Cartographic methodology for assessing aquifer recharge potential: a case study of the Paracatu river basin, Brazil

Metodologia cartográfica para avaliação de favorabilidade de recarga de aquíferos: estudo de caso para a bacia do rio Paracatu, Brasil

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Abstract: This article presents a proposal for a methodology to demarcate and characterize areas that might be conducive to aquifer recharge. The guiding principle is the hydrogeological inference of areas uphill from springs. A kriging interpolation plane of the elevation of the springs is the basis for the delimitation of these areas. The characterization of recharge potential rests on lithostratigraphy, geomorphology, and soil studies, on climatological data, and on altimetric differential of springs and downstream watercourses. The maps suggest that the Western portion of the Paracatu basin would hold greater potential for recharge, followed by highland plateaus and table lands. These cartographic products may be useful to integrate the management of water resources and land use.

Keywords: Hydrogeology. Aquifer recharge. Environment. Geoprocessing. Water resources.

Resumo: Este artigo apresenta a proposta de uma metodologia para delimitação e caracterização das zonas favoráveis à recarga de aquíferos. Toma-se como estudo de caso a bacia hidrográfica de Paracatu (SF-7). Utiliza-se, como fundamento, a inferência hidrogeológica pelas áreas altimetricamente mais elevadas em relação às surgências. A delimitação dessas áreas teve como base a elaboração de um plano de interpolação por krigagem da altitude das surgências. A caracterização quanto à favorabilidade da recarga teve como subsídio estudos de litoestratigrafia, geomorfologia, pedologia, dados climatológicos e a diferença altimétrica em relação às surgências e aos cursos d'água de jusante. Os mapas obtidos apontam que a porção oeste da bacia do Paracatu apresentaria maior potencial de recarga, seguida pelos planaltos e superfícies tabulares mais elevados. Esses produtos cartográficos apresentam-se úteis para integrar a gestão dos recursos hídricos com a gestão da ocupação territorial.

Palavras-chave: Hidrogeologia. Recarga de aquíferos. Meio ambiente. Geoprocessamento. Recursos hídricos.

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INTRODUCTION

Recovery and maintenance of the hydrological cycle, in quantitative and qualitative terms, depend on proper planning regarding environmental impact in terms of soil and biota. Maintenance of the vegetation cover and land use management in the dominant aquifer recharge areas are essential for preserving water resources, given that this would make percolation of water viable, thereby ensuring a more stable flow to surface bodies of water, especially in the dry season.

Therefore, recognition of the hydrogeological process becomes an effective means for integrating management of land use and water resources. In particular, the analysis of the relationship between spatial differentiation of environmental features of the basin, recharge processes, and aquifer discharge would provide useful information for planning good practices for agricultural projects, engineering construction, and other land uses. An understanding of these processes is also essential to achieve integrated management of surface water and groundwater resources.

Among the most widely used techniques for analyzing aquifer recharge are field methods (with the use of piezometers, lysimeters, and tracers, among others) and the ones using indirect inference (such as water balance and the evaluation of hydrographs). The use of field methods for large basins, in addition to involving elevated costs insofar as the necessary sampling grid is concerned, generates additional uncertainty by virtue of the spatial heterogeneity of hydrogeological processes. On the other hand, indirect methods, despite their usefulness for evaluating recharge in hydrographic basins, also present drawbacks in that they do not differentiate among environmental features (soil, geomorphology, and lithostratigraphy) within and among basins.

As a stage prior to the use of direct and indirect methods for estimating recharge, Scanlon *et al*. (2002, p.19 and 33) suggested that a conceptual model for recharge should be given regarding the physiographic features of the hydrogeological basins. In addition to providing a preliminary understanding of ongoing hydrogeological processes, this modeling would also help to select and plan subsequent, more in-depth studies that rely on indirect and/or direct inference. In developing countries which still have few systematized databases and limited financial resources for field surveys, conceptual modeling of this type may often be the only viable methodology for gaining a baseline understanding of hydrogeological processes in a region.

For this conceptual modeling, Scanlon *et al*. (2002, p. 19) endorsed the classification of the hydrogeomorphic units as proposed by Tóth (1963) and implemented in various applied studies, such as that of Salama *et al*. (1994). An analogous approach, using hydrologic landscape units, was proposed by Winter (2001) and implemented by Wolock *et al.* (2004). Tague & Grant (2004) described several patterns of aquifer recharge and discharge related to geological and geomorphological features.

Lanni *et al.* (2011) emphasized the need for physiographic modeling of rainwater infiltration to include the evaluation of subsurface hydraulic connectivity of a cross-scale type (slope/basin), by considering the fluctuation of the phreatic level, pre-rain soil humidity and hydraulic discharge onto springs and watercourses. Gharari *et al.* (2011) and Nobre *et al.* (2011) explored this concept in relation to the geomorphometric criteria of height to the downstream drainage, thus obtaining consistent hydrological results.

During the course of preliminary conceptual modeling, an essential issue is the demarcation of areas showing greater potential for recharge. One should not overlook the fact that, for unconfined aquifers, the entire surface land shows, to a greater or lesser extent, potential for infiltration and percolation. However, in the perennial river basins, areas that are topographically higher when compared to the springs have distinct hydrogeological functions from those downstream. Crave & Gascuel-Odoux (1997), when reviewing integrated models of surface/groundwater flow and field validations, demonstrated that areas that are altimetrically higher in relation to the springs have greater infiltration and less runoff. As a result of the movement of groundwater/subsurface water driven by hydraulic/gravitational potential, these higher areas present less surface humidity in the soil before rainfall events and have greater depth of the saturated zone level. In this way, mapping activities focused on these areas become a management tool, towards the adoption of conservationist actions by various land and water users, government planners, and basin committees, among other interested players.

The purpose of this article is to propose a methodology which reveals, cartographically, the most favorable areas for aquifer recharge. Thus, the specific objectives of this article are: to establish an adequate method of study in order to treat hilltops as one way of assessing the potential of the occurrence of aquifer recharge under conditions of effluent drainage; to evaluate the case of the Paracatu Valley basin SF-7 as an applied study; to establish the practical usefulness of this method as a way of dealing with the question of recharge, by inquiring in qualitative terms into broad areas.

The practical results of this methodology have immediate application in the comprehensive management of water resources, given that management of soil and water conservation acquires greater relevance regarding the growing significance of their role in preserving available water, both for human activities as well as the preservation of environmental processes.

LOCATION OF THE STUDY AREA

The Paracatu river hydrographic basin is located almost entirely in the northwestern region of the State of Minas Gerais (Brazil), with small areas extending into the State of Goiás and the Federal District (maps in Figures 1 and 2). The basin has a surface area of 45,154 km^2, being the largest basin among the direct tributaries of the San Francisco river.

Since the year 1970, the progressive establishment of extensive irrigation districts has been observed in this basin (Rodriguez, 2004). It is characterized by agriculture using the latest technology models, including the frequent use of center irrigation pivots. During periods of severe drought, it is not uncommon the occurrence of local conflicts among farmers due to scarce water resources (Pruski *et al*., 2007).

CLIMATIC AND HYDROGEOLOGICAL CHARACTERIZATION

Drawing on data taken from rainfall and climatological seasons presented by Brasil (1996) and Nunes & Nascimento (2004), it is possible to infer a strong spatial correlation among climatic characteristics in this region. This correlation is consistent with aspects of climate genesis, especially by virtue of the fact that rainfall is controlled by air currents disturbed by climatic systems from the west, originated by lines of tropical instability (Brasil, 1996). These lines of instability are formed by barometric depressions induced by high-pressure ridges (Gamache & Houze Junior, 1982; Dias, 1987), usually over the States of Mato Grosso and Goiás and displaced by gusts of wind to the west of Minas Gerais. Such data leads to prevailing winds flowing to E and NE direction across the basin (Brasil, 1996).

By virtue of the fact that the rainfall monitoring stations are better distributed than weather stations, the spatial variation of climate features can be observed comprehensively by the rainfall map (Figure 3). In this way, Vasconcelos *et al.* (2012), when analyzing the climatological data provided by Brasil (1996), detected that, starting with the limits of the headwaters in the northeast, west, and southwest and following along in the direction of the sub-basins towards the east and the Paracatu river mouth in the northeast, the following trends could be observed:

- annual average temperature increased by just 2 °C (from 22 °C to 24 °C), following the topographic level and without significant variations in latitude;
- annual average relative air humidity increased from 69% to 79.4%;
- annual average exposure to the sun is increasing, with 2,106.8 hours in the city of Paracatu and 2,596.1 hours in the city of João Pinheiro;

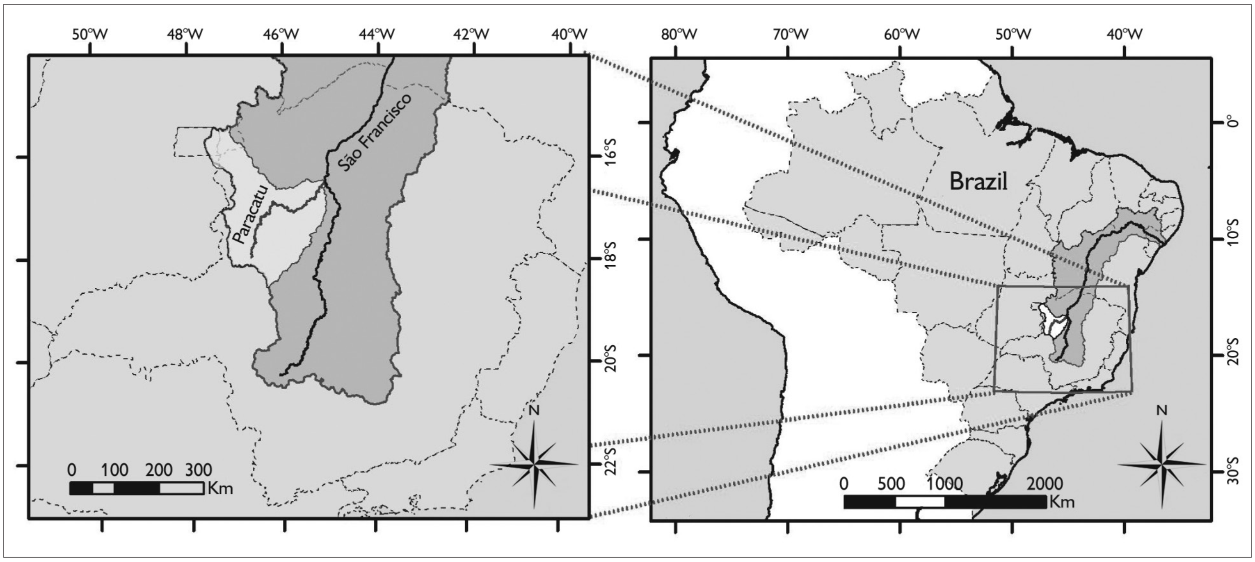

Figure 1. Location map of the Paracatu river basin.

- cloudiness is decreasing, with an average of 5.7 tenths of cloudless sky in Paracatu and 5.2 tenths in João Pinheiro and Bonfinópolis de Minas;
- potential evapotranspiration rates are increasing, from 1,000 mm to 1,350 mm;
- real evapotranspiration rates are increasing, with 823.9 mm in Cabeceira Grande and 1,036.2 mm in Cachoeira Paredão;
- water surplus decreased (in the wet season), with 738.3 mm in Guarda-Mor and 143.5 mm in Porto Alegre (district next to the outfall of the basin);
- water deficit is increasing (in the dry season), with 132.1 mm in Guarda-Mor and with 498.5 mm in Porto Alegre.

Elevation, slope, soil, geomorphology and aquifer typology maps are shown in Figures 4, 5, 6, 7, and 8. Below are discussed the primary aspects of these environmental features and their relationship with hydrogeological processes.

Using the graph method of Barnes (1939), Fundação Centro Tecnológico de Minas Gerais (CETEC, 1981) estimated that there was a contribution by aquifers of between 32% and 48% at different points in the river Paracatu basin for maintaining the flow of watercourses. This contribution increases as the watercourses have greater recharge areas of Cretaceous sandstone and Terciary-Quaternary sedimentary cover – an observation that supports the choice of these areas as the more favorable to recharge. On the other hand, these calculations consider that the infiltration and contribution arising from fractured and karst formations of the Bambuí aquifer would be much lower, or practically non-existent, when compared to the granular aquifers cited above. Ramos & Paixão (2004) also stressed the importance of porous sediment aquifers in the perpetuation of the rivers in the São Francisco basin.

The Cretaceous geological units of the Areado and Urucuia Formations are characterized by unconfined aquifers which supply significant amount of water through hillside springs (CETEC, 1981, p. 102). They are formed by thick sandstone (up to 140 meters) and rest directly on an impermeable substratum of the Bambuí Group (Eo-Cambrian Period) (CETEC, 1981, p. 102-104). At the same time, underlying meso-scale fractures identified in the Bambuí Group may increase the complexity of these aquifers through a combination of fractured aquifers underneath the granular aquifers (Martins Junior *et al.*, 2006). The Mata da Corda Formation, up to 100 meters

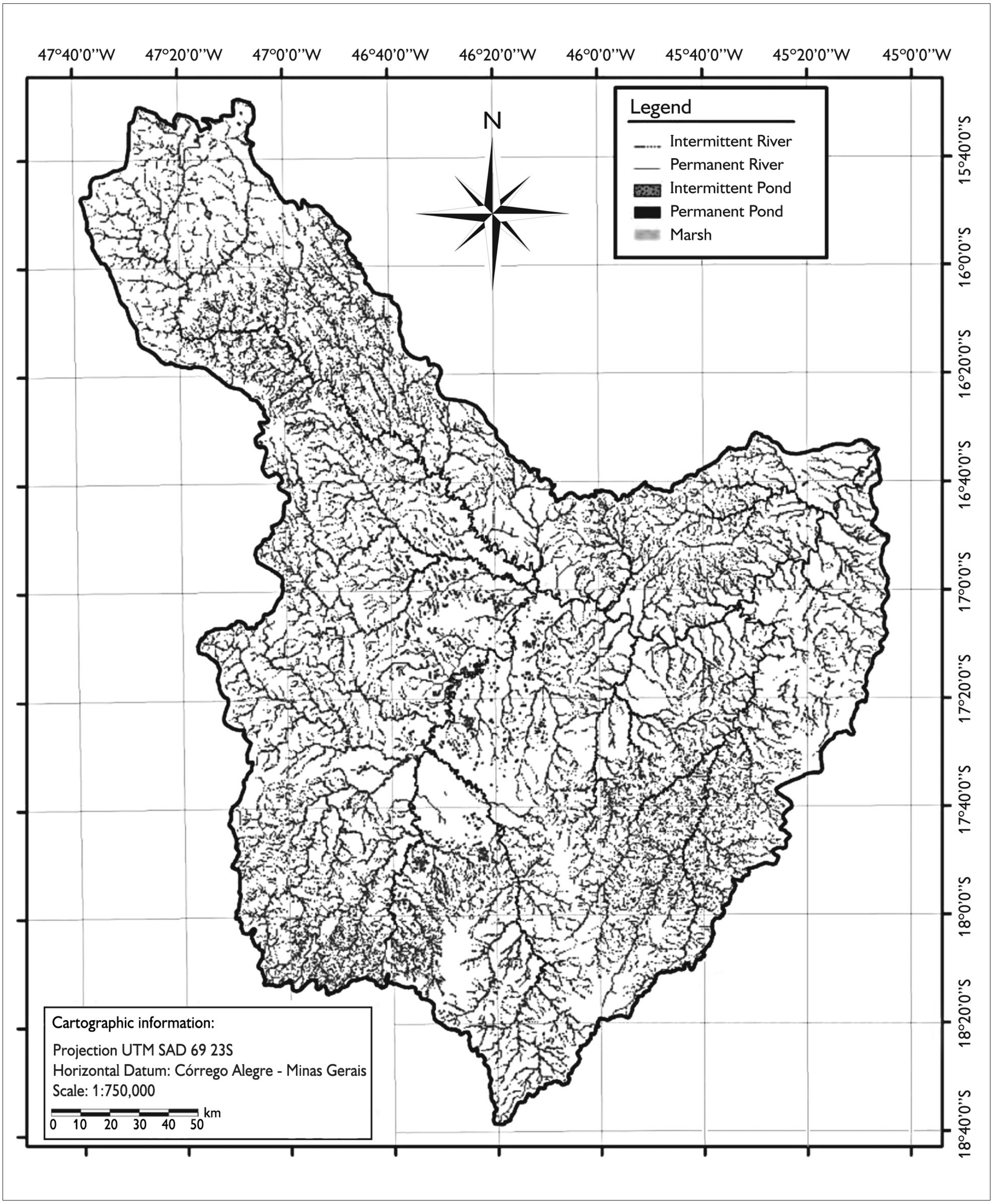

Figure 2. Hydrographic map of Paracatu river basin.

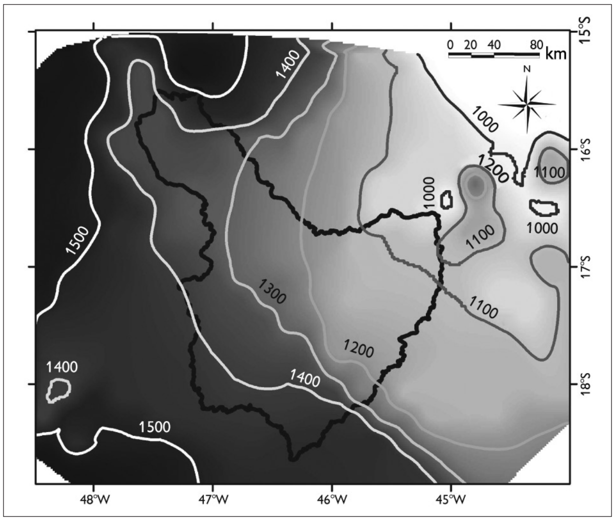

Figure 3. Map of isohyets of average annual rainfall in the Paracatu river basin (in mm).

thick, also forms a porous aquifer, overlying the Areado Formation (Brasil, 1996).

Morphologically, these porous aquifers of the older tertiary-quaternary cover lie under the São Francisco Residual Highland Plateaus, forming tabular surfaces arising to heights of about 900 meters above the sea level (Andrade, 2007). In the Paracatu river basin, there are tabular surfaces which show very little reworking, with practically a complete absence of drainage and characterized by a thick sediment layer possessing a high capacity for potential infiltration (CETEC, 1981, p. 105). These aquifers have an average thickness of ten meters, although in exceptional circumstances they may reach 30 meters (Brasil, 1996, p. 10), with thicknesses of up to 80 meters having been recorded (Mourão, 2001).

Primary areas of discharge are located at the bottom of the elevations, along the side or at the edge of the table lands (Figure 9), where the porous aquifer is in contact with the impermeable substrate. The surface of the phreatic aquifer follows a marked topography profile, with converging flow lines in the direction of the main drainage courses, indicating that they are effluent watercourses, i.e., they receive the contribution of groundwater (CETEC, 1981, p. 105).

More recent Tertiary-Quaternary sedimentary aquifers, located on the lowland plains of the Paracatu river basin (São Francisco Depression), recover pelites (mudstone and siltstone) of low permeability of the Bambuí Group; oozing is frequently observed in the contact area between these two lithologies (CETEC, 1981, p. 104; Mourão, 2001). By the predominant geomorphology of leveling surfaces over this aquifer system (Andrade, 2007), can be assumed the existence of local and regional baseline flows, when a hydraulic connection is verified between these aquifers and rivers – in this way, these aquifers works as regulators of watercourse flow (CETEC, 1981, p. 105). Their potential for water storage is lower than in the other porous aquifers of the basin, by virtue of their reduced thickness – on average, five meters (Brasil, 1996, p. 10, 40 and 44).

The fissured lithosomes correspond mainly to the Bambuí and Canastra Groups and the Paracatu, Vazante, and Paranoá Formations. They are characterized by the permeability of fissures and joints. The potential of these rocks for groundwater storage and circulation depends on the extension, continuity, and interconnection of the fracturing, as well as on the openings and void volume inside these structures. The possibility of direct surface water infiltration in these reservoir rocks is reduced, given that discontinuing fractures constitute relatively localized traits (Mourão, 2001). Recharge occurs due to descending vertical infiltration through the soil or deeper infiltration from the Cretaceous and Tertiary-Quaternary sedimentary layer, as well as from points where drainage connects fractures; in other words, through the watercourse channels controlled by fractures (Brasil, 1996, p. 44).

The karst aquifers in the Paracatu basin mainly correspond to geomorphological areas of steep ridges and v-slopes (Andrade, 2007). Since they are distributed by the Ridge Deformation Area of Unaí, which was affected by strong tectonic processes (thrust faulting, strike-slip faults, and folding structures), is assumed they have a high degree of fracturing. In addition, the presence of dolines, caverns,

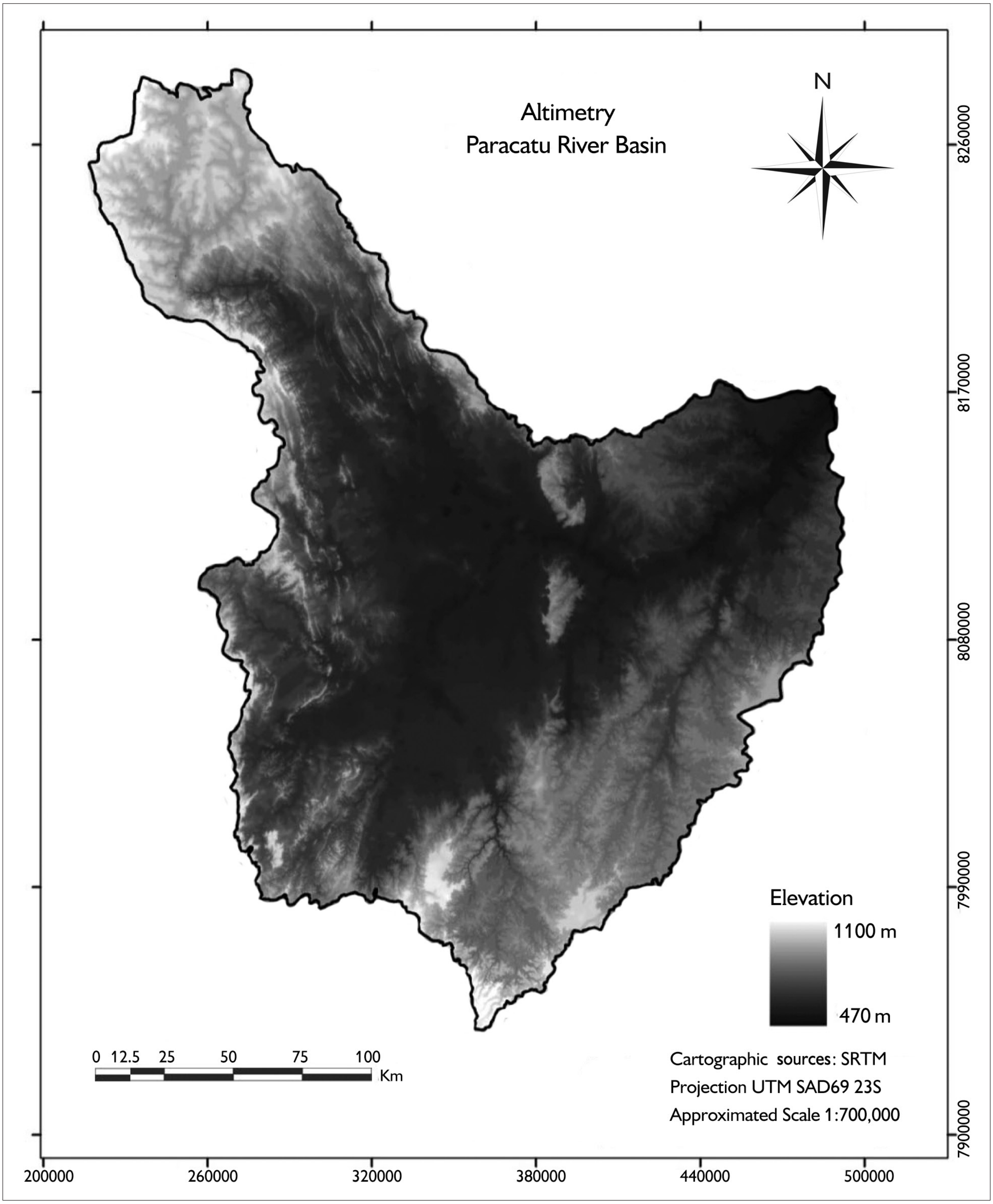

Figure 4. Elevation map of the Paracatu river basin.

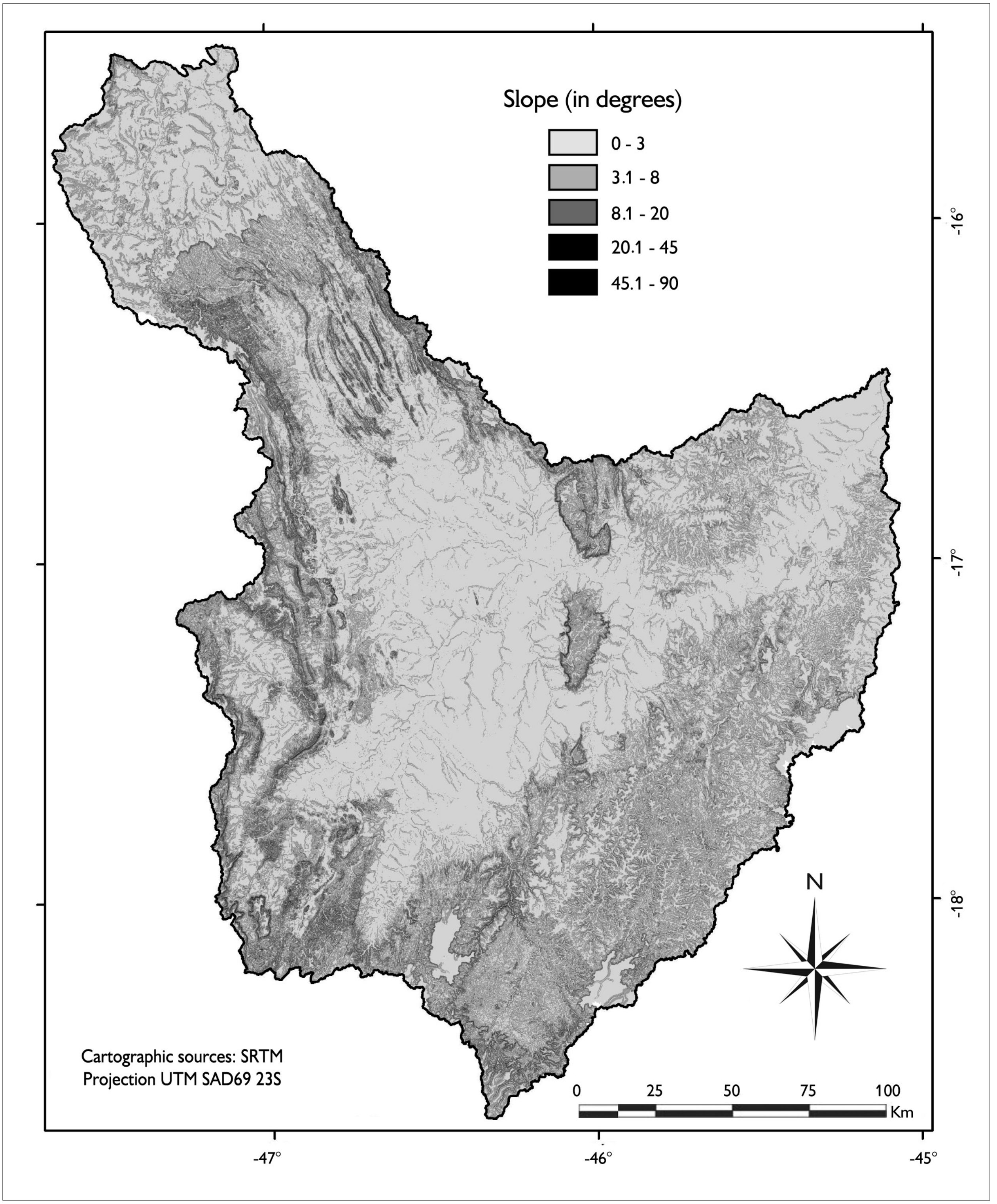

Figure 5. Map showing slope gradient in the Paracatu river basin.

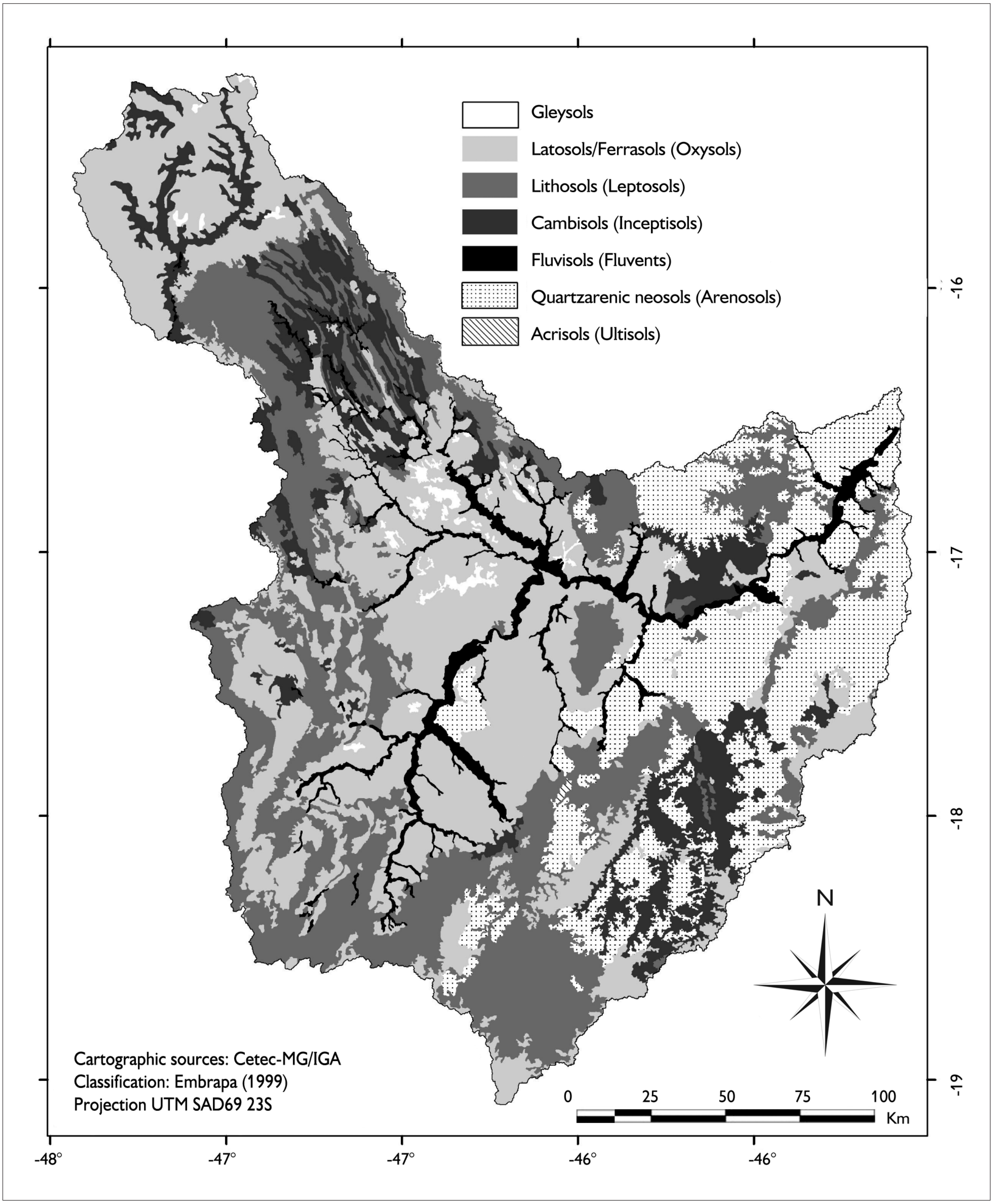

Figure 6. Map showing soil distribution in the Paracatu river basin.

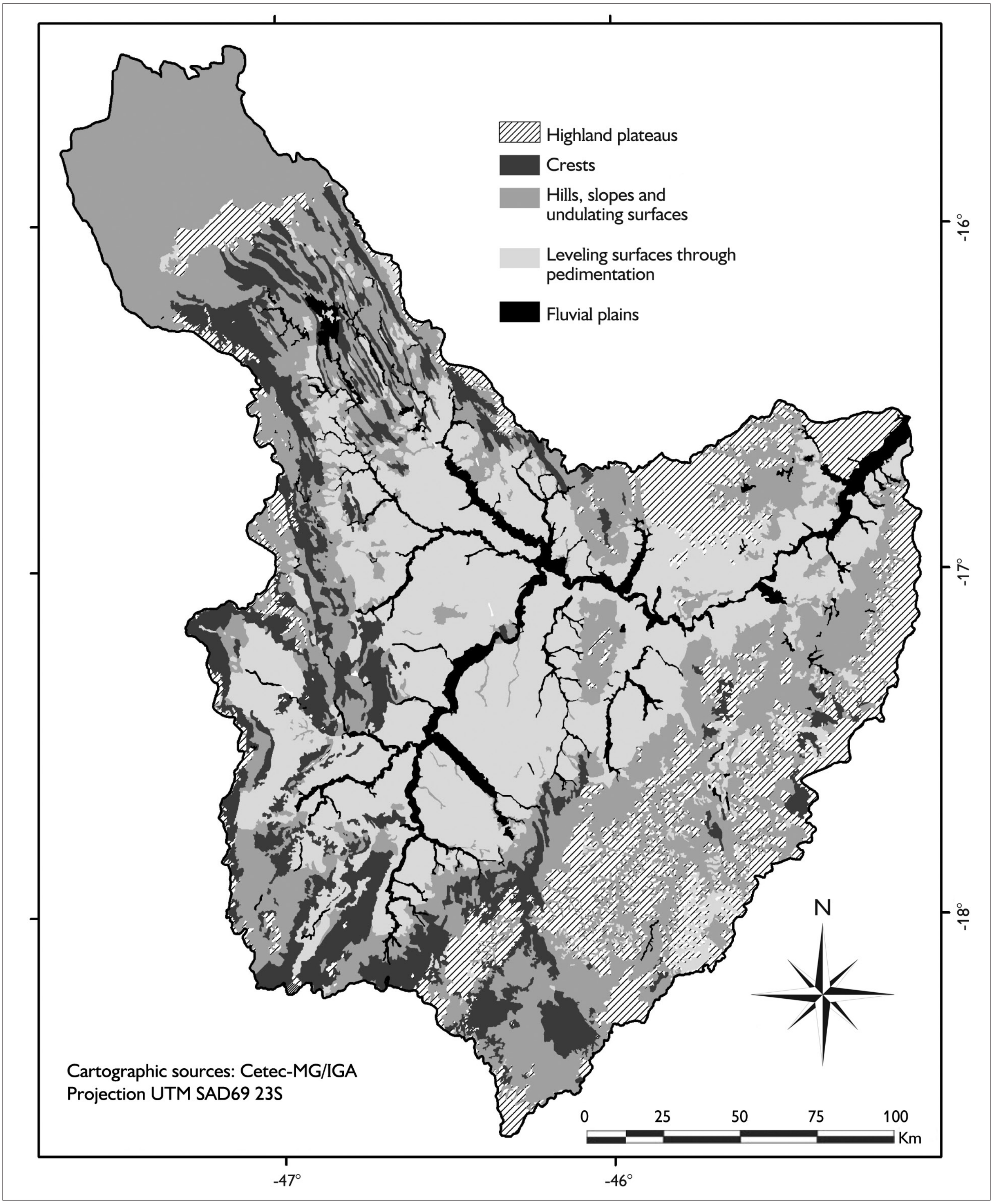

Figure 7. Geomorphological map of the Paracatu river basin.

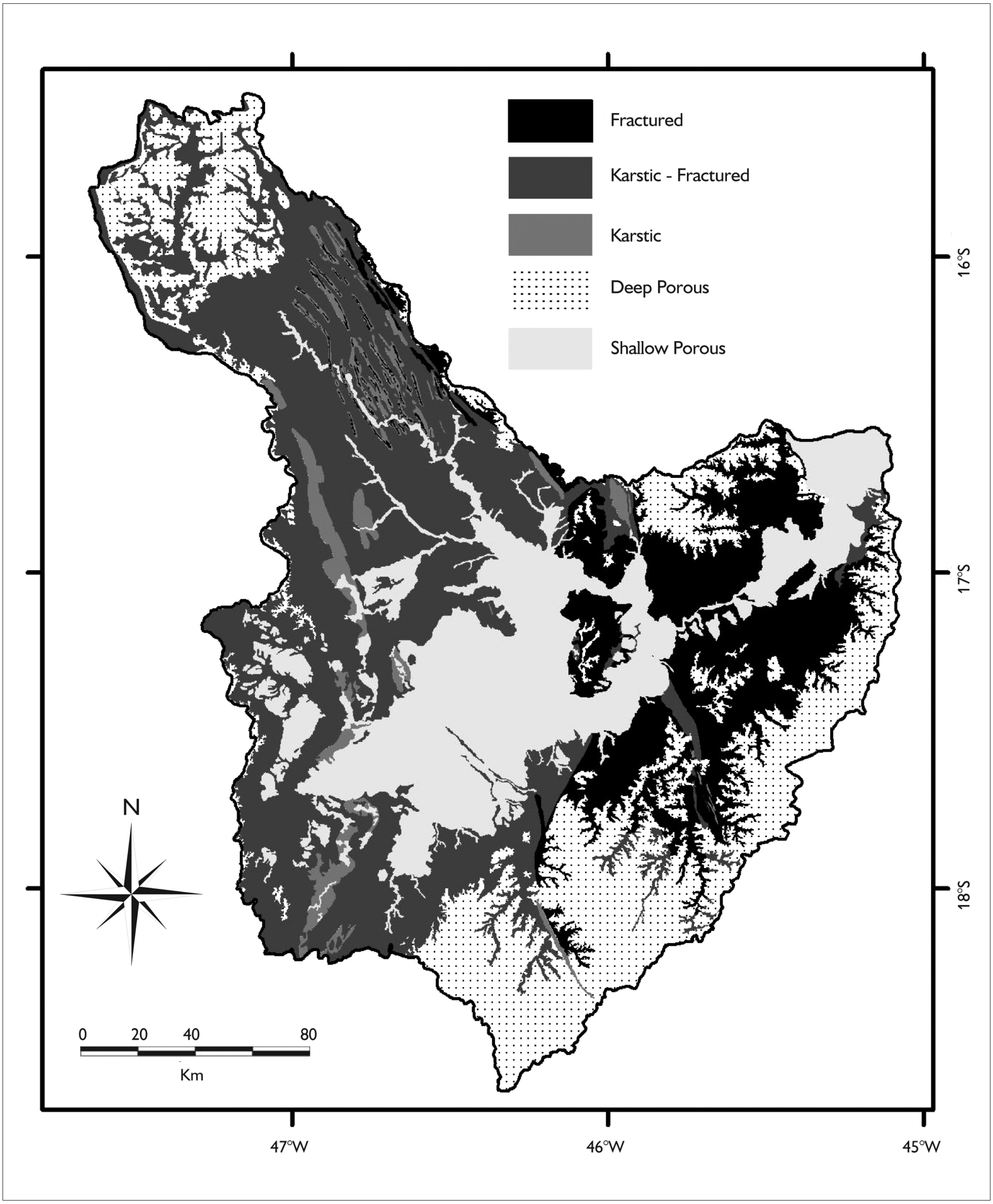

Figure 8. Map of aquifer typology of the Paracatu river basin.

Figure 9. Discharge areas of highland plateaus in the Paracatu river basin. Settlement Project Quinze de Novembro (Ferreira Neto, 2005, p. 14).

and sinkholes indicate endokarstic development. Given this, it can be assumed that such aquifers would allow for significant hydrogeological flow. However, by virtue of the expressivity of pipe flow inherent to evolved karstic forms, such aquifers exhibit a more pronounced recession coefficient, draining more rapidly and thus providing less water to river sources during the peak of the dry season.

Aquifers of quaternary alluvial deposits are found in a generalized way alongside the drainage network, on the floodplains and terraces. They constitute active areas of water exchange, receiving recharge from the rivers during periods of high water and replenishment the rivers flow during dry periods (Mourão, 2001).

In areas of transition between the residual highland plateaus and the São Francisco depression, in the Paracatu basin, reworked geomorphological features of hills and hillsides predominate, where such features assume a hydrogeological role as areas of transience (or transport areas). Nevertheless, it is worth noting that the entire surface area with weathered profile contributes in part to the phreatic aquifer recharge.

MATERIALS AND METHODS

The proposed methodology encompasses three mainstages. In the first stage, altimetrically higher areas in relation to springs are demarcated. Thereafter, those areas are characterized in relation to the physiographic features which would tend to favor aquifer recharge processes. Finally, consideration is given to physiographic parameters, in order to prepare a qualitative index map showing the general potential of such areas for recharge.

The altimetric information of springs was the cartographic basis to demarcate the transition line between the areas where aquifer recharge and discharge processes predominate. The points locating the springs were positioned based on the cartographic data base from the Instituto Brasileiro de Geografia e Estatística (IBGE, 1971), on a 1:100,000 scale, with a total of 5,413 springpoints (8.34 per km^2). The altitude of each point was obtained from a Hydrologically Consistent Elevation Model (HCEM). The HCEM was prepared based on topography treatment drawn from the Shuttle Radar Topography Mission (SRTM) (Jarvis *et al.*, 2008) and hydrography mapping, on a scale of 1:100,000, from the IBGE (1971), which was then reworked using the Hydrotools extension for ArcGis 10 and Saga 2.0.8 software pre-processing algorithms.

The altimetry of each springs served as a basis for preparing a three-dimensional map based on geostatistical interpolation by regular Gaussian kriging, with two to five neighbors per quadrant (45°). The kriging method, as well as its parameters, was chosen and optimized interactively using the extension algorithm, Geostatistical Analyst, of the ArcGis 10.1 software. The kriged map was subtracted from the digital elevation model by map algebra, drawing the altimetrically higher areas in relation to springs as a product.

The general characteristics of the hydrogeological systems and the main recharge areas occurring in the São Francisco valley and in the northwestern Minas Gerais are described in the Northwest Plan II (CETEC, 1981) and in Ramos & Paixão (2004). The most regionalized study of recharge areas in the Paracatu basin was carried out by Brasil (1996) and Martins Junior (2009). These studies are important because they indicate which geoenvironmental units (regarding lithostratigraphy, geomorphology, soils, and rainfall) would be most significant for aquifer recharge in the Paracatu basin. Based on the studies described above, the following typology was adopted which would characterize those features which tend to favor aquifer recharge and which are located in altimetrically higher areas in relation to the springs of this basin:

- Lithostratigraphy: porous aquifer.
- Geomorphology: tabular leveled areas formed by pedimentation processes.
- Soils: quartzarenic neosol.

With the overlapping results from the lithostratigraphy, geomorphology and soil cartographic bases, it is possible to map all the forms of combination among the different features that would favor recharge. In this way, sites where there is a concomitant favorability among the three cartographic attributes would be areas with greatest potential for aquifer recharge. Following, the sites where the potential of two cartographic attributes coincides would display a greater potential for recharge than areas with potential based on just one of the attributes. Finally, areas located altimetrically higher in relation to the springs which do not exhibit any of the favorable features mentioned above would have lower potential for aquifer recharge.

Using lithostratigraphy, geomorphology and soil maps of the region prepared by Martins Junior (2006) and based on the Planoroeste II (CETEC, 1981), it has become possible to map the attributes of recharge areas on a detailed scale of 1:250,000. These cartographic products were compared against data from the weather and rainfall stations present in Brasil (1996) and Nunes & Nascimento (2004). Rainfall cartography was obtained using the sum of rainfall data in the dry and wet semesters compiled by Nunes & Nascimento (2004), interpolated by the natural neighbor method.

Based on the available cartographic data, was obtained a weighted index of favorability for recharge of the aquifers. The method chosen was that of knowledge-based modeling, relying on access to specialists and consolidated bibliography. In this way, the considerations combined qualitative and quantitative approaches. The following factors were used for analysis:

- Lithostratigraphy and soil mapping (Martins Junior, 2006);
- Rainfall (Nunes & Nascimento, 2004);
- Slope gradient from the altimetry obtained by radar from the SRTM project (Jarvis *et al*., 2008);
- Height in relation to the level of springs, and height to downstream watercourses, drawing on altimetry from the SRTM and hydrography from IBGE (1971).

Saga 2.0.8 software was used to calculate the difference of topographic height of the springs in relation to the downstream watercourse by applying the algorithm described in Rennó *et al*. (2008).

Soil types were ranked according their drainage properties, following the typology proposed by the Sociedade Brasileira de Ciência do Solo (Santos *et al*., 2005) and based on primary data from soil surveys in the region (CETEC, 1981). In this way, the classification of soil drainage in the Paracatu basin, from the most easily drained to the less drainable, was: quartzarenic neosols (arenosols), latosols/ferrasols (oxysols), cambisols (inceptisols), acrisols (ultisols - textural horizon B soil), lithosols (leptosols), fluvisols (fluvents), and gleysols. Lithostratigraphy classes, in turn, were grouped into deep sedimentary aquifers, shallow sedimentary aquifers, karstic, karstic-fractured, and fractured aquifers, thus arranged from the most relevant to the least relevant, in relation to their theoretical capacity for recharge of ground waterflow.

For soil types, the benchmark reference was the Hydrology of Soil Types System (HOST) (Boorman *et al*., 1995), adopted by the United Kingdom, which brought together quantitative estimates criteria for soil drainage, permanent or seasonal depth of phreatic aquifers, and the presence of impermeable or semi-permeable beds. For use in Brazil, we undertook a correspondence between the *HOST* typology and the Brazilian Soil Classification System (EMBRAPA, 1999), taking into account the typical infiltration rates for these types of soil (Rocha & Daltrozo, 2008; Mendonça *et al*., 2009; Rawls *et al*., 1982; Bouwer, 1999) and estimated runoff coefficients rates (Carvalho, 2009). These latter coefficients were also used as benchmark for determining the influence of slope gradient on aquifer recharge.

As to the influence of the potential of aquifer recharge (lithostratigraphic types), the regressions relating lithostratigraphy to the base flow carried by Bloomfield *et al.* (2009) were used as main benchmark, supplemented by estimated outflows of wells in various aquifer systems (Rebouças, 2008, p. 23-26; Mente, 2008, p. 38-47).

The approach involving hydrological landscape units was used to handle topographic height in relation to springs and watercourses, based on altimetric criteria used by Rennó *et al*. (2008) and Gharari *et al*. (2011) and classified in terms of recharge, transience and discharge (Souza & Fernandes, 2000). The weighted variables relied, as a basis, on extensive studies conducted on slope transects, in reference to patterns of hydraulic conductivity (Lewis *et al*., 2011), pre-rain soil humidity (Crave & Gascuel-Odoux, 1997; Famiglietti *et al*., 1998; Brocca *et al*., 2007), and depth of phreatic level (Nobre *et al*., 2011).

Weighted values are shown in Table 1. For rainfall, weight was given directly in terms of estimated rainfall (in meters/year) for each square in the raster map.

Criteria for calculating partial totals is given by multiplying the indices for each feature. The multi-feature modeling approach by multiplication followed the recommendations of Clarke (2009), Tucci (2009), and Naghettini & Pinto (2007) for hydrogeological and hydrological modeling. It is based on the theoretical modeling supposition that there is a continuous flow of water (from precipitation to discharge), which will be boosted or restricted quantitatively and qualitatively by environmental characteristics, including iterative effects (USEPA, 1986).

RESULTS AND DISCUSSION

The results of demarcating and characterizing areas conducive to aquifer recharge are presented in Figure 10. This figure also shows the parameters optimized by kriging interpolation, together with the interpolation maps and their standard deviation of prediction, as well as an ancillary map which extends the characterization for the whole area of the basin.

The characterization of recharge potential in Figure 10 shows just the potential of soil, rock, and geomorphology features. For a more precise notion of effective aquifer recharge, it would be necessary to compare that map to the spatial distribution of climatic parameters of the hydrographic basin. In this respect, despite soils, geomorphological and geological features indicating that the most favorable areas would be found to the east of the basin, the climatic parameters are more conducive to aquifer recharge in the western region of the basin.

The maps of hydrological landscape units in reference to altimetric difference related to springs and watercourses are shown in Figures 11 and 12. The classification of altimetric difference in relation to watercourses proved to focus more on the microrelief of the basin, while altimetric difference in relation to springs proved to focus more on the macro relief of the basin. The pairing of weighted values of these two topographic criteria is shown in Figure 13, transmitting paired information from both types of approach.

Table 1. Weighting of features used to evaluate soil drainage and aquifer recharge potential.

Soil (drainage)				
Quartzarenic neosols	Latosols	Cambisol, Textural or Plinthic Horizon B soil	Lithosols	Gleysols and fluvisols
6	2.5	1	0.6	0.3
Lithostratigraphy (aquifer recharge)				
Deep porous aquifers	Shallow porous aquifers	Karst	Karstic/fissured	Fissured
3	2.2	1.4	1.1	0.7
Slope (infiltration)				
Flat 0-3%	Gentle-Undulating 3-8%	Undulating 8-20%	Steep-Undulating 20-45%	Steep > 45%
2.5	1.5	1	0.5	0.25
Rainfall				
Meters of rainfall/year				
Topographic height to the level of the 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

Analysis of combined recharge potential, considered in terms of altimetric difference, soil, geology, relief, and rainfall, can be evaluated by the recharge potential index, as seen in Figure 14. The edges of the eastern half of the basin still show an even greater potential for recharge, while also highlighting the potential of the tablelands in the south of the basin and the highland plateaus in the northwest.

The maps shown in Figures 10 and 14 demonstrate the diversity of recharge potential throughout the entire basin, making it possible to select areas that would be more conducive for recharge within each sub-region, including sites located in areas in which the greatest conflicts over water use occur, and in accordance with the demands for water resource management. From the perspective of territorial planning, ventures aimed at a major use of groundwater could be installed in areas with greater recharge potential, thus ensuring the sustainability of water reserves. In the case of the Paracatu basin, areas of greatest recharge which are located over deep porous aquifers are also those which theoretically present the greatest capacity for storage. In areas which are more conducive to recharge, the effects of soil and water management may also be enhanced through such measures as dams for water reservoir or for infiltration of rainfall, direct (no till) and/or terraced planting, among others.

It should be pointed out that the work to identify and demarcate these areas was based on the reference studies, secondary data, cartographic analysis, and geoprocessing techniques. To achieve a more precise characterization of recharge areas, more detailed

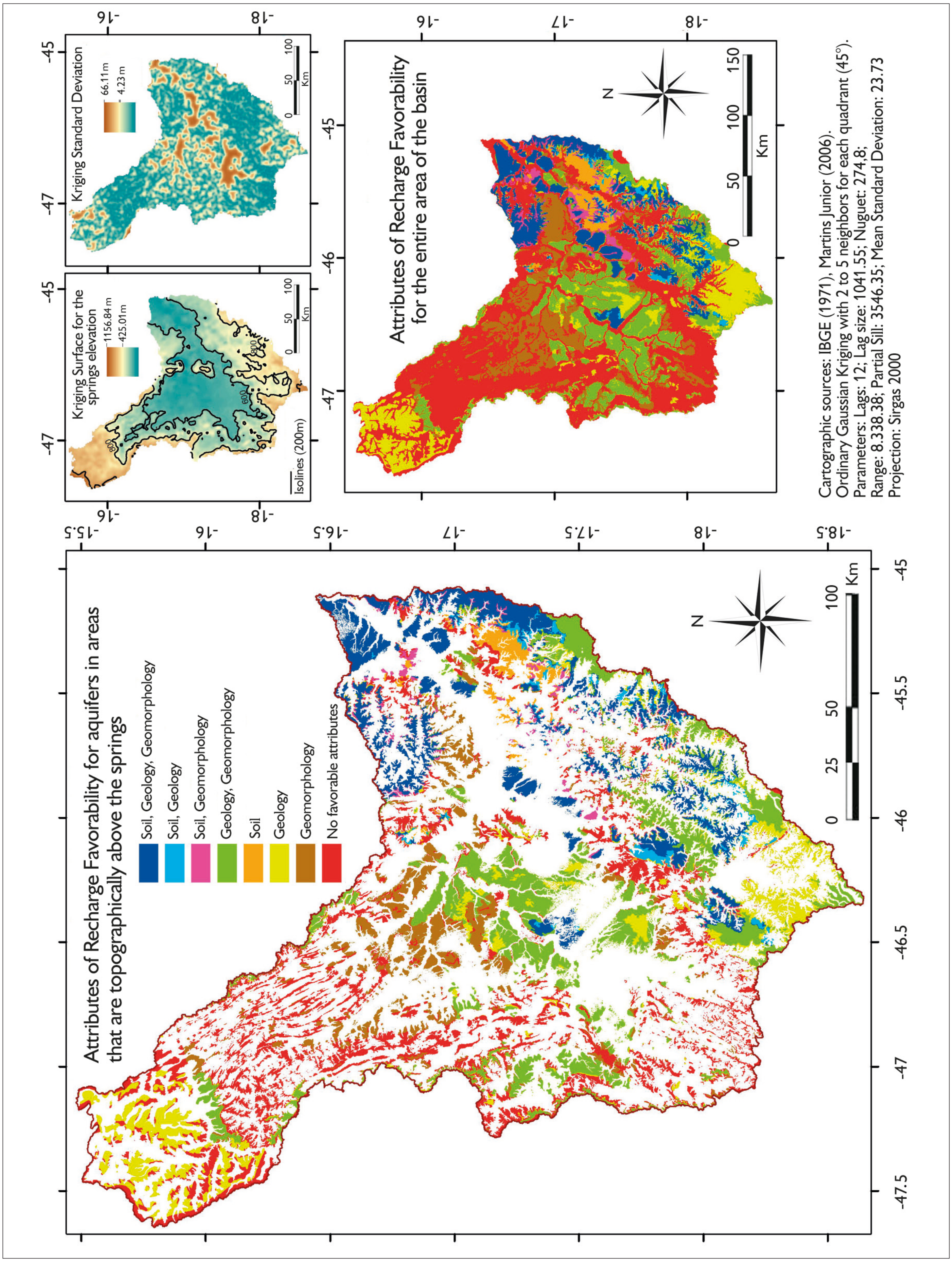

Figure 10. Map showing characterization of areas with recharge potential in the Paracatu river basin. The colors of classes of recharge potential are applied to the map of higher areas in relation to springs, as well as to the general map for the entire area of the basin.

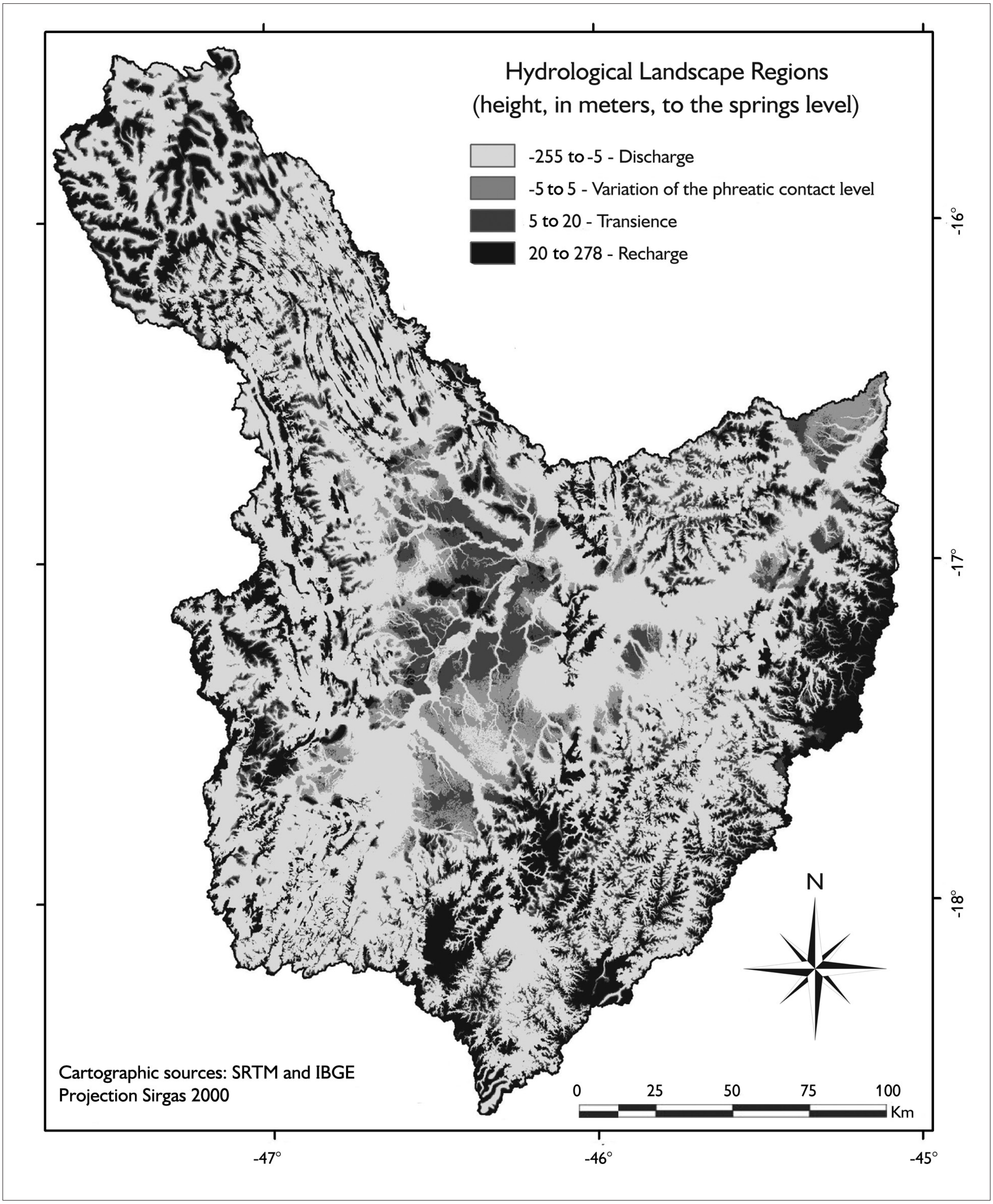

Figure 11. Map showing distribution of landscape hydrological units regarding altimetric difference in relation to the springs.

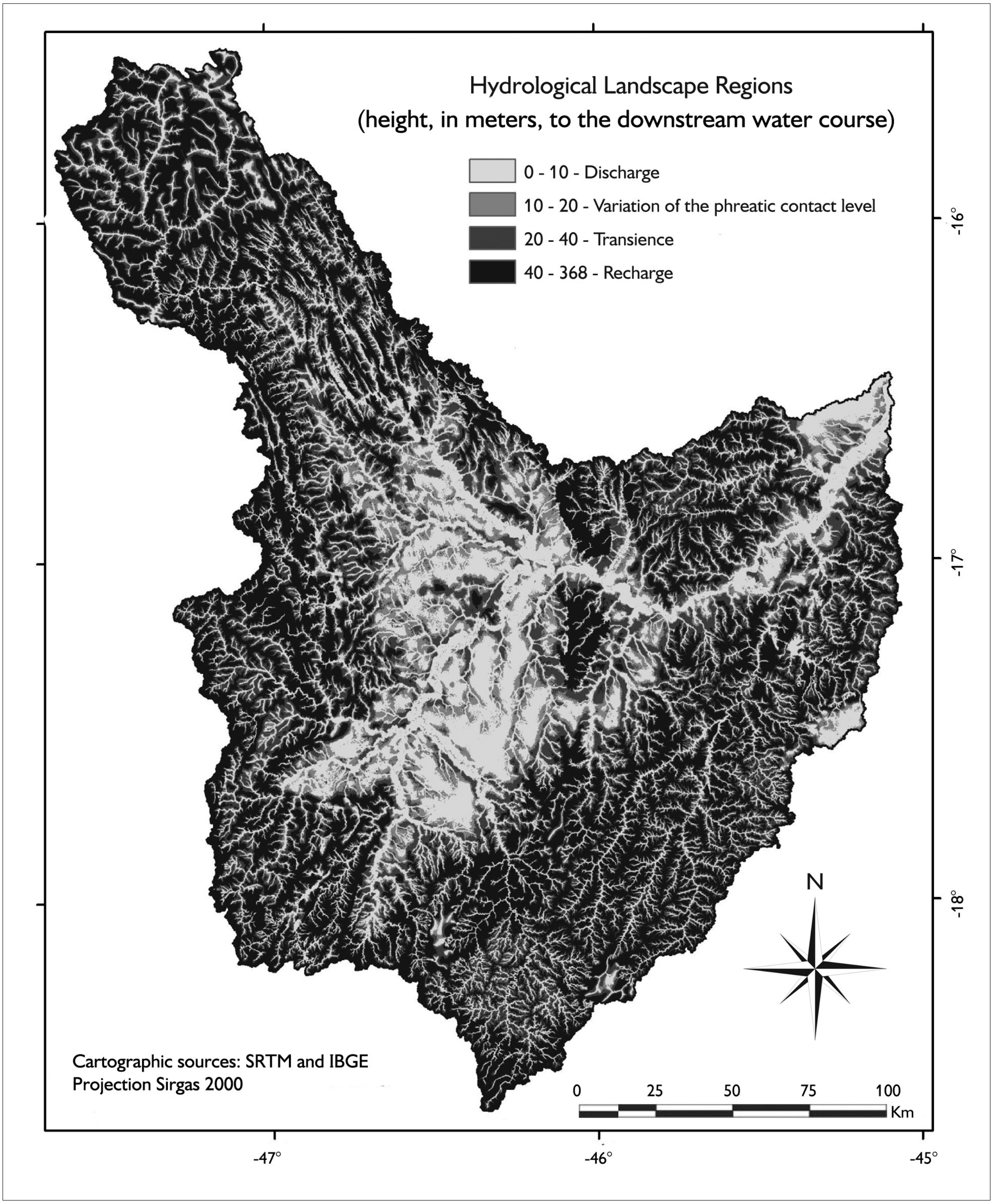

Figure 12. Map showing the distribution of landscape hydrological units regarding height to the downstream watercourses.

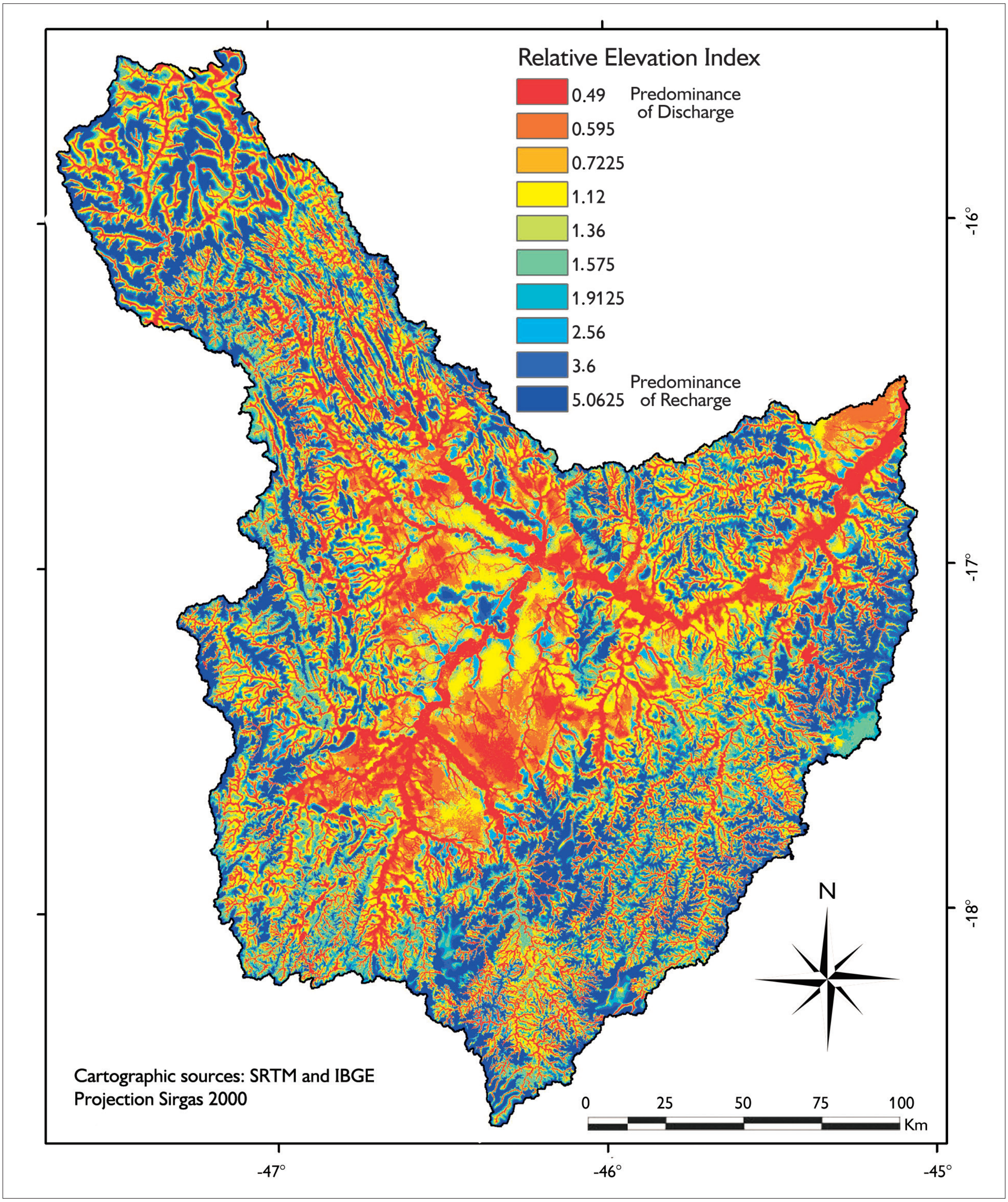

Figure 13. Mapping of index resulting from weighting landscape hydrological units showing altimetric difference in relation to the level of springs and downstream watercourses.

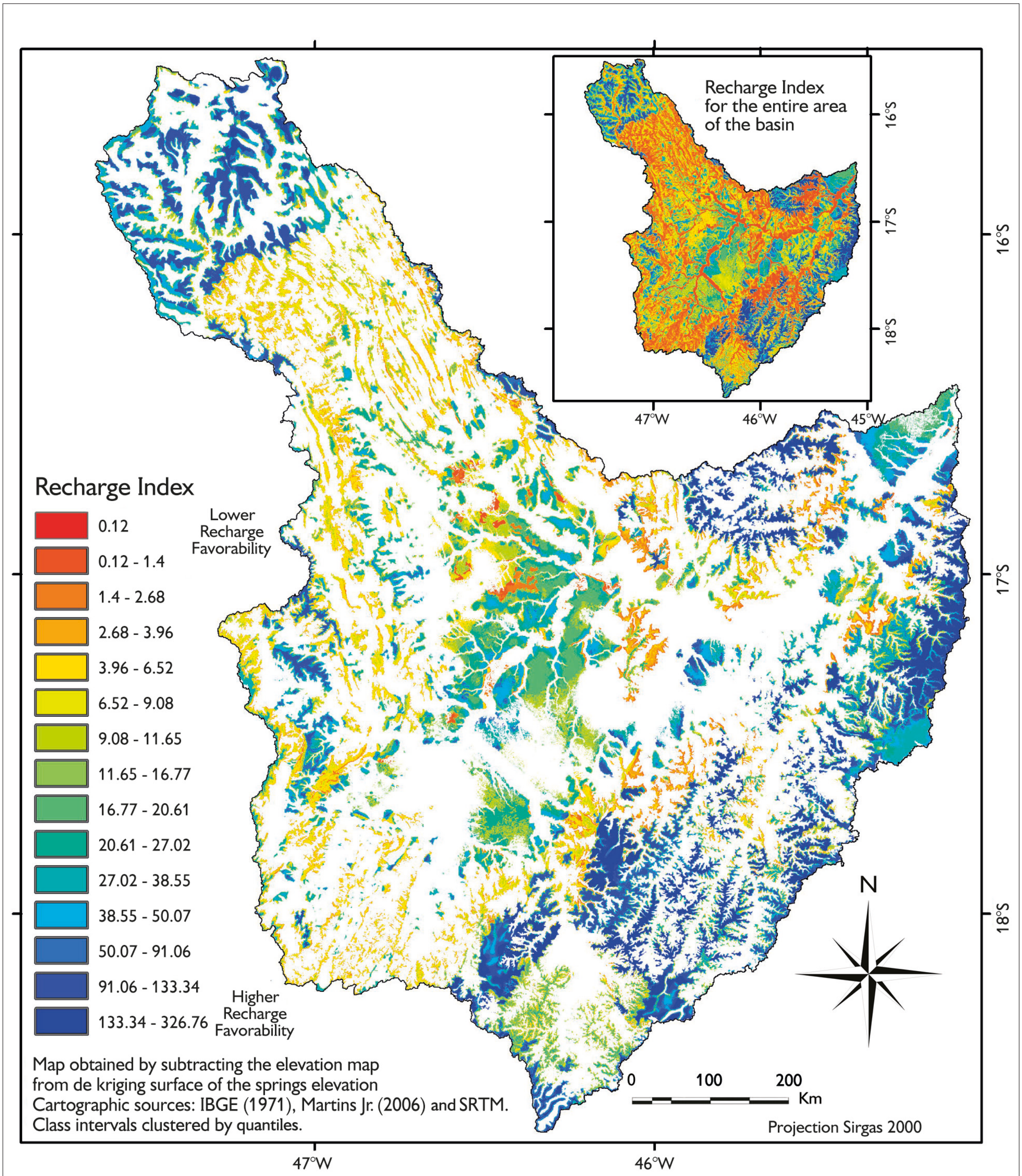

Figure 14. Map showing potential recharge capacity of aquifer systems in altimetrically higher areas in relation to the springs in the Paracatu river basin. The colors of the classes of recharge potential are applied to the map of higher areas in relation to the springs, as well as to the general map of the entire area of the basin.

hydrogeological studies would be necessary, using a greater abundance of primary data drawn from well drilling studies, tracers, and chemical analyses of surface water and groundwater (Arraes, 2008). Such data should be reviewed in conjunction with more detailed studies on structural geology, lines of piezometric potential, identification of hydrogeochemical facies of surface and underground water, as well as hydroclimatological balances. These studies would be able to identify and quantify more precisely the likely groundwater flow.

CONCLUSIONS

The methodology presented in this paper is capable of providing evidence for spatial variability of factors which would be conducive to aquifer recharge in the proposed case study. Demarcation of altimetrically higher areas in relation to springs using the kriging method, followed by the characterization of features suggestive of aquifer recharge potential, when also compared against climatological data, provided evidence that aquifer recharge should not be considered regardless from its spatial distribution in the hydrographic basin. By virtue of the extensive hydrography and altimetry coverage provided by the IBGE and altimetry results from the Shuttle Radar Topography Mission (SRTM) of the Brazilian territory, demarcation of altimetrically higher areas in relation to springs has been shown to offer easy reproducibility for other hydrographic basins, as an initial step towards identifying areas of greater recharge. It is important to stress the innovative aspect of this analysis, conjoining altimetry in relation to springs and watercourses, thus creating a unified topographic indicator which assess together discharge and recharge processes and incorporates information from both criteria of relative altimetric difference.

The characterization of features conducive to recharge uses basic thematic mapping that is usually available for various hydrographic basins, especially when such basins already have a master plan. Nevertheless, the features related to recharge potential, used as attributes in the maps, may be readapted in accordance with available cartography and the hydrogeological context of each basin. In this study case, for instance, the slope gradient, extractable from the topography, can be used as a substitute for geomorphological mapping. Such flexibility appears as one of the strong points for potential reproducibility of the methodology proposed in this paper.

The cartographic method proposed is also valid for application on various scales of analysis. This application just depends on the existence of planialtimetric and thematic maps on a scale compatible with the proposed study area, and whether they are intended to provide a regional or a detailed perspective.

The results obtained for the Paracatu river basin demonstrate that, while it should be emphasized that climatological features more favorable to recharge are located in the western area, the features which suggest greater recharge potential are more pronounced in the eastern portion of the basin – leaving the tablelands in the south of the basin and the highland plateaus in the northwest positions of intermediate prominence.

These cartographic products serve as relevant support for sustainable territorial management, encompassing water, environmental, and economic management in relation to the expansion of human activities which require the use of natural resources.

The results of this methodology are restricted to a qualitative evaluation of the recharge potential of aquifers, based on the characterization of areas that are altimetrically higher in relation to the springs, compared against the spatial distribution of geosystems attributes, rainfall and other correlated climatological data. For a quantitative evaluation of recharge, it is recommended, as a possible extension of the methodology presented here, to trace geostatistical relationships among the following cartographic bases:

- rainfall;
- recharge potential of altimetrically higher areas in relation to springs, as presented in this paper;
- specific base flow maps derived by separating the base flow component from hydrographs of gauging stations.

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REFERENCES

ANDRADE, L. M. G., 2007. **Uso optimal do território de bacia hidrográfica com fundamentos no conceito de Geociências Agrárias e Ambientais**: 1-203. Dissertação (Mestrado em Geologia Ambiental e Conservação de Recursos Naturais) – Universidade Federal de Ouro Preto, Ouro Preto. Available at: <http://www.slideshare.net/Projeto_SACD/uso-optimal-do-territrio-de-bacia-hidrogrfica-com-fundamentos>. Accessed on: 25 March 2013.

ARRAES, T. M., 2008. **Proposição de critérios e métodos para delimitação de bacias hidrogeológicas**: 1-125. Dissertação (Mestrado em Geologia) – Universidade de Brasília, Brasília. Available at: <http://repositorio.bce.unb.br/handle/10482/2679>. Accessed on: 31 March 2013.

BARNES, B. S., 1939. The structure of discharge recession curves. **Transactions of the American Geophysical Union** 20: 721-725.

BLOOMFIELD, J. P., D. J. ALLEN & K. J. GRIFFITH, 2009. Examining geological controls on Baseflow Index (BFI) using regression analysis: an illustration from the Thames Basin, UK. **Journal of Hydrology** 373(1-2): 164-176.

BOORMAN, D. B., J. M. HOLLIS & A. LILLY, 1995. **Hydrology of soil types**: a hydrologically-based classification of the soils of the United Kingdom: 1-137. Institute of Hydrology (Report n. 126), Oxfordshire.

BOUWER, H., 1999. Artificial recharge of groundwater: systems, design, and management. In: L. W. MAYS (Ed.): **Hydraulic design handbook**. McGraw-Hill, New York.

BRASIL, Governo Federal; MINAS GERAIS, Governo do Estado; DISTRITO FEDERAL, 1996. **Plano Diretor de Recursos Hídricos da Bacia do Rio Paracatu - PLANPAR**. Belo Horizonte. v. 1, T. 1. CD-ROM.

BROCCA, L., R. MORBIDELLI, F. MELONE & T. MORAMARCO, 2007. Soil moisture spatial variability in experimental areas of central Italy. **Journal of Hydrology** 333(2-4): 356-373.

CARVALHO, D. F., 2009. **Manejo e conservação do solo e da água**: 1-71. Universidade Federal Rural do Rio de Janeiro, Seropédica.

CLARKE, R. T., 2009. Hidrologia estatística. In: C. E. M. TUCCI (Org.): **Hidrologia**: ciência e aplicação: 1-944. Editora da Universidade Federal do Rio Grande do Sul, Porto Alegre.

CRAVE, A. & C. GASCUEL-ODOUX, 1997. The influence of topography on time and space distribution of soil surface water content. **Hydrological Processes** 11(2): 203-210.

DIAS, M. A. F. S., 1987. Sistemas de mesoescala e previsão de tempo a curto prazo. **Revista Brasileira de Meteorologia** 2: 133-150.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA), 1999. **Sistema Brasileiro de Classificação de Solos**: 1-412. Embrapa Solos, Brasília.

FAMIGLIETTI, J. S., J. W. RUDNICKI & M. RODELL, 1998. Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. **Journal of Hydrology** 210(1-4): 259-281.

FERREIRA NETO, J. A. (Coord.), 2005. **Diagnóstico socioeconômico e ambiental e Projeto Final de Assentamento do Projeto de Assentamento XV de Novembro**. Universidade Federal de Viçosa e Fundação Artur Bernardes, Viçosa. Available at: <http://www.slideshare.net/Projeto_SACD/pfa-pa-xv-novembro>. Accessed on: 25 March 2013.

FUNDAÇÃO CENTRO TECNOLÓGICO DE MINAS GERAIS (CETEC), 1981. **Segundo plano de desenvolvimento integrado do Noroeste Mineiro**: recursos naturais. CETEC, Belo Horizonte.

GAMACHE, J. F. & R. A. HOUZE JUNIOR, 1982. Mesoscale air motions associated with a tropical squall line. **Monthly Weather Review** 110(2): 118-135.

GHARARI, S., F. FENICIA, M. HRACHOWITZ & H. H. G. SAVENIJE, 2011. Land classification based on hydrological landscape units. **Hydrology and Earth System Sciences Discussions** 8: 4381-4425.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE), 1971. **Levantamento Topográfico Brasileiro**. Maps. IGBE, Rio de Janeiro. Available at: <http://www.ibge.gov.br/home/geociencias/download/arquivos/index1.shtm>. Accessed on: 10 January 2013.

JARVIS, A., H. I. REUTER, A. NELSON & E. GUEVARA, 2008. **Hole-filled SRTM for the globe Version 4**. CGIAR-SXI SRTM 90 m database. Available at: <http://srtm.csi.cgiar.org>. Accessed on: 31 March 2013.

LANNI, C., J. J. MCDONNELL & R. RIGON, 2011. On the relative role of upslope and downslope topography for describing water flow path and storage dynamics: a theoretical analysis. **Hydrological Processes** 25(25): 3909-3923.

LEWIS, C., J. ALBERTSON, X. XU & G. KIELY, 2011. Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. **Hydrological Processes** 26(10): 1527-1537.

MARTINS JUNIOR, P. P. (Coord.), 2006. **Projeto CRHA**: Conservação de Recursos Hídricos no âmbito da Gestão Ambiental e Agrícola de Bacia Hidrográfica. Financiadora de Estudos e Projetos e Fundação Centro Tecnológico de Minas Gerais, Belo Horizonte.

MARTINS JUNIOR, P. P. (Coord.), 2009. **Projeto GZRP**: gestão de zonas de recarga de aquíferos partilhadas entre as Bacias de Paracatu, São Marcos e Alto Paranaíba. Fundação de Amparo à Pesquisa do Estado de Minas Gerais e Fundação Centro Tecnológico de Minas Gerais, Belo Horizonte.

MARTINS JUNIOR, P. P., I. ENDO, J. A. CARNEIRO, L. A. NOVAES, M. A. S. PEREIRA & V. V. VASCONCELOS, 2006. Modelo de integração de conhecimentos geológicos para auxílio à decisão sobre uso da terra em zonas de recarga de aqüífero. **Revista Brasileira de Geociências** 36(4): 651-662.

MENDONÇA, L. A. R., M. A. N. VASQUEZ, J. V. FEITOSA, J. F. OLIVEIRA, R. M. FRANCA, E. M. F. VÁSQUEZ & H. FRISHKORN, 2009. Avaliação da capacidade de infiltração de solos submetidos a diferentes tipos de manejo. **Engenharia Sanitária e Ambiental** 14(1): 89-98.

MENTE, A., 2008. A água subterrânea no Brasil. In: F. A. C. FEITOSA, J. M. FILHO, E. FEITOSA & J. G. A. DEMÉTRIO (Orgs.): **Hidrogeologia**: conceitos e aplicações: 31-50. CPRM, Rio de Janeiro.

MOURÃO, M. A. A. (Coord.), 2001. **Caracterização hidrogeológica da microrregião de Unaí**. Projeto São Francisco. Província Mineral Bambuí (MG): 1-86. Companhia de Pesquisa de Recursos Minerais, Serviço Geológico do Brasil. Ministério das Minas e Energia, Brasília.

NAGHETTINI, M. & E. J. A. PINTO, 2007. **Hidrologia estatística**: 1-552. CPRM, Belo Horizonte.

NOBRE, A. D., L. A. CUARTAS, M. HODNETT, C. D. RENNÓ, G. RODRIGUES, A. SILVEIRA, M. WATERLOO & S. SALESKA, 2011. Height Above the Nearest Drainage – a hydrologically relevant new terrain model. **Journal of Hydrology** 404(1-2): 13-29.

NUNES, H. T. & O. B. NASCIMENTO, 2004. Base de dados meteorológicos. Nota Técnica NT-CRHA 17/2004. In: P. P. MARTINS JUNIOR (Coord.): **Projeto CRHA – Conservação de Recursos Hídricos no âmbito da Gestão Ambiental e Agrícola de Bacia Hidrográfica**: 1-40. Relatório final. Financiadora de Estudos e Projetos e Fundação Centro Tecnológico de Minas Gerais, Belo Horizonte.

PRUSKI, F. F., R. G. RODRIGUEZ, L. F. NOVAES, D. D. SILVA, M. M. RAMOS & A. F. TEIXEIRA, 2007. Impacto das vazões demandadas pela irrigação e pelos abastecimentos animal e humano, na Bacia do Paracatu. **Revista Brasileira de Engenharia Agrícola e Ambiental** 11(2): 199-210.

RAMOS, M. L. S. & M. M. O. M. PAIXÃO, 2004. Disponibilidade hídrica de águas subterrâneas: produtividade de poços e reservas explotáveis dos principais sistemas aqüíferos. In: AGÊNCIA NACIONAL DE ÁGUAS (ANA) (Ed.): **Plano diretor de recursos hídricos da bacia do Rio São Francisco**: 1-41. Ministério do Meio Ambiente, Brasília.

RAWLS, W. J., D. L. BRAKENSIEK & K. E. SAXTON, 1982. Estimation of soil water properties. **Transactions of the ASAE** 25(5): 1316-1320 & 1328.

REBOUÇAS, A. C., 2008. Importância da água subterrânea. In: F. A. C. FEITOSA, J. M. FILHO, E. FEITOSA & J. G. A. DEMÉTRIO (Orgs.): **Hidrogeologia**: conceitos e aplicações: 13-30. CPRM/LABHID, Rio de Janeiro.

RENNÓ, C. D., A. D. NOBRE, L. A. CUARTAS, J. V. SOARES, M. G. HODNETT, J. TOMASELLA & M. J. WATERLOO, 2008. HAND, a new terrain descriptor using SRTM-DEM: mapping terra-firme rainforest environments in Amazonia. **Remote Sensing of Environment** 112(9): 3469-3481.

ROCHA, J. S. M. & C. C. DALTROZO, 2008. Florestamentos compensatórios para retenção de água em microbacias. **Revista Educação Agrícola Superior** 23(1): 71-75. Available at: <http://www.abeas.com.br/wt/download.php?download=100%E2%80%8E>. Accessed on: 10 January 2013.

RODRIGUEZ, R. G., 2004. **Metodologia para a estimativa de demandas e disponibilidades hídricas**: estudo de caso da Bacia do Paracatu: 1-94. Dissertação (Mestrado em Engenharia Agrícola) – Universidade Federal de Viçosa, Viçosa. Available at: <http://www.gprh.ufv.br/docs/Dissertacoes_mestrado/Renata.PDF>. Accessed on: 30 March 2013.

SALAMA, R. B., I. TAPLEY, T. ISHII & G. HAWKES, 1994. Identification of areas of recharge and discharge using Landsat-TM satellite imagery and aerial photography mapping techniques. **Journal of Hydrology** 162(1-2): 119-141.

SANTOS, R. D., R. C. LEMOS, H. G. SANTOS, J. C. KER & L. H. C. ANJOS, 2005. **Manual de descrição e coleta de solo no campo**: 1-92. Sociedade Brasileira de Ciência do Solo, Viçosa.

SCANLON, B. R., R. W. HEALY & P. G. COOK, 2002. Choosing appropriate techniques for quantifying groundwater recharge. **Hydrogeology Journal** 10(1): 18-39.

SOUZA, E. R. & M. R. FERNANDES, 2000. Sub-bacias hidrográficas: unidades básicas para o planejamento e a gestão sustentáveis das atividades rurais. **Informe Agropecuário** 21(207): 15-20.

TAGUE, C. & G. E. GRANT, 2004. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. **Water Resources Research** 40(4): 1-9.

TÓTH, J., 1963. A theoretical analysis of groundwater flow in small drainage basins. **Journal of Geophysical Research** 68(16): 4795-4812.

TUCCI, C. E. M. (Org.), 2009. **Hidrologia**: ciência e aplicação: 1-944. Editora da Universidade Federal do Rio Grande do Sul, Porto Alegre.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (USEPA), 1986. **Guidelines for Ground-Water Classification under the [1984] EPA Ground-Water Protection Strategy**: 1-385. Office of Ground Water Protection, Washington.

VASCONCELOS, V. V., P. P. MARTINS JUNIOR & R. M. HADAD, 2012. **Caracterização ambiental da Bacia do Rio Paracatu**: 1-75. Projeto SACD – Sistemas de Arquitetura de Conhecimentos e de Auxílio à Decisão na Gestão Geoambiental e Econômica de Bacias Hidrográficas e Propriedades Rurais. Universidade Federal de Ouro Preto. Available at: <http://pt.scribd.com/doc/98405182/CARACTERIZACAO-AMBIENTAL-DA-BACIA-DO-RIO-PARACATU>. Accessed on: 17 March 2013.

WINTER, T. C., 2001. The concept of hydrologic landscapes. **Journal of the American Water Resources Association** 37(2): 335-349.

WOLOCK, D. M., T. C. WINTER & G. MCMAHON, 2004. Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. **Environmental Management** 34(S1): S71-S88.