Enhanced groundwater vulnerability assessment in geological homogeneous areas: a case study from the Argentine Pampas

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Abstract The southeast area of the Argentine Pampas is characterized by the presence of an unconfined aquifer in a wide plain. A methodology is proposed that deals with the aquifer vulnerability where the homogeneity of the hydrogeological variables used by traditional methods (in this case, DRASTIC-P) causes vulnerability maps to show more than 80% of the territory under the same class. This absence of discrimination renders vulnerability maps of little use to decision-makers. In addition, the proposed methodology avoids the traditional vague classification (high, low, and moderate vulnerability) which is highly dependent on subjectivity in its association of each class with hydrogeological considerations. That traditional vulnerability assessment methodology was adapted using a geographic information system to reclassify classes, based on the Natural Breaks (Jenks) method. The pixel-to-pixel comparison between the result obtained by the DRASTIC-P and the reclassified classes generates the so-called operational vulnerability index (OVI), which shows four classes, associating each with different hydrogeological requirements to make decisions.

Keywords Vulnerability mapping · Aquifer pollution · Land-use planning · Geographic information systems · Argentina

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Introduction

The concept of aquifer vulnerability to pollution was introduced in the 1960s by Margat (1968). Vrba and Zaporocec (1994) defined vulnerability as an intrinsic property of groundwater, depending on its susceptibility to natural and/or human impact. Since Margat (1968), there have been several attempts to establish a methodology to assess that vulnerability and its representation in a map, which have strengthened steadily since the mid 1980s. Two of the pioneers are the methods called DRASTIC (Aller et al. 1987) and GOD (Foster 1987).

To quantify aquifer vulnerability, the most common approach at present is the index method, whereby the protective effect of the overlying layers is expressed in a semi-quantitative way (Frind et al. 2006). The kinds of vulnerability identified by different methodologies are many, but they always have a qualitative label associated with a wide range of index values. The separation into categories will depend, therefore, on the index values obtained and the number of categories the authors consider most appropriate.

As Aller et al. (1987) indicate, "…the groundwater pollution potential can be estimated by choosing appropriate ranges for each DRASTIC parameter…"; the same could apply to the range and number of categories in the final vulnerability index, since "…the index´s numerical value has no intrinsic meaning. That number is of value only with respect to other numbers generated by the same DRASTIC index" (Aller et al. 1987).

In the last 20 years, other methodologies have been developed, with specific applications being thoroughly analyzed and tested for different environments (Cramer and Vrba 1987; Rodriguez et al. 2003; GEAM 2005; Allen and Milenic 2007). Moreover, many works have used different scales and sources of base information for the application of these methodologies (Secunda et al. 1998; Foster et al. 2002; Civita and De Maio 2004; Wang et al. 2007). In addition, efforts have been made to try to overcome the three main limitations of these methods:

1. The use of a qualitative definition of groundwater vulnerability, as opposed to a quantitative definition (Gogu et al. 2003; Frind et al 2006; Popescu et al. 2008)

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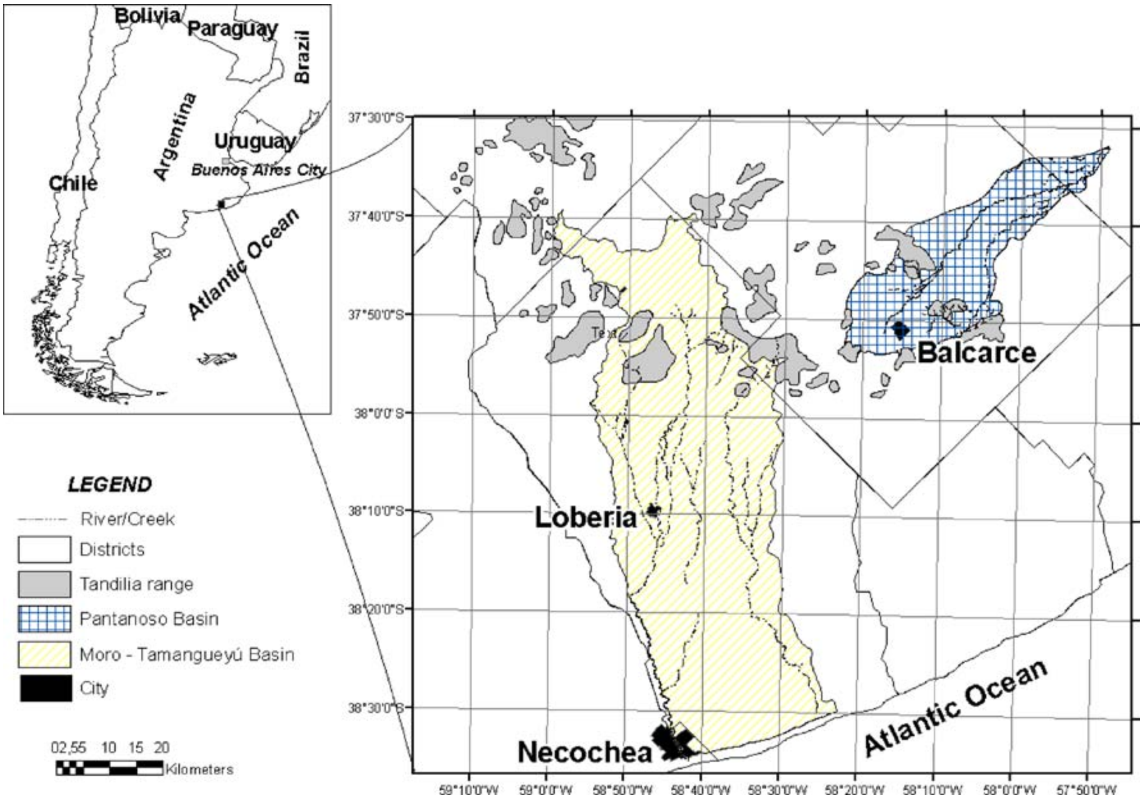


Fig. 1 Location map

2. Difficulties in gathering more information on uncertainty associated with vulnerability assessments and in developing ways to handle and display this aspect (Gogu and Dassargues 2000)
3. Homogeneity in the results, which does not allow for discrimination and delimitation of areas of different vulnerability to pollution. This is of central importance in the development of aquifer protection strategies, but many areas around the world frequently show strong homogeneity in the results of aquifer vulnerability assessment. To decision makers, this represents a problem that has not been addressed yet.

The aim of this paper is to present a proposal which allows one to discriminate units with different categories of vulnerability in geological homogeneous environments, and to avoid the use of qualitative adjectives such as "low" or "moderate" because of their subjective meaning. This will be useful for the application or design of aquifer protection strategies in the areas under study and may be applied to others with similar features.

Table 1 An example of ranges and ratings for soil media using DRASTIC (Aller et al. 1987)

Range	Rating
Soil thin or absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or aggregated clay	7
Sandy loam	4
Loam	5
Silty loam	4
Clay loam	3
Muck	2
Nonshrinking and nonaggregated clay	1

Study area

The Pampean plains of southeastern Buenos Aires province (Argentina) are characterized by a geomorphological environment which corresponds mostly to that of gently sloped plains (<0.5%) crossed by a block mountain system ("Tandilia Range"). The climate is dry sub-humid mesothermal type "B2" (Thornthwaite 1948). Over the past 10 years, annual precipitation values have ranged from 703 to 1,400 mm/year, with an average of 943 mm/year. The

Table 2 Weight factors for DRASTIC and Pesticide DRASTIC (Aller et al. 1987)

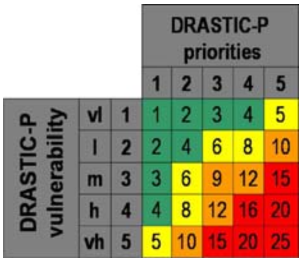
Thematic map	Weight	
	DRASTIC	DRASTIC-P
Depth to water table (D)	5	5
Net recharge (R)	4	4
Aquifer media (A)	3	3
Soil media (S)	2	5
Topography (T)	1	3
Impact of vadose zone (I)	5	4
Hydraulic conductivity (C)	3	2

main economic activity in the area is agriculture (soya beans, wheat, sunflowers, corn, potatoes).

The area under study comprises two basins that are representative of this type of geomorphological environment: the basin of “Pantanoso Creek” (on the northern slope of the Tandilia range, where the city of Balcarce is located) occupying 679 km^2 and the the basin of “El Moro-Tamangueyu Creeks” (on the southern slope of the Tandilia range, where there are two main cities: Necochea and Loberia) with a surface area of 2,264 km^2 (Fig. 1).

In the study area, the Tandilia Range has a maximum altitude of about 400 meters above sea level (m asl) and forms the upper edge of the basins. It consists of two big stratigraphical units: a Precambrian crystalline bedrock called Complejo Buenos Aires (Marchese and Di Paola 1975), and a set of sedimentary rocks of Precambrian-Lower Paleozoic origin, grouped under the name of Balcarce Formation (Dalla Salda and Iñiguez 1978). They are both considered as an impermeable sequence. An inter-range fringe that is a few hundred metres wide surrounds the blocks; it is formed by hills which quickly give way to the plain areas that reach the sea. Hills and plains are formed by Cenozoic loess-like sediments (especially of Pleistocene-Holocene age).

The regional hydrogeological features in the study area have been described by Sala (1975), Massone et al. (2005) and Quiroz Londoño et al. (2006). From a hydrogeological point of view, two main units can be recognized: the impermeable bedrock, which includes both the “Complejo Buenos Aires” and “Balcarce” Formations, and the aquifer sequence, formed by the Quaternary deposits called “Pampean sediments” or “loess-like sediments”. They are formed by silts and silty-to-sandy sediments with variable amounts of calcium carbonate that reach a thickness of up to 100 m. This defines a multi-layered unconfined aquifer with a thickness ranging from 30 to 100 m, and a hydraulic conductivity 10 m/d. The transmissivity is about 800–1,000 m^2/d. The storage coefficient, estimated from pumping tests, is 0.001, and the porosity is 0.15. The mineral composition of the aquifer is mainly quartz, plagioclases, and orthoclase with variable amounts of volcanic glass shards, with the occasional occurrence of mica and opaque minerals (Teruggi 1954). Another feature of the inter-range and plain areas is the remarkable regional homogeneity shown by some parameters associated to traditional aquifer vulnerability assessment methods.



		DRASTIC-P priorities				
DRASTIC-P vulnerability		1	2	3	4	5
vl	1	1	2	3	4	5
l	2	2	4	6	8	10
m	3	3	6	9	12	15
h	4	4	8	12	16	20
vh	5	5	10	15	20	25

Fig 2 Combination of vulnerability ranges to obtain the OVI. *vl* very low, *l* low, *m* moderate, *h* high, *vh* very high. *1–5* priorities: *1* lower priority to *5* higher priority

Methodology

The US Environmental Protection Agency (EPA) developed DRASTIC (Aller et al. 1987) as a method for assessing groundwater pollution potential, which is a “point count system model” (Vrba and Zaporozec 1994). This method considers the following seven parameters: depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). Each mapped factor is classified either into ranges (for continuous variables) or into significant media types (for thematic data) which have an impact on pollution potential.

The typical rating range is from 1 to 10 (as an example see Table 1). Weight factors are used for each parameter to balance and enhance their importance. The final vulnerability index (Di) is a weighted sum of the seven parameters and can be computed using the formula:

$$\mathrm{Di} = \mathrm{DrDw} + \mathrm{RrRw} + \mathrm{ArAw} + \mathrm{SrSw} + \mathrm{TrTw} + \mathrm{IrIw} + \mathrm{CrCw}$$

Di	DRASTIC Index for a mapping unit
w	Weight factor for each parameter
r	Rating for each parameter

DRASTIC provides two weight classifications (Table 2), one for general conditions and the other one for conditions with intense agricultural activity. The latter, called the Pesticide DRASTIC index (DRASTIC-P), represents a

Table 3 Parameters for DRASTIC-P methodology. Sources of data for the Pampas study area

Thematic map	Source
Net recharge (R)	Hydraulic balance (Massone et al. 2005; Quiroz Londoño et al. 2006)
Aquifer media (A)	Previous geological information (Massone et al. 2005; Quiroz Londoño et al. 2006)
Soil media (S)	National Institute of Agricultural Technology-INTA, Map of soils. INTA (1989)
Topography(T)	Digital terrain model and cartography from “Instituto Geográfico Militar” of Argentina (IGM) and Shuttle Radar Terrain Mapper (SRTM)
Impact of vadose zone (I)	National Institute of Agricultural Technology-INTA, Map of soils. INTA (1989) and previous geological information (Massone et al. 2005; Quiroz Londoño et al. 2006)
Hydraulic conductivity (C)	Previous studies on hydraulic parameters in Pampean and Postpampean sediments (Auge 2004)

Table 4 Values or range of values used for each variable in each pixel

	D	R	A	S	T	I	C
Plain	10–9	5	2–3	1–3	10	6	2
Inter-range fringe	7–3	5	4–5	2–4	10–9.5	7	2
DRASTIC-P weights	5	4	3	5	3	4	2

specific vulnerability assessment approach. For this study, DRASTIC-P methodology was selected, since it is the most suitable methodology in plain areas like the Pampas, mainly due to the greater weight given to the variables of soil and slope types (Massone et al. 2007).

The work was carried out within a geographic information system (GIS) ArcGIS 9.2 environment and it involved four steps:

1. Preparation of base thematic maps (as a polygonal entity) for each variable under consideration (Table 3) using GIS software packages. Subsequently, a transformation of each map into raster format (using the spatial analysis module of ArcGIS) took place. For the cases studied, a spatial cell resolution of 200×200 m was used.
2. Application of the procedure indicated by methodology for the assignment of weights and values to each layer of information (Aller et al. 1987) and the application of map algebra to obtain the aquifer vulnerability maps, called "DRASTIC-P vulnerability maps". It was considered convenient to discretize the DRASTIC-P index values into five classes (very low, low, moderate, high and very high), since this is the number of classes that allows one to recognize both the "best" values and the worst ones as two alternatives (high and very high or low and very low); this is better than recognizing only three classes where there is only one possible option towards each end (low or high). This is favourable to decision-making related to the use of soil in land-use planning, in environmental impact evaluations, etc.
3. Reclassification of these DRASTIC-P vulnerability maps according to the Natural Breaks (Jenks) method (provided by ArcGIS 9.2), to obtain the "DRASTIC-P-priorities", which recognise five classes from priority 1 (lower values in the series) to priority 5 (higher values). Five classes have been selected to make it coincident with the criteria utilized in DRASTIC-P methodology (step b). In this reclassification, classes are based on natural groupings in the data distribution. This method identifies breakpoints between classes using a statistical formula called Jenks' optimization (Jenks and Caspall 1971; Jenks 1977). This method is rather complex, but basically Jenks' method minimizes the sum of the variance within each class (Slocum 1999; Murray and Shyy 2000).
4. Combination of the DRASTIC-P vulnerability map with the DRASTIC-P-priorities to generate an operational vulnerability index (OVI). For this operation, both the vulnerability map and the DRASTIC-P-priorities were reclassified, assigning to each qualitative class a numerical value ranging from 1 (the lower class) to 5 (the higher one). These values were selected so that the product will allow identification of four classes under a traffic light code that is visually easy to interpret: two of them requiring work on a detailed scale and two allowing work on a regional scale (Fig. 2). Even though the values 1–5, arbitrary as they are, serve the purpose adequately, other values whose product meets the same requirement could be used. However, further research is needed to legitimize these values.

The OVI results from the following formula applied to each píxel:

$$\mathrm{OVI} = \mathrm{DRASTIC} - \mathrm{P} \times \mathrm{DRASTIC} - \mathrm{P} - \mathrm{priorities}$$

The four following classes are suggested:

Green	$\mathrm{OVI} \leq 4$
Yellow	$5 \geq \mathrm{OVI} \leq 8$
Orange	$9 \geq \mathrm{OVI} \leq 14$
Red	$\mathrm{OVI} \geq 15$

The operational advice that is proposed for each class is as follows—*green*: hydrogeological evaluation only with currently available data and on a regional scale (1:50,000 or less detailed scale); *yellow*: hydrogeological evaluation (1:25,000–1:50,000) with preceding information; caution in the case of persistent and/or mobile pollutant; *orange*: evaluation of detail (1:25,000–1:10,000) is recommended using data that can establish a hydrogeological and hydrochemical baseline; special care in the case of persistent and/or mobile pollutant; *red*: a study of detail is essential (1:10,000 or greater) and a

Table 5 Vulnerability categories and their areas

Methodology	Rank	Class	Pantanoso Basin		Moro Tamangueyú Basin	
			Area (km^2)	% area	Area (km^2)	% area
DRASTIC-P	<81	Very low	0	0	0	0
	81–120	Low	9.92	1.36	1	0.02
	120–160	Moderate	718.28	98.42	293	11.08
	160–200	High	1.64	0.22	2,325	88
	>200	Very high	0	0	24	0.9

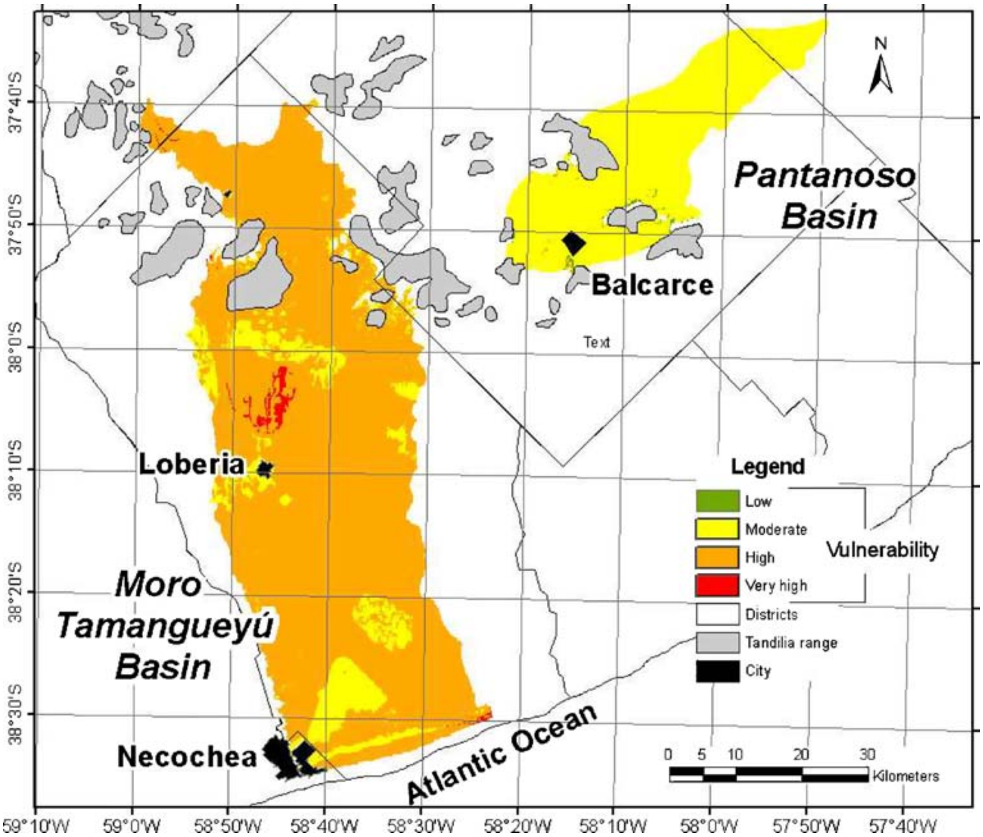


Fig. 3 Aquifer vulnerability map according to DRASTIC-P methodology in the Pantanoso and Moro Tamangueyú Basins. Very low class does not exist in this area

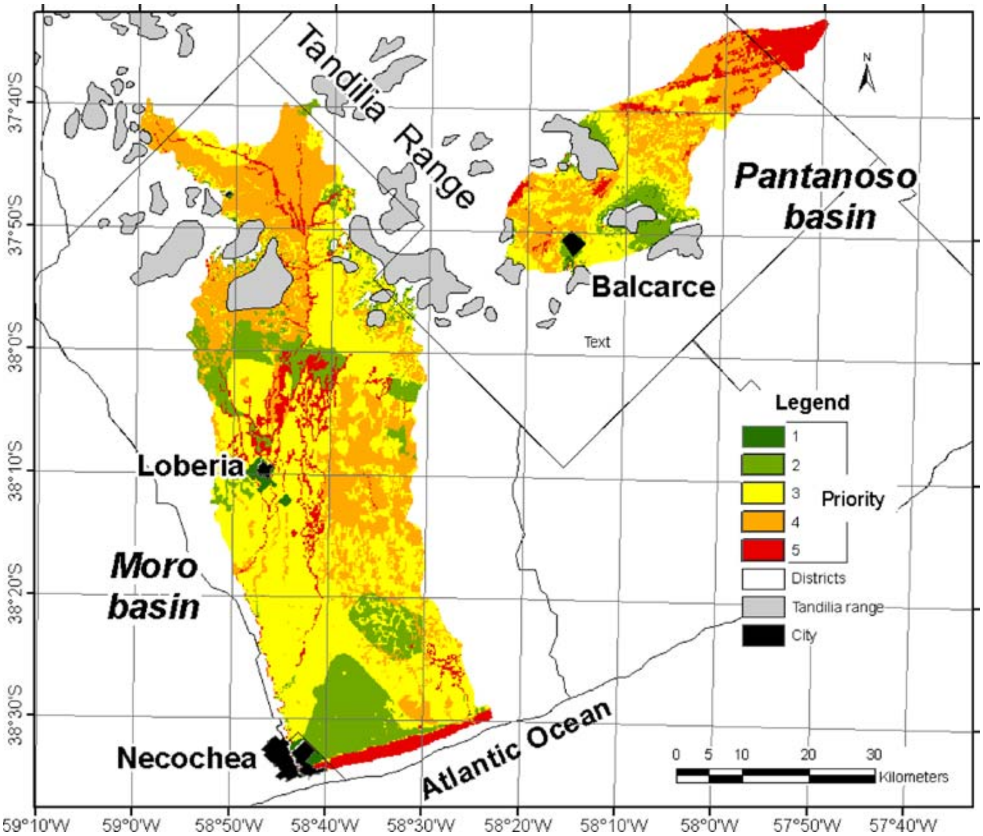


Fig. 4 DRASTIC-P- priorities map of the Pantanoso and Moro Tamangueyú Basins

Table 6 Reclassified values using Natural Break (Jenks) methodology

	Rank	Priority	Pantanoso basin		Moro Tamangueyú basin	
			Area (km^2)	% area	Area (km^2)	% area
DRASTIC-P-priorities	81–122	1	12	1.6	26.0	0.98
	122–136	2	106.52	14.6	403.0	15.25
	136–144	3	244.48	33.5	1267.0	47.94
	144–152	4	277.2	38.0	749.0	*28.36*
	152–187	5	89.64	12.3	197.0	7.47

hydrogeological and hydrochemical baseline must be established; special precautions must be taken with any type of pollutant. The operational advice of each class and the requirements for analysis mentioned in this paper are appropriate for study areas with characteristics similar to those of the Argentine Pampas, provided the operative advice can be adapted to suit the other zones.

Results

Aquifer vulnerability assessment using DRASTIC-P methodology

According to Aller et al. (1987), a weight between 1 and 5 was assigned to each variable, and a value ranging between 1 and 10 was assigned for its discretization, as shown in Table 4. As seen in Table 5 and Fig. 3, applying these classes with the inherent limits of the original methodology leads to a high homogeneity of results: for instance, in the case of the Pantanoso Basin more than 95% of the area is classified as having moderate vulnerability, while in the case of Moro Tamangueyú Basin, more than 85% is classified as having high vulnerability (Fig. 3).

Natural Break (Jenks) reclassification to obtain DRASTIC-P-priorities

Taking into account the limitations mentioned above, the DRASTIC-P-priorities were developed considering the distribution of data obtained in each basin by means of the traditional methodologies. It was based on a rearrangement of classes, following the Natural Breaks (Jenks) methodology. Five subclasses (priorities) were identified, numbered from 1 (the lowest value) to 5 (the highest value), as shown in Fig. 4 and Table 6.

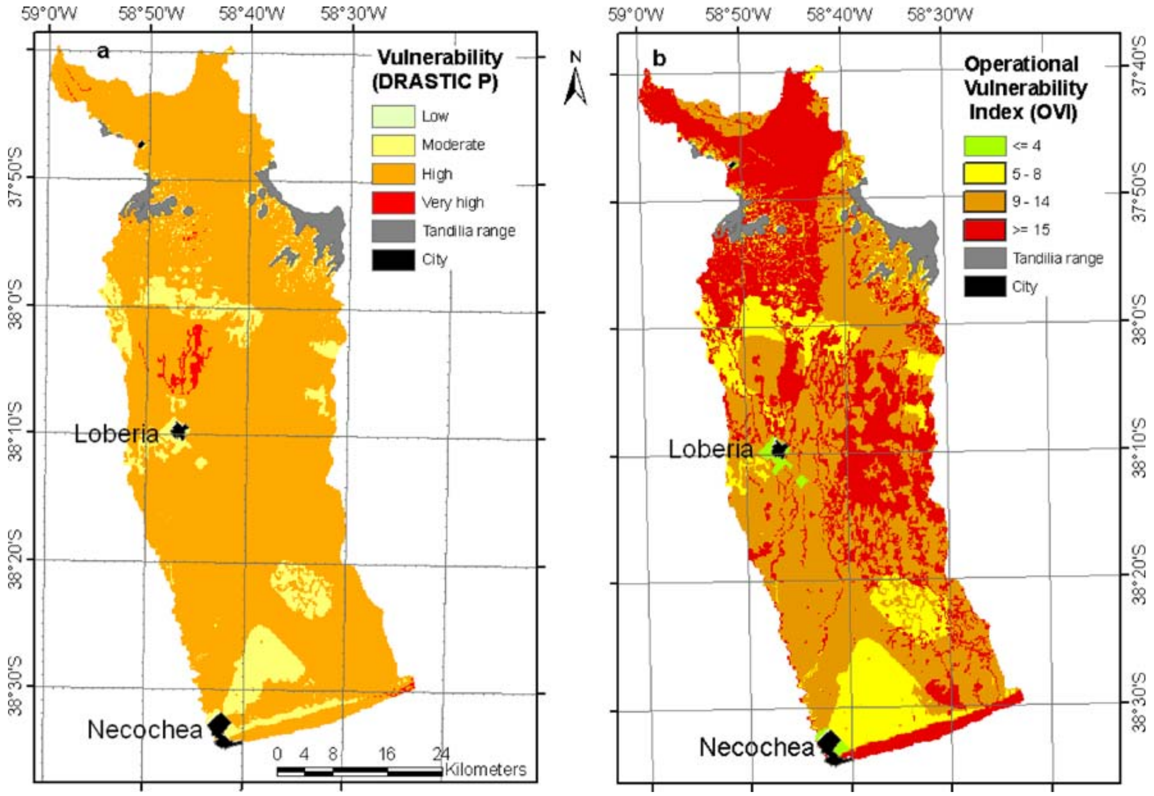


Fig. 5 Comparison between the aquifer vulnerability maps according to the **a** DRASTIC-P classes and **b** OVI indexes applied to the Moro Tamangueyú Basin

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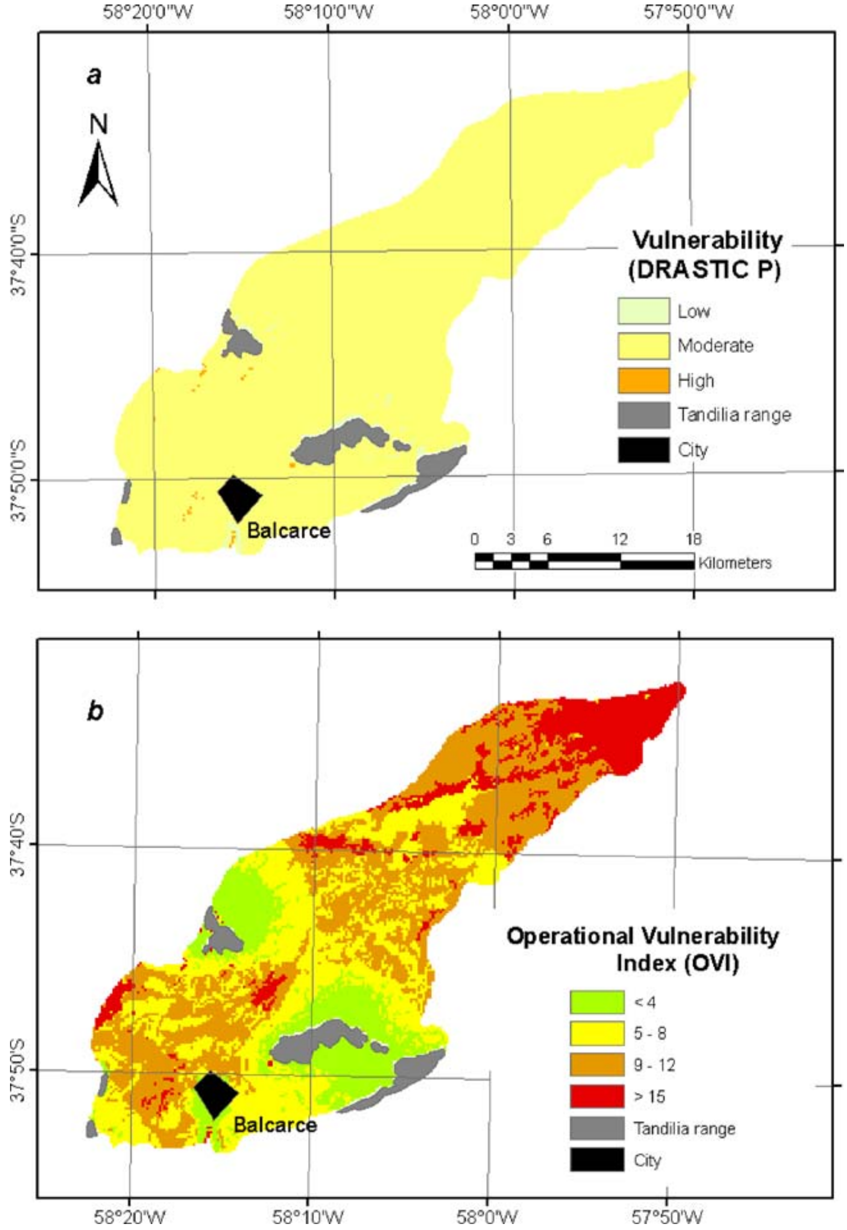

Fig. 6 Comparison between the aquifer vulnerability maps according to the **a** DRASTIC-P classes and **b** OVI indexes applied to the Pantanoso Basin

The final aquifer operational vulnerability index (OVI)

The results of the application of this methodology are shown in the maps of Figs. 5 and 6 and in Table 7. The basins under study showed 15% of the area under green-yellow categories while the other 75% is orange-red.

Discussion and conclusions

Many unconfined aquifers within plain areas present homogeneity in most of the variables involving vulnerability assessment (especially in the case of the DRASTIC

Table 7 Distribution of OVI categories in the final maps

Category		Moro Tamangueyú Basin		Pantanoso Basin	
		No. of pixels	Area (km^2)	No. of pixels	Area (km^2)
Green	OVI ≤ 4	675	27	305	12.2
Yellow	$5 \geq$ OVI ≤ 8	10,946	438	2,615	104.6
Orange	$9 \geq$ OVI ≤ 14	34,282	1,371	13,131	525.24
Red	OVI ≥ 15	26,292	1,052	2,569	102.76
Total		72,195	2,888	18,620	745

method), mainly at local and regional scales. This similarity is noticeable in attributes such as slope, soils, aquifer lithology and impact of vadose zone. Thus, traditional assessment methods of aquifer vulnerability yield results whose homogeneity makes decision-making altogether difficult. These decisions may be about land use, monitoring plans, environmental impact assessment, or other aquifer protection strategies. Therefore, the homogeneity of results in the lower categories, even though in principle it makes decision-making easier, may lead to excessive confidence, leading to a rejection of protection measures or decisions taken with scarce attention to prevention. In the case of the Pantanoso Basin, the class of "moderate vulnerability" implies a high degree of uncertainty, since the meaning of this class is not accurately defined. Furthermore, in the Moro Tamangueyú Basin, the "high vulnerability" class would inhibit any kind of action.

In view of this high homogeneity of results (in any class whatsoever), the question one must ask is, How can one establish, within these areas of homogeneous vulnerability, sub-areas where more attention should be paid when it comes to making decisions regarding land use?

The reclassification of vulnerability values using the Natural Breaks (Jenks) methodology has enabled "priorities maps" to be obtained, which show a higher discrimination of units in the territory. Being only a statistical reclassification of original data, it does not allow one to associate these priorities directly with intrinsic vulnerability categories. If the Jenks method were used indiscriminately in homogeneous zones with high vulnerability, it could yield dangerously lower vulnerability ranges. On the other hand, this reclassification method could exaggerate the vulnerability of low vulnerability homogeneous zones. This is the reason why the discrimination provided by the Jenks methodology has been characterized as "priorities" and not as vulnerability categories. If these priorities are combined with the vulnerability ranges defined by the traditional method, classes may arise for which actions aimed at protecting the resource may have different requirements. This would turn the methodology into a useful tool for the decision-makers in areas where the vulnerability is homogeneous, no matter whether it is high or low.

Even though the five vulnerability classes of the traditional methodology were obtained and the reclassification according to the Jenks methodology also yielded five classes, it was not considered appropriate to keep this number of classes in the final OVI index for two reasons: first, because when five classes are present, the intermediate one is always difficult to contextualize and define ("moderate"); second, because recognizing only four operative classes allows one to identify two classes with less requirements for the analysis (scale 1:25,000–1:50,000 in this study area) and two others which require detailed study (work scale >1:25,000 in this study area) before any decision is made about the use of the territory. It also allows one to relate it better to a traffic light code, which becomes more practical for decision-makers.

The OVI index has advantages over the traditional methodology since it allows for a better discrimination in homogeneous areas, which not only involves statistics but also the physical characteristics of the aquifer. Finally, it also allows one to abandon the traditional qualitative classification of vulnerability classes (which is always dependent on subjective interpretation) and to use a classification based on minimum information requirements which may be easily adapted to each study area. The OVI´s index distribution in the analyzed basins showed that in 75% of both areas, hydrogeological studies on a detailed scale are required when making land-use decisions. Plain areas with similar features could have the same requirements.

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References

Allen A, Milenic D (2007) Groundwater vulnerability assessment of the Cork Harbour area, SW Ireland. Env Geol 53:485–492

Aller L, Bennett T, Lehr J, Petty R (1987) DRASTIC: a standardized system for evaluating ground water pollution. Doc. EPA/600/2-85/018, US EPA, Washington, DC, 157 pp

Auge, M (2004) Vulnerabilidad de Acuíferos: Conceptos y Métodos [Aquifers vulnerability: concepts and methodologies]. Available via:http://tierra.rediris.es/hidrored/ebvulnerabilidad.html. Cited 30 July 2009

Civita M, De Maio M (2004) Assessing and mapping groundwater vulnerability to contamination: the Italian "combined" approach. GeofiÂs Int 43(4):513–532

Cramer W, Vrba J (1987) Vulnerability mapping. Proceedings of the International Conference on Vulnerability of Soil and Groundwater to Pollutants. Woordrijk aan Zee, The Netherlands, 30 March–3 April 1987, pp 45–48

Dalla Salda L, Iñiguez M (1978) La Tinta: Precámbrico y Paleozoico de Buenos Aires ["La Tinta": Precambric and Paleozoic of Buenos Aires]. VII Congreso Geológico Argentino, Neuquén, Argentina, vol 1, pp 539–550

Foster S (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvenbooden W, van Waegeningh H (eds) Vulnerability of soil and groundwater to pollutants. Proceedings and Information no. 38, TNO Committee on Hydrological Research, The Hague, pp 69–86

Foster S, Hirata R, Gomes D, D´Elia M, y Paris, M (2002). Protección de la Calidad del Agua Subterránea [Protection of groundwater quality]. GW-MATE-UNESCO-World Bank, Washington, DC, 115 pp

Frind E, Molson J, Rudolph D (2006) Well vulnerability: a quantitative approach for source water protection. Ground Water 44(5):732–742

GEAM (Associazione Georisorce é ambiente) (2005). Aquifer vulnerability and risk. Proceedings of the 2nd Workshop, CNR-GNDCI, Parma, Italy, September 2005

Gogu R, Dassargues A (2000) Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Env Geol 39(6):549–559

Gogu R, Hallet V, Dassargues A (2003) Comparison of aquifer vulnerability assessment techniques: application to the Néblon River basin (Belgium). Env Geol 44:881–892

INTA (Instituto Nacional de Tecnología Agropecuaria) (1989) Carta de Suelos de la República Argentina (1:50.000) [Soils chart of

Argentina] Proyecto PNUD ARG 85/019. Secretaría de Agricultura, Ganadería y Pesca-INTA, Buenos Aires, Argentina

Jenks G (1977) Optimal data classification for choropleth maps. Department of Geography occasional paper no. 2, University of Kansas, Lawrence, Kansas

Jenks G, Caspall F (1971) Error on choropleth maps: definition, measurement, and reduction. Ann Assoc Am Geogr 61(2):217–244

Marchese H, Di Paola E (1975) Reinterpretación estratigráfica de la perforación Punta Mogotes 1: Provincia de Buenos Aires, República Argentina [Stratigraphic interpretation of “Punta Mogotes 1” well: Buenos Aires Province, Argentina]. Rev Assoc Geol Arg, Buenos Aires 30(1):44–52

Margat J (1968) Groundwater vulnerability to contamination. Publication 68, BRGM, Orleans, France

Massone H, Tomas M, Farenga M (2005) Una aproximación geológica a la planificación de usos del territorio utilizando técnicas SIG. Balcarce (Argentina) como estudio de caso [A geologic approach to land-use planning by use of GIS: Balcarce (Argentina) as study case]. XVI Congreso Geológico Argentino, Actas V, La Plata, Argentina

Massone H, Quiroz Londoño M, Tomas M, Ferrante A (2007) Evaluación de la vulnerabilidad de acuíferos en cuencas de llanura periserranas. Estudio de caso, Balcarce, Provincia de Buenos Aires. (aquifer vulnerability assessment in inter-range basins. Balcarce, Buenos Aires Province as study case). V Congreso Argentino de Hidrogeología, vol , IAH, Paraná, Argentina, pp 149–158

Murray A, Shyy T (2000) Integrating attribute and space characteristics in choropleth display and spatial data mining. Int J Geogr Inform Sci 14(7):649–667

Popescu IC, Gardin N, Brouyere S, Dassargues A (2008) Groundwater vulnerability assessment using physically-based modelling: from challenges to pragmatic solutions. In: Calibration and reliability in groundwater modelling: credibility of modelling. Proceedings of ModelCARE 2007 Conference, Denmark, September 2007, IAHS Publ. 320, IAHS, Wallingford, UK

Quiroz Londoño O, Martínez D, Massone H, Bocanegra E, Ferrante A (2006) Hidrogeología del Área Interserrana Bonaerense: Cuencas de los Arroyos El Moro, Tamangueyú y Seco [Hydrogeology of the Inter-range area of Buenos Aires province: el Moro, Tamangueyú and Seco creeks]. VIII Congreso Latinoamericano de Hidrología Subterránea y EXPOAGUA 2006, Asunción, Paraguay

Rodriguez R, Civita M, de Maio M (2003) Aquifer vulnerability and risk. 1st International Workshop, Proceedings, UNAM, Guanajuato, Mexico, May 2003

Sala J (1975) Recursos Hídricos [Hydraulic resources]. Relatorio VI Congreso Geológico Argentino, Bahia Blanca, Argentina, pp 169–194

Secunda S, Collin M, Molloul A (1998) Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Israel’s Sharon region. J Environ Manage 54:39–57

Slocum TA (1999) Thematic cartography and visualization. Prentice-Hall, Upper Saddle River, NJ

Teruggi M (1954) El mineral volcánico-piroclástico en la sedimentación cuaternaria Argentina [The volcanic-pyroclastic mineral in the quaternary sedimentation of Argentina]. Rev Asoc Geol Arg (Buenos Aires) IX(3):184–191

Thornthwaite C (1948) An approach toward a rational classification of climate. Geogr Rev 38:55–94

Vrba J, Zaporozec A (1994) Guidebook on mapping groundwater vulnerability. Int. Cont. Hydrogeol, vol 16, Heise, Hannover

Wang Y, Merkel B, Li Y, Ye H, Fu S, Ihm D (2007) Vulnerability of groundwater in Quaternary aquifers to organic contaminants: a case study in Wuham City, China. Env Geol 53:479–484