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Mapping land use and land cover in the Brazilian Cerrado Domains: an unsupervised approach using high spatial resolution Orbital Remote Sensing data (WPM-CBERS-4A) and clustering algorithm (K-means)

Mapeamento da cobertura e uso da terra nos Domínios do Cerrado Brasileiro: uma abordagem não supervisionada utilizando dados de Sensoriamento Remoto Orbital de alta resolução espacial (WPM-CBERS-4A) e algoritmo de agrupamento (K-means)

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Abstract

The Brazilian Cerrado is the second largest biogeographic system in Brazil and South America, comprising the most biodiverse savannah in the world. With a high degree of endemism, a remarkable diversity of vegetation physiognomy and a complex mosaic of different landscapes, the Cerrado is currently one of the Brazilian ecosystems most profoundly degraded by human activities. It is estimated that, due to rapid changes in land use and land cover, by the year 2022 more than 50% of its natural vegetation cover will have been suppressed to implement other forms of land use, predominantly related to agricultural activities. The aim of this study was to use Digital Image Processing (DIP) techniques on high spatial resolution images from Optical Orbital Remote Sensing, to produce a detailed land use and land cover map of the Ribeirão Paçoca watershed, located in the north part of the state of Goiás, a core area of the Brazilian Cerrado. We used 2 m spatial resolution data from the WPM (Multispectral Camera and Panchromatic Wide - Scan) multispectral sensor system on board the CBERS 4A (China-Brazil Earth Resources Satellite) satellite, georeferenced and orthorectified data for the dry season (July 2023). An unsupervised approach was used, using the K-means classifier algorithm. The results showed that 65% of the study area is used for anthropogenic activities, including baresoil and pasture. The areas with natural vegetation cover are restricted to isolated fragments, surrounded by land used for agricultural activities.

Keywords: Tropical Savannah; Land use and land cover; Orbital Remote Sensing.

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Resumo

O Cerrado brasileiro é o segundo maior Sistema Biogeográfico do Brasil e da América do Sul, compreendendo a Savana mais biodiversa do mundo. Com um alto grau de endemismo, uma notável diversidade de fitofisionomias e um complexo mosaico de diferentes paisagens, o Cerrado é atualmente um dos ecossistemas brasileiros mais profundamente degradados pelas atividades humanas. Estima-se que, devido às rápidas mudanças na cobertura e uso da terra, até o ano 2022, mais de 50% da sua cobertura vegetal natural já havia sido suprimida para implementação de outras formas de uso da terra, predominantemente, relacionadas às atividades agropecuárias. O objetivo deste estudo foi empregar técnicas de Processamento Digital de Imagens (PDI), sob imagens com propriedade de alta resolução espacial, provenientes de Sensoriamento Remoto Orbital Óptico, e produzir um mapa de cobertura e uso da terra, em escala de detalhe, da bacia hidrográfica do Ribeirão Paçoca, situada no extremo norte do estado de Goiás, área core do Cerrado brasileiro. Utilizou-se dados com 2 m de resolução espacial, provenientes do sistema sensor multispectral WPM (*Multispectral Camera and Panchromatic Wide – Scan*), a bordo do satélite CBERS 4A (*China-Brazil Earth Resources Satellite*), dados georreferenciados e ortorretificados referentes à estação seca (Julho de 2023). Utilizou-se uma abordagem não supervisionada, mediante o algoritmo classificador K-means. Os resultados indicaram que 65% da área em estudo apresenta usos relacionados às atividades antrópicas, incluindo solo exposto e pastagens. As áreas com coberturas vegetais naturais estão restritas a fragmentos isolados entre si, cercados por terras de uso nas atividades agropecuárias.

Palavras-Chave Savana Tropical; Cobertura e uso da terra; Sensoriamento Remoto Orbital.

Introduction

Orbital remote sensing images are the most comprehensive source of data on the Earth's surface, its ecosystems and landscapes, contributing directly to monitoring and understanding the processes that act to transform it (JENSEN, 2007). In this sense, they represent one of the viable alternatives for studying the dynamics that occur within the Brazilian Morphoclimatic Domains, especially as they provide opportunities for synoptic analyses of large areas (ASNER et al., 2005). Among the possible Orbital Remote Sensing data applications, in this study, attention is drawn to mapping land use and land cover, especially at the scale of river watershed, as this is the main unit for planning and managing water resources in Brazil (TUCCI, 1997; MMA, 2007).

Land use and land cover maps describe the terrestrial environment in terms of natural vegetation cover and uses related to human activities, respectively (CIHLAR and JENSEN, 2001). In this perspective, the expression "land cover" refers more directly to the surface covering, while the term "land use" denotes its cultural use, referring to the activities that are carried out on it (NOVO, 1989, ARAÚJO FILHO, 2007). Therefore, land cover and land use mappings comprise a basic input for environmental and/or economic planning and management, by providing detailed and up-to-date information, on the elements of the landscape, as well as the potential, restrictions or even inconsistencies in the use of resources (SILVA et al., 2023).

Changes in land use and land cover are one of the main drivers of a series of environmental, climatic, economic and social impacts (IPCC, 2007, 2021). From this perspective, their study is fundamentally important for implementing strategic public policies for environmental management, biodiversity conservation, planning and territorial development (CAMARA et al., 2023). For instance, they corroborate the Nationally Determined Contribution (NDC) that Brazil presented in 2015 to the United Nations Framework Convention on Climate Change, where it emphasizes its commitment to achieving zero illegal deforestation by the year 2030, in addition to offsetting greenhouse gas (GHG) emissions from the suppression and changes in natural vegetation cover (BRASIL, 2016).

Of the natural ecosystems that compose the Brazilian environmental matrix, the Cerrado Biogeographic System has been one of the most profoundly degraded by human activities in recent decades (BARBOSA, 2011). The degradation of the Brazilian Cerrado, as a process, is related with various drivers, especially the expansion of economic frontiers, which are directly or indirectly associated with the state, public policies, the development discourse of the national economy, the international division of labor, national and international geopolitics, among others (SILVA, 2018). Statistically, it is known that, the degradation rates of the Brazilian Cerrado by human activities, as those by suppression of its natural vegetation cover, is markedly higher than that observed in other Brazilian Morphoclimatic Domains, such as in the Amazônia (MMA, 2017; MAPBIOMAS, 2023).

Historically, changes in land use and land cover represent one of the factors with the greatest impact on and threat to the Brazilian Cerrado, causing significant losses of habitat, biodiversity and, consequently, ecosystem services (MYERS et al., 2000). Has been estimated that, by the mid-2000s, almost half of the continuous landscapes associated with the Cerrado's vegetation cover had already been removed for other forms of land use (MESSIAS, 2022). New data shows that, in 2022, the suppression of natural vegetation cover in the Cerrado increased by 25% compared to 2021, indicating that more than 50% of its remnants have in fact already been suppressed, and that changes in land use and land cover are mainly related to the expansion of areas used for agriculture and cultivated pastures (CHAVES, 2023).

In this context, the objective of this study was to apply Digital Image Processing (DIP) techniques on high spatial resolution Optical Orbital Remote Sensing data derived from the WPM (Multispectral Camera and Panchromatic Wide - Scan) multispectral sensor system on board the CBERS 4A (China-Brazil Earth Resources Satellite) satellite, in order to map and analyze land use and land cover conditions in the Ribeirão Paçoca watershed, Goiás State. The Ribeirão Paçoca watershed is located in the north part of this state, a core area of the Cerrado Biogeographic System (BARBOSA, 2011). Here we show the potential of using CBERS 4A data, a very important opened dataset for various applications that require mapping on a refined scale, exploring the integration between panchromatic and multispectral bands in order to implement land use and land cover mapping at a detailed scale (1:25.000).

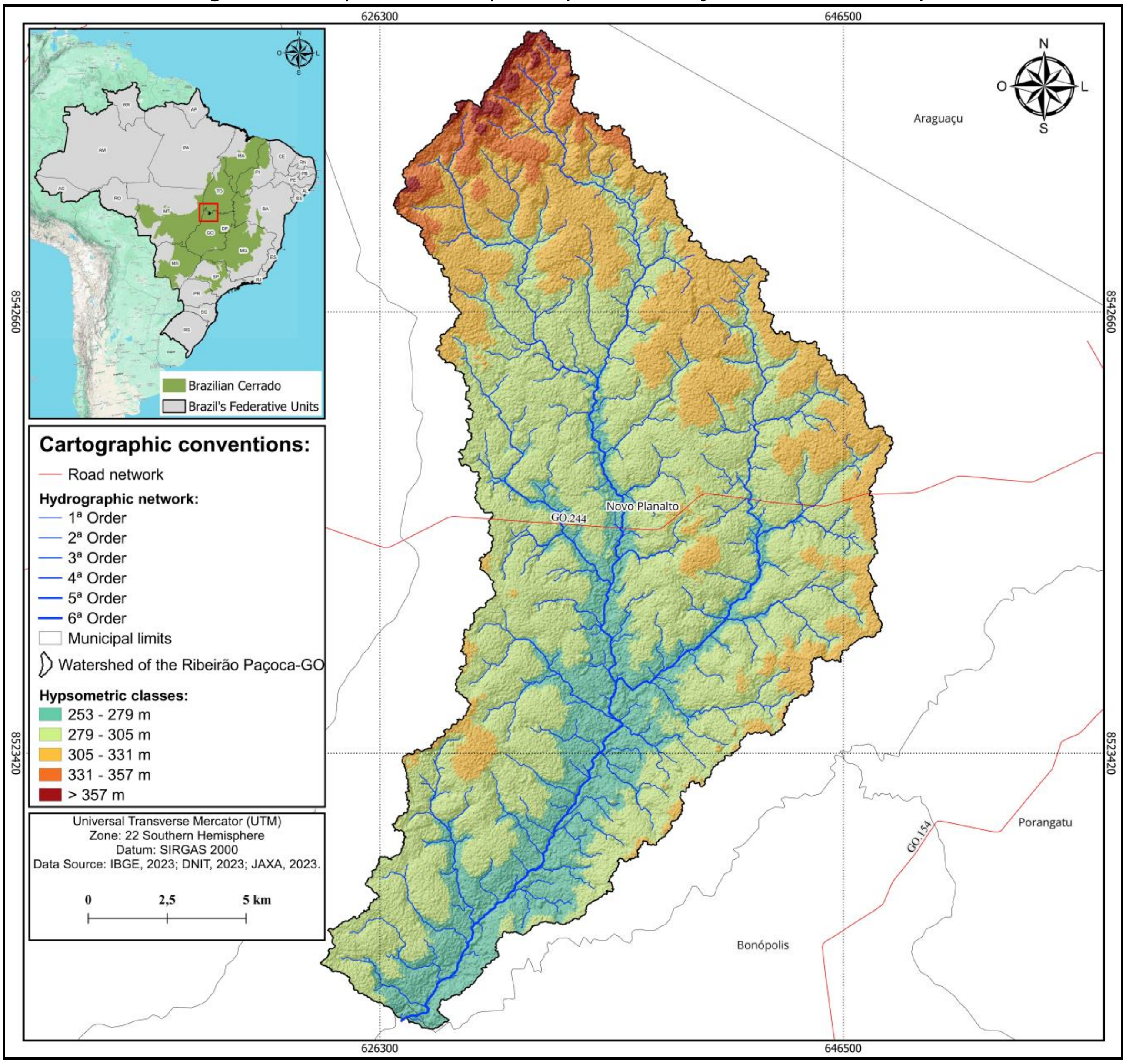
Despite the existence of a growing library of mapping relating to natural vegetation cover and anthropogenic uses in the context of the Brazilian Cerrado, it is so important highlight that, for the most part these products comprise and serve reconnaissance scales and are not applicable, for example, to large scales (e.g., 1:25,000). In other words, the most part these products are not applicable on scales of small hydrographic watershed, such as the Ribeirão Paçoca-GO hydrographic watershed, which requires the use of data with greater spatial resolution (MENEZES and ALMEIDA, 2012). The justification for this study consisted on the premise that up-to-date and detailed land use and land cover mapping is of great importance for multiple applications in the field of environmental and territorial planning (NOVO, 1989). Furthermore, studies applying unsupervised digital classification implemented on high spatial resolution data (e.g., WPM-CBERS-4A) are still scarce in literature (SILVA, 2022).

Methodology

Study Area

The study area comprises the Ribeirão Paçoca watershed (Figure 1), with an area of 53.285 ha, located in the north region of the state of Goiás, a core area of the Brazilian Cerrado.

Figure 1 – Map of the study area (Ribeirão Paçoca watershed-GO).



Source: Created by the authors (2024).

The Ribeirão Paçoca watershed is located entirely in the Novo Planalto-GO municipality, and represents more than 58% of municipality territorial area. In the recent decades, the region where the Ribeirão Paçoca watershed is located has become a stage for significant changes in land use and land cover, with a strong process of suppression of natural vegetation cover and of its conversion for land use areas by cultivated pastures and agricultural activity (SUESS and SOBRINHO, 2014; ANDRADE et al., 2017; FERREIRA and LINO, 2021).

According to the latest demographic census carried out by the Brazilian Institute of Geography and Statistics (IBGE), the municipal population is approximately 3.716 inhabitants, with a population density of 2.96 inhabitants per square kilometer (IBGE, 2022). The municipality has an estimated Gross Domestic Product (GDP) of R$25.200.40. In this context, its main socio-economic activities include cattle breeding and the production of agricultural commodities. According to data from the IBGE (IBGE, 2022), it is estimated that by 2021, this municipality had allocated approximately 10% (13.100 ha) of its land just to the soy and corn commodities production.

Theoretical-methodological approach

The methodology of this study consisted of a literature review and the use of DIP techniques for digital classification, specifically, in high spatial resolution images (2 m). The delimitation of the Ribeirão Paçoca watershed (Figure 1), as well as the extraction and hierarchization of its hydrography network (STRAHLER, 1957), was carried out using the Geographic Resources Analysis Support System-GRASS software. The procedure was based on the Digital Elevation Model (MDE), derived from Shuttle Radar Topography Mission, made available free on the website of Brazilian Geomorphometric Database (TOPODATA), in the context of the National Institute for Space Research (INPE), with a final spatial resolution of 30 m, contributing to diverse applications in environmental modeling (VALERIANO, 2008).

As a result of successive advances in orbital sensor systems, more detailed studies, for example at a scale of 1:25.000, can now rely on data obtained from sensors with decimetric spatial resolution (SANO et al., 2009). This is the case with the WPM (Multispectral Camera and Panchromatic Wide - Scan) multispectral sensor system, on board the CBERS 4A (China-Brazil Earth

Resources Satellite) satellite, which provides data with up to 4 m and 2 m spatial resolution, in the multispectral and panchromatic bands, respectively. In this study, data from the WPM multispectral sensor system was used to map and analyze land use and land cover conditions in the Ribeirão Paçoca watershed-GO, using georeferenced, orthorectified and high spatial resolution (2 m) Orbital Remote Sensing data from the Cerrado dry season as a reference (HOFMANN et al., 2023).

The data used in this study dates from the 15th and 20th of July 2023, as this is a month that historically has low cloud cover in the context of the study area. Specifically, the cloud cover in the images used is 0%, and the images correspond to the following path/row: 209/130 and 210/130. The data was accessed and acquired from the Image Generation Division (IGD) of the National Institute for Space Research (INPE). All the data processing routines were implemented in the Google Earth Engine platform. One of the advantages of this processing environment is that, in addition to the possibility of working with big Earth Observation Data collections, it has extensive computing capacity for processing geospatial data in the cloud (Cloud Services), where users have at their disposal, free access to data processing algorithms (GORELICK et al., 2017).

With regard to the digital classification of the images, in order to map the different forms of use cover and land cover, this study used the Space-First approach, a concept of satellite image classification that considers the choice of individual images from specific dates for mapping (SIMOES et al., 2021). The digital classification of the images was based on the non-supervised approach, using the K-means classifier algorithm, one of the most widely used data clustering methods, which is relatively simple to apply to satellite images in Google Earth Engine (OUCHRA et al., 2023).

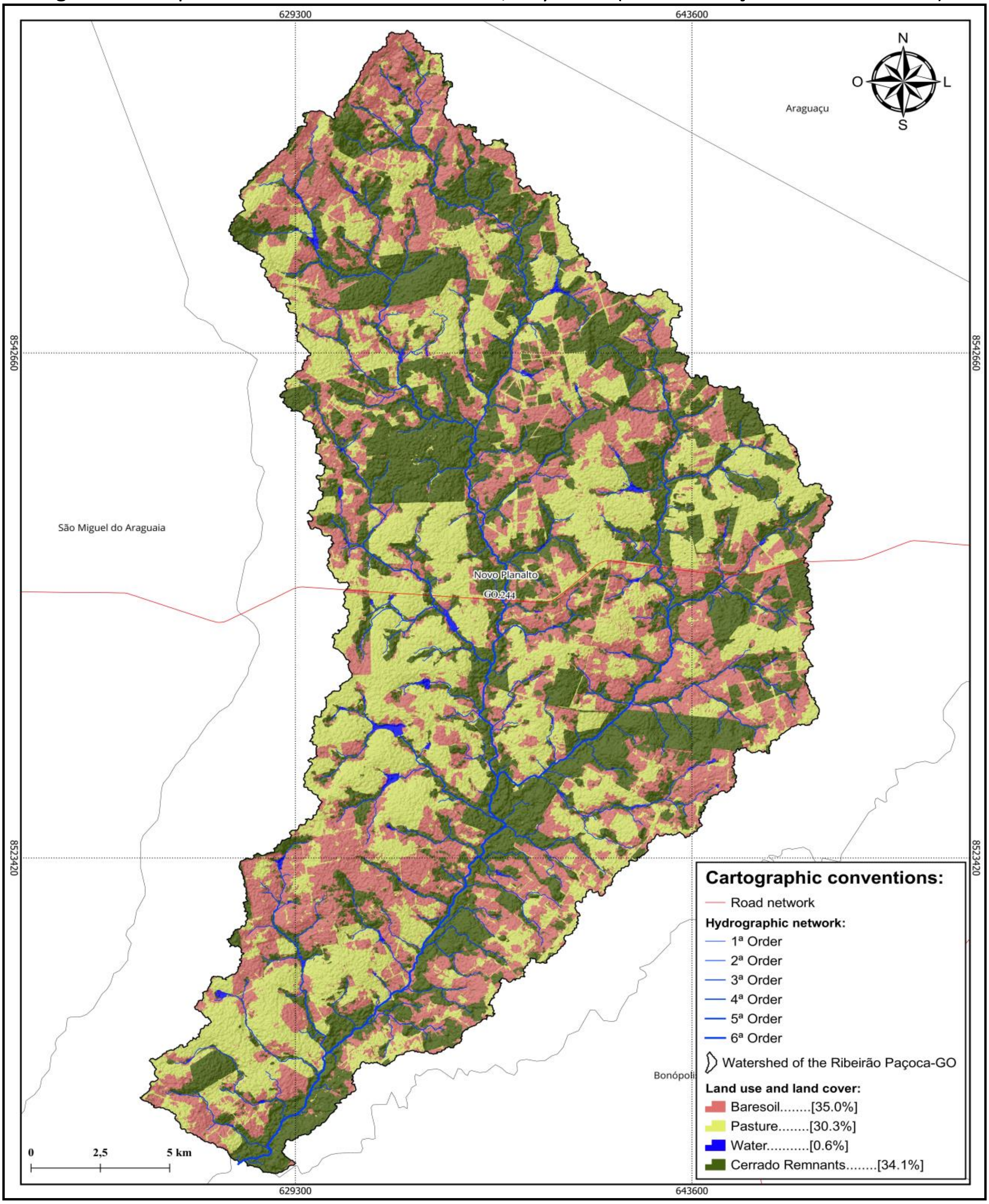
By extracting initial grouping averages from random samples defined by the user from the input data, K-means returns a rigid classification (GULÁCSI and KOVÁCS, 2020). As summarized by Likas et al. (2003), the main objective of this method is to find similarities in the data set by segmenting the P data into K groups, with the aim of reducing the distance between the respective clusters. It should be noted that, among the various methods for calculating distances between data, the Euclidean distance was used for this work, precisely because it is the standard configuration (PILOYAN, 2017). A random sample of 2.000 pixels from the mosaic was used as training data, with the number of output clusters set at 4 (four). The output was the image with each pixel grouped into one of the N clusters (BORRA et al. 2019), which comprise the following thematic mapping classes: Cerrado Remnants, Pasture, Baresoil and Water.

In terms of validation, a random sample of 1.200 points was generated under the classified image. Each pixel drawn was validated individually through visual interpretation, considering the classified image and the respective input data (mosaic). At the end of this analysis routine, the confusion matrix was generated, which allowed the classification algorithm's performance metrics to be obtained. An overall accuracy of 0.98 and a Kappa coefficient of 0.97 were obtained, demonstrating that the classification algorithm performed well in relation to the data used (COHEN, 1960). The subsequent procedures consisted of exporting the classified image to the Geographic Information System (GIS) environment, using the free and open source software QGIs, version 3.22 Biatowieza; vectorization, calculation of the area of the thematic classes and cartographic elaboration.

Results and discussion

Considering Figure 2, it is possible to observe the different conditions of land use and land cover, highlighting the different natural and anthropogenic aspects on a landscape scale in the Ribeirão Paçoca-GO watershed. In this sense, it can be seen that the land cover conditions evidenced by the Cerrado Remnants thematic class are mainly associated with the hydrographic network, comprising ecosystems where Gallery Forest and Riparian Forest formations predominate. Other smaller fragments of Cerrado Remnants are also identified scattered throughout the watershed area, contrasting with vast areas of land use with cultivated pastures and areas of exposed soil. While the largest fragments of Cerrado Remnants are associated with the main channel of the hydrographic network, most of the first and second order channels are located in areas of anthropogenic use, with areas of exposed soil prevailing upstream, and areas used for pasture downstream.

Figure 2 – Map of the land use and land cover, July 2023 (Ribeirão Paçoca watershed-GO).



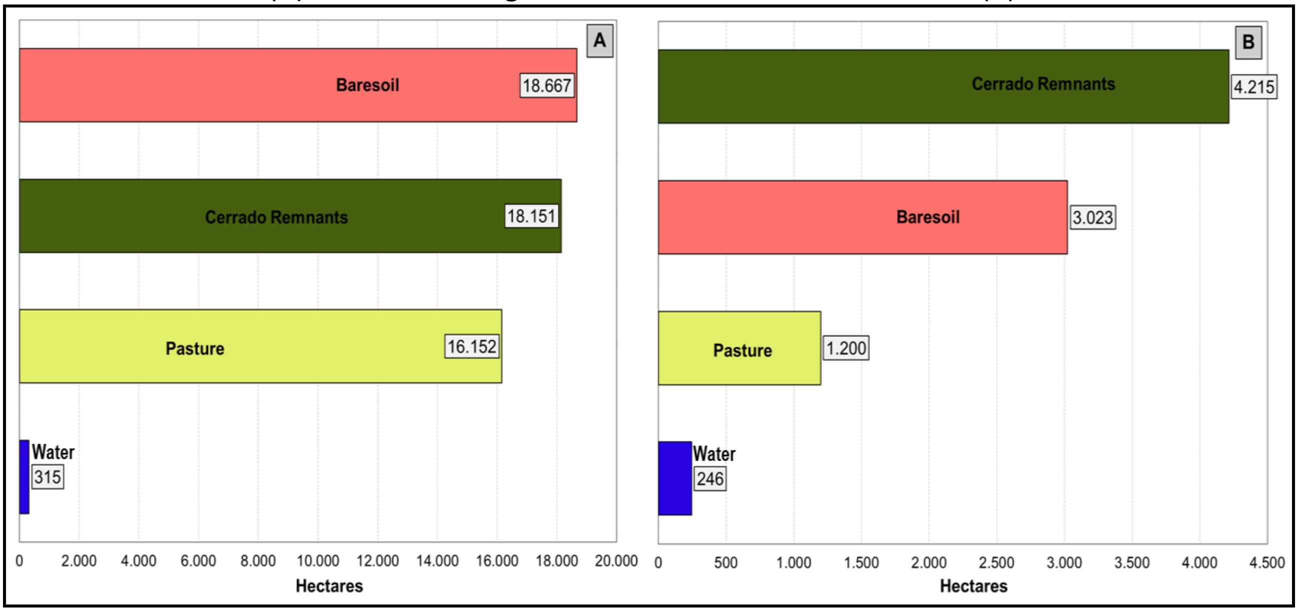
Source: Created by the authors (2024).

From this mapping (Figure 2), most of the headwater areas have no natural vegetation cover. In this sense, attention is drawn to the importance of detailed and up-to-date land use and land cover mapping in the formulation of soil management and protection practices, in the face of its disintegration, transportation and subsequent deposition along the channels of the hydrographic network, through erosive processes (BOTELHO, 1999). The fact that pasture areas are one of the main forms of land use in the watershed highlights the importance of conservation practices aimed a proper pasture management, given the impacts of the degradation of planted pastures on the soils and water resources of the Brazilian Cerrado (ABDON, 2004; MOTA JUNIOR et al., 2020; REIS et al., 2023).

The areas whose land use is cultivated pasture are spatially distributed throughout the all Ribeirão Paçoca watershed. To a greater extent, the areas where land is used for cultivated pastures can be identified in the north-central part of the watershed. Given this context, it is understood that the area under study reflects the current land use scenario in the Brazilian Cerrado domains, predominantly uses related to anthropogenic activities, with an emphasis on land use for pasture. The fragments of Cerrado Remnants in the study area show the process of suppression of its natural vegetation cover and its impacts on biodiversity and ecosystem services (GRANDE et al., 2020).

Considering Figure 3, it is possible to observe the statistics of the thematic mapping classes in the context of the watershed and the Permanent Preservation Areas of the hydrography network. As can be seen, the majority (65%) of the Ribeirão Paçoca watershed area has land uses related to anthropogenic activities, predominantly pasturelands and agricultural activities. In this context, it is important to note that most of the areas mapped as exposed soil are associated with the occurrence of degraded pastures and areas of land use geared towards agricultural activities, specifically areas where corn and soybeans are grown, thus comprising arable land that is fallow and/or being prepared for new plantings. The dynamics of agricultural land use in the Brazilian Cerrado is not only environmentally complex and shows significant variations between its regions, but is also associated with various factors and can be better understood, for example, in the light of the agricultural calendar (VALE, 2017).

Figure 3 – Summary of land use and land cover areas (ha) in the context of the studied watershed (A) and considering the Permanent Preservation Areas (B).



Source: Created by the authors (2024).

Representing more than 50 million hectares (ha) in the Brazilian Cerrado domains (MAPBIOMAS, 2023), land used for cultivated pasture comprises approximately 30% of the total area of the Ribeirão Paçoca watershed, showing the strong presence of extensive cattle breeding systems. An important aspect related to this form of land use is that, historically, most part of the pastures cultivated in the context of the Central Brazil region, the core area of the Cerrado Biogeographic System, are high degraded, comprising one of the greatest obstacles to the effective establishment of environmentally and economically sustainable cattle ranching in the Brazilian Cerrado (PERON and EVANGELISTA, 2004). In this sense, the importance of mapping and monitoring the quality of Brazilian cultivated pastures is needed, given their representativeness in terms of land use (FERREIRA et al., 2013).

In addition to planted pastures and areas with exposed soil, in relation to the different forms of land appropriation and use in the Ribeirão Paçoca watershed, this study draws attention to the significant occurrence of small dams in water bodies associated with the hydrographic network and Permanent Preservation Areas (Figure 2). Based on the detailed map showed here, it was possible to identify several dams along the 3rd, 4th and 5th fluvial order rivers. In total, 98 watercourse dams were identified and mapped. With a high density throughout the watershed, more than 99% of these mapped dams have an area greater than 1 Ha, which reinforces direct human interference in the Cerrado ecosystems. It is important to note that, although these dams certainly have important and diverse uses, they can have considerable socio-environmental impacts, as well as posing obvious degradation risks to ecosystems and it services (NAVA, 2018).

The high density/quantity of watercourse dams, together with the representativeness of uses related to anthropic activities in Permanent Preservation Areas, highlights the need for sustainable practices in the Ribeirão Paçoca watershed (Figure 3). Permanent Preservation Areas are intended to protect soils and, above all, riparian and gallery forests. These areas comprise ecosystems that perform critical ecosystem services in a scenario where the Brazilian Cerrado is becoming increasingly hot and dry (HOFMANN, 2021). Examples include, but are not limited to: the maintenance of headwatersand rivers; maintenance of the groundwater; prevention of soil salinization; maintaining edaphic fauna; cycling of nutrients and organic carbon; replenishment of the topsoil and maintenance of soil fertility; containment of erosion processes and silting up of the channels.

Final remarks

The results of this study indicate that, around 65% of the Ribeirão Paçoca watershed has land uses related to anthropic activities. Based on our detailed mapping, it is estimated that more than half (51.1%) of the Permanent Preservation Areas associated with the hydrographic network have uses related to anthropic activities. The land covered by natural vegetation is restricted to isolated fragments (Cerrado Remnants), mostly associated with the Permanent Preservation Areas of watercourses above the 4th order, according to Strahler's classification (1957). In this sense, attention should be drawn to the fact that these areas are, for the most part, hydrologically sensitive to anthropogenic uses (SIEFERT and SANTOS, 2015). These areas play a crucial role in maintenance of the groundwater, as they are surrounded by land used intensively for agricultural activities, where there is a predominance of cultivated pasturelands and commodity agriculture.

The results shows here suggests that further studies dedicated to the analysis of landscape metrics in the Ribeirão Paçoca watershed are needed, where the land use and land cover data presented here can be used as reference for environmental analysis in fine scale. Considering the predominance of areas of baresoil in this watershed, it is also suggested that further studies must be dedicated to distinguish what is effectively Exposed Soil related to agricultural activities and what are areas of Exposed Soil related to degraded pastures. In both cases, it should be noted that these areas can directly contribute to land degradation, for example, through soil compaction or disintegration, transportation and deposition, which can directly interfere the hydrological balance of the watershed.

The WPM multispectral sensor system on board the CBERS 4A satellite used here was not only helpful to map and analyze land use and land cover conditions, but also to map water bodies on a detailed scale. A detailed mapping of water bodies can reflect and contribute directly to the formulation and implementation of a new water use policy in the Brazilian Cerrado, especially in the Goiás state, where the multiple water uses have historically been marked not only by various conflicts between the actors who make use of this resource, but also by serious impacts on ecosystems (MENDONÇA, 2004, 2015; CORRÊA e GONÇALVES, 2019).

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