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ORIGINAL ARTICLE

A Discussion on the Quantification and Classification of Geodiversity Indices Based on GIS Methodological Tests

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Abstract

Quantitative assessment methods are attaining special attention in geodiversity research. Procedures to map geodiversity indices have been proposed by several authors though there is no consensus on how to best apply and replicate them in diverse areas. A contribution to the quantitative mapping of geodiversity using GIS tools of quantification and classification is presented. These procedures were applied in the municipality of Miguel Pereira, Rio de Janeiro, Brazil. A quantification stage is supported by the multiparts technique, in which the geodiversity elements are considered without pondering their repetition, and by the singleparts technique, where the repetitions are counted. Geodiversity is then mapped and classified according to the MOV (maximum obtained value) that considers the highest score obtained by the sum of the geodiversity sub-indices and to the MPV (maximum possible value) defined by the sum of the maximum scores in each of the geodiversity sub-indices. The maps produced according to the singleparts tools reflect a higher difference between the minimum and maximum scores of geodiversity, and using the MPV more areas are classified with low geodiversity. Fieldwork surveys support the idea that combining the multiparts technique for geodiversity quantification with the MOV to its classification is more appropriate to characterize the geodiversity of the area. Nevertheless, using different methodological approaches may generate significantly different results, what must be taken into account when considering geodiversity as a support tool in land management.

Keywords Geodiversity · Quantitative assessment · Methodologies · Land management · Indices · Miguel Pereira

Introduction

Geodiversity is the abiotic equivalent of biodiversity (Gray 2004). Despite the existence of several definitions in the literature emphasizing the importance of geodiversity in human activities and in other nature features (e.g. Sharples 1995; Johansson et al. 1999; Nieto 2001; Commonwealth of Australia 2002; Kozlowski 2004; Gray 2004, 2013; Rojas-López 2005; CPRM 2006; Serrano and Ruiz-Flaño 2007a, b; Martínez et al. 2008), the scientific and technical literature on biodiversity is far more abundant and generally lacks this abiotic provision.

Gray et al. (2013) defines geodiversity as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes". Being one of the most cited definitions, this approach is limited to natural diversity, not considering anthropogenic influence like in those proposed by Kozlowski (2004), Rojas-López (2005), and Serrano and Ruiz-Flaño (2007a, b).

This topic is relevant and prone to discussion because some minerals might be formed in part by the influence of anthropogenic activities in mines or quarries when rocks or minerals are exposed to atmosphere or groundwater effects (Hazen et al. 2017). In this case, they can generally be accepted as minerals. Yet, they might result in part due to the interaction of existing minerals with substances of non-geological origin (e.g. industrially contaminated water, corroded human artefacts). In this case, they could not be considered as minerals. According to some authors like Carcavilla et al.

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Fig. 1 Location of Miguel Pereira municipality (projected coordinate system: UTM zone 23S, SIRGAS-2000)

(2008) and Santos et al. (2017), the incorporation of the anthropic factor can complicate the geodiversity concept application and specifically its quantitative mapping.

Geodiversity and biodiversity constitute the natural diversity whereas biodiversity is strongly conditioned by geodiversity since organisms require specific abiotic

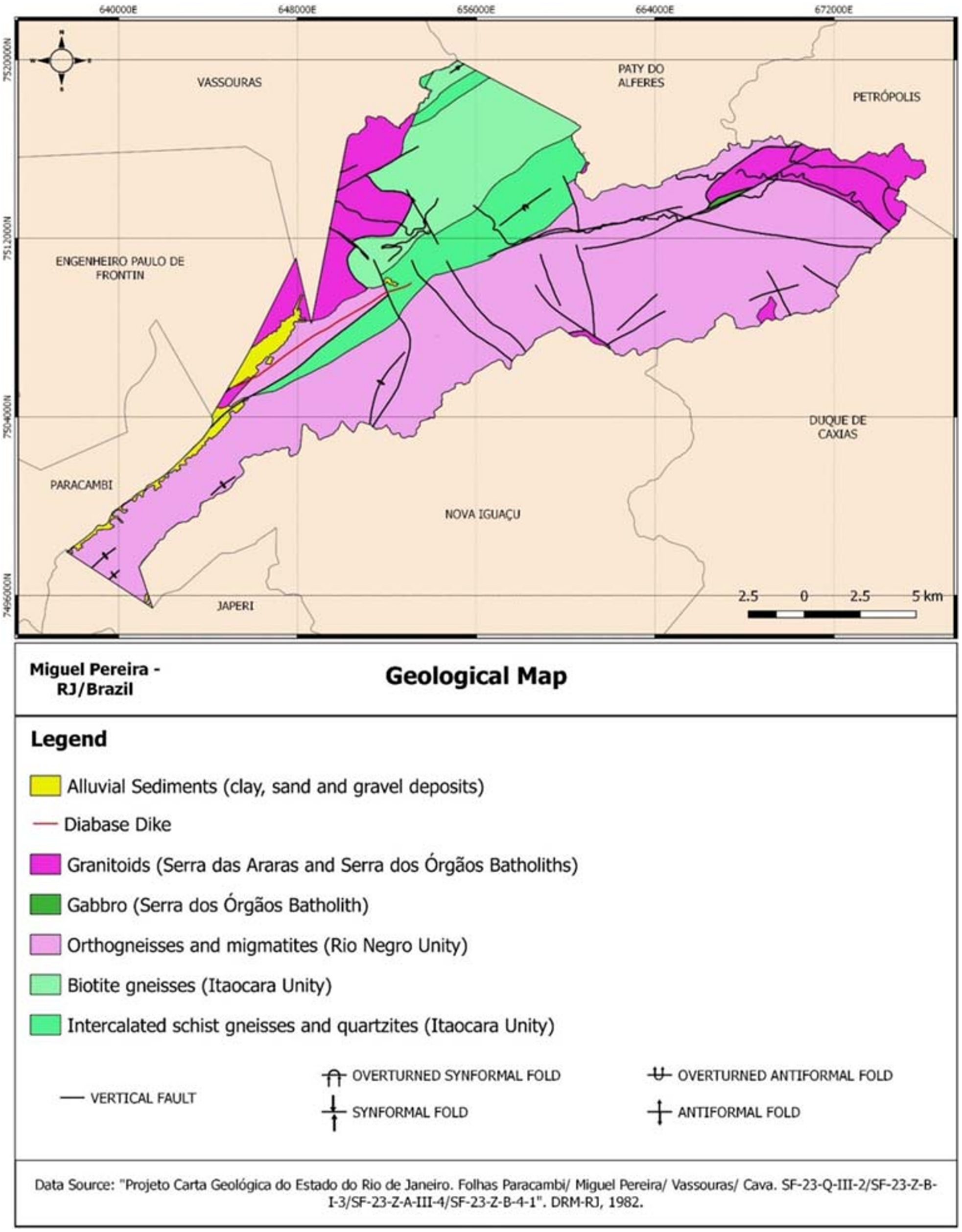

Fig. 2 Geological map of Miguel Pereira (modified and translated from DRM-RJ 1982). Projected coordinate system: UTM zone 23S, SIRGAS-2000

conditions for their existence (Brilha 2005; Serrano and Ruiz-Flaño 2007a, b; Matthews 2014). Furthermore, recent studies on the relationships between biodiversity and geodiversity contribute to a better knowledge of their types and spatial variations (Jačková and Romportl 2008; Hjort et al. 2012; Tukiainen et al. 2016; Räsänen et al. 2016). In that scope, it is expected that the identification and spatial characterization of geodiversity contribute to territorial management policies and to more accurate protection and management of natural areas. With geodiversity being the backbone of geoheritage (Gray 2018b), it could even support sustainable human activities in these areas, especially geotourism initiatives, with environmental, social and economic benefits (Forte et al. 2012; Brilha et al. 2018).

Geodiversity elements are also relevant in the context of the ecosystem services since they play a fundamental role in the goods and services supplied to societies. The ecosystem approach is nowadays a key international policy driver supporting quantitative and qualitative judgements about the value of nature and its sustainable management (Brilha et al. 2018). Thereby, the diverse types of values of geodiversity are set according to these services, observed at global to local scales and assessed to support land management policies (Gordon and Barron 2013; Gray et al. 2013; Gray 2018a, b).

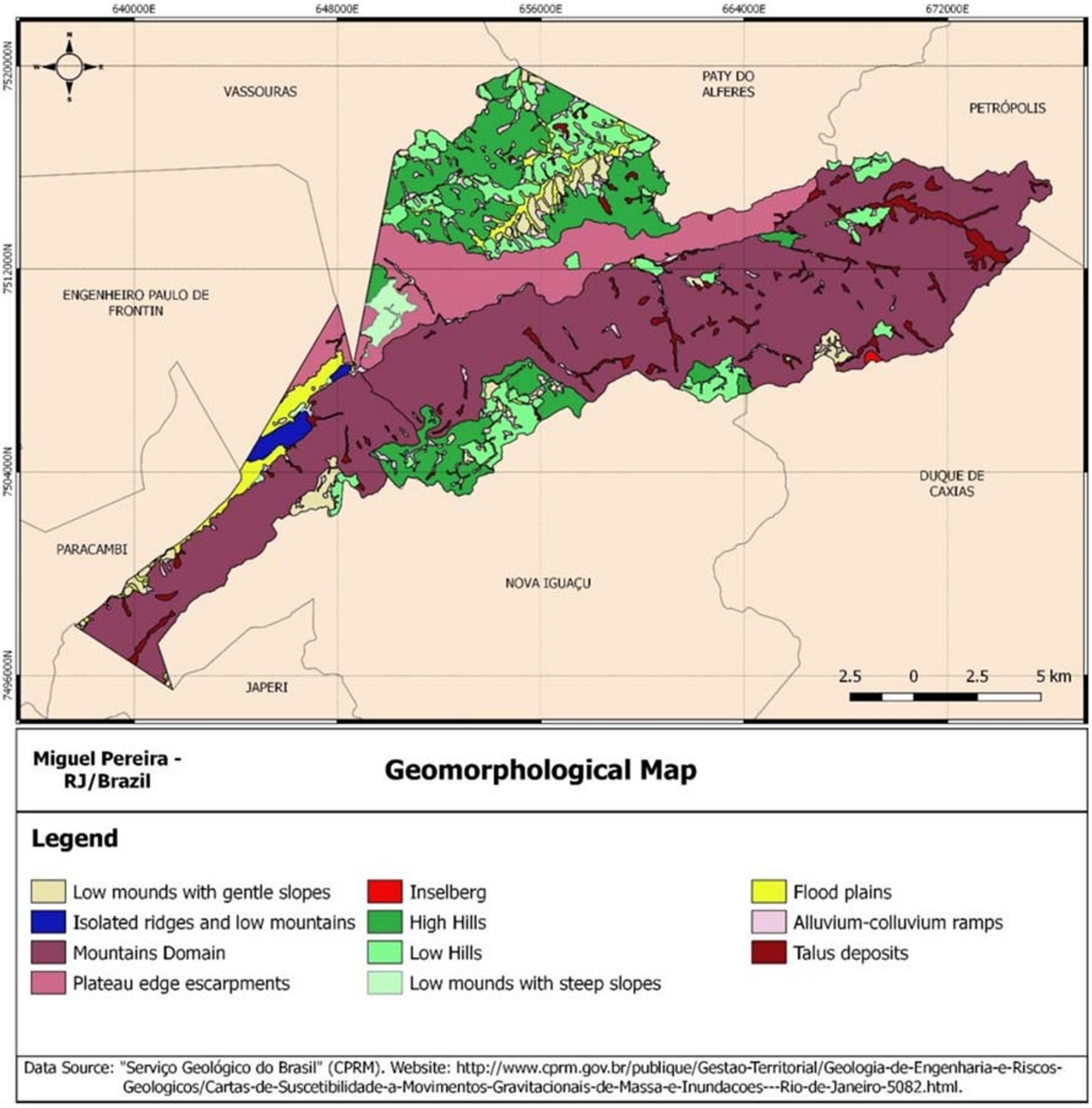

Fig. 3 Geomorphological units map of Miguel Pereira (modified and translated from CPRM 2017). Projected coordinate system: UTM zone 23S, SIRGAS-2000

Several methodologies have been proposed for assessing geodiversity using quantitative criteria that focus on the spatial diversity (e.g. Xavier-da-Silva et al. 2001; Kozlowski 2004; Serrano and Ruiz-Flaño 2007a, b; Carcavilla et al. 2008; Benito-Calvo et al. 2009; Zwolinski 2009; Hjort and Luoto 2010; Pellitero et al. 2011; Pellitero 2012; Pereira et al. 2013; Forte 2014; Najwer and Zwoliński 2014; Pellitero et al. 2014; Silva et al. 2015; Manosso and Nóbrega 2016; Argyriou et al. 2016; Stepišnik and Trenchovska 2016; Santos et al. 2017; Araujo and Pereira 2018).

However, as it occurs with other quantitative spatial analyses, it has been difficult to find a methodology that is replicable to different areas, mainly regarding land management purposes (Zwoliñski et al. 2018). The problems reported include the scale of analysis, the study area dimensions and the availability of cartographic data (Santos et al. 2017). The settlement on a simple and objective methodology is therefore regarded as a goal in this topic and a valuable tool in territorial studies (Pereira et al. 2013).

The purpose of this work was to perform a quantitative assessment of geodiversity, contributing for the development of these methodologies and their implementation in land management studies. The study was applied in Miguel Pereira municipality (Rio de Janeiro State, Brazil). Geodiversity index maps were generated according to different quantitative approaches, i.e. applying geoprocessing tools (multiparts and singleparts) and two different classifications (MOV, maximum obtained value and MPV, maximum possible value) in order to verify and discuss disparities in the results and their cartographic illustration.

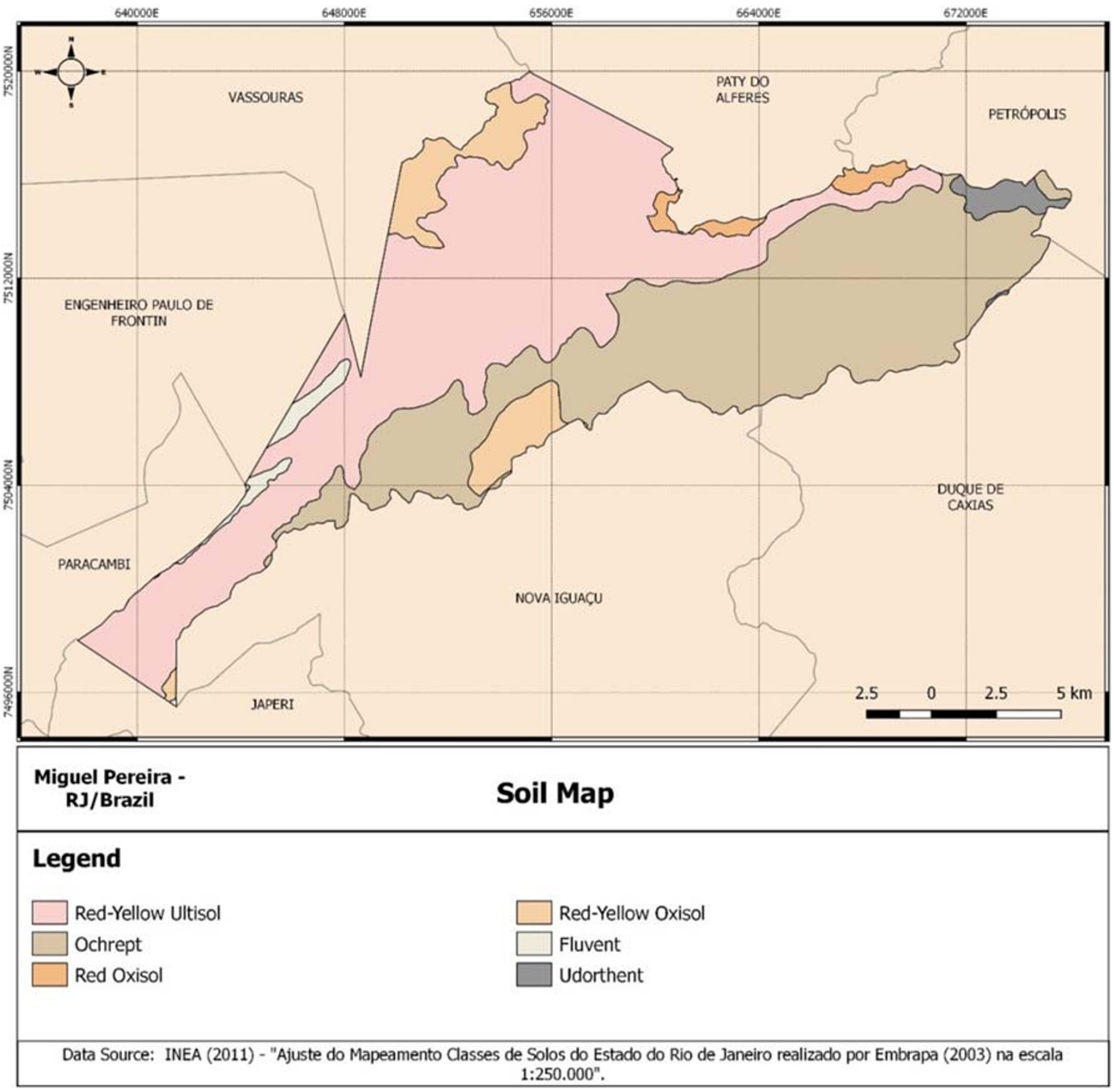

Fig. 4 Soil map of Miguel Pereira (modified and translated from INEA 2011). Projected coordinate system: UTM zone 23S, SIRGAS-2000

Study Area

The study area is the municipality of Miguel Pereira situated in Rio de Janeiro State, Brazil (Fig. 1). In geological terms, the municipality is located in Ribeira Orogen, which belongs to Mantiqueira province, being affected by the Neoproterozoic/Cambrian cycle (Brasiliano–Pan-African event) in South America originated from the West Gondwana amalgamation (Almeida et al. 1981; Heilbron et al. 2004; Silva and Cunha 2001). The Ribeira Orogen is subdivided in Occidental, Oriental, Paraíba do Sul and Embú terrains amalgamated at ca. 580 Ma and Cabo Frio terrain added to the others at ca. 520 Ma (Heilbron et al. 2004; Schmitt et al. 2016).

A Brasiliano–Pan-African suture zone called *Central Tectonic Boundary* (CTB) in Miguel Pereira divides the Oriental (Rio Negro magmatic arc) and the Occidental terrains. The Arcádia-Areal shear zone is located on the northwest side of this zone. It is a mylonitic zone that controls the Santana river graben configuration, which is a result of its reactivation during the Cenozoic. Triangular facets landforms occur associated to the graben border faults and the quaternary colluvial deposits. These triangular facets separate the graben from the horsts (Gontijo-Pascutti et al. 2010). Regarding lithologies, the study area basically includes metamorphic rocks (Itaocara and Rio Negro units) and granitoids (Serra das Araras and Serra dos Órgãos batholiths) from the Neoproterozoic, Lower Cretaceous diabase dikes (Serra do Mar Dyke Swarm, SMDS) and Quaternary alluvial sediments (clay, sand and gravel deposits, Fig. 2).

The relations between geological, geomorphological, and soil characteristics are remarkable in Miguel Pereira. The geomorphological features are mostly represented by steep relief

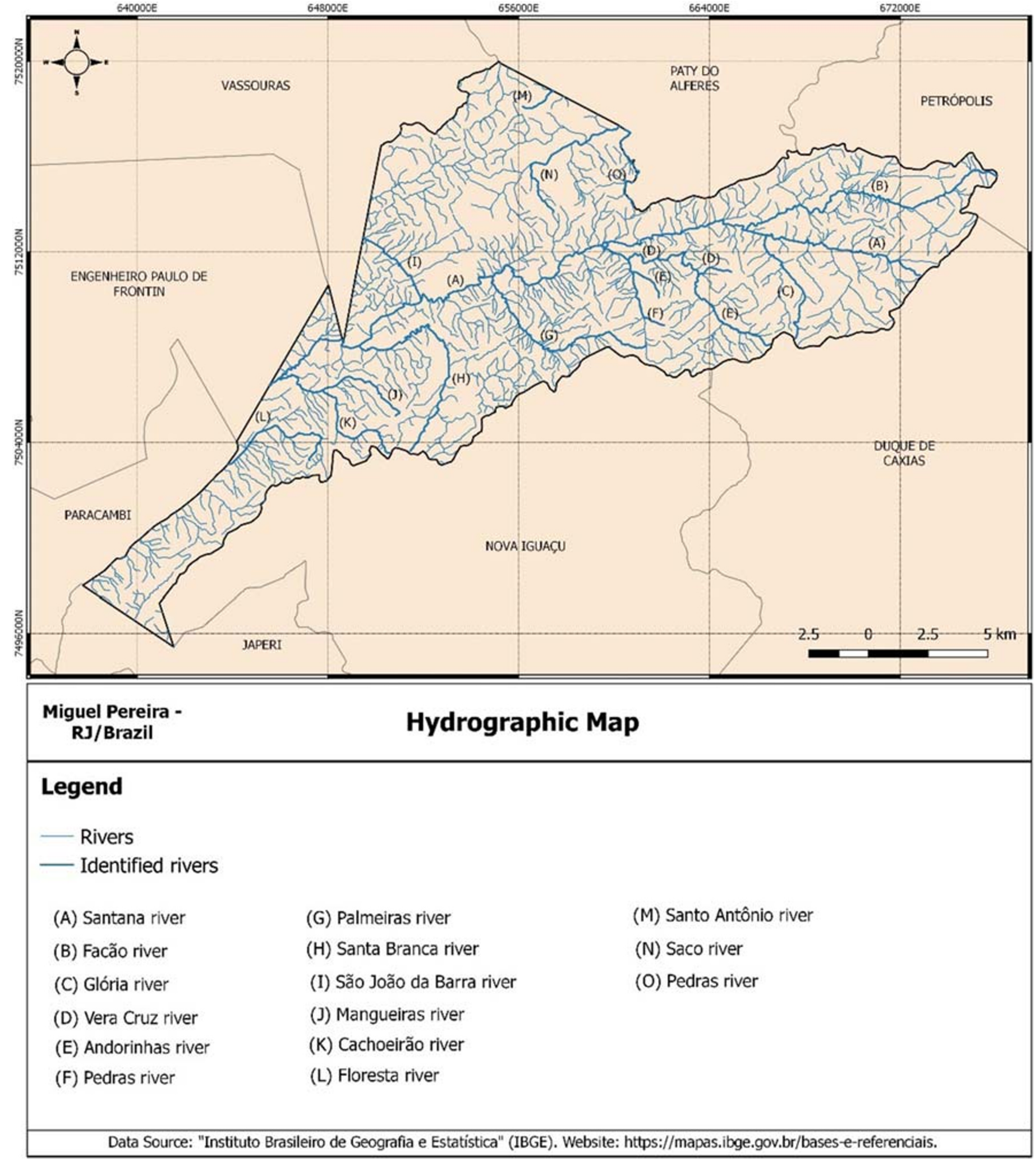

Fig. 5 Hydrographic map of Miguel Pereira (modified and translated from IBGE 2018). Projected coordinate system: UTM zone 23S, SIRGAS-2000

areas (Fig. 3), associated with granitoids, orthogneisses and migmatites, and also a small gabbro occurrence. Triangular facets are also present in these higher slope areas associated with graben border faults. Lower areas are mainly associated with biotite gneisses and intercalated schist gneisses and quartzites, besides quaternary deposits. The main shear zone in this study area, CTB, is associated to the most expressive geomorphological unity represented by the Santana river valley that comprises the major river in this region called Santana River.

Steep areas are mostly associated to the ochrept and udorthent soil types occurrence. In gentle relief areas, red oxisol, red-yellow oxisol and red-yellow ultisol soil types are more common. Flood plains areas are associated to the fluvent soil type (Fig. 4).

Miguel Pereira comprises a hydrographic network with a variety of temporary and permanent regime channels (Fig. 5). Santana river is the major permanent river and one of the tributaries of Guandu, the greatest river in the region, covering several municipalities.

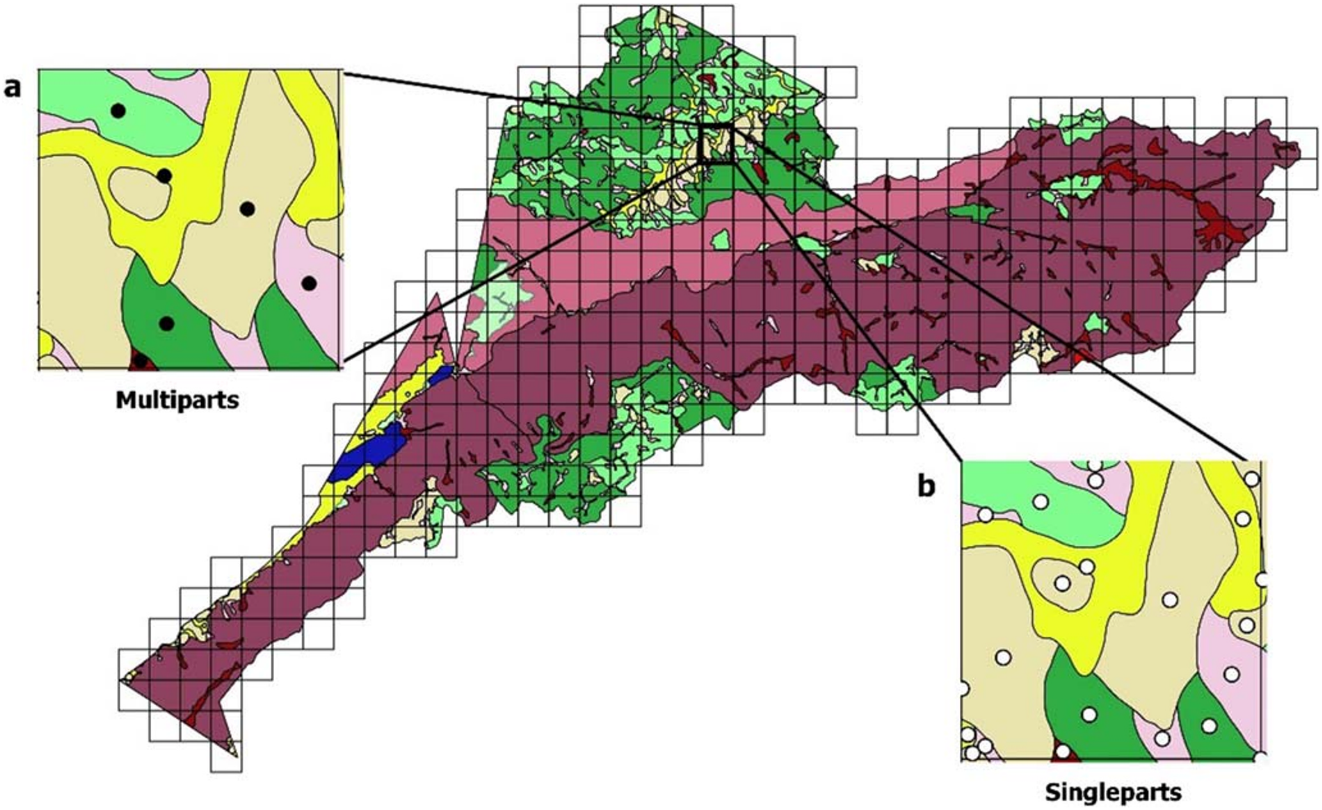

Fig. 6 Geomorphological units map overlaid by a 1000 × 1000-m grid showing the counting of occurrences (relief patterns) in each cell of the grid, by creating centroids (points) through multiparts (**a**) and singleparts (**b**) tools

Material and Methods

Geodiversity index maps were developed based on the methodology described by Pereira et al. (2013) by creating a grid that overlays the analysed maps and counting the occurrences in every cell of the grid. Previously, Santos et al. (2017) exhibited an adaptation of Pereira et al. (2013) methodology. The present work aims to improve this methodological adaptation, testing and comparing different techniques of geodiversity quantification.

The classes to be assessed were defined according to the work scale and data availability. Considering Miguel Pereira area size, the geodiversity assessment was carried out using maps varying from 1:25,000 to 1:100,000 scales. Thus, the assessed classes were as follows:

- Geology (lithological units and structures—scale 1:50,000. DRM-RJ 1982)
- Geomorphology (relief patterns—scale 1:25,000. CPRM 2017)

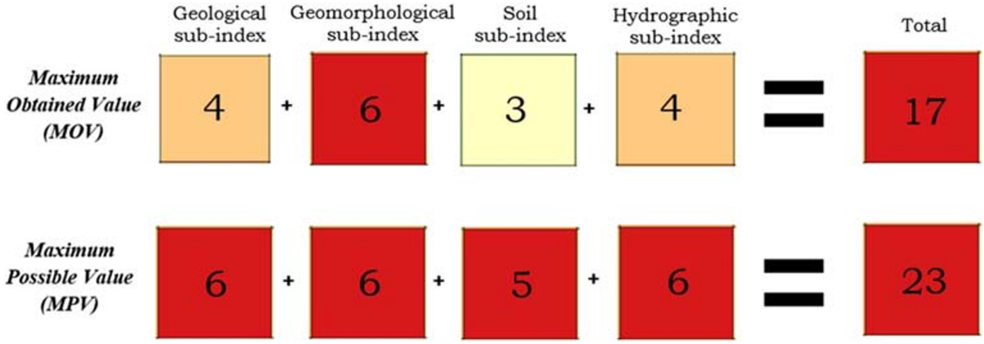

Fig. 7 Example of the sub-indices' quantification using MOV and MPV classification. The red cells in each sub-index using MPV represent the maximum values that these sub-indices can reach in a cell of the grid. The cells from the sub-indices quantification using MOV show that the cell with the highest value from the quantification of each sub-index is not necessarily the maximum value that each sub-index can reach (represented by the cells with lighter colours)

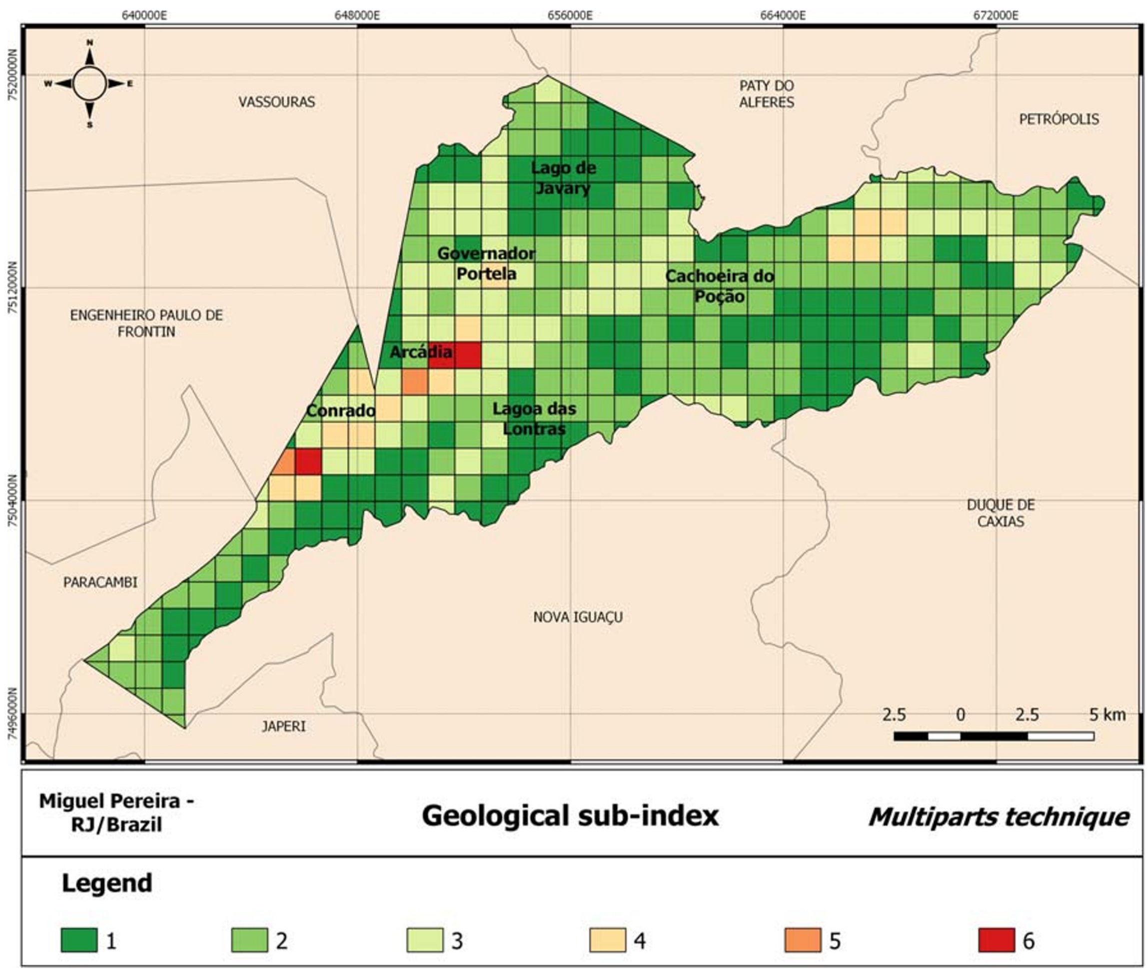

Fig. 8 Geological sub-index map using multiparts technique. Projected coordinate system: UTM zone 23S, SIRGAS-2000

- Pedology (soils subclasses—scale 1:100,000. EMBRAPA 2003; INEA 2011);
- Hydrography (rivers—scale 1:25,000. IBGE 2018)

The final geodiversity index map scale is 1:100,000, which is the scale of the less detailed map used (soil map). Therefore, a grid with cells measuring 1000 × 1000 m was defined. As described in Pereira et al. (2013), the grid overlays maps representing geodiversity elements (rocks, structures, landforms, soils and rivers), and centroids were assigned to each polygon to be counted in each cell of the grid. To create the grid, the *vector grid* tool in QGIS® software was performed. Using the *Join* tool, the values obtained in all sub-indices were summed up, resulting in the final quantification and eventually in the geodiversity index map.

The counting of occurrences in every cell of the grid in each sub-index was performed with two different techniques (Fig. 6):

"Multiparts": Geometries with the same attribute were counted only once, independent if it appears in more than one polygon inside a cell. This procedure is already performed automatically when the centroids are generated. The geometries present in each cell are then counted, without considering their repetitions. This method is the more common in previous studies (e.g. Hjort and Luoto 2010; Pereira et al. 2013; Pellitero et al. 2014; Manosso and Nóbrega 2016; Silva et al. 2015; Santos et al. 2017).

"Singleparts": In this case, the geometries are separated in unique parts ("singleparts") counting every geometry (including their repetitions) in each cell of the grid.

This approach can be seen as a revision of the Pereira et al. (2013) method. Forte et al. (2018) used the "singleparts" analysis, but they did not apply it to sub-indices.

However, in the hydrographic sub-index quantification multiparts and singleparts tools were not used. The assessment was based on the drainage density, defined by Horton (1932, 1945) and applied by other authors like Bandara (1974) and Tarboton et al. (1992). This way, it is possible to consider data regarding surface runoff, important for the purposes of water resources and protection against flood events or landslides.

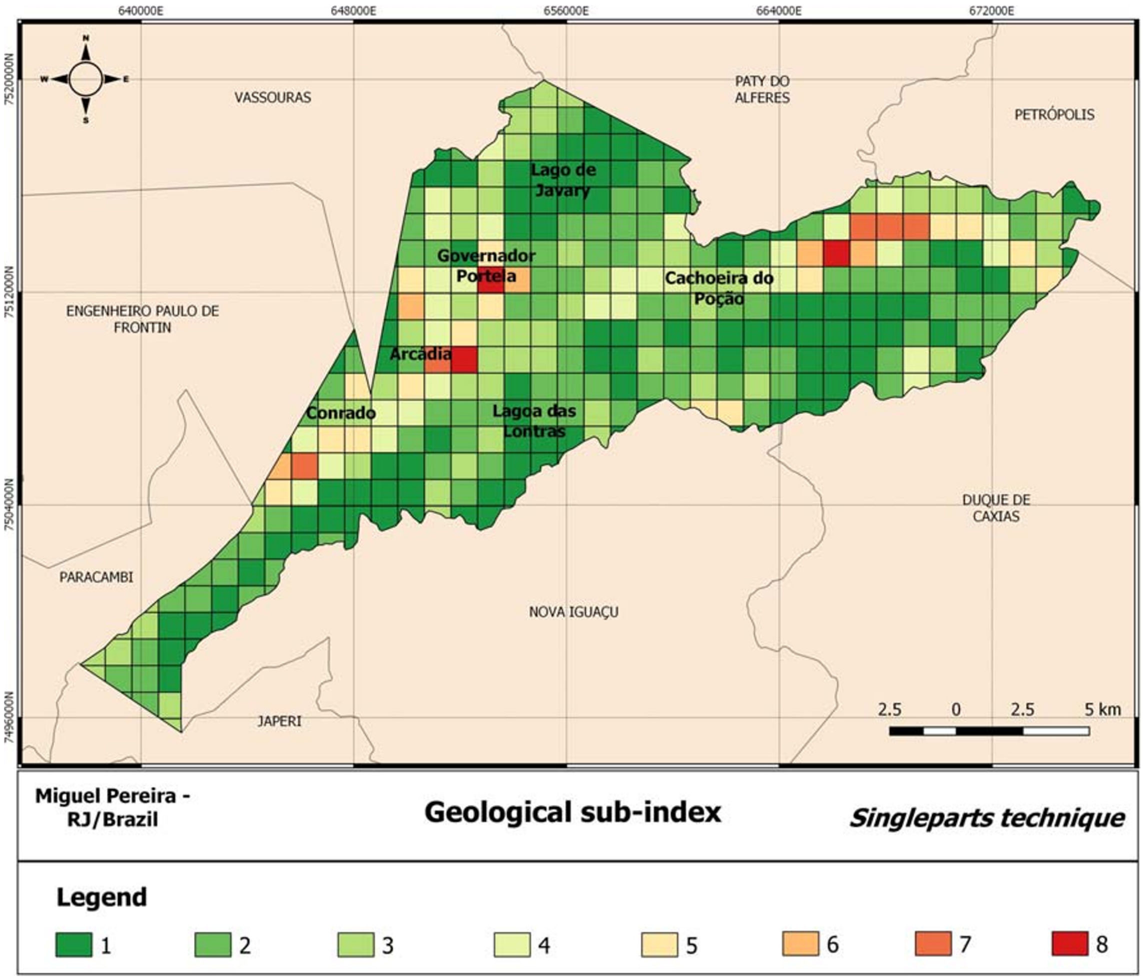

Fig. 9 Geological sub-index map using singleparts technique. Projected coordinate system: UTM zone 23S, SIRGAS-2000

With the geodiversity index maps (multiparts and singleparts) ready, class intervals were defined according to "maximum obtained value" (MOV) and "maximum possible value" (MPV), in order to assess differences in the results acquired in both classification methods. MOV is represented by the cell which has the highest score, from the sum of the four sub-indices (geology, geomorphology, soil and hydrography). MPV is obtained from the sum of the highest scores in the cells of each of the sub-indices, considering only the cells of the grid where the sub-indices reach the maximum value (Fig. 7).

The ranges of the classes were defined according to MOV and MPV, and the conversion of the grid-based maps into isoline maps was carried out for a better interpretation of the results. Therefore, vector polygons were converted into points with each point being located at the centre of each cell. The point maps went then through an interpolation process (inverse distance weighting, as described by Silva et al. 2013), resulting in isoline maps.

The results obtained from both quantification processes (multiparts and singleparts) were checked during fieldwork, with the purpose of verifying and validating the areas with higher and lower indices using the maps as a guide.

Results

The integration of geodiversity sub-index maps led to the geodiversity index maps for both multiparts and singleparts approaches.

The geological sub-index was obtained from quantification of lithological units and structures (faults and folds). Its quantification resulted in values ranging from 1 to 6 applying the multiparts tool (Fig. 8) and 1 to 8 using the singleparts tool (Fig. 9). The highest values in both analyses occur in the regions of Conrado and Arcádia. The locations of Governador Portela and Cachoeira do Poção (up to the eastern limit of Miguel Pereira) are also highlighted in the singleparts analysis. The cells with lower values obtained using both tools are distributed in greater quantity in the study area.

The geomorphological sub-index had values ranging from 1 to 6 using multiparts tool (Fig. 10) and 1 to 20 applying

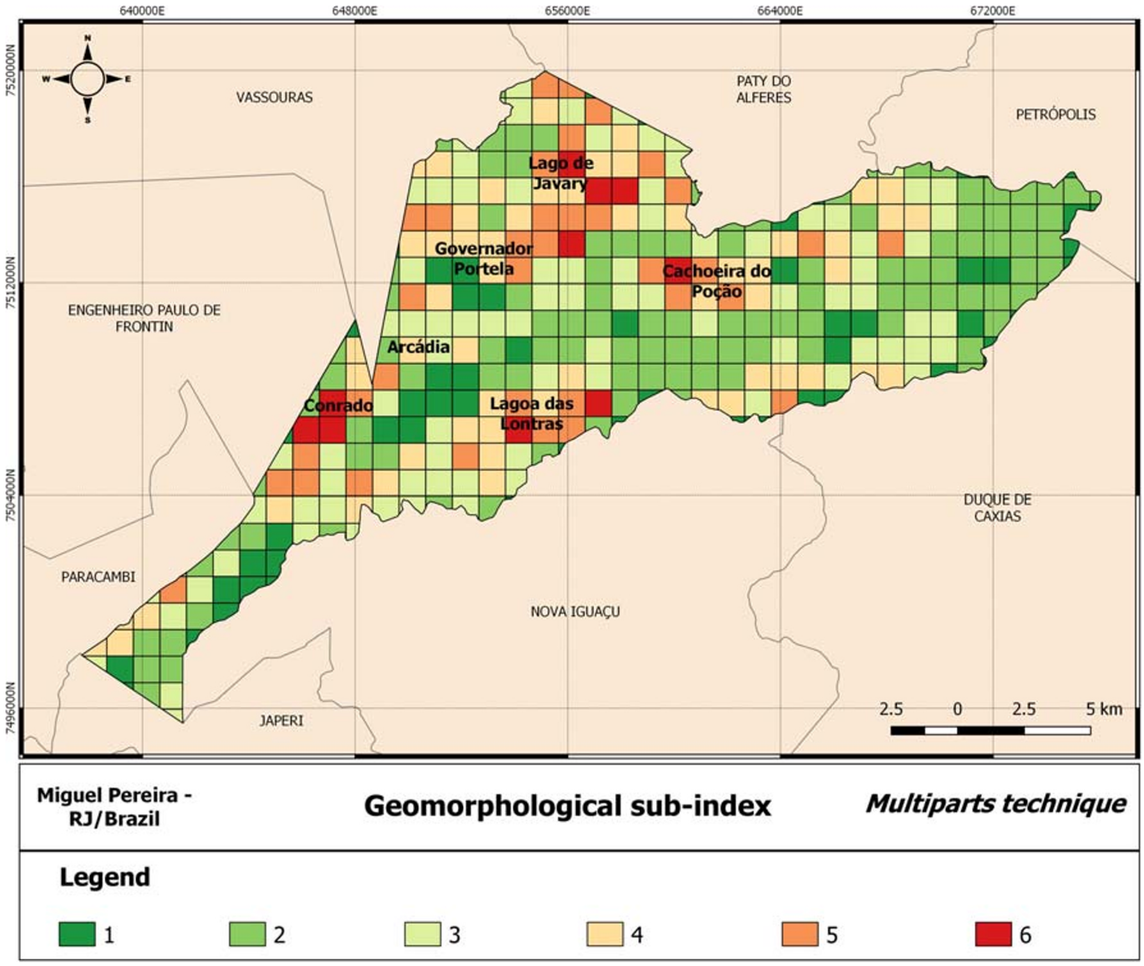

Fig. 10 Geomorphological sub-index map using multiparts technique. Projected coordinate system: UTM Zone 23S, SIRGAS-2000

singleparts tool (Fig. 11). The cells with higher values in the multiparts analysis have higher distribution in the study area, occurring high indices in the regions of Conrado, Arcádia, Governador Portela, Lago de Javary, Lagoa das Lontras and Cachoeira do Poção. The use of the singleparts tool shows the highest indices occurring only in Lago de Javary and Lagoa das Lontras. The lower values prevail in both maps.

The quantification of soil subclasses had values varying from 1 to 5 in both multiparts (Fig. 12) and singleparts (Fig. 13) tools. The highest scores in both analyses are associated to the quaternary deposits and the steep relief of the Mountains Domain. The lowest values are predominant.

The hydrographic sub-index (Fig. 14), achieved by applying a drainage density method, ranges from 0 to 6 with the highest scores occurring in the areas with steep slopes and incised valleys, such as the Santana River valley, where the run-off and discharge are high. The lowest scores are related with plain areas.

The sum of the geodiversity sub-indices, applying both multiparts and singleparts tools methods, and the classification using MOV and MPV for each analysis were performed, totalizing 4 geodiversity index maps (Figs. 15, 16, 17 and 18). The scores obtained were classified in very low, low, medium, high and very high. Table 1 summarizes the occurrence and distribution of these qualitative classes in each map.

The areas with very high geodiversity in the geodiversity index maps were then checked in the field: Arcádia (Fig. 19a); Conrado (Fig. 19a, b and c); boundary with Paracambi (Fig. 19d); Lago de Javary (Fig. 19e); Lagoa das Lontras (Fig. 19f); east region near the boundary with Petrópolis (Fig. 19g); and Cachoeira do Poção (Fig. 19h). In addition, sites with high geodiversity were also surveyed in these areas.

Discussion

In this work, the geodiversity assessment was mainly based in the methodology described in Pereira et al. (2013) and in the main methodologies that use grids and geoprocessing software to quantify geodiversity elements (e.g. Jačková and Romportl 2008; Pellitero et al. 2014; Silva et al. 2013, 2015; Santos et al. 2017). Using some of the adaptations previously

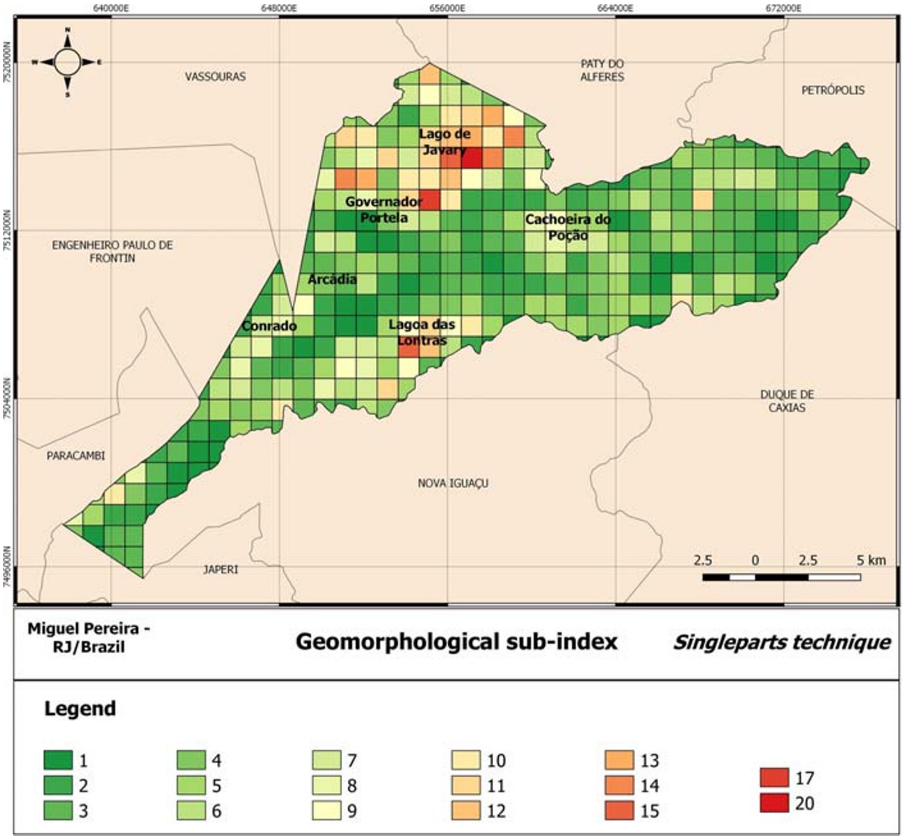

Fig. 11 Geomorphological sub-index map using singleparts technique. Projected coordinate system: UTM zone 23S, SIRGAS-2000

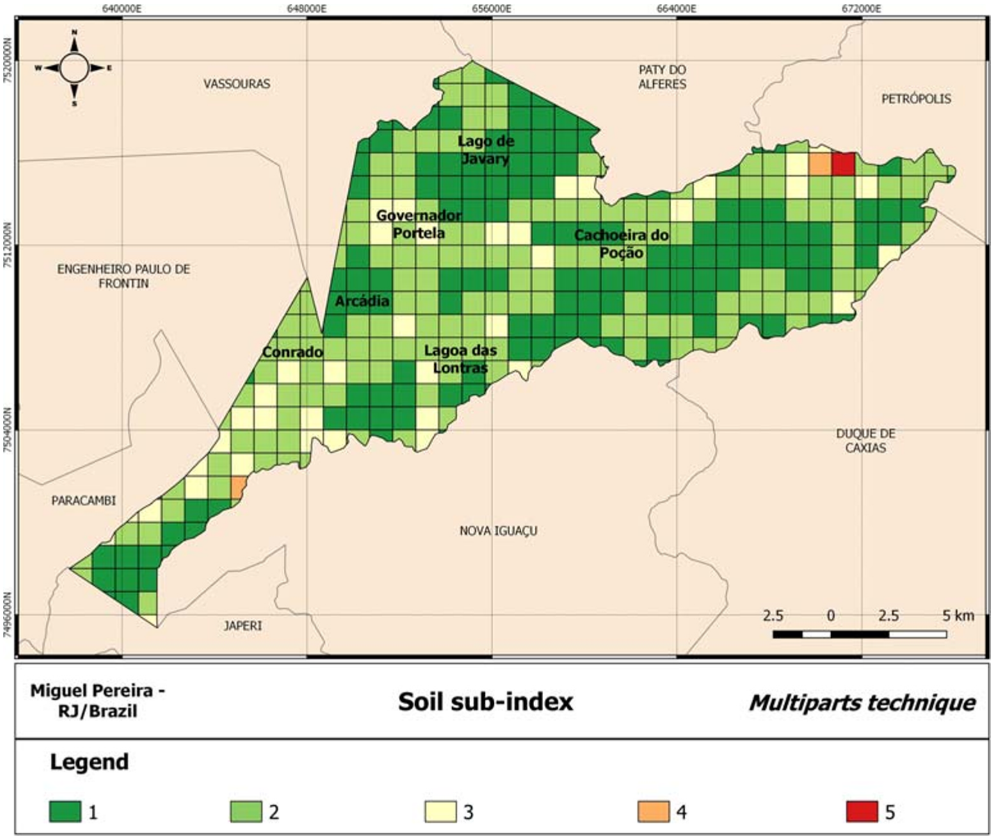

Fig. 12 Soil sub-index map using multiparts technique. Projected coordinate system: UTM zone 23S, SIRGAS-2000

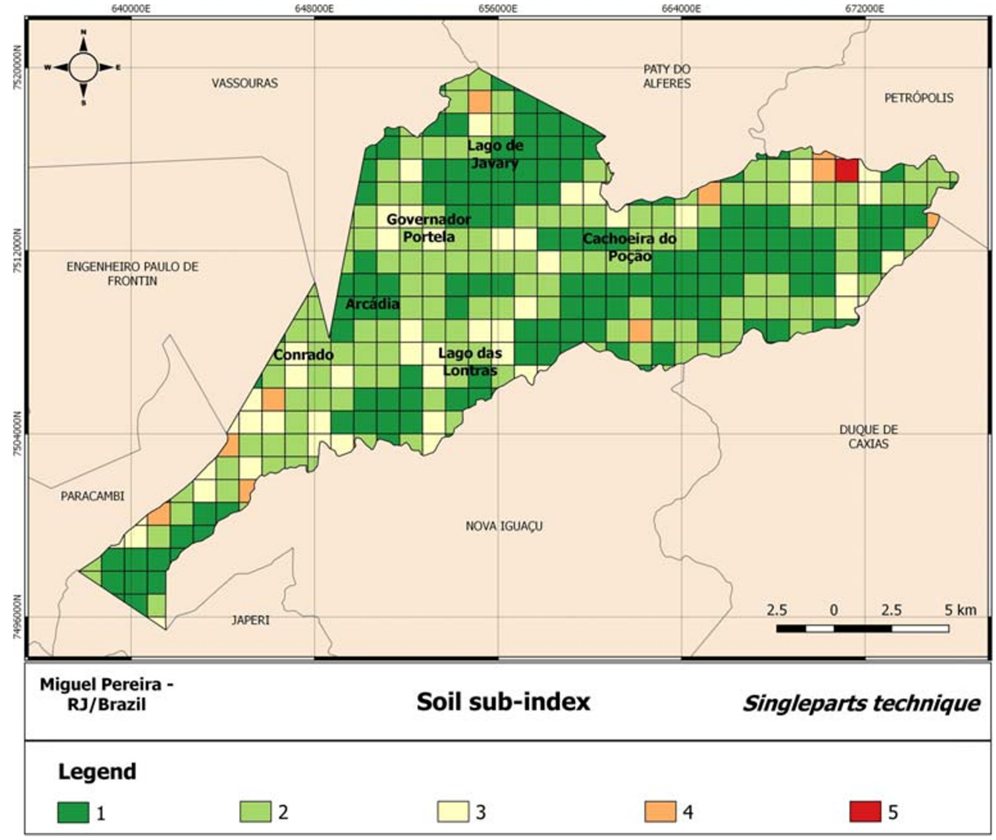

Fig. 13 Soil sub-index map using singleparts technique. Projected coordinate system: UTM zone 23S, SIRGAS-2000

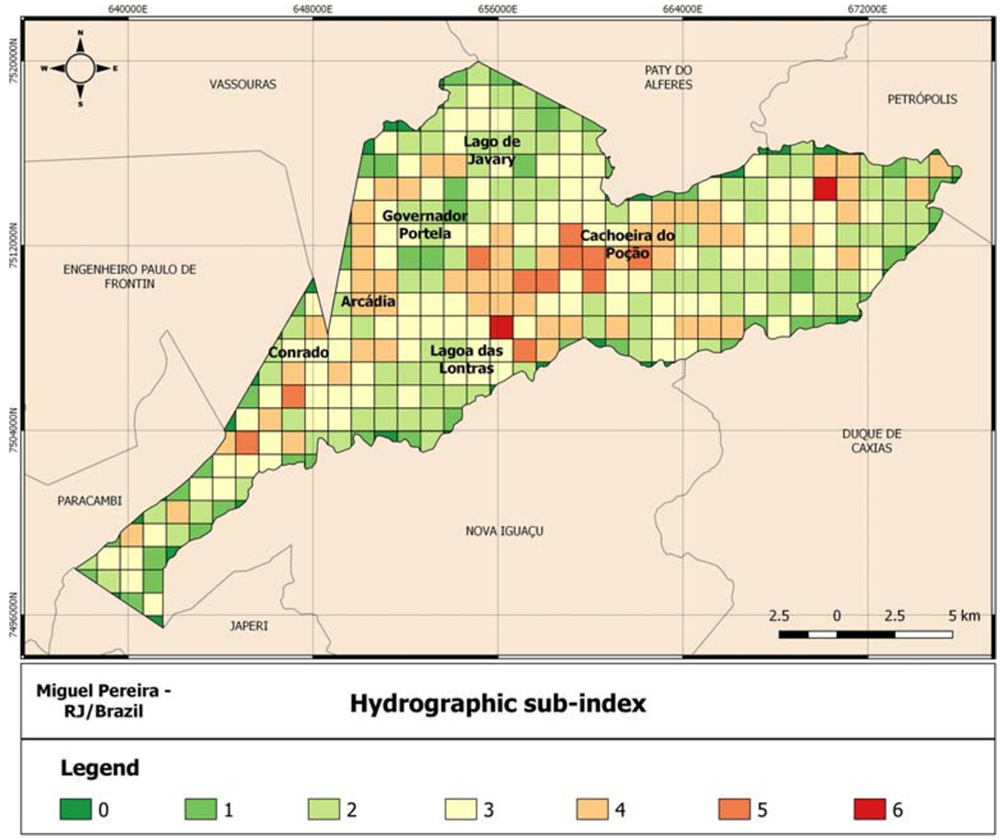

Fig. 14 Hydrographic sub-index map. Projected coordinate system: UTM zone 23S, SIRGAS-2000

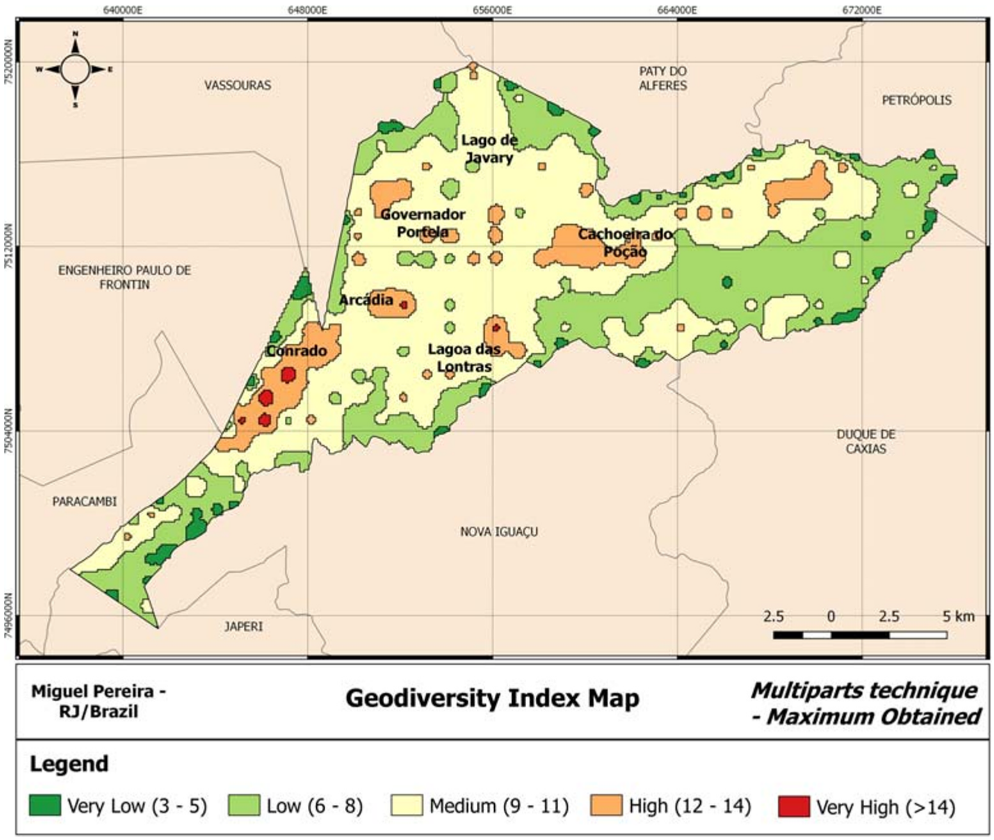

Fig. 15 Geodiversity index map of Miguel Pereira using multiparts technique and MOV classification. Projected coordinate system: UTM zone 23S, SIRGAS-2000

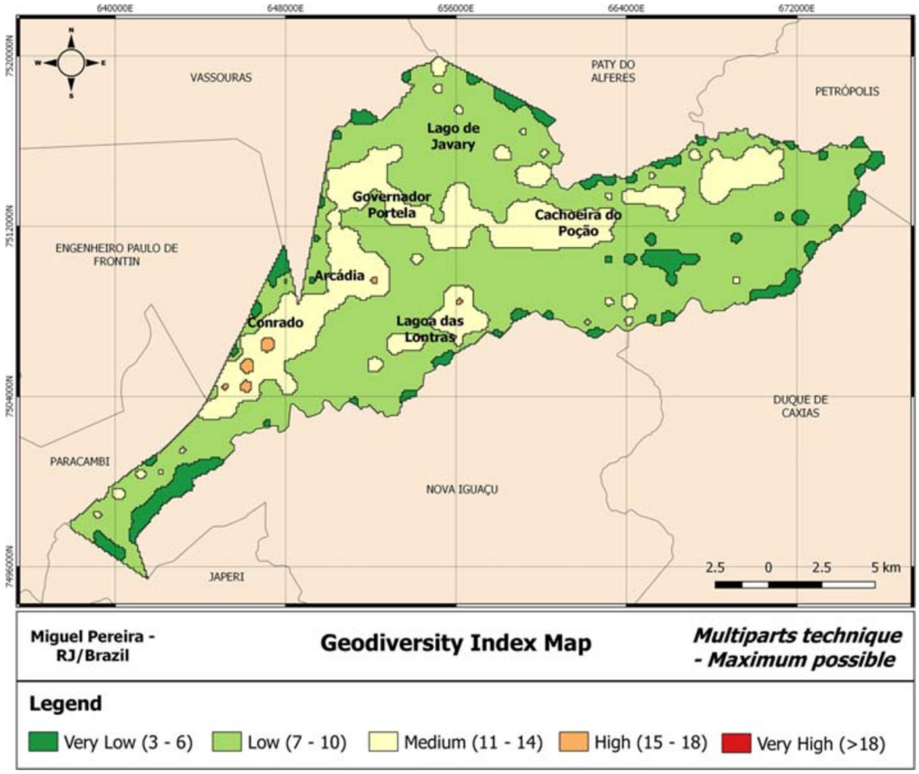

Fig. 16 Geodiversity index map of Miguel Pereira using multiparts technique and MPV classification. Projected coordinate system: UTM Zone 23S, SIRGAS-2000

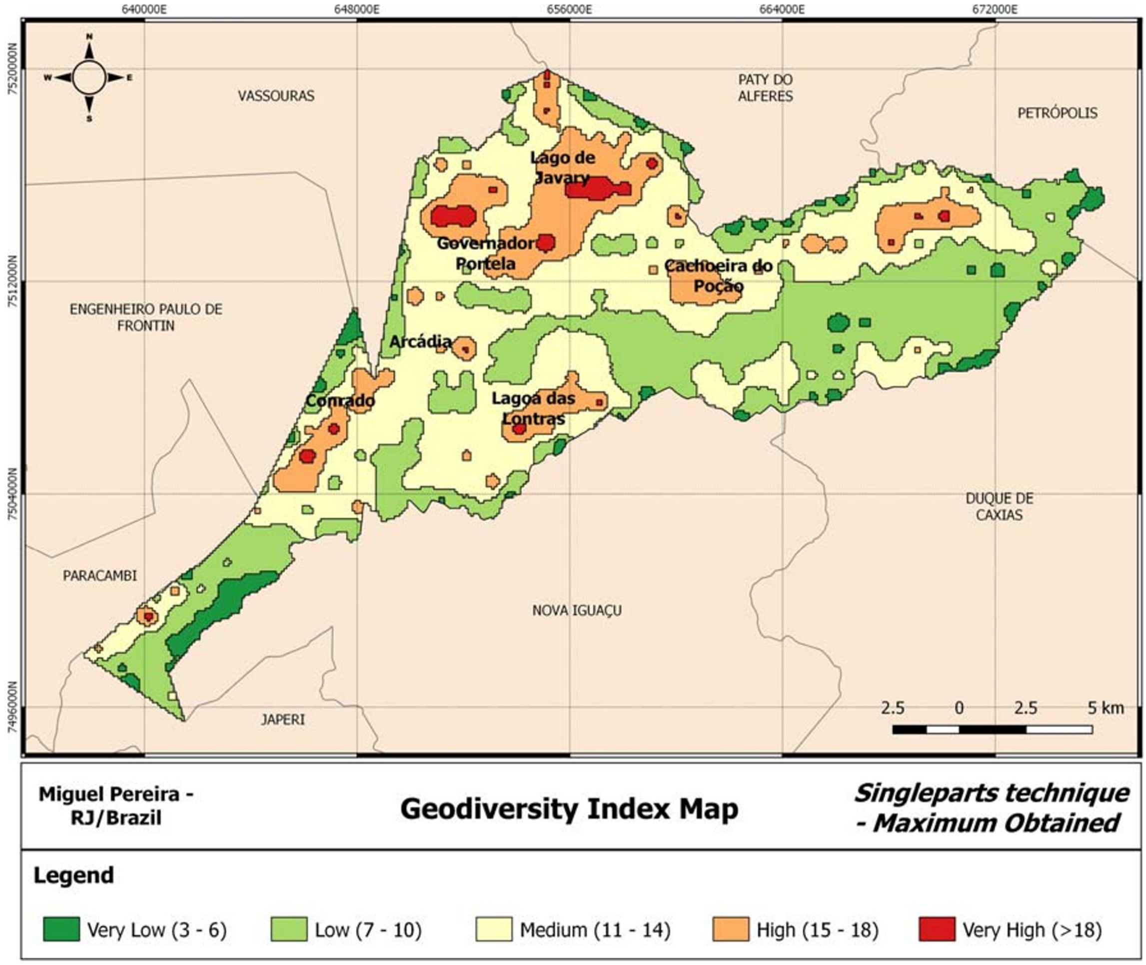

Fig. 17 Geodiversity index map of Miguel Pereira using singleparts technique and MOV classification. Projected coordinate system: UTM zone 23S, SIRGAS-2000

made by Santos et al. (2017), two quantification tools (multiparts and singleparts) were applied to verify the difference in their results. In addition, two geodiversity index classification methods (MOV and MPV) were added, considering the potential scores of geodiversity elements.

A landscape scale was adopted, following the geodiversity analysis scales proposed by Serrano and Ruiz-Flaño (2007a, b). The size of the grid cells (1000 × 1000 m) was defined taking into account the lowest scale of the maps used (soil map, 1:100,000), as defined by Pellitero et al. (2014) and followed by Santos et al. (2017). As in Santos et al. (2017), mineral occurrences were not considered in the quantification since these elements are not compatible with the landscape scale. A paleontologic sub-index was not considered either, since there are no fossiliferous occurrences in the study area. The most detailed parameters were obtained from the geomorphological units map (relief patterns) and the soil map (subclasses). For the latter, this work differs from Pereira et al. (2013), which used orders, and Santos et al. (2017), which used suborders.

The scale of the maps used for geodiversity assessment is discussed in several works. Despite the difficulties in gathering maps at the same scale, it is undeniable that the results of a geodiversity quantitative assessment can be more accurate in such conditions. Besides that, the grid cells size also can influence the final results, depending of the maps scale. In this work, maps at different scales were used, and it was observed that the soil map, which has the smallest scale, presents lower variations in relation to the others sub-indices quantification. This fact was also observed in Santos et al. (2017) and is probably explained by the difference in the scale. The grid cell size was defined according to the soil map scale; thus the information contained in this map could be missed if highest scale maps were used to define the grid cell size (1:25,000 or 1:50,000). Therefore, the idea that the absence of data at the same scale still represents a limitation for this type of assessment is endorsed, and the application and interpretation of different grid cell sizes should be present in future studies.

The maps were therefore produced at 1:100,000 scale using a 1000 × 1000-m grid size. Higher scale maps (1:25,000 or

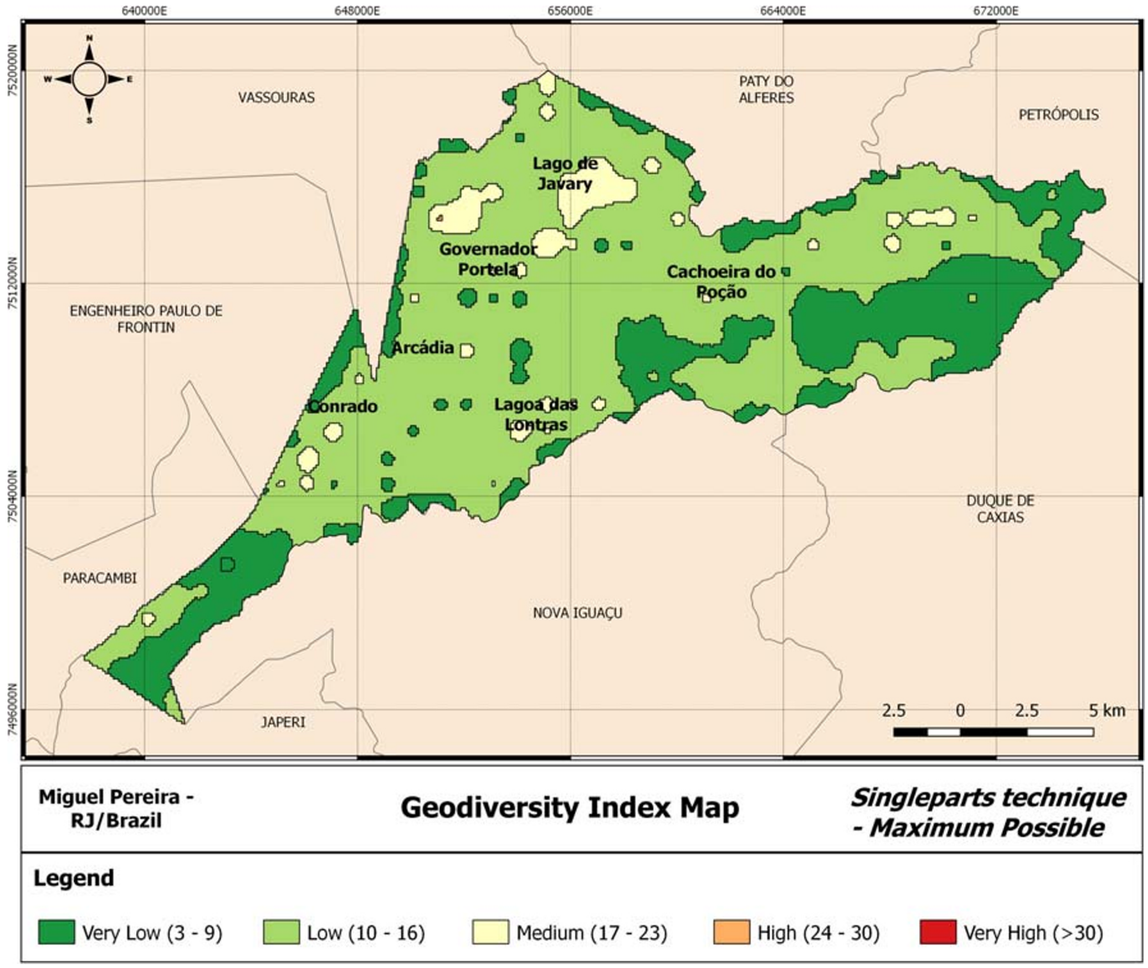

Fig. 18 Geodiversity index map of Miguel Pereira using singleparts technique and MPV classification. Projected coordinate system: UTM zone 23S, SIRGAS-2000

1:50,000) would derive a smaller grid size (Pellitero et al. 2014). For being more detailed, these maps can show more elements that may be absent in a 1:100,000 work scale. However, if a higher scale was used, the smaller cells would have less information about the soil subclasses map (at 1:100,000), influencing the quantification results.

The hydrographic quantification did not follow previous works, instead considering the use of drainage density parameter, which is widely used in hydrography studies. Adapting it to geodiversity quantitative assessment seems to be adequate, since it allows the identification of important areas for conservation, considering threats such as urban expansion or even possible landslides and floods caused by high surface runoff.

The use of the singleparts tool in the geodiversity quantification (also used by Forte et al. 2018) allowed a comparative analysis in relation to the multiparts approach. Silva et al. (2019) did a similar analysis, but they focused on the comparison of a grid cell-based method (Pereira et al. 2013) and a kernel density method (Forte et al. 2018). In this study, we considered only a grid cell-based method introducing the singleparts analysis described in Forte et al. (2018) to compare with the multiparts tool and observe the differences between them. The singleparts tool showed a significantly higher interval between the maximum and minimum scores for geodiversity sub-indices than using multiparts tool, especially in the geomorphological sub-index that exhibited scores ranging from 1 to 20 (Fig. 20). In this case, this range is explained by the high concentration of relief patterns associated to steep relief. High slopes in association to the wet climate of the region are responsible for the occurrence of many alluvium-colluvium ramps. The repetition of these landforms explains the high range of this sub-index. Because of the significative differences in comparison to the other elements, it could be interpreted as an imbalance in which geomorphology would have a higher relevance in detriment of geology, soils and hydrography. In the multiparts analysis, this does not occur, since the interval between the maximum and minimum scores of the geomorphological sub-index (1 to 6) is closer to the intervals of the other sub-indices.

The geological sub-index also presents a higher range using singleparts tool but with a lower difference in relation to multiparts range, when comparing with the

Table 1 Summary of qualitative classes distribution in each map

	Multiparts technique		Singleparts technique	
Classification	MOV	MPV	MOV	MPV
Very High	Arcadia Conrado Lagoa das Lontras	No occurrence (no area has reached the maximum potential of geodiversity)	Arcadia Conrado Lagoa das Lontras Lago de Javary Governador Portela East region near the boundary with Petrópolis Boundary with Paracambi	No occurrence (no area has reached the maximum potential of geodiversity)
High	Arcadia Conrado Lagoa das Lontras Governador Portela Lago de Javary Cachoeira do Poção East region near the boundary with Petrópolis Boundary with Paracambi	Arcadia Conrado Lagoa das Lontras	Arcadia Conrado Lagoa das Lontras Governador Portela Lago de Javary Cachoeira do Poção East region near the boundary with Petrópolis Boundary with Paracambi	Governador Portela
Medium	Highest prevalence index in the study area	Arcadia Conrado Lagoa das Lontras Governador Portela Lago de Javary Cachoeira do Poção East region near the boundary with Petrópolis	High occurrence and distribution but less than low index	Few occurrences, appearing mainly in Lago de Javary
Low	High occurrence and distribution but less than medium index	Highest prevalence index in the study area	Highest prevalence index in the study area	Highest prevalence index in the study area
Very Low	Some occurrences, appearing mainly near the limits of the study area	Some occurrences, appearing mainly near the limits of the study area but with greatest range than MOV	Some occurrences, appearing mainly near the limits of the study area	High occurrence and distribution but less than low index

Multiparts technique, MOV; multiparts technique, MPV; singleparts technique, MOV; and singleparts technique, MPV

geomorphological sub-index. The singleparts analysis resulted in more areas with higher geological diversity (Governador Portela and the region near the boundary with Petropolis) than in the multiparts analysis. This can be explained by the counting of each element (and its repetition) with singleparts technique, which considers more faults and folds influencing the results.

The geodiversity index was defined by five classes: very low, low, medium, high and very high. This type of qualitative classification allows an easy and objective reading of the results, giving clear information about the areas with the highest or the lowest geodiversity. The final geodiversity index maps, as expected, present higher indices using the singleparts technique than applying the multiparts technique for both MOV and MPV. Regarding MOV maps, the singleparts tool resulted in areas classified as very high where the relief patterns occur repetitively (e.g. Lago de Javary) showing that geomorphology is the main responsible for these very high values.

MPV represents the maximum potential scores in geodiversity assessment of an area by using the highest scores obtained in each sub-index. When summing up the maximum values of the sub-indices and considering the result as the upper limit of the classes, the final classification showed higher intervals between values than MOV. In the case of the municipality of Miguel Pereira, no cell has a very high geodiversity, showing that no area achieved this potential.

Thus, the maps obtained with the singleparts technique using both MOV and MPV generally present a low geodiversity in the study area. The map obtained applying the MOV through multiparts technique shows a medium geodiversity classification, presenting a low geodiversity if using MPV.

Although the comparison between different areas is not a goal in this work, this is important for management and territorial planning policies and nature conservation. As it is always very difficult to obtain cartographic bases at the same scale, that type of comparison would benefit by defining the

Fig. 19 Sites located in areas with high and very high geodiversity indices in Miguel Pereira municipality, according to the geodiversity index maps: **a** Arcadia and Conrado, **b** and **c** Conrado, **d** boundary with Paracambi, **e** Lago de Javary, **f** Lagoa das Lontras, **g** east region near the boundary with Petrópolis, **h** Cachoeira do Poção

MPV and applying a qualitative classification (very low, low, medium, etc.), supported in the maximum potential geodiversity in each area. Nevertheless, the comparison might still be incomplete due to scale differences; thus further studies should be carried using MPV at different scale analysis.

Based in the geodiversity definition by Gray et al. (2013) and in the methodology for its assessment described in Pereira et al. (2013), geodiversity index maps were obtained from the quantification of the geodiversity elements. From the maps' results and checking them through fieldwork, it was considered that the geodiversity of Miguel Pereira municipality is best represented using the multiparts technique and MOV. The high scores obtained from the singleparts technique are mostly related to areas with high geomorphological diversity, though that is effectively expressed in the landscape as a repetition of a same relief pattern. As highlighted in Pereira et al. (2013), it is important to assess geodiversity in a balanced manner. In this case, the use of the singleparts tool expresses a significant imbalance between geomorphology and the other elements assessed. In addition, the use of MOV is adequate to represent the geodiversity of the study area, since the objective of this work is not to compare different areas,

The geodiversity assessment is based on occurrences (geology, geomorphology and soils) and drainage density (hydrography) simply and objectively quantified, with the maps obtained being easy to read, even by non-geoscientists. These circumstances make the method a direct and efficient way to evaluate the richness of the physical environment, in

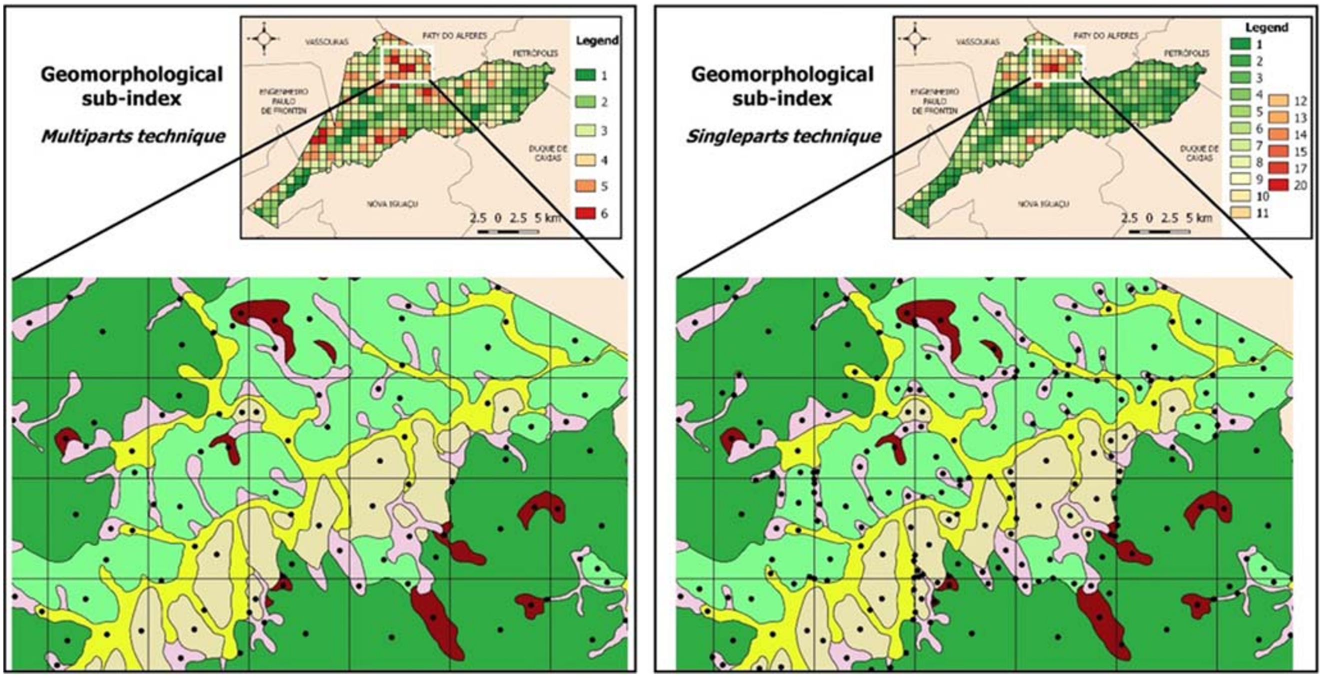

Fig. 20 Geomorphological sub-index results using the multiparts and singleparts tools, showing clear differences

line with what has been observed in previous works such as Hjort and Luoto (2010) and Santos et al. (2017).

The geodiversity index map can be used in territorial management and geoconservation, in addition to other common management tools. It allows the identification of priority areas for geodiversity management, being a clear and objective representation of the nature elements in an area, as observed also by Pereira et al. (2013).

Conclusion

The main objective of this work was to carry out methodological tests in geodiversity quantitative assessment procedures, in order to contribute to methodological discussions and the implementation of geodiversity topics in land use management. The methods performed in this study were based on some of the main methods proposed previously. Geodiversity index maps of the Miguel Pereira municipality were obtained through different techniques, using a georeferenced database representing the physical environment (geodiversity elements). The scale of the maps, the size of the grid cells, the level of detail of each map and the range of geodiversity classes were taken into account. Objective methodologies were used to obtain clear and easily readable results.

The tools performed to count geodiversity occurrences (multiparts and singleparts) supported a discussion on the improvement of the mapping methodologies, with different outputs resulting from each technique. It was considered that the geodiversity index map using multiparts technique and MOV represents more accurately the geodiversity of Miguel Pereira. However, it should be stressed that these observations are not enough to define which method is the best or even if there is a best method, since it depends on specific conditions like the geological environment and the available cartographic data.

Nevertheless, the geodiversity index map can be seen as a tool for territorial planning and management, since it provides a clear and objective information of the physical environment richness, allowing an easy interpretation. Regarding this perspective, more studies need to be performed, with the development and consolidation of methodologies that can be widely applied and replicated in different areas. Moreover, it is recommended that multiparts and singleparts comparative analyses should be applied in future studies in different scales and grid sizes, with the expectation that the results presented in this work could be compared with other areas or using different methodological approaches.

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