic	Paleogene	Sandstones Siltstones Claystones	Interbedded Layers Layer thickness smaller than 5 m	Gradational	Fractures closed or filled	Very high heterogeneous	Free aquifer	Low
Serra Geral	Mesozoic	Cretaceous	Basalts	Layers with thickness less than 50 m occurring in scarps with declivity higher than 100%	Gradational	Fractures can be open and closed, and some filled	High heterogeneity	Fractured aquifer	Low to medium
			Diabases	Sills distributed in the basin but not continuous	Gradational/Abrupt	Fractures are closed	Intermediate Heterogeneity		
Botucatu		Jurassic	Cemented sandstones	Cement is silica/ Very Hard/Fractured	Abrupt	Fractures are predominantly open	High heterogeneity		
			Sandstones	Low cementation degree/ Very porous	Gradational	Fractures are not important for water flow	Very low heterogeneity	Porous aquifer/High Transmissivity	High

surface layer is currently much modified due to the ploughing process and management practices of land uses. Frequently, the surface layers are compacted because of the weight of the machines and intense use of fertilizers that function as a deflocculant, affecting the volumetric characteristics of the geological materials.

Unconsolidated materials map

The unconsolidated materials were classified according to their genesis as residuals or transported, with three residual unconsolidated materials (RUMs) and six transported materials. Figure 4c shows the spatial distribution of the units. In general, the study area is primarily composed of sandy texture materials (residual from the Botucatu Formation, sandy transported 1 and sandy colluvium), representing 65.75% (160 km^2) of the RFB. The other unconsolidated materials (28%; 68 km^2) present textures varying from sandy clayey to clayey sandy (residual from Itaqueri Formation, sandy transported 2, sandy transported 3, and alluvium and lateritic concretion) except for the residual from Serra Geral Formation (6%; 15 km^2), which is a clayey texture unit.

Groundwater level position map

To classify the different terrain units, especially with respect to the position of the top of the saturated zone being below or above the top of the rock substrate, a map (Fig. 4d) was prepared with the classification of 94 units, where 39 units have the top of the saturated zone above the rock substrate, and therefore, the transport of the contaminants is not influenced by the components of the rock substrate; 55 units have the top of the saturated zone below the top of the rock substrate. Considering the distribution of the units for the two conditions, it is found that approximately 40% have the top of the saturated zone above the top of the rock substrate, whereby the rock substrate materials do not interfere with the contaminant flow between the base of the contaminant sources and the top of the saturated zone.

Engineering geological units

The combination of the unconsolidated material units with lithological types generates the geotechnical and geological units that were used as a natural division of the basin. Each unit is characterized with the attributes that constituted the groups of hierarchical level 3 (unconsolidated materials 1, 2, and 3 and rock substrates 1, 2, and 3), as shown in Table 1.

Association of geotechnical and geological with land-use type units

Based on the distribution of the engineering geological aspects and land-use types, the units were defined and delimited. Figure 5 shows the unit map with 29 different units, and Table 3 lists their main geological and geotechnical characteristics. Considering these conditions, the basin was divided into 94 territorial units, which provided better control of the possible contaminant sources and geological and geotechnical units. This analysis facilitated the contaminant source map reflecting an intermediate vulnerability index, which permitted better analysis of the final results.

Contaminant source map

The contaminant sources were mapped based on the different land-use types as well as management procedures such that the different land-use types have a temporal continuity. Aspects resulting from land uses characterized as sources of contaminants were also considered, including deposits of agricultural industry and animal wastes. There are also urbanized areas in the region with sewage systems containing septic tanks, such as hotels, fuel stations, restaurants, and poultry, cattle, pig, and horse farming. Considering all possible types of sources and respective attributes, the first step was to calculate the maximum and the minimum values that a unit could reach (0.0471762 and 0.0063378, respectively). The second step was to obtain the total intermediate index value for each unit considering that the total partial index from Table 1 (col. 8) is related to the contaminant sources. The third step was to obtain the final partial indices as percentages between the total intermediate index values of the contaminant sources and the maximum value that a unit could reach (0.0471762). In Fig. 6a, the final partial indices are displayed for each unit. The results show a maximum value of 0.6779608, a minimum value of 0.172163, a mean of 0.401426, and a standard deviation of 0.13902856.

From the mean and standard deviation, four classes were defined (Table 4) to fit each unit. Figure 7a shows a map with the classification of the units in terms of the final partial indices; the map refers to the existing types of contaminant sources, which was considered in the analysis of the final vulnerability index.

In terms of the magnitude of the contaminant sources in each unit, 25, 15, and 36 units are of Classes 1, 2, and 3, respectively; only 18 units are of Class 4, smaller magnitude. Thus, approximately 25% of the units have indices of the highest magnitude class in terms of contamination sources, which implies that these units should be better assessed in terms of the land uses that are under development in addition to management.

Fig. 5 Map of land unit and engineering geological conditions associated land-use units of the Ribeirão do Feijão Basin
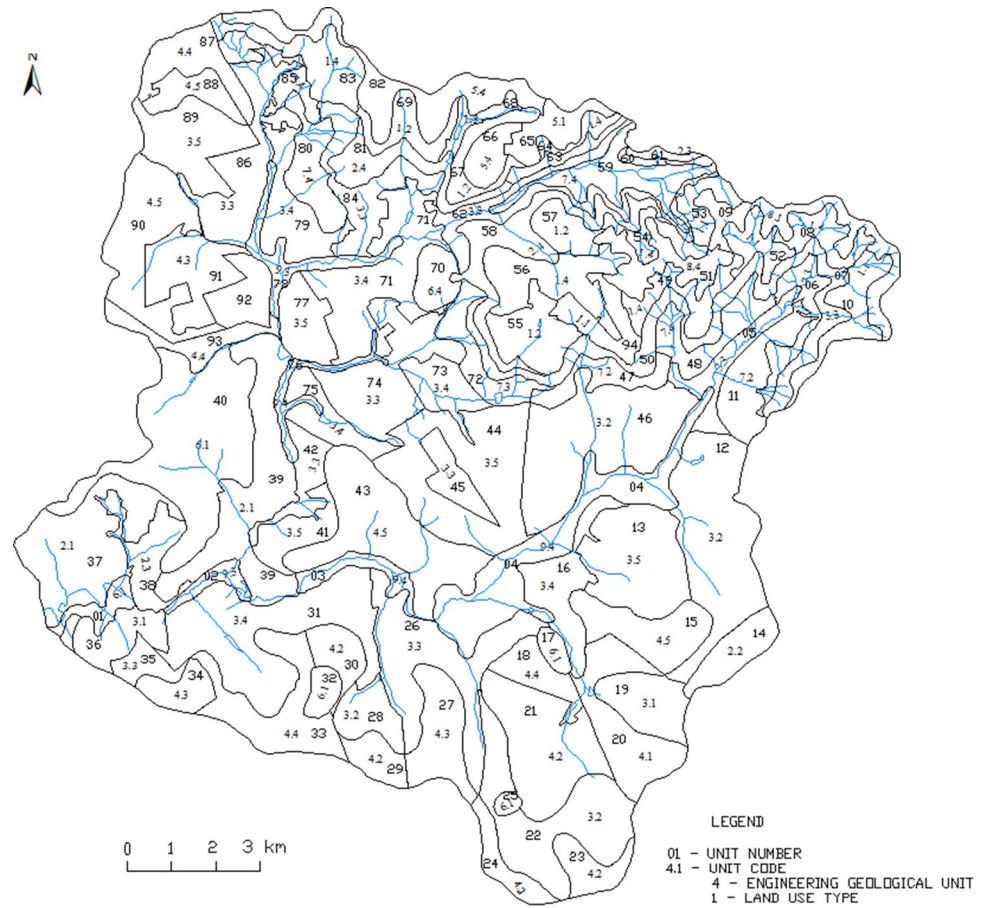
Natural attenuation map

The natural attenuation conditions were evaluated considering the groundwater level below and above the rock top to evaluate the natural attenuation differences for the different groups of attributes and classes.

Considering the position of the groundwater level below the top of the rock substrate (Condition 1) or above (Condition 2), the first step was to obtain the maximum and the minimum values that a unit could reach for Condition 1 (0.18659532 and 0.0264970, respectively) and Condition 2 (0.12292319 and 0.01774036, respectively). The second step was to calculate the total intermediate index value for each unit considering the total partial index from Table 1 (col. 8), which is related to the natural attenuation attributes for Conditions 1 and 2. The third step was to obtain the final partial indices as percentages between the total index values of the natural attenuation and the maximum value that a unit could reach (Condition 1 of 0.18659532 and Condition 2 of 0.12292319).

Figure 6b, c is related to the condition of the saturated zone below the top of the rock substrate (Condition 1) and the saturated zone above the rock substrate (Condition 2), respectively. The results obtained for Condition 1 show a

mean of 0.38054675 and standard deviation of 0.07798768, and Condition 2 has a mean and is 0.51185113 and standard deviation of 0.09360793. These values allowed for the definition of the classes, as listed in Table 4.

Figure 7b shows a distribution map of the classification of the units for the two conditions, and the 25 units in Class 1, under both conditions, are highlighted; 15, 36, and 18 units are in Classes 2, 3, and 4, respectively. It is found that 40 units, or approximately 40% of the units, are in the classes with the highest contaminant load, which places the basin and natural spring on alert.

Final vulnerability index

The procedures to obtain the final vulnerability index for the individual units were developed considering three conditions: the first is a general condition for all 94 units, considering the depth target of the assessment greater than 30 m; the second one considers the top of the saturated zone above the rock substrate; and the third condition considers the position below the rock substrate. The first condition aims to evaluate all units for a deep groundwater level and reflects the conditions of intrinsic vulnerability

Table 3 Summary of the basic geotechnical characteristics of the Engineering Geological units of the Ribeirão do Feijão Basin

ICU	Area (km²)	Texture	Grain specific weight (kN/m³)	Dry specific weight (kN/m³)	Void ratio	Porosity	Potential infiltration capacity (mm/h)	Sorptivity (mm h$^{-1/2}$)	Water content at field capacity (cm³/cm³)	Water content at wilting point (cm³/cm³)
1.1	5.72	SCl-CS	26.725	14.710	0.82	0.45	9.8	6.9	0.320	0.188
1.2	6.24		26.725	14.314	0.87	0.46	28.8	20.8	0.327	0.192
1.3	0.68		26.725	11.760	1.27	0.56	14.4	5.2	0.398	0.234
1.4	10.33		26.725	14.706	0.82	0.45	6.5	3.9	0.320	0.188
2.1	12.37	Cl-ClSil	28.970	13.000	1.23	0.55	18.0	11.5	0.382	0.189
2.2	1.72		28.970	15.200	0.91	0.48	8.0	13.4	0.334	0.165
2.3	2.33		28.970	12.000	1.41	0.59	48.0	106.7	0.410	0.203
2.4	5.94		28.970	15.200	0.91	0.48	8.0	13.4	0.334	0.165
3.1	4.22	S	27.400	14.875	0.84	0.46	34.0	24.5	0.202	0.079
3.2	22.22		26.700	15.255	0.75	0.43	14.7	13.6	0.189	0.074
3.3	30.78		25.668	13.800	0.86	0.46	34.0	24.5	0.202	0.079
3.4	23.6		27.400	15.100	0.81	0.45	14.8	13.2	0.197	0.078
3.5	19.15		27.495	15.112	0.82	0.45	18.0	15.4	0.197	0.078
4.1	3.74	S	27.400	14.875	0.84	0.46	34.0	24.5	0.201	0.085
4.2	10.37		26.700	15.255	0.75	0.43	14.7	13.6	0.188	0.079
4.3	7.22		25.668	13.800	0.86	0.46	34.0	24.5	0.201	0.085
4.4	9.21		27.400	15.100	0.81	0.45	14.8	13.2	0.196	0.083
4.5	17.52		27.495	15.112	0.82	0.45	18.0	15.4	0.196	0.083
5.1	3.74	SilC	26.667	13.431	0.99	0.5	24.0	14.9	0.361	0.214
5.4	5.18	SSi	26.667	16.280	0.64	0.39	13.8	6.1	0.281	0.167
6.1	11.71	SCl	27.000	14.700	0.84	0.46	23.0	15.7	0.263	0.121
6.4	1.22		27.000	15.400	0.75	0.43	14.8	10.6	0.245	0.113
7.2	3.96	S	25.988	15.500	0.68	0.4	9.6	10.2	0.175	0.074
7.3	3.46		25.988	14.500	0.79	0.44	28.0	11.8	0.192	0.081
7.4	6.97		25.988	16.000	0.62	0.38	4.5	17.2	0.166	0.070
8.1	2.76	ClS	26.400	8.624	2.06	0.67	27.0	75.9	0.473	0.276
8.4	2.14		26.400	8.820	1.99	0.67	12.0	112.9	0.473	0.276
9.3	0.73	SSil	26.740	15.777	0.69	0.41	20.0	18.0	0.180	0.070
9.4	9.8		26.740	17.381	0.54	0.35	9.8	29.3	0.153	0.060

ICU Infiltration condition unit, (unconsolidated material+land-use type), *C* layey, *Sil* silty, *S* sandy

Engineering Geological material: 1 = Residual from Itaqueri Formation. 2 = Residual from Serra Geral Formation. 3 = Residual from Botucatu Formation. 4 = Sandy Transported 1. 5 = Sandy Transported 2. 6 = Sandy Transported 3. 7 = Sandy Colluvium. 8 = Lateritic Concretions. 9 = Alluvium zone

Land-use type: 1 = Sugar Cane plantations. 2 = Orange and fruit plantations. 3 = Forest. 4 = Pasture. 5 = Forestation

Fig. 6 **a** Partial index values for 94 units considering contaminant source attributes. **b** Partial index values for units considering natural attenuation for Condition 1. **c** For Condition 2
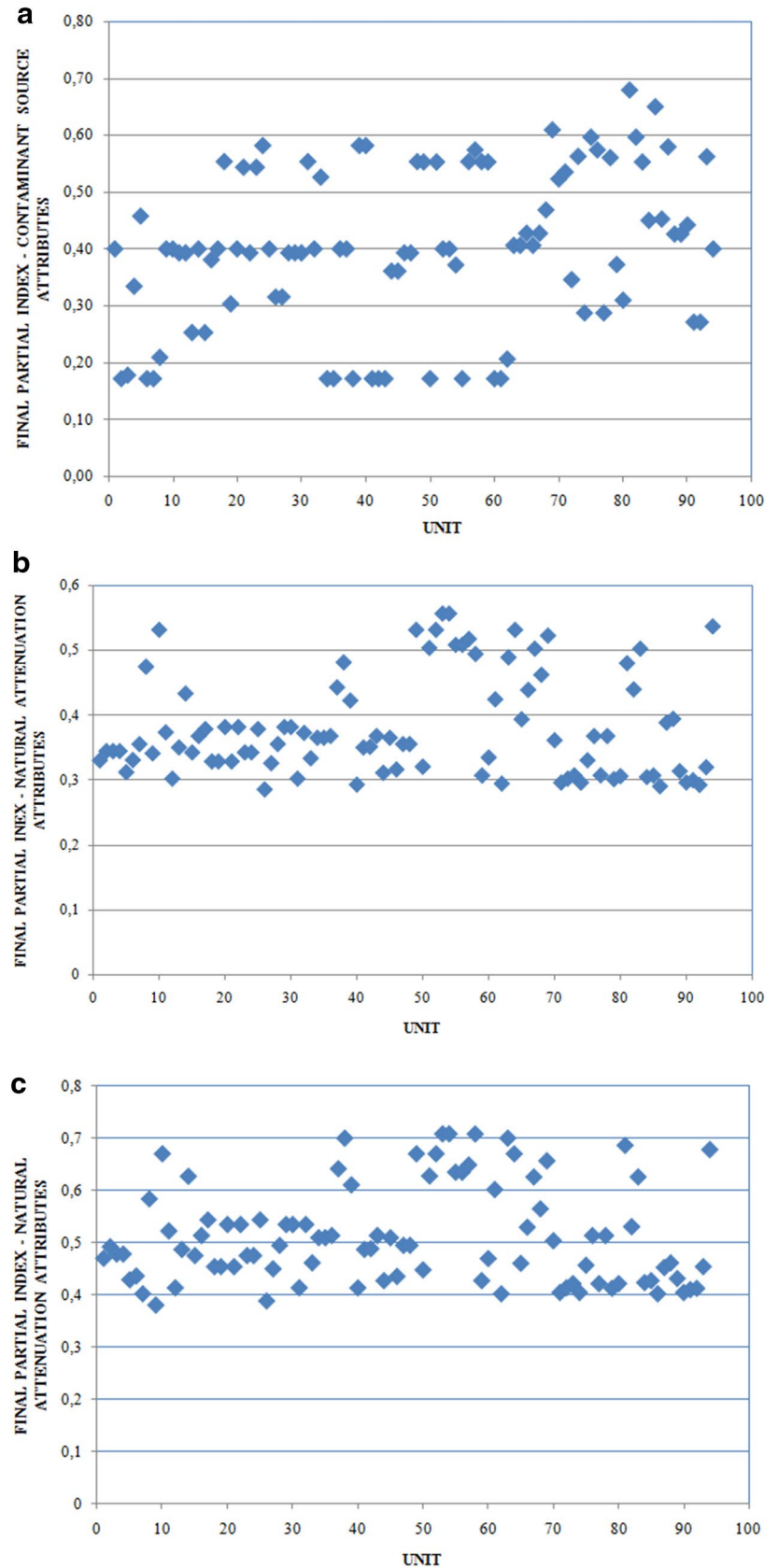
Table 4 Adopted classes for contaminant sources, natural attenuation, groundwater level depth higher than 30 m, groundwater level above and below the rock substrate surface unit classification

Classes	Criteria	Limits values of final partial index considered for unit classification						
		Contaminant Sources	Natural attenuation		Groundwater level depth higher than 30 m	Groundwater level position in relation with the top of rock substrate		
			Condition 1	Condition 2		Below	Above	
							Specific classes	Limit values
1	Results are higher than the sum of the mean and standard deviation	> 0.540454	> 0.45853443	> 0.60545906	> 0.61135874	> 0.71816814	A	> 0.69480547
2	Results are between mean and the sum of the mean and standard deviation (smallest value of the class 1)	0.401426 to 0.540454	0.38054675 to 0.45853443	0.51185113 to 0.60545906	0.452888069 to 0.61135874	0.5462516 to 0.71816814	B	0.60612652 to 0.69480547
3	Results are between mean and the mean subtracted the standard deviation (highest value of the class 4)	0.262397 to 0.401426	0.30255907 to 0.38054675	0.4182432 to 0.51185113	0.452888069 to 0.2944174	0.37433509 to 0.5462516	C	0.60612652 to 0.51744757
4	Results are less than mean substracted the standard deviation	< 0.262397	< 0.30255907	< 0.4182432	< 0.2944174	< 0.37433509	D	< 0.51744757

of each unit, because it involves all considered attributes. The other two conditions are the real conditions in terms of the depth of the saturated zone, as shown in Fig. 4d. The final vulnerability index for the three conditions was acquired according to the procedure outlined in "Materials and methods."

First condition

The 94 units have the final vulnerability indices (FVIs) ranging between 0.00773 and 0.683, according to Fig. 8a, with a mean value of 0.452888069 and standard deviation of 0.15847067. From these data, four classes were defined for vulnerability grading, according to Table 4. In this case, the considerable range between the minimum and maximum values is verified, reflecting the variability of the characteristics of the units.

Second condition

There are 39 units with the top of the saturated zone above the top of the rock substrate. In this situation, the following attributes were considered: point and non-point sources, subsurface water, rainfall, and unconsolidated materials 1, 2, and 3. The final vulnerability index (FVI) values ranged from 0.438 to 0.753 according to the data in Fig. 8b, with a mean value of 0.60612652 and a standard deviation of 0.08867895, and 4 classes were defined for vulnerability grading according to Table 4. The final vulnerability index values do not exhibit significant amplitudes; however, in this condition, the highest final vulnerability index (FVI) values were obtained.

Fig. 7 **a** Map of the land unit classification according to final partial index related to contaminant sources, **b** Map of the land unit distribution related to natural attenuation for conditions 1 and 2
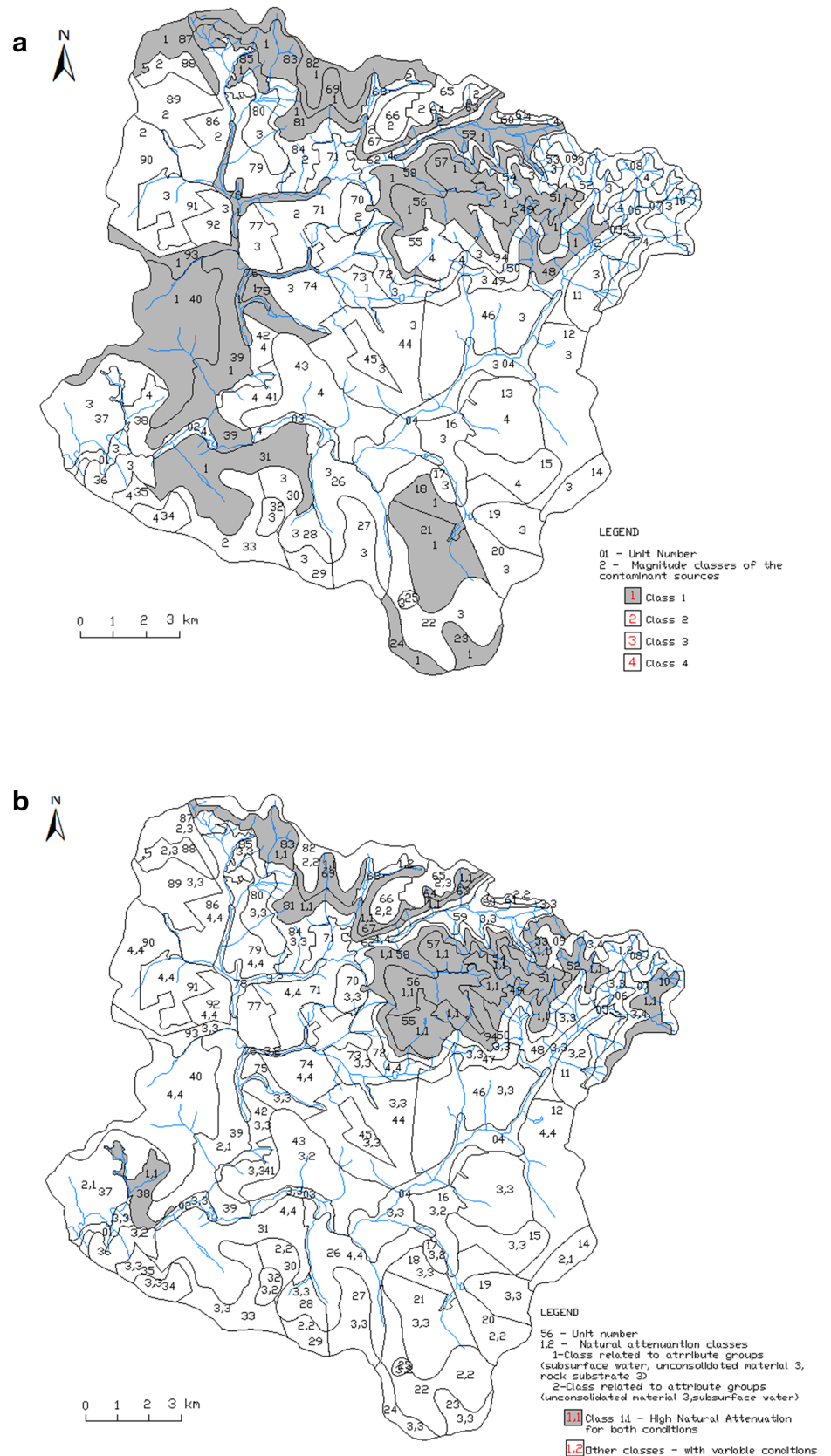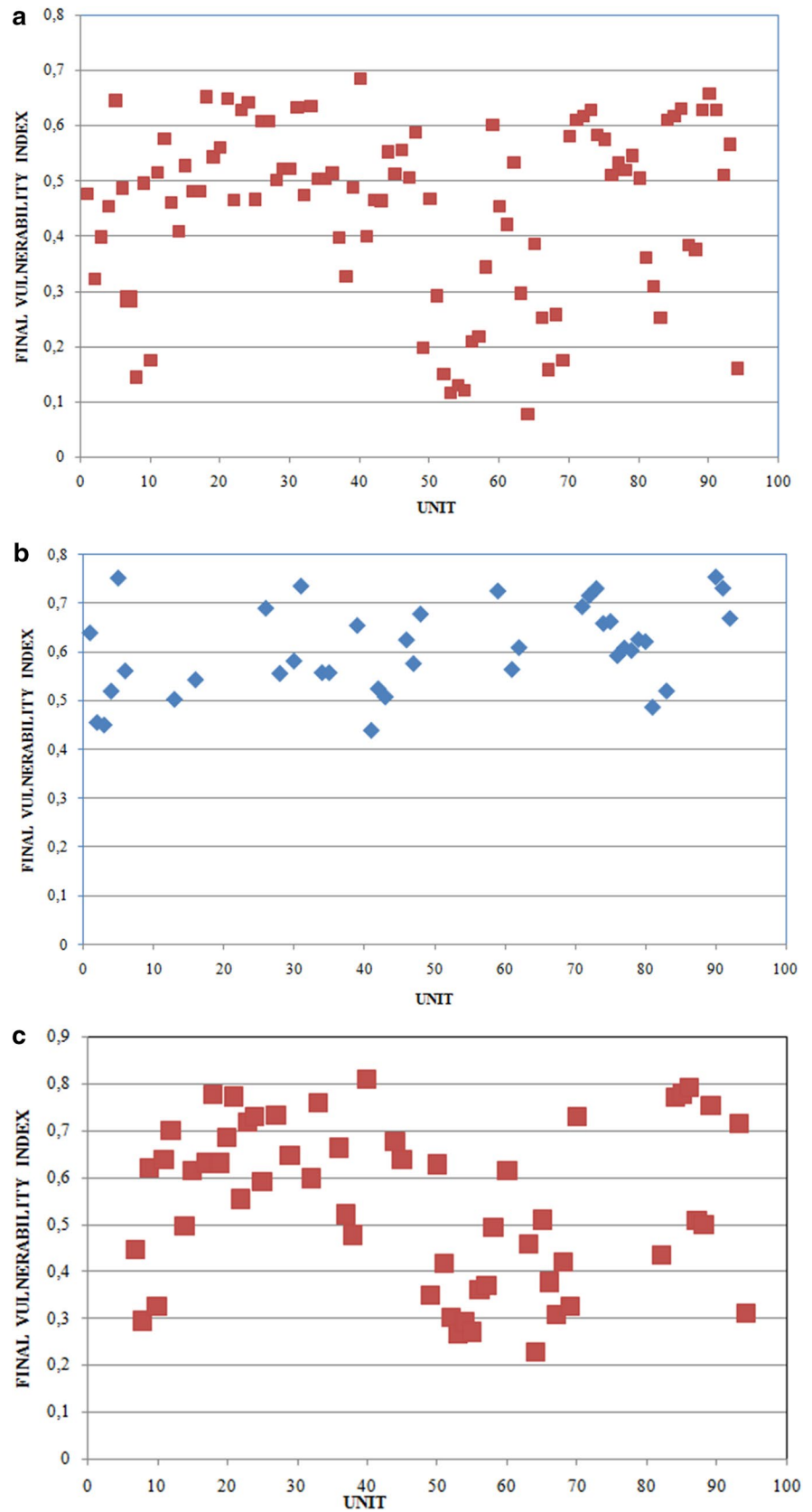
Fig. 8 Final vulnerability index values: **a** for units considering the groundwater level depth higher than 30 m, **b** for units with groundwater level above the upper rock substrate surface (39 units), **c** for units for groundwater level below the upper rock substrate surface (55 units)

Third condition

The third condition includes the units with the top of the saturated zone below the top of the rock substrate, resulting in 55 units. All attribute groups (hierarchical level 3) were considered. The final vulnerability index (FVI) values ranged from 0.4228 to 0.809, as shown in Fig. 8c, with a mean value of 0.5462516 and standard deviation of 0.1719165. Four classes were defined for vulnerability grading according to Table 4.

Figure 9 shows the classification map for the different units in terms of the magnitudes of the final vulnerability index values considering a target depth of more than 30 m and both the groundwater level above and below the top of the rock substrate.

The amplitude of the resulting values for the three considered conditions is compatible with the general difference between the maximum and minimum values. For the first condition (target depth > 30 m), no unit is in Class 1, i.e., the highest degree of vulnerability. Approximately 60% of the units are in Classes 3 and 4, which have smaller magnitudes. These data, associated with the classification of contaminant sources in Fig. 6a, reflect the natural attenuation capacity of the geological materials as well as the transport behaviour, because none of the 25 units classified in the highest contaminant source class exhibit vulnerability in the highest class.

Furthermore, in units under Condition 2 (top of the saturated zone above the top of the rock substrate), there are no units classified at the lowest vulnerability level (Class 4), and only 6 units (17%) are in Class 1 (high), all of which are in Class 1 in terms of contaminant sources. Regarding Condition 3 (top of the saturated zone below the top of the rocky substrate), there are 11 units (25%) in the high vulnerability class (Class 1), and 18, 13, and 13 units are in Classes 2, 3, and 4, respectively.

According to the results of Conditions 2 and 3, 17 units (5, 18, 21, 24, 27, 31, 33, 40, 59, 70, 73, 84, 85, 86, 89, 90, and 91) fit the highest vulnerability class, whereas only units 18, 21, 24, 31, 40, 59, 73, and 85 are in Class 1 in terms of contaminant sources. Thus, the index reveals that there is a group of units (5, 27, 33, 70, 84, 86, 89, 90, and 91) that are in the highest class of vulnerability even with low contaminant sources. These units should receive special care, because if the magnitude of the contaminant sources increases, the contamination of the saturated zone waters will be unavoidable due to the low attenuation capacity. For natural attenuation, both saturated zone conditions were analysed, and 18 units (10, 38, 49, 51, 52, 53, 54, 55, 56, 57, 58, 63, 64, 67, 69, 81, 83, and 94) were classified in the highest natural attenuation category for both conditions (Class 1).

Fig. 9 Vulnerability gradation map with unit classification based on final vulnerability index classes for three conditions (for units considering the groundwater level depth higher than 30 m, for units with groundwater level above the upper rock substrate surface—39 units, for units for groundwater level below the upper rock substrate surface—55 units)
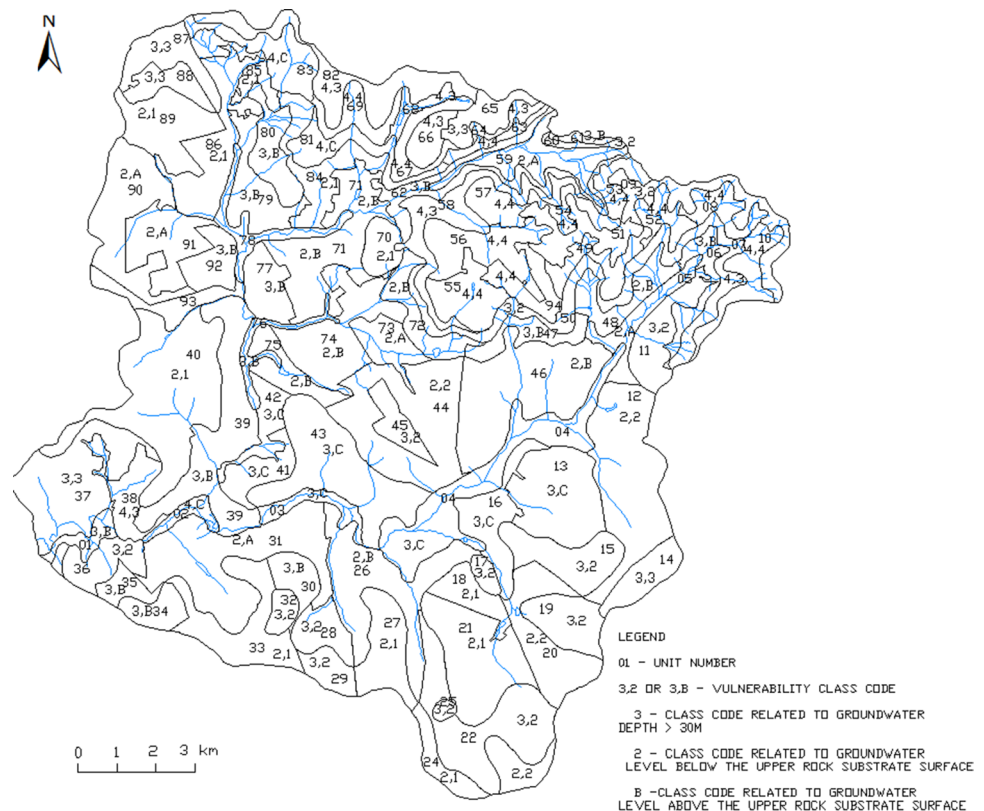
Conclusion

This proposal considers a group of information that could be considered large, although the necessary information can be obtained by fieldwork and the use of simple and low-cost laboratory equipment, especially if procedures such as engineering geological mapping are followed. The set of information can be processed using different resources, including not only geographic information systems but also other, more robust systems, such as MATLAB (MATrix LABoratory), Mathcad and other data processing software, such as Excel.

From the analysed group of attributes and classes, one can select attributes that permit specific analyses for the different contaminants. It is also possible to select attributes or groups for intermediate analyses, which generate interesting results, as done in this study for natural attenuation and contaminant sources.

The use of terrain units with practical significance and easy delimitation is fundamental to assess, verify, and validate the results of the final vulnerability indices as well as to adopt territorial and environmental planning guidelines. In this case, the combination of engineering geological units with the types of land uses permit an assessment of the influence of the land-use management practices and the contaminant source magnitudes.

The set of information also allows the terrain units to be analysed and classified in terms of the intrinsic characteristics and sources, thus allowing the adoption of specific guidelines for each unit in terms of territorial and environmental planning. Moreover, the adoption of terrain units permits the processing of information in spreadsheets, which facilitates the verification of variability for each unit. In addition, the dynamic analysis can be performed with changes in only attributes and classes; therefore, results can be obtained for each unit without having to prepare new maps and characterizations.

The difference between the maximum and minimum values allows the proposal to be applied in areas with a great diversity of natural and anthropogenic characteristics; framing terrain units in different categories of final vulnerability index values, there are wide possibilities of application for different areas with very broad natural and anthropogenic characteristics.

The proposed vulnerability index permits the classification of each unit of a basin, reflecting the different natural and anthropogenic conditions, and consequently with spatial detail compatible with the scale. In addition, when comparing the results for the water-level condition greater than 30 m with the other two conditions, the results vary, although this is compatible with the actual conditions of each unit, predominantly increasing the degree of vulnerability.

The proposal allows considering the final vulnerability index, i.e., the gradation, dynamically with the analysis of the temporal variation of the sources as a function of changes in land use and both territorial and environmental planning standards.

References

Albinet M, Margat J (1970) Cartographie de la vulnerabilité a la pollution des nappes d'eausouterraine. Bull BRGM 2 3(4):13–22

Baalousha H (2017) Vulnerability, probability and groundwater contamination risk. Environ Earth Sci 76(11):1

Bonfanti M, Ducci D, Masetti M, Sellerino M, Stevenazzi S (2016) Using statistical analyses for improving rating methods for groundwater vulnerability in contamination maps. Environ Earth Sci 75:1003. https://doi.org/10.1007/s12665-016-5793-0

Boufekane A, Saighi O. ('2018) Application of groundwater vulnerability overlayand index methods to the Jijel Plain Area (Algeria). Ground Water 56(1):143–156. https://doi.org/10.1111/gwat.12582. Epub 2017 Aug 21

Dickson-Anderson S, Lubianetzky T, Guo Y (2015) Proposed method: incorporation of fractured rock in aquifer vulnerability assessments. Environ Earth Sci. https://doi.org/10.1007/s12665-015-4471-y

Duarte L, Teodoro AC, Gonçalves JA et al (2015) A dynamic map application for the assessment of groundwater vulnerability to pollution. Environ Earth Sci 74:2315. https://doi.org/10.1007/s12665-015-4222-0

Gogu RC, Dassargues A (2000) Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environ Geol 39:549–559

Gogu RC, Hallet V, Dassargues A (2003) Comparison of aquifer vulnerability assessment techniques. Application to the Néblon river basin (Belgium). Environ Geol 44:881–892

Huneau F, Jaunat J, Kavouri K, Plagnes V, Rey F, Dörfliger N (2013) Intrinsic vulnerability mapping for small mountains karst aquifers, implementation of the new PaPRIKa method to Western Pyrenees (France). EngGeol 161:81–93

Iván V, Mádl-Szőnyi J (2017) Vulnerability assessment and its validation: the Gomor-Torna Karst, Hungary and Slovakia. Geological Society, London **(Special Publications, 466, 29 November)**

Jia R, Zhou JY, Zhou Y, Li Q, Gao YA (2014) Vulnerability evaluation of the phreatic water in the plain area of the Junggar Basin, Xinjiang Based on the VDEAL Model. Sustainability 6:8604–8617. https://doi.org/10.3390/su6128604

Le Grand HE (1964) System for evaluating the contamination potential of some waste sites. J A Water Works Assoc 56(8):959–974

Mishima Y, Takada M, Kitagawa R (2011) Evaluation of intrinsic vulnerability to nitrate contamination of groundwater: appropriate fertilizer application management. Environ Earth Sci 63:571. https://doi.org/10.1007/s12665-010-0725-

Neukum C, Hötzl H (2006) Standardization of vulnerability maps. Environ Geol. https://doi.org/10.1007/s00254-006-0380-4

Palmstrom A (2005) Measurements of and correlations between block size and rock quality designation (RQD). Tunn Undergr Space Technol 20:362–377

Peel MC, Finlayson BL, Mcmahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrology and earth system sciences discussions. Eur Geosci Union 4(2):439–473

Rao PSC, Alley WM (1993) Pesticides. In: Alley WM (ed) Regional groundwater quality. Van Nostrand Reinhold, New York, pp 345–382

Saaty TL (1980) The Analytic Hierarchy Process. McGraw-Hill, New York

Sahoo S, Dhar A, Kar A et al (2016) Index-based groundwater vulnerability mapping using quantitative parameters. Environ Earth Sci 75:522. https://doi.org/10.1007/s12665-016-5395-x

Vrba J, Zaporozec A (1994) Guidebook on mapping groundwater vulnerability, vol. 16. International contributions to hydrogeology (IAH). Verlag Heinz Heise, Hannover, p 131

Witkowski AJ (2016) Groundwater vulnerability: from scientific concept to practical application. Environ Earth Sci 75:1134. https://doi.org/10.1007/s12665-016-5896-7

Worrall F, Kolpin DW (2004) Aquifer vulnerability to pesticide pollution-combining soil, land-use and aquifer properties with molecular descriptors. J Hydrol 293:191–204

Zaporozec A (ed) (2002) Groundwater contamination inventory: a methodological guide. IHP-VI Series on Groundwater No. 2. UNESCO, U.N. Educ. Sci. Cult. Organ., Paris

Zhou CS, Zhen XQ, Zang HF (2012) Assessment of groundwater vulnerability in Jingsheng Basin based on PCSM-AHP system. Water Resour Power 30:12–15, 214

Zuquette LV, Pejon OJ, Collares JQ (2004) Engineering geological mapping developed in Fortaleza metropolitan region, state of Ceará, Brazil. Eng Geol 71:227–253