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Geo-environmental characteristics of the Pardo River Watershed, Mato Grosso do Sul: knowledge bases for territorial planning purposes

Características geoambientais da Bacia Hidrográfica do Rio Pardo, Mato Grosso do Sul: bases de conhecimento para fins de planejamento territorial

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ABSTRACT: This study presents the results of the geo-environmental characterization of the Pardo River watershed, in the state of Mato Grosso do Sul, Brazil. The main objective was to evaluate the environmental conditions to generate data that can support territorial planning and ordering. The area was chosen due to the approval of the seven axes for the implementation of Small Hydroelectric Power Plants (SHPPs). The geospatial data used were obtained from the USGS, CPRM, IBGE and MapBiomas repositories. Lithology, climate, soils, geomorphology, geomorphometry (drainage network, watershed geometry, relief characteristics) and land use and cover were analyzed. ArcMap 10.8.2 was used. The results show an ecologically fragile environment that is highly susceptible to soil erosion and sandification. Agricultural activities carried out in the area, for the most part, do not consider agricultural suitability and restrictions, and are practiced in a predatory manner. Changes in land use and cover have impacted terrestrial (erosion, sandification, sedimentation) and aquatic ecosystems (degradation of water quality and quantity). The expansion of soy and eucalyptus cultures and the construction of SHPPs will put even more pressure on the watershed natural resources and generate socio-environmental conflicts.

Keywords: predatory agriculture; human impact; soil erosion; soil sanding; land-use change.

RESUMO: Este trabalho apresenta os resultados da caracterização geoambiental da bacia hidrográfico do rio Pardo, localizada no estado de Mato Grosso do Sul (Brasil). O objetivo principal foi avaliar as condições ambientais a fim de gerar dados que subsidiem o planejamento e ordenamento territorial. A escolha da área foi motivada pela aprovação de sete eixos para implantação de Pequenas Centrais Hidrelétricas (PCHs). Os dados geoespaciais utilizados foram obtidos nos repositórios da USGS, CPRM, IBGE e MapBiomas. Os parâmetros analisados foram: litologia, clima, solos, geomorfologia, geomorfometria (rede de drenagem, geometria e características do relevo) e uso e cobertura da terra. O *software* utilizado foi o ArcMap 10.8.2. Os resultados obtidos mostram um ambiente ecologicamente frágil, altamente suscetível à erosão do solo e ao processo de arenização. As atividades agrícolas desenvolvidas na área, em sua maioria, não consideram as aptidões e restrições agrícolas, e são praticadas de forma predatória. As mudanças no uso e cobertura da terra têm impactado os ecossistemas terrestres (erosão, arenização, sedimentação) e aquáticos (degradação da qualidade e quantidade de água). O avanço dos monocultivos de soja e eucalipto e a construção de PCHs irão pressionar ainda mais os recursos naturais da bacia hidrográfica e gerar conflitos socioambientais.

Palavras-chave: agricultura predatória; impactos humanos; erosão do solo; arenização; mudanças no uso.

1. Introduction

Soil erosion is considered one of the most serious environmental problems associated with land use (Morgan, 2005), due to the extensive elimination of primary vegetation cover and the adoption of production systems that use management practices that are incompatible with the fragility of the environment. These changes directly affect nutrient and carbon cycling and soil productivity, generating a significant impact on the environment and the global economy (Borrelli *et al.*, 2017).

According to Strahler (1956), erosion is characterized by the transport of matter or sediment particles from their initial location through a fluid agent. In nature, the main fluid media acting on the Earth's crust are water, air, and ice (Zăvoianu, 1985). The factors that influence the emergence, development, and outcome of the erosion process include climatic, hydrological, topographic, geological, pedological conditions, vegetation cover, as well as economic, technical, and socioeconomic conditions (Williams, 2003). Although these factors combine and interact, one factor, or group of factors, may prevail and become the most important. For Poesen (2018), accelerated erosion is mainly driven by changes in land cover, use, and management. The problem is aggravated in areas with sandy soils, which in addition to being chemically poor, have low water storage capacity and high susceptibility to erosion.

In the Pardo River Watershed (PRW), located in the eastern region of the state of Mato Grosso do Sul, sandy soils originated from the sandstones of the Caiua Group (undivided) correspond to 37.6% of the watershed area. These soils are subjected to intense agricultural exploitation, mainly with extensive animal farming, which can quickly lead to degradation, as demonstrated by the work of Sousa (2021) in the Ribeirão das Botas watershed, sub-watershed of the Pardo River. Degraded pastures and areas in sandification processes were also reported by Capoane (2021; 2022) in the Guariroba stream watershed, sub-watershed of Ribeirão das Botas.

In 2019, the *Inventário Participativo de Potencial Hidrelétrico* [Participatory Inventory of Hydroelectric Potential] in the Pardo River Watershed was carried out in collaboration between the Mato

Grosso do Sul Environment Institute (IMASUL) and the National Electric Energy Agency (ANEEL), resulting in the approval of seven axes for the implementation of Small Hydroelectric Power Plants (SHPPs) (IMASUL, 2019; ANEEL, 2019; 2021). It is noteworthy that in this watershed there is already a Hydroelectric Power Plant (HPP) in operation, the Mimoso HPP, and two Small Hydroelectric Power Stations, Santa Izabel and Energia Maia Ltda. In addition to the energy potential, the PRW plays a crucial role in the production of raw water, providing 50% of the water that supplies the city of Campo Grande, capital of Mato Grosso do Sul state. In addition, the municipalities of Ribas do Rio Pardo, Bataguassu, and Jaraguari also depend on surface water sources to meet their public water supply needs. This interconnection among agricultural and energy production and water supply further emphasizes the relevance of the PRW in the region.

Given the importance of the Pardo River watershed in water, energy, and food production, and recognizing that knowledge of environmental conditions is fundamental to understanding its dynamics and for proper management of natural resources, this work aims to generate data on the geo-environmental aspects of the area. This information has the potential to assist planners and managers in making informed decisions, since, as demonstrated by Nkonya *et al*. (2015), the cost of action against land degradation is considerably lower than the cost of inaction, and the returns from action are highly favorable.

2. Methodology

2.1. Study area

The Pardo River Watershed is located in the eastern half of the state of Mato Grosso do Sul (Figure 1), covering 14 municipalities, the three with the largest area being Ribas do Rio Pardo (37.0%), Campo Grande (22.3%), and Santa Rita do Pardo (12.9%). The other municipalities, in descending order of area representation, are: Jaraguari (6.1%), Bandeirantes (5.8%), Nova Alvorada do Sul (5.0%), Bataguassu (3.9%), Nova Andradina (3.3%), Sidrolândia (2.8%), Camapuã (0.6%), Anaurilândia (0.2%), Terenos (0.06%), Brasilândia (0.03%), and Rochedo (0.00003%).

In the context of geographical micro-regions, the study area is within Três Lagoas (49.91%), Campo Grande (37.04%), Nova Andradina (7.43%), Dourados (5.04%), and Alto Taquari (0.58%). The expansion of forestry activity is notable in the Três Lagoas micro-region, as the area occupied with planted forests (eucalyptus and rubber trees) is the largest in the state of Mato Grosso do Sul. Eucalyptus plantations tend to grow with the installation of one of the world's largest pulp mills in the municipality of Ribas de Rio Pardo. This micro-region is the state's fourth most populous, concentrating 6.4% of the population, and the municipality of Três Lagoas is the state's third most populous municipality (IBGE, 2015). According to Tisott *et al.* (2017), the insertion of forestry activity influenced the migration of labor from animal farming, the predominant agricultural activity (MapBiomas, 2022). The micro-region of Campo Grande is considered the major economic center of the state and, according to data from the State Secretariat for the Environment, Planning, Science and Technology (SEMAC), the most influential sectors are industry and trade and services.

The land occupation of Mato Grosso do Sul is characterized as concentrated, the result of the historical process of capitalist appropriation of land by the alliance between landowners and the State (Nardoque, 2016). This alliance allowed landowners to accumulate large tracts of land, whereas most the rural population is made up of small farmers, squatters, and landless rural workers. This land concentration holds significant consequences for the state's economy, society, and environment.

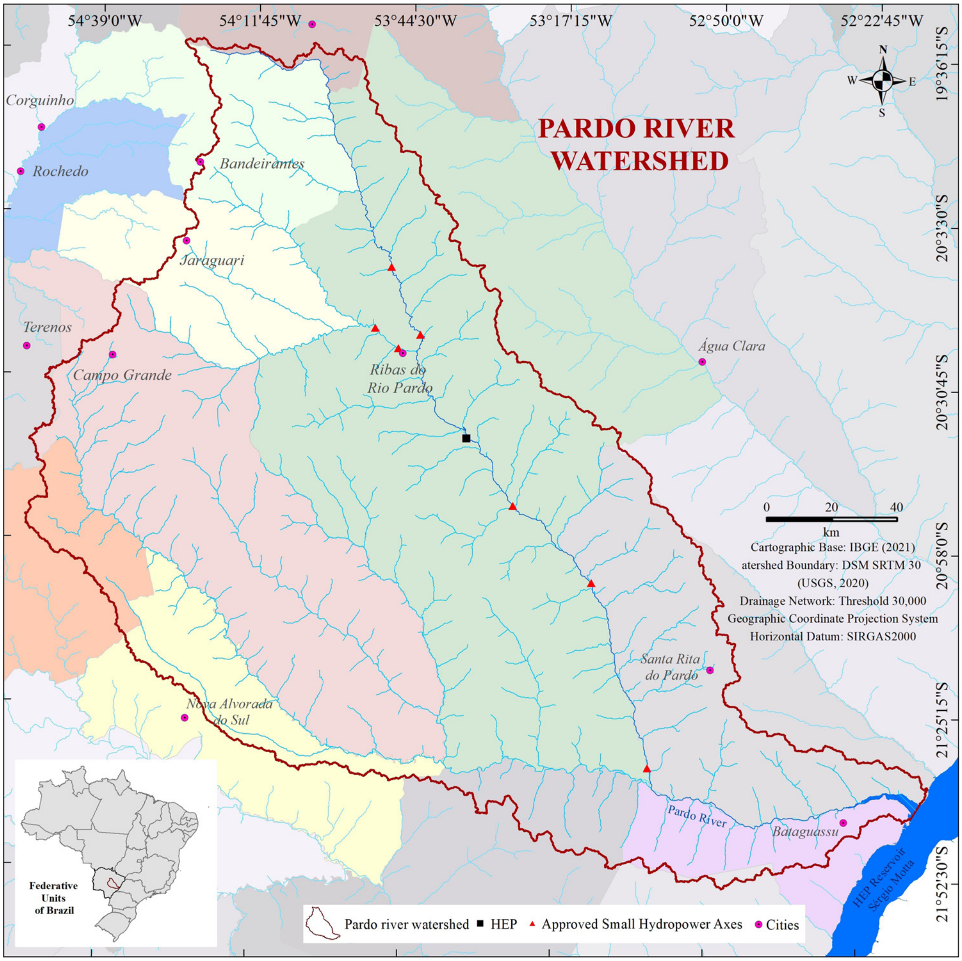

FIGURE 1 – Brazil, with emphasis on the state of Mato Grosso do Sul and the Pardo River Watershed, and the municipalities where the study area is located.

SOURCES: U.S. Geological Survey (USGS, 2020) and Brazilian Institute of Geography and Statistics (IBGE, 2021).

Most small rural properties are in Agrarian Reform Settlement Projects and, according to data from the MS Portal of Information and Geopositioning (PIN/MS, 2023), there are currently 20 federal settlements and two state settlements in the PRW, making up 2.4% of the territory. There are also 11 Settlement Projects created with funding from the Land Bank Program, covering 3,585.05 hectares, which corresponds to 0.11% of the PRW. These settlement projects are of great importance for the region, as family farming is responsible for producing a large part of the food consumed by the Brazilian population, in addition to generating jobs and income for local communities.

2.2. Geographical data

The reference geospatial data used were: the Shuttle Radar Topography Mission 30 m (SRTM) Digital Surface Model (DSM) of the year 2000 (USGS, 2020), used as the cartographic base from which the geomorphometric attributes were derived; the lithology vector base provided by the Mineral Resources Research Company (CPRM) at a scale of 1:1,000,000 (Lacerda Filho *et al.*, 2006), updated by the IBGE (2021); the vector base of soils at a scale of 1:250,000 (IBGE, 2021); the work of Alvares *et al.* (2014) with the climate classification; the representation of the biome boundaries compatible with the scale of 1:250,000 (IBGE, 2019); and the work of Sano *et al.* (2019), which delineated 19 units of the Brazilian savannah based on geomorphology, soil, geology, vegetation, plant diversity, and rainfall.

Land use and land cover were analyzed based on data provided by the MapBiomas Network, collection 6 (MapBiomas, 2021), whose classification methodology can be found in Souza *et al.* (2020) and in the MapBiomas hub. The time periods selected for the analysis were 1985, 1995, 2005, and 2020. The year 1985 corresponds to the beginning of the historical series of Landsat images. The quantification for each class of use was carried out using the ArcGIS 10.8.2 software (Environmental Systems Research Institute - ESRI, 2022). Land use and land cover data were also correlated with the Rural Environmental Registry (CAR) declarations in order to identify environmental liabilities (BRASIL, 2012; MATO GROSSO DO SUL, 2014).

The results of the geo-environmental characterization are presented in thematic maps. Spatial clippings from Google Earth, together with photographs taken during fieldwork, are used to complement the analysis and discussion of the results.

3. Results and discussion

The geology of the PRW (Figure 2a) is composed of the basalts of the Serra Geral Formation (13.9%), which are over the aeolian sandstones of the Botucatu Formation and under the Neo Cretaceous siliciclastic rocks of the undivided Caiua Group (78.3%), Santo Anastácio Formation (1.5%), and Neogene Lateritic-Detritus Covers (1.8%). Pleistocene Terraces (1.4%), Holocene Terraces (2.6%), Holocene Alluvial Deposits (0.3%), Holocene Colluvial Deposits (0.02%), Holocene Fluvial-lacustrine Alluvium (0.02%), and continental water bodies (0.2%) make up the rest of the PRW area (IBGE, 2021).

The lava flows of the Serra Geral Formation, one of the largest volcanic provinces in the world

(Bigarella *et al.*, 1985), date back to the Early Cretaceous and covered a large intracratonic sedimentary basin (Paraná Basin) that began to sink at the beginning of the Paleozoic. The largest volume of lava was extruded around 134.5 Ma (Pinto *et al.*, 2011; Janasi *et al.*, 2011), but, according to Brückmann *et al.* (2013), fissure volcanism manifested itself over a longer period of time, up to 129 Ma. In a study developed by Hartmann *et al.* (2019), the authors estimated that the duration of the magmatism of the Serra Geral Formation was longer than previously thought, and would have lasted approximately 16 Ma.

The dominant volcanic rocks (95% of the volume) in the Serra Geral Formation are basalt, basaltic andesite, and andesite, followed by rhyodacite and little rhyolite (Hartmann, 2014). These cover the sandstones of the Botucatu Formation (Machado *et*

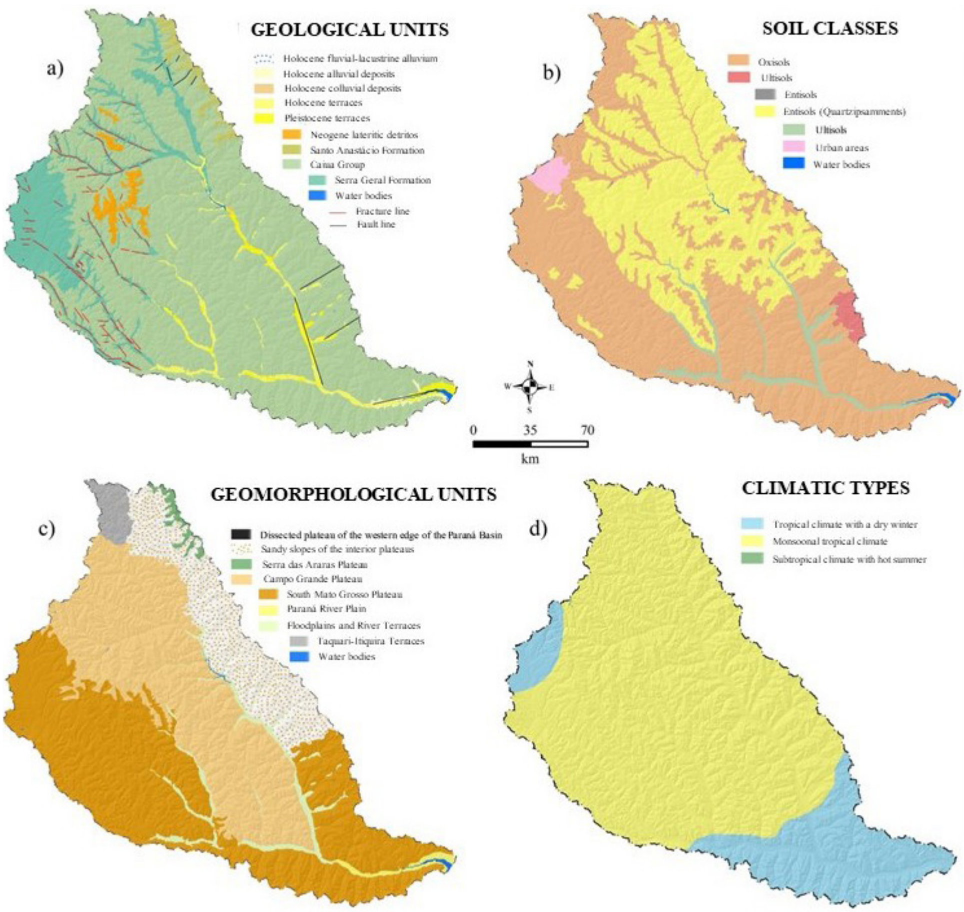

FIGURE 2 – Geological units (a), soil classes (b), geomorphological units (c), and climatic types (d) in the Pardo River watershed.
SOURCES: Geological units, soil types, geomorphological units (IBGE, 2021); Climate: Alvares et al. (2014).

al., 2015). The lava flows contain scattered vesicles and sand-filled fractures (clastic dikes) at their base and top edges, as well as intercalated sandstones with irregular contacts and varying thicknesses (Machado *et al.*, 2015). The dikes are, as a rule, made of sandy material, which penetrate the basalts, both vertically forming clastic dikes, and horizontally forming sills at times. The clastic intrusions observed in the field vary in shape and dimension.

According to Hartmann (2014), during the entire effusive process that generated the volcanic group, the climate would have remained arid, as there are no indications of the presence of sediments formed in lakes or rivers. The thickness of the stratum of extrusive igneous rocks before erosion is estimated at 5,000 m near the Atlantic coast and 3,000 m in the interior of the continent, with the maximum thickness (1,755 m) measured in a borehole in the southwest of São Paulo (Hartman, 2014). The work of Wildner *et al.* (2006) showed that there are large extensions with 500–1,000 m of thickness in the depocenter of the Paraná Basin.

The lava flows show a zonality in the distribution of high titanium (Ti) volcanic rocks in the northern part of the volcanic province and low-Ti in the southern portion, but there are exceptions in some parts. According to Hartmann (2014), the compositional variations, the geochronological data, the textural characteristics, and the arrangement between the basin's flows and intrusives made it possible to divide the Serra Geral magmatism into distinct facies, six related to mafic magmatism (Gramado, Paranapanema, Pitanga, Esmeralda, Campo Erê, and Lomba Grande facies), and four to intermediate to felsic magmatism (Palmas, Chapecó, Várzea do Cedro, and Alegrete facies). Licht & Arioli (2012), based on the statistical treatment of a large number of chemical analyses of volcanic rocks in the Group, suggest the existence of a greater number of chemical types.

The Bauru sedimentary basin (Fernandes & Coimbra, 1996) covers 370,000 km² and is of the intracratonic type of isostatic subsidence developed in the Late Cretaceous, after the rupture of the continent Gondwana (Silva *et al.*, 2003; Fernandes & Ribeiro, 2015; Batezelli, 2015). In lithostratigraphic terms, it has a sedimentary package of around 480 meters in thickness that compose two chrono-correlated units: Caiua Group (Paraná River, Goio Erê, and Santo Anastácio Formations) and Bauru Group (Uberaba, Vale do Rio do Peixe, Araçatuba, São José do Rio Preto, Presidente Prudente, and Marília Formations, including the Taiúva Analcimites) (Fernandes & Coimbra, 2000; Fernandes, 2004).

The filling of the Bauru basin would have occurred in semi-arid conditions on the banks of the basin and in desert conditions in the interior, in two phases of deposition: the first phase a desert system and the second, a fluvial-wind system (Fernandes & Coimbra, 2000; Fernandes & Ribeiro, 2015). The Bauru Supersequence of the Late Cretaceous (Milani *et al.*, 2007) covers part of the states of São Paulo, Paraná, Mato Grosso do Sul, Minas Gerais, and Goiás in Brazil, and part of northeastern Paraguay (Fernandes & Ribeiro, 2015).

According to Fernandes (2004), at the end of the Cretaceous, vertical forces in the opposite direction, generated by compensatory reaction, began to dominate, starting the phase of tectonic "inversion" of the basin and erosion of the Neo Cretaceous supra-basaltic package. According to him, the reactivation of tectonic structures on the banks caused important changes in the geographical framework of the basin, promoting the advance of alluvial fans into its interior, such as the one found in the upper course of the Ribeirão das Botas watershed (Figure 3), close to the interfluvium of the Paraguay and Paraná basins (20°15'13.31"S; 54°29'3.44"W). At the same time, gradual climate changes, perhaps caused by the transformations of the relief, brought greater humidity to the marginal zones. According to Almeida (1980), a large part of the sedimentary record was removed during the regional elevation in the Cenozoic. In the fieldwork, the presence of silicified sandstones was observed, the occurrence of which may be associated with Neo Cretaceous alkaline magmatism identified in the southern portion of the Bauru basin by Fernandes, Coimbra & Brandt Neto (1993).

In the PRW, the suprabasalt lithofaciological set corresponds to the Caiua Group, undivided (78.33%), and the Santo Anastácio Formation (1.50%). According to Freitas (1973), the Caiua Group, composed of fine to medium quartzose to subarcosean sandstones, originated from the erosion by running waters of the Paraná "trapp" plateau, and its source were the Botucatu sandstone and former Oxisols, the result of the decomposition of basalt under a humid climate. For this author, the surface reworking in the sedimentation of the Bauru Group, represented by the Santo Anastácio Formation, indicates a new sedimentary cycle. This Formation consists of tabular sandy strata with a massive appearance, of decimetric thickness, with rare intercalations of mudstone and argillite strata. Sandstones are subarcosean quartzose, almost always massive, fine to very fine, poorly sorted, with a subordinate silt fraction, and a small amount of silt-clayey matrix (Lacerda Filho *et al.*, 2006).

The Neogene lateritic-detritus covers can directly cover the basalts of the Serra Geral Formation and the sandstones of the Caiua Group. This material is found in massive plateaus and ferruginous, sometimes concrete, detrital horizons, as shown in Figure 4. These covers are formed by alluvial and/or colluvial sediments (sands, gravel, silts/clays), totally or partially laterized (sandstones, conglomerates, and mudstones), and autochthonous laterites with ferruginous shells, whose formation environment is continental (Theodorovicz & Theodorovicz, 2010). In the field, it was found that there are many spots with very hardened laterite crusts that are not mapped at the scale of 1:1,000,000 (Lacerda-Filho *et al.*, 2006).

The most representative soil classes (Figure 2b) in the PRW area are: Oxisols (57.6%) and Quartzipsamments (37.6%). Oxisols, Quartzipsamments, Dystrophic Haplic Ultisols, Eutrophic Red Ultisol, Acriferric Red Oxisols, Dystroferric Red Oxisols, Dystrophic Red Ultisol, Eutrophic Red-Yellow Oxisols, Eutrophic Red Oxisols, Eutrophic Litholic Entisols, correspond to an area of 56.3%, 37.6%, 3.4%, 0.8%, 0.7%, 0.5%, 0.3%, 0.1%, 0.01%, and 0.0002%, respectively. Although the cartographic base is presented at a 1:250,000 scale (IBGE, 2021), the thematic content refers to a pedological survey at a 1:1,000,000 scale (IBGE, 2018).

In the headwaters of the drainage (northwest and southwest quadrants), the clayey soils are related to the source material, basalts of the Serra Geral Formation. In the lower course of the watershed, the genesis of soils is related to the morphodynamic processes of erosion, transport, and deposition. The presence of Oxisols in the valleys of the upper course of the Pardo River is related to the denudation processes that removed the sedimentary package of the Caiua Group, exposing the basalts. However, in

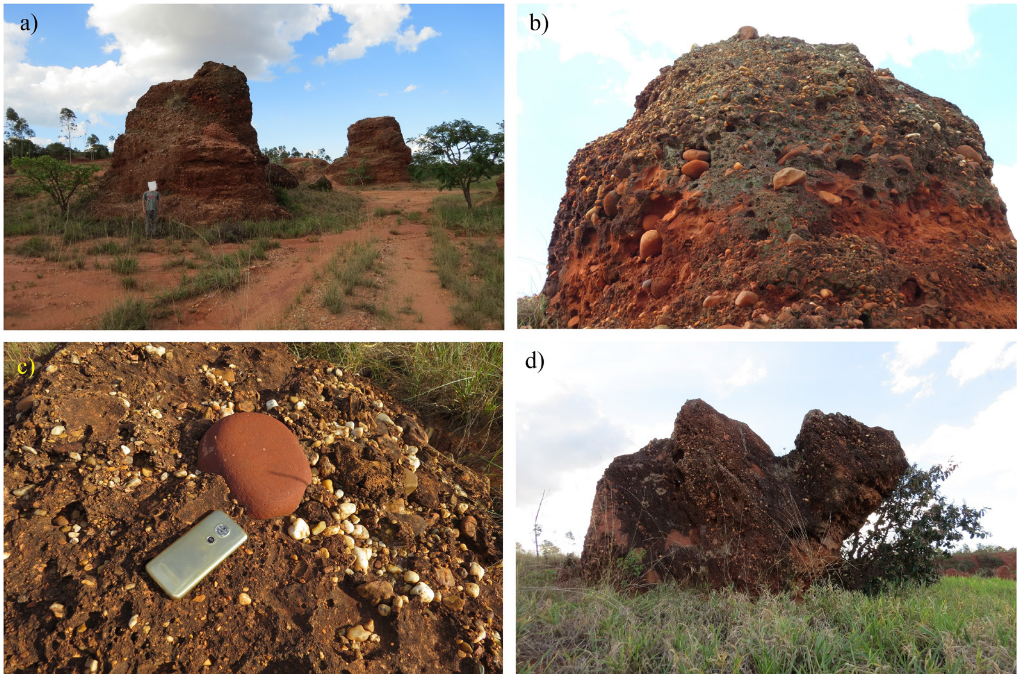

FIGURE 3 – Alluvial fan system near the drainage divide of the Paraguay and Paraná basins.
SOURCE: the author’s personal archive (2021).

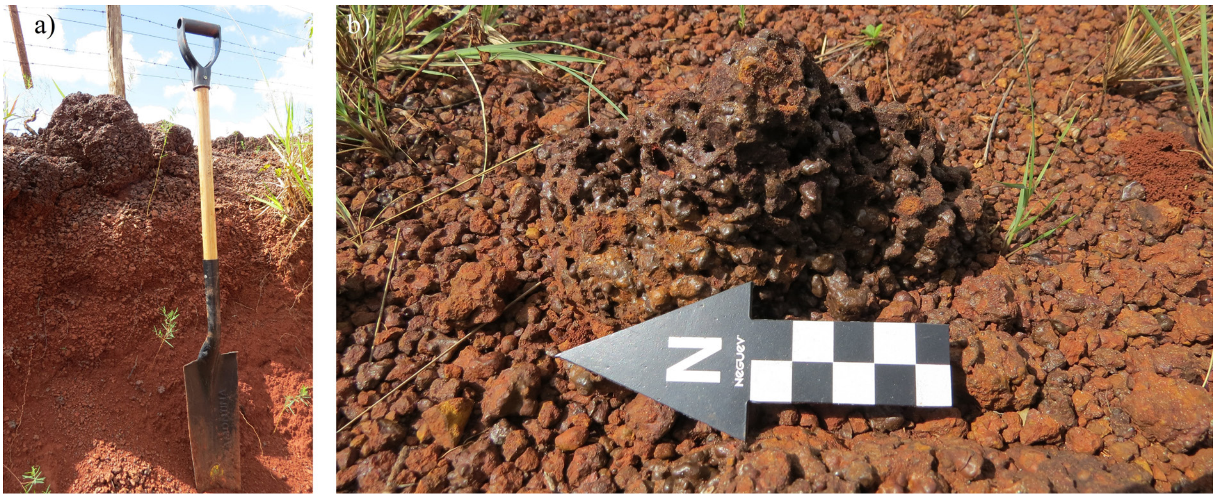

FIGURE 4 – Outcrop of laterite covers on a road cut slope (a) and pasture area (b).
SOURCE: the author's personal archive (2023).

these places, it is necessary to consider the mapping scale factor.

The climate of the region is markedly seasonal, with rainy summers and dry winters with strong winds. According to the climatic classification of Alvares *et al.* (2014), the predominant climatic type (80%) is the monsoonal tropical, in which rainfall varies from 1,600 to 1,900 mm year^{-1}. The tropical savanna climate corresponds to 19.9% of the area, is markedly seasonal, occurring in the Paraná River valley and in the central region of the state. The humid subtropical climate occurs in small areas (0.02%) in the *Cerrado* of Mato Grosso do Sul, which may be related to the meteorological data available for the region. The distribution of climatic types can be seen in Figure 2d.

The predominant geomorphological units (Figure 2c) in the area are: Plateaus of South Mato Grosso (MS, 42.7%) and Campo Grande (35.1%), and Sandy Slopes of the Interior Plateaus (15.2%). The Floodplains and River Terraces, Taquari-Itiquira Terraces, Serra das Araras Plateau, Paraná River Plain, Dissected Plateau of the Western Edge of the Paraná Basin, and Inter-terraces Depression correspond to 3.1%, 2.1%, 0.8%, 0.8%, 0.003%, and 0.0003% of the area, respectively.

The minimum elevation of the PRW is 232.0 m and the maximum is 743.0 m (Figure 5a, Table 1), with a mean of 556.9 m and an amplitude of 511.0 m. The shadow values, derived from the MDS SRTM 30 using the hillshade algorithm (azimuth 345, altitude 45), ranged from 0 to 255 (Figure 5b). The interpretation of shading maps is similar to the interpretation of remote sensing images, and is based on the recognition or identification of relief features from illumination (Imhof, 2007). The shading allows for an interpretation closer to reality (Tinós *et al.*, 2014), from larger features such as escarpments, abrupt slope changes, and staggered topography, to subtle variations in topography., This attribute also allowed the visualization of vegetation artifacts, in which forest fragments correspond to elevation noise, because the altitude value (Z) is somewhere between the bare land surface and the top of the canopy.

The slope ranged from 0.00002 to 56.6% (Figure 5c), with a 4.2% mean and a 2.3 standard deviation. The highest values are associated with areas of dissected relief such as valleys. Vegetation artifacts (forest fragments) influence slope values, with overestimation of slope areas, such as at the edges of forest fragments. Class ranges (Lepsch *et al.*, 2015) show that gentle slope (2-5%) predominates in the area (52.8%), followed by moderately sloping (5-10%) with 31.3%; flat or nearly flat (0-2%) at 14.3%; strongly sloping (10-15%) at 1.5%; very steeply sloping (10-45%) at 0.2%; and steep mountainous at 0.001% of the watershed area.

The relief ratio (R_h) is 0.0016 (Table 1). This parameter is the relationship between the altimetric amplitude of the watershed and the horizontal distance from the main drainage, being an indicator of the intensity of the erosion processes that operate on the slopes (Schumm, 1956). The percentage of relative relief (R_{hp}) is 0.030 (Table 1). This parameter is calculated using the perimeter and the total amplitude of the watershed (Melton, 1957). Soils with low R_{hp} values are less prone to erosion than those with high values. However, as presented above, sandy soils, which make up 37.6% of the PRW, are highly susceptible to soil erosion. The 0.69 dissection index (Table 1) indicates moderate dissection, which shows that, although young, the type of soil and management practices that do not

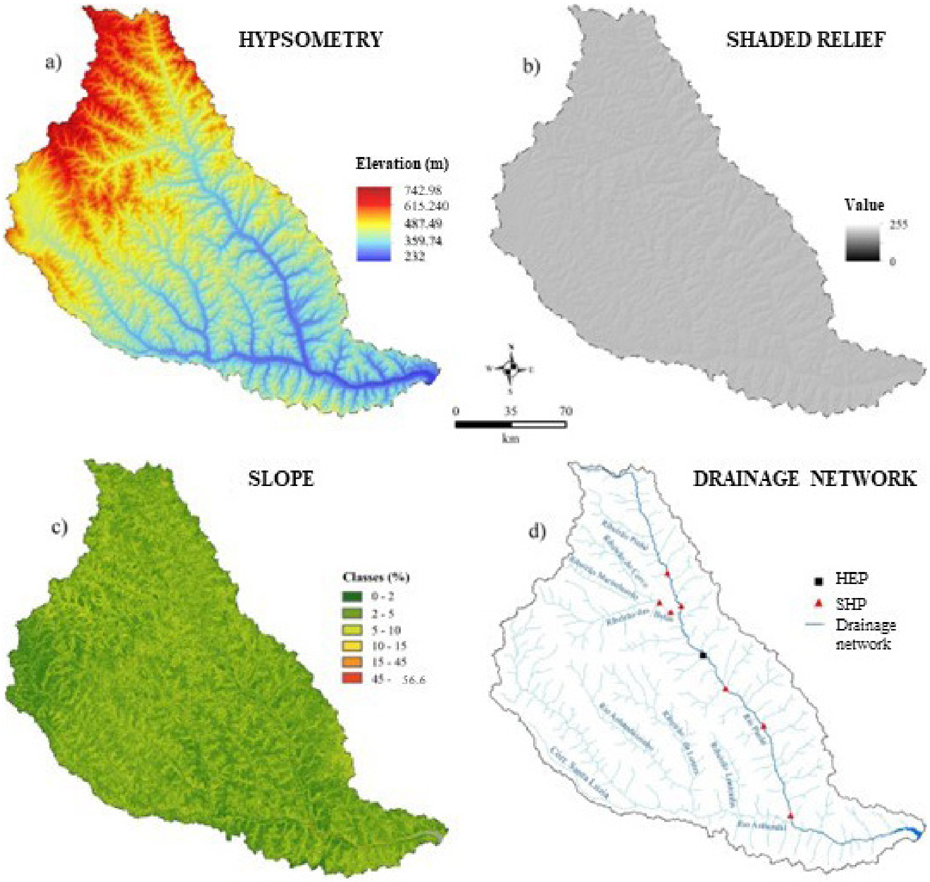

FIGURE 5 – Hypsometry (a), shade (b), slope (c), and drainage network (d) of the Pardo River watershed. Cartographic base: MDS SRTM 30 m; Hydrography threshold 30,000 (D8)
SOURCE: USGS (2020).

consider susceptibility to erosion contribute to the acceleration of dissection.

The hydrography of the area (Figure 5d) shows the structural control (Figure 2a) in the main drainages. For the thematic presentation, the threshold was 30,000 (Figure 5d), and for the quantification (Table 1), the threshold was 800. The threshold of 800 was the closest to the existing drainage network when superimposed on the high spatial resolution images from the ArcMap's World Imagery.

The fluvial hierarchy, which represents a measure of the extent of flow branching within a watershed (Strahler, 1964), is eighth-order (threshold 800); the total length of the channels is 26,108.14 km; the drainage density, which expresses the ratio between the total length of the waterways in a watershed and its total area, is 0.78 (Table 1). This variable is directly related to the climatic processes acting in the area, which influence the supply and transport of detrital material. In less permeable soils, such as Oxisols with a clayey texture, the conditions for surface runoff are better, enabling the formation of channels and, consequently, increasing the drainage density. The opposite happens with coarse-grained rocks, from which sandy soils such as Quartzipsamments are derived (Horton, 1945). According to Pedron, Dalmolin & Flores (2019), sandy soils have low water retention capacity due to the dominant macroporosity. In these soils, the decrease in organic matter content also affects water retention in the soil.

The sinuosity index found was 1.56 (Table 1), which indicates transitional forms between rectilinear and sinuous channels. The meandering channels are predominantly found in the lower course of the Pardo River, in the floodplains, and in the lower course of the main tributary watersheds. Meandering channels are also observed in the middle and upper course and are directly related to the material of sedimentary origin (sandstones of the Caiua Group).

The gradient of the main channel is 0.91 (Table 1), being steeper in the upper course and becoming gentler as it approaches the Paraná River valley (Figure 6). The geological constitution of the PRW influences the predominant gentle relief, thus, the slope gradient of the main channel demonstrates that the area drained by this fluvial system suffers a greater pressure by fluvial erosion in the upper course, denoting the great importance of the erosive processes in the headwaters of the drainage in the modelling of the channels.

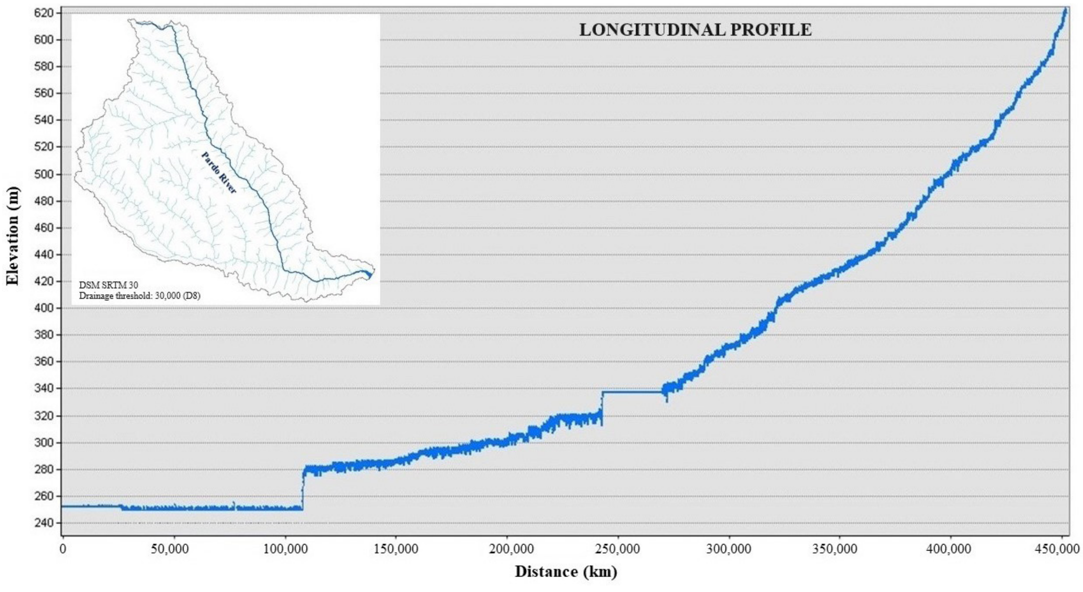

FIGURE 6 – Hydrographic network with emphasis on the main channel and longitudinal profile of the Pardo River/MS.
SOURCE: MDS SRTM 30 m.

The axial length of the PRW is 326.5 km, the area is 33,674.1 km², and the perimeter is 1675.5 km (Table 1). The values for the form factor (F_f), elongation ratio (R_e), circularity ratio (R_c), and compactness coefficient (C_c) were 0.32, 0.63, 0.15, and 2.57 (Table 1). F_f has been used in maximum flood flow analyses. In the case of long and narrow watersheds, such as those occupying synclinal valleys and rift valleys, the form factor is indicative of the flood stage of the stream. For irregularly shaped watersheds, especially those with permeable soils such as the PRW, the form factor is not a sensitive indicator of hydrological characteristics. According to the classification proposed by Shumm (1956), the PRW is elongated (0.5-0.7). These results indicate that in rainfall events the concentration time will be longer with a decrease in the tendency to have flood peaks. For R_c, low values such as those obtained in this study (0.15) indicate a young geomorphic stage (Miller, 1953).

The PRW is predominantly found in the *Cerrado* biome (99.89%), in the Planalto Guimarães ecoregion (Sano *et al*., 2019), and a small part (0.11%), along the channels of the Pardo and Anhanduí rivers, in the Atlantic Forest biome. Originally, the entire region had an exuberant vegetation cover belonging to different phytogeographic units, however, the natural vegetation was practically decimated (Figure 7d), and the remnants are fragmented and many uncharacterized. Low-order springs and rivers are devoid of riparian forests (environmental liabilities provided for in federal and state legislation) which, according to Curcio (2017), necessarily results in a loss of water resource quality, as well as the loss of ecological corridors and their multiple functionalities. Although the PRW has five Conservation Units (CUs) classified as restricted use, namely: the Private Reserves of Environmental Heritage of the Federal University of Mato Grosso do Sul, Vale do Sol II, Vale do Anhanduí, and the State Parks of Prosa and Matas do Segredo, these areas represent only 0.06% of the total extent of the PRW. On the other hand, the four CUs that fall under the sustainable use category, specifically the Environmental Protection Areas (EPAs) of the Anhanduí Pardo Microbasin, the Sub-Basin of the Rio Pardo, and the headwaters of the Guariroba and Lajeado Streams, cover a significant 23.1% of the total area of the PRW. Despite their substantial size, the EPAs face environmental challenges and conflicts like those in areas outside the CUs, even with the implementation of Management Plans.

The time periods of land use and land cover show a significant reduction in forest, savannah, and grassland formations from 1985 to 2020 (Figure 7). The area of forest formation, which in 1985 corresponded to 22.8% of the PRW, decreased to 13.7% in 1995, 9.5% in 2005, and 9.1% in 2020. The period of greatest deforestation is related to the commodities boom in the country. The savannah vegetation, which in 1985 accounted for 13.6% of the PRW, decreased to 11.5% in 1995, 8.1% in 2005, and 7.1% in 2020. The grassland formation showed an increase in area of 0.71% in 1985; 0.73% in 1995, 0.9% in 2005, and 1.1% in 2020. This results from the decharacterization of forest and savannah formations.

The areas with native vegetation that were initially converted to extensive animal farming—in 1985 this class corresponded to 44.9% of the area, in 1995 64.5%, in 2005 71.6%—are being converted to soybean plantations and "planted forests" of eucalyptus and rubber trees (0.4% in 1985, 1.2% in 1995, 0.9% in 2005, and 4.0% in 2020). From

TABLE 1 – Geomorphometric attributes of the Pardo River watershed/MS.

Watershed geometry			
Basin length (L_b) (km)	–	Horton (1932)	326.50
Basin area (A) (km2)	–	–	33,674.1
Basin perimeter (P) (km)	–	–	1,675.5
Form factor (F_f)	$F_f = A/L_b^2$	Horton (1932)	0.32
Elongation ratio (R_e)	$R_e = (2/L_b) \times (A/\pi)^{0.5}$	Schumm (1956)	0.63
Circularity ratio (R_c)	$R_c = 4\pi A/P^2$	Miller (1953)	0.15
Compactness coefficient (C_c)	$C_c = 0.282 * P/\text{root } A$	Gravelius (1914)	2.57
Drainage network			
Stream order (U)	Hierarchical rank	Strahler (1964)	8*
Stream length (L_u) (km)	$L_u = L_1 + L_2 + \ldots + L_n$	Horton (1945)	26,108.14*
Drainage density (D_d)	$D_d = L_u/A$	Horton (1945)	0.78*
Sinuosity Index (Is)	I_s= Channel length/straight-line valley length	Schumm (1963)	1.56
Channel gradient	$C_g = (Z_{headwater} - Z_{outlet})$/ main channel length	–	0.91
Relief characteristics			
Height of basin outlet (Z_{min}) (m)	–	–	232.0
Maximum height of basin (Z_{max}) (m)	–	–	743.0
Total basin relief (H) (m)	$H = Z_{máx} - Z_{min}$	Strahler (1952)	510.99
Relief ratio (R_h)	$R_h = H \text{ (km)}/L_b$	Schumm (1956)	0.0016
Relative relief (R_{hp})	$R_{hp} = H \text{ (km)} \times 100/P$	Melton (1957)	0.030
Dissection index (Dis)	$Dis = H/Z_{máx}$	Gravelius (1914)	0.688

* Flow distribution algorithm: D8, threshold 800.

SOURCE: DSM SRTM 30.

2005 to 2020, the pasture class showed a reduction in area of 13.4%. Although since 2005 pasture areas have decreased to the detriment of "planted forests" and soybean crops, this class of use still occupies the largest area of the PRW with 62.0% in 2020. In the Environmental Protection Areas, a significant reduction of native vegetation was observed, corroborating Lima (2011) when he says that the CUs are environmental half-achievements because, once created, no real conditions are offered to manage them properly via management plans.

Most of the pasture areas are poorly managed, with numerous areas in the process of sandification, as shown in Figures 8 and 9a. The sandification

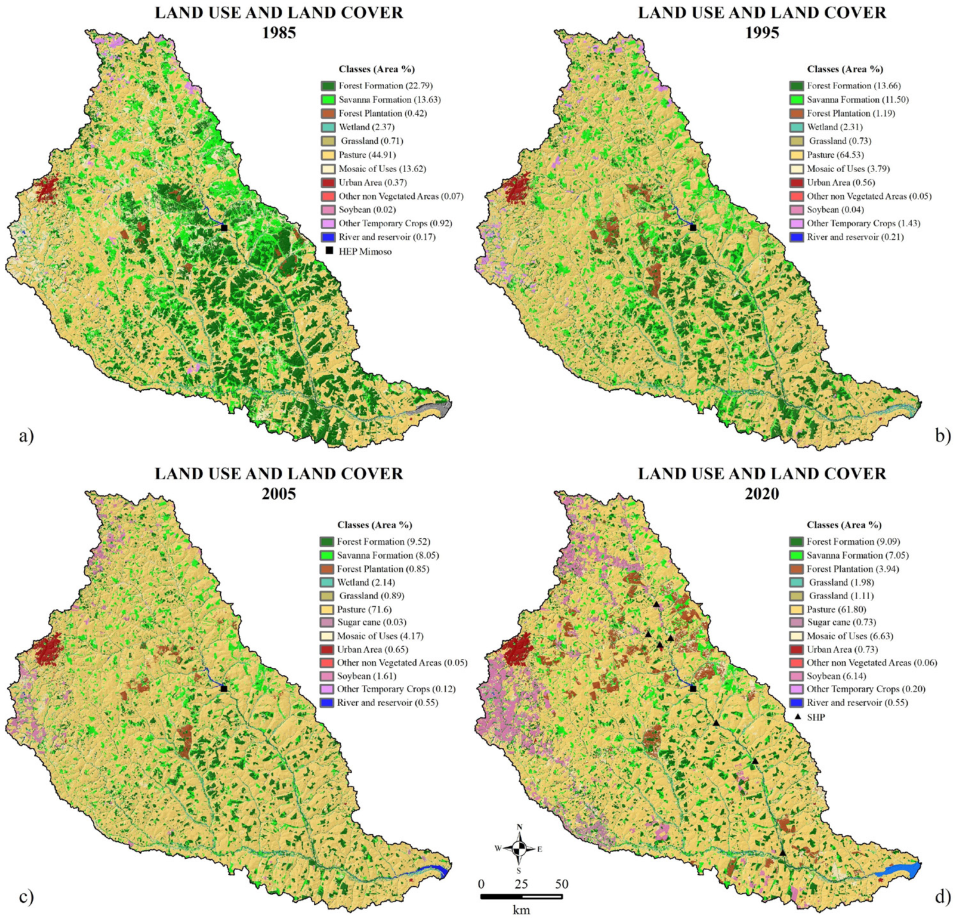

FIGURE 7 – Land use and land cover in the Pardo River watershed in the years 1985 (a), 1995 (b), 2005 (c), and 2020 (d).
SOURCE: MapBiomas, collection 6.

process consists of the reworking of little or not at all consolidated deposits, which hinders the fixation of vegetation due to the mobility of the sediments (Suertegaray, 1987). According to this author, in southwestern Rio Grande do Sul, the sands are of natural origin, associated with Quaternary deposits settled on the sandstone substrate of the Botucatu and Guará Formations, and the recent evolution is related to anthropic activities.

In the context of this work, the origin of the sands is anthropic, resulting from a combination of factors such as: the sandstone substrate (Caiua Group) that gives rise to sandy soils (Quartzipsamments), the extensive elimination of the primary vegetation cover and the conversion to poorly

FIGURE 8 – Focus of sandification with vegetation being buried (a) and dunes advancing on vegetation (b) in the Guariroba stream watershed (20°36’57.82”S; 54°23’26.73”W).

SOURCE: the author's personal archive (2023).

managed animal farming. This makes soils more vulnerable to the action of water (pluvio-denudation) and wind (deflation) processes.

In animal farming areas, in addition to the gullies on slopes and tops, there are numerous alluvial gullies formed by the traffic of animals to the river for drinking and crossing (Figure 9b). Numerous paleogullies were also observed, some of them reactivated (Figure 9c), which may be due to a combination of factors such as climate, tectonism, removal of natural vegetation cover, and predatory agriculture.

In 1985, soybean was present in only 0.02% of the area (788.4 ha); in 1995 in 0.04% (1,414.9 ha); in 2005 in 1.6% (54,197.4 ha); and in 2020, 6.2%. Soybean areas predominate in clayey soils derived from the Serra Geral Formation (Figure 2b), however, soybean cultivation has advanced in areas of sandy soils (Figures 7d and 2b), which can result in contamination of surface and groundwater (Bauru aquifer). Also increasing in the PRW are center pivot irrigation systems (Figure 9d), which are characterized by a mobile lateral line with multiple emitters, supported above ground by towers that rotate around a center pivot mechanism, thus irrigating a circular area (Phocaides, 2000). In the PRW, irrigated soybean areas are found in the vicinity of surface waters (rivers and reservoirs formed from the construction of earth dams), which increases the risk of sediments and pollutants being released into waterways. According to Batista *et al.* (2023), irrigation in the Cerrado causes and/or aggravates soil erosion and the problem has been neglected.

The area of forest formation, which in 1985 corresponded to 2.4% of the PRW, decreased to 2.3% in 1995, 2.1% in 2005, and 2.0% in 2020. The impacts on the hydrological cycle in the watershed are related to changes in land cover (natural vegetation–agriculture) and land use and cover (animal farming–soybean; animal farming–silviculture), and to climate changes.

The increase in water mass from 0.17% in 1985 to 0.55% in 2020 corresponds mainly to the reservoir of the Engenheiro Sérgio Motta Hydroelectric Power Plant at the Paraná River, inaugurated in 2003. In the *Cerrado*, natural water, from free-flowing rivers, is losing space to anthropic water, in reservoirs. There is a combination of regions with reduction and others with increased water surface in dams in the *Cerrado*, leading to a slight loss of water surface in this biome (World Wide Fund for Nature, 2021).

The time periods of land use and land cover show the expansion of the urban area, especially in Campo Grande. In the PRW, this class' area corresponded to 0.37% in 1985, 0.56% in 1995, 0.65% in 2005, and 0.74% in 2020. Unlike what happened

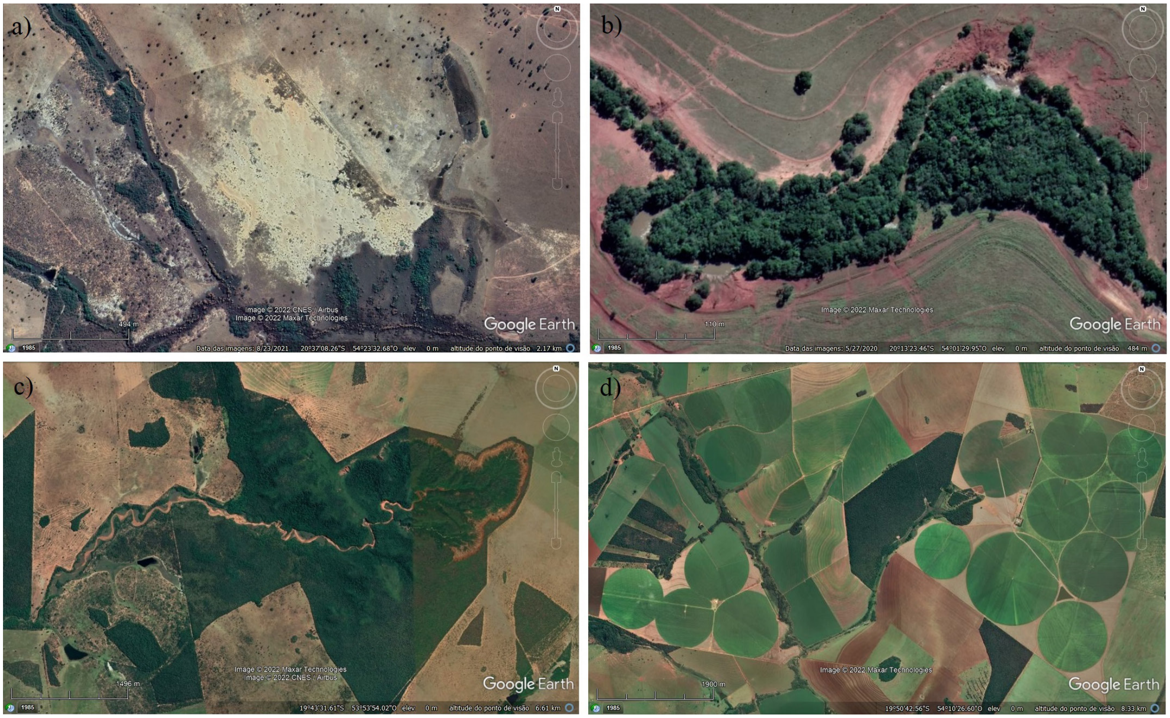

FIGURE 9 – a) Sandification focus; b) Alluvial gullies in animal farming areas; c) Reactivated paleogully; d) Soybean crops irrigated by center pivot.

SOURCE: Google Earth (2023).

in the 1970s when urban areas faced dramatic increases in population due to the influx from rural areas, where employment opportunities were few due to agricultural mechanization, according to Vieira Neto (2008), recent urban expansion in the Midwestern region is directly linked to the urban.

The results presented here show that the conversion of natural systems (*Cerrado* and Atlantic Forest) to agricultural environments, in a predatory way, and without considering agricultural suitability and restrictions, has profoundly impacted ecosystem services such as water flow regulation, soil fertility, habitat and habitat connectivity, biodiversity, and climate. The initial dynamics of change were the decline of forest and savannah formations and expansion of transitional forests, grassland formations, and planted pastures. In 1985, although the predominant use was extensive animal farming, 36.4% of the area was composed of forest and savannah formations, in 2020 this number reduced to 16.2%.

The main recent change in land use is the conversion of pastures to soybean crops and planted forests—mainly eucalyptus. The advance of soybean crops occurs in areas of sandy soils (Quartzipsamments), which have a predominance of macropores, resulting in high drainage and low water retention capacity, therefore, low filter potential (Curcio, 2017). The low levels of clay and organic matter give these soils a low fertility and aggregation, thus making them highly susceptible to water and wind erosion processes (Pedron & Dalmolin, 2019). As an aggravating factor, most of the low-order waterways (Strahler) are not protected by fluvial forest cover (gallery forests), which makes them very fragile to fluvial environments.

The harmful impacts of the accelerated process of soil erosion caused by deforestation, overgrazing, soil preparation, and inadequate agricultural practices are well known and documented, as are the mechanics of the erosion process (Lal, 2001; Montgomery, 2007; Pimentel & Burgess, 2013; Walling, 2013). For Borrelli *et al.* (2017), the impacts can be severe not only by land degradation and loss of fertility, but by external effects, for example, sedimentation, siltation, and eutrophication of waterways and reservoirs or intensified flooding. The annual global cost of land degradation due to land use/cover change and the use of inappropriate management practices is around 300 billion dollars (Nkonya *et al.*, 2015). In the context of anthropogenic climate changes, soil erosion can also increase or decrease carbon dioxide emissions by enhanced mineralization and sediment burial (Lal, 2004; Van Oost *et al.*, 2007). Off-site impacts will also affect hydropower production, by the death of springs and silting of rivers and reservoirs, and this will greatly increase the overall annual costs of soil degradation.

With regard to energy production, contrary to what has been happening in Europe and North America, where they are removing dams and investing in solar, wind, and biomass energy (Moran *et al.*, 2018), developing countries such as Brazil are building dams for energy production (HPPs and SHPPs). The recent trend of building large hydroelectric dams and small hydroelectric power plants shows that certain sectors ignore the social and environmental externalities of these projects, as well as the unsustainability of this energy model.

For Lima (2011), market action is guided exclusively by the profitability of invested capital and the short term, which for him does not guarantee rational responses to environmental problems, equity in dealing with social justice, and respect for the frequent ethical dilemmas in the construction of democratic sustainability. At a time when innovative solutions are needed, such as solar and wind energy, and other renewable sources, the governance and sustainability of the hydropower model are not discussed (Moran *et al.*, 2018).

As mentioned above, there is one Hydroelectric Power Plant in operation in the Pardo River watershed and seven axes have been approved for the implementation of SHPPs. In the context of climate changes, deforestation and agricultural land degradation, accelerated erosion, and sandification are being ignored, and the benefits of SHPPs overestimated. Given the degree of environmental degradation such as soil degradation (erosion, sandification, sedimentation, leaching, among others), environmental liabilities in permanent preservation areas and legal reserves, and the cumulative impacts of small earth dams (Capoane, 2021), it is urgent that managers (at municipal and state levels) consider the interactions of climate, socioeconomic activities, and the degradation of natural soil and water resources. The correlation between abiotic and land use and land cover aspects are fundamental for the creation of government policies and programs for the effective protection of the environment.

4. Final considerations

The geo-environmental characterization shows an ecologically fragile environment, highly susceptible to soil erosion and the sandification process. The agricultural activities developed in the area do not consider agricultural suitability and restrictions, and most of them occur in a predatory way. Environmental liabilities in permanent preservation areas around springs, waterways, and reservoirs increase slope–river–reservoir connectivity. The areas with the highest environmental liabilities are the headwaters of a drainage and low-order channels (Stralher), which are completely ignored in the Rural Environmental Registry.

Changes in land use and land cover have impacted terrestrial (erosion, sandification, sedimentation) and aquatic (degradation of water quality and quantity) systems. The inclusion of soybean monoculture, which uses high doses of fertilizers and pesticides, and eucalyptus monoculture, which also uses pesticides and whose transpiration is much higher than that of native vegetation, as well as the approval of the seven axes for the implementation of SHPPs, will put even more pressure on the PRW's natural resources and generate socio-environmental conflicts.

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