BGJournal
BRAZILIAN GEOGRAPHICAL JOURNAL
GEOSCIENCES AND HUMANITIES RESEARCH MEDIUM

ISSN 2179-2321
UNIVERSIDADE FEDERAL DE UBERLÂNDIA
FACULDADE DE CIÊNCIAS INTEGRADAS DO PONTAL
Articles | Artigos | Artículos | Articles

INTEGRATED ANALYSIS OF AQUIFER RECHARGE: support for water resource and environmental management in the Paracatu river watershed, Brazil

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KEYWORDS:
Aquifers; Hydrogeology; Water Resources; Spatial Analysis; Environment.

ABSTRACT:
The paperpresentstools for the spatial characterization of aquifer recharge and discharge on multiple scales to support management instruments for water and environmental policies. This method consists of the followingfive procedures: rapidassessment of aquifer recharge on a local scale; spatio-temporal characterization of land occupation dynamics in areas of high recharge potential; mapping of aquifer recharge potential; mapping of the contributions of the specific flows of theflow components (quick, base and interflow); and spatial modeling of the effects of environmental attributes onthe flow components. This method was appliedto the watershed of the ParacatuRiver, a tributary of the São FranciscoRiver, in Brazil. The results were interpretedacross various scales and provide important information for the sustainable use of water resources in terms ofland use and occupation.

ANÁLISE INTEGRADA DE RECARGA DE AQUÍFEROS: SUBSÍDIOS À GESTÃO HÍDRICA E AMBIENTAL NA BACIA DO RIO PARACATU, BRASIL

PALAVRAS-CHAVE:
O objetivo deste estudo é apresentar ferramentas metodológicas para caracterização espacial dos processos de recarga e descarga de aquíferos em múltiplas escalas de abordagem, como subsídio para instrumentos de gestão das políticas de recursos hídricos e de meio ambiente. Esse método consiste em: diagnóstico expedito de recarga de aquíferos em contextos locais; caracterização espaço-temporal da dinâmica de ocupação do solo em áreas com maior favorabilidade de recarga; caracterização cartográfica de favorabilidade de recarga de aquíferos; mapeamento da contribuição de vazão específica para componentes de fluxo (rápido, interfluxo e base); modelagem espacial da influência dos atributos ambientais sobre os componentes de fluxo. Os métodos foram aplicados na bacia hidrográfica do rio Paracatu, afluente do rio São Francisco, no Brasil. Os resultados são interpretados de maneira interescalar e oferecem informações úteis para o uso sustentável dos recursos hídricos,em relação ao uso e ocupação do solo.

RESUMO:
Aquíferos; Hidrogeologia; Recursos Hídricos; Análise Espacial; Meio Ambiente.

ANÁLISIS INTEGRADA DE RECARGA DE AQUÍFEROS: SUBSIDIOS A LA GESTIÓN HÍDRICA Y AMBIENTALNA BACIA DEL RIO PARACATU, BRASIL

PALABRAS CLAVE:
Acuíferos, Hidrogeología, Recursos Hídricos, Análisis Espacial, Medio Ambiente

RESUMEN:
El objetivo de esto artigo es presentar herramientas metodológicas para la caracterización espacial de los procesos de recarga y descarga de acuíferos en múltiples escalas de análisis, como soporte para instrumentos de gestión de las políticas ambientales y de recursos hídricos. Este método consiste en: evaluación rápida de recarga de acuíferos en contextos locales; caracterización de la dinámica espacio-temporal de ocupación del solo en áreas de mayor favorabilidad de recarga; caracterización cartográfica de favorabilidad de recarga de los acuíferos; mapeo de la contribución de lo flujo específico para los componentes rápido, interflujo y de base; y modelado espacial de la influencia de los atributos ambientales sobre los componentes de flujo. La cuenca del rio Paracatu, tributario del rio São Francisco, en Brasil, fue el estudio de caso. Se interpretan los resultados de manera inter-escalar, y ofrecen información útil para el uso sostenible de los recursos hídricos, con respecto al uso y ocupación del suelo.

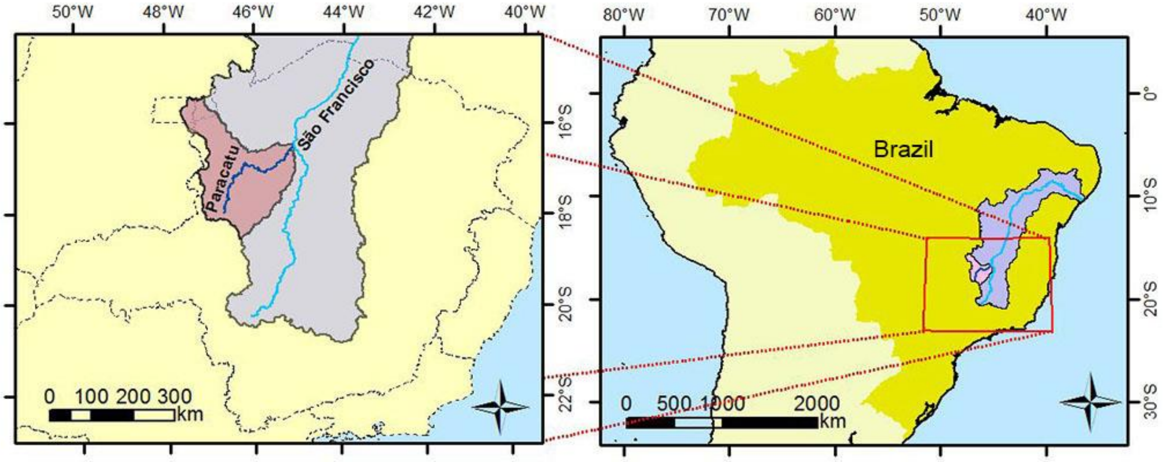
INTRODUCTION

Assessinghydrogeological processes is an efficient means for integrating landuse management and water resource management. In particular, analysis of the relationship between the spatial variations in environmental attributes of a watershed and the processes of aquifer recharge and discharge may support the planning of good practices for agricultural projects, engineering works and other land uses. Understanding these processes is also essential for integrated management of surface and groundwater resources.

However, existing methods used in hydrogeological studies are not always suitable for application to public environmental and water management policies. Such inadequacy may be due to several factors such as [1] the availability of initial data,[2] scale(s) of spatial extent and detail,[3] availability of professionals,[4] time and financial resources,[5] demands for rapid response,and [6] demands for a high level of certainty. This issue is even more challenging in developing countries, such as Brazil, because of limitations in existing databases and in the human and financial resources available to meet the demands of society.

The aim of this study was to provide an analytical method for evaluating environmental impacts and for the combined management of surface water, groundwater and land use; this method may provide strategic information for application to management instruments for water and environmental policies. The ParacatuRiver watershed (Figure 1) was chosen because, since the 1980s, it has been the scene of several conflicts regarding water and land useincludingirrigation projects, hydroelectric dams and land-reform settlements(VASCONCELOS; MARTINS JUNIOR; HADAD, 2012a).

Figura 1: Location of the ParacatuRiver watershed.



MATERIALS AND METHODS

Study Site

The ParacatuRiver watershed (Fig. 2) has an area of 45,154km^{2}and is the second largest watershed among those draining into the São FranciscoRiver. The climate is typically rainy with a unimodal rainfall pattern concentrated in the period of October to April, when an averageof 93% of the annual rainfalloccurs (RURALMINAS, 1996). The lithostratigraphyof the ParacatuRiver watershed, which controls the aquifer systems (Fig. 3), is characterized by a thicksedimentary sequence;a shallow detrital–lateritic soil cover of Tertiary–Quaternary age; and fracture-controlled, karstic and metamorphic aquifers (CETEC, 1981).

Figura 2: Topography and hydrography of the Paracatu River watershed.

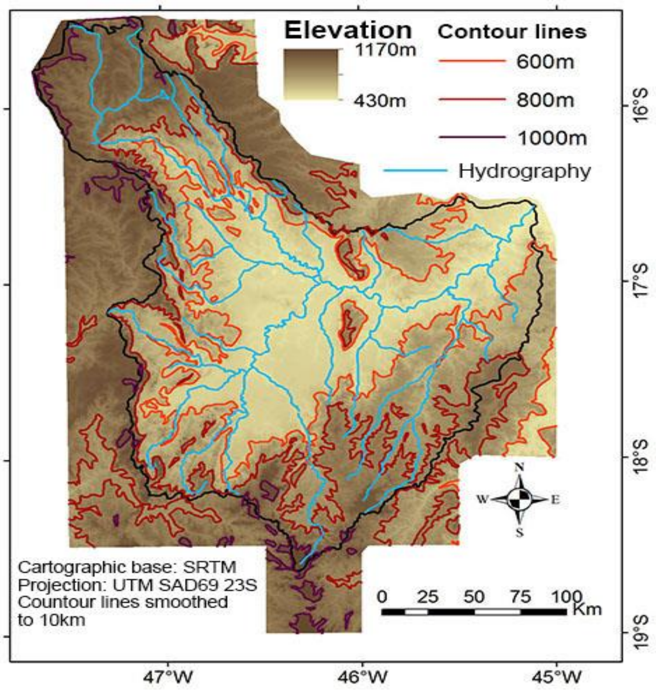
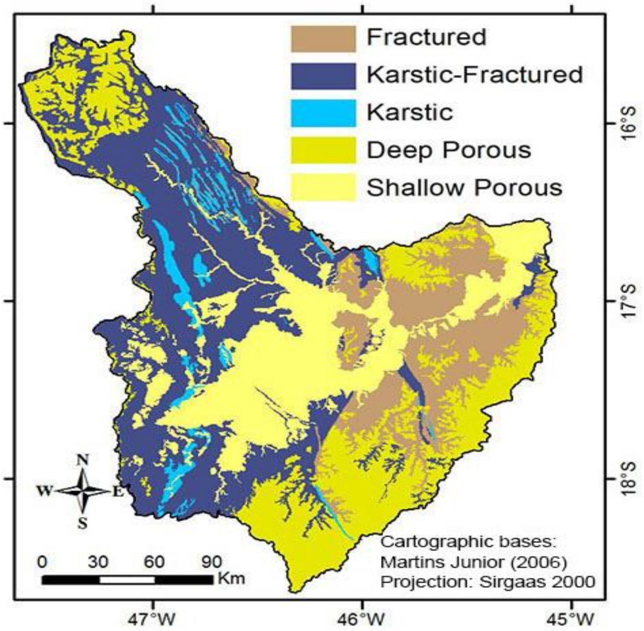


Figura 3: Aquifers of the ParacatuRiver watershed.



Methodology

The methodological propositions of this paper are based on the following research hypotheses:

1: The environmental attributes (soil, rock, vegetation, relief, rainfall, etc.) influence in different manners how the flow components (deep, subsurface and surface flows) are generated in rivers.
2: The spatial pattern of springs and the behavior of stream flow along the rivers' channels can indicate quantitatively and qualitatively the relationship among aquifer recharge and deep, subsurface and surface flows.
3: The comparison among the phenomena referred by hypotheses 1 and 2 allows mapping the areas with higher potential of aquifer recharge.

The study method consists of five stages:

1) Rapid assessment of aquifer recharge on a local scale;
2) Spatio–temporal characterization of the landuse dynamics in areas of high recharge potential;
3)Mapping of the aquifer rechargepotential;
4)Mapping of the contributions of thespecific flowsofflow components (quick, interflow and base);
5)Spatial modeling of the effects of environmental attributes on the flow components.

RapidAssessment of Aquifer Recharge on a Local Scale

The first stage occurs in the context of local environmental regulation involving instruments such as surveillance inspections, deforestation permits, environmental impact assessments and reports,and legal reserve area establishments. Additionally, this stage may also be used as an educational resource for training professionals in hydrogeology. This stage consists of rapid environmental delineation and characterization of recharge areas involving office and field work. The office work consists ofcharacterizing the geologicalsetting and delineating areas with high recharge potential, which are preliminarily mappedas the areas that aretopographically higher than the springs.

The field work involves the preparation and validation of work products(maps) followed by the rapid hydrogeological and environmental assessment of the delineated areas using weightingspreadsheetsspecially developed for this purpose and focusing on water quantity and quality (Boxes 1 and 2).The total value calculated in the spreadsheetis obtained by multiplying the indices of each attribute.

Box 1: Worksheet for rapidassessment of aquifer recharge (water quantity)

	ATTRIBUTE					**Tableofcontents**
POTENTIAL OF RECHARGE (AMOUNT OF WATER)	**Vegetation in the area of recharging** (infiltration less evapotranspiration)					
	Field Savannah	Forested Savannah Deciduous forest Forested Steppe	Permanentcrop Temporarycrop	Deforested area Semi deciduous forest Steppe	Riparian forest Hygrophytes or hydrophilic vegetation Evergreenforest	
	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 (deepsandy 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)	Hydromorphicand alluvialsoils	
	6	2.5	1	0.6	0.3	
	Rocks (water potential of the aquifer)					
	Sandstone (porousdeep)	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	Headspringoffracture	Intermittent spring (independente of the type)	
	1.5	1.3	1.2	0.8	0.4	
	Land use (soil compaction and sealing)					
	Native	Permanentcrop Temporarycrop	Pasture	Exposedsoil	Urban Industrial	
	1.5	0.8	0.5	0.3	0.1	
	Techniques for the conservation of soil and water					
	Percolation dams	Terracing	Ridgesoncontourlines	Tillage	Withouttechniques	
	3	1.5	1.4	1.2	1	
TOTAL						

Box 2: Worksheet for rapidassessment of aquifer recharge (water quality)

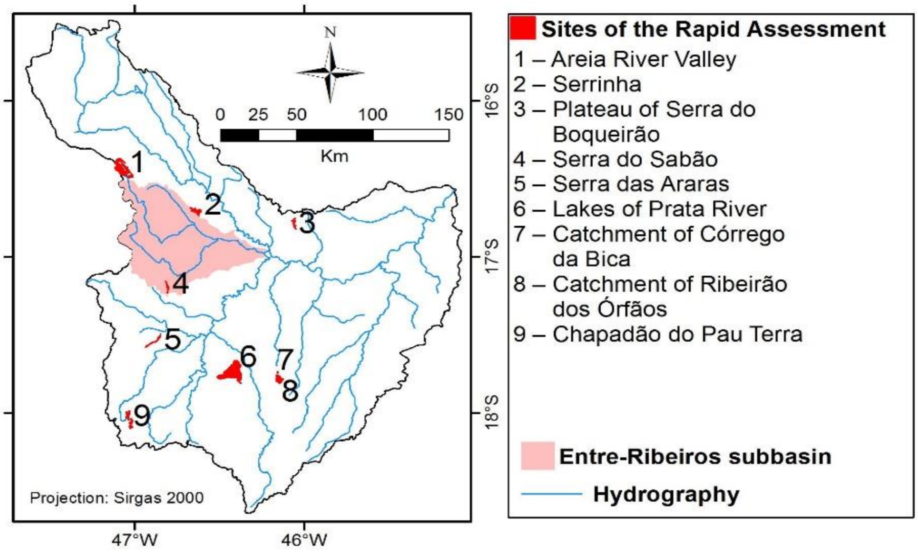
	ATTRIBUTE					Tableof contents
PROTECTION ON THE RECHARGE (WATER QUALITY)	**Pollutionsources**					
	Untreatedsewage	Treated sewage Black pit Garbage Dump Mining (metals)	Septic pit Sanitarylandfill	Pigsty Corral Grange Mining (non-metals)	Pasture Planting	
	0.1	0.3	0.5	0.7	0.9	
	Distance from the source of pollution to the discharge point (subsurface and underground depuration of the pollutant)					
	Directdump	1-5 meters	6-25 meters	26-50 meters Diffusepollution	> 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 (except floodplain)	Hillside	Top of elevation	Plateau on the top of the elevation	
	0.2	0.4	1	4	10	
	Transmission in the soil (under surface depuration of the pollutant)					
	Hydromorphicand alluvialsoils	Lithic entisols (very shallow soils with rocky outcrops)	Quartzipsamments (deepsandysoils)	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 (sinksandresurgences)	Karstic (ducts) Basaltic	Alluvial	Fractured	Porous	
	0.3	0.5	0.6	1	3	
	Erosional processes					
	Gullyerosions	Ravines	Furrows	Laminar	Withouterosion	
	0.8	0.85	0.9	0.95	1	
	River bedaggradation					
	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	5-30 meters of forests > 10 meters of savannah	> 30 metersofforest	
	0.25	0.5	0.75	1	1.5	
	Techniques for the conservation of soil and water					
	Withouttechniques	Tillage	Ridgesoncontourlines	Terracing	Percolationdams	
	1	1.3	1.7	2	3	
TOTAL						

The rapidassessment criteria are based on a small set of schematic geomorphological visual models of the classic conditions of aquifer recharge and discharge with a focus on springs(CUSTÓDIO; LLAMAS, 1976; DAHL; HINSBY, 2008; JUNQUEIRA JÚNIOR, 2006; VALENTE; GOMES, 2005). Soil classes are evaluated in terms of their drainage characteristicsusing the typology proposed by the Brazilian Society of Soil Science (SANTOS *et al.*, 2005). The reference system that was usedwas the Hydrology of Soil Types (HOST;BOORMAN; HOLLIS; LILLY, 1995), which has been adopted in the United Kingdom and combines quantitative estimates of soil drainage, permanent or seasonal depthsto aquifers, and the presence of an impermeable or semipermeable layer. For application in Brazil, the HOST typology was matched to the Brazilian System of Soil Classification (EMBRAPA, 1999) based onestimated surface runoff (CARVALHO, 2009) and infiltration rates (MENDONÇA *et al.*, 2009; RAWLS; BRAKENSIEK; SAXTON, 1982; ROCHA; DALTROZO, 2008). Regarding lithostratigraphic influence, statistical correlations were developed between the lithostratigraphyand thebase flowofBloomfield, Allen and Griffith (2009), whichwere used as a reference,complemented by flow estimates of wells in several aquifer systems (MENTE, 2008; REBOUÇAS, 2008). The effects of land use and cover on recharge were based on the theoretical classifications of Valente and Gomes (2005) and Gomes (2008), on the systems and experiments ofBruijinzeel (2004), Wickel (2009) andWickelandBruijinzeel (2009), and onthe rates of surface runoff and infiltration reported by theseauthors, which they used to evaluate the recharge potential based onsoil classes.

The weighting criterion of protection of groundwater is in accordance with widely used methods for the evaluation of vulnerability to contamination, such as DRASTIC (ALLER *et al.*, 1987)and RAVE (DELUCA; JOHNSON, 1990),and methods for theevaluation of potential contaminant loads, such as POSH (FOSTER *et al.*, 2003), SEEPAGE (MOORE, 1988) and RZWQM (MA *et al.*, 2000). The remaining weighting criteria follow the guidelines for environmental evaluation of aquifers proposed by the United States Environmental Protection Agency (1986, 1993, 2008) and by the European Communities (2003).

The assessment also includes cartographic and photographic products and a written report. Figure 4 shows the study sites evaluated in the Paracatu watershed. The fieldworkwas performed from July to October in 2011.

Figura 4: Locations of study sites for the rapidassessmentprocedure and location of the Entre-Ribeirossubwatershed, which was used as a case study for the spatio–temporal characterization of the landuse dynamics in areas of high recharge potential.



Furthermore, the proposed procedure of rapidassessmentmay be usedto develop more extensive and detailed mapping and for characterizing internal and external areas to delineate areas of high recharge potential. The AreiaRiver was selected for this extensive mapping, which spannednot only areas of high recharge potential but also the entire subwatershed. For this subwatershed, maps were developed showingclasses of recharge quantity and quality in each geotope (i.e., each distinct geomorphic area). A criterion for differentiation was to reduce the recharge potential (water quantity) ofgeotopesoutside the delineated area of high recharge potentialby one order of magnitude based on studies of patterns of hydraulic conductivity (LEWIS *et al.*, 2011) and of pre-rain surface moisture (BROCCA *et al.*, 2007; CRAVE; GASCUEL-ODOUX, 1997; FAMIGLIETTI; RUDNICKI; RODELL, 1998). The spreadsheet for recharge safety (water quality) already takes into account the relative topographic position of the geotope.

Spatio–temporal characterization of landuse dynamics in areas of high recharge potential

The second procedure is the use of thematic cartography (lithostratigraphy, geomorphology, and soils) and mapping of land uses in various yearsvia remote sensing. The Entre-Rios subwatershed, located in the Paracatu watershed, was used as a case study (Fig. 4).

The hydrography of lotic water bodies and the soil cartographyare usedto identify the limits in a watershed profile where seepage startsto predominate over recharge and generates hydromorphic soils and ephemeral lakes. In the high-elevation areas of the watershed, i.e., the upstream portion of the hydromorphic environment, the areas of high recharge potential were delineated based onavailable thematic cartography of the region at a scale of 1:250,000 (MARTINS JUNIOR, 2006). This delineation was based on twotypologic themes:

- The lithostratigraphy, i.e.,aquifer-bearing porous lithosomes.
- The geomorphology, i.e.,plateaus formed by pedimentationprocesses.

The mapping of land use and land cover of 1975, 1989 and 2008 was based on landuse changes due to development of farming systems observed in the Landsat satellite images of each year. The land use changes were statistically comparedin the watershed as a whole and separately in the recharge areas, thereby allowing for interpretations of impacts on groundwater circulation.

Cartographic Characterization of Aquifer Recharge Potential

The third methodological procedure is the quali-quantitative characterization of the attributes of recharge potential. This procedure is based on the hydrogeological interpretation of areas at elevations higher than the springs. The delineation of these areas is based on a Kriging interpolationplane of the elevations of the springs. The springsof the Paracatu watershed were located using the cartographic database of the Brazilian Institute of Geography and Statistics (InstitutoBrasileiro de Geografia e Estatística, IBGE, 1971), at a scale of 1:100,000. This Krigingplanewas subtracted from the digital elevation model usingmap algebra, which resultedin a map of the elevations relative to the springs.

The mapping of recharge potentialgenerates two products: (1)a map of qualitative classesand (2)a map of the multiplicative product of weighted factors, which yields a recharge potential index. In both maps, areas at elevations higher than springsare highlighted to yielda tool for visualizing areas where recharge predominates.

The mapping of qualitative classes was based on the soils (quartzarenicneosols–arenosols), geomorphology (planar and tabular surfaces) andlithostratigraphy (porous aquifers), usingthe 1:250,000-scalecartographic bases of Martins Junior (2006). The locations of overlaps among the three cartographic bases are thus the areas of highest aquifer recharge potential,and areas of progressively lesser potential are those represented by overlaps between two bases,followed by theareas that appear on only one base and, finally,onnoneof the bases.

Hydrologic landscape units were used to interpret the elevation difference in relation to the springs and water bodiesin accordance with the elevationcriteria used byRennó*et al.* (2008) andGharari*et al.* (2011). The units were classified in terms of predominant processes ofrecharge, transience ordischarge (SOUZA; FERNANDES, 2000). The weightings (Box 3) took into account studies on patterns of hydraulic conductivity and pre-rain surface moisture (mentioned in the description of the rapidassessment procedure)and studies on the depth to groundwater (NOBRE *et al.*, 2011). The software Saga 2.0.8 was used to calculate the elevation difference in relation to the downstream water body, applying the algorithm described by Rennó*et al.*(2008).

Box 3: Weighting of attributes of the hydrologic landscape units

Height to the level of springs			
Below -5 meters *Discharge*	From -5 to 5 meters *Fluctuation of phreatic contact*	From 5 to 20 meters *Transience*	Above 20 meters *Recharge*
0.7	0.85	1.6	2.25
Height to the downstream watercourse			
Below 10 meters *Discharge*	From 10 to 20 meters *Fluctuation of phreatic contact*	From 20 to 40 meters *Transience*	Above 40 meters *Recharge*
0.7	0.85	1.6	2.25

The quantitative index of recharge potential was based on maps of the lithostratigraphyandpedology (MARTINS JUNIOR, 2006), rainfall (NUNES; NASCIMENTO, 2004), slope gradient from the SRTM altimetry (JARVIS *et al.*, 2008) and the weightings presented inBox3. For the soil variables, slope gradient and lithostratigraphy, the same weighting values as in the rapidassessmentspreadsheetwere used. The weighting of rainfall was baseddirectly on the interpolated rainfall estimate (in meters/year) of each square rastercell. Multiplying each weightingyields the general recharge potential index.

Mapping the Specific Flows of Flow Components

The fourth procedurewas based onhydrological data from 1976 to 2001 measured at the gaugingstations of the National Water Agency (AgênciaNacional de Águas, ANA)(Figure5). These data were used to separate the base flow, interflow and quick flow using the BFLOW recursive filter (LYNE; HOLLICK, 1979).The recursive filterswere calibrated based on(a) the effects of surface runoff (LYNSLEY *et al.*, 1975)and (b) the inflection inthe recession curve throughout the dry season (BARNES, 1939), according to Figure6. A logical restrictorwas used to limit the overestimation of the total flowin each iteration of the algorithm in order toensure the consistency of the results produced by the recursive filters. The filters and the logical restrictorconsisted of recursive functions in anExcel 2007spreadsheet[1].Finally, maps showing thespecific flowof eachflow component in eachsubwatershedupstream of the stations were generated.

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[1] Spreadsheets with the functions may be accessed at: <https://www.box.com/s/vxs2gysqpan47lkn29jm> (access in 7/8/2013).

Figura 5. Gauging stations.

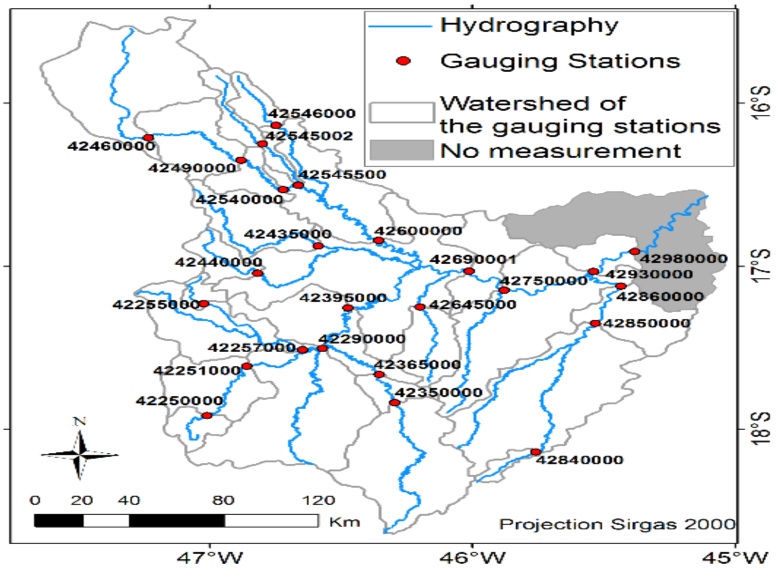
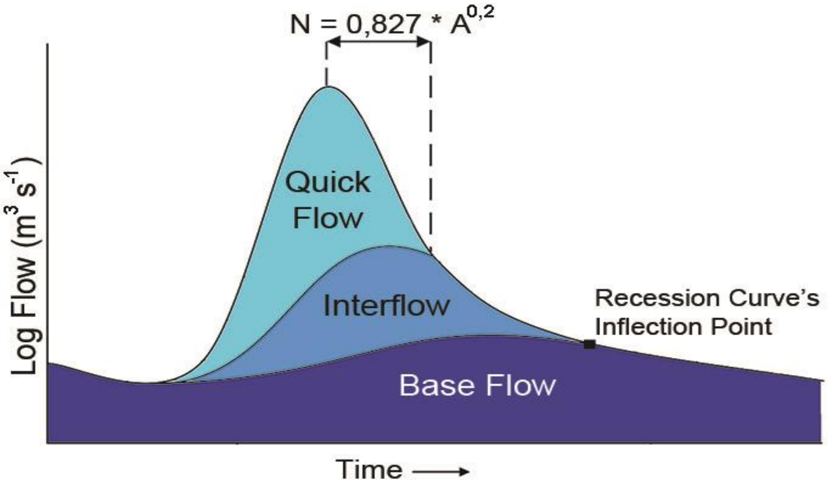


Figura 6. Conceptual hydrographfor partitioning of the surface runoff. *N*is the number of days after a peak in the hydrograph during which rainfall contributesto the surface runoff, and *A*is the area (km^2) of the watershed(LYNSLEY *et al.*, 1975).



Spatial Modeling of the Effects of Environmental Attributes on Flow Components

An extension of the previous procedural stageallows for the investigation, using multivariate statistical techniques, of the spatial relationships ofthe environmental attributes of the subwatersheds in comparison to the total flow, base flow, interflow and quick flow. This procedure relies on cartographic databases that are available or that maybe createdas part ofmost environmental studies in Brazil and other developing countries. The partial least squares (PLS) regressions indicate the role of each attribute in the hydrology and hydrogeology. The dependent variables were the total flowand its respective base, interflow and quick flow components, which were estimatedin the fourth stage of the study. The environmental variables shown in Box4were used as independent variables. The morphometric and hydromorphometric variables were calculatedusing Saga 2.0.8, Envi 4.8 and the extension Spatial Analistin ArcGis 10.1. More detailed explanations of the calculation of the independent variables and their cartographic visualization in the Paracatu watershed can be found in Vasconcelos, Martins Junior andHadad (2012a).

Box 4: Databases used

	Attribute	**Source**	**Scale**
Independentvariables	Morphometric variables: elevation, normalized elevation, standardized elevation, mass balance, slope height, slope, accumulated slope of the watershed, curvature, absolute curvature, convergence index, ruggedness index, vectorial ruggedness index, flow dispersion, topographic wetness index, topographic index of subsurface flow, sky view factor, land view factor, sky visibility, total annual insolation, diurnal anisotropic heating, prevailing windward index (East-Northeast - ENE), prevailing leeward index (ENE), prevailing wind effect index (ENE), effective strength of the prevailing air flow (ENE)	Hydrologically consistent Digital Elevation Model (DEM) based on data from the Shuttle Radar Topography Mission (SRTM) compared to IBGE hydrography data	1:100,000
	Morphometric drainage variables: channel network base level, water springs level, vertical distance to channel network base level, horizontal overland distance to watercourse, vertical overland distance to watercourse, distance to basin outfall (mouth)	IBGE hydrography and altimetry from the SRTM satellite	1:100,000
	DistancetoBrittleStructures	Performed through aerial photographs, Martins Junior (2006)	1:50,000
	Averageannualrainfall	Regionalized rainfall stations, Nunes and Nascimento (2004)	5,221 km^2/station in the interpolation mesh (stations inside and outside the basin)
	Drilled Wells Attributes (flow stabilization, specific flow, dynamic level, water table lowering)	Underground Water Information System (SIAGAS) accessed in 3/28/2012	148 km^2/wells inside the watershed
	Space Variables (latitude, longitude, distance to the edge of the basin)		
DependentVariable	Total Flow, Base Flow, Interflow and Quickflow	Gauging stations in National Water Agency (ANA) network, accessed in 3/20/2011	1,802 km^2/ station

Following the recommendationof Barclay, Higgins and Thompson (1995) for developing a PLS regression, a maximum of one predictor component was used for every 10 cases in the sampling population, thereby limiting thenumber to two components extracted from the multivariate clustering of the independent variables for each regression to adependent variable. The regression was analyzed based on the coefficient of determination (R^2) relative tothe standard deviations of the residuals and to the Q^2 (variation that can be predicted by the components, in a cumulative manner), as recommended by Umetrics (2008). In the regression model, the independent variables were analyzed based on theirvariable influence on projection (VIP), on their standardized coefficient (allowing for a comparison between them) and on their residual standarddeviation of their respective VIP andcoefficient (obtained by resampling the standardized dependent and independent variables [*Z*]), as recommended byUmetrics (2008).

Two statistical models were tested. Because nested watersheds were evaluated, the first model groups variables in each section of the watershed based on the drainage upstream of the gauging stations; therefore, each section of the watershed is used only once in the regression.

The second model is based on the hypothesis of the presence of regional flows, which cross the sections, draininginto the water body downstream of the gauging station. For this model, we used the variables grouped by watershed of the total drainage measured at eachgaugingstation assuming that all the area upstream of the station affects its flow components.

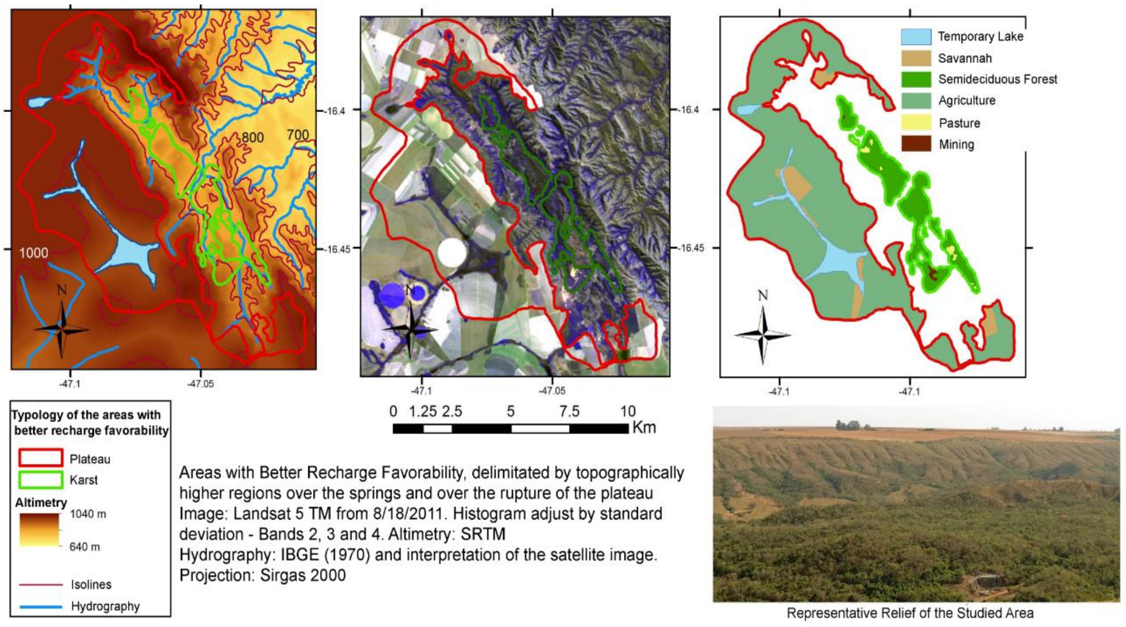
Based on the sum of the weighted thematic layers of these results, maps of specific flowwere generatedfor each flow component. Furthermore, it waspossible to extrapolate the flow componentsto locations where there are no gauging stations.

RESULTS AND DISCUSSION

RapidAssessment of Aquifer Recharge on a Local Scale

The textual, cartographic and photographic results for thesubwatershedof the AreiaRiver (Figure7), including the complete mapping of the geotopes in the watershed (Figure8), based on the spreadsheets of Boxes 1 and 2, are presented next.The detailed results for the remaining study sites can be found in Vasconcelos, Martins Junior andHadad (2012b). Table1shows the data of the rapidassessment spreadsheets for the area of high recharge potential in each study site based on the criteria presented in Boxes 1 and 2.

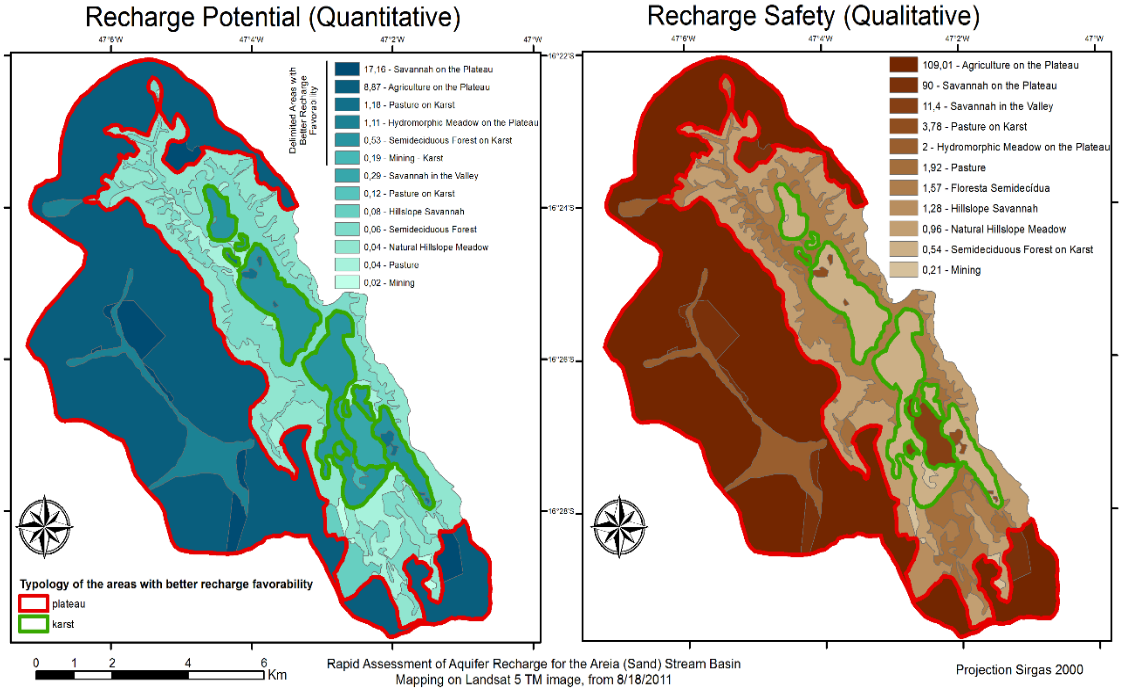
Figura 7: Characterization of the areas of high recharge potential in theAreia River subwatershed.



Areas with Better Recharge Favorability, delimitated by topographically higher regions over the springs and over the rupture of the plateau
Image: Landsat 5 TM from 8/18/2011. Histogram adjust by standard deviation - Bands 2, 3 and 4. Altimetry: SRTM
Hydrography: IBGE (1970) and interpretation of the satellite image.
Projection: Sirgas 2000

Representative Relief of the Studied Area

Figura 8: Extensive mapping of theAreiaRiver subwatershed.



Rapid Assessment of Aquifer Recharge for the Areia (Sand) Stream Basin
Mapping on Landsat 5 TM image, from 8/18/2011

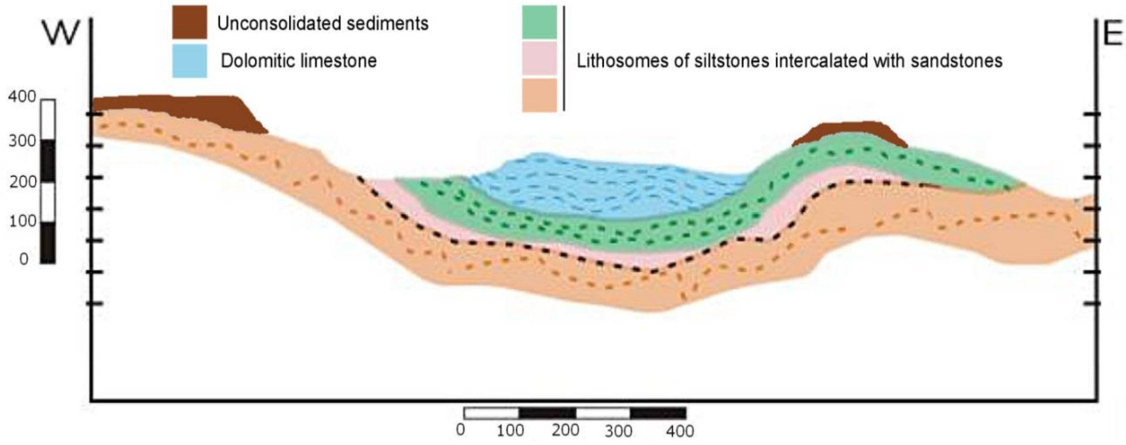
Projection Sirgas 2000

Written Report for theAreiaRiver Subwatershed

The study site consists of two distinct geoenvironmental compartments in terms of aquifer recharge, which are separately analyzedin the rapidassessment procedure:

theplateauin the headand thekarst in thevalley. Underlyingthese two geoenvironmental compartments, there is a syncline involvingpredominantlysiltstonewith sandstone and argillite lenses (FURUHASHI et al., 2005a). This structural configurationis shown in Figure 9.

Figura 9: Stratigraphyof theAreiaRiver valley, based onFuruhashi*et al.* (2005a).



In the higher area, above an elevation of 1,000m, there are red-yellow latosols(oxisols) underlying an area ofplanar to slightly undulating topography These soilsformed by laterization of Tertiary–Quaternary sediments (CETEC, 1981; FURUHASHI *et al.*, 2005a) prior to the dissectionof the Paracatu watershed. The entire plateauis occupied by high-technology mechanized agriculture that includes severalcenter-pivot irrigation systems. This area also containsephemeral lakes, which are hydrogeologically connected to the main springsonthe valley slope via very evident linear structures.

The interior of the valley, at elevations between 840m and 880m, is underlain by the Vazante Formation (COMPANHIA DE PESQUISA DE RECURSOS MINERAIS – CPRM, 2003), which is responsible for akarst topography that includesprominent dolomite outcrops, sinks, caves (some more than two kilometers long), a massif and limestone pavements (FURUHASHI *et al.*, 2005b). A well-preserved semideciduous forest grows in this geoenvironmental compartment inlitholicneosols (leptosols) or in outcrops of the carbonate rock.

Summary of the RapidAssessment of the Study Sites

As indicated byTable 1, the plateau underlain byquartzarenicneosols (Boqueirão mountain range) displays the highest recharge potential, whereas the two plateaus underlain by latosols(AreiaRiver plateau and Pau Terra plateau) display the highest recharge protection. The areas of lowest recharge potential were located in the steeply sloping areas, where fractured aquifers predominate (Araras mountain range), even wherekarst rocks are present (as in Serrinha). Conversely, the areas of lowest protection of water quality in the aquifer recharge were located in the hydromorphic fields (PrataRiver lakes) andkarst valleys (AreiaRiver valley). The remaining study sites showed intermediate levels consistent with the attributes related to the hydrogeologic cycle.

In the extensive mapping of the AreiaRiver watershed (Figure8), areas of mining showed the lowest values of recharge potential and qualitative protection. The karst areas and the sloping areas underlain by fractured terrigenousrocks also displayed low values of recharge potential and protection. The plateaus (except for hydromorphic fields) displayed the highest values of both measurements.

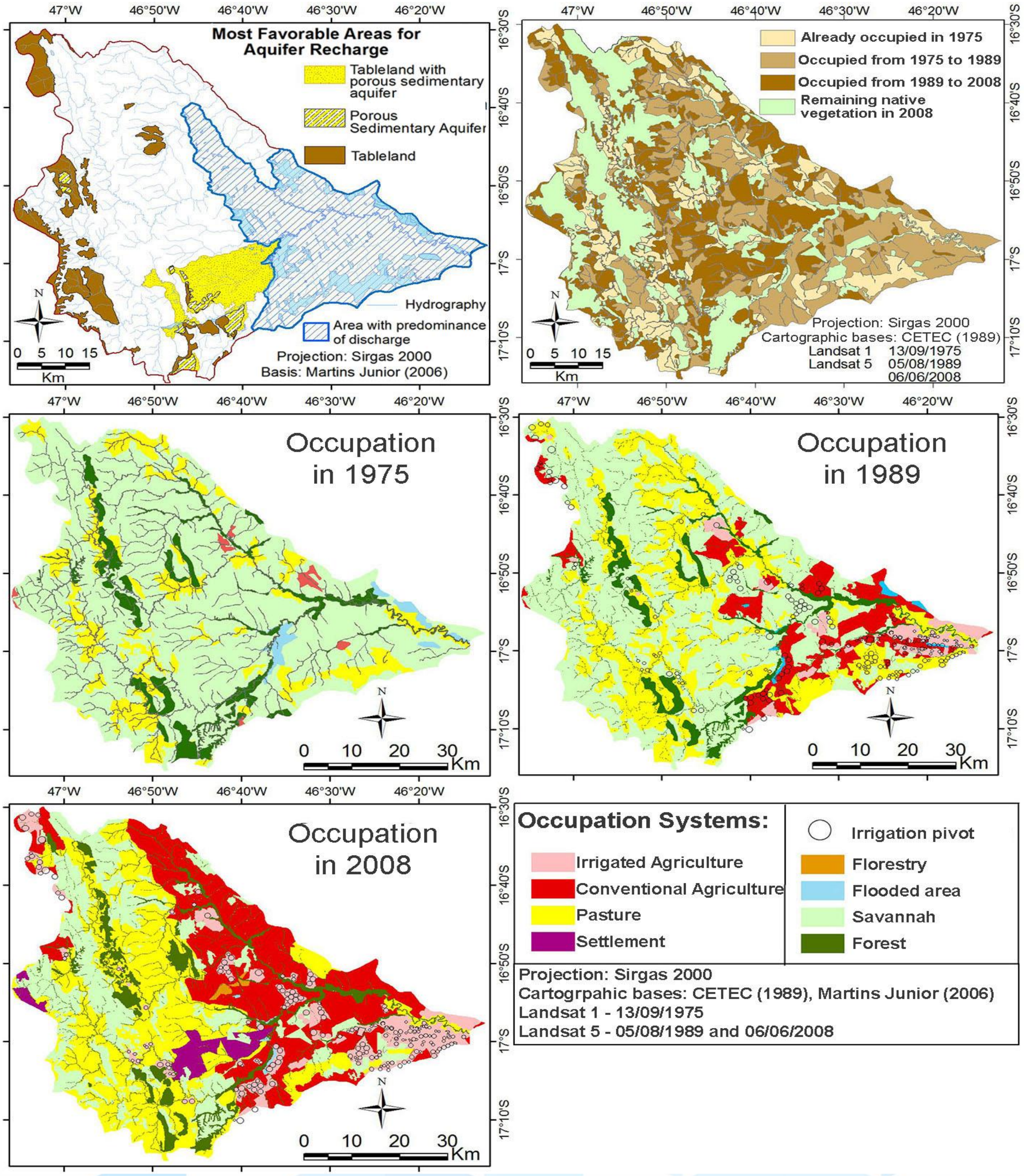
Table 2: Summary of the rapidassessment of recharge in the study sites based on the criteria of Boxes 1 and 2

Studyarea	**Potential of recharge (amount of water)**							**Protection on the recharge (water quality)**									**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**	**Pollutionsources**	**Distance from the source of pollution to the discharge point**	**Topographic position of the source of pollution to the discharge point**	**Transmission in thesoil**	**Transmission in aquifer**	**Erosional processes**	**River bedaggradation**	**Vegetation in the vicinity of the discharge point**	**Techniques for the conservation of soil and water**		
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**
Catchmentof 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**
Catchmentof 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**
Plateauofthe 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**

Spatio–Temporal Characterization of the Land Occupation Dynamics in Areas of High Recharge Potential

Figure10shows the preferred recharge areas in the Entre-Ribeirossubwatershedfollowed by maps showing the land use dynamics in the subwatershed.

Figura 10: Characterization of the recharge and dynamics of land use in the Entre-Ribeirossubwatershed.



The data regarding land use in the watershed and the data regarding land use in preferred recharge areas are shown in Tables 2 and 3.

Table 2: Areas, percentages and changes in land use in the Entre-Ribeirossubwatershed

Classes	1975		Variation 1975-1989 (%)	1989		Variation1989-2008 (%)	2008		Variation 1975-2008 (%)
	Hectare	%		Hectare	%		Hectare	%	
Conventional Agriculture	3,287.91	0.83	+1189.18	42,387.22	10.70	+135.47	99,808.69	25.20	+2,935.63
Irrigation	0.00	0.00	-	14,743.63	3.72	+165.41	39,131.38	9.88	-
Cattle Raising	58,564.34	14.78	+83.01	107,181.11	27.06	+7.72	115,452.98	29.14	+97.14
Settlements	0.00	0.00	-	0.00	0.00	-	11,426.19	2.88	-
Forestry	0.00	0.00	-	0.00	0.00	-	1,230.89	0.31	-
Flooded Area	6,011.93	1.52	-69.12	1,856.74	0.47	-61.79	709.38	0.18	-88.20
Savannah	285,968.28	72.19	-32.23	193,797.94	48.92	-55.72	8,5821.77	21.66	-69.99
Forest	42,300.10	10.68	-14.50	36,168.39	9.13	+17.66	42,555.09	10.74	+0.60
Subtotal Antropic	61,852.25	15.61	+165.65	164,311.96	41.48	+62.53	267,050.13	67.41	+331.75
Subtotal Native	334,280.32	84.39	-30.65	231,823.07	58.52	-44.32	129,086.24	32.59	-61.38
Total	396,132.57	100.00		396,135.03	100.00		396,136.36	100.00	

Note: numbers in blue denote an increase in area, and numbers in red denote a decrease in area.

Table3: Land use in areas of high recharge potentialin the Entre-Ribeirossubwatershed

Classes	1975		Variation 1975-1989 (%)	1989		Variation 1989-2008 (%)	2008		Variation 1975-2008 (%)
	Hectare	%		Hectare	%		Hectare	%	
Conventional Agriculture	277.25	0.44	+1,244.57	3,727.76	5.97	+108.26	7,763.27	12.43	+2,700.14
Irrigation	0.00	0.00	-	256.51	0.41	+2,150.62	5,773.15	9.25	-
Pasture	7,274.44	11.65	+112.95	15,491.11	24.81	+60.75	24,901.27	39.88	+242.31
Settlements	0.00	0.00	-	0.00	0.00	-	9,674.50	15.49	-
Forestry	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
Flooded Area	124.99	0.20	0.00	124.99	0.20	0.00	124.99	0.20	0.00
Savannah	48,555.24	77.76	-21.15	38,287.76	61.31	-75.60	9,341.92	14.96	-80.76
Forest	6,212.83	9.95	-26.65	4,557.05	7.30	+6.78	4,866.17	7.79	-21.68
Subtotal Antropic	7,551.69	12.09	+157.89	19,475.38	31.19	+147.04	48,112.19	77.05	+537.10
Subtotal Native	54,893.06	87.91	-21.72	42,969.79	68.81	-66.64	14,333.08	22.95	-73.89
Total	62,444.75	100.00		62,445.17	100.00		62,445.27	100.00	

Note: numbers in blue denote an increase in area, and numbers in red denote a decrease in area.

In terms of the recent dynamics in land use in the areas of high recharge potential in the Entre-Ribeiros watershed, the significant presence of land reform settlements (15.49%) is noteworthy. Essentially the entire area of these settlements overlaps with the areas of highest recharge.

A comparison of the data in Tables 2 and 3 with the maps of land use and the geomorphological mapping (MARTINS JUNIOR, 2006) indicates that the recharge areas corresponding to porous Tertiary–Quaternary sandstones underlying smooth to undulating topography were used for cattle ranching, which is also very extensive in areas of high recharge potential (39.88%, in 2008).

These data also corroborate the observation that agricultural cultivation in the eastern half of the watershed caused the shifting of cattle ranching to the western half, where the main recharge areas are located. Furthermore, in the plateaus of the headwaters in the northwestern portion of the watershed, there was significant expansion of traditional and irrigated agriculture.

Cartographic Characterization of the Aquifer RechargePotential

Figure11shows the recharge potential in the Paracatu watershed in relation to the soil attributes, geomorphology and lithostratigraphy, with a general view of the watershed and another view focusing only on the areas at elevations above the springs. Figure12shows the distribution of the recharge index across the watershed both in the general view and in the view focused on the areas abovethe springs.

Figura 11: Map of the attributes of recharge potential in the Paracatu watershed.

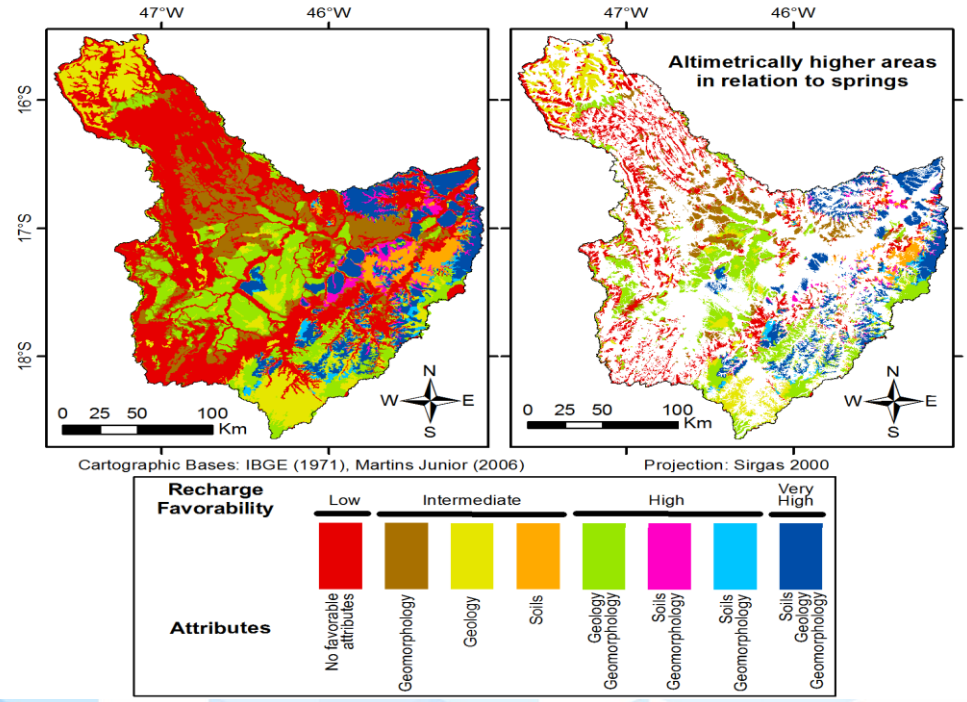
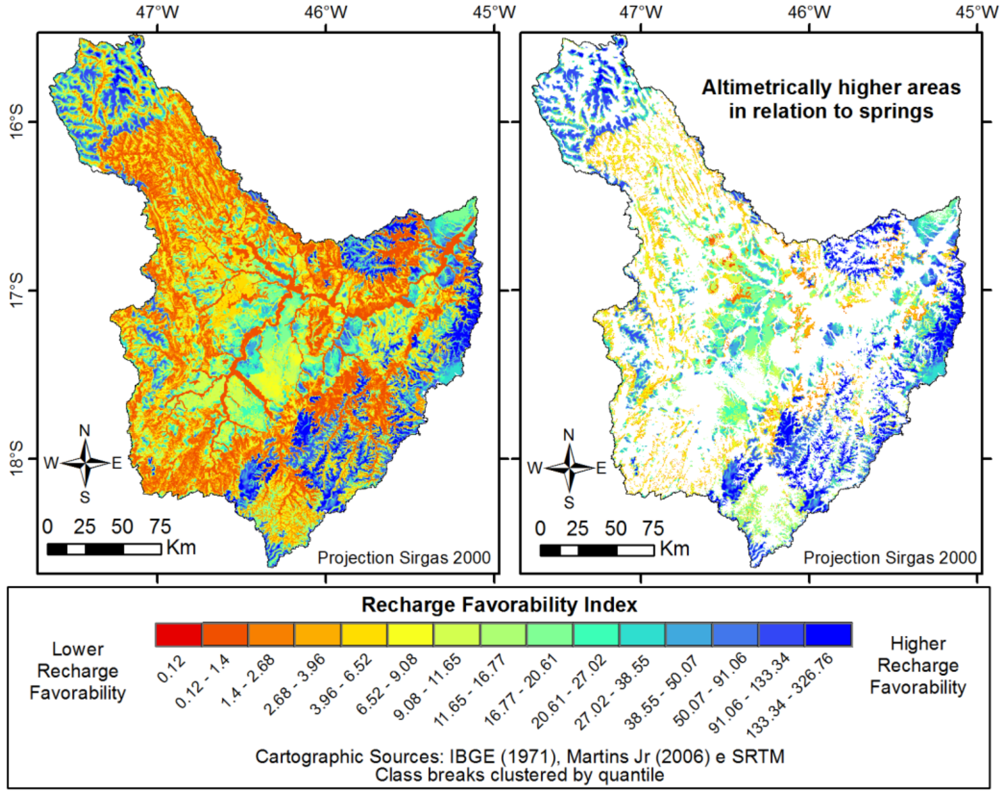


Figura 12: Mapsof the aquifer recharge potentialindex in the Paracatu

watershed.

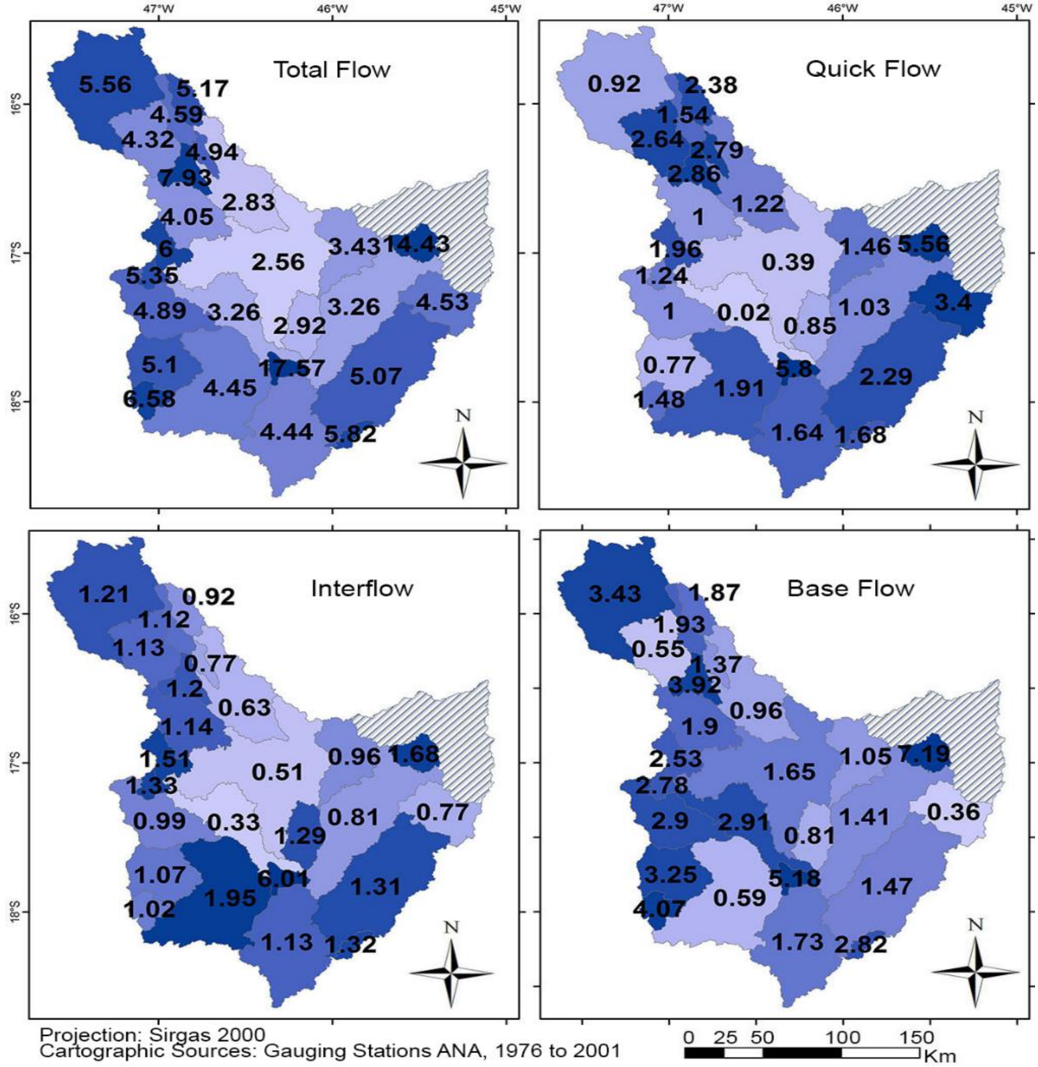


The results obtained for the Paracatuwatershed indicate that therecharge potential is greater in the eastern portion of the watershed, thereby assigning an intermediate importance to the plateaus in the south of the watershed and the highlandsin the northwest of the watershed. The ridgesunderlain by fractured rocksshowed the lowest recharge potential among the areas at elevations above the springs. The river valleys also showed low values, especially considering the elevation difference in relation to the springs and the downstream water bodies.

Mapping of the Contributions of Specific Flows to the Flow Compartments

The specific flow maps (Figure13)indicate that the contribution of the base flow is more significant in the headwater subwatersheds(primarily in the western portion, which receives the most rainfall). This distribution also reinforces the role of recharge in the plateausunderlain byporoussedimentary rocks in the headwaters of the watershed. Progressively farthertoward the lowlands of the central Paracatu watershed, the contribution of the base flow decreases significantly.

Figura 13: Mapof total specific flow and specificflows of flow components (in m^3.s/km^2).



Projection: Sirgas 2000
Cartographic Sources: Gauging Stations ANA, 1976 to 2001

Spatial Modeling of the Effects of Environmental Attributes on Flow Components

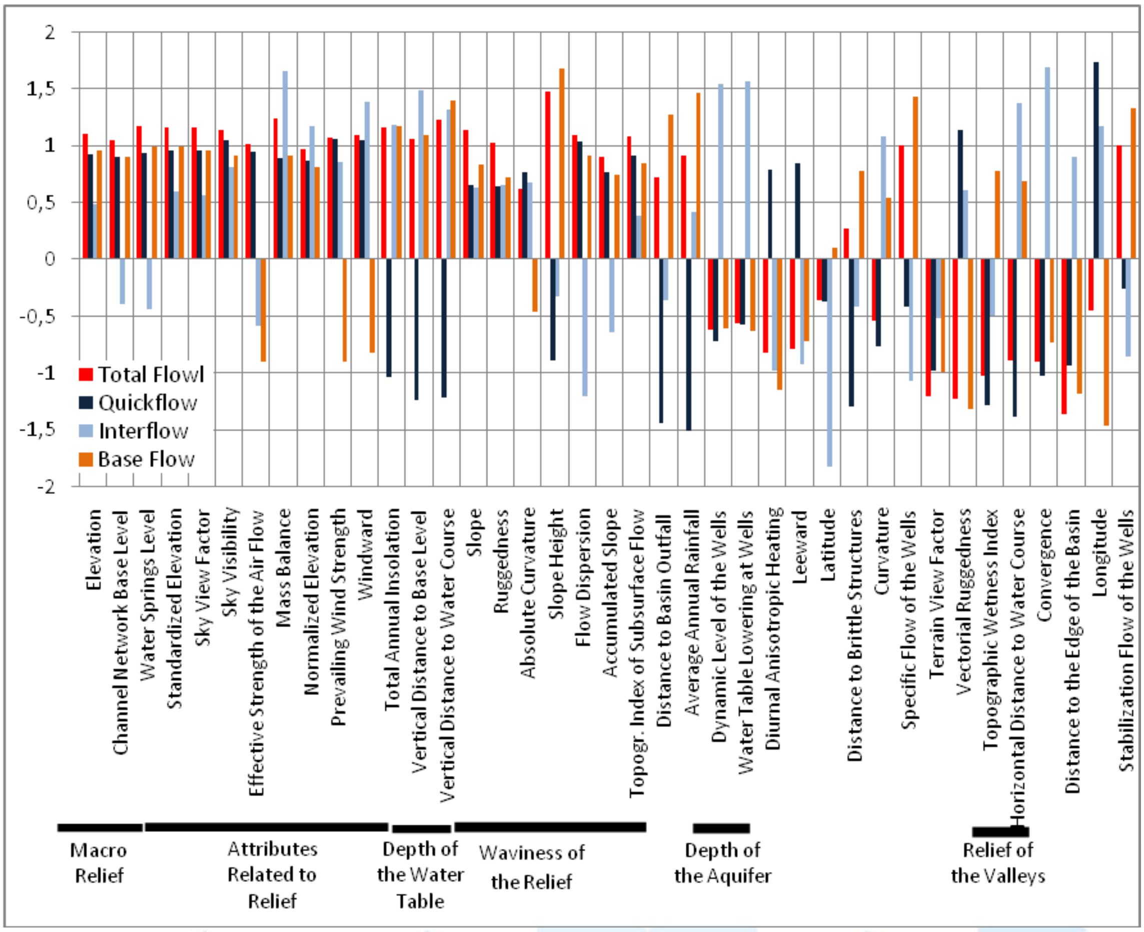
The results of the two regression models are presented in Table 4. The model based on the concept of regional flows showed an improvement in R^{2}and in the standard deviation of all the regressions despite a small decrease in Q^{2}of the interflow regression. Therefore, the incorporation of the hypothesis of regional flows increased the explanatory power of the model and generally decreased the risk of overfitting.

Table4: Results of the regression

Regression	**Modelwithout regional flows**			**Modelwith regional flows**		
	R²	**Q²**	**Standard deviation**	**R²**	**Q²**	**Standard deviation**
Total flow	0.35	-0.10	0.84	0.84	0.73	0.42
Quickflow	0.40	-0.12	0.81	0.76	0.43	0.51
Interflow	0.40	-0.04	0.81	0.43	-0.12	0.79
Base flow	0.35	-0.21	0.85	0.84	0.67	0.42

Figure 14shows the VIP of the independent variable multiplied by the sign of the respective coefficient for each regression of the model of regional groundwater flows.

Figura 14: VIPsof the independent variables multiplied by the signs of the respective coefficients.



The diurnal anisotropic heating index showed apositive coefficient with influence over the total flow and even more strongly over the base flow. The model is consistent, therefore, with the microclimatic hypothesis that the slopes with the most exposure to solar radiation would exhibit more evapotranspiration, therebycontributing to less infiltration and, consequently, to lessflowinthe water system.

The regression involving the base flowalso showed the positive effectsof the variables related to the macro relief (e.g.,absolute elevation, elevations of springs and base level, distance to the mouth and rainfall), to the meso relief (e.g.,standardized elevation) and to the micro relief (e.g.,elevations of slopes, mass balance, normalized elevation, elevation in relation to the base level, elevation in relation to rivers, and horizontal distance to rivers), therebyindicating that the highest areas would be more important for recharge of the aquifers in the watershed. The coefficients of these groups of variables in the regression involving the quick flow were generally lower or even negative values, indicating that these variables affect the separation of pluvial waters between infiltration and surface runoff.

The increased contribution to the quick flow of areas with proximity (horizontal and vertical) to rivers and vertical proximity to the base level is well expressed. This relationship between the quickflow and those locationsis consistent with the idea that river valleys saturate more quickly during rainfall events, therebydiverting the flow to surface runoff.

The positive effects of the stabilization flow and the specific flow of wells on the base flow are also notable, demonstrating that aquifers with greater flow contribute both to wells and surfacewater bodies.

Areas with a lower fracture density were more favorable for the base flow, whereas areas with a greater fracture densitywere favorable for the surface flow. The fracture density, however, did not affect the total flow. This difference may be due to the distribution of porous aquifers (and thus the formation of sandier and better draining soils) with fewer fractures, where there is more deep infiltration, versus fractured aquifers, which tend to produce moresurface runoff to the rivers. Furthermore, regarding the karstic areas, the systems of fractures may contain conduits that quickly direct water to the rivers.

Convergent topography (more-concave valleys) in areas of greater mass balance (high areas in the micro relief) tend to correspond to greater contributions to the interflow. There isalso an interesting positive effect associated with well depths, typical of areas with confined aquifers, which implies that a confining aquiclude prevents local deep infiltration, thereby redirecting the flow to rivers in the form of interflow.

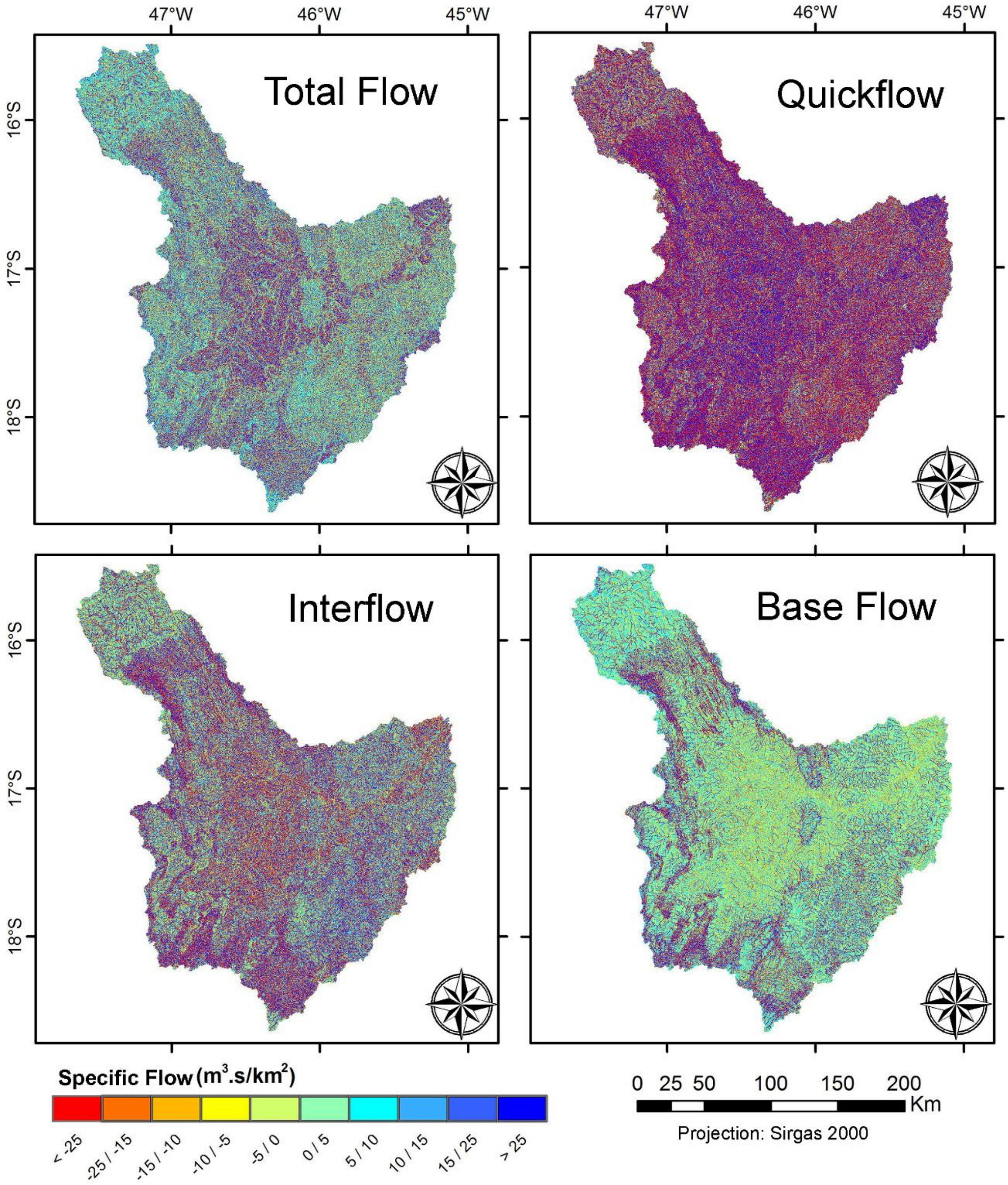
Table5presents the extrapolation of the regression tothe mouth of the Paracatu watershed, consideringan adjustment regardingthe predicted deviation inthe last station upstream of the mouth. The sum of these components – the quick flow, interflow and base flow – was consistentwith the predicted total flow, thus confirming the consistency of the statistical model.

Table 5: Extrapolation of flows and their respective components throughout the Paracatu watershed.

	Predicted		***Corrected with prediction deviation for the last station upstream***	
	Specific Flow (m^3.s/km^2)	***Annual Avg, Flow (m^3.s)***	***Specific Flow (m^3.s/km^2)***	***Annual Avg, Flow (m^3.s)***
Total flow	*4.31*	*194719.87*	*4.41*	*199070.70*
Quickflow	*1.48*	*66703.57*	*1.50*	*67917.31*
Interflow	*1.19*	*53411.52*	*1.10*	*49518.00*
Base flow	*1.67*	*75184.58*	*1.81*	*81797.97*
Sum ofComponents	*4.33*	*195299.67*	*4.41*	*199233.30*

The maps showing the redistribution of the coefficients over the dependent variables are shownin Figure 15. In the areas with undulating micro relief, the values of specific flowsdisplayed the greatest spatial heterogeneity. This variation is due mainly to the diversity of geotopes in these areas, with multiple combinations of convergence, slope gradient, roughness, slope aspect (exposure to sunlight and wind) and curvature. The quick flow was the component most affected by the topography, followed by the interflow, total flow andbase flow, in descending order.

Figura 15: Maps of specific flowin the Paracatu watershed, based on the PLS modeling.



The raster cells near the waterways displayed the lowest contributions to the base flow and interflow, particularly in the deep valleys, and displayed the highest values of quick and total flow. This distribution is consistent with the assumption that rainfall on and near rivers is converted almost completely to quick flow, and this relationship is accentuated with increasingdepthof the valley.

The method of local assessment benefits from the products based on remote sensing, such as land use mapping. As the analysis is extended to wider areas, the development of land use maps based on remote sensing becomes more laborious and dependent on the availability of time and human resources. Nonetheless, understanding the variations in regionalland use in areas of higher recharge potential offers important information for developing policies of water resource conservation, as demonstrated in the regional study of the Entre-Ribeirossubwatershed.

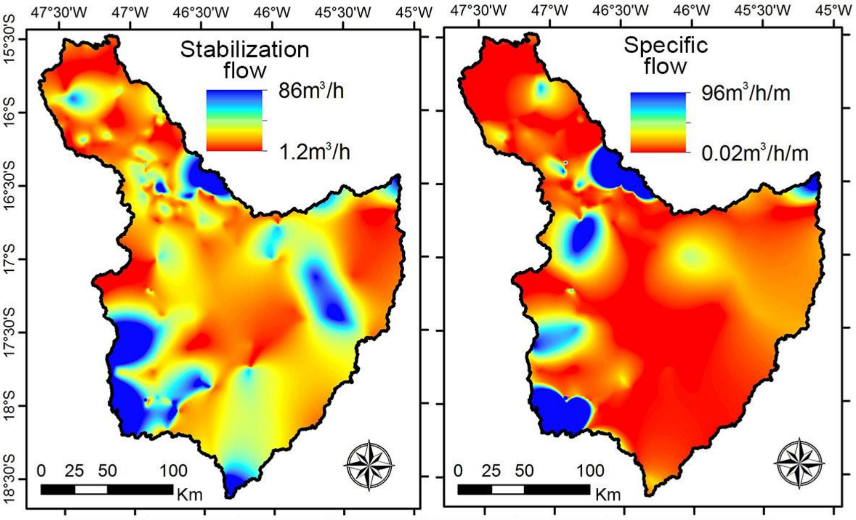
The method of local assessment and mapping the recharge potentialindex originate from knowledge-based modeling, i.e., access to indices and attribute comparison scales available in the specialized literature andprepared by experts. In this context, its quali-quantitative approach allows for the use of thematic cartography, with the same weighting criteria for soils (drainage), lithostratigraphy (aquifer potential) and slope gradient (quantification ofinfiltration versus surface runoff). However, the local method allows incorporating the entire diversity of characterization that may be obtained in the field with several other attributes in the rapidassessment spreadsheet and in the report text. In turn, the spatial differentiation of rainfall can be used in the recharge potentialindex and in the PLS modeling because of its regional scale. The PLS modeling also indicateda significant influence of rainfall on the base flow.

The mapping of the specific flow and the modeling by partial least squares, in contrast to previous methods, are basedon quantitative cartographic descriptors. Because they are based on variables obtained from fluviometry, topography and hydrographic network, they allow obtaining information complementary to the remaining methods.Although they require a large study site for incorporate gauging stations as boundary conditions for the regression, the final maps show the details of the raster cells of the original morphometric variables, thereby providing cartographic products that are useful to later studies of small subregions of the watershed.

The mapping of the specific flowat the stations and the mapping of the PLS modeling are broader than just the modeling of the groundwateraquifers because they also incorporate the components of total and surface flow. Therefore,theycan be thought of as a modeling of the water systems and can be useful in watersheds with problems of flooding or erosion by indicating areas where water and land conservation may reduce the quick flow related to surface runoff.

The PLS modeling suggests that the High PretoRiver (northwest of the watershed) and High PrataRiver (south of the watershed)might be receiving significant groundwater flows from adjacent watersheds. The maps of specific flow and well stabilization (Figure 16) show considerable increases in the flow of wells near the borders of the watersheds to the southwest (subwatersheds of the rivers Escuro,Escurinhoand High Paracatu) and at the northeastern border of the Lower PretoRiver, also indicating possible groundwater flows of external origin. Furthermore, there are possible contributions of small systems in the interfluvial areas of adjacent watersheds, as was noted in the systems of lakes/fractures in the AreiaRiver subwatershed (middlePretoRiver, adjacent to the São MarcosRiver watershed) during application of the local assessment method. The fact that the Paracatu watershed is lower in elevation than the adjacent highlands (Central Plateau to the west and Urucuia plateauto the north) suggests the possibility of groundwater catchment fromthese areas.

Figura 16: Maps showing the characteristics of wells in the Paracatu watershed.



Characteristics of drilled wells in Paracatu River Basin
Exponential Ordinary Kriging, with 2 to 5 neighbors by quadrant (45 degrees)
Linear histogram adjustment, with bi-tale cut of 5% Projection: Sirgas 2000
Source: SIAGAS system, accessed on April 2, 2012

Although the mapping of the recharge potential index indicates a higher infiltration potential in the eastern portion of the watershed, the PLS analysis indicated that the western portion is most important for maintaining the base flow, whereas the eastern portion contributes more to the quick flow. A factor that was already analyzed and may contribute to this situation is the catchment of groundwater flows from adjacent watersheds. Furthermore, in analyzing the Paracatuwatershed on a larger scale,such as that of the São FranciscoRiver watershed, it may be assumed that a fraction of the infiltration in the sandy plateaus in the easternParacatuwatershed may be flowing through the porous Areado aquifer, which is located east of the watershed, and dischargesdirectly toward the São FranciscoRiver.This hypothesis would be consistent with the general topographic convergence of the São Francisco watershed toward its main channel (the watershed wasclassified as a synform-type watershed by Feboli (1985)), whichimplied slope gradientsin the residual plateaus and thetilting of the underlying geologic strata.

Another complementary hypothesis is that the piston effect(KIRCHNER, 2003) in the deep, sandy, porous aquifers in the eastern portion of the watershed would be stronger because of the fasterlocal groundwater flow. This effect maytransform rainfall impulses into quick flows, similar to a system of communicating vessels, which would stabilize rapidlyfollowing periods of rainfall. Conversely, the aquifers in the western portion of the watershed, where the matrix is less sandy, would exhibit slower flow and contribute more consistently during the dry season. Studies involving daily monitoring of tracers and isotopes would be needed to confirm these processes. Nevertheless, these differences in the behavior of the aquifers are important for integrated management of the groundwater and surface water resources.

A third complementary hypothesis, suggested by the application of the local diagnostic method (in the Ribeirão dos Órfãos location), is that the presence of pelitic lenses crossing the porous aquifers, which was also reportedin the lithostratigraphic mapping byCetec(1981),may partially hamperthe deep percolation of water in the eastern portion of the watershed. These lenses may be responsible for the springs in the *veredas* (a type of vegetation that grows in hydromorphic soils), which are common in areas of porous aquifers (Areado, Urucuia and Mata da Corda) in the watershed, as indicated by the application of local assessments. The conservation of these *veredas* and their turf substrate is essential for ensuring minimum flowsduring the dry season in the waterways connected with the sandy aquifers (NEVES, 2011).

From a perspective of land use planning, enterprises with a higher use of groundwatercould be installed preferentially in areas with greater infiltration potential, thereby ensuring the sustainability of the groundwater reserves. The areas of greatest recharge in the Paracatu watershed are located over deep porous aquifers and theoretically have the greatest storage capacity.

The maps of specific flows by flow componentscould be used to give priority to the sustainable management of land uses in the areas with the largest contributions to the base flow, which would help avoid conflicts involving activities that depend on flows during the dry season, such as irrigation and run-of-the-river hydropower plants. The quick flow map may, in turn,indicatethe most interesting areas for storingand normalizing water flows: flows during the rainy season could be retained and used for multiple purposes or be released during the dry season.

In the areas of greater infiltration potential and of greater contributionsto the base flow, land and water management techniques (such as dams for retention and infiltration of rainwaters, no-tillage and/or contour planting systems, and terracing) can be used in a strategy of integrated management of landuse and groundwater and surface water.

The proposedmethodological procedures are based on indirect analyses of hydrogeological processes and on reference studies, secondary data, surface observations, cartographic analysis and geoprocessing techniques. The products allow the general characterization of likely patterns of aquifer recharge and discharge. However, for more reliable interpretation of the results, a wider understanding of the hydrologic, hydrogeologic and climatic phenomena in the area is necessary. When possible, to ensure more accurate characterization of aquifer recharge and discharge, the products herein can be complemented by more detailed primary data obtained from lysimeters, tracers and chemical analyses of surfacewater and groundwater. The products may even be combined with more-detailed studies of the structural geology, piezometric potential lines, hydrogeochemicalfacies of surfacewater and groundwater, and hydroclimatologic balances. Such studies can help verify the hypotheses suggested by the products of the proposed methods by contributing to a better identification and quantification of likely groundwater flows.

CONCLUSIONS

The cartographic products obtained with this method serve as important support for the sustainable management of land use, water resources, the environment and economic activity,given the expansion of the anthropic activities that depend on local natural resources. A strategy of combined environmental and water management may involve the use ofthese several methods to develop analyses and action plans on various scales and extract a maximum amount of information. The results can be usedto recommend techniques ofland and water conservation in a context of regional environmental planning or for selecting sites for the application of public policies with the aim of a better cost/benefit ratio associated with the regional water balance in the watershed.

Considering different scales and approaches, the integrated use of the five methodological tools provide a wide view of the functioning of the hydrologicsystems in the Paracatu watershed, particularly those regarding the hydrogeological processes and their relation to the geosystemsof the watershed. The results have been discussedbythe ParacatuRiver watershed committee and have provided support forthe management of the watershed.

The proposed methodological procedures arebased oncartographic andfluviometricdata that are typically available for watersheds in Brazil and elsewhere in the world, which facilitates their replication. The tools are sufficiently flexiblefor their adaptation to situations in whichcertaindatabases are unavailable or additional databasesare available. Each of the procedures can also be appliedonother analytical scales assuming there are databases at a scale compatible with the study area, whether regional or highly localized.

The tools can support the delineation and characterization of the recharge potential and the evaluation of impacts and risks associated with the circulation and quality of water in local and regional contexts andwithin a framework of management policies for the environment and water resources[2], such as the following:

- Designation of legal reserve areas regulated by Federal Law Number nº 12.651, of 2012, for the protection of native vegetation;
- Zoning of enterprises at the stage of studying alternative locations for environmental licensing in accordance withConama Resolution number 1,of 1986, which establishes definitions, responsibilities, basic criteria and general directives for the use and implementation of the Environmental Impact Assessment;
- Creation of conservation units for the protection of water resources (springsand wells) and the development of their management plans. In cases where a recharge area is already partially or entirely occupied, the weighting of quality attributes of the recharge water can serve as a guide for evaluating existing risks;
- Studies for the delineation of buffer zones around conservation units (Zona de Amortecimento de Unidade de Conservação) in accordance with Federal Law Number 9.985, of 2000, which instituted the National System of Conservation Units (Sistema Nacional de Unidades de Conservação da Natureza);
- Delineation and characterization of zones of influence, transport, and contribution for the protection of the recharge of mineral water sources (extracted from wells or springs), as required by Directive DNPM number 231, of 1998, which regulates

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[2] The information originated from the method proposed in this study, although useful for the public policy instruments here cited, may require complementation by several other environmental data and analysis techniques for the efficient application of each instrument.

the protection of the sources of mineral waters;

- Delineation of areas of maximum protection, areas of restriction and control, and areas of protection of wells and other catchment systems in accordance with state laws for the protection of groundwater;
- Delineation of areas with the right of preemption (buying preference by the government) or expropriation and delineation of areas with differentiated use coefficients in the urban environment, in accordance with municipal directive plans and Federal Law Number 10.257, of 2001.

Furthermore, the methods we describe may also provide information on various scales that complement technical studies of other important environmental and water resources policy instrumentssuch as national and state water resource plans, watershed master plans, and ecological–economic zoning. The rapid field assessment method has promising use forthe following two instruments, among others:

- Technical reports for requests of concession of water usage rights for wells, springs and catchment systems in waterways of small watersheds;
- Reports of environmental surveillanceand reports of civil public inquiries,evaluating the possibility of increasing penalties and fees for environmental crimesbecause of the impact on water circulation.

As a summary of the application of the methods in the Paracatu watershed, in all stages, the areas at elevations above the springswere shownto be relevant landscape units for aquifer recharge. On a regional scale, although the quartzarenicneosolsunderlain by porous aquifers in the eastern portion of the ParacatuRiver watershed display the highest potential for infiltration and groundwater storage, the latosols in the plateaus in the southwest, west and northwest margins play an important role in the maintenance of the base flows of the rivers during the dry season.

The following is a summary of the contributions of this study:

a) Corroboration of relevant scientific hypothesis:

- Viability of the PLS modeling in relation to hydrologic attributes with spatial environmental variables, as proposed by Gebrehiwot*et al.* (2011).

- Identification of a pattern of recharge of and discharge from porous aquifers in the Paracatu River watershed that is compatible with the concept of the hydrogeologic piston proposed by Kirchner (2003).

b)Technical/scientific innovations:

- Proposal of five complementary tools for the evaluation of aquifer recharge onmultiple scales;

- Mapping of the areas at elevations above the springs viaKriging, resulting in a cartographic resource focusing on the areas of highpotential recharge;

- Partitioning of the flow into three components (quick flow, interflow and base flow) using digital recursive filters calibrated by a recombination of the empiric formula of Lynsley*et al.* (1975) and by the graphic criterion of Barnes (1939);

- Implementation of a logical restrictor to avoid the overestimation of flow components when using the digital recursive filters;

- Incorporation of the hypothesis of groundwater flows into the PLS modeling of the flow components, thereby allowing for the evaluation of the prediction uncertainty of the model in each nested section of the watershed;

- Use of data fromwells, available in the SIAGAS system, for spatial modeling of the relations between groundwater and surface water;
- Use of the PLS modeling to extrapolate the flow predictionthroughout the basin region;
- Use of data of flow components and the results of the PLS modeling to map the specific contribution ($m^3.s/km^2$) of each flow component and the total flow.

According to the French writer JeanGiradoux (1946), “Water is the one substance from which the earth can conceal nothing; it sucks out its innermost secrets and brings them to our very lips”.It is because of this intrinsic relationship between water and the geosystems that the proposed methodological advance of this paper intends to contribute so that, by understanding the secrets of the hydrogeology of each region, we may be able to manage our natural resources and continue to bring water to the lips of those who need it.

ACKNOWLEDGMENTS

We thank the Funding Agency for Studies and Projects (Financiadora de Estudos e Projetos, Finep)/ CT-HIDRO Sector Fund (Fundo Setorial CT-HIDRO), the National Council for Scientific and Technological Development (ConselhoNacional de DesenvolvimentoCientífico e Tecnológico, CNPq), the Brazilian Federal Agency for the Support and Evaluation of GraduateEducation (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Capes, grant number 5937-13-2) and the Minas Gerais Research Foundation (Fundação de Amparo à Pesquisa do Estado de Minas Gerais, Fapemig)for their support for this research. This study is related to the doctoral studies of the Graduate Program in Crustal Evolution and Natural Resources (Programa de Pós-GraduaçãoemEvolução Crustal e RecursosNaturais) of the Department of Geology (Departamento de Geologia) of the Minas School of the Federal University of OuroPreto (Escola de Minas da Universidade Federal de OuroPreto), which we also thank.

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Recebido em: 12/08/2016

Aprovado para publicação em: 21/12/2017