

# The use of geoprocessing to assess vulnerability on the east coast aquifers of Rio de Janeiro State, Brazil

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**Abstract** The east coast of Rio de Janeiro State, Brazil, shows a worrying overlap between areas with intrinsic groundwater vulnerability and the most significant urban expansion zones. It experienced a rapid population growth in recent years, mainly due to the tourism industry, resulting in a significant pressure on drinking groundwater resources. In this regard, development and use of techniques to control and protect areas susceptible to contamination is crucial. The elaboration of aquifer vulnerability maps is thus extremely helpful to support water resources management. The aim of the work is to present the methodological approach in the use of Geoprocessing techniques to obtain a suitable groundwater vulnerability model in Rio de Janeiro east coast. Considering the existing problems and the current land use and characteristics of the study region, it is clear that the most vulnerable areas (that is, “extreme” and “very high” vulnerability areas), coincide with the most significant zones of urban occupation, corresponding to 11% of the total study area, demanding adoption of urgent measures in the near future. Geoprocessing tools and remote sensing for characterization of Rio de Janeiro’s east coast aquifer vulnerability gave good results, representing a satisfactory method for management actions at low cost.

**Keywords** Groundwater vulnerability models · Coastal aquifers · Rio de Janeiro · Geoprocessing

## Introduction

Water, a strategic and vulnerable resource, must be managed on a well planned and sustainable basis. With respect to groundwater, additional care must be taken since, once a contamination occurs, removal of contaminants becomes a much more difficult task to carry through than with surface waters. The problem in some cases is irreversible.

It is clear that technical and economical limitations and lack of skilled professionals, especially in developing countries, make remediation of contaminated aquifers an improbable task to accomplish. Due to this situation, an increasing number of aquifer control and protection techniques have been developed, with continuous improvement (Hammerlinck and Arneson 1998; Hoffmann and Sander 2007). Among those techniques, elaboration of aquifer vulnerability indexes allows the establishment of zones with distinct degrees of vulnerability and their spatial distribution. Currently, groundwater vulnerability maps are an important tool for environment management and protection.

The study was carried out in water table porous aquifers of Rio de Janeiro State east coast, Brazil, a tourist area between Niterói and Rio das Ostras townships. This region today has a fast population growth rate, resulting in an increasing drinking groundwater demand and, therefore, a growing pressure on the coastal aquifers, frequently the only source of potable water. Those aquifers are the subject of intense exploitation, mainly during summer season, when a significant increase in population occurs due to tourism.

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Simultaneously, a high load of domestic effluents is released, as these regions generally lack sewage systems (Silva 2002). Consequently, aquifer vulnerability analyses is of basic importance for decision making and territorial zoning mainly in regions where this resource is the only source of drinking water, as is the case in most of Rio de Janeiro State east coast.

#### Brief literature review

The term *aquifer vulnerability*, as used in literature, refers to the sensitivity of aquifers to contaminant loads as a function of their intrinsic characteristics. This concept is very close to the concept of *aquifer sensitivity*, which considers sensitivity as a function of the intrinsic characteristics of the geologic materials in question (USEPA 1993). *Specific vulnerability* is at times referred to as the evaluation of vulnerability related to a specific type of contaminant. Ross et al. (2004) regard the usual definition of aquifer vulnerability as conservative, since it ignores some important processes that would considerably influence the impact of contamination, such as adsorption, dispersion, transport and fate of the contaminant.

Therefore, the vulnerability of an aquifer also depends on the type of potential pollutant. For example, an aquifer can be highly vulnerable to a nitrate load and less vulnerable to contaminants of another nature. However, the creation of maps for specific contaminants or for each type of activity represents an enormous amount of necessary data.

The first attempts to map the aquifer vulnerability were aimed at selecting safe areas for waste disposal, as sanitary landfills or stabilization lagoons (Le Grand 1964). Weighing of attributes like distance to producing wells, depth to water table, aquifer gradients, and soil permeability attenuation capacity was accomplished to obtain vulnerability indices to specific contaminants or threats.

Various other methods are available for aquifer vulnerability evaluation (Foster and Hirata 1988; Van

Stempvoort et al. 1992; Adams and Foster 1992, among others). A standardized index has been adopted initially in the US and Canada and is currently used in various countries, the DRASTIC index, developed by Aller et al. (1987) for the USEPA. The DRASTIC index is today one of the most widely used models to assess groundwater vulnerability for a wide range of potential contaminants. Table 1 shows recent evolution and major adaptations of DRASTIC method more widely used. Adopting and adapting adequately them for specific purposes has become a major practical issue in any research or potential use.

Kumar and Engel (1994) compared the results found for the DRASTIC and the SEEPAGE (Richert et al. 1994), a method that considers the soil attenuation potential to a given pollutant in agricultural areas (fertilizers and pesticides). As a specific model to assess contamination for a type of polluting activity—agricultural—results for SEEPAGE revealed a better distribution than those found in DRASTIC. However, the great number of variables and the difficulty of obtaining some of them create obstacles to the practical application of the model and other similar models.

With the increasing scarcity of financial resources and staff in environmental agencies to deal with overwhelming problems, the use of the remote sensing as a source of data at relatively low cost has become frequent recently (Tweed et al. 2007; Herlinger and Viero 2007). In hydrogeological studies, there is a great potential for use of orbital images in mapping vulnerable areas and risk of contamination (Stigter et al. 2006). However, the application of these tools in hydrogeological studies is still scarce. Object oriented multi-segmentation techniques can be used for generation of thematic maps of land use and cover (Cruz et al. 2007). It aims at simulating visual interpretation techniques to identify land features, based in the description standards (color, texture, area, context), making it possible to use the next neighbor technique for spectral signature and free application of Boolean or fuzzy models.

**Table 1** Some examples of adaptations to DRASTIC vulnerability index

Model name (when available)	Adaptations	Reference
SINTACS	Alteration of variable weights	Civita et al. (1990)
–	Modification in weights and loads to each variable	Hammerlinck and Arneson (1998)
–	Addition of variables related to flow of groundwater	Brown (1998)
AHP-DRASTIC	Modification in variable weights, multicriteria analysis and use of analytic hierarchical method (AHP)	Thirumalaivasan et al. (2003)
–	Data integration with land use and cover map (sources of contamination)	Al-Adamat et al. (2003)
SI-DRASTIC	Alteration in variable weight and addition of land use and cover criterion and use of the <i>Specific Susceptibility Index</i>	Stigter et al. (2006)

**Study area**

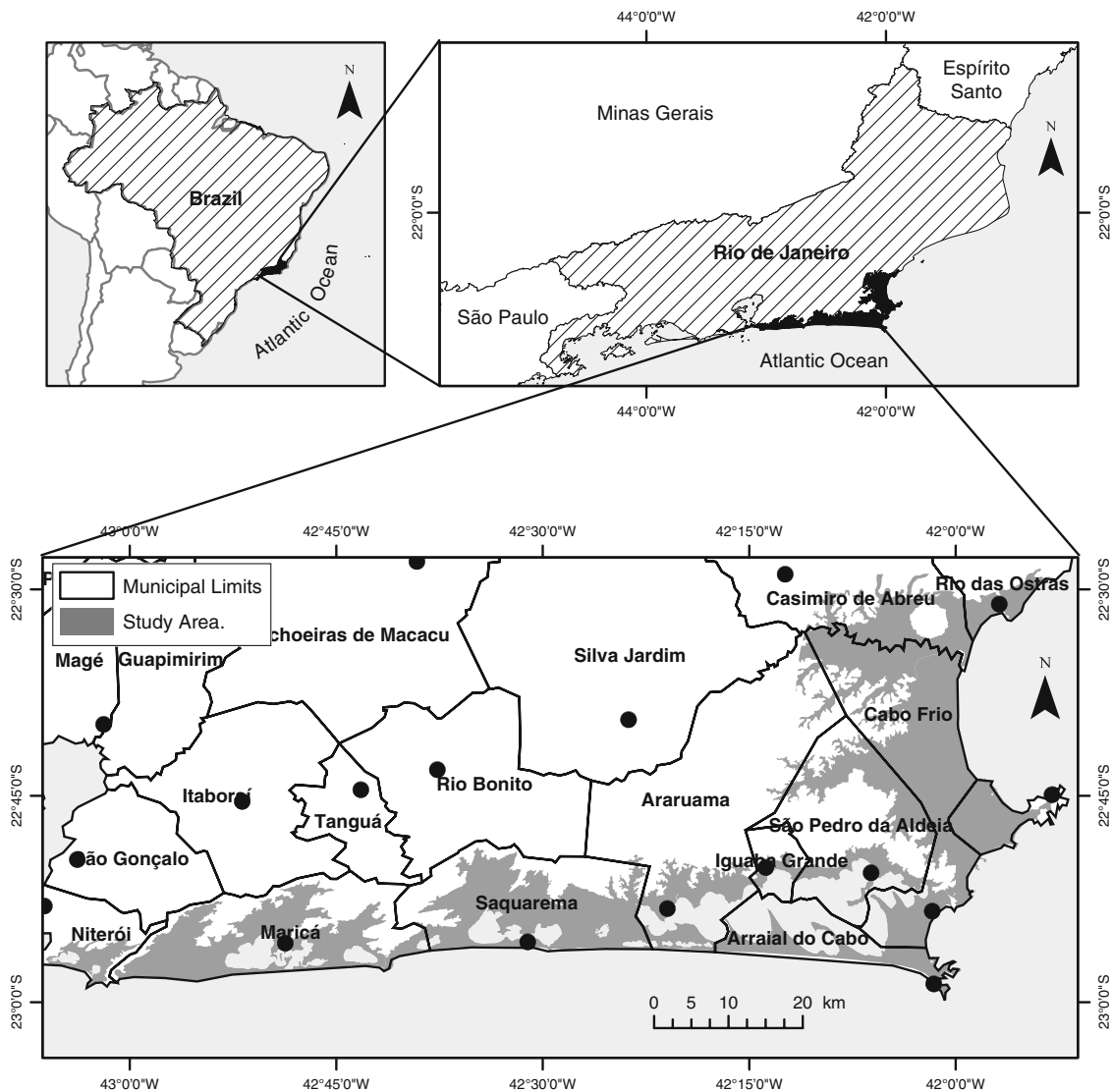
Geology and geomorphology

The study area is located eastwards of Rio de Janeiro city and comprehends the coastal sedimentary plains of eleven municipalities. The total surface is 881 km<sup>2</sup> and is situated between latitude 22°25'00"S and 23°00'S and longitude 43°09'00"W and 41°48"W (Fig. 1). Geologically the coastal sediments cover two important tectono-magmatic Pre-Cambrian to early Cambrian domains of Rio de Janeiro State: The Serra do Mar and the Região dos Lagos Domains. Both constitute the basement rocks in the region and are composed by migmatites, gneisses and intrusive orogenic granitoids (CPRM 2001).

This paper presents results of an ongoing research of coastal aquifers in Brazilian southeastern region States

(Seabra 2007). The scope was limited to the sedimentary covers that overlie part of the previously mentioned domains. Most of the sedimentary covers characterize a succession of coastal plain beach arcs tending to increase width eastwards (Muehe 1982). The main feature of the coastal landscape is the development of sandy barriers parallel to the shoreline (Muehe 1998), frequently occurring as double parallel sandy barriers separated by a narrow depression, filled or not with saltwater. The sandy barriers give a rectilinear shape to the coastline, only interrupted by rocky coastal hills that limit the coastal plains.

Muehe (1998) stresses that migration of sandy barriers depends on variations of sea level, with the inner barrier associated to the Pleistocene transgression and the one closer to the sea to post-glacial transgression. In some points sea breaks the barrier during storms due to storm waves, causing the overwash. Morphology of shore barriers



**Fig. 1** Location of the study area

repeats the typical pattern in many points of the South-eastern and South Brazilian coast, with the inner sandy barrier wider and higher than the frontal barrier. The difference in height between barriers is around 2–4 m. Between both sandy barriers, and between those and crystalline bedrock, two lagoon systems usually occur in the study area (Turc et al. 1999):

- The innermost system is formed by great lagoons that are located between the crystalline formations and the Pleistocene sandy barrier, such as Araruama, Saquarema, Guarapina and Maricá lagoons (see Fig. 2). This system was developed during Pleistocene age and was again submerged during the Holocenic transgression;
- Pleistocene and Holocene sandy barriers, a lagoon system was originated during the maximum of last transgression, between 7,000 and 5,000 years B.P. These shallow small lagoons all tend to dry up.

The geomorphologic features in the area, according to the Geomorphologic Map of Rio de Janeiro State (CPRM 2001) are: Isolated Hills, Coastal and Interior Massif, Coastal Hilly Domains, Hilly Domains, Plains, Fluvio-Lacustrine Plains and Marine Plains. Three of those units are representative of the studied sediments:

- Marine Plains are smooth low-lying terrains, with gradients converging to the shoreline, poorly drained with a meander channel pattern. It is common the presence of leveled out surfaces and small hill adjusted to the local base level.
- Fluvio-Lacustrine plains are poorly drained lands with a very shallow phreatic level.
- The Coastal Plains are horizontal surfaces with wavy microrelief of topographical amplitude inferior to

20 m. They are well-drained terrains with a parallel drainage pattern, following the interbarrier depressions.

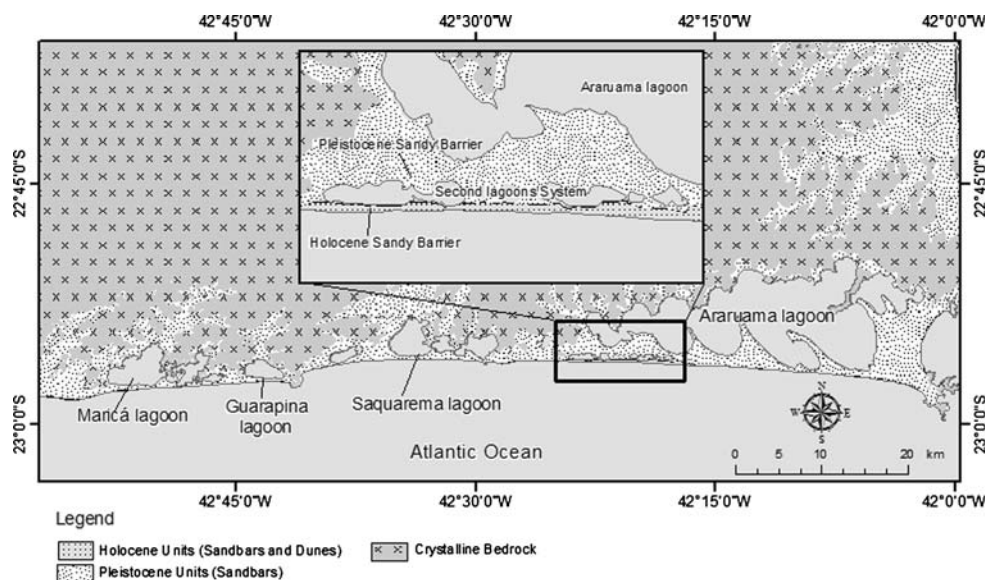
The tropical latitude and the proximity of the ocean, associated to the existing dynamics of the air masses in the region, bring important particularities and different types of climate to the east coast of Rio de Janeiro State. In the occidental portion, west of Araruama lagoon, there is a humid tropical climate, with pluviometric indices above 1,000 mm per year. In the eastern portion there is a semi-arid climate, with the smaller rain indices of Rio de Janeiro State and Brazilian Southeastern Region (Bidegain 2002), with an average rainfall lower than 750 mm per year (Fig. 3).

In the semi-arid subregion, evapotranspiration is greater than precipitation, generating a significant water deficit. This deficit has been correlated, among other reasons, to the distance between the coast and the mountain ranges, which eliminates the possibility of rain occurrence due to orographic effect. The effect of a coastal upwelling phenomenon in Cabo Frio associated with the prevailing northeast wind has also influence on aridity of the area. Regional winds blow with intensity throughout the year, mainly in S/SE (associated to cold fronts) and N/NW (summer rain) directions.

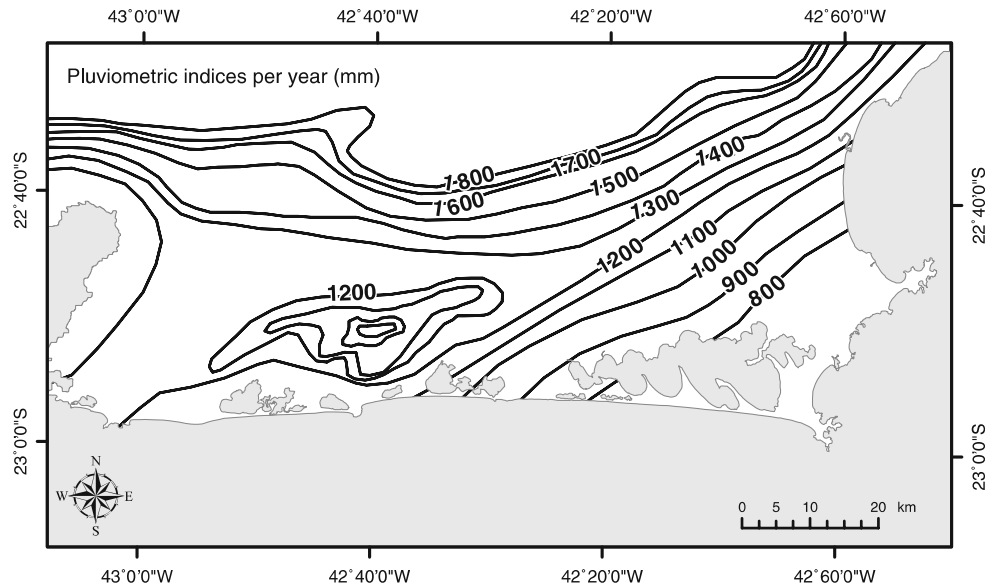
#### Hydrogeology

The study area is composed granular type aquifers, with lateral and perpendicular variation with respect to the shoreline. They were formed as a consequence of the formation of coastal plains during the last sea level transgressive and regressive variations during the Holocene between 5,000 and 7,000 years B.P. The coastal plain is

**Fig. 2** Location of the lagoons with respect to main geological units



**Fig. 3** Rainfall distribution map



formed by intercalations of more elevated sandy bars, covered with sandy barrier vegetation, with lower flood prone sandy–clayey sediments, all parallel to the sea. The water level is generally shallow, with depths of some centimeters up to a few meters. In the area of the sandy barriers, which corresponds to slightly more elevated portions of terrain, the water is generally less salty and turbid than that of the muddy depressions, sometimes subject to flood events.

Water quality is generally related to the aquifer emplacement: generally water salinity increases with the proximity of the coast and, at the same time, with depth. Salinity is also controlled by human occupation density. Nevertheless, there are other factors controlling groundwater salinity, as in the case of Cabo Frio city, near the Una River estuary, where other conditioning features to distribution of groundwater salinity may exist, as stratigraphic and structural factors (Cruz and Silva 2006). In sandy barriers, water table in the central strips is deeper, becoming shallower as it approaches the ocean and the inner lagoons. Such characteristics, particularly in alluvial deposits, give the water table aquifers a high susceptibility to bacteriological contamination.

Other factors that expose local aquifers to a high vulnerability to bacteriological contamination are: slope in the lower areas is practically null, making groundwater runoff difficult; areas next to lagoons are subjected to tide oscillation and periodic flooding during intense rainfall events; in most cases, septic tanks or sinks, constructed without adequate guidance, are too close to water wells; and well construction lacks adequate sanitary protection system (Cruz and Silva 2006). Porous aquifers in east coast of Rio de Janeiro State are subdivided in CPRM (2001):

- *alluvial-lacustrine* water table aquifers, formed by intercalation of sands and clays with the frequent occurrence of organic matter, with intense compositional variation. They overly the crystalline basement or oldest sediments. Thickness is 20 m on average, reaching up to 100 m in some places. Water is generally fair, and sometimes slightly ferruginous.
- *sandy barriers* and terraces aquifers, formed by fine to coarse sands, with silty and clayey matrix. They are free shallow aquifers, normally with lenses of fresh water with good quality.

**Materials and methods**

The present work consisted on the generation and manipulation of different types of data, acquired from: (1) Landsat images 7 Enhanced Thematic Mapper Plus (ETM+); (2) vectorization of 1:50,000 Rio de Janeiro geological maps; (3) vectorization of thematic maps produced by the Brazilian Geological Survey; (4) processing of digital elevation model data (DEM) acquired from Shuttle Radar Topography Mission (SRTM): SRTM-DEM. The work steps were organized according to the different types of data through simultaneous implementation of tasks. The Landsat ETM+ images were subjected to a process of segmentation and generation of different color compositions. The color compositions and shaded images obtained from mosaics of the SRTM-DEM supported the elaboration of thematic maps, particularly in the adjustment of the coastline and other water bodies.

Digital processing of Landsat ETM+ images and field-work in May and October 2006 allowed the construction of



a 1:50,000 scale land use and cover map. SRTM-DEM mosaics facilitated elaboration of overlapping images, as well as other plans of information such as slope, aspect and hypsometry. All the generated data and products and the acquired cartographic base were incorporated to an *ArcGIS*<sup>®</sup> Geographic Data Bank (GDB). A detailed literature review supported the achievement of the vulnerability model.

#### Generation of DEM and cartographic products

Between 11 and 22 February 2000 National Aeronautics and Space Administration (NASA), along with National Imagery and Mapping Agency (NIMA), the German Space Agency (DLR) and Italian Space Agency (ASI) launched SRTM mission aimed at generating an earth digital elevation model (DEM) using an interferometric radar. Data was released in two different resolutions: 1 s of arc (30 m) and 3 s of arc (90 m). In the present work, to generate the DEM and the *hypsometric map*, the pixel used had a resolution of 3 s of arc, approximately 1 pixel corresponding to 90 m.

In the process of image acquisition, the emitted signal is received by two antennas separated by a fixed distance (60 m), which allows the calculation of the surface elevation with an absolute resolution of 16 m in the vertical (90% confidence) despite various studies report a greater precision. The data available are the DEM (not the image) in a matrix file, with radiometric resolution of 16 bits in geographic projection, elevations referenced to the WGS 84 EGM 96 geoid and horizontal datum WGS 84. The use of SRTM is better in areas of smooth relief, as in the working area. Recent scientific studies, such as the one from Barros and Cruz (2007), endorse the use of models generated by SRTM in 1:100,000 scale, class A, in 1:50,000, class C, analyzed according to the Brazilian Map Accuracy Standard (Padrão de Exatidão Cartográfica—PEC).

The *geological map* was obtained from vectorization of analogical maps published by Rio de Janeiro State Geological Survey (DRM-RJ) in 1:50,000 scale. The association

of classes, generation of topology and area determination were carried out in *ArcGIS*<sup>®</sup> system. Generation of thematic attributes of geological units (polygon areas) and lineaments (line extension) was possible with *Xtools Pro-ArcGIS*<sup>®</sup> extension. Shaded images were generated from SRTM-DEM with the aid of *SPRING 4.3*<sup>®</sup> software to visualize relief differences.

The map of *rainfall distribution and aquifer recharge* was obtained using the method proposed by Al-Adamat et al. (2003) who estimated recharge weighing landscape features, slope, total rainfall and aquifer permeability for coastal aquifers in Jordan River. Recharge is strongly related to other factors, such as: vegetation cover, land use, topography, hydraulic conductivity and soil type (Tweed et al. 2007). Each of those factors was weighed multiplying their weight by their rating. In the present work *rainfall* rate was vectorized, and *slope* and *hypsometry* were extracted from SRTM-DEM. Final recharge relative magnitudes were calculated as follows:

$$\begin{aligned} \text{Final recharge} = & (\text{hypsometry}_w \times \text{hypsometry}_r) \\ & + (\text{slope}_w \times \text{slope}_r) + (\text{rainfall}_w \times \text{rainfall}_r) \\ & + (\text{soil}_w \times \text{soil}_r) \end{aligned} \quad (1)$$

where attribute<sub>r</sub> is the attribute rate and attribute<sub>w</sub> is the attribute weight.

The weights and rates of equation (1) are given in Table 2. Final rainfall magnitude ratings are presented in Table 3. Although the estimation is not entirely quantitative, final rating reflects the absolute values of rainfall, plus slope, altitude and soil type. Results need detailed field measurements for a reliable quantitative assessment. Silva et al. (2000) calculated recharge in Piratininga, in the study area, based on groundwater flow to quantify recharge resulting in recharge values ranging between 25 and 35% of rainfall. The *water table depth map* was the outcome of measurements executed in October 2006 in 404 wells catalogued during a previous work by Silva and Pizani (2003). Preliminary results showed a strong relationship between phreatic level and the altimetric values: a higher altitude of the measuring point corresponds to a deeper

**Table 2** Weights and ratings for recharge estimation

Hypsometry weight = 3	Rating	Slope weight = 7	Rating	Soil weight = 5	Rating	Rainfall (weight = 9)	Rating
Up to 10 m	0.3	0–2%	0.9	Gleysol	0.1	<800 mm	0.1
10–20 m	0.5	2–4%	0.7	Flúvic Neosol	0.5	800–1,000 mm	0.3
20–40 m	0.7	4–6%	0.5	Podzolic	0.6	1,000–1,200 mm	0.5
>40 m	0.9	6–12%	0.3	Planosol	0.7	1,200–1,400 mm	0.7
			0.1	Spodosol	0.9	1,400–1,600 mm	0.8
				Dunes	1	1,600–1,800 mm	0.9
						>1,800 mm	1

**Table 3** Rating of rainfall magnitude according to equation (1)

Recharge magnitude	Final recharge rating
Very high	>16
High	14–16
Moderate	12–14
Low	10–12
Very low	<10

water table. This correlation contributed for the division of the mapping classes, and helped the definition of space limits for water table depth in the region as a whole, adjusted to the topographical limits in the DEM. The depth classes were divided as <2 m, between 2 and 4 m, from 4 to 8 m and >8 m.

The *land use and cover map* was built with 2 Landsat *ETM+* scenes, with acquisition date back to October 2000 and April 2001. An object-guided classification was adopted, with the use of *Ecognition*® software. The object-guided analysis was possible after segmentation for creation of recognizable objects in the image, with parameters (similarity 10) chosen in order to attend to the scale of mapping (1:50,000). Following segmentation, definition of thematic classes to be represented in the mapping was necessary. A hierarchy of classes and identification of representative samples was established for the design of the spectral signatures. These steps have been supported with field observations.

The definition of classes as well as the choice of samples that represent each class was based on the data acquired during fieldwork. Using GPS, digital cameras and field reports, distribution of the different uses in the study area could be evaluated. Selected samples were taken from the distinct classes to define descriptors, consisting in characterization of each class through its spectral behavior in each spectral band. The adopted descriptors were: average and standard deviation standard of each band, rating of each band by the sum of all bands, brightness, sum of bands in the red and next infra-red (Band 3 + Band 4), and the normalized difference vegetation index (NDVI). After pre-classification, a second field campaign was made to validate mapping and to correct some errors. The classification resulted in 17 categories of land use and cover, varying from water bodies and bedrock exposures to various types of urban occupation.

**Map of vulnerability to aquifer contamination**

The map of general vulnerability to aquifer contamination in Rio de Janeiro State east coast was made with the adaptation of the DRASTIC model considering particularities of the study area. The complexity of the hydrogeological setting

and parameter selection makes the elaboration of an absolute vulnerability classification a difficult, if not unattainable, task. The classification and mapping of the area is, as a result, presented in relative and qualitative terms. Table 4 shows weights and rates of the adopted vulnerability parameters.

Due to the aquifer characteristics (shallow water table aquifers, in sedimentary environments), the “type of aquifer” and “characteristics of vadose zone”, from original DRASTIC were represented by the attribute *Aquifer Lithology*, to which a weight 4 was given in multicriteria analysis. The soil characteristics and the hydraulic conductivity were analyzed jointly and represented in the model with the attribute *Soil Type* with weight 2.

The slope classes were determined in intervals that allowed differentiating the angle of slope as an inducing or retarding factor in recharge, in accordance with the study area.

Classes of vulnerability were defined varying from “insignificant” to “extreme”, as it can be observed in Table 5. The final map of aquifer vulnerability was generated from the intersection of the considered variables, in GIS environment (*ArcGis*® platform), where the sum of the weights of each subject, multiplied by the rating of each class, resulted in the general vulnerability value, as shown in equation 2.

$$\begin{aligned} \text{General vulnerability} = & (W_{\text{soils}} \times R_{\text{soils}}) \\ & + (W_{\text{recharge}} \times R_{\text{recharge}}) + (W_{\text{slope}} \times R_{\text{slope}}) \\ & + (W_{\text{depth}} \times R_{\text{depth}}) + (W_{\text{lithology}} \times R_{\text{lithology}}) \end{aligned} \quad (2)$$

where  $W_{\text{parameter}}$  represents the weight of the variable and  $R_{\text{parameter}}$  represents the rating of the variable.

**Results**

Topography plus thematic and newly generated maps (land use and cover, geology, conservation units, pedology, geomorphology, slope, relief compartments, aspect, shading and aquifer vulnerability), all in 1:50,000 scale, were incorporated in a database, allowing a joint analysis of processes and phenomena that influence the groundwater vulnerability or contamination risk. These elements were made available in a Geologic Database in *ArcGIS* 8.3 platform.

The use of SRTM-DEM proved satisfactory to build the hypsometric map for the study areas. From the model, it is observed that most of the mapping area is represented by Coastal Plains, Fluvio-Lacustrine Plains and Colluvial–Alluvial Plains, generally with a low altitude <20 m.

The classification oriented to objects is aimed at selecting and modeling descriptors representative for each

**Table 4** Parameter weights and rates of groundwater vulnerability map

Aquifer lithology weight = 4	R	Soil type weight = 2	R	Slope weight = 5	R	Recharge weight = 3	R	Water table depth weight = 5	R
Fluvio-Lacustrine	0.4	Podzolic	0.4	0–2%	1	Very high	1	0–2 m	1
Colluvium-alluvial	0.6	Dune deposits	1	2–4%	0.8	High	0.8	2–4 m	0.7
Marine-Beach	0.9	Spodosol	0.9	4–6%	0.6	Moderate	0.6	4–8 m	0.4
Marine-Beach or lacustrine	0.8	Gleysol	0.1	6–12%	0.4	Low	0.4	>8 m	0.1
Marine-Beach. Eolic or lacustrine	1	Latosol	0.7	12–18%	0.2	Very Low	0.2		
Lacustrine	0.4	Fluvic Neosol	0.5	>18%	0.1				
Barreiras formation (Tertiary continental)	0.2	Solodic Planosol	0.7						

R rating

**Table 5** Groundwater vulnerability classes defined by the study method

Rating	Vulnerability classes
3.8–7.8	Insignificant
7.8–10.1	Very low
10.1–11.7	Low
11.7–13.2	Moderate
13.2–14.8	High
14.8–16.4	Very high
16.4–18.8	Extreme

class. In this process, samples selected with a conventional training process for supervised classifications may or may not be considered. Fuzzy models specific for each class were used, through comparison between different classes and descriptors. The most representative descriptors were: the average of spectral bands, the brightness, the ratio of the spectral bands, the standard deviation between the bands and normalized difference vegetation index (NDVI). A preliminary classification was achieved after the second field campaign, when some adjustments were made for final edition.

#### Thematic maps: relevant results

The construction of a *geological map* from several sheets, made by Rio de Janeiro State Geological Service and originally in 1:50,000 scale, was incorporated to the GIS Database. Geoprocessing allowed the generation of DB attributes. The use of Landsat *ETM+* image for a better delimitation of the thematic classes presented good results, particularly near water bodies. The shaded images made possible adjustments in location of geologic structures (fractures, faults, breccias, dikes and lineaments), allowing a better representation of this subject.

From the *rainfall distribution map* (Fig. 3), one observes that rainfall rates and distribution of different soil types were the main conditioning factors for coastal aquifer recharge variation in the study area.

The *water table depth map* shows groundwater is very shallow, with more than 85% of the area having phreatic level at depth less than 4 m. The wells, where the water table depth is above 8 m, are generally located in areas of sediment materials proceeding coming from hillsides from coastal mountain chains. Approximately 68% of the area is covered by pasture or grassland. The water bodies (lagoons, rivers) represent 17% of the total area, even considering successive earthworks and landfills reducing their area in the last few decades. Urban areas are distributed mainly next to the sea and at the margins of coastal lagoons.

#### Aquifer vulnerability map

The model used to elaborate the map of aquifer vulnerability to contamination proved well suited to the region's particularities, once results of the map have a strong correlation with field conditions. The areas covered with marine/coastal sediments were mostly characterized as areas of extreme or very high vulnerability to contamination. This is due to the fact water table in these areas is very shallow, terrain has a low declivity and geologic materials have a high permeability.

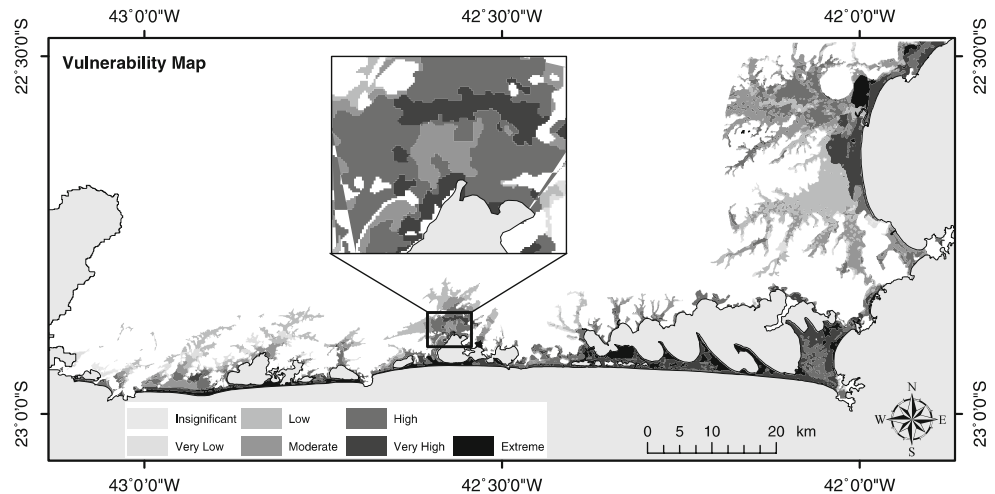
Areas of extreme to high vulnerability cover approximately 49% of the total area, while moderate vulnerability areas about 22% (Fig. 4). Moderate vulnerability areas are generally represented by permeable sediments far from the coast.

Low to very low vulnerability areas, which correspond to 28% of the study area, are generally distant from shoreline, and are composed by sediments originated from colluvium or fluvial deposits. Greater values of water table depth (above 4 m) and declivity (above 4%) prevail in those areas.

Few areas were considered as of insignificant vulnerability, representing less than 1% of the total. In these areas, unfavorable conditions for percolation occur, as steeper slopes, high depths of water table or presence of materials with very low permeability.



**Fig. 4** Groundwater vulnerability map of Rio de Janeiro State east coast



**Concluding remarks**

The use of geoprocessing tools and remote sensing for characterization of Rio de Janeiro’s east coast aquifer vulnerability gave good results, representing a set of low cost solutions. Method based on the digital elevation model obtained from the SRTM data proved satisfactory for generation of slope map and shaded images. Using new SRTM data with greater resolution in the future could result in even more accurate products.

Elaboration of the aquifer recharge map was possible through the intersection of the isohyet’s map of Rio de Janeiro State with slope and geomorphologic compartmentation maps, coming from SRTM-DEM. The weights and ratings given to each subject in the construction recharge map with the definition of recharge class limits resulted in a map that characterizes adequately aquifer recharge in Rio de Janeiro State east coast. Creation of a Geology and Soils thematic maps with the aid of Landsat *ETM+* images and SRTM-DEM allowed optimum adjustments and better positioning of geological structures and soil units limits. Results found in both geological and soil maps, proved satisfactory and contributed positively to execution of the final product, the general vulnerability aquifer map.

The map of depth to water table resulted very close to the field reality, as tested after its elaboration. The use remote sensing techniques for construction of land use and cover map with the use of a object oriented classification showed results much more satisfactory than the traditional methods, resulting in reduction of final map edition effort.

The remote image data collecting, field surveys and literature review, as well as their insertion and processing in a geographic database, allowed to locate environmental impacts, such as urban occupation intensification in areas already occupied. This can cause an acute increase on groundwater consumption in localized areas, creating

conditions favorable to an advance of seawater intrusion. Fate of domestic sewage can be considered another potential source of aquifer contamination, but further studies are necessary to address this particular issue.

Development of specific vulnerability maps for different contaminants is necessary, and these could be integrated through GIS. Aquifer vulnerability maps, associated to land use and cover mapping, must be used for management actions according to intrinsic aquifer characteristics. The geographic database allows interactive visualization of geographic data and generation of new information and insertion of new data, which makes it a very important tool in hydrogeological studies, useful in the processes of decision making and planning.

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