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Methodology for rapid assessment of aquifer recharge areas

Metodologia para diagnóstico rápido de áreas de recarga de aquíferos

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Abstract

The environmental tools of local appliance, such as surveillance and permits of deforestations and water use, environmental impact assessments of local scale, and delimitation of preservation areas, demand customized methodologies to deal with hydrogeological issues. In this study, a structured one for rapid environmental assessment aiming at recharge of aquifers safety was presented. This comprises qualitative and quantitative evaluations by means of textual and cartographical descriptions, complemented by weighted spreadsheets for rapid assessment. Applications in case studies took place in sites selected in the Paracatu River Basin. The results showed a positive potential for knowledge and protection of aquifers in micro-watersheds.

Keywords: Hydrogeology; Rapid assessment; Aquifers; Environment; Recharge.

Resumo

Os instrumentos ambientais de aplicação local, tais como fiscalização, autorizações de desmate e de uso da água, estudos de impacto ambiental, de impacto local e averbações de reserva legal, demandam metodologias customizadas para o tratamento de questões hidrogeológicas. Neste estudo, apresentou-se um método estruturado para o diagnóstico ambiental expedito visando à segurança da recarga de aquíferos. Este constitui-se de avaliações qualitativas e quantitativas por meio de descrições textuais e cartográficas, complementadas por planilhas ponderadas para análise rápida. Aplicações em estudos de caso foram realizadas em locais selecionados na Bacia do Rio Paracatu. Os resultados mostraram potencial positivo para o conhecimento e a proteção de aquíferos em microbacias.

Palavras-chave: Hidrogeologia; Diagnóstico expedito; Aquíferos; Meio ambiente; Recarga.

INTRODUCTION

Application context

The recovery and maintenance of the hydrological balance, in quantitative and qualitative terms, depend on the proper planning of environmental impacts on soil and biota. The vegetation maintenance and soil management in predominance areas of recharge of aquifers are crucial to water resources preservation. Those sustainable practices enable the percolation of water in the subsoil, ensuring a more stable flow for the bodies of water, especially in the drought season. Therefore, the compaction and pollution of soils present obvious impacts on water systems. The understanding of the aquifer recharge process is an important step to integrate the management of land use with that of water resources.

Despite the fact that technicians are becoming increasingly aware that the hydrogeological analysis is necessary in the contexts of water and environmental management, its effective application is rarely seen. Particularly, the lack of basic training in hydrogeology for many professionals who work in teams of environmental studies brings difficulties even for initial dialogues on the subject.

Moreover, the existing methods for hydrogeological studies are not always suitable to implement in the practical contexts of environmental and water use issues. This inadequacy can be seen in various aspects, such as: initial data available, scale(s) of spatial extent and detail, available professionals, time and financial resources, required response, and level of certainty. In the implementation of the instruments of the Brazilian National Policy on Environment and the Brazilian National Policy on Water Resources, the application of hydrogeological knowledge, although necessary, presents different contexts of the traditional methods developed in an academic environment.

Instruments of the national policy on environment involving local actions by agents of environmental agencies or by the technician in charge of the technical report are relevant to the safety of aquifers recharge. Among them, there are surveillance, permits of deforestation, delimitation of preservation reserves, technical reports for the granting of water use, among others. The basic characteristic of these instruments is their expedited nature (few days), usually performed by only one professional, with a preparatory phase in the office, a field visit and, finally, presentation of a report on the conclusions.

Rapid environmental assessment

The rapid assessment protocols are part of the methods of environmental impact assessment (EIA), one of the instruments of the Brazilian National Policy on Environment. Among the methods of rapid assessments accepted in EIA, this study focused on the spreadsheet of weighted checklist (Lohani et al., 1997). The checklist spreadsheets are a listing of environmental characteristics and possible impacts and risks to be observed by the professional in the field and to be described in a standardized table. In such table, each observed characteristic shall transmit a specific numerical weight, established in an attached template. Once filling of the checklist is completed, a simple mathematical calculation on the numerical weights frames the location in a particular level of environmental risk or quality.

The weighted checklist spreadsheets are easy to learn and apply in the field. They have as main objective guiding the performance of professionals in the field, so as not to overlook the essential aspects required for analysis. Furthermore, the output of standardized information enables future comparative studies through statistics programs, database, and geographic information systems (GIS). In addition to the application in specific cases, rapid environmental assessment techniques have good potential for use as a learning tool to introduce professionals and students to specific contexts of environmental assessment (Callisto et al., 2002; Abreu et al., 2006).

In the United Kingdom, weighted checklist spreadsheets have been used systematically as assessment instruments for the safety of recharge of aquifers. Its use allows a preliminary assessment at low cost, allowing sorting what will be the cases that deserve special attention from the environmental agency or whether the case needs more detailed studies. The United Kingdom Environmental Protection Agency (2008) uses checklist spreadsheets systematized for permits of groundwater use, assessment of hydrogeological contamination by sanitary landfills, and remediation of contaminated aquifers.

In a rapid environmental assessment, it is essential to delimitate the areas likely to have the greatest potential for recharging. In an oriented approach towards contexts of local recharge, the technical possibility of inferences about piezometrics, recharge and discharge of groundwater aquifers through the evaluation of springs elevation, was clarified by Rennó and Soares (2003). Souza and Fernandes (2000), in another similar approach, proposed the delimitation of recharge areas, transmittance and discharge by the criteria of steepness and altimetry topology. However, the concept of transmittance is already used conventionally in a stricter context, as hydraulic parameter in aquifer tests. On the other hand, Souza and Fernandes (2000) employ the idea of transmittance zone referring to a more generalist interpretation of the aquifer systems functioning. In order to avoid inaccuracies of interpretation, we propose using the term area of transiency instead of area of transmittance.

The propositions of Rennó and Soares (2003) and Souza and Fernandes (2000) are based on the principle that, in basins with perennial rivers, the movement of water in existing aquifers follows a pronounced topographic control with flow lines converging toward the main drains, indicating that the main water courses are effluent, i.e. receiving groundwater contributions (CETEC, 1981).

The focus in the areas of recharge above springs favors shallow aquifers management, in meso- and micro scales, which shows great potential for resolution of conflicts. Lima (2010) considers that many of the conflicts due to water use in Brazil are in micro-watersheds, for they are more sensitive to the practices of land use over limited water reserves, commonly contrasting with the beds and alluvial aquifers of the downstream great rivers still presenting stream flow available for new utilizations. Shah (2010), in the same line of reasoning, showed that, in India, programs for infiltration and community management of groundwater for irrigation have achieved greater success in specifically located shallow aquifers than in areas of extensive porous ones. In the micro scale aquifers, users and people better observe the effects of the increased recharges in the springs flow and in the water available for the wells (Shah, 2010; Lima, 2010).

OBJECTIVES

This study consists in the proposition of a delimitation methodology and rapid environmental characterization for areas of recharge, which may be used in the implementation of local operational instruments present in public policies of environmental and water managements. The results of case studies in the Paracatu Basin (SF7) are presented, analyzed, and discussed.

METHODOLOGY

The methodology presented is intended to be feasible to the context of time, technical resources and qualifications in the implementation of local operational instruments of public policies of environmental and water managements. Therefore, there is an assumption that there will be only one professional with a day in the office for preparation of the material for the fieldwork, one in fieldwork, and one more to prepare the final report. The office step is to identify the geological field, delimit the altitudes of springs and identify the flat areas that would have greater potential for contributing to the recharge of these springs. The field stage involves validating and detailing office products, followed by a hydrogeological and environmental rapid assessment with a weighted spreadsheet developed especially for this purpose.

The additional assumption included is that the method should be useful for both the professional with experience in geology and hydrogeology and for others of environmental sciences as a tool for learning, even if they do not possess geo-processing know-how. Within these possibilities, this paper presents a suitable method for the production of rapid environmental assessment of aquifer recharge in local contexts. A flow chart of proposed steps within this methodology is shown in Figure 1.

Due to the inherent limitations of in-depth understanding of hydrogeological analyzes by many environmental professionals, the main epistemological premise of this methodology is its possibility of being learned and applied. With this regard, didactics and epistemological care has been taken for the easier assimilation of reasoning on temporal and spatial scales in fieldwork analysis (Compiani, 2007), as well as for the semiotics of cartographic products to be developed (Carvalho and Moura, 2008) in order that they could be feasible with the skills, knowledge, and limitations of the users. A methodology of difficult understanding would not meet the goals and context of the instruments of environmental public policies, at the risk of not being accepted by its agents.

Office activities

The first office activity is to identify which is the geological domain of the rocks with aquifers in the study area, from a lithostratigraphic map in the available scale, or a textual indication from some environmental study reference. The goal is to differentiate, at minimum, the contexts related to four basic hydrogeological typologies: sedimentary, fractured, basaltic, and karstic aquifers. Each of these routes to differentiated assessments with regards to acknowledgment of noteworthy surface landforms, of the assumptions regarding the underground hydrological processes, and of the assessment of environmental impacts. If there is availability, references to the soil and the geomorphology are also added by means of secondary references.

Also in the office phase, the cartographic base of topography and hydrography is required as a source of information, which can be both the printed map, such as the provided by the official cartography agency, or data in a GIS, if the professional possesses ability in its handling.

In the office, the delimitation of the area that mostly favors recharging begins with the interpretation of the area topographically higher than the springs, indicating those with the greatest potential for contributing to the recharging of the respective aquifers. We do not ignore that, for an unconfined groundwater aquifer, the entire surface of the terrain shows potential of infiltration and percolation, in

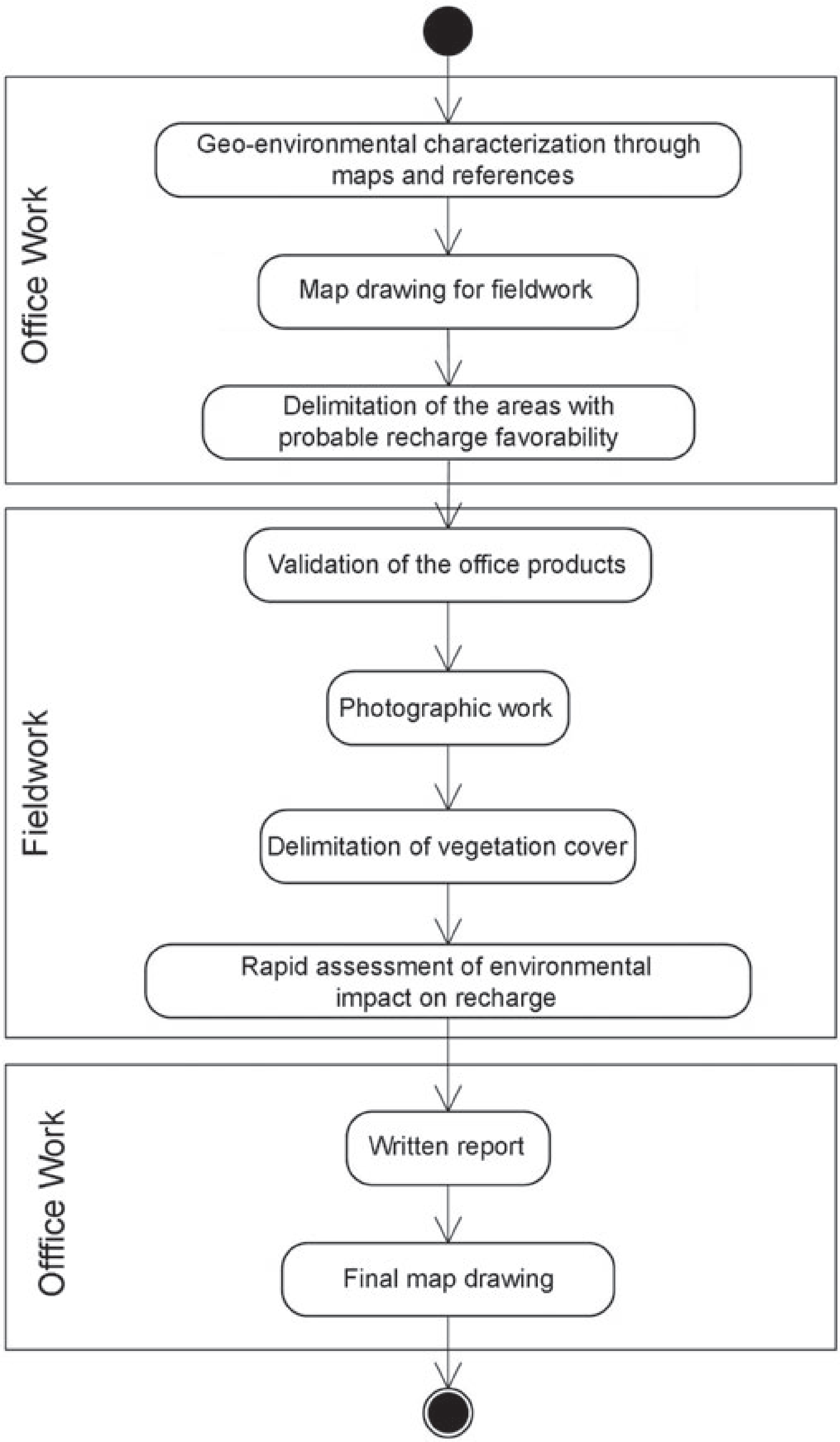

Figure 1. Flowchart of assessment methodology of recharging in the context of local instruments of public policies.

greater or lesser degrees. However, in basins of perennial rivers, the areas topographically above the springs present hydrogeological features that are different from the downstream ones, particularly regarding the predominance of the aquifers recharge function. Therefore, this mapping modality indicates sites with higher hydraulic gradient and lower soil moisture before rainfall events, contributing more to water infiltration and percolation.

Thus, this analysis is refined by interpretation of the rupture limits between the flat areas and steeper slopes, given that the flattened places show, by principle, better infiltration. For example, in a prominence of tableland, or plateau, the limits of the upper edge overlap with the delimitation of the preferential recharge area. A map overlaying the hydrography basis with the remote sensing one (if available) becomes an important material for location, orientation, and analysis in the inspection fieldwork.

Fieldwork activities

In the fieldwork stage, the first actions to be taken are the assessment and possible correction of the information previously received in office. Some basic visual observations allow the preliminary check as to the truthfulness of the aquifer typology indicated. There is also the need to observe if the map data of hydrography and topographic contour lines correspond to the reality of the field, because frequently the maps do not have the detailed scale to the desired action level — in addition to the possibility of errors in the preparation of the cartographic products. The fieldwork will also bring the opportunity to check the soil type, the vegetation coverage, and the land use of the areas of greatest interest for recharging, as well as potential sources of aquifer pollution. With the mapping of the most relevant areas to recharge, the last field activity will be a rapid assessment of the environmental impact and risk about the recharge areas.

The criteria to be analyzed for the impact and environmental risk assessment of areas of recharge are based on the existing checklists for the topic, proposed by Ousley (2003) and Wilkerson (2007). The structuring of the tables and the weighted calculation take as their starting point the conventional model of rapid assessment for benthic ecosystems (Barbour et al., 1999; Callisto et al., 2002; Rodrigues, 2008). The items listed and the weighted calculation are aimed to characterize and interrelate water quantity and quality in recharging, the environmental impacts present, and the risks to the existing or desired local usage.

The weighting criterion for quality of underground water follows that presented by broadly used methods, such as DRASTIC (Aller et al., 1987), POSH (Foster et al., 2003), SEEPAGE (Moore, 1988), RAVE (DeLuca and Johnson, 1990), and RZWQM (Ma et al., 2000), as well as weighted ones developed for specific areas (Cates and Madison, 1990; Hearne et al., 1992; Lemme et al., 1989; Wisconsin, 1987). The remaining checking items follow the guidelines for environmental assessment of aquifers proposed by the USA Environmental Protection Agency (1986, 1993, 1998, 2008) and the European Communities (2003).

Soil classes are weighted according to their water drainage, in line with the typology proposed by the Brazilian Society of Soil Science (Santos et al., 2005). Because it is a generalist attribute, with emphasis on the result of water movement, the concept of drainage incorporates the processes carried out under the influence of some parameters, such as permeability, structure and conductivity. However, taken on a scale of broader analysis that incorporates the storage capacity of the soil profile, the variation of the saturated level in the profile and the flux processes in the hydrogeological basin.

For the soil types, the main reference was the Hydrology of Soil Types (HOST) system (Boorman, Hollis, Lilly, 1995), adopted in the United Kingdom. It combines quantitative estimates to the criteria for soil drainage, permanent or seasonal depth of groundwater aquifers, and presence of impermeable or semipermeable layer. In order to be used in Brazil, it was necessary to do the correspondence between the HOST typology and the Brazilian System of Classification of Soils (EMBRAPA, 1999), taking into account the estimates of rates of runoff (Carvalho, 2009) and infiltration (Rawls, Brakensiek, Saxton, 1982; Rocha and Daltrozo, 2008; Mendonça et al., 2009). As for the influence of the aquifer potential (lithostratigraphy), the statistical correlations between lithostratigraphy and basis flow of Bloomfield, Allen, and Griffith (2009) were preliminary considered, supplemented by estimates of well discharge in different aquifers (Rebouças, 2008; Mente, 2008).

The influence of land use and vegetation cover in recharge was based on the theoretical classification of Valente and Gomes (2005) and Gomes (2008), and the systematization of experiments performed by Bruijinzeel (2004), Wickel (2009) and Wickel and Bruijinzeel (2009). Such studies associate the processes of interception, infiltration, and evapotranspiration of various types of vegetation, in accordance with its influence to the hydrogeological cycle. The quantitative weighting also considers the same literature based on the runoff and infiltration rates used for assessing the potential of recharge by soil classes.

For the criteria of rapid assessment, it is taken as reference a small range of schematic geomorphological visual models covering classic situations of recharge and discharge of aquifers with focus on springs (Custódio and Llamas, 1976; Valente and Gomes, 2005; Junqueira Júnior, 2006; Donovan, Kistinger, Acheampon, 2007; Dahl and Hinsby, 2008; Martins Junior, 2009). The models listed for analysis of water flows were: (A) karstic resurgence, (B) wetlands (*Veredas*), (C) soil and lithostratigraphic contacts, (D) fracture springs, and (E) intermittent springs. For the issues of water quality, we selected (F) plateaus, (G) wavy and mountainous reliefs, (H) slopes, (I) river valleys, and (G) floodplains. The identification of these conceptual models allows the professional to infer a general understanding of the processes of recharging and discharging, without being limited to weighting of the spreadsheets.

A forewarning to many of the assessment methods, as to the vulnerability of groundwater pollution (USEPA, 1993; Aller et al., 1987), refer to contexts for well drilling. In these cases, the existence of layers, which are impermeable or restrictive to the flow, is seen as beneficial for isolating the deep aquifers from the percolation of pollutant. In the method presented in this paper, the focus is directed to shallow aquifers (unconfined, in most of the cases), in direct communication with the springs. Thus, the layers that are impermeable or restrictive to the flow could increase the direct runoff of the effluent to watercourses, in addition to hampering the important process of underground depuration of the pollutant.

Regarding the sub and grand totals obtained in the list of weighting, though they are the quantitative weights of field qualitative interpretations, they have no direct correspondence to water flow magnitude or physicochemical parameters of the waters. Such a comparison would go beyond the possibilities of detailing a simplified method (rapid assessment). The intention is to provide the applier only an idea of the importance of the aquifer recharge area, comparing with adjacent ones of the site. For this reason, we have chosen to not include climatological data, since those of the network of weather stations do not have a scale with enough details to capture the variations in these local contexts, and that would turn the methods considerably more complex.

It should be considered for future enhancements that the inclusion of parameters of precipitation and evapotranspiration could approximate the direct correspondence to the parameters of flow in springs. However, as to the proposed application, it must be considered that, where local climate is drier, the recharge of aquifers, even the minor ones, may represent a crucial usefulness for their purposes of human use and maintenance of ecological attributes. In several cases, therefore, the excess of precipitation would be, in practical terms, inversely proportional to the importance of recharging for local human use.

The attributes applied in the rapid assessment, based on lists of environmental factors and theoretical classifications, as well as conceptual or empirical weighting criteria, were obtained from the bibliographies indicated in Table 1. For most of the attributes (examples: slope, soil drainage, vegetation, etc.), the internal weighting presents a relatively satisfactory reliability, because it has been established from specialist, empirical, or conceptual studies. Nevertheless, inter-attributes weighting (i.e. which influences more in the total partial and final index) still lack the existence of scientific and consistent studies. Most methods of multiple weighting, in order to avoid such impairment, assign the same weight to each of the attributes (example, from 0 to 10). However, we tried to build more on studies that have sought differential criteria, with all the caveats about the uncertainties and gaps in scientific consensual knowledge.

For the quantitative assessment of recharge, more weighting was given to the type of soil and potential of the aquifer, as they are considered by reference literature as the most important factors — besides the precipitation, which was not included in this methodology. On the other hand, for the assessment of water quality, more weight was given to depuration of the pollutants held by soil, for the specialized studies show that the vadose (or aeration) zone presents the greatest potential for pathogens elimination (FUNASA, 2006; USEPA, 2008), breaking of chemical chains of agricultural inputs (DeLuca and Johnson, 1990; Ma et al., 2000) and overall purification of pollution (USEPA, 1993).

The relative depth of water table can be indirectly estimated by geomorphological-topographical criteria (National Park Service, 2008; Rennó and Soares, 2003). The aquifer, in turn, was evaluated by the speed of transmission. The karstic aquifers demonstrated different classifications based on the presence of sinks and resurgences, not only by the significant effect on groundwater circulation, but mainly as general indicators of the evolution degree of karstic conductivity (Doerfliger, Jeannin, Zwahlen, 1999; White, 2003). Lower scalable weight was assigned to erosion and sedimentation processes, providing lower risks to human health and other living beings.

The calculation criterion of partial totals is the multiplication of the indices of each attribute. The multiple attribute modeling by multiplying follows the recommendations of Clarke (2009), Tucci (2009) and Naguettini and Pinto (2007) for the analysis of the effect of variables in hydrogeological and hydrological studies. The theoretical assumption is that a continuous flow of water is modeled (from precipitation to discharging), which will be intensified or restricted on a quantitative and qualitative way by the environmental characteristics, including the iterative effects (USEPA, 1986).

The multiplicative model has also the advantage of making it possible to withdraw and add variables, increasing its use flexibility. It is proposed that the general average of an attribute is one (to the extent of available scientific knowledge). Therefore, if there is no way to obtain one of the attributes, or even if it does not apply to a

Table 1. Attributes for rapid environmental assessment of recharge of aquifers areas.

	Attribute	Studies of reference (see sources in the legend)																									
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Potentiality of recharging (quantity)	Vegetation in the area of recharging (infiltration less evapotranspiration)	x	x	x	x					x							x		x					x			
	Steepness (infiltration)		x			x		x			x	x		x			x	x					x	x	x		x
	Soils (drainage)		x	x		x	x	x	x		x			x		x								x	x	x	x
	Lithostratigraphic domain (water potential of the aquifer)		x											x				x			x	x		x	x	x	
	Typology of recharging and discharging	x																x									
	Land use (soil compaction and sealing)			x	x	x	x	x		x		x					x		x								
	Techniques for the conservation of soil and water	x																		x			x	x			
Risk on the recharging (water quality)	Pollution sources				x								x	x	x									x		x	x
	Distance from the source of pollution to discharge point (surface and underground depuration of the pollutant)				x										x									x			x
	Transmission in the soil (under surface depuration of the pollutant)										x		x	x	x									x	x	x	x
	Topographic position of the source of pollution to the discharge point (depth of water table)													x											x		
	Transmission of the aquifer (underground depuration of the pollutant)													x										x	x	x	
	Erosional processes			x	x																		x	x			
	River bed aggradation			x	x																		x				
	Vegetation in the vicinity of the spring (buffer function and biological filtration)			x	x																			x			
	Techniques for soil and water conservation												x										x	x			

Sources: A: Valente and Gomes (2005); B: Gomes (2008); C: Wickel (2009); D: Wickel and Bruijinzeel (2009); E: Carvalho (2009); F: USDA (1972); G: Tucci (2009); H: Ottoni Filho (2003); I: Borges et al. (2005); J: Gomes, Spadotto and Pessoa (2002); K: CETESB (1986); L: Foster et al. (2003); M: Aller et al. (1987); N: FUNASA (2006); O: Rawls, Brakensiek and Saxton (1982); P: Tucci (2002); Q: Custódio and Llamas (1976); R: Mendonça et al. (2009); S: Azooz and Arshad (1996); T: Rebouças (2008); U: Mente (2008); V: Silva (2002); W: USEPA (1993); X: Hearne et al. (1992); Y: Berg, Kempton and Cartwright (1984); Z: Moore (1988).

Table 1. Continuation.

	Attribute	Studies of reference (see sources in the legend)																	
		A1	B1	C1	D1	E1	F1	G1	H1	I1	J1	K1	L1	M1	N1	O1	P1	Q1	R1
Potentiality of recharging (quantity)	Vegetation in the area of recharging (infiltration less evapotranspiration)					x	x										x		
	Steepness (infiltration)		x		x				x	x			x					x	x
	Soils (drainage)	x	x			x			x	x			x					x	x
	Lithostratigraphic domain (water potential of the aquifer)		x							x			x			x	x		x
	Typology of recharging and discharging									x				x		x			
	Land use (soil compaction and sealing)						x										x		
	Techniques for the conservation of soil and water																x		
Risk on the recharging (water quality)	Pollution sources				x			x	x	x	x	x	x		x				
	Distance from the source of pollution to discharge point (surface and underground depuration of the pollutant)				x					x	x	x			x				
	Transmission in the soil (under surface depuration of the pollutant)	x	x	x	x	x				x	x	x	x		x				
	Topographic position of the source of pollution to the discharge point (depth of water table)				x	x				x		x			x			x	x
	Transmission of the aquifer (underground depuration of the pollutant)			x						x	x	x	x			x			
	Erosional processes							x											
	River bed aggradation							x									x		
	Vegetation in the vicinity of the discharge point (buffer function and biological filtration)							x							x	x			
	Techniques for soil and water conservation				x	x											x		

Sources: A1: Cates and Madison (1990); B1: Lemme et al. (1989); C1: Wisconsin (1987); D1: DeLuca and Johnson (1990); E1: Ma et al. (2000); F1: Latuf (2007); G1: Callisto et al. (2002); H1: Blanchard (2002); I1: USEPA (1986); J1: USEPA (2008); K1: Paris (2007); L1: Evans and Myers (1990); M1: Donovan, Kistinger and Acheampon (2007); N1: National Park Service (2008); O1: Dahl and Hinsby (2008); P1: Bruijinzeel (2004); Q1: Farquharson et al. (1978); R1: Boorman, Hollis and Lilly (1995).

specific context, simply place the index 1 in the column on the right, thus asserting that the result will not be biased. For example, weighting for quality of recharge, in a place where there are no sources of pollution, can be adapted to reflect the sensitivity of the aquifer to future occupations by simply removing the variables that are not being used (match to weight one). The proposal of structured assessment is presented in Tables 2 and 3.

In order to consolidate the field information, a brief textual description of the site was elaborated, which is complemented by cartographic products in the form of an integrated presentation of three maps: (A) altimetry and hydrography; (B) image of remote sensing; and (C) mapping of vegetation cover and land use. In all maps, the area demarcation that most favors recharging is presented as a reference for spatial analysis. A representative photograph of the landscape of the study area is also displayed.

The methodology presented in the case studies of this article has its focus on the delimitation and characterization of the area that mostly favors aquifers recharge to be prioritized for better soil and water conservation by means of instruments of public policies of environment and water

Table 2. Rapid environmental assessment form for recharging of aquifers (quantity).

	Attribute					Score
Potential of recharge (amount of water)	**Vegetation in the area of recharging (infiltration less evapotranspiration)**					
	Steppe Field Savannah	Forested Savannah Deciduous forest Forested Steppe	Permanent crop Temporary crop	Deforested area Semi deciduous forest	Riparian forest Hygrophytes or hydrophilic vegetation Evergreen forest	
	1.3	1.1	0.9	0.8	0.7	....
	Steepness (infiltration)					
	Plan (0 – 3%)	Smooth-wavy (3 – 8%)	Wavy (8 – 20%)	Hard-wavy (20 – 45%)	Rugged > 45%	
	2.5	1.5	1	0.5	0.25	....
	Soils (drainage)					
	Quartzipsamments (deep sandy soils)	Latosols (deep non sandy soils – oxisols)	Cambisols (shallow soils) Soils of textural B horizon (soils with clay layer) or Plinthic (hardened)	Lithic entisols (very shallow soils with rocky outcrops)	Hydromorphic and alluvial soils	
	6	2.5	1	0.6	0.3	....
	Rocks (water potential of the aquifer)					
	Sandstone (porous deep)	Detritus-laterite deposits (porous shallow)	Karst	Basaltic	Fissured	
	3	2.2	1.4	0.9	0.7	....
	Typology of recharging and discharging					
	Sinks and resurgences on karst	Wetlands (*Veredas*) Dolines	Headspring of lithological contact or water bed	Headspring of fracture	Intermittent spring	
	1.5	1.3	1.2	0.8	0.4	....
	Land use (soil compaction and sealing)					
	Native	Permanent crop Temporary crop	Pasture	Exposed soil	Urban Industrial	
	1.5	0.8	0.5	0.3	0.1	....
	Techniques for soil and water conservation					
	Percolation dams	Terracing	Ridges on contour lines	Tillage	Without techniques	
	3	1.5	1.4	1.2	1	....
Total						....

Table 3. Rapid environmental assessment form for recharging of aquifers (quality).

	Attribute					Score
Protection on the recharge (water quality)	**Pollution sources**					
	Untreated sewage	Treated sewage Black pit Garbage dump Mining (metals)	Septic pit Sanitary landfill	Pigsty Corral Grange Mining (non-metals)	Pasture Planting	
	0.1	0.3	0.5	0.7	0.9	....
	Distance from the source of pollution to the discharge point (subsurface and underground depuration of the pollutant)					
	Direct dump	1 to 5 meters	6 to 25 meters	26 to 50 meters Diffuse pollution	> 50 meters	
	0.1	0.2	0.5	0.8	1	....
	Topographic position of the source of pollution to the discharge point (depth of groundwater level)					
	Floodplain	River valley	Hillside	Top of elevation (wavy or mountainous topography)	Plateau on the top of the elevation	
	0.2	0.4	1	4	10	....
	Transmission in the soil (under surface depuration of the pollutant)					
	Hydromorphic and alluvial soils	Lithic entisols (very shallow soils with rocky outcrops)	Quartzipsamments (deep sandy soils)	Cambisols (shallow soils) Soils of textural B horizon (soils with clay layer)	Latosols (deep non sandy soils - Oxisols)	
	0.1	0.3	0.5	1	3	....
	Transmission of the aquifer (underground depuration of the pollutant)					
	Karstic (sinks and resurgences)	Karstic (ducts) Basaltic	Alluvial	Fractured	Porous	
	0.3	0.5	0.6	1	3	....
	Erosional processes					
	Gully erosions	Ravines	Furrows	Laminar	Without erosion	
	0.8	0.85	0.9	0.95	1	....
	River bed aggradation					
	Sediments do not allow water to emerge	More than 50% of the width of the bed with emerging sediments	Sediment banks emerging in the riverbed	Sediments at the bottom of the riverbed	Without sediments (less than 5% of the bottom of the riverbed)	
	0.6	0.75	0.9	1	1.2	....
	Vegetation in the vicinity of the discharge point (buffer function and biological filtration)					
	No vegetation, with sealed or compacted soil	No vegetation, with permeable soil	Meadow Up to 5 meters of forest Up to 10 meters of savannah	5 to 30 meters of forests > 10 meters of savannah	> 30 meters of forest	
	0.25	0.5	0.75	1	1.5	....
	Techniques for soil and water conservation					
	Without techniques	Tillage	Ridges on contour lines	Terracing	Percolation dams	
	1	1.3	1.7	2	3	....
Total						....

resources. This area is the focus of mappings, assessment of the weighted spreadsheet, and the textual report in each of the case studies.

However, the proposed rapid assessment method, both for quantity and quality, can be used in more extensive and detailed mapping, differentiating internal and external areas to those delimited as mostly favorable for recharging. Thus, it becomes possible to cartographically differentiate geotopes (subsystems encompassing rock, soil, topography, and vegetation) of an entire watershed, in different classes of recharge potential and vulnerability to contamination, obtaining maps with classes calculated by means of weighted spreadsheets, complemented by textual and photographic interpretations of the site.

The mapping of an entire basin will be performed for one of the study areas, taken as example. As a criteria of differentiation, the results regarding recharge potential (quantity) for the geotopes that are outside the delimited area with better recharge favorability were decreased in one order of magnitude (division by ten), with reference in the results of extensive surveys on hillslopes, regarding hydraulic conductivity patterns (Lewis et al., 2011), soil moisture before rainfall (Crave and Gascuel-Odoux, 1997; Famiglietti, Rudnicki, Rodell, 1998; Brocca et al., 2007), and water table depth (Nobre et al., 2011). The weighted checklist assessment of recharge safety (qualitative) already takes the relative topographic position of the geotope into account.

Case study

The Paracatu River Basin, tributary of the São Francisco River, has 45.154 km² and is located almost entirely in the State of Minas Gerais (Northwest Region), with small top areas entering the State of Goiás and the Federal District (maps in Figure 2). Nine areas of study were selected for the Paracatu Basin (Figure 3), encompassing several typologies of recharging of aquifers, as well as different scenarios of water and land use, associated with the distinct environmental impacts. Therefore, the sites were selected covering different combinations of: fractured (metamorphic), karstic and terrigenous sedimentary lithostratigraphies; oxisols/latosols, quartzipsamments, cambisols, lithic entisols and hydromorphic soil; flat, wavy, and sloping areas; plateaus, valleys, and wetlands (*veredas*); forest cover, Savannah, native meadows, pastures, forestry and mechanized agriculture; areas of water use for irrigation, animal and human watering; potential contamination by agricultural inputs, and sanitary urban sewerage. Field studies were conducted from July to October, in 2011.

One of the study sites (*Serrinha*) was chosen for an alternative cartographic approach in order to evaluate its possibility of application by users without training on GIS. In this case, we used the standard topographic chart of the cartography agency as a map of altimetry, over which was drawn the delimitation of the most favorable area of recharging. For remote sensing map, a 2008 image from satellite Quickbird was used, obtained from Google Earth. The map of land use and vegetation cover was drawn by means of overlapping semi-transparent paper over the satellite image, aided by field knowledge, which has proven to not have had significant changes from 2008 to 2011.

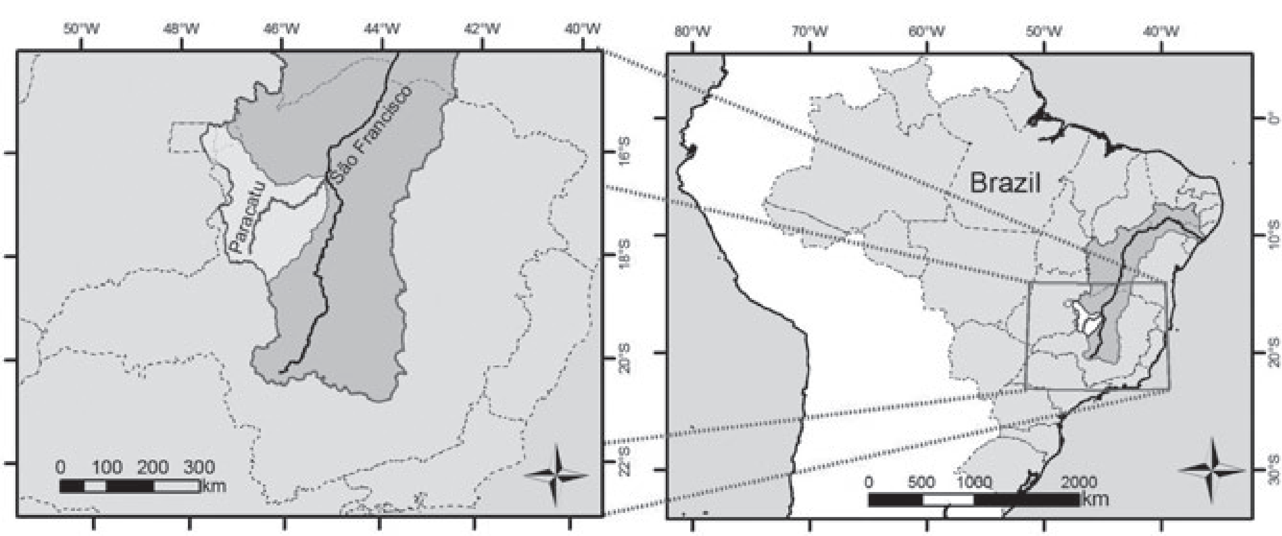

Figure 2. Location of the *Paracatu* Basin, inserted in the *São Francisco* Basin, highlighting the Brazilian states.

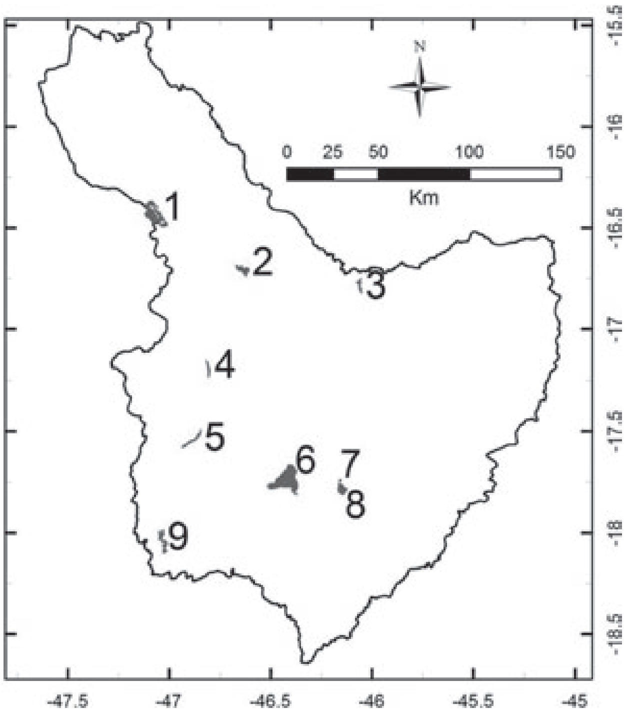

Figure 3. Location of the study areas: 1 – *Areia* Stream Valley; 2 – *Serrinha*; 3 – Plateau of the *Serra do Boqueirão*; 4 – *Serra do Sabão*; 5 – *Serra das Araras*; 6 – Lakes of the *Prata* River; 7 – Water abstraction of the *Córrego da Bica*; 8 – Water abstraction of the *Ribeirão dos Órfãos*; 9 – *Chapadão do Pau Terra.*

Areia Stream was chosen for the extended mapping, covering the entire basin and not only the most favorable area of recharging. Maps are presented and evaluated with the classes of the categories of quantity and quality of recharge, for each basin geotope.

RESULTS

The following products were obtained by applying the rapid assessment method in the study areas selected, comprising textual description of the study areas, cartographic and photographic products, and weighted spreadsheet of rapid assessment.

Description of the study areas

Areia Stream Valley

The study area is comprised of two geo-environmental compartments regarding the recharge of aquifers. Each one of these geosystems was analyzed separately by rapid assessment. Underneath these two geo-environmental compartments, there is a syncline structure where siltstones prevail, intercalated with sandstone and argillite lenses (Furuhashi et al., 2005a). The structural diagram is shown in Figure 4.

In the upper area, above 1.000 m of altitude, there are red-yellow oxisols (latosols) in the form of a tabular relief, from plan to soft wavy, formed by the process of pedimentation of tertiary-quaternary laterization sediments (CETEC, 1981; Furuhashi et al., 2005a) prior to the dissection of the Paracatu Basin. The whole plateau is occupied by mechanized agriculture of high technological level, including some irrigation pivots. In this area, there are also temporary lakes, hydrogeologically connected to the main headsprings of the valley slope through rather evident linear structures.

Inside the valley, between the altitude of 840 and 880 m, there are well-developed karstic lithosomes with dolomite outcrops, sinks, caves (some with more than two kilometers

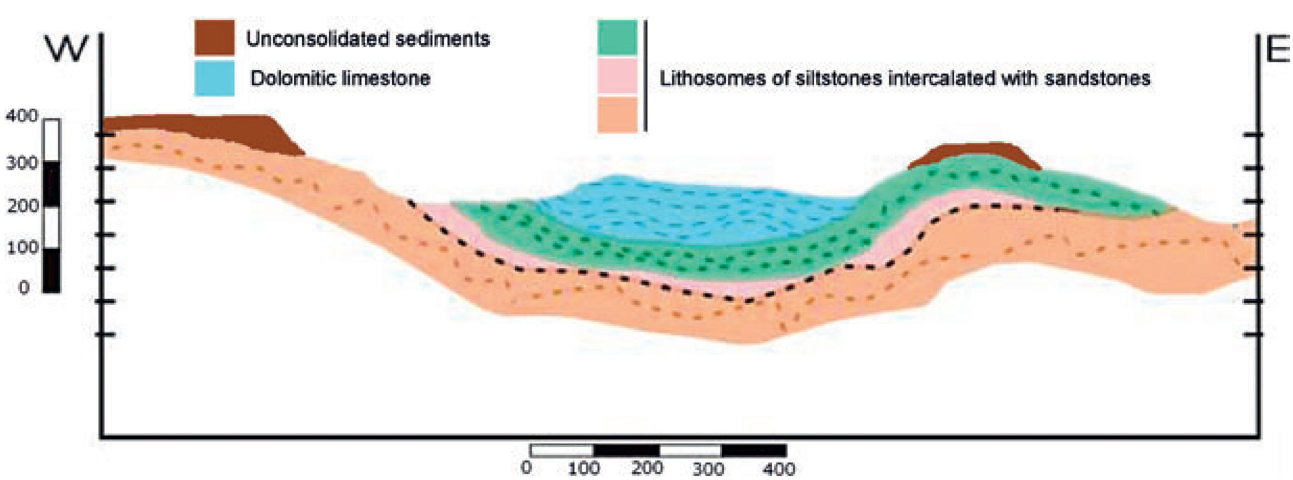

Figure 4. Stratigraphy of the *Areia* Stream Valley, based on Furuhashi et al. (2005a) and measured in meters.

long), massifs, and karstic rocky fields (Furuhashi et al., 2005b), incorporating the *Vazante* Formation (CPRM, 2003). A well preserved seasonal semi deciduous forest recovers this geo-environmental compartment on lithic entisols or virtually on the outcropping carbonate rock.

Serrinha

This area presents the geomorphology of structural ridges in the Southeast-northwest direction, showing slopes with ravines and v-valleys (CETEC, 1981), circumscribed in a greater geodomain of flattened surfaces and deep soils in the depression of São Francisco River (IGAM, 2006). Its saddle points have approximately 620 m of elevation, with ridge lines ranging between 720 and 760 m. It is located on the *Paraopeba* Formation, *Bambuí* Group (CPRM, 2003). In the middle of the frequent rocky outcrops, there are chernosolic or typical eutrophic cambisols on the lithological domain of meta-calcareous and marls on the forested slopes, contrasting with dystrophic lithic entisols on mudstones and meta-siltstones under spots of savannah. These are used for unconfined cattle grazing. The occurrence of springs is infrequent, although it is usual the construction of dams in temporary flow riverbeds, and the access to the aquifer by tanks in oxisols (latosols) in the surroundings of *Serrinha*, predominantly for extensive livestock farming.

Plateau of the Serra do Boqueirão

This site is a plateau with tabular surface at 840 m of altitude, in which there are quartzipsamments overlapping the sandstones of *Urucuia* Formation (CETEC, 1981; CPRM, 2003). The top of the plateau is almost all covered by savannah (cerrado *strictu sensu*), with small spots of pasture. Surrounding the upper edges of the plateau, at the break of the relief, ferric lateritic crust acts as geomorphic sills. At the foot of the plateau, there is a lithological contact with arkoses and arkosean siltstones of *Três Marias* Formation, with a geomorphology of slopes formed by alluvial-colluvial pedimentation from the upstream sandstone (CETEC, 1981). Exactly in this contact, because of the relative lower permeability of arkoses and arkosean siltstones, the contact headsprings take place. Downstream of these springs, still on the domain of arkoses of *Três Marias* Formation and surrounding the plateau, there are surfaces of ravine fluvial dissection with v-valleys (CETEC, 1981). In the west contour of the plateau, the exudation takes place through wetlands (*veredas*).

Serra do Sabão

Geomorphologically, it is a ridge with North-south direction, altitude variation from 680 to 760 m, with ravines and v-valleys. To the West, there are lithic slopes in chevron, influenced by folding. The Eastern slopes run to wavy landscapes, yet more evened out to the Southeast. The predominant lithostratigraphy refers to limestone and marls of the *Paraopeba* Formation (CETEC, 1981), covered by seasonal semi-deciduous forest. In specific areas where the influence of terrigenous sedimentary lithologies is increased, either in the composition of the carbonated rock or in the presence of lenses, the semi deciduous forest passes to the phytophysiognomy of savannah (cerrado *strictu sensu*). The soils are shallow, yet eutrophic, predominantly lithic entisols on the slopes, although there is occurrence of cambisols in curvatures on the edges of the crest. The crest vegetation is well preserved, although the region surrounding, originally of semi deciduous forest on eutrophic soil on limestone and cherts, is almost completely deforested for livestock and, to a lesser extent, agriculture.

In the top half of the crest, the greater drainability of soils and the lowering of the groundwater level are felt by the greater deciduous aspect of the vegetation, showing the predominance of hydrogeological recharging function. In the lower half, the more verdant strands within demonstrate the presence of a higher soil moisture, including aquifers discharging as headsprings. There are archaeological trails through which slaves and *quilombola* communities sought water for their homes in these slopes.

Serra das Araras

It is in a morphological domain of flattened surfaces on stratigraphy of sericite-phyllite, where sparse ridges outcrop. Locally, there is a ridge with Southwest-northeast direction, whose foothills at 720 m altitude and top ridged to approximately 920 m, with slightly flattened edge and slope with ravines and v-valleys, and headsprings are found on their bottoms. The lithology of the crest is made of metamorphic strata with predominance of quartzite in the lower slope and sericite-phyllite in the upper one. At the bottom, there are carbonaceous sericite-phyllite and quartzite of the *Paracatu* Formation (CPRM, 2003). It is covered by dystrophic lithic entisols with significant occurrence of outcrops. The vegetation comprises open savannah grassland, passing to savannah *strictu sensu* at the bottom of the v-valleys.

Lakes of the Prata River

According to *Fundação Centro Tecnológico de Minas Gerais* – CETEC (1981), Oliveira, Valle and Féboli (2002), CPRM (2003) and Almeida et al. (2010), this study area is located on the unconsolidated tertiary-quaternary ferruginous detritus-laterite sediment, formed from the process of transport and deposition mainly from the reworking of the

Areado Group, upstream. Almeida (2009) indicates that this stratum is superimposed on the karstic-fissured lithostratigraphy of *Bambuí* Group.

With regards to the geomorphological context, the region is in the depression corresponding to the bottom lands of middle Paracatu River, at altitudes between 560 to 590 m. CETEC (1981) classifies it as a shallow depression of flat bottom, highlighting it as an area of poor drainage with little pronounced abasement, occurrence of hydromorphic soil, and concentration of temporary lakes. Its development happened by exudation, in which the surrounding areas (also on the unconsolidated sediments) suffered fluvial dissection and pedimentation.

The predominant soils found are related to dystrophic red-yellow oxisols (latosols) with plinthic clayey horizon (CETEC, 1981). Because of the sedimentary inheritance of the *Areado* Group, the texture of the soil variably passes to quartzipsamments. The soils are well drained during periods of drought (except banks of ponds and wetlands/*veredas*), however they become waterlogged during periods of intense rainfall.

The study area was occupied by forestry in the 1970s and abandoned in 1983. Most of it had its native meadow vegetation regenerated, in addition to sparse cores of forested savanna. Subsequently, some areas were occupied again by planted pastures, forestry, and agriculture.

The soils present high surface permeability, which is also favored by the flat landscape. Nevertheless, the main hydrogeological control is performed by the plinthic clayey horizon, which prevents direct percolation of water and routes the drainage to subsurface processes, toward the ponds in the study area, and especially toward the wetlands (*veredas*) nearby.

The existing ponds, in addition to feature areas of accumulation of groundwater level above the plinthic horizon, may also indicate preference points of deep percolation, as dolines in a karstic or pseudo-karstic context. Almeida (2009) presents the hypothesis that the ponds could be associated with the drainage preferences in the karstic-fissured aquifer underneath the unconsolidated sediments. However, it was not possible to obtain evidence to prove this hypothesis, keeping the possibility that the drainage of the ponds may happen only by a preferential access by plinthic horizon, flowing through the tertiary-quaternary regional surficial sedimentary aquifer in a pseudo-karstic context.

Ribeirão dos Órfãos and Córrego da Bica

The areas of recharging of the *Ribeirão dos Órfãos* and *Córrego da Bica* are located in the vicinity of the city of João Pinheiro, between 800 and 900 m of altitude, and they present a similar hydrogeological scheme, even though in well distinct spatial scales. In addition, both springs are used for urban water supply, which justify their importance for the local population.

The two areas of recharge feature sandstone of the *Areado* Formation, with soils of textural variation between typical oxisols (latosols) to quartzipsamments under vegetation of the savannah *strictu sensu* on wavy to hard wavy relieves (CETEC, 1981). The exudation in the slopes occurs at the point of contact with more pelitic strata, featuring the transition of processes from elution to alluvium. From there, the riparian perennial forest starts on alluvial eutrophic soils with clay and silt prevailing in the texture.

In the *Ribeirão dos Órfãos*, the exudation takes place in the context of wetlands (*Vereda* ecosystem). In certain sections of the upstream recharging area of the headspring of *Ribeirão dos Órfãos*, a surface layer of botryoidal (globular) ferric laterite with gravel granulation acts as a geomorphic sill of more abrupt escarpments. In the points at which this laterite was mined for the extraction of gravel, the local geomorphic balance broke off and started the development of erosive processes of gullies on the deep soil of sandy matrix with low cohesion. To stabilize the erosive activity and prevent the sedimentation on watercourses, the *Companhia de Saneamento de Minas Gerais* (COPASA) has been performing, since 2004, revitalization initiatives of the *Ribeirão dos Órfãos* Basin, with special focus on the construction of small dams for retention of runoff in the areas of greater ground instability. The retention dams show median state of conservation.

The recharging area upstream to headspring of *Córrego da Bica* is circumscribed in the urban area of the city of João Pinheiro, whose lots occupy a portion of its East drainage shed. From 2009 to 2011, in a partnership between the sanitation company COPASA, the NGO GreenJop and the Government, the basin has been revitalized and sewage has been integrated into the municipal collection system. The area of recharging is crossed by BR-040 road that separates it into topographically upper and lower halves. The lower half is fenced, and visits are prohibited. The flow of the upper half finds an obstacle on the ridge built for the highway, concentrating on canalized passages.

Chapadão do Pau Terra

This site is a plateau with top edge at 960 m of altitude and foothills between 720 and 800 m of altitude, comprising unconsolidated ferruginous detritus-laterite sediments of Tertiary-Quaternary, covered with typical dystrophic red latosols (CETEC, 1981). The sediment of Tertiary-Quaternary are stratigraphically overlapping quartzites and carbonaceous sericite-phyllite of the *Canastra* Group (CETEC, 1981) or *Paracatu* Formation (CPRM, 2003), which operate as barriers for the hydrogeological flow, forcing the exudation by lithostratigraphic contact. The flat tabular surface is surrounded by headsprings that drain in a geomorphological context of slopes with ravine and v-valleys and sparse ridges (CETEC, 1981). The surface of the plateau was occupied all over by non-irrigated mechanized agriculture and forestry.

Cartographic products and the results of the spreadsheets of rapid assessment

Figures 5 to 14 show the cartographic products of the rapid assessment methodology for each site under study. The consolidation of the rapid assessments of recharging is in Tables 4 and 5.

DISCUSSION

Weighting on heterogeneous areas

In the cases where an attribute was not homogeneous in the study area, a proportional weighting was performed in its respective index. In the occurrence of a spatial adjacency of classes of attributes (for example, two distinct types of soils), the weighting was guided by proportion of areas. Differently, in the observation of attributes with a gradual transition (for example, an oxisol/latosol with significantly sandy texture, almost being classified as a quartzipsamment), the weighting was performed in terms of qualitative predominance. In the latter case, the level of technical proficiency of the professional in the fieldwork becomes a more important factor.

Distance to possible pollution sources

In all case studies, the criterion "Distance from the source of pollution" was not applied, either because it is nonexistent or it is spatially diffuse. However, we decided to keep this criterion in the method presented, since it can be useful in future works and its weighting criteria are well substantiated by referenced literature. Notwithstanding, the possibility of exclusion of criteria is one of the characteristics that brings flexibility to this methodology.

Spreadsheet of weighted checking

The results of Tables 4 and 5 show that the plateau with quartzipsamments (*Serra do Boqueirão*) had the highest

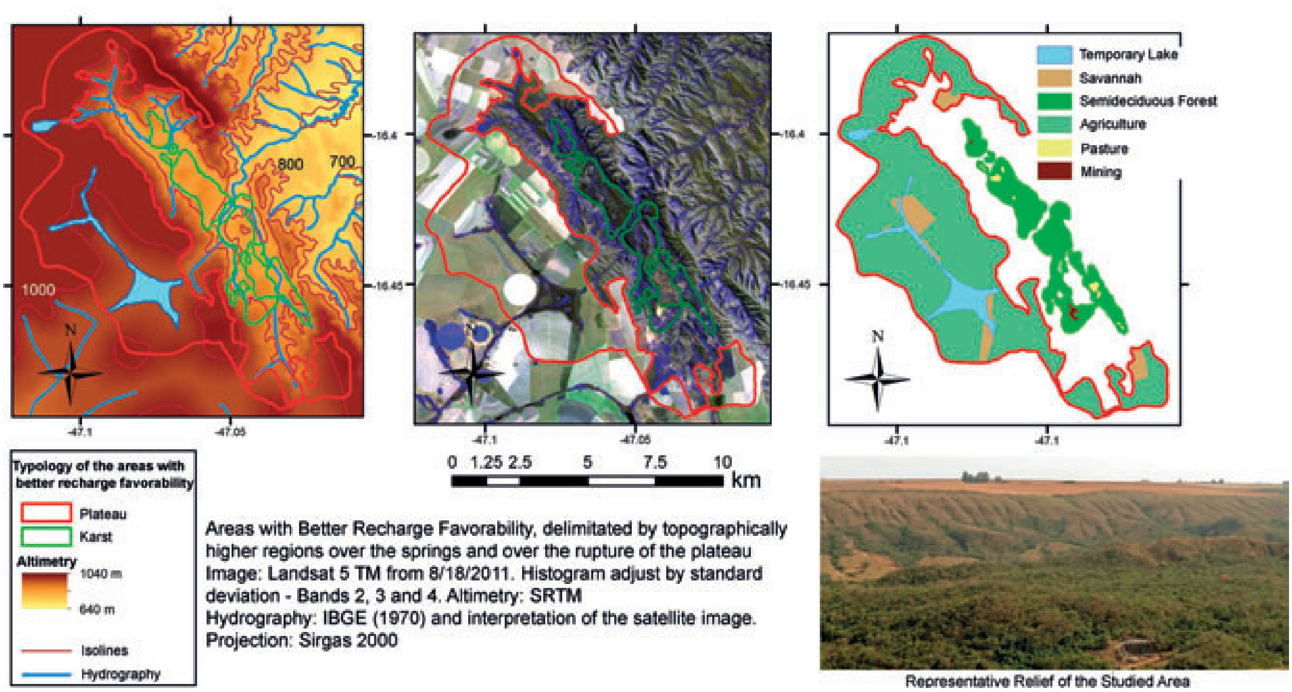

Figure 5. Cartographic characterization of the most favorable areas for recharging in the *Areia* Stream Valley.

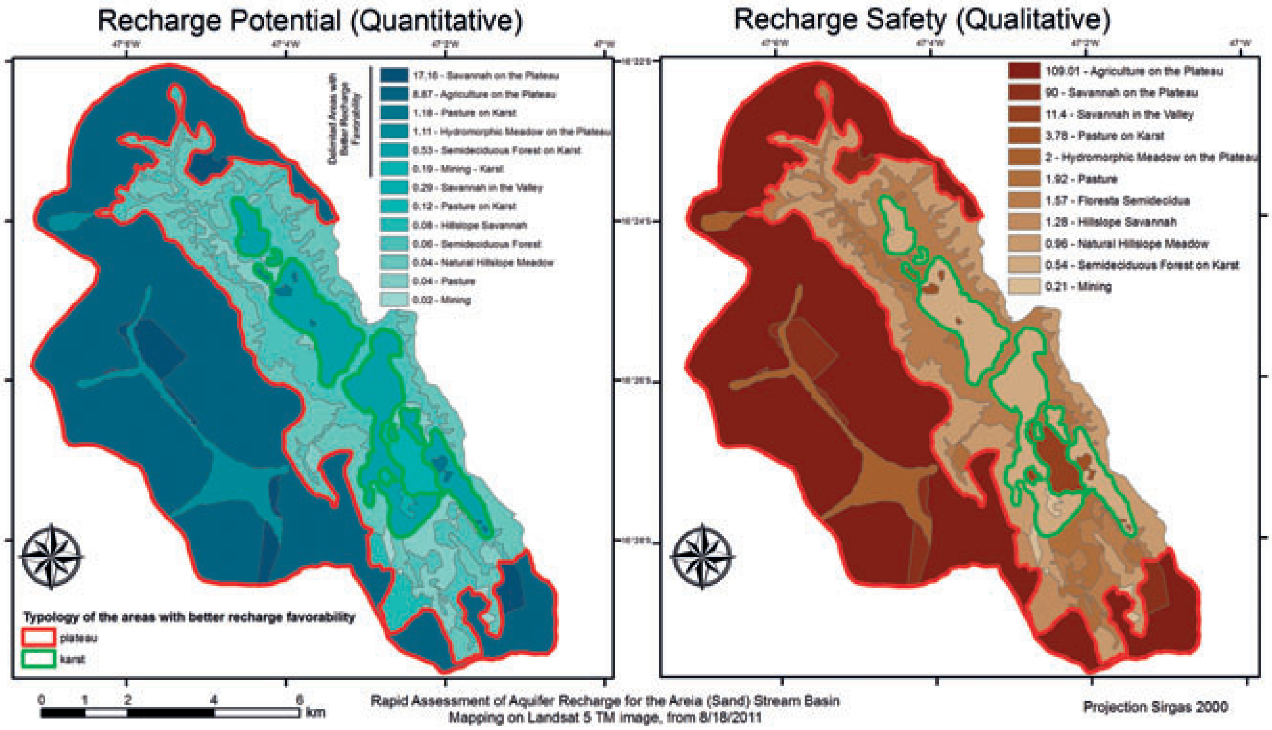

Figure 6. Rapid assessment of recharge of aquifers for the *Areia* Stream Basin.

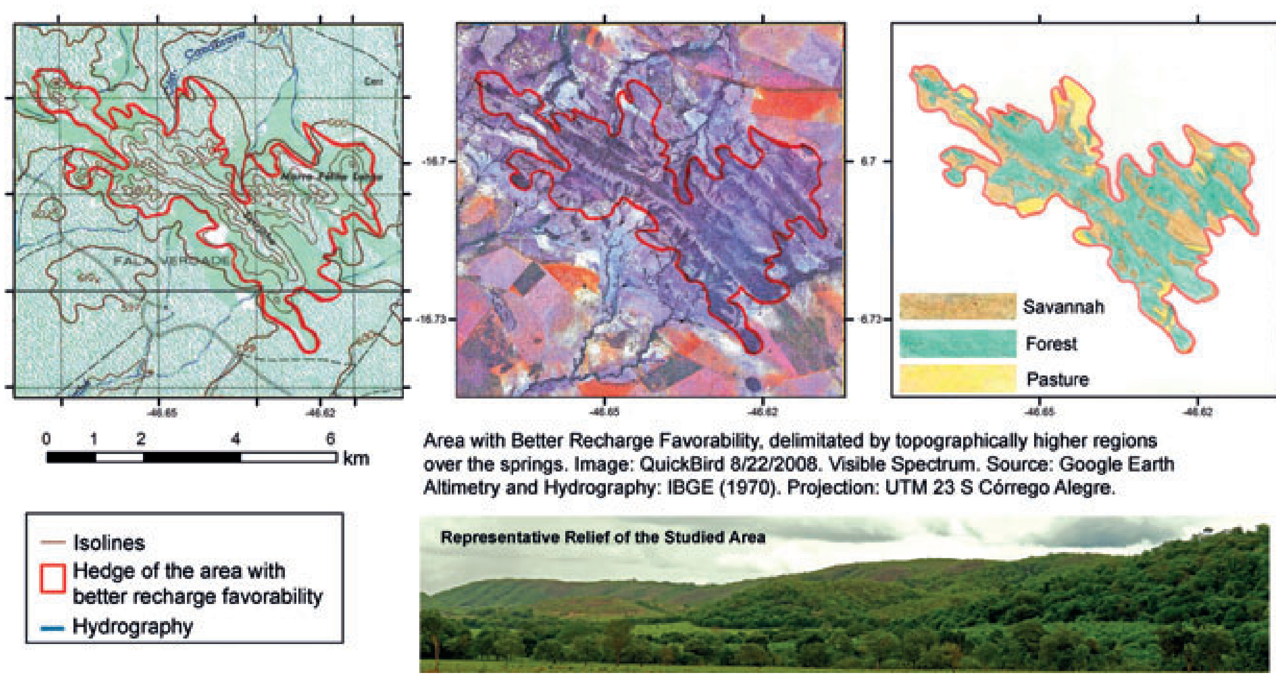

Figure 7. Cartographic characterization with manual delimitation (without the aid of geographical information systems – SIG) of the most favorable areas of recharging in *Serrinha*, as a practical example of this methodological possibility.

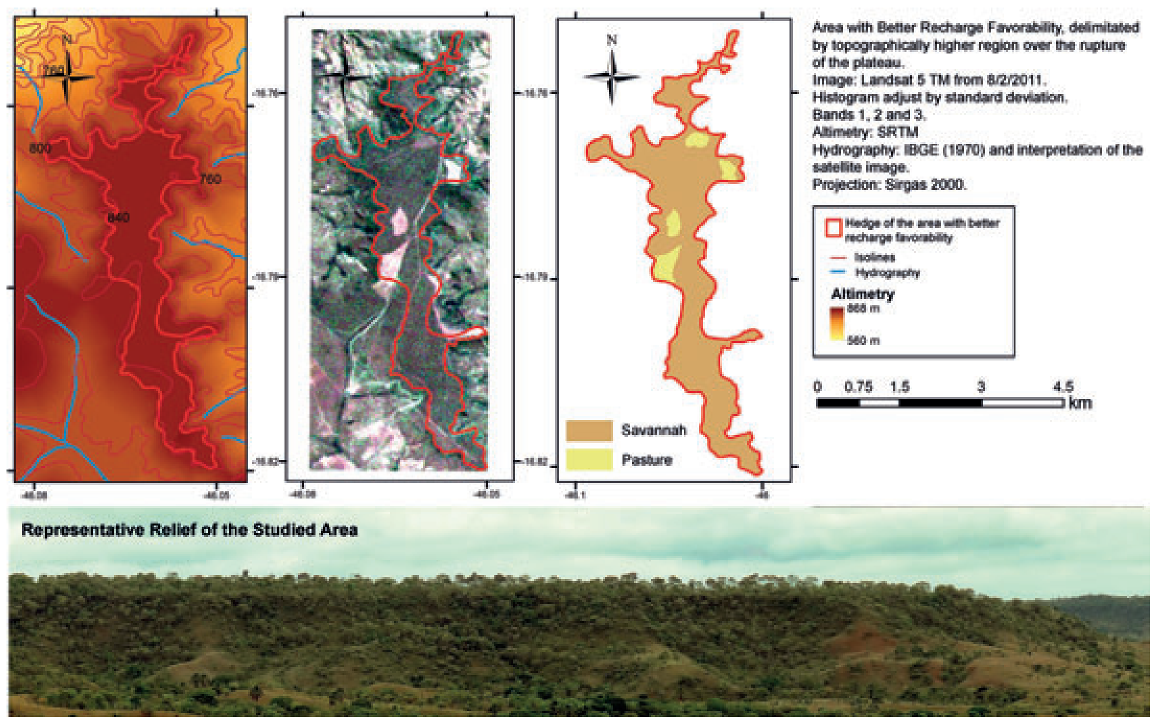

Figure 8. Cartographic characterization of the most favorable areas for recharging in the Plateau of the *Serra do Boqueirão*.

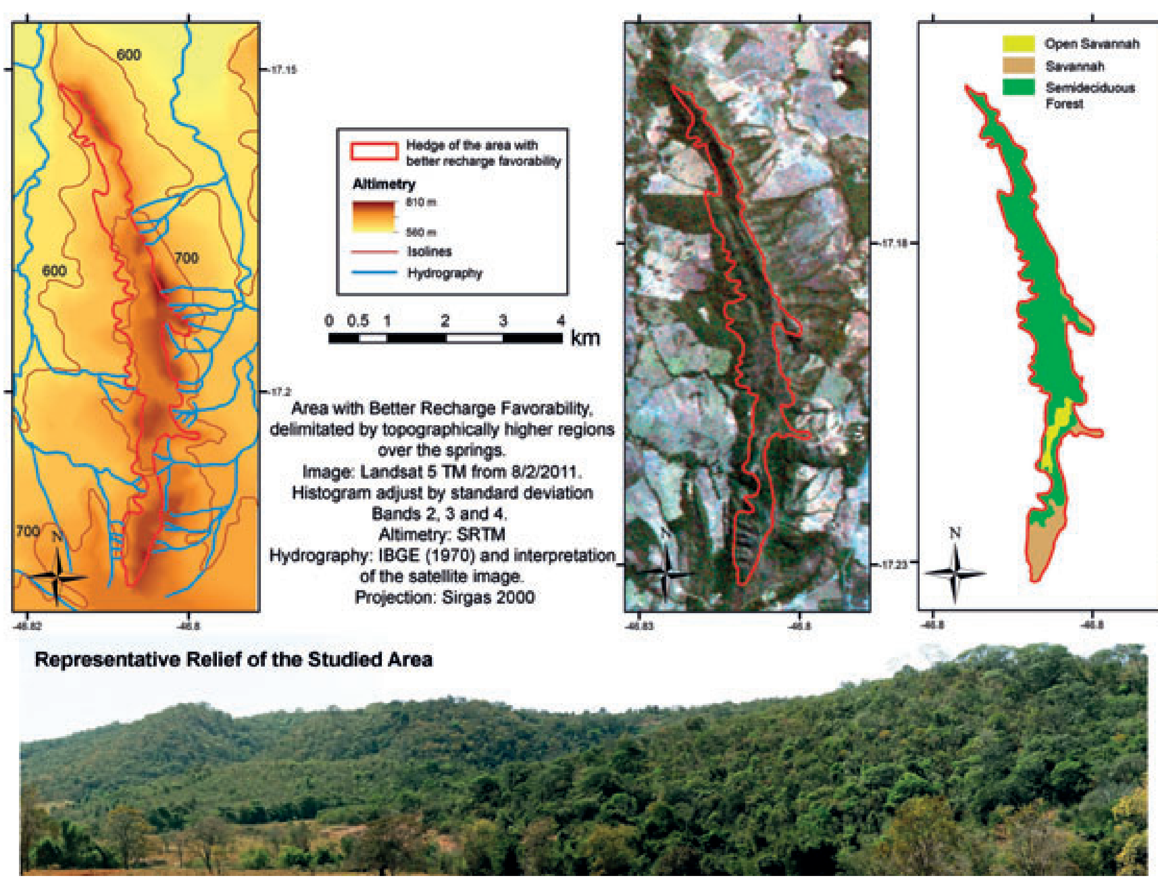

Figure 9. Cartographic characterization of the most favorable areas for recharging in the *Serra do Sabão*.

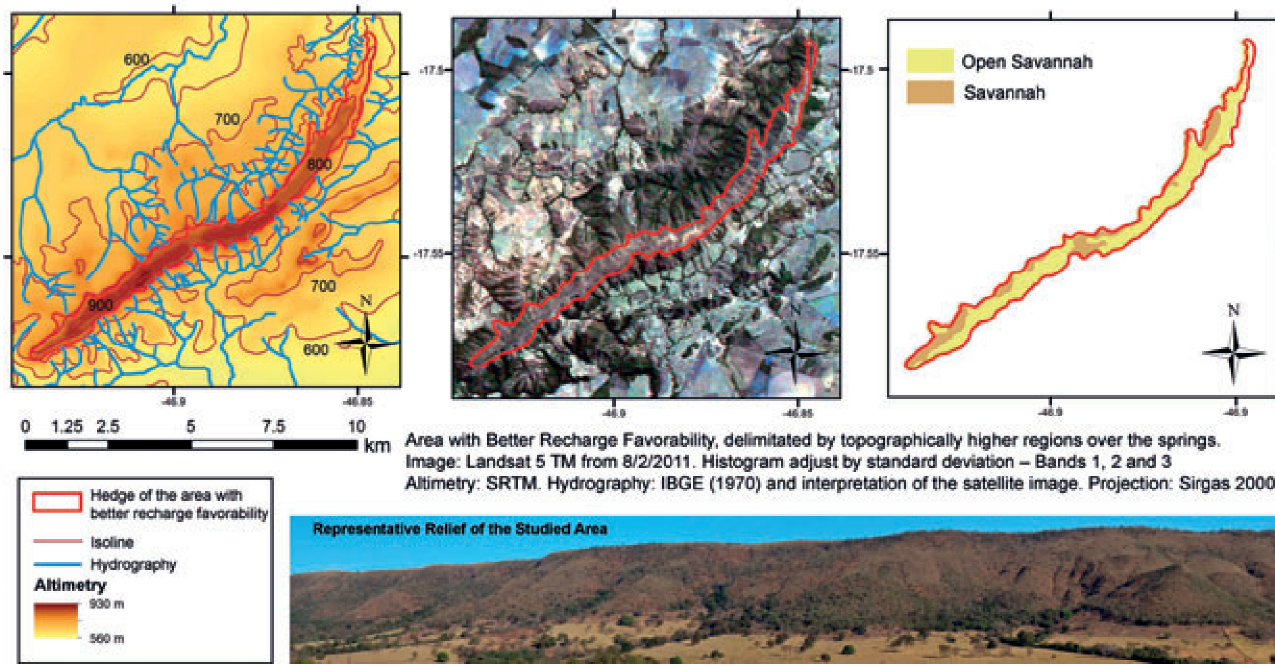

Figure 10. Cartographic characterization of the most favorable areas for recharging in the *Serra das Araras*.

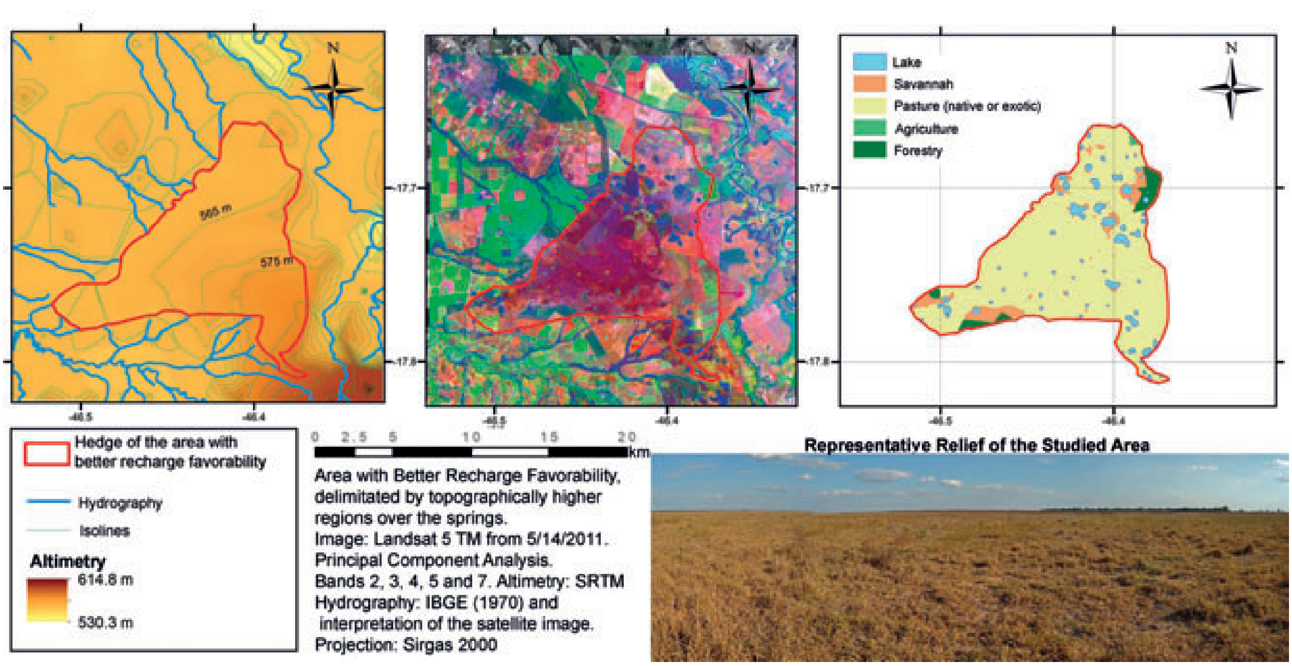

Figure 11. Cartographic characterization of the most favorable areas for recharging in the region of Lakes of the *Prata* River.

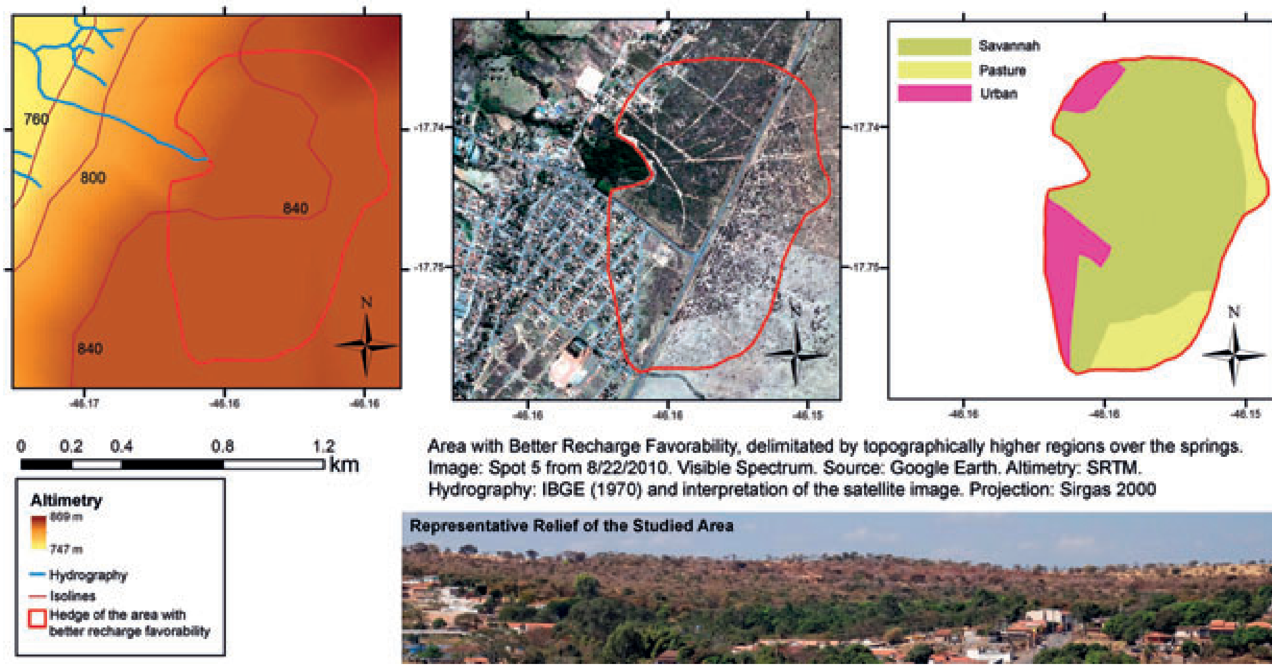

Figure 12. Cartographic characterization of the most favorable areas for recharging of the *Córrego da Bica*.

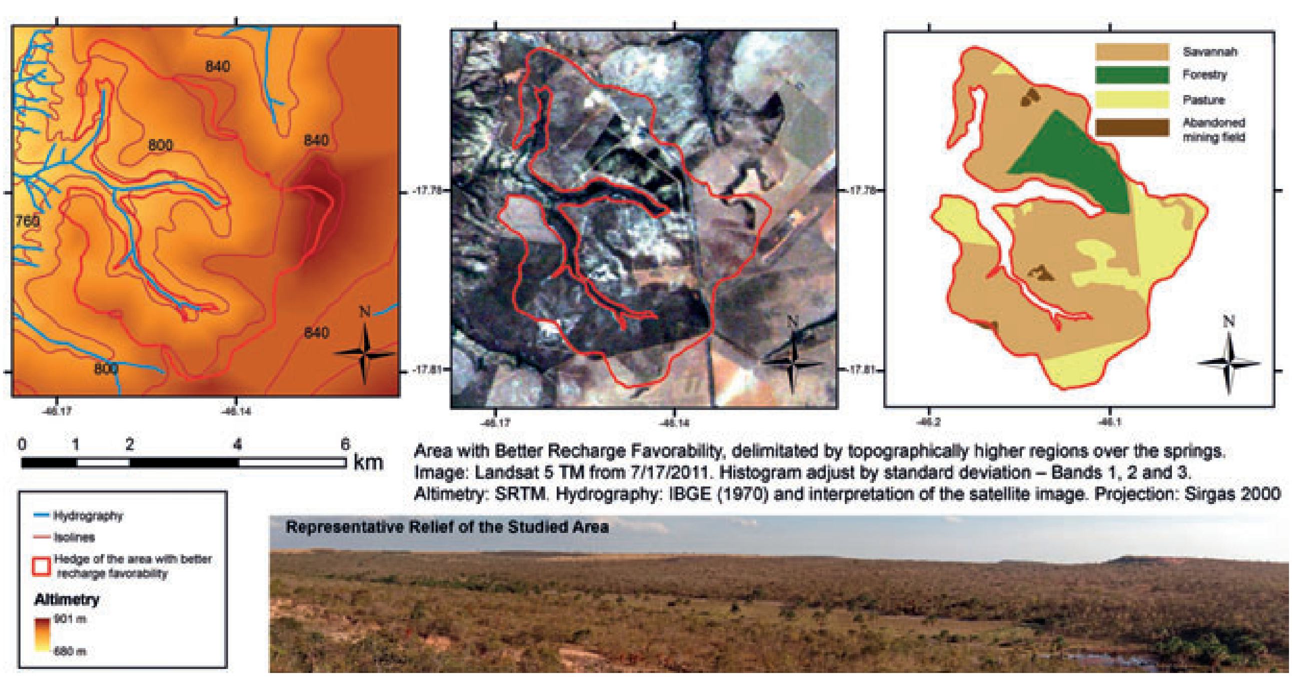

Figure 13. Cartographic characterization of the most favorable areas for recharging of *Ribeirão dos Órfãos*.

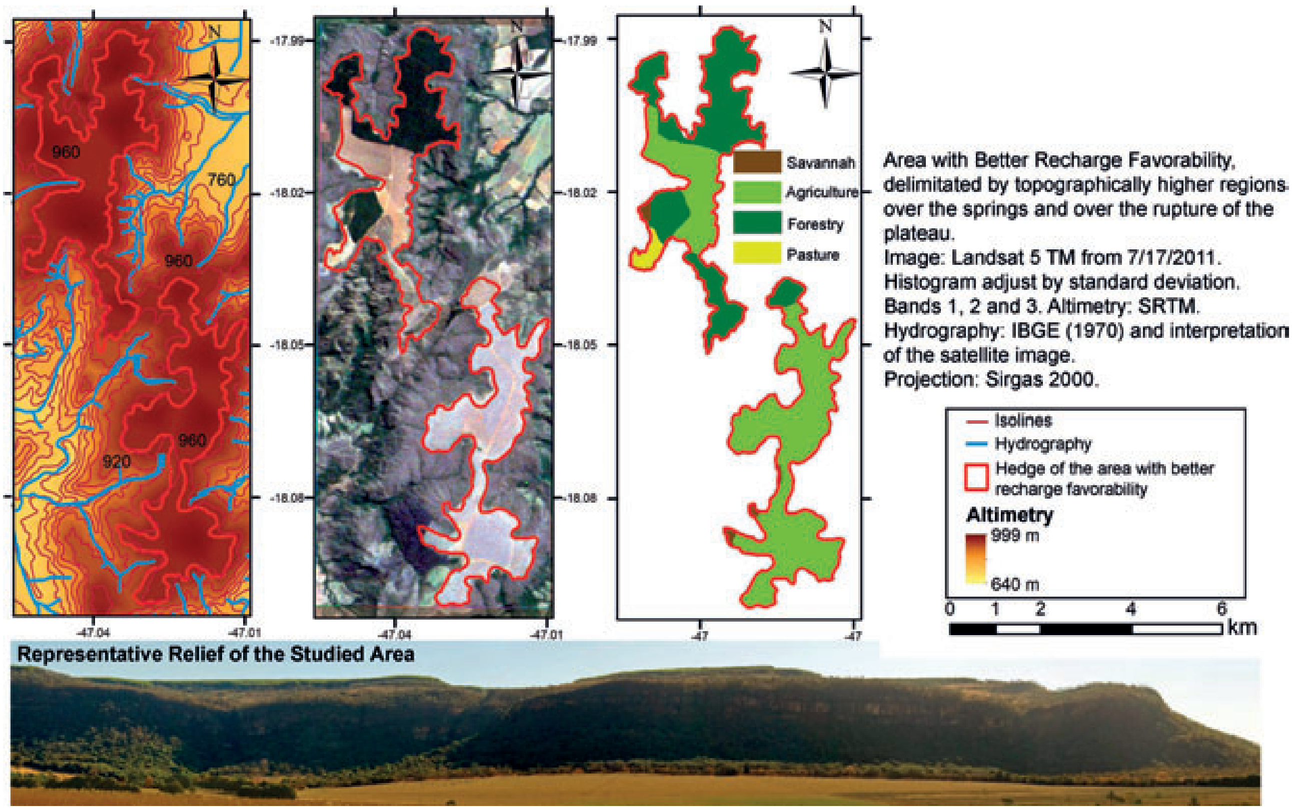

Figure 14. Cartographic characterization of the most favorable areas for recharging in *Chapadão do Pau Terra*.

potential for recharging, while the two ones with oxisols/latosols (*Areia* Stream and *Chapadão do Pau Terra*) presented the greatest protection to recharge. The lower potential of recharge took place in steeper slopes areas with predominance of fractured aquifers (*Serra das Araras*), even when partially associated with karstic rocks (as in *Serrinha*). The areas with less protection of water quality in recharging took place in hydromorphic fields (Lakes of the *Prata* River) and karstic valleys (*Areia* Stream Valley). The other study sites showed intermediate graduations consistent with their attributes pertaining to the hydrogeological cycle. The relevant contrasts between the indices of the study areas point to the need for differentiated strategies and public policies for the management of water resources in each of them, concerning recharging aquifers.

As to the extensive mapping of *Areia* Stream Basin (Table 5), the mining showed the worst values for potential recharge and its qualitative protection. The karstic and hillslope areas on fractured terrigenous lithology also had low values for potential recharge and protection. The regions on the plateau (except the hydromorphic fields) had the highest values for both weights. The results are consistent with a guideline for the basin management, in which one should be more concerned about the sensitivity to contamination in the karstic areas with the bias to degradation of the soil on the slopes, while the plateau presents greater capacity to potentiate initiatives that seek to increase the infiltration, in order to ensure the flow of the basin springs.

Potential and limitations

One of the restrictions of application refers to the scale of details available for the maps of altimetry, hydrography, and images of remote sensing for the study area. Notwithstanding, the existence of a remote sensing image with a good scale of details may serve as the basis of interpretation for the inferences of relief and hydrography necessary for the delineation and characterization of the area that favors aquifer recharging.

It is recognized that the proposed methodology for instruments of local action is not intended to ignore or even compete with the quality of field assessment by an experienced hydrogeologist. A more detailed and technical analysis could adapt the weight of each attribute to the specificities of local hydrogeological processes. Local inferences about potential aquicludes and aquifugals, as well as on the likelihood of vertical and horizontal hydraulic gradients, require a considerable expertise, but they would bring much greater consistency as to the delineation and characterization of recharge and discharge areas of aquifers. The knowledge on permeability and transmittance in soils and rocks with aquifers can also reveal important elements of analysis, which are ignored or simplified by the weighting methodology. The same exception applies to factors that were not considered in the list of attributes, such as interconnection of aquifers, infiltration for deep aquifers and artificial recharge (for example, irrigation). The final report and the

Table 4. Consolidation of the rapid assessments for recharging of aquifers in the selected study sites.

Study area	Potential of recharge (amount of water)							Protection on the recharge (water quality)										
	Vegetation in the area of recharge	Steepness	Soils	Geology	Typology of recharging and discharging	Land use	Techniques for the conservation of soil and water	Pollution sources	Distance from the source of pollution to the discharge point	Topographic position of the source of pollution to the discharge point	Transmission in the soil	Transmission in aquifer	Erosional processes	River bed aggradation	Vegetation in the vicinity of the discharge point	Techniques for soil and water conservation	Potential of recharge (amount of water)	Protection on the recharge (water quality)
Lakes of the *Prata* River	0.8	2.5	1	2.2	1.3	0.7	1	0.95	1	0.2	0.8	3	0.95	1	1	1	4	0.43
Areia Valley – Plateau	0.9	2	2.5	2.2	0.8	0.8	1.4	0.9	1	10	3	2.5	0.95	1	1	1.7	8.87	109.01
Areia Valley – Karst	0.8	0.35	0.6	1.4	1.5	1.5	1	-	-	4	0.3	0.3	1	1	1.5	1	0.53	0.54
Serra do Sabão	0.9	0.5	0.8	1.2	-	1.5	1	-	-	4	0.6	0.6	1	1	1.5	1	0.65	2.16
Collection of *Córrego da Bica*	1.3	0.75	4	3	1.2	1	1	0.5	1	2.5	1.7	3	0.9	0.9	1	1	14.04	5.16
Collection of *Ribeirão dos Órfãos*	1.3	0.75	4	3	1.3	1.2	1.5	0.95	1	2.5	1.7	3	0.8	0.9	0.8	1.5	27.38	10.46
Chapadão do Pau Terra	0.9	2.5	2.5	2.2	1.2	0.8	1.2	0.9	1	10	3	3	0.95	1	1	1.3	14.26	100.04
Serra das Araras	1.3	0.4	0.6	0.7	0.8	1.5	1	-	-	4	0.3	1	0.95	1	1	1	0.26	1.14
Serrinha	0.9	0.35	0.9	1.1	-	1.3	1	0.95	1	4	0.8	0.75	1	-	0.75	1	0.41	1.71
Plateau of the *Serra do Boqueirão*	1.3	2.5	6	3	1.25	1.3	1	0.95	1	10	0.5	3	1	1	0.75	1	90.31	10.69

descriptive cartography, proposed in this methodology, would be as much more complete and reliable as the expertise of the performer in hydrogeology and cartography.

Furthermore, concerning factors that were not considered, the rapid assessment model for recharging protection presents a general index that does not incorporate the volume and constancy of the dumping of pollutants, as well as the hydrogeological behavior, toxicity and the half-life of specific biochemical elements. According to the conceptualization of Vrba and Zaporozec (2004), the rapid

Table 5. Consolidation of rapid assessment of recharge of aquifers in the *Areia* Stream Basin.

Position regarding the area with better recharge favorability	Study sites	Potential of recharge (amount of water)							Protection on the recharge (water quality)										
		Vegetation in the area of recharge	Steepness	Soils	Geology	Typology of recharging and discharging	Land use	Techniques for soil and water conservation	Pollution sources	Distance from the source of pollution to the discharge point	Topographic position of the source of pollution to the discharge point	Transmission in the soil	Transmission in aquifer	Erosional processes	River bed aggradation	Vegetation in the vicinity of the discharge point	Techniques for soil and water conservation	Potential of recharge (amount of water)	Protection on the recharge (water quality)
Internal	Agriculture in the Plateau	0.9	2	2.5	2.2	0.8	0.8	1.4	0.9	1	10	3	2.5	0.95	1	1	1.7	8.87	109.01
	Savannah in the Plateau	1.3	2	2.5	2.2	0.8	1.5	1	0.9	1	10	3	2.5	1	1.2	1	1	17.16	90
	Hydromorphic fields in the plateau	0.7	2	0.3	2.2	0.8	1.5	1	0.9	1	10	0.1	2	1	1	1	1	1.11	2
	Pasture in Karst	1	0.75	1.5	1.4	1.5	0.5	1	0.9	1	4	2	0.3	0.95	1	1.5	1	1.18	3.78
	Semi deciduous forest in Karst	0.8	0.35	0.6	1.4	1.5	1.5	1	-	-	4	0.3	0.3	1	1	1.5	1	0.53	0.54
	Mining – Karst	0.8	0.5	0.6	1.4	1.5	0.3	1.25	0.7	1	2.5	0.3	0.3	0.9	1	1	1.5	0.19	0.21
External	Savannah on the slope	1.3	0.5	1	1	0.8	1.5	1	0.9	1	1	1	1.5	0.95	1	1	1	0.08	1.28
	Native field on the slope	1.3	0.25	1	1	0.8	1.5	1	0.9	1	1	1	1.5	0.95	1	0.75	1	0.04	0.96
	Savannah in the valley	1.3	1	1.5	1	1	1.5	1	-	-	4	2	1.5	0.95	1	1	1	0.29	11.4
	Semi deciduous forest	0.8	0.5	1	1	1	1.5	1	-	-	0.7	1	1.5	1	1	1.5	1	0.06	1.57
	Pasture in Karst	1	0.75	1.5	1.4	1.5	0.5	1	0.9	1	4	2	0.3	0.95	1	1.5	1	0.12	3.78
	Pasture	1	0.5	1.5	1	1	0.5	1	0.9	1	1	2	1.5	0.95	1	0.75	1	0.04	1.92
	Mining	0.8	0.5	0.6	1.4	1.5	0.3	1.25	0.7	1	2.5	0.3	0.3	0.9	1	1	1.5	0.02	0.21

assessment wants to deal with the intrinsic vulnerability (potential) of a location, more than its specific vulnerability (certain sources of contamination).

The fact that the presented methodology focus on local assessments hinders the hydrogeological processes of broader scales that could deserve a better characterization. The existences of regional flows, as well as more extensive complex karstic networks, are examples of phenomena that are beyond this methodology. As to the temporal scale of analysis, the fact that the fieldwork is restricted to a few days does not allow a greater certainty in considerations about seasonal variations of hydrological flows, relatively common in karstic and/or semi-arid areas.

CONCLUSIONS

The development of feasible methods to instruments of environmental and water resources management must take into account the limitations of time, human resources, information sources, and legal possibilities inherent in their respective contexts of application. The methodological developments proposed in this study seek to precisely suit these possibilities of action.

Case studies in the Paracatu Basin have revealed a range of different situations for dealing with the conservation of aquifers. The proposed method showed them, presenting consistent products for characterization of these areas. The results can be used for recommendations as to the techniques of soil and water conservation, whether in the context of micro-regional environmental planning or in the selection of sites for the implementation of public policies with the aim of a better cost-benefit ratio for the regional water balance of the hydrographic basin.

The example of assessment for *Serrinha* showed that it is possible to perform the rapid assessment even without prior skills on geoprocessing and remote sensing, while the example of extended mapping for the *Areia* Stream Basin showed how this recharging heterogeneity can be assessed over a hydrographic basin.

The limitations and restrictions as to the application of this methodology mainly refer to the application context and the instruments used. Nevertheless, its main positive point is to serve as a guiding thread for professionals and students of various degrees of ability in hydrogeology and cartography. The employment of this method allows the beginner applier to take advantage and learn over the course of practice, achieving a consistent product to the end of activities. For the experienced professional, this is flexible enough to incorporate more complex analyzes, even adaptations for specific contexts or with access restriction to data and information.

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