



Quaternary formations mapping in the region of Volta Grande do Rio Uruguai (Brazil)

Mapeamento das formações superficiais Quaternárias na região de Volta Grande do Rio Uruguai (Brasil)

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Abstract: Quaternary formations (detrital and weathered materials) are an important natural resource for different areas of scientific investigation, from understanding their relation to erosive processes and morphodynamic processes that create landforms or to understanding the history of the first human settlements (geoarcheology). Quaternary coverings can be formed in situ or be transported by external geologic agents. Regarding soils, Quaternary formations are related to landscape topography and are transformed according to the characteristics of this topography. Hence, classifying and mapping these soils is not always easy. The present article aims to map the Quaternary formations along a stretch of the Uruguay River basin known as Volta Grande (SC/RS-Brazil), by using topographic attributes derived from the SRTM GL1-Up Sampled digital elevation model, soil particle-size analysis, and a generated Multiresolution Index of Valley Bottom Flatness (MRVBF) index. The results of the analysis show that: (i) colluvium is the predominant Quaternary formation in the study area; (ii) there is a predominance of clay, corroborating previous studies of the region; (iii) the spatial distribution of the study area's Quaternary formations reflect local slope dynamics based on morphology and topographic position; and, (iv) the existence of colluvium-alluvium on the Uruguay River's banks indicates that slope attributes contributed to the pedogeomorphological dynamics of the study area and not only fluvial dynamics. Based on the results, the methodology applied in this study might be useful for pedogeomorphological studies, notably in the analysis and mapping of Quaternary formations, despite some of its limitations.

Keywords: Curvature; Soil-particle size; Colluvium.

Resumo: As coberturas ou formações superficiais quaternárias constituem recurso natural importante sob diferentes abordagens – desde o entendimento de suas relações com processos erosivos e das dinâmicas de esculturação da paisagem ao entendimento da história de ocupações humanas pretéritas (geoarqueologia). As formações superficiais podem ter origem in situ, ou podem ser remobilizadas pelos diversos agentes da geodinâmica superficial. Incluso os solos em si, tais formações estão relacionadas com a topografia e se transformam conforme as características dessa topografia. Daí a dificuldade, muitas vezes, em classificá-las e mapeá-las. O presente trabalho teve como objetivo a elaboração de um mapa das formações superficiais na bacia do rio Uruguai, no trecho conhecido como Volta Grande (SC/RS), por meio de atributos do relevo derivados do SRTM GL1-Up Sampled, do solo (granulometria) e do índice MRVBF – Multiresolution Index of Valley Bottom Flatness. Os resultados encontrados foram: (i) predominância de formação coluvial; (ii) predominância de argila corroborando estudos diagnósticos realizados na região; (iii) a distribuição espacial das formações superficiais na área de estudo refletiu a dinâmica das vertentes com base na sua morfologia e posição topográfica; (iv) a ocorrência de formações colúvio-aluviais às margens do rio Uruguai, nas áreas de planície, indica contribuição das vertentes na dinâmica pedogeomorfológica da área de estudo e não somente dinâmica fluvial, considerando a característica de vale encaixado do rio Uruguai (planícies estreitas). Com base nos resultados, portanto, a metodologia aplicada neste trabalho demonstrou

potencialidade, com algumas limitações, de aplicação em estudos pedogeomorfológicos, notadamente, na análise e mapeamento das coberturas superficiais.

Palavras-chaves: *Curvatura; Granulometria; Colúvio.*

1. Introduction

This study is the result of applied geoscience research in the context of Quaternary formations. Quaternary formations, a generic term in geologic and geomorphologic disciplines, refers to a class of mostly weathered materials formed by meteoric action as well as morphodynamic surface and subsurface processes that cover bedrock. The term, therefore, includes the soil and part of the subsoil (GUERRA, 1993; QUEIROZ NETO, 2001). These materials are organized temporally and spatially in the landscape as sediment deposits that change due to weathering forces and agents. Moreover, they often serving as the markers of current or past geomorphological and sedimentary processes that shape or model landscapes (PROGNON, 2012).

Quaternary formations are organized in a mantle of metric to pluridecametric thickness, whether pedogenized in character, rarely reaching over a hundred meters. They can either originate *in situ*, characterizing them as autochthonous (or eluvial), or they can be transported by external geologic agents, thus classifying them as alluvium and colluvium. Some of the main conditioning geneses of Quaternary formations are related to the topographic surface characteristics and to the role of runoff and climate on these coverings (LEOPOLD; VÖLKEL, 2007). In morphostratigraphic terms, but possibly discordant with the current topographic conformation, Quaternary formations may result from exhumed ancient coverings, such as paleosols (PROGNON, 2012).

Understanding the geographic distribution of Quaternary coverings (or formations) is important for environmental studies, including land use and regional planning. The most noteworthy examples highlighting the necessity to pay them heed include: (i) the intrinsic vulnerabilities of their composing sedimentary materials and thus relation to erosive processes (BEZERRA *et al.*, 2009; PEDROSA; MARTINS, 2011; JINSHI LIN *et al.*, 2018) ; (ii) their movement and instability risks due to anthropic occupation (FERREIRA, 1999; PEDROSA; MARTINS, 2001; BRAGA *et al.*, 2016); (iii) their use in providing information for the understanding of geomorphological dynamics, and either marine, wind, lacustrine or fluvial processes (PINHEIRO *et al.*, 2016; JESUS *et al.*, 2020; MASSELINK *et al.*, 2020); and, (iv) their role in supporting timeline estimates via sediment dating techniques, such as Optically Stimulated Luminescence (OSL) and Thermoluminescence (TL), for archaeological, geomorphological and geological studies (LORDEAU *et al.*, 2016, SAWAKUCHI *et al.*, 2016, CORRÊA *et al.*, 2016; SANTOS, 2018).

The study area investigated is located in the upper basin of the Uruguay River (between the States of Santa Catarina and Rio Grande do Sul, Brazil), in a stretch known as Volta Grande. The area features typical morphological characteristics associated with fluvial dissection, such as steep slopes and a predominantly homogeneous basaltic lithology.

A challenge that arose during fieldwork in the study area was the difficulty in mapping the region's Quaternary formation distributions and understanding their spatial patterns in relation to the evolutionary dynamics of the landscape. This is due to the area is marked by the riverbank slope asymmetry as well as by the type of surface coverings interdigitate themselves in the plains. In this context, the objective of this study was to map the Quaternary formations in the Volta Grande region of the Uruguay River. The results were achieved by implementing cartographic techniques and using variables such as relief, soil (particle-size) and the Multiresolution Index of Valley Bottom Flatness (MRVBF) (GALLANT; DOWLING, 2003), and may contribute to future pedogeomorphological research in the region.

2. Methodological procedures

2.1. Characterization of study area

The study area is located in the upper Uruguay River basin, between the states of Santa Catarina and Rio Grande do Sul, Brazil, in a stretch of the river forming a meander known as Volta Grande. Volta Grande is directly downstream from the Foz do Chapecó Hydropower Plant (HPP) and serves as a border for the cities of Palmitos, São Carlos, and Águas de Chapecó in the state of Santa Catarina, and the city of Alpestre in the state of Rio Grande do Sul (**Figure 1**). The defined study area not only includes the Volta Grande meander and surrounding landscape but also three archaeological sites found in the Uruguay River alluvial plain:

ACH-LP-07, RS-URG-01, and Ilha Redonda 1. These archeological findings are among the oldest archeologically significant sites in the state of Santa Catarina and among the oldest in southern Brazil. They are the vestiges of the region's oldest human settlements dating from the Pleistocene-Holocene transition, more than 11,000 years ago (LORDEAU *et al.*, 2016).

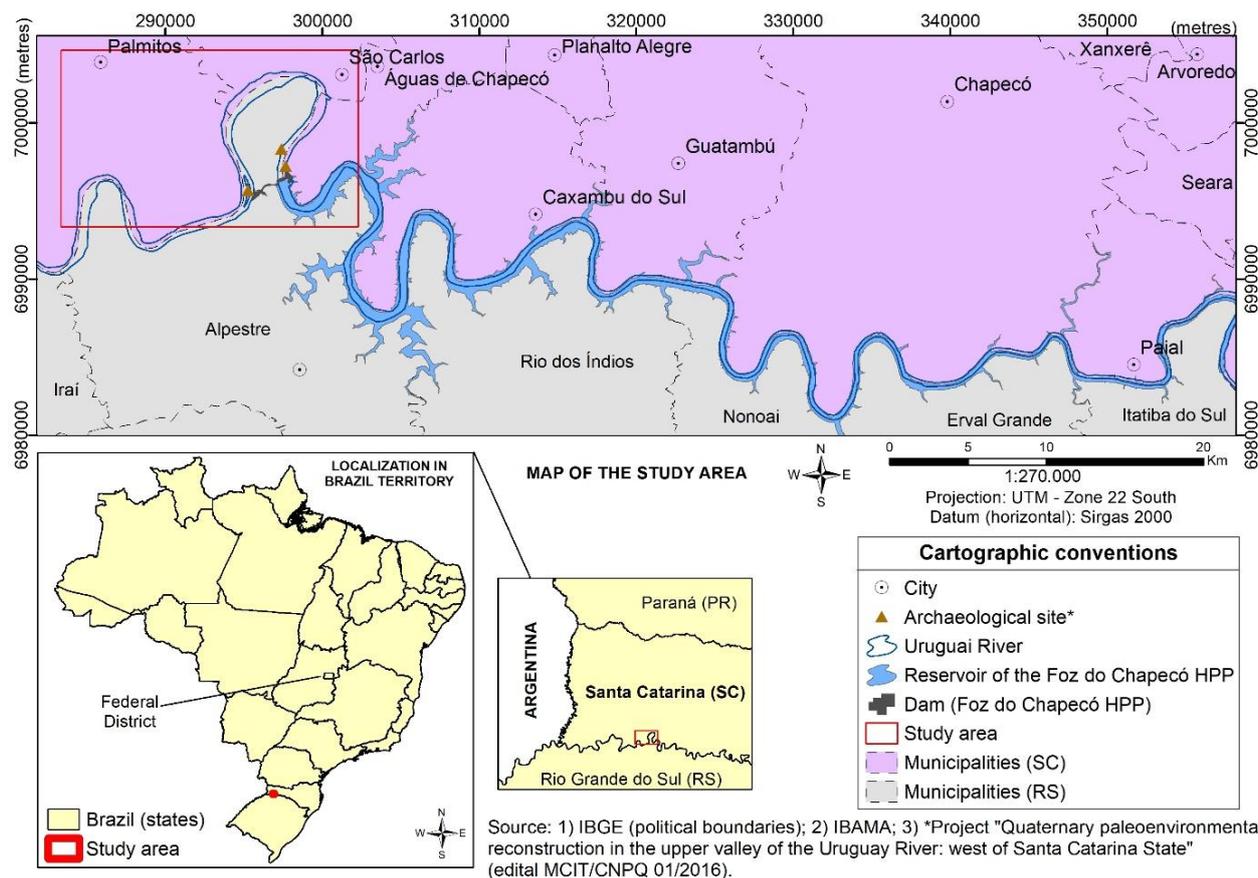


Figure 1: Location map of the study area.

Geologically, Volta Grande is part of the Serra Geral Formation which is part of the Magmatic Province of Paraná and is predominantly represented by lavas spills dating from between 133 and 119 Ma during the Juro-Cretaceous period (MARQUES; ERNESTO, 2004; CPRM, 2010).

Geomorphologically, it is situated in the domain of the Meridional Plateau, and in a landscape characterized by deep valleys and uneven topography, which is regionally called the ‘Dissected Plateau’ of the Uruguai River. The terrain is dominated by plateau and hills separated by hollows with gently inclined floors, sculpted in a weathered clayey soil mantle (RADAM BRASIL, 1987). However, the region’s hill slope gradients can be characterized as forming a predominantly wavy landscape terrain. The dissection of the relief is defined as extraordinarily strong, with drainage incision reaching depths in the order of 171 meters to 250 meters but with average drainage densities (IBGE, 2005). The relief difference in the Volta Grande meander is approximately 200 meters, from the highest hilltop to the Uruguai River’s surface level. Incised steep slopes commonly reaching the river’s bank levels characterize the margins alongside this stretch of the Uruguai River. These steep slopes are associated with erosive cliffs.

Because of intense fracturing of the basalt in the region a large amount of gravel, boulders and even rounded blocks are commonly found in the middle of the pedogenized mass of the unconsolidated soil (**Figure 2BC**). These coarse sediments originated from the bedrock and were mixed with the soil mass by means of transport, however, they also occur *in situ*.



Figure 2: Area landscape features include large slopes with differing curvatures and a first order tributary plain on the northern bank of the Uruguay River (A); shallow pedogenized surface cover at a medium slope (backslope position) over basaltic rock (B), and low slope on a saponite of basalt (C). The locations of the photos are indicated on the map in **Figure 3**.

The results of radiocarbon dating (^{14}C) tests of samples taken from the ACH-LP-07 archaeological site on the bank of the Uruguay River indicate that historic human settlement occurred between 9.470 and 11.400 years BP (LOURDEAU *et al.*, 2016), corresponding to the Pleistocene-Holocene limit. The thick clayey soil mantle next to the ACH-LP-07 archaeological site consists of fine homogeneous alluvial sediments in terms of color and texture, formed primarily from kaolinite and illite (SANTOS, 2018)

2.2. Fieldwork and soil particle size analysis

Fieldwork was carried out in May (15th and 16th), 2019 and October (19th and 23rd), 2019 with the purpose of: (i) obtaining soil samples for particle size analysis; (ii) conducting soil identification and documenting profile descriptions; (iii) undertaking qualitative landscape analysis in terms of physiographic and human elements (land use and occupation); (iv) making relief analyses (curvature of the slopes); and, (v) taking photographic records.

The soil particle-size analyses were undertaken at the geology laboratory at the Chapecó campus of the Federal University of Fronteira Sul (UFFS) using the pipette method (TEIXEIRA *et al.*, 2017) and classified according to Ruiz (2005) as described in the next paragraph. For the soil profiles, the pedological horizons were identified according to the methodology of Santos *et al.* (2005). Soil profiles were described with different sequences of pedological horizons.

After collection, the samples were taken to the laboratory where they were dried in the air. Pistil and grail were used to obtain an air-dried fine soil - TFSA. Sodium hydroxide (NaOH) was used in the dispersion of the fine fraction at a concentration of 1.5 mol / L and in the proportionality of 25 ml to 20 g of TFSA, according to Almeida *et al.* (2018). Afterward, the samples were taken directly to the shaker in which a mechanical dispersion of the solution took place at 155 cpm for 15 hours. The solution was washed with deionized water over a 0.053 mm sieve to retain the sand fraction. The sandy fraction retained in the sieve was transferred to a 50 ml beaker. The silt+clay solution in the beaker was manually stirred for 1 minute for homogenization and, immediately afterward, a volume of 25 ml was collected with a pipette. For sedimentation of the silt fraction according to Stokes' Law, a volume of 25 ml at 5 cm depth was pipetted

from the test tube meniscus, representative only of the clay fraction still in suspension. Each sample was taken to an oven for drying at 105°C for 24 hours. After the removal of the oven and cooling to room temperature of the beakers, they were reweighed in order to proceed to calculations for granulometric classification according to Ruiz (2005). Factor *f* (residual moisture) was also calculated. The separation between fine and coarse sand by sieving in the laboratory was carried out using the 250 µm mark.

A total of 47 points were sampled whose spatial distribution is shown in **Figure 3**. The satellite image (Sentinel-2) in Figure 3, is from May 2019 and is used only for visualizing the sample points' distribution. We sought to carry out a sampling in order to obtain a representative sample of the different segments of the slopes in the study area.

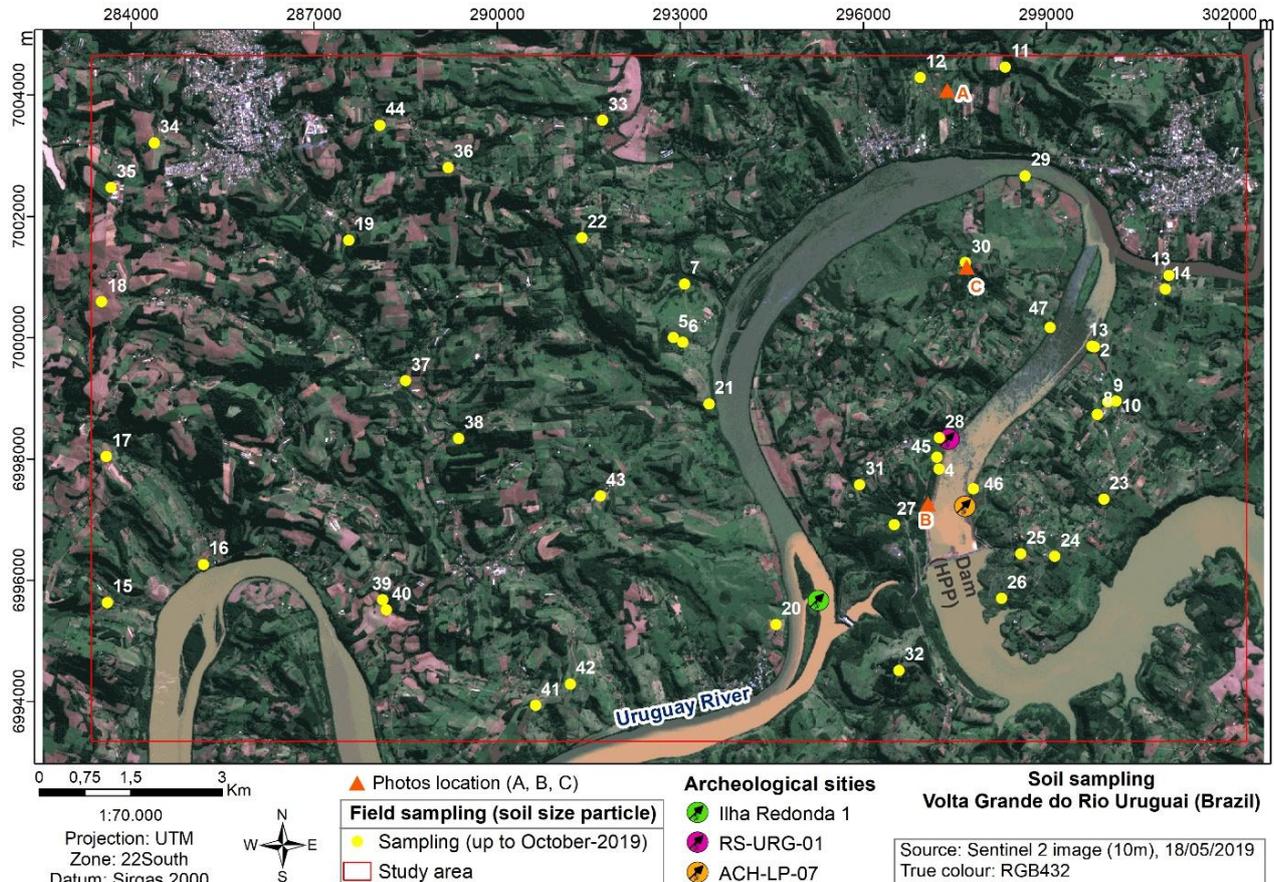


Figure 3: Locations of the soil particle size sampling.

2.3. Cartographic base

The spatial hydrographic data from the Environmental Resources and Hydrometeorology Information Center of Santa Catarina (Ciram-Epagri) database was used for mapping. Moreover, the documented hydrography was useful for referencing slopes and surface coverings.

The SRTM GL1-*Up Sampled* Digital Elevation Model (DEM), with a spatial resolution of 12.5 meters and publicly accessible via the United States' National Aeronautics and Space Administration's (NASA) Alaska Satellite Facility (ASF), was used to obtain the slope grades and curvatures throughout the study area's topography. This geomorphometric information was important for verifying the relationships between the shape of the slopes and the soil particle-size distribution as well as for the identification of the types of Quaternary formations (alluvium, colluvium, and eluvium). The choice in using the specific *Up Sampled* SRTM DEM is justified by its spatial resolution compatibility with the spatial resolution of the Sentinel-2 optical satellite image (10 meters) that was also used in this study.

The mentioned DEM is a resampling of the standard SRTM DEM from 30 meters to 12.5 meters. It also have the orthometric altitude of its EGM-96 geoid model converted to ellipsoidal altitude WGS-84 to correct the PALSAR sensor images (radiometric and geometric) on board the ALOS satellite (ASF, 2015), since they have a resolution of 12.5 meters in Fine Beam Dual (FBD) and Polarimetric (PLR) imaging modes.

2.4. Geomorphometry

Relief distribution is an environmental variable that, together with lithology, influences soil characteristics (JUNIOR *et al.*, 2014). Slope steepness and curvature (**Figure 4**) were the morphometric relief parameters used to assist in mapping the study area's Quaternary formations. Slope curvature plays an indirect role in the balance of pedogenesis and morphogenesis processes because it is related to matter migration and accumulation processes (water, minerals, and organic matter) across the surface (VALERIANO, 2008).

In this analysis, vertical curvature – derived from the SRTM GL1-*Up Sampled* – refers to the shape of the slope when observed in profile and expresses the variation in the slope over a given distance. This parameter was obtained using ArcGIS software whose algorithm calculates the value of the second derivative of the input surface (DEM raster) cell by cell. Resulting positive values correspond to convex surfaces, negative to concave surfaces, and null values indicate rectilinear surfaces (both in the uplands and in bottomlands). The vertical curvature distribution has a direct relationship with pedological and geological maps (VALERIANO, 2008).

As a direct method for mapping the Quaternary formations, the Multiresolution Index of Valley Bottom Flatness – MRVBF (GALLANT; DOWNLING, 2003) was used. These authors applied the MRVBF in two regions in Australia to identify areas of valley bottoms and ridges (tops) and to separate erosive and depositional areas. They highlight that the MRVBF index can be applied to analyze hydrological contexts (characterizing the hydrological behavior of catchment or drainage basins) and soil-landscape contexts (inferring spatial variation in pedogenetic processes or patterns of soil properties within mapped units).

Examples of its application, involving studies from a soil-landscape perspective, can be found in Prates *et al.* (2012) whose results show that the MRVBF index, among other indices, proves to be efficient in supporting the delimitation of landscape units; and in Junior *et al.* (2014) who show the utility in applying the MRVBF index for the delimitation of depositional areas as one of the environmental covariables in a digital model mapping soil properties.

Using a DEM as input, the MRVBF algorithm identifies valley bottoms using a slope classification constrained to converging areas, under the assumptions: (i) “the valley floor is low and flat in relation to its surroundings; (ii) valley bottoms occur at a variety of scales; and, (iii) large valley bottoms are flatter than smaller ones” (GALLANT; DOWLING, 2003).

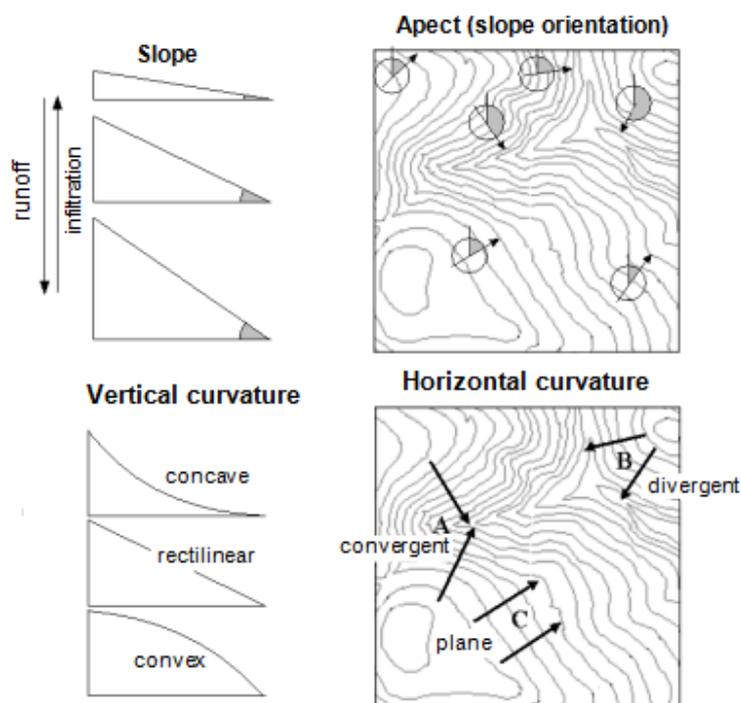


Figure 4: Geomorphometric variables derived from the DEM. Source: Valeriano (2008). Adapted by the authors.

The algorithm was originally developed using a DEM with 25-meter spatial resolution, but it can be applied with a DEM of any spatial resolution by making the necessary parameter adjustments (GALLANT; DOWLING, 2003). The authors consider the need for parametric adjustments in the case of resolutions substantially greater than 25 meters, such as those greater than 75 meters. From the results of this index, the reference values for the separation between erosive and depositional surfaces are less than 0.5 (<0.5) and more than 0.5 (> 0.5) respectively.

The Quaternary formations were delineated from the MRVBF, considering some assumptions. Firstly, eluvium is generally associated with erosive surfaces, on the summit hillslope position and on the slope shoulder (SCHOENEGER *et al.*, 2012) and with steep slopes (slopes greater than 45 degrees); secondly, colluvial and alluvial formations are generally associated with backslope and footslope positions (SCHOENEGER *et al.*, 2012), depositional surfaces as well as in drainage channels. It is important to note that colluvial formations are understood in this paper as a set of detrital sediments transported and deposited by various slope processes, still close to their source area, along the slope or at the base – toeslope position (PEDERSON *et al.*, 2000). Altitude isolines (12 meters equidistant) derived from the input DEM were used to distinguish the formations on depositional surfaces. Colluviums formed a wide range of slopes (0 ~ 44 degrees), given their occurrence on (colluvial) ramps and drainage channels. This dovetails with the concept of the colluvial formation coined by Pederson *et al.* (2000). Furthermore, concavities on the back and shoulder portions of slopes are common in the study area, in which sediments are deposited as slightly thicker colluviums.

For the purposes established here, the same parameters in **Table 1** were applied to the 12.5 meter DEM used (compatible with the 25 meter DEM) in the SAGA-GIS software since this algorithm is already implemented in its structure computational.

Table 1: Parameters of the MRVBF Index.

Parameter	Value
Initial Threshold for Slope	16,0
Threshold for Elevation Percentile (Lowness)	0,4
Threshold for Elevation Percentile (Upness)	0,35
Shape Parameter for Slope	4,0
Shape Parameter for Elevation Percentile	3,0

Source: Gallant and Dowling (2003).

3. Results and discussion

One of the first findings that come from the identification of soil profiles and field observations in the study area is that the Quaternary formations, in the Volta Grande region, are mostly shallow and gravelly, but with thickness fluctuations over short distances, given that the study area is marked by the riverbank slope asymmetry. In turn, the thickness fluctuations reflect the area's varying slope curvature lengths, even though the area's slope curvature lengths can almost all be generally categorized as quite extensive.

Moreover, concavities on the back and shoulder portions of slopes are common (**Figure 2A**) - as sediments in these locations are deposited as slightly thicker colluviums as opposed to on rectilinear slopes or on extremely steep slopes. In this sense, one could think of thicker colluvium in the concavities whose origin may be related to both mass movement and thin colluvial layers. The latter is more expressive in the landscape of the study area and covers a large part of its slopes' surface. Whether these two categories of colluviums indicate distinct morphodynamic phases of the landscape, is an issue that needs further investigation.

Basalt rock, appearing as saprolites at different weathering stages, is often close to the surface (**Figure 2BC**), constitutes shallow pedogenized formations mainly on the hill summits and on the slope shoulder, and is normally associated with Cambisols (Inceptisols) and Leptsols or Entisols (**Figure 5**). The surface horizons of these soils seem to constitute themselves as a result of thin colluvium previously mentioned. The Quaternary formations in bottomlands next to the discontinuous stretches of the Uruguay River plain (and some of its tributaries of greater fluvial order network) are thicker than the ones situated on the back and shoulder portions of slopes (**Figure 5**). They are made up of a predominantly clay-silt texture, except the surface layers resulting from the last annual flood events.

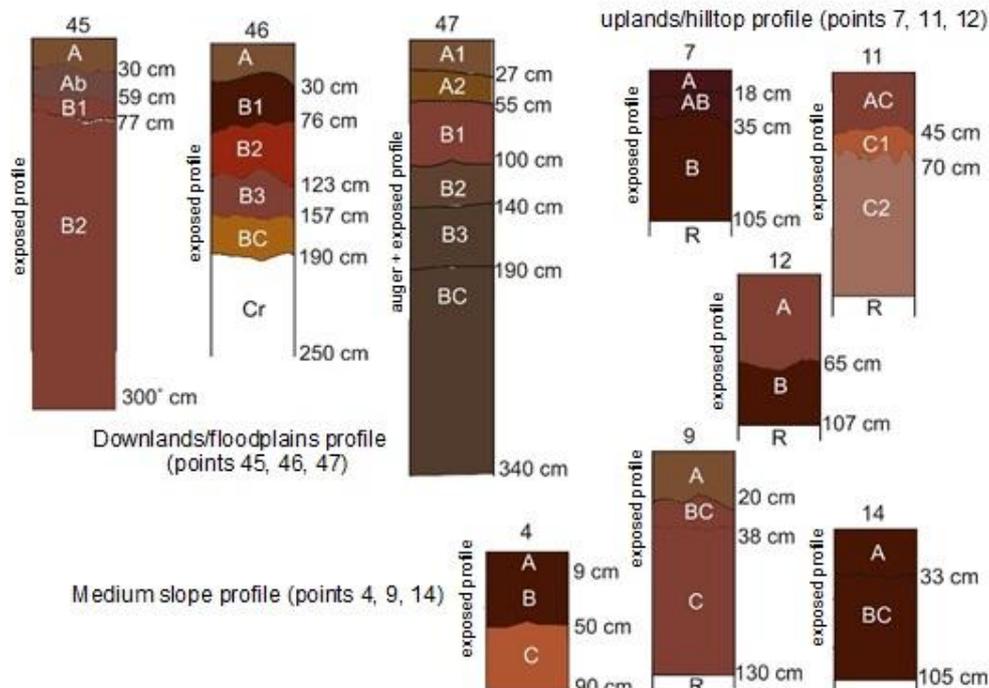


Figure 5: Representative soil profiles of Quaternary formations in Volta Grande. The locations of these profiles are shown in Figure 3. Source: The authors (2020).

Of the total points sampled in the field and classified in the laboratory as described in the methodological session, 70% of the samples were predominantly clay (**Figure 6**), as would be expected from chemical weathering of the basaltic lithological domain. The presence of silt in many of the samples on top of the slopes indicates a poorly developed weathering stage of the pedogenized formations.

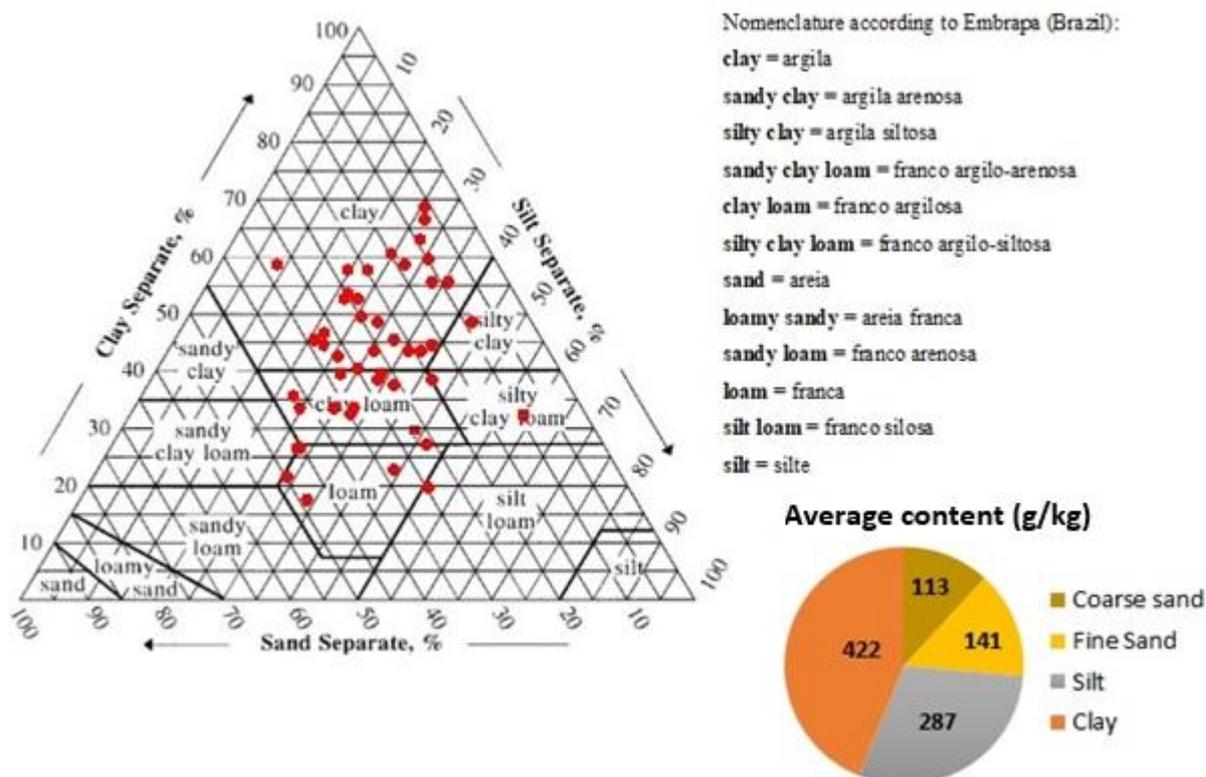


Figure 6: Textural diagram of all soil samples classified in the laboratory. Source: Created by the authors from the Soil Texture Calculator (United States Department of Agriculture – USDA).

The resulting curvature and slope gradient models derived from the input DEM indicate that the majority of the study area's slopes present a mostly convex profile (**Figure 7**), which is reflected by the landscape's predominantly wavy topography. However, concave slope curvature is more noticeable along the region's principal elongated river valleys as these slopes, when reaching the river's margins, form abrupt and noticeably steeper riverbanks than the banks opposite (**Figure 8**). In fact, asymmetrical river margins are a common geomorphological feature of the study area. This common relief characteristic overwhelmingly presents slope grades greater than 32%.

The distribution of the varying Quaternary formation textures found in the study area did not present a clearly spatial pattern in relation to the slopes' vertical curvature nor in relation to positions on the slopes (shoulder, backslope or footslope). Based on field observations and soil particle-size sampling, clay occurred on both concave and convex slopes. This result is coherent because of the basaltic environment and basalt's weathering commonly resulting in clay.

The sand tended to occur on the toe slope positions of convex and rectilinear slopes and floodplains along the Uruguay River. In these places, it is assumed that there is a mixture of deposits from both in situ weathering and short distance colluviums. This does not mean a result in abrupt changes of very expressive granulometry in terms of thickness of the pedogenized coverings. Moreover, soil profile descriptions resulted in differing profile for samples from the same topographic positions as well as similar sample profiles from differing topographic situations (**Figure 5**). From the sample profile descriptions, we can hypothesize that different weathering times might be considered as an intervening factor in the development of the pedological coverings and their soil texture, as the source material approaches the soil surface.

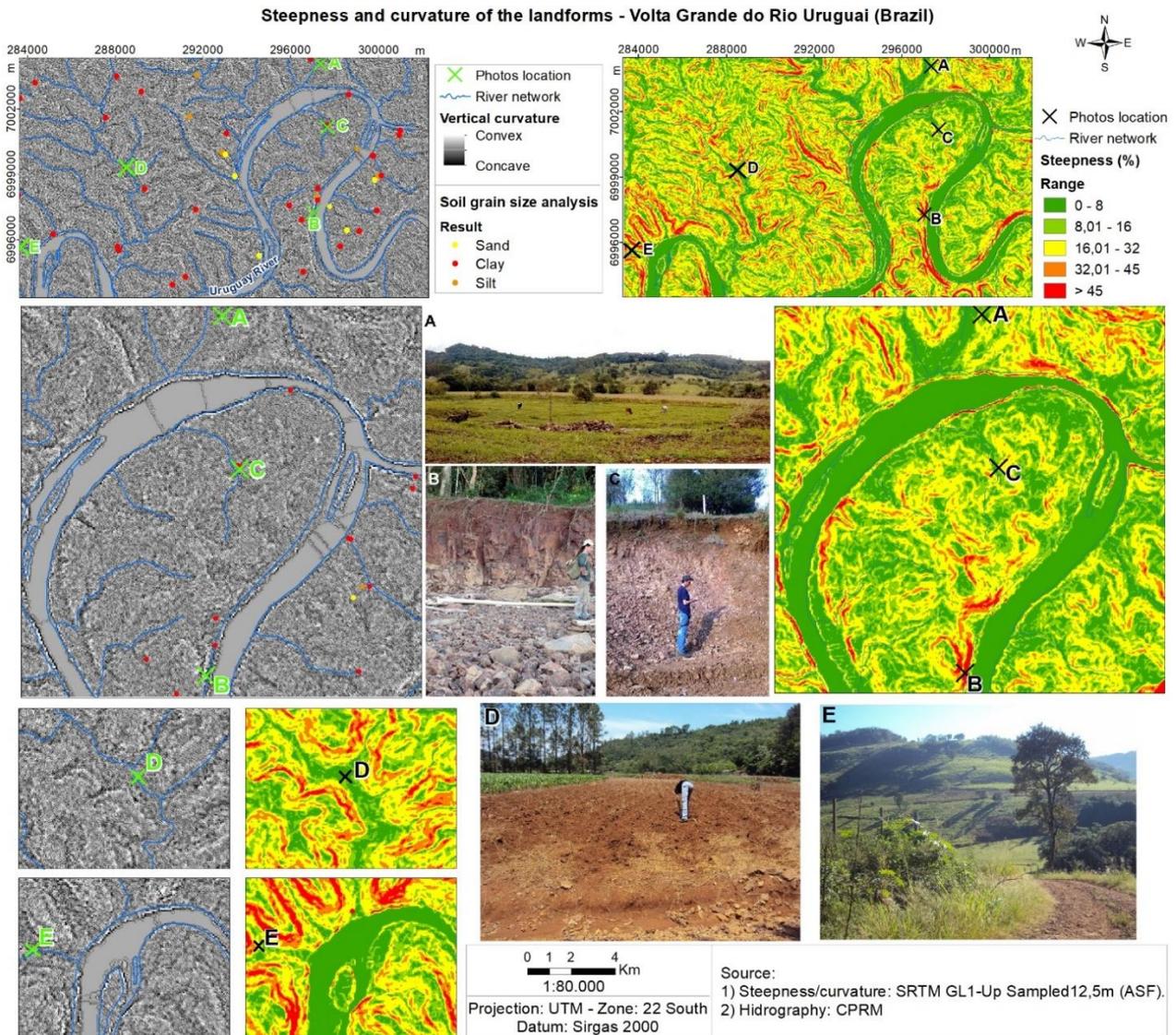


Figure 7: Steepness and slope curvature.

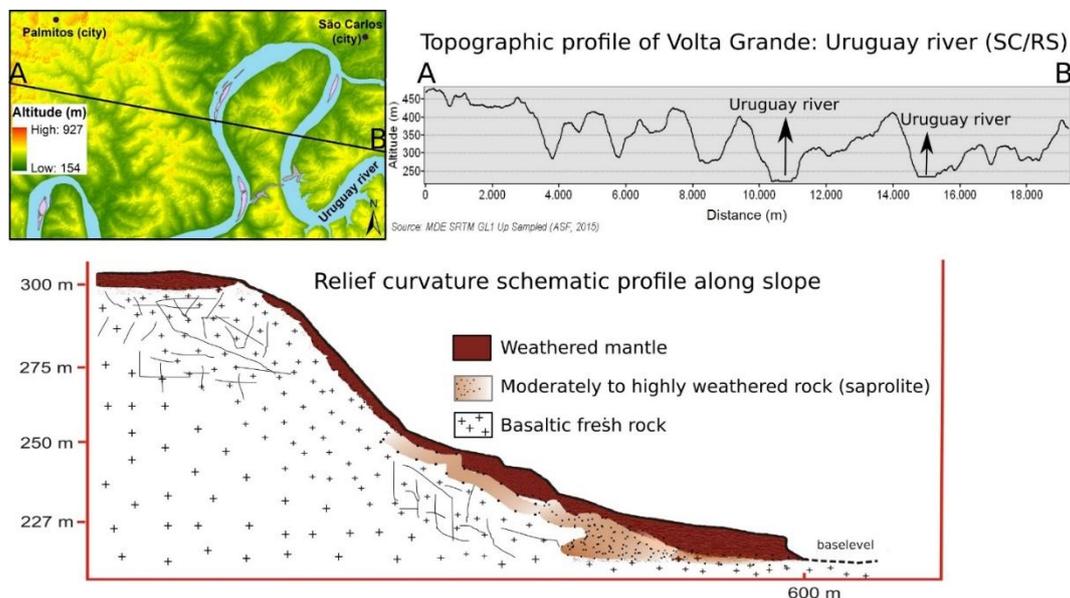


Figure 8: Topographic profile of Volta Grande and relief curvature schematic profile along slope.

According to what is observed in the field, slightly deep and shallow coverings are commonplace on hill summits with a slight increase in depth on slope shoulders and backslopes according to their concavity (**Figure 8**). This is probably due to erosion and colluvial formation while also not discarding the role of slow-motion landslides. Moreover, there is an increase in thickness on footslopes and in the floodplains. The common presence of pebbles (2 cm to 20 cm in diameter) and even boulders (20 cm to 100 cm in diameter) in the surface and subsurface horizons are found at several locations on slope shoulders and backslopes. This characteristic tends to indicate a colluvial nature for the genesis of surface-based formations in these areas and is featured by concavities (RENEAU *et al.*, 1990).

The MRVBF index was useful for interpreting relief by distinguishing depositional parts of the landscape such as valley bottom areas (or bottomlands) from erosive surfaces like hillslopes (**Figure 9**). The valley bottoms are easily observable when coinciding with principal drainage channels (with greater fluvial order network) and their floodplains. Such areas correspond to 0-8% grade on the slope map. Therefore, the use of the MRVBF algorithm was efficient in delimiting depositional surfaces in the Volta Grande area.

Eluvium occurs in the uplands, and on summits or hilltops (even flat surfaces), as well as on the slope shoulders in narrow valleys that coincide with erosive and convex surfaces. There is an important ambiguity in the distinction between colluvium and eluvium in the study area, whilst the MRVBF index was not able to point out any attribute or element that could be useful to this endeavour. In this sense, a fundamental question is that of related to the concept of allochthonia and autochthonia for pedogenized materials. For example, sediments that have been transported and deposited by the river on its banks, and remain on the plain for a time long enough for the pedogenesis. Could they be deemed as allochthonous or understood as autochthonous? Such a question needs further investigation in future works.

In the Volta Grande valley, the morphology clearly indicates a pedogenic/morphogenic balance whose weight trends to morphogenic factors. With this in mind and considering the steep grades of many backslopes and slope shoulders, we hypothesize that there is a rejuvenation of pedological coverings along with a fluvial incision in the Uruguay River valley. This might have started happening around the Pleistocene / Holocene interval.

The concave slopes that end in flat areas, such as the floodplains of the Uruguay River, result in colluvial-alluvial ramps. This type of Quaternary formation is sometimes found throughout the floodplain environment and along the main river channels and coincides with depositional surfaces with grades up to 16%. In Volta Grande, particularly in the concave (inner) part of the bank of the Uruguay River, these sort of deposits also occur along the floodplains, whose margin is noticeable in the field as a result of lower surface levels of Uruguay River – due to the Foz do Chapecó HPP dam lying directly upstream from Volta Grande.

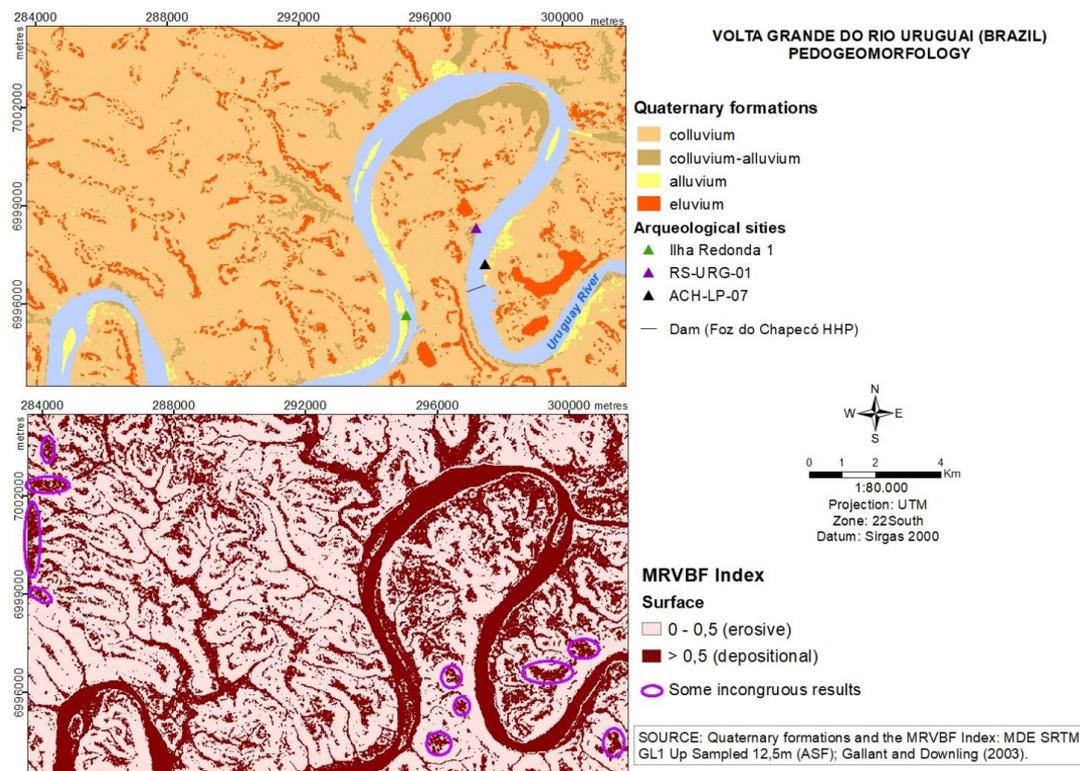


Figure 9: Quaternary formations, erosive and depositional surfaces of the study area.

Most of the area was represented by colluviums. This result is coherent with field observations, in the light of the widely distributed extensive and steep slopes found in the dissected landscape relief. According to is observable in the field, concave slopes that retained and deposited colluviums on their backslopes and slope shoulders as well as on erosive and depositional surfaces are common. This is expected since erosive transport processes usually occur on slope shoulders and back slopes (LEOPOLD; VÖLKEL, 2007). On depositional surfaces, colluvium is found at both the bottom of river channels and on valley toeslopes (SCHOENEBERGE *et al.*, 2012) where it is also common for alluvium to be intermixed. This is identifiable, by the predominant presence of round and polished sand, as indicated by Bertolini *et al.* (2016). It is important to highlight that many colluvium in Volta Grande refer to an A pedogenic horizons, which are generally gravely to very gravely in character.

Santos (2018) also found colluvium deposited at the bottom of the Volta Grande, mainly at the archaeological site on the bank of Volta Grande (URG-01), as well as fine sandy sediments on Ilha Redonda. These results are similar to those depicted in the Quaternary formation distribution map (**Figure 9**).

It can be argued that, on both the northern and southern margins of the Volta Grande meander of the Uruguay River there is a certain heterogeneity of Quaternary and pedological coverings. Such heterogeneity is conditioned by: (i) the proximity of the basaltic rock to the surface; and, (ii) by the denudational dynamics and morphology of the slopes and the erosive dynamics of the Uruguay River channel on the footslopes and floodplains.

As the slopes are very often extensive and divided in subsectors, the depth of the pedological cover varies over short distances from the hill summits to the valley bottoms. The role that relief (slope) plays as a primary driver of the evolution of pedological coverage in the Volta Grande region is undeniable.

Despite the coherence of the results from mapping the Quaternary coverings with the aid of field observations as well as with the findings by Santos (2018), the method used in this study to delimit the alluvium, colluvium and eluvium does present some errors (**Figure 9**). For instance, the algorithm classified flatter hill summit areas (erosive uplands) as depositional surfaces. This can be observed in the vertical curvature map (**Figure 8**) through convex surface. Therefore, some portions of these areas were classified as alluvial deposits instead of eluvial formations. Adjustments based on geoprocessing techniques, such as feature editing and raster reclassification as well as field observations, were necessary to correct the information in the map. In every cartographic product, it is important to validate the results with fieldwork so as to achieve results adequately similar to the real world and in accordance with the spatial scale of the project.

The DEM used in this research (12.5 meters) was adequate for obtaining the MRVBF index and for the mapping of surface coverings on the adopted scale (1: 85,000). That is, considering the spatial resolution of the DEM falls within the parameters of the methodology proposed by Gallant and Dowling (2003) as well as in consideration of the size of the study area (214 km²). However, in terms of detail (scales below 1: 5000) and in regards of field observations, the resulting map showed generalizations for colluvial-alluvial formations in some areas, likely due to the narrow floodplains in some of the stretches of the Uruguay River.

Moreover, there was difficulty in distinguishing colluvium and eluvium in Volta Grande due to the high degree of textural homogeneity and proximity of basaltic rock to the surface both in the uplands and in bottomlands. There is an exception for the concavities, even locally; as they were properly demarcated in the DEM such as in the archaeological site RS-URG-01, although this study focuses on a regional mapping approach and not a slope scale-based approach.

4. Conclusions

The soil-landscape relationship in the study area highlights the complexity of its pedogeomorphological reality, despite the homogeneity of its lithological substrate (basalt). On the one hand, in consideration of the characteristics of the Uruguay River's embedded valley (barely pronounced to narrow floodplains), the presence of colluvial-alluvial formations on its banks indicates the contribution of the slopes and not only the influence of river dynamics to area erosion dynamics. On the other hand, the geomorphological conditions of the area (asymmetric river margins, for example) were and are essential for the development of Quaternary coverings with a predominance of colluvial formations.

Variations in the thickness of pedogenized coverings indicate surface erosive rework at short distances of the previously weathered sediments and mixed with varying amounts of gravel (2 mm to 2 cm in diameter), pebbles (2 cm to 20 cm in diameter) and boulders (> 20 cm in diameter) along the slopes. From the morphopedological point of view, it is understood that these Quaternary formations are related to variable episodes of colluvium occurring throughout the Holocene, as they are associated with the topsoil and the surface horizons of the Quaternary surface coverings.

The method used in this study to map the Quaternary coverings of the study area served as a complementary tool for mapping colluvial and eluvial coverings, regarding the classification of erosive and depositional surfaces. However, field analysis and the understanding of the materials, shapes, and processes of landscape pointed out a greater complexity of these Quaternary surface coverings. While the methodology resulted in some classification failures with respect to depositional surfaces and required adjustments supported by field observations, this is common and necessary procedure for any cartographic product. Thereby, to sort out this issue, the model may be improved by adapting the index parameters through other values used as input, in order to better fit in with the study area and, thus, get better results.

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