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ORIGINAL ARTICLE

Geoecological diagnosis of landscapes of the Formoso River Watershed, Bonito/MS, Brazil

Rafael B. Medeiros[1] · Eduardo S. Chávez[2] · Charlei A. da Silva[3] · André G. Berezuk[3]

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Abstract
The landscape geoecology aims at a systemic and integrated comprehension of physical–natural and anthropic components. It cooperates to identify and map landscape units, as well as to define indicators that establish their geoecological diagnosis mitigating measurements for preservation and use. The objective is to determine the state and geoecological diagnosis of landscapes of the Formoso River Watershed, located in the municipality of Bonito/MS, Brazil. The methodology consists of four stages: (i) the organization to define the study area and worked themes; (ii) the inventory and analysis characterizing the rocks, soils, relief, and anthropic use to define the landscape units; (iii) the diagnosis to establish the condition and geoecological diagnosis of landscapes; and (iv) the prognosis and proposals to define recommendations, envisioning trend, and desired scenarios for the watershed. The delimitation, classification, and mapping of landscape units, on a scale of 1:100,000, allow to identify the existing landscape heterogeneity. Thus, the condition and geoecological diagnosis are determined highlighting that extensive areas of "Altered Landscapes" potentialize the current watershed environmental problems: a fact that contributes to define future development scenarios, as well as recommendations to ensure a harmonious use to preserve the landscapes. The present work aims to contribute to the advancement of landscape geoecology and the study of tropical karst landscapes in a theoretical– methodological and practical way. Moreover, it is essential to support public power decision making, and assist researchers, institutions in charge of conservation and tourism to search solutions to watershed current and future environmental problems.

Keywords Landscape geoecology · Karst landscape · Land use conflicts · Environmental fragility · Watershed

Introduction

Karst systems are extremely complex and unique environments in which chemical dissolution processes of rocks shape the landscape. Karst systems may be comprehended as geosystems from the perspective of their fragility and correlated to intensive anthropic use. Thus, different ways and means emerge to understand and work with karst landscapes from a geosystemic perspective. The concept of landscape and its polysemic and integrated character have been the basis for research on environmental and geoecological themes. It is highlighted in several areas using methodologies, scales of analysis and varied taxonomies. Geographic landscapes, as a complex and open system of ecological and human processes and functions are the result of relationships and interrelationships of multiple scales among their components. For decades, it has been considered the basis for conducting research aiming at the sustainable development of socio-ecological systems (Mateo 2011; Khoroshev and

✉ Rafael B. Medeiros
rafael_bmedeiros@hotmail.com

Eduardo S. Chávez
esalinasc@yahoo.com

Charlei A. da Silva
chgiu@hotmail.com

André G. Berezuk
andreberezuk@ufgd.edu.br

1 Postgraduate Program in Geography, Nature and Space Dynamics, Maranhão State University, Cidade Universitária Paulo VI, P.O. Box 09, São Luís, MA 65055-310, Brazil

2 Institute for Regional Development, University of Granada, Granada, Spain

3 Faculty of Humanities, Federal University of Grande Dourados, Laboratory of Physical Geography, Dourados, Brazil

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Dyakonov, 2020). In this way and at the risk of being reductionist, the landscape, in a historical laconic, still with Alexander von Humboldt and later with Vasily Dokuchaev, had its foundation focused on research to comprehend and analyze nature under the integrated approach. In the twentieth century, Berg (1913) instituted the scientific notion of landscape, and later its geographical character was expanded by Russian researchers and complemented by Troll (1932). Carl introduced ecological aspects, and Sochava proposed the concept of geosystem from the perspective of the General Theory of Systems. The concept consolidated "Landscape Geoecology" as a transdisciplinary scientific discipline, and recently has been accepted as the basis for environment spatial research (Antrop, 2000; Mateo et al. 2013; Frolova, 2018; Brugnolli, 2020; Khoroshev and Dyakonov, 2020).

The landscape geoecology is one among a large theoretical and methodological available arsenal available to work with the concept of landscape, and it may be used as a tool to interpret and research landscapes, especially karst landscapes. Studying it as an environmental system and its units as physical–territorial complexes, properly delimited and mapped, is a fundamental piece in the operational puzzle of this type of holistic and systemic methodology. The analysis of karst landscape is essentially systemic, due to the complexity in the relationship with its physical–natural, biotic and anthropic environment. The relationship between its components and processes affects the dynamics of geographic phenomena, both spatial and temporal. Analyzing the landscape according to the geoecological view is to comprehend the existing interactions between its components, identifying, classifying, and mapping landscape units characterized by relative homogeneity. This form of analysis has improved environmental research, defining geoecological potentialities and instabilities, and proposing ways to preserve and/or recover it (Cullum et al. 2016; Simensen et al. 2018). Evaluating the geoecological state to make a diagnosis of these landscape units allows us to define the harmony between the ecological potential and the current anthropic use. Mateo and Silva (2013) define the diagnosis as a mandatory phase in the levels and categories of environmental planning. The basic purpose is to clarify environmental system state resulting from society use and exploitation of resources and services.

The geoecological diagnosis of landscapes is an essential step. By using tools and methods, we assess the fragilities/potentials, risks and environmental problems, and define the capacity of landscape units. We also evaluate the human impact on the environment, as well as the character and degree of territory transformation by social and economic activities (Bastian et al., 2006a, b; Mateo and Silva, 2013; Miravet et al., 2014). The geoecology approach is supported due to the processes used to assess the structure, functioning, dynamics and evolution of landscapes under different scales, applications and with varied taxonomies. These ideas were spread due to advances in research, and the demand for theoretical and practical models applied to the themes studied, inserted in a scale that would reveal particularities of the study areas. Carl Troll and Sochava point guiding lines to study and analyze various works linking geoecology with karst geosystems from the perspective of Landscape Geoecology and Geosystemic Theory, with Salinas Chávez and Ribeiro (2017), Solodyankina et al. (2018) Plyusnin et al. (2018), Brugnolli (2020), and Santos et al. (2021), among others. These researches have been performed for the last 5 years, and have increasingly incorporated these complex, unique landscapes, and with little territorial coverage. One of them is linked to the Formoso River Watershed, which is the present area of study.

The Formoso River Watershed (FRW), located in the municipality of Bonito, Mato Grosso do Sul, presents a unique landscape, karst with scenic beauty recognized worldwide for its vegetation in dissected and karst hills and, mainly, for its rivers with translucent waters. The characteristics are intertwined with some recurring facts that have continuously affected FRW. Thus, it is essential to study the landscape dynamics, the geomorphological, anthropic and geoecological dynamics. The instability of landscapes is remarkable in view of the recurrent negative environmental impacts that are indicated on surface waters. According to Silva, (2015); Ribeiro, (2018); Brugnolli et al. (2019); Brugnolli et al. (2020), the instabilities are caused by agriculture, livestock, and the existence of roads with significant drainage system problems. Therefore, the research tried to address two main subjects. The first is whether this watershed is deeply impacted in its environmental context, and the second, how the watershed may improve its mitigation activities and increase environmental resilience. The present work aims at the geoecological diagnosis of landscapes based on the determining environmental fragility of its physical–natural and anthropic components; usage compatibility expressed by the potential versus current usage relationship; and the potential generators of negative environmental impacts, under the terms of "environmental risks" and "environmental problems". The study proposes recommendations and identifies future scenarios for the basin, guiding decision making by the public power, as well as assisting researchers who intend to get into the subject and study the unique and sensitive area of Mato Grosso do Sul, and Brazil.

Theoretical–methodological assumptions

Studying karst landscapes requires the introduction, identification and classification of landscape units that are linked to the compartmentalization of homogeneous units of any extension. Each unit is the result of the interaction of components and physical–natural and anthropic processes. The interaction provides unique structure, dynamics and processes at various stages of evolution, presenting a functional, topological and morphological differentiation, perceived as geosystemic entities. The criterion to differentiate these complexes is the relative similarity and the repeatability in space establishing a subordinate hierarchy. The spatial relationships and the evolutionary–historical development result from the character of the interrelationships and interactions between the components. Therefore, each physical–territorial complex is characteristic of an interrelated individual system of units (types, classes, landscape species, etc.) (Sotchava, 1977; Isachenko, 1991; Mateo et al. 2013). The study of karst landscapes adopts regional and local scales, taking regionalization and typology in the foreground, where specific nomenclature corresponds to a certain territorial area. The definition of local level units of the (topological) landscape adopts a taxonomic principle, in which the relief is the centerpiece, as the agent with capacity to redistribute energy and matter from the interior and exterior of the system, as highlighted by García et al. (2019) and Comerlato et al. (2020). The landscape units provide ways to assess the state and the geoecological diagnosis of landscapes that form them. Thus, the results obtained in the analysis of landscape characteristics, their possibilities of use, and problems derived from current use are synthesized. In this stage, we evaluated the environmental problems that determine the geoecological state of landscape units, and the relationship between impact, cause, and consequence. Several methods may be used to identify the geoecological state of landscapes and its consequent diagnosis. We highlight the analysis of relationship between problems/environmental quality, and the consistency in determining the environmental state of the territory by using geoecological indicators selected or included in the assessment of impacts and their financial cost (Del Risco, 2000; Domínguez, 2003; Trombeta, 2019; García et al. 2019). According to Mateo (1991), Bastian et al. (2006a, b), Ruiz and Delgado (2012), La et al. (2012) and Miravet et al. (2014), five fundamental tasks are required: (a) assess the land use potential of different socioeconomic activities developed or those that are intended to be developed; (b) the efficiency in the use of landscapes (potential versus current use); (c) identify environmental risks and problems; (d) assess the geoecological state of landscapes; (e) carry out the integrated diagnosis of landscapes.

The starting point is to assess the potential of landscapes, commonly recognized by aptitude or capacity. We point out as the productive, informative, and regulatory capacity of landscapes associated with certain possibilities and conditions for different types of landscape use. The proposal is to meet society needs (Mazur and Drdos, 1984; Shishenko, 1986; Salinas, 1991) by covering land suitability for the use of socioeconomic activities that may reflect on certain socioeconomic functions attributed to landscapes, depending on their physical–natural properties.

Bastian (1998), Salas (2002) and Bastian et al. (2012) bring up the synonym "landscape function", which reflects the effects realized in a concrete and immediate way by the landscape for society in a broad sense. The effects may be classified as economic, social, and ecological. In recent decades, it has been related to the so-called ecological or environmental services offered by landscapes (Laterra et al. 2011; Bastian et al. 2013). The ways to assess the potential of landscapes are adding the partial potentials of landscape components, using index in each component, as well as the use of global values or indexes. Then, the analysis of efficiency in use is carried out by comparing the potential of the landscapes with the current land use, based on the analysis of spatial incongruencies of incompatible sectorial activities. The analysis expresses the level of conflicts in a synthesis map. It reflects the intensity gradient according to the proposal of current activities and those that they wish to carry out (INE-SEMARNAT, 2006; Ramón and Salinas, 2009; Bacani, 2010; Dibieso, 2013; Cárdenas et al. 2018; Brugnolli, 2020). The purpose is bringing numerous variables to guide the identification of risks and environmental problems. The existing plans to manage territories are not applied to landscapes that have already been altered by society, reflecting on depletion of natural resources. Environmental problems emerge when human intervention exceeds acceptable limits of landscape potential. Piñeiro et al. (2013) and Cárdenas et al. (2018) state that interventions in the landscape indicate the interrelationships between its components, proceeding in changes in resilience, homeostasis, and in the structure of the affected geosystems. Such interventions are incompatible with a man–nature relationship based on sustainability. The occurrence of environmental risks and problems raise the need to comprehend and evaluate them. In Brazil, the demand for studies in landscapes and karst watersheds is fundamental. The areas are subjected to dangers, such as slumps, due to the instability of their slopes, floods by intense rains, accelerated chemical dissolution of limestone and, consequently, the propensity for terrain subsidence, and turbidity of rivers. The government decision making, formulation of instruments for environmental and territorial management, depends on the analysis of fragility, conflicts, and environmental problems. Thus, a performance model may be created with emphasis on preventive and mitigation aspects (Salinas et al. 2006).

The definition of geoecological state is inserted in this issue to define and map landscapes in their peculiarities of systemic attributes and spatial expression, their risks, problems, conflicts, and fragility. Mateo (1991) defines the concept as the geoecological situation of a given landscape, determined by the type and degree of impact, and capacity of absorption. Therefore, the geoecological diagnosis is essential to assess landscape stability and sensitivity, as well as anthropic modification. The diagnosis presents the character and degree of transformation that have occurred in the territory by social and economic activities (Glushko and Ermakov, 1988; Domínguez, 2003; Gagarinova and Kovalchuk, 2010; Mateo, 2011).

Methodological procedures

The procedures are summarized in four main steps (Fig. 1): (1) organization; (2) inventory and analysis; (3) diagnosis; (4) prognosis and proposal. The steps are sequential and present a systemic perspective facing some methodologies

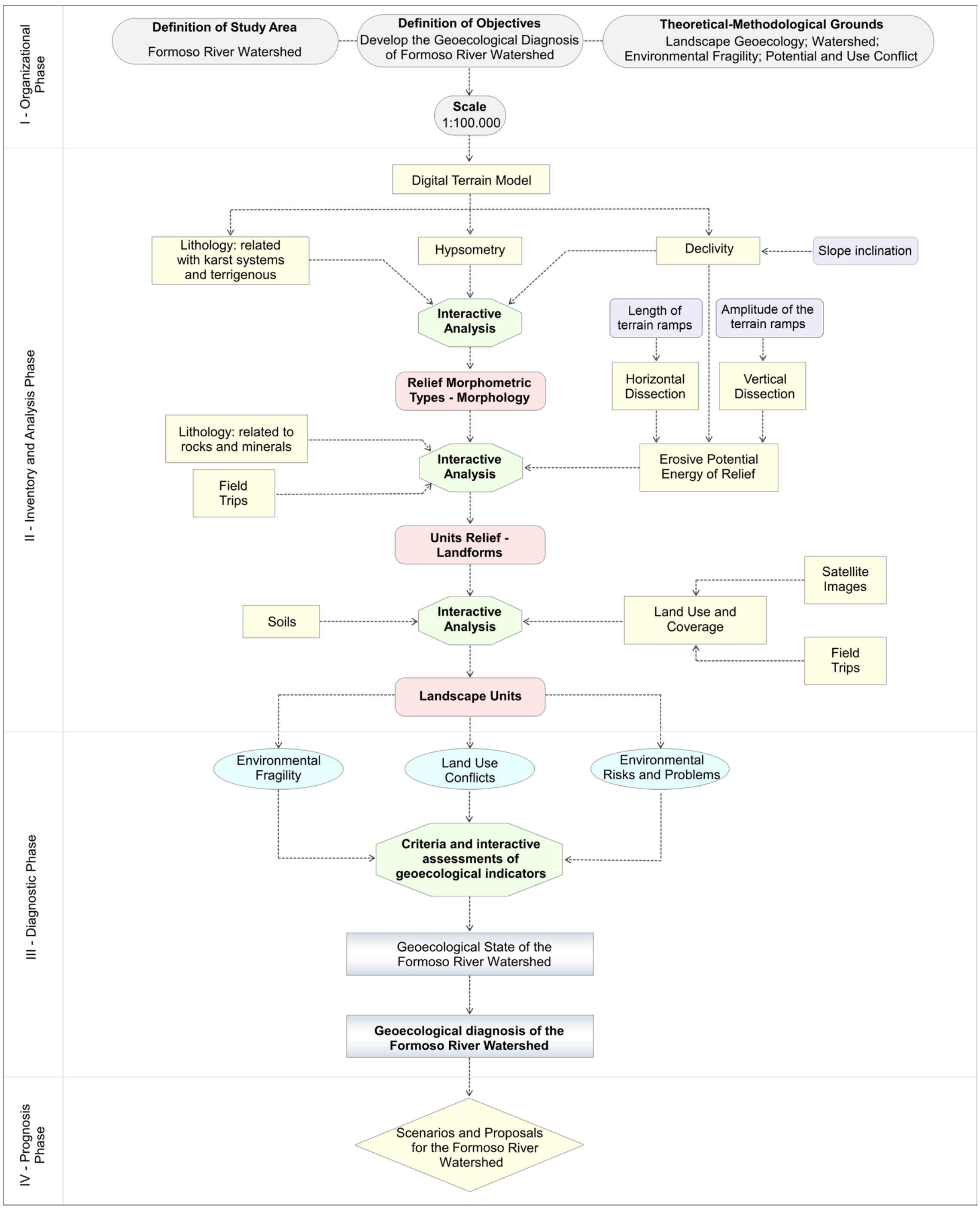

Fig. 1 Methodological flowchart for landscape geoecological diagnosis of the Formoso River Watershed, Bonito/MS

used in their essence, adapted and/or modified, according to Mateo (1994), Mateo et al. (2013), Miravet et al. (2014), Salinas and Ribeiro (2017), Trumpet (2019), García et al. (2019); and Brugnolli (2020). For all procedures, the Geographic Information System (GIS) environment ArcGis 10 (Esri 2011) was used.

The first stage (organization) consisted of collecting a set of theoretical and methodological references regarding the themes that have already been worked and researched in the study area, starting with the delimitation of FRW through topographic maps provided by the Geographic Service of Brazil (DSG), (Diretoria de Serviço Geográfico, 1980), and the digital elevation model (DEM/SRTM), (United States Geological Survey, 2000). The second stage (inventory and analysis) focused on addressing data of physical–natural and anthropic components that support the system (Santos, 2004; Mateo and Silva, 2013). The second stage aims to identify homogeneous landscape units characterized by certain geoecological functions. It starts the compartmentalization based on DEM/SRTM, in which hypsometry and slope were made. Moreover, the karst and terrigenous systems were differentiated through data obtained at the Geological Service of Brazil—CPRM (2006), and the RADAM/BRASIL project. Field trips investigated differences between mapping and terrestrial reality. Then, the lithological components, such as rocks and surface deposits, were separated using the same bases as CPRM (2006). In the sequency, the inventory and analysis of the relief were performed through horizontal and vertical dissections, according to Spiridonov (1981).

The slope and dissection data provided the assessment of potential erosive energy, considering the methodology of Mendes (1993). The analysis of rocky and relief substrate components and their correlations identified relief units. According to Salinas and Ribeiro (2017), García et al. (2019), Trombeta (2019) and Brugnolli (2020), they correspond to the first and second level of landscape units, uniting the relief morphometry with geological formations and their hypsometry. Searching to achieve the landscape mapping in the methodological sequence, correlations were made with soils, according to data obtained at the Brazilian Agricultural Research Corporation—EMBRAPA (2018). The same procedures were followed regarding the rocks. Field trips to define current details, as well as land use and land cover, followed the precepts of digital processing satellite images—Sentinel 2A images, MSI sensor, orbit 135, point 101, available from the United States Geological Survey (2017). The result was the final map for landscape units in FRW. According to Santos (2004) and Mateo and Silva (2013), the diagnosis stage assesses successes and conflicts in the relationship between components, the potentialities and limitations for the use, analysis and geoecological diagnosis of landscapes, strategies of plans, identification of critical areas, and past, present, and future scenarios. Thus, we started identifying the environmental fragility through the interaction of physical–natural environment (rocks, relief, and soils) and anthropic use. The most fragile places were identified according to their current use, which may cause environmental problems. We followed Ross (1994) and Amaral and Ross (2009) proposal, which systematizes hierarchies according to their degree of environmental fragility represented as very low (1), low (2), medium (3), high (4), and very high (5). The following step defined the conflicts of use identified in the relationship between potential use of land and current use. We aimed to comprehend the conflict impacts on the environment and the interferences in the study area. Through the interpretation of all relationships, empirical knowledge of the research area, and the environmental components, classes of conflict were defined as: without conflict; very low conflict; low conflict; medium conflict; high conflict; and very high conflict.

Field trips occurred in November 2016, March and September 2017, July and December 2018 to define and characterize the site, and to map environmental risks and problems. Thus, areas that present potential risk were identified, as well as areas that have already suffered erosion processes, soil impoverishment, river contamination due to mining activities, and sediment transport. In the sequence, in each landscape unit, the landscape geoecological state was evaluated, through a triple entry matrix, that is, the relationship between environmental fragility, land use conflicts, and environmental risks and problems. The product of such intersection presented four possible geoecological states: stable, moderately stable, unstable, and critical. Thus, all previous results were synthesized in the map of geoecological state to carry out the integrated diagnosis of landscapes or geoecological diagnosis, as well as particularities of the landscape units with synthetic indexes, such as stability, sensitivity, and anthropic modification. According to Glushko and Ermakov (1988), Domínguez (2003), and Mateo (2011), the diagnosis distinguishes landscape classes as optimized, compensated, altered, and exhausted.

Finally, the prognostic and proposal stage, which according to Santos (2004) and Mateo and Silva (2013), consists of proposing ways to use and explore environmental systems, identifying alternatives and building possible future scenarios. In this stage, proposals were pointed out for land use changes or maintenance. This contribution aided to define desired and trend perspectives for each landscape unit.

Landscapes of the Formoso River Basin

The Formoso River Basin, located in the municipality of Bonito, Mato Grosso do Sul, presents a drainage area of 1324.67 km^2 (Fig. 2). The Formoso River has its springs in Serra da Bodoquena and flows approximately 97.27 km until its mouth. The river characteristics are deeply linked to the structural elements of the substrate. It presents meander characteristics when crosses planed areas, while it is notched when it crosses hilly areas, exhibiting waterfalls, rapids, and great scenic beauty, due to its translucency, bringing significant tourist attractiveness.

The karst element presents a central role in sculpting the FRW relief. The main geomorphological process of soluble and carbonate rocks occurs due to the chemical dissolution of limestone and dolomite, resulting in unique endocartic and exocartic forms. In tropical and humid climate regions, such as Bonito, the power of dissolution develops in an accelerated manner (Christofoletti, 1980; Bigarella et al. 1994; Piló, 2000; Júnior et al. 2008; Kohler and Castro, 2009; Travassos, 2019). Yet, the continental tropical mass (Zavatini, 1992) presents effective participation so that the karst features are clear in the landscape and in continuous development. The existing geological diversity brought clear elevation levels to the relief. On a first level (reaching 740 m) occurs the rocky massif of Serra da Bodoquena, in which the dissected relief with fragile soils is highlighted among forest vegetation. On a second altimetric compartment, the process of chemical dissolution of limestones is responsible to areas of poljes presenting extremely flat, fertile, and fragile relief (with predominance of chernosols). Soybean crops have transformed the karst landscape, formerly covered by Cerrado with Atlantic Forest enclaves. Surrounded by cultures, in the medium course, elongated and steep rock masses (residual hills) stand out in the landscape. Beyond (west–east transect), it presents numerous carbonate gaps that overlap in morphostructural elements that alternate with non-karst formations of the Cuiabá Group, mostly phyllites with quartzite intercalations (Baptista et al. 1984). The formations favor the predominance of smooth wavy relief with deep and well-drained soils (latosols) related to pastures. Thus, it reaches a third altimetric level in which the terrigenous rock substrate (non-karst) stands out with some wet areas with gleisols and latosols, and pastures in the low course of the basin. Therefore, the FRW landscape stands out for its high anthropic transformation, where the native Cerrado vegetation has almost disappeared. Few sectors of typical cerrado, cerradão, remain, as well as gallery forests and remnants of the Atlantic Forest. The remnants occur close to river courses, residual hills and in Serra da Bodoquena resulting in high spatial heterogeneity of landscapes (Fig. 3).

The *alluvial-terrigenous plain* comprises flattened and smooth wavy areas superimposed on quaternary deposits, sandstones, and other terrigenous rocks. Located close to river courses, floodplains, valley bottoms, and river terraces

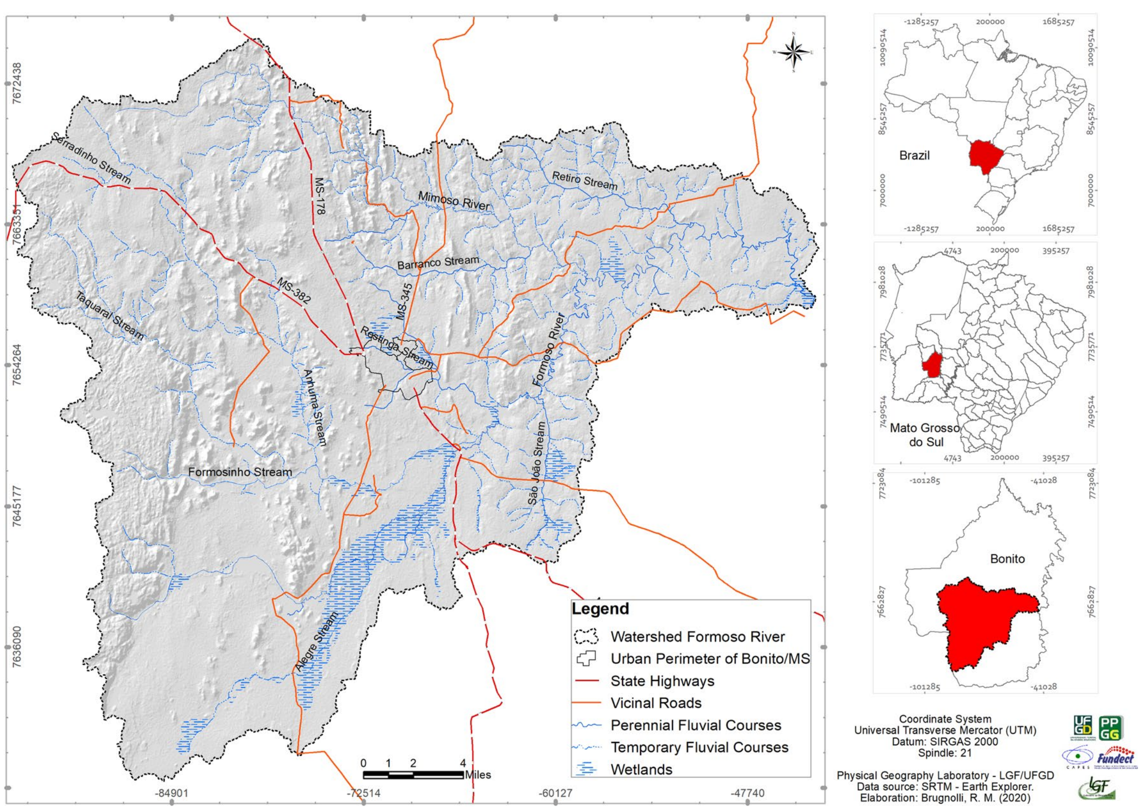

Fig. 2 Geographic location of the Formoso River Watershed, Bonito/MS, Brazil

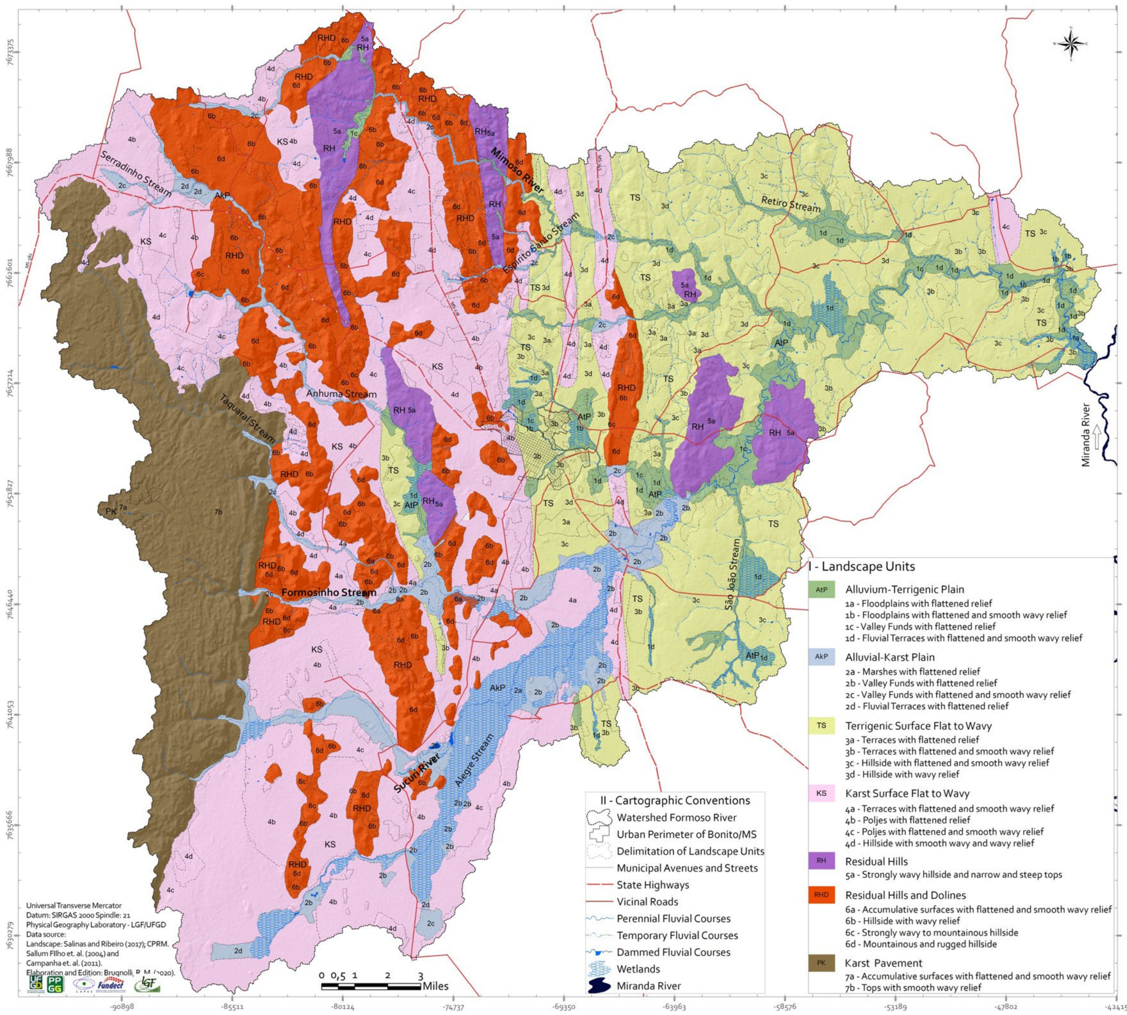

Fig. 3 Landscape units of the Formoso River Watershed, Bonito/MS, Brazil

with less than 8% slope and predominance of gleisols (periodically or partially saturated with water). The forest vegetation, especially gallery forests and remnants of the Atlantic Forest stand out in the landscape in its four subunits.

The *alluvial-karst plain* includes flattened to smooth wavy areas that reach up to 8% slope, occupying valley bottoms and karst river terraces, especially limestone and calcitic, dolomitic marbles, as well as bathed on limestone and travertine tufts. Gleisols, forest and undergrowth vegetation predominate the area. The undergrowth vegetation occupies most areas of the Formoso River, as a significant refuge for biodiversity. It includes four subunits.

The *flat to wavy terrigenous surface* over sandstones and other terrestrial rocks presents between 0.0 and 20.0% declivity on terraces with flat to smooth wavy relief, and slopes with smooth wavy to wavy relief. The latosols that originated the implantation of pastures predominate. Some scattered patches of forest vegetation occur in the medium and low course of the FRW, along its four subunits.

The *flat to wavy karst surface* is linked to limestone, calcitic and dolomitic marbles on terraces composed of limestone and travertine tufts, poles with flat to smooth wavy relief, and slopes with smooth wavy to wavy relief. The declivity reaches 20%; however, the vast majority is located in extremely flat relief in areas of poljes, where fertile and fragile soils predominate, such as the orthic rendzic chernosol in the central region of the FRW. The natural fertility of the soil is due to the limestone, which favors the growth of crops (the main use of the unit). In addition, the flat relief benefits mechanization; however, a relevant counterpoint is its high fragility in the face of chemical dissolution of limestone. The anthropic action in the karst brings instability to the fragile terrain, and undermining may occur, in case of unknown substrate characteristics (De Waele et al. 2011; Gutiérrez et al. 2014; Parise et al. 2015; Travassos, 2019). This landscape unit is divided into four relatively homogeneous subunits.

The *residual hill* unit covers terrigenous rocks with steep slopes with topographical irregularity reaching 75%, with embedded valleys and restricted plains. It presents very wavy slopes and narrow, steep tops. Its hillsides are short with varied width, and soils range from deep latosols to recent and fragile neosol and chernosol. Forest vegetation predominates with relevant Atlantic Forest enclaves. The unit comprises one subunit.

The *residual hill and doline* unit develops on limestone, and calcitic and dolomitic marbles on accumulative surfaces on calcareous tufts. The relief presents flat to smooth wavy characteristics, wavy slopes, very wavy, mountainous, and scarped, from 3.0 to more than 75% declivity. Latosols, nitosols, and chernosols predominate the unit with forest vegetation, as well as some pastures. The unit remains with most of its vegetation preserved; however, pastures have advanced on steeper slopes of its residual karst hills. It includes four subunits.

The *limestone pavement* unit is distinct from all other units. It is characterized by dissected surfaces and elongated hills of Serra da Bodoquena, with calcitic and dolomitic limestones from the Bocaina Formation, in which horizontal stratification plan prevails. The landscape unit is divided into two subunits, and both present Orthic Rendzic Chernosol. One subunit is with pasture and the other with forest vegetation. The Serra da Bodoquena acts as a significant protector of this karst area, as well as its underground water reservoir that supplies the FRW.

Geoecological diagnosis of landscapes of the Formoso River Basin

Methodologies that use geotechnologies may define the landscape mapping and the geoecological state. Therefore, areas where the landscape units are in a stable, moderately stable, unstable, or critical situation were spatialized, reflecting the close relationship between their physical–natural and anthropic components (Fig. 4).

Discussing the geoecological state of landscapes demands working with three points of analysis: land use conflicts, environmental fragility and environmental risks and problems. The first deals with the relationship between potential use (capacity or aptitude for use through its physical components) and actual use of land (current anthropic use) bringing up the analysis of existing conflicts and possible adaptation strategies. The aim is to draw a parallel between the physical environment and its current use, to identify conflicts, and to use levels for such conflicts. Such levels are based on geoecological indicators, assigning quantitative weights to the physical environment and land use and cover. We highlight the fact that even a fragile area with carbonate rocks and fragile soils becomes "conflict free" if it presents forest vegetation to protect the soil. Conversely, if the same area presents exposed soil, conflicts are significant. In the BHRF, the vast majority of conflicts are located in areas of carbonate rocks, fragile soils such as chernosol and gleissol, and areas close to the Formoso River marsh, a significant and fragile refuge for biodiversity. Environmental fragility, as discussed in the methodological sub-item, is evaluated by the pressure that an environment is subjected to when the physical–natural components are related to different degrees of land use intensity. The more conflicting the relationship is, the greater the fragility of systems to suffer damages and imbalance. The intense fragilities are associated with karst, especially in soybean crops and marshland. The BHRF is heavily impacted affecting the recurrent turbidity of river courses, widely discussed in Brugnolli (2020). According to the facts, we identified a close relationship between conflicts in land use and environmental risks and problems in BHRF that tend to become significantly visible in medium and long term. The numerous environmental problems in the area go from advanced processes of silting up rivers, development of erosion, dumping of solid waste, point of water contamination to problems that change what is preached in Bonito—its scenic and translucent rivers recognized worldwide and the karst landscape. Thus, there is need for performing landscape assessments (state and geoecological diagnosis) so that proposals and suggestions may improve environmental quality, increasing resilience and proposing mitigation actions.

The description of the FRW geoecological state begins with the *stable units* that cover 513.94 km^2, representing 38.80% of the basin. Extensive areas were formed predominantly by forest vegetation. However, few points of erosions and other environmental problems were recorded. Land use conflicts were not identified, and the environmental fragility is varied. The highest areas present karst rock substrate and high fragility. The geoecological state remains stable due to the vegetation present in the areas, acting as a positive balance. Thus, they represent landscapes with natural geoecological processes that preserve the original structure with little or no anthropic influence. The area presents well-preserved characteristics due to its landscapes.

The landscape units in a *moderately stable* state cover 390.22 km^2 or 29.46% of the basin. They present several denudational processes and solid waste disposal, increasing risks of instability. Pastures predominate with potential for various uses, provided that they are used for extensive agricultural practices and checking the fragility of environmental components. The landscapes show little change in their structure and low-intensity environmental problems**.** The land use remains balanced in terms of potential.

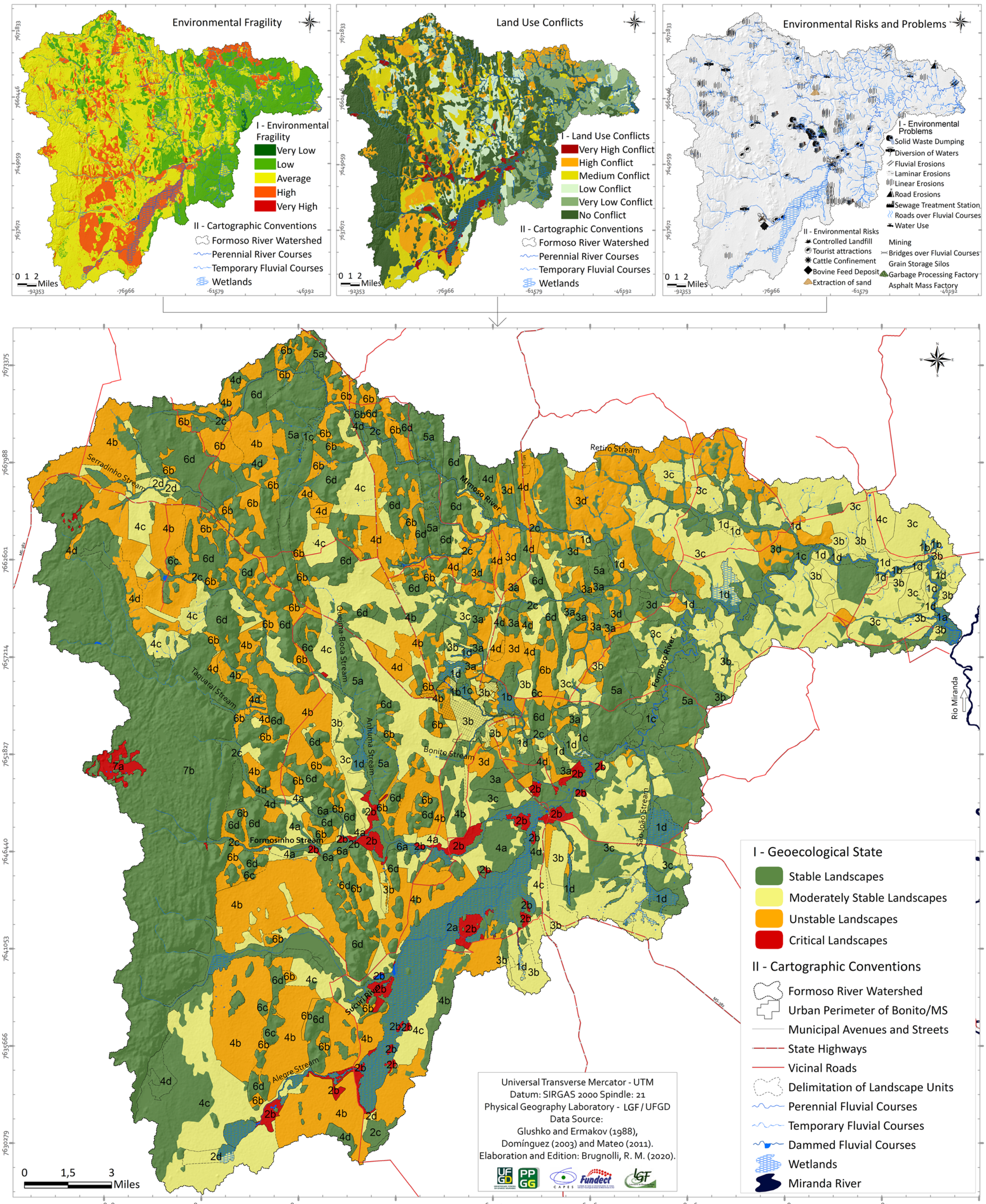

Fig.4 Geoecological state of landscapes of the Formoso River Watershed, Bonito/MS, Brazil

Units with *unstable* geoecological *state* present linear, laminar erosions and ravines. They predominate overlapping cultures in karst terrain, mainly in chernosols (fragile). The instability is the cause of recurrent surface water turbidity in the municipality of Bonito generating numerous ecological/environmental, economic, and social difficulties. In medium and long term, the trend scenario becomes obscure and critical. The landscapes are characterized by strong changes in the spatial and functional structure and their current use is greater than the landscape potential. They cover 402.11 km^2 or 30.36% of the basin, located in the medium and low course. Burri et al. (1999), Boggiani et al. (2002), De Waele et al. (2011) and Silva and Morais (2011) highlight the relationship between anthropic action and karst system, stating that monocultures have been occupying these systems intensively, due to their fertile and flattened characteristics (poljes and karst depressions). The monocultures stand out as the most prominent activity to generate implications in karst, contributing to depletion.

The units in *critical* geoecological state cover small portions (18.40 km^2 or 1.39%), despite not necessarily less worrying. They present characteristics that differ from all other classes with high and maximum incongruities in land use conflicts. The pastures and crops in plains are covered with limestone tufts and travertine of the Xaraiés Formation (extremely fragile and porous). In the residual hills and in Serra da Bodoquena, they are covered with limestones of Corumbá Group (Bocaina and Cerradinho). The areas present fragile soils, such as gleisols and chernosols.

Critical areas identified in the analyses are related to the slope and the type of land use. Figure 5a represents an area of exposed soil and the beginning of a steep slope and with high fragility. Figure 5b, c shows soil loss in an area with linear ravine erosion, fragile with high declivity and lack of significant vegetation to protect the soil.

The critical landscape units present changes in spatial and functional structure with gradual loss of their geoecological functions and significant environmental problems. Land use has exceeded the landscape potential and the areas demand urgent mitigation measures to restore their geoecological value. Thus, all these regions are only suitable for the reestablishment of forest vegetation, since they are not suitable for pasture and crops due to their high fragility. These areas are susceptible to erosive processes, due to the inappropriate use of the soil, added to its great exposure (exposed soil), especially when it comes to areas with the presence of crops. Erosion occurs by the dragging of soil particles by rain, as well as the coarse texture of some soils (neosol). Thus, vegetation recomposition is indicated for the maintenance and protection of the soil, favoring the development of native species of fauna and flora (Atlantic Forest and Cerrado), in

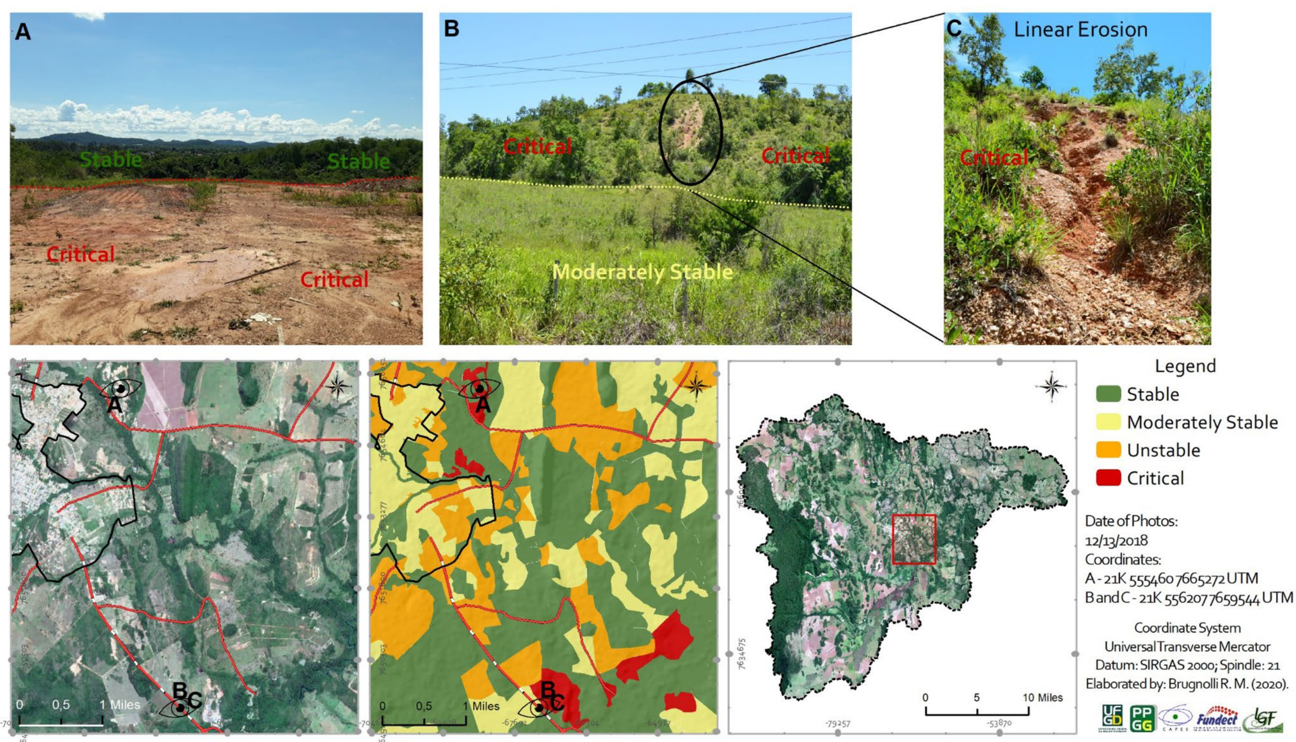

Fig. 5 Controlled landfill in critical areas (Photo **A**), and linear erosion triggered by land misuse (Photo **B** and **C**) in the medium course of Formoso River Watershed, Bonito/MS, Brazil

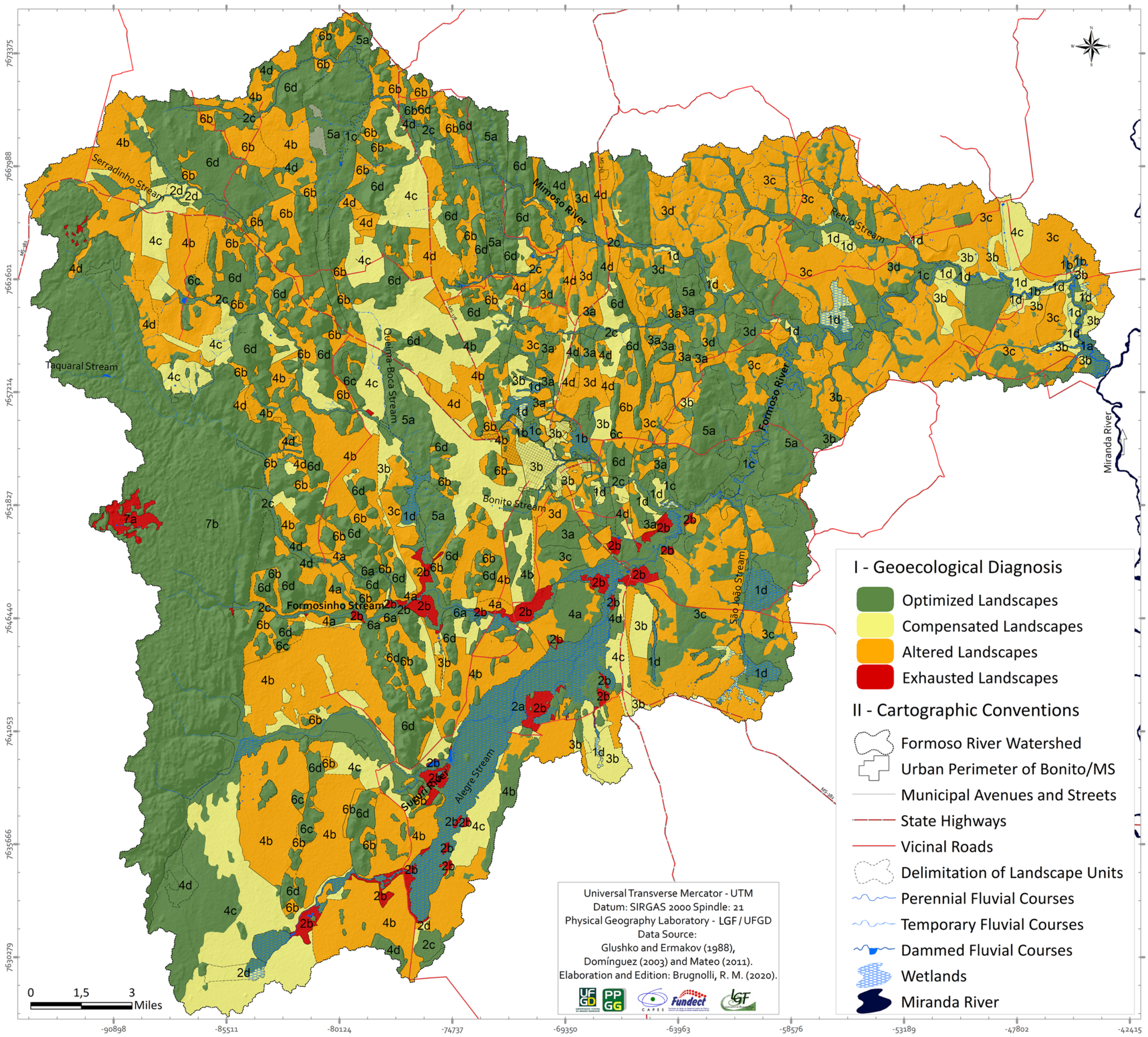

Fig. 6 Geoecological diagnosis of landscapes of the Formoso River Watershed, Bonito/MS, Brazil

the vicinity of the Formoso River. The aim is to increase the capacity of water infiltration into the soil and to reduce erosion processes and river damming increasingly recurrent in BHRF. The geoecological diagnosis of FRW was defined through the geoecological state that acts precisely according to the definition of characterization with physical–natural components, anthropic environment, environmental fragility, environmental risks and problems, and conflicts in land use. The study was based on the integrated and systemic analysis, contributing to decision making, and defining trend and desired scenarios (Fig. 6, and Tables 1, 2).

Optimized landscapes present high geoecological stability and have received one or more compatible socioeconomic functions. They include landscapes where human activity has promoted rehabilitation and/or conservation measurements to increase capacity for production and reproduction of natural resources. They occupy all regions of FRW, 513.94 km^2 or 38.8% of the total basin and located in natural areas (forest and undergrowth), close to river courses and humid areas, such as the Formoso River marshland, where gleisol predominates. Uninterrupted preservation is demanded as it assists water infiltration into the soil and supplies the Formoso River marsh, mainly to sustain drought periods. Yet, optimized landscapes are found in the most dissected areas of the residual hills of the high and medium course and karst pavement of Serra da Bodoquena in the high course, places where the chernosols and gleisols predominate.

Table 1 Synthesis of the geoecological diagnosis of landscape units I, II, and III of the Formoso River Watershed, Bonito/MS, Brazil

UP's 1st level	UP's 2nd level	Environmental fragility	Land use potential	Current use	Land use conflicts	Environmental risks	Environmental problems	Geoecological state	Geoecological diagnosis
I	1a	Medium	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Absence	Absent	Stable	Optimized
	1b	Low	Recommended for forest vegetation preservation	Forest vegetation	No conflict	One landfill; one tourist atraction	Two river erosions; one point where the road crosses the riverbed	Stable	Optimized
	1c	Medium	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Three tourist attractions	Laminar erosion; a sewage treatment plant; two points where water is used to supply dams; seven points with solid waste dumps; and five points where the roads cross the riverbed	Stable	Optimized
	1d	Medium	Unit recommended for various uses of extensive agricultural practices	Pastures with sparse forest Vegetation	Low conflict	Absence	Two laminar erosions; and three river erosions	Moderately stable	Compensated
II	2a	High	Recommended for forest vegetation preservation	Forest and Undergrowth vegetation	No conflict	Seven tourist attractions	One point with solid waste dump; one point where water is used to supply dams; one linear erosion; and four points where the roads cross the riverbed	Stable	Optimized
	2b	High	Unit recommended for plant restoration and unsuitable for any use	Pastures with small culture areas	Very high Conflict	One tourist attraction	Four laminar erosions; five linear erosions; four points where the roads cross the riverbed	Critical	Exhausted
	2c	Medium	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Absence	One linear erosion; and two points where surface water is used for water supply;	Stable	Optimized
	2d	Medium	Unit recommended for various uses of extensive agricultural practices	Pasture and soy crop	Low conflict	Absence	Absent	Moderately stable	Compensated

Table 1 (continued)

UP's		Environmental fragility	Land use potential	Current use	Land use conflicts	Environmental risks	Environmental problems	Geoecological state	Geoecological diagnosis
1st level	2nd level								
III	3a	Low	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Absence	One linear erosion; and one point where the road crosses the riverbed	Stable	Optimized
	3b	Medium	Unit recommended for various uses of extensive agricultural practices	Soy crop and pasture	Medium conflict	A waste processing plant; and two storage silos	One point where the road crosses the riverbed	Moderately stable	Compensated
	3c	Low	Unit recommended for various uses of extensive agricultural practices	Pasture	Medium conflict	Absence	Ten laminar erosions; eight linear erosions; and six points where the roads cross the riverbed	Moderately stable	Altered
	3d	Medium	Unit recommended for various uses of extensive agricultural practices	Pasture with sparse Forest vegetation	Medium Conflict	Absence	Three points with waste disposal; three river erosions; twenty laminar erosions; six linear erosions; and four points with roads crossing the riverbed	Unstable	Changed

Table 2 Synthesis of the geoecological diagnosis of landscape units IV, V, VI, and VII of the Formoso River Watershed, Bonito/MS, Brazil

UPs 1st level	UPs 2nd level	Environmental fragility	Land use potential	Current use	Land use conflicts	Environmental risks	Environmental problems	Geoecological state	Geo-ecological diagnosis
IV	4a	High	Recommended for pastures provided conservation practices are carried out. Cultures exhibit limitations, such as rotation and intercropping	Soy crops and pasture	High conflict	Absent	Two laminar erosions; six linear erosions	Moderately stable	Altered
	4b	High	Recommended for pastures provided conservation practices are carried out. Cultures exhibit limitations, such as rotation and intercropping	Soy crops	High conflict	One tourist attraction	Three laminar erosions; seven linear erosions; and one point where the road crosses the riverbed	Unstable	Altered
	4c	Medium	Unit recommended for various uses of extensive agricultural practices	Pasture	Medium conflict	Five tourist attractions; and one plant of asphalt mass	One point with solid waste dump; one point with diversion of water from river courses to supply dams; river erosion; and four laminar erosions	Moderately stable	Altered
	4d	Medium	Unit recommended for various uses of extensive agricultural practices	Pasture and soy crops	Medium conflict	One area of sand and gravel extraction	Two laminar erosions; and seven linear erosions	Unstable	Altered
V	5a	Medium	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Absent	Six laminar erosions; linear erosion; and five points where the roads cross the riverbed	Stable	Optimized
VI	6a	Medium	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Absent	Absent	Stable	Optimized
	6b	High	Recommended for pastures provided conservation practices are carried out. Cultures exhibit limitations, such as rotation and intercropping	Pasture and soy crops	High conflict	One stock containment area	One place with solid waste dump; one point with diversion of water from river courses; seven laminar erosions; four linear erosions; and one point where the road crosses the riverbed	Unstable	Altered
	6c	Medium	Recommended for forest vegetation preservation	Forest vegetation	No Conflict	Absent	Absent	Stable	Optimized
	6d	Medium	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Four tourist attractions; and one deposit for cattle feed	Two laminar erosions; and one point where the road crosses the riverbed	Stable	Optimized

Table 2 (continued)

UPs 1st level	UPs 2nd level	Environmental fragility	Land use potential	Current use	Land use conflicts	Environmental risks	Environmental problems	Geoecological state	Geo-ecological diagnosis
VII	7a	High	Unit recommended for plant restoration and unsuitable for any use	Pasture	Very high conflict	Absent	Laminar erosion; linear erosion; and pasture sites in conservation unit areas—PARNA of Serra da Bodoquena	Critical	Exhausted
	7b	Medium	Recommended for forest vegetation preservation	Forest vegetation	No conflict	Absent	Absent	Stable	Optimized

Compensated landscapes present high levels of geoecological sensitivity, but land use is balanced with or even below its potential. Despite presenting anthropic changes, the vertical and horizontal structure of landscapes continues to fulfill its geoecological functions and services. The landscapes occupy 197.48 km^2 or 14.91% of FRW. The areas present medium fragility with pastures in oxisols and nitosols, well drained and deep. They present medium and low incongruities with balance, and still fulfilling the geoecological functions.

Altered landscapes require attention. They occupy 594.85 km^2 or 43.90% of the basin, and despite fulfilling geoecological functions, mainly agricultural and livestock production, they present several local environmental risks and problems. Silva (2015), Ribeiro (2018), Brugnolli et al. (2019) and Brugnolli et al. (2020) highlight it as the cause of recurrent turbidity to the FRW river courses, the main negative environmental impact that the basin has been suffering since the early twenty-first century. The problems impact the social and economic environmental framework of Bonito municipality (effectively linked to tourism in the translucent waters of the rivers). These landscapes present their current use oversized, due to the lack of adequate capacity to assimilate the current anthropic actions. Significant changes in structure, and substantial changes in the functioning have occured, weakening the internal relationships between their components. The overexploitation of resources leads to a decrease in their productive potential (including biological productivity), and the development of intense degradation processes manifested in soils and water regime.

Exhausted landscapes present high geoecological sensitivity and the exploitation regime overcomes the limitations that impose potential. The assigned socioeconomic functions are different from the landscape's possibilities of offering a prolonged productive response. These areas occupy 18.40 km^2 or 1.39% of the basin. Though not extensive, the location is disturbing. In addition to pasture areas on the western edge of Serra da Bodoquena, they include recent river deposits, naturally eroded and extremely fragile, close to the Formoso River. One of the sectors exhibits major environmental problems related to intensive use in karst and fragile floodplain areas.

Scenarios and proposals for the Formoso River Basin

Endless discussions about Bonito cover its relationship of unstable and critical geoecological diagnosis, scenic surface waters, agriculture, and tourism. However, the lack of effective proposals of improvement brings a trend scenario in which the translucent and highly scenic rivers give rise to an

Table 3 General proposals, trend and desired scenarios approaching the geoecological state of the Formoso River Watershed, Bonito/MS, Brazil

Geoecological diagnosis	General proposals	Trend scenario	Desired scenario with the implementation of proposals
Optimized landscapes	•Maintenance of forest remnants •Prioritization of environmental education actions in tourist attractions •Construction of bridges that cross the river courses contemplating the river regime •Monitoring of surface water quality •Intensive treatment of waste from the sewage treatment station •The preservation of karst areas and limestone tufts is indispensable	•Tendency to remove vegetation in the medium and low course affecting all geoecological stability •Worrying scenario with crops and pastures entering legally restricted areas, such as plains and residual hills •Degraded landscapes and turbidity reflections in waters with an increase in denudational processes, reduction of perennial rivers, and the water capacity of the Formoso River •At the Sewage Treatment Station, the tendency to increase demand and greater waste dumping in the river course	•Maintenance of current use and biodiversity with positive effect on regional microclimate •Tourist attractions with actions and signs regarding the care with limestone tufts, fish, aquatic vegetation, and environmental quality •Roads pass through springs by means of bridges and not on the bed, favoring the natural flow, and assisting perennial river courses reducing the recurrence of turbidity •Improve the treatment of effluents from the sewage treatment station and reduce disposal of solid waste
Compensated landscapes	•May be used according to their potential. Must present management with level curves, rotating animals in paddocks, enhancing the pasture and favoring protection to the soil •In erosions, the insertion of vegetation is required, leaving them fallow to recover the geoecological value •Control and inspection of solid waste disposal	•Maintenance of its current uses and entry of new cultures in the medium course planed sectors •Lack of land management results in increased sediment dragging, developing new erosive processes and increasing existing ones •Advancement of pastures over permanent preservation areas, causing the silting of springs •Disposal of solid waste result in soil and groundwater contamination	•Pastures managed with infiltration increase and soil compaction decrease •Reduction in solid waste dumping •Erosion processes controlled and/or minimized with vegetation to guarantee water infiltration •Roads with correct drainage system with well-supported side trenches directing rainwater to retention boxes to reduce sediment drag •Increase of perennial river courses
Altered landscapes	•Crops need management, such as no-till, to minimize rainwater from reaching the soil directly •Interspersed harvest to avoid large areas of exposed soil during rainy seasons •Control the use of agrochemicals •Level curves and containment basins •Insertion of vegetation in erosions leaving them fallow, to recover the geoecological value •Monitoring instabilities in karst terrains	•The maintenance of their uses and agrochemicals may cause surface and groundwater damages, in addition to soil contamination •Increase of sediment drag due to superficial *runoff* mainly in rainy seasons and increase recurrence of turbidity in the rivers •Silting up river courses •Advanced erosion processes, degrading the area and increasing the quantity of sediments transported	•Crops managed with level curves and interspersed harvests to reduce soil compaction and intense rainwater infiltration •Pastures with level curves to increase soil infiltration and decrease compaction •In areas with legal restrictions, recomposing the vegetation and increasing the permanence of river courses may reduce recurrence of turbidity •Units with diverse rock outcrops and conserved limestone tufts
Exhausted landscapes	•Total alteration of the current uses •Restore its high geoecological value through the restoration of forest vegetation, providing the conservation of limestone tufts and rocky outcrops •Monitoring the quality of scenic waters to achieve positive aspects with soil and karst conservation and remediation practices	•Increase in the intensity and scope of anthropic actions •Forest vegetation and river courses negatively impacted •Reduction in the water capacity of the Formoso River marshland area with the addition of agrochemicals •Increase of soil waterproofing and sediment dragging, increasing the turbidity of rivers	•Unit with recomposed forest vegetation •Return of biodiversity and positive effect on fauna, flora, and regional microclimate •Reduction of surface *runoff*, causing a decrease in erosive processes •Increase in the permanence of river courses and reduction of turbidity •Acceptable water quality •Positive impacts on Bonito's geoecological, social and economic framework

affected river system. Therefore, the aim of our research is to comprehend the processes acting in a peculiar, sensitive, and complex area, as well as generating proposals (Table 3), and possible tendency and desired scenarios in face of the suggested recommendations.

Conclusions

Determining the geoecological diagnosis of the landscapes has generated recommendations to preserve and to recover fragile areas, areas of intact native vegetation, the alluvial plains, the Formoso River marshlands, and the steep hillsides, thus favoring the maintenance of ecological balance and increasing environmental resilience to reduce negative environmental impacts.

The questions were widely debated and achieved their main objective, that was to identify that FRW landscapes are severely impacted, despite having extensive preserved areas in Serra da Bodoquena and close to some river courses. However, large areas of flattened or wavy terrains, karst or terrigenous have already been dominated by pastures and crops changing the basin landscape into an anthropized landscape. In fact, it contradicts what is preached in Bonito regarding the preservation of river courses. The use of indicators to evaluate the geoecological diagnosis of landscapes has been practiced in geography; however, the proposal discussed here evaluates its use for karst environments still little studied in Brazil. Besides supporting the study of some variables already known as environmental risks and problems, as well as conflicts of use, the use of such indicators enables the adoption of environmental fragility—which is high in karst regions—as one of these indicators. It validates the proposal and allows to generate a reliable and applicable product in karstic watersheds.

Countless environmental problems already affect the karst, waters, and the economy of the region. The karst is characterized as a geosystem with mutual interactions and high fragility in the face of disturbances linked to anthropic use. Its complexity is subject to natural pressures, as the dynamics of the landscape itself or, mainly, anthropic actions. Thus, the actions proposed by this study are essential to protect the karst and to define specific regulations to properly safeguard it.

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