

THE IMPORTANCE OF RETROSPECTIVE GEOMORPHOLOGICAL CARTOGRAPHY FOR THE DEFINITION OF COMPLEX MORPHOLOGICAL UNITS – THE TAMANDUATEÍ RIVER BASIN, METROPOLITAN REGION OF SÃO PAULO

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ABSTRACT

The article presents the methodological approach adopted for the production of the Map of Complex Morphological Units of the Tamanduateí River basin in the Metropolitan Region of São Paulo. This cartographic product results from the correlation between the Pre-Urban Geomorphology and Anthropogenic Morphologies maps and, therefore, relies on retrospective and evolutionary geomorphological cartography. Retrospective and evolutionary cartography consists of identifying and representing the original morphology (pre-urbanization phase) and the sequence of interventions in surface forms and materials, providing an important tool for identifying and interpreting changes in processes. The recognition of the original morphology was based on the general principles of geomorphological cartography, from the analysis and interpretation of aerial photographs from 1952 and 1962, old topographic and planimetric maps, historiography of the city of São Paulo and its surroundings, and iconographic materials. For the preparation of the Anthropogenic Morphology Map, the Land Use and Occupation Maps of the Metropolitan Region of São Paulo and Alto Tietê Basin (Empresa Paulista de Planejamento Metropolitano do Estado de São Paulo [EMPLASA/SP], 2005) were used, as the legend offers important information reflecting some of the indicators of changes pointed out by Rodrigues (2008) for the evaluation of hydrogeomorphological impacts and changes. From the correlation between six units of Original Morphology and seven units of Anthropogenic Morphologies, a total of 33 Complex Morphological Units were obtained. This synthesis allowed the identification of changes processed over more than 150 years and the identification of the types of original morphology on which they were processed.

Keywords: Retrospective and evolutionary geomorphological cartography; Pre-urban geomorphology; Anthropogenic morphologies; Complex morphological units; Tamanduateí river basin.

RESUMO

A IMPORTÂNCIA DA CARTOGRAFIA GEOMORFOLÓGICA RETROSPECTIVA PARA DEFINIÇÃO DE UNIDADES MORFOLÓGICAS COMPLEXAS – A BACIA HIDROGRÁFICA DO RIO TAMANDUATEÍ, REGIÃO METROPOLITANA DE SÃO PAULO

¹ This article presents part of the author's doctoral thesis, "From the originality of the urban site of São Paulo to anthropic forms: application of the Anthropogenic Geomorphology approach in the Tamanduateí River Basin, in the Metropolitan Region of São Paulo", Department of Geography of FFLCH, University of São Paulo, São Paulo, 2010, 363 p.

PAULO. O artigo apresenta o percurso metodológico adotado para a produção do Mapa de Unidades Morfológicas Complexas da bacia hidrográfica do rio Tamanduateí, na Região Metropolitana de São Paulo. Esse produto cartográfico é resultante da correlação entre os mapas de Geomorfologia Pré-Urbana e de Morfologias Antropogênicas e, portanto, apoia-se na cartografia geomorfológica retrospectiva e evolutiva. A cartografia retrospectiva e evolutiva consiste na identificação e representação da morfologia original (fase pré-urbanização) e a sequência de intervenções nas formas e materiais superficiais, oferecendo importante instrumento de identificação e interpretação de mudanças nos processos. O reconhecimento da morfologia original baseou-se nos princípios gerais da cartografia geomorfológica, a partir da análise e interpretação de fotografias aéreas dos anos de 1952 e 1962, mapas topográficos e planimétricos antigos, historiografia da cidade de São Paulo e seus arredores, e materiais iconográficos. Para a elaboração do Mapa de Morfologias Antropogênicas foram utilizadas as Cartas de Uso e Ocupação do Solo da Região Metropolitana de São Paulo e Bacia do Alto Tietê (EMPLASA, 2005), pelo fato da legenda oferecer importantes informações que refletem alguns dos indicadores de mudanças apontados por Rodrigues (2008), para a avaliação de impactos e mudanças hidrogeomorfológicas. Da correlação entre seis unidades de Morfologia Original e sete unidades de Morfologias Antropogênicas, obteve-se um total de 33 Unidades Morfológicas Complexas. Tal síntese permitiu identificar as mudanças processadas ao longo de mais de 150 anos e, identificar sobre quais tipos de morfologia original elas se processaram.

Palavras-chave: Cartografia geomorfológica retrospectiva e evolutiva; Geomorfologia pré-urbana; Morfologias antropogênicas; Unidades morfológicas complexas; Bacia hidrográfica do rio Tamanduateí.

RESUMEN

LA IMPORTANCIA DE LA CARTOGRAFÍA GEOMORFOLÓGICA RETROSPECTIVA PARA LA DEFINICIÓN DE UNIDADES MORFOLÓGICAS COMPLEJAS—LACUENCA DEL RÍO TAMANDUATEÍ, REGIÓN METROPOLITANA DE SÃO PAULO. El artículo presenta el abordaje metodológico adoptado para producir el Mapa de Unidades Morfológicas Complejas de la cuenca del río Tamanduateí, en la Región Metropolitana de São Paulo. Este producto cartográfico es el resultado de la correlación entre los mapas de Geomorfología Preurbana y de Morfología Antropogénica y, por lo tanto, se basa en la cartografía geomorfológica retrospectiva y evolutiva. La cartografía retrospectiva y evolutiva consiste en identificar y representar la morfología original (fase de preurbanización), así como la secuencia de intervenciones en las formas superficiales y los materiales, ofreciendo una importante herramienta para identificar e interpretar los cambios en los procesos. El reconocimiento de la morfología original se basó en los principios generales de la cartografía geomorfológica, a partir del análisis e interpretación de fotografías aéreas de 1952 y 1962, mapas topográficos y planimétricos antiguos, historiografía de la ciudad de São Paulo y su entorno, y materiales iconográficos. Para la elaboración del Mapa de Morfologías Antropogénicas se utilizaron los Mapas de Uso y Ocupación del Suelo de la Región Metropolitana de São Paulo y de la Cuenca del Alto Tietê (EMPLASA, 2005), ya que la leyenda proporciona información importante que refleja algunos de los indicadores de cambio señalados por Rodrigues (2008) para evaluar los impactos y cambios hidrogeomorfológicos. La correlación entre seis unidades de Morfología Original y siete unidades de Morfología Antropogénica resultó en un total de 33 Unidades Morfológicas Complejas. Esta síntesis permitió identificar los cambios que han tenido lugar a lo largo de más de 150 años e identificar los tipos de morfología original sobre los que se han producido.

Palabras clave: Cartografía geomorfológica retrospectiva y evolutiva; Geomorfología preurbana; Morfologías antropogénicas; Unidades morfológicas complejas; Cuenca del río Tamanduateí.

1 INTRODUCTION

The mapping of Complex Morphological Units in the Tamanduateí River Basin was conducted based on the methodology of Rodrigues (2004, 2005, 2010), which draws from practical tests and experiences in environmental assessment as well as references in pure and applied geomorphology (Hart, 1986; Nir, 1983; Toy & Hadley, 1987; Tricart, 1978; Verstappen, 1983). The approach aims to recognize geomorphological systems at various stages of anthropogenic intervention, emphasizing urban environments through retrospective and evolutionary geomorphological cartography.

Retrospective evolutionary geomorphological cartography consists of the reconstruction, identification, and representation of original morphologies and the sequence of anthropic interventions in surface forms and materials. This approach enables the identification and interpretation of changes in hydrogeomorphological processes, such as increased concentrated surface runoff, among others, which may lead to a rise in the frequency and magnitude of floods or erosive processes created or induced by human activity. References to retrospective evolutionary geomorphological cartography can be found in Lima (1990); Batista (2002); Carvalho (2002); Silva (2005); Berges (2013); Claro (2013); Luz e Rodrigues (2013); Luz (2014); Moroz-Caccia Gouveia e Rodrigues (2017), Luz (2024), Rodrigues (2024), among others.

In this approach, anthropic action should be understood as a set and sequence of intervention modalities on morphological units. According to Nir (1983), such modalities include deforestation, grazing and agricultural activities, mining, linear interventions (such as railways, bridges, highways), interventions in the hydrological system (such as channel straightening, damming, and levees), and processes resulting from urbanization. According to Rodrigues (1997, 2024), each of these major categories of anthropic interference can and should be subdivided and interpreted through the lens of geomorphological perspective or approach.

Thus, it is important to clarify that the categories of anthropic intervention considered in this study refer exclusively to interventions of the 'urbanization' modality. The study adopts the understanding of 'original morphology' as the morphology prior to intervention, or more precisely, prior to urbanization.

Original morphology, therefore, refers to forms that have not undergone direct intervention in their original shapes nor significant alterations in their

materials, although their processes may be modified by other types of intervention, such as the removal of vegetation cover.

In this sense, original morphology is understood as that whose attributes (extent, slopes, slope breaks and changes, among others) have not experienced significant direct modifications—measurable in metric dimensions—due to direct or indirect anthropic intervention (Rodrigues, 2005, p. 103).

According to Rodrigues (2005), in retrospective cartographic studies already conducted at large scales, morphometric attributes have been surveyed and analyzed, such as: slope geometry (linearities, convexities, and concavities); slope extent and inclination; geometry of slope subsectors (amphitheatres with spring niches, ruptures, slope changes) and their respective positions on the slope (upper, middle, and lower thirds); as well as morphological parameters of surface materials and soils, such as depth, texture, structure, density, porosity, and characteristic transitions between soil horizons. Rescuing original morphology can also rely on other sources of information, such as documents from historical works, iconographic records, and testimonies from long-time residents in recently urbanized areas. Rodrigues et al. (2024) outline the procedures and recommended information sources for a historical approach in geomorphology.

The mapping of anthropogenic morphologies can be performed through evolutionary cartography, encompassing chronological sequences of interventions. For interventions within the “urbanization” category, it is essential to identify subcategories, such as stages of urban consolidation, as proposed by Rodrigues (2005, 2010, 2014). The author asserts that detailed scales necessitate investigating street patterns, building densities, and stages of urban consolidation. These data can be obtained through photointerpretation of chronological sequences aiming to recover intervention types by analyzing base cartography from various periods, as well as through interviews and field surveys (Rodrigues, 2005, p. 106).

In retrospective and evolutionary geomorphological cartography studies conducted at various scales and areas within the São Paulo Metropolitan Region, Rodrigues (2005) identified so-called “complex morphological units.” These units result from the correlation between original morphologies and sequences of anthropogenic interventions. They are, therefore, spatial units that simultaneously share similar characteristics with respect to both sets of data and may consequently

exhibit similar hydrogeomorphological dynamics. (Moroz-Caccia Gouveia e Rodrigues, 2017; Rodrigues, 2005). Identifying complex units is critical for urban planning, as it provides insights into potential modifications in processes resulting from specific categories of anthropogenic interventions on original morphologies with unique combinations.

This article aimed to highlight the relevance of retrospective geomorphological cartography in identifying complex morphological units, as well as to emphasize the potential of these units in urban contexts, providing a foundation for decision-making related to territorial and environmental management, the implementation of impact prevention or mitigation measures, and the development of public policies.

2 STUDY AREA

The Tamanduateí River Basin (TRB) is located in the state of São Paulo and encompasses parts of the municipalities of Mauá, São Bernardo do Campo, Diadema, Santo André, São Caetano do Sul, and São Paulo, which together form the São Paulo Metropolitan Region (Figure 1). The Tamanduateí River originates in the municipality of Mauá and flows into the Tietê River in the city of São Paulo. According to Departamento de Águas e Energia

Elétrica (DAEE, 2008), the Tamanduateí River Basin covers an area of 323 km². Its western and southern boundaries correspond to the divides separating it from the Pinheiros River Basin, while its eastern and northeastern boundaries correspond to the divides separating it from the Guaió River, Aricanduva River, and Tatuapé Creek.

The upper portion of the Tamanduateí River Basin (TRB) is situated above the crystalline basement, represented by the lithological units of the Embu Complex and, more specifically, the Undifferentiated Granitic Suites. Its middle section lies on Cenozoic sediments of the São Paulo Sedimentary Basin, while the downstream section corresponds to the occurrence of Quaternary alluvial sediments.

According to Ross and Moroz (1997), the upper part of the TRB, encompassing the municipalities of Mauá, Diadema, São Bernardo do Campo, Santo André, São Caetano do Sul, and the southern region of São Paulo city, falls within the morphostructure known as the Atlantic Orogenic Belt, specifically within the morphosculptural unit termed "Paulista Plateau." This region is dominated by denudational relief forms, characterized essentially by medium to high hills with moderate dissection and convex tops. The predominant altitudes range between 800 and 1,000 meters. The lithology primarily consists

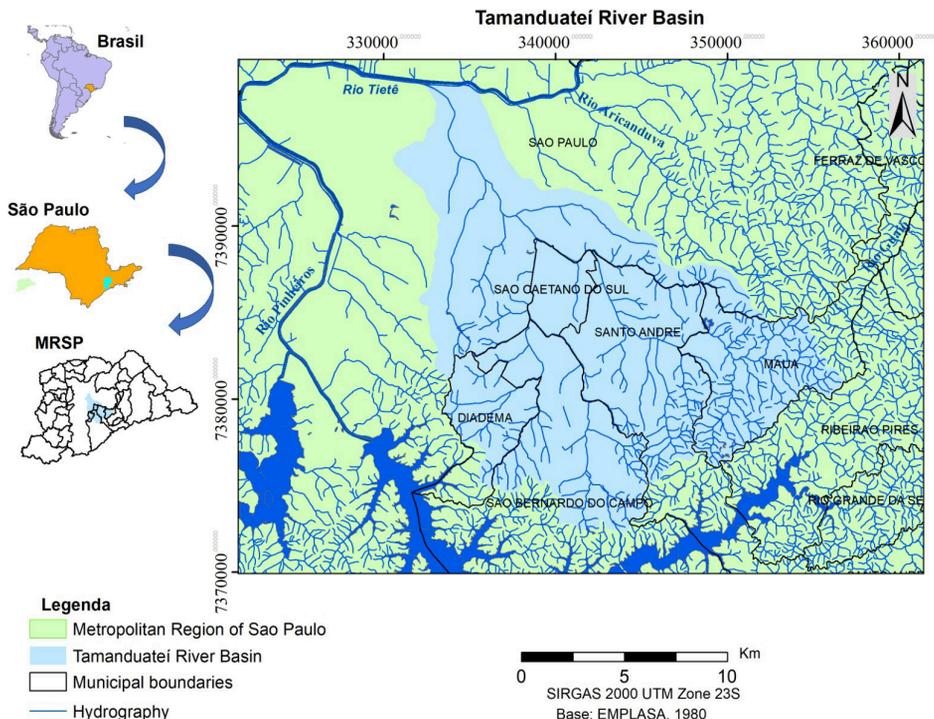


FIGURE 1 – Location of the Tamanduateí River basin.

of migmatites, granites, mica schists, and gneisses. Drainage patterns exhibit dendritic characteristics, with medium to high densities and incised valleys.

The middle and lower portions of the Tamanduateí River watershed are located within the morphostructural unit referred to by Ross and Moroz (1997) as “Cenozoic Sedimentary Basins”. Regarding morphosculptural units, the middle portion of the TRB encompasses the morphosculpture known as the São Paulo Plateau, while the lower portion corresponds to fluvial plains.

According to Ross and Moroz (1997), the São Paulo Plateau is primarily characterized by denudational relief forms, consisting essentially of hills and flattened terraces, with prominent fluvial valleys featuring deeply incised headwaters, while the terraces exhibit shallow incision. The predominant altitudes range between 700 and 800 meters, with flattened terraces generally situated at approximately 740 meters, and the hilly sector between 760 and 800 meters. The lithology of this unit mainly comprises clays, sands, and lenses of conglomerates.

The fluvial plain of the Tamanduateí River is situated at altitudes between 720 and 730 meters. These are flat terrains of Quaternary fluvial sedimentary nature, where fluvial terrace features are observed, approximately 1 to 2 meters higher than the floodplains. In the more detailed mapping of the original morphology, these morphometric characteristics were also confirmed (Moroz-Caccia Gouveia, 2010).

3 MAP OF PRE-URBAN GEOMORPHOLOGY (APPENDIX – MAP 1)

To restore the original morphology, Coltrinari (1996) suggests utilizing aerial and terrestrial photographs, both current and historical topographic maps, as well as technical, scientific, political, and socioeconomic reports that can provide a diagnosis of the environment. In addition to these sources, Rodrigues (2004) further recommends incorporating historical archives of engineering works, along with iconographic materials (newspapers, illustrations, photographs, paintings, among others),

and interviews with longtime residents, from a geomorphologist's perspective (Carvalho, 2006; Gurnell et al., 2003; Trimble, 2008).

The restoration of the original morphology was fundamentally based on the analysis and interpretation of aerial photographs and topographic maps. This effort was complemented by historical records, such as studies on the history of São Paulo city and its surroundings, and iconographic materials. Additionally, geomorphological and geological information was utilized (Ab’Saber, 1957; Almeida, 1953; EMPLASA, 1980; Melo et al., 1989; Riccomini & Coimbra, 1992; Riccomini et al., 1992; among others), alongside data obtained from historical analyses.

Although these historical studies were dispersed across various works, they could be spatialized after meticulous selection, thorough analysis, and precise spatial localization. Although the cartographic documents used as a base (aerial photographs from 1952 and 1962; SARA BRASIL topographic maps from 1930; and the 1980 cartographic base of the Metropolitan Cartographic System) are from dates significantly later than the initial interventions and already reflect substantial modifications to the area, they allowed for the identification of certain "interpretation windows"² that provide valuable insights for reconstructing the natural environment.

The identification of the original morphology is grounded in the general principles of geomorphological cartography. For detailed scales, topographic maps and aerial photographs with the oldest possible dates are used, as they provide partial but valuable information on the spatial distribution of pre-intervention morphology (Rodrigues, 2024).

Anthropic actions, from the perspective of anthropogenic geomorphology, should be understood as a set of intervention modalities driven by social, economic, and political factors, yet expressed through geomorphological processes. According to Nir (1983) and Rodrigues (1997), among other authors, these modalities include various types of deforestation, grazing and agricultural activities, mining, linear interventions (such as railways, bridges, highways), interventions in the hydrological

² “When we attempt to reconstruct the past evolution of the physical landscape and to establish the chronology of its stages of evolution, we are confined to ‘windows’ of limited and varying size and opacity (Lewin, 1980). It is through the ‘windows’ that survive that we can gather the evidence needed to permit environmental reconstruction, and, necessarily, the amount of evidence remaining in a given area will depend on the age of the landscape and on the subsequent changes affecting that landscape. The evidence that can be obtained through the available windows is of four main types. First, there is evidence relating to the morphology of the environment, and a portion of a river terrace might be a fragment of evidence, through the ‘window’, of a much more extensive valley floor in the past. Second, there is evidence of sediments and materials, and the material composing the river terrace might be used to infer something about the mode of deposition and the physical environment at the time. Thirdly, there is knowledge about the processes operating in the landscape, and this can be obtained from historical records or by analogy with situations elsewhere. Fourthly, there are the fragments of evidence that allow relative and absolute dating to be carried out by an increasingly varied range of techniques.” (Gregory, 1992, pp.107-108).

system (such as channel straightening, damming, and levees), and processes resulting from urbanization and settlement.

This study identified the pre-intervention or pre-urbanization period as the time preceding the latter half of the 19th century. Although the settlement of São Paulo's urban site had begun three centuries earlier, it was only from this point onward that more significant interventions in the physical environment, directly linked to the urbanization process, were initiated.

Table 1 provides the cartographic documentation used to create the map of pre-urban geomorphology (original morphology).

The recovery of the original morphology of the Tamanduateí River Watershed proved to be a true “puzzle” due to the complete dispersion of the collected information.

With regard to historical planialtimetric cartographic bases, the only available resource was a topographic map (Sheet IV) at a 1:20,000

scale from 1930, produced by the company SARA BRASIL, With the caveat that the document covers only the municipality of São Paulo. It is important to emphasize that the aerial photogrammetric survey carried out for the production of this set of topographic maps has been lost over time. The negatives of the aerial photographs, which were handed over by SARA BRASIL S/A to the São Paulo City Hall at the time, have since disappeared. Even the company's headquarters in Italy no longer retains this material, as it was lost during the upheavals of World War II.

In light of this, the oldest available aerial photogrammetric survey for the area dates back to 1952, conducted by the company Serviços Aerofotogramétricos Cruzeiro do Sul, at a 1:25,000 scale. However, this survey covers only about 80% of the total area of the watershed, making it necessary to supplement the data with aerial photographs from 1962, also at a 1:25,000 scale, produced by the Instituto Agrônômico de Campinas.

TABLE 1 – Cartographic documentation used to create the map of pre-urban geomorphology (original morphology).

<i>CARTOGRAPHIC MATERIALS</i>	<i>REFERENCES</i>
Map of the Imperial City of São Paulo (1810; reissued in 1941 with additions). Approximate scale 1:10,000.	Costa (1810/1954)
Map of the City of São Paulo (1841). Approximate scale 1:5,000.	Bresser (1841/1954a)
Map of the City of São Paulo and its Suburbs (c. 1847, undated). Approximate scale 1:5,000.	Bresser (1847/1954b)
Map of the Imperial City of São Paulo (1855). Approximate scale 1:10,000	Rath (1855/1954a)
Map of the City of São Paulo (1868). Approximate scale 1:10,000.	Rath (1868/1954b)
Map of the Capital of the Province of São Paulo (1877). Approximate scale 1:3,500.	Albuquerque & Martin (1877/1954)
Map of the Capital of the State of São Paulo and Surroundings (1890). Approximate scale 1:6,000.	Martin (1890/1954)
Map of the City of São Paulo (1895). Scale 1:10,000.	Bonvicini (1895/1954)
General Map of the Capital of São Paulo (1897). Approximate scale 1:20,000.	Cardim (1897/1954)
General Map of the City of São Paulo (1905). Scale 1:20,000	Cococi & Costa (n.d.)
General Map of the City of São Paulo (1914). Scale 1:20,000.	Comissão Geographica e Geológica (1914)
Topographic Map of the Municipality of São Paulo (1930). Scale 1:30,000, sheet IV.	Sara Brasil S/A (1930a)
Topographic Map of the Municipality of São Paulo (1930). Scale 1:5,000, sheets 37, 50, 51, 52, 65, and 66.	Sara Brasil S/A (1930b)
Map of the City of São Paulo and Surrounding Municipalities (1943). Scale 1:50,000.	The São Paulo Tramway Light & Power Co. LTD. (1943) In Secretaria do Estado de Economia e Planejamento/Instituto Geográfico e Cartográfico (IGC)
Aerial Photographs (1952). Scale 1:20,000.	Serviços Aerofotogramétricos Cruzeiro do Sul. Strip 5 (094-091); Strip 4 (070 – 076); Strip 3 (053-048); Strip 2 (034-042) e Strip 1 (013-003).
Geomorphological Map of the Paulistano Plateau and Surroundings (1953). Approximate scale 1:200,000.	Almeida (1953)
Schematic Geomorphological Map of the Urban Site of São Paulo (1957). Approximate scale 1:75,000.	Ab'Saber (1957)
Aerial Photographs (1962). Scale 1:25,000.	Instituto Agrônômico de Campinas. Aerofoto Natividade S/A Região 7 T 4015-4007.

Source: Moroz-Caccia Gouveia e Rodrigues (2017).

The photogrammetric survey for these images was conducted by Aerofoto Natividade S/A, thereby enabling complete coverage of the area.

These limitations, along with the extent of the Tamanduateí River Basin, justify the selection of the 1:25,000 scale for this research.

As previously noted, the available base materials correspond to periods when significant anthropogenic interventions had already taken place, particularly within the São Paulo portion of the Tamanduateí River Basin. In addition to the effort to identify remnants or “interpretive windows” for the recovery of the original morphology, a thorough analysis was conducted of 19th and early 20th century cartographic documents, historical records, iconographic materials, and historical studies.

These procedures, in turn, presented several challenges. For instance, maps of the city of São Paulo from the 19th and early 20th centuries, in addition to lacking topographic information, were created using various cartographic references (projections, scales, coordinates, among others), and – due to the limited technical resources available at the time – lack precision. Furthermore, many of these documents have been altered by users over time (scribbles, pencil skamong othershes, stains, tears), which often compromises the reliability of the information they contain.

The search for information related to the original morphology in historical studies about the city of São Paulo and its surroundings also presented some challenges. In addition to the geographically oriented data being highly dispersed among historical interpretations, such information is rarely spatialized or adequately contextualized within the broader landscape, requiring extensive systematization efforts for effective cartographic spatialization.

The first stage in the development of the Pre-Urban Geomorphology Map consisted of interpreting aerial photographs from 1952 and 1962 (Tables 2 and 3). The photointerpretation, carried out

using stereoscopic pairs and a pocket stereoscope, enabled the identification and mapping – on overlays – of elements such as watercourses, spring niches, drainage divides and interfluvial systems, slope breaks, and changes in gradient. It is worth noting that, although by the time the aerial photographs were taken (1952 and 1962) the area was already heavily anthropized – particularly along the Tamanduateí River floodplain – it was still possible to identify certain vestiges of the original morphology, such as remnants of fluvial terraces, abandoned meanders, and floodplain boundaries. This information was subsequently cross-referenced with the findings of Ab’Sáber (1957) and Almeida (1953), as well as with the Geological Map of the São Paulo Metropolitan Region (EMPLASA, 1980), revealing a high degree of consistency.

In a second phase, the overlays were superimposed and adjusted to the 1:25,000 scale topographic base (EMPLASA, 1980). The topographic base was subsequently supplemented with additional hydrographic network information, as the original courses of water bodies could be inferred from historical documents – both cartographic and textual.

With the data obtained through photointerpretation, analysis of the topographic

TABLE 3 – Topographic maps (1:25,000) used to create the cartographic base.

<i>Topographic maps 1:25.000 EMPLASA (1980)</i>	
331	SF-23-Y-C-VI-2-NO
332	SF-23-Y-C-VI-2-NE
333	SF-23-Y-C-VI-2-SO
334	SF-23-Y-C-VI-2-SE
322	SF-23-Y-C-VI-4-NE
431	SF-23-Y-D-IV-1-NO
433	SF-23-Y-D-IV-1-SO

TABLE 2 – Aerial photographs used in the elaboration of the Pre-Urban Geomorphology Map of the Tamanduateí River Basin.

<i>YEAR</i>	<i>STRIP</i>	<i>NÚMBER</i>	<i>SCALE</i>	<i>EXECUTION</i>
1952	STRIP 5	094 - 091	1:20.000	Serviços Aerofotogramétricos Cruzeiro do Sul
	STRIP 4	070 - 076		
	STRIP 3	053 - 048		
	STRIP 2	034 - 042		
	STRIP 1	013 - 003		
1962	REGION 7 T	4015 -4007	1:25.000	Instituto Agronômico de Campinas - Aerofoto Natividade S/A

base, and historical research, it was then possible to produce the complete geomorphological mapping.

In addition to information related to morphology, the analysis of topographic maps also provided morphometric data included in the map's legend. Through photointerpretation and with the aid of topographic maps, it was possible to identify morphology with respect to the following attributes: the geometry of slopes (rectilinear, convex, and concave forms); the geometry of slope subsectors (amphitheaters with spring niches, slope breaks, and changes in gradients) and their respective positions on the slope (upper, middle, and lower thirds); as well as basic aspects related to morphogenesis, such as denudational and aggradational processes. It should be noted that, due to the mapping scale, some elements needed to be grouped (for instance, summits, plateaus, and convex and plano-convex elements were categorized as "Convex and Plano-Convex Elements of High Slope"). These simplifications or generalizations took into account the morphodynamic significance of the geometry of the forms and were based on Lima (1990).

As can be observed (Appendix – Map 1), the legend of this map presents a structure that partially aligns with the Relief Taxonomy proposed by Ross (1992).

For the delineation of the first three taxons (Morphostructural Units, Morphosculptural Units, and Units of Similar Form Patterns), the boundaries of Relief Form Types (4th Taxon) were compared, highlighted by morphological and morphometric differences against the lithological boundaries of the Geological Map of the Metropolitan Region of Sao Paulo (EMPLASA, 1980).

Given the selected mapping scale (1:25,000) and the level of detail required to assess changes in forms, materials, and processes, certain principles and concepts of detailed cartography were employed for mapping the 5th and 6th taxons (Slope Elements and Fluvial Plain and Small Forms, respectively), as proposed by Rodrigues (2024) and his legend structure, which can be articulated with that of Ross (1992).

The legend further emphasizes aspects critical to morphodynamic analysis, including geometry (morphology) and morphometry of slope segments, their positioning on the slope (high or mid-lower slopes), and the boundaries of these elements, defined by slope breaks or changes in gradient. These considerations are based on Lima (1990) and Rodrigues (2024), who draws on Dylik (1968) concept of the slope and references three

parameters (shape, gradients, and positioning) that must be considered in defining slope elements. The significance of these units for understanding current processes lies in the fact that the intensity of slope hydrological processes also depends on the gradients and the relative position of these units, as represented by morphological boundaries (Lima, 1990; Rodrigues, 2024).

Interpretations regarding slope element geometry and hydrodynamic behavior trends were based on Ruhe (1975), Colângelo (1996), and Ross (1990, 1992, 2004), Furian et al. (2002), among other authors.

After the analog development of the Pre-Urban Geomorphology Map, the map was scanned, vectorized, and georeferenced using the ArcGIS 9 program (ArcMap 9.2). This procedure, in addition to graphic editing, aimed to enable the correlation of this product with the Map of Anthropogenic Morphologies and further support the development of a synthesis cartographic product – the Map of Complex Morphological Units. The resources of the Geographic Information System facilitated the measurement of spatialized data on original morphologies and anthropogenic morphologies, enabling a quantitative analysis of changes in the Tamanduateí River basin.

4 MAP OF ANTHROPOGENIC MORPHOLOGIES (APPENDIX – MAP 2)

In this second stage, the first step was to identify the types of anthropic interventions that could be mapped at the scale of analysis (1:25,000). These selections were based on the indicators (morphological, surface material, and hydrogeomorphological) according to the selection by Rodrigues (2008).

The Map of Anthropogenic Morphologies was produced based on an update and reinterpretation of the Land Use and Occupation Maps of the São Paulo Metropolitan Region (RMSP) and the Upper Tietê Basin – 2005, developed by EMLASA, at a scale of 1:25,000.

The choice to use this Land Use mapping is justified by the availability of the material at the same scale adopted in this study (1:25,000), and by the fact that its legend provides important information reflecting some of the change indicators suggested by Rodrigues (2008) for assessing hydrogeomorphological impacts and transformations, related to the type of urban intervention.

The contents of the original legend of the Land Use Maps (EMPLASA, 2005) were grouped according to hydrogeomorphological criteria, as shown in Table 4.

Original or semi-preserved morphologies are regarded as areas that have not yet undergone significant alterations in terms of forms, materials, and processes stemming from urbanization.

The "Areas predominantly covered by vegetation (forests, secondary forests, grasslands, floodplain vegetation, or reforestation)" correspond to parks and green areas, unoccupied lands, or even leisure farms and areas with horticultural activities. Although these areas may have experienced anthropogenic interventions, they do not exhibit anthropogenic morphologies directly resulting from urbanization. For instance, leisure farms and reforested areas may no longer retain their original vegetation cover; however, they do not feature extensive portions of exposed or impermeable soil. Although it is acknowledged that the hydrodynamics and morphodynamics of these areas may have undergone changes, it is assumed that such changes are of a smaller scale compared to those resulting from urbanization.

In some cases, it is necessary to go further and examine whether changes have occurred in the morphology and surface materials. For example,

areas classified as fields or secondary vegetation may correspond to landfills or earthworks that, once abandoned, allowed vegetation to establish – thus appearing in the historical sequence of interventions. However, at the scale of analysis and mapping adopted in the present study, it was not possible to identify such differences.

The category "Floodplain Vegetation" indicates the preservation of the original morphology, suggesting that the locations where it occurs – floodplains – still maintain their original functionality in terms of both hydrodynamics and morphodynamics.

The morphologies corresponding to the Initial Stage of Urbanization include unoccupied subdivisions or those in the early stages of occupation, constituting areas devoid of vegetation cover and delineated by roads, where surface runoff contributes to high sediment production rates and, consequently, to the sedimentation of fluvial channels. The removal of vegetation cover, the initial step for urban settlement, already implies a significant change in the hydrological cycle and the morphodynamic balance, according to Lima (1992).

The removal of vegetation cover, the initial step in urban settlement, necessarily entails a significant alteration in the hydrological cycle

TABLE 4 – Correspondence between the contents of the Land Use and Occupation Charts (EMPLASA) and the Map of Anthropogenic Morphologies of the Tamanduateí River Basin.

<i>EMPLASA (2005)</i>	<i>MAP OF ANTHROPOGENICS MORPHOLOGIES</i>
Forest	Original or semi-preserved morphology
Shrubland	
Field	
Floodplain vegetation	
Reforestation	
Farms (leisure or horticultural activities)	
Unoccupied lots	Morphologies related to the Initial Stage of Urbanization (Unoccupied lots or in the process of being occupied)
Slum	Morphologies related to the Intermediate Stage of Urbanization (Highly impermeable urban areas, without infrastructure)
Industries	Morphologies related to the Final Stage of Urbanization (Highly waterproofed consolidated urban areas, generally with infrastructure)
Urbanized area	
Urban equipment	
Landfill	Technogenic deposits
Dump	
Mining	Mining
Exposed Soil/Soil Movement	Exposed Soil/Soil Movement
Detention Reservoir	Detention Reservoir

and the morphodynamic balance. The absence of vegetation cover restricts—and in some cases eliminates—the role of evapotranspiration in the cycle, and reduces the soil's water infiltration capacity. This, in turn, diminishes subsurface water circulation, groundwater recharge, and baseflow. As infiltration decreases, the magnitude of surface runoff increases. The opening of roadways also contributes to the intensification of concentrated surface runoff due to impermeabilization and the creation of morphological disruptions, often aligned with the steepest slopes, considering the original slope profiles.

The increase in surface runoff results in a shorter water concentration time within the watershed, meaning that the precipitated volume drains more rapidly to the lower parts of the basin, reaching fluvial channels that, during periods of frequent or intense rainfall, overflow. Conversely, the reduction in soil infiltration decreases storage capacity in microbasins, accentuating seasonal differences in the hydrological regime—during dry periods, flows are drastically reduced.

As natural infiltration and surface runoff processes are altered, and as watercourses become sedimented, even rainfall events of lower intensity and duration become sufficient to cause flooding—increasing the frequency and magnitude of these events.

The Intermediate Stage of Urbanization, in the case of the Tamanduateí River Basin (TRB), corresponds to slum areas. Although these areas are largely impermeable due to high housing density, most lack paved streets and micro-drainage systems. In exposed soil along roadways, linear erosion processes such as rills and gullies often occur, making these areas significant sediment sources. Additionally, in the Tamanduateí River Basin, a substantial portion of this category is located on crystalline terrains (69%), which correspond to steep slopes where the construction of cuts and fills for housing development is common.

The morphologies relative to the Final Stage of Urbanization correspond to highly consolidated urban areas with extensive impermeabilization. As urbanization within a watershed intensifies and consolidates, surface runoff plays an increasingly significant role in hydrodynamics. The impermeabilization of surfaces (buildings, paved plots, and roads), the installation of stormwater conduits, and road construction drastically reduce water infiltration into the soil while accelerating the velocity of surface runoff flows. This reduces water

concentration time in the basin and anticipates peak flow. Tucci e Bertoni (2003) cite that Leopold (1968) estimated the increase in average flood discharge as a function of impervious area and drainage system channelization. The variable 'conduit rate' has been considered in urban flood studies as a component of connectivity, according to Simas (2023).

Tucci (2000), analyzing small basins, identified the following indicators: (1) an individual produces approximately 49 m² of impermeable area within a basin; (2) road construction alone results in a 260% increase in runoff volume and coefficient; and (3) for every 13% of a lot covered by impermeable surfaces, the runoff coefficient increases by 115%. The author emphasizes that these figures are averages but offer insights into the quantitative impacts of urbanization on a watershed.

In the case of the TRB, this relationship is even more pronounced. According to the DAEE (2008), during the first canalization project in 1890, the projected flow rate at the mouth of the Tamanduateí River was 30 m³/s. Simulations by the CTH (Hydraulic Technology Center-USP) in the 1990s indicated that if urban sprawl continued and the basin became fully impermeable, the flow at the mouth could exceed 800 m³/s. Currently, during certain events, the flow is estimated to reach 700 m³/s (Travassos, 2008). In this case, there is evidence that the peak flood discharge has increased more than 23-fold, despite morphological differences, which suggests a change in the order of magnitude of extreme flow rates.

The Anthropogenic Morphologies Map also considered the following land uses: sanitary landfill and open dumpsite, mining, exposed soil/earthworks, and detention reservoirs.

The map's legend was inspired by anthropogenic morphology mappings developed by Lima (1990), Rodrigues (2004, 2006), and Fujimoto (2001), Rodrigues and Moroz-Caccia Gouveia (2013), among others. All selected information was compiled in the legend of the Anthropogenic Morphologies Map (Appendix – Map 2).

The organized land-use categories facilitated subsequent qualitative and quantitative analyses of the following geoindicators outlined by Rodrigues (2008):

- *Fluvial Channels:*

- Geoindicators of Original Morphology and Anthropogenic Morphology: length and pattern

These geoindicators enabled the identification that 42% of the hydrographic network of the TRB

underwent rectifications, 26% are obstructed, and the remainder, although its pattern is preserved, may have been subjected to channeling (e.g., deepening, widening, or lining of the channel).

- Floodplains:

- Geoindicators of Original Morphology: area, planform shape, altitude.
- Geoindicators of Original and Anthropogenic Surface Materials: autochthonous or allochthonous surface materials, hydrological properties, impermeabilization rates, urbanized surfaces (continuous or discontinuous), indicating the percentage of subsystem suppression.
- Hydrogeomorphological Indicators: Hydrodynamic balance, aggradational or erosional processes.

These geoindicators estimated that the TRB originally had a floodplain area of 44.1 km² and 12.4 km² of fluvial terraces. By 2010, only 4.2 km² of semi-preserved floodplains and 1.3 km² of semi-preserved fluvial terraces remained. It was also estimated that the floodplain areas in the TRB originally had the capacity to store 44,100,000 m³ of water during rainfall events, estimated from mean precipitation levels. Currently, the few semi-preserved floodplain areas can store only 4,200,000 m³ of water (a reduction of 82.6%).

- Interfluvial and Hillslope Units:

- Morphological Geoindicators: Area, shape, altitude.
- Surface Material Geoindicators: Surface materials (autochthonous or allochthonous), hydrological properties, impermeability rates, urbanized surfaces (continuous or discontinuous).
- Hydrogeomorphological Geoindicators: Hydromorphodynamic behavior.

In the original conditions of the TRB, given the morphological and phytostability conditions, the balance among infiltration rates, diffuse surface runoff, and concentrated surface runoff showed a certain degree of equilibrium (24% of the total area of the watershed had a tendency toward infiltration, 32% toward diffuse surface runoff, and 25.4% toward concentrated surface runoff). Although the tendency toward infiltration was lower than surface runoff during certain precipitation events, it is important to emphasize that these estimates were based solely on slope geometry and accumulated knowledge from studies of similar landscapes. It is believed that, in the original setting, this

difference was less significant due to the presence of vegetation cover.

In the current scenario, it is estimated that the tendency toward concentrated surface runoff is nearly five times greater than that of infiltration and diffuse surface runoff.

The research also included an evolutionary analysis of urbanization and anthropogenic changes with the following temporal divisions: 1881–1929; 1930–1951; 1952–1982; 1983–2000; and 2001–2010. The most intense modifications were observed between 1983 and 2000, with no significant changes detected between 2001 and 2010. By 2010, 88% of the TRB area already exhibited anthropogenic morphologies, suggesting that the results presented here remain consistent with the current reality of the area.

5 MAP OF COMPLEX MORPHOLOGICAL UNITS (APPENDIX – MAP 3)

The overlay of the Pre-Urban Geomorphology Map (Map 1) and the Anthropogenic Morphologies Map (Map 2) resulted in the Complex Morphological Units Map (Map 3).

This synthesis made it possible to identify the changes that occurred over more than 150 years and to determine the types of original morphologies upon which these transformations took place. Through the use of a Geographic Information System, it was also possible to spatially quantify these changes.

The intersection of the six Original Morphology units with the seven Anthropogenic Morphology units yielded a total of 33 Complex Morphological Units.

The following section briefly presents how the trends of hydromorphodynamic processes associated with each original morphology may be altered according to the type of anthropogenic morphology.

- Convex and Plano-Convex Segments of the Upper Hillslope

Slope segments originally characterized by convex geometry tend to disperse water flows both at the surface and subsurface levels. However, in the studied area, when these segments are located in the upper third of the slope, they exhibit moderate inclinations, which attenuates this dispersive tendency. In such cases, a balance tends to be established between surface runoff and infiltration, approaching neutrality (Colângelo, 1996; Ruhe,

1975). This behavior is typically observed when the original morphology is preserved or semi-preserved, particularly when covered by vegetation.

However, when vegetation is removed and the soil is exposed – or when the upper soil horizons are stripped – the balance between infiltration and surface runoff, as well as the tendency for flow dispersion, may be significantly altered. For instance, diffuse surface runoff may, in theory, exceed infiltration. In such cases, morphogenesis tends to prevail over pedogenesis, and erosion processes may become dominant, resulting in increased sediment mobilization. These changes can be observed in the presence of anthropogenic morphologies, such as those mapped as “Exposed Soil / Earthworks”.

During the “initial phase of urbanization,” characterized by land parceling and lot development, surface runoff tends to become concentrated, giving rise to predominantly linear erosive processes, which can lead to the formation of rills and gullies.

Areas in the “intermediate phase of urbanization” – which, in the mapped region, are primarily defined by the densification of informal settlements (favelas) in zones lacking basic infrastructure – also exhibit concentrated surface runoff and a pronounced tendency for sediment mobilization. This is mainly due to the absence of paved streets and the lack or inadequacy of micro-drainage and sanitation systems.

Areas in the “final phase of urbanization,” which are highly impermeable and generally equipped with urban infrastructure, also show a tendency toward concentrated surface runoff, with its characteristic morphological discontinuities, and when these areas include underground systems (e.g., water supply, sanitation, telecommunications, and transportation), issues of slope instability may arise due to pipe ruptures, lowering of the water table, or the presence of concentrated subsurface drainage.

The development of “technogenic or anthropogenic deposits” (e.g., landfills and dumpsites) on this type of original morphology results in increased slope angles due to landfilling and waste deposition. This, in turn, accelerates surface runoff. On the other hand, the heterogeneous nature of the deposited materials and the discontinuity in permeability between these and the original materials represent a new pedological and stratigraphic condition regarding infiltration rates and subsurface flow concentration. This may

create planes of lower cohesion between materials, favoring slope instability and potentially triggering mass movements (Rodrigues, 2004).

“Mining activities,” in turn, significantly alter the original slope geometry, producing large-scale disturbances and remobilizing substantial volumes of material. Earthworks, road construction, waste dumps, dikes, and dams often expose and disaggregate various soil and rock horizons, making these surfaces more susceptible to erosion. As a consequence, such disturbances may lead to the silting of watercourses. Moreover, the formation of subvertical slopes may increase the risk of instability and trigger mass movement events.

- *Saddles*

Saddles are hillslope segments that naturally tend to concentrate both surface and subsurface water flows, as well as fine debris transported by surface and subsurface runoff. These areas typically exhibit a tendency for thickening of the weathering mantle and are naturally prone to headward erosion processes.

When these areas present “exposed soil,” there is an increased tendency for surface water flows to become concentrated, potentially leading to the development of concentrated runoff and linear erosive features. In such cases, concentrated flows directed toward drainage headwaters may intensify headward erosion. Due to the high concentration of fine debris, these areas can become unstable when subjected to “earthworks.”

For instance, in the case of landfills, the heterogeneity of deposited materials and the discontinuity in permeability between fill and native soils may create planes of reduced cohesion, increasing susceptibility to instability.

During the “initial phase of urbanization,” the subdivision of land for development may lead to problems associated with concentrated surface and subsurface runoff.

Urban occupations typical of the “intermediate phase of urbanization” may experience instability issues due to the presence of deposits composed of fine and unconsolidated sediments.

In areas in the “final phase of urbanization,” which are highly impermeable and generally equipped with urban infrastructure, there remains a strong tendency for concentrated surface runoff. These areas may also face stability issues related to pipe failures, lowering of the water table, or the effects of concentrated subsurface drainage.

- Convex and Plano-Concave Segments of the Lower Hillslope

Segments with convex geometry tend to disperse water flows through surface runoff. When devoid of vegetation cover – classified as “Exposed Soil / Earthworks” – these areas exhibit a tendency toward diffuse surface runoff and sheet erosion processes, resulting in substantial material mobilization.

In areas undergoing the “initial phase of urbanization,” a similar pattern of surface runoff is observed. However, the construction of streets disrupts the natural slope geometry, concentrating runoff and triggering linear erosive processes.

This behavior also predominates in zones associated with the “intermediate phase of urbanization.” In areas at the “final phase of urbanization,” which are highly impervious and typically equipped with infrastructure such as street paving, there remains a tendency for flash floods during rainfall events, particularly where these segments coincide with steep slopes. If urban micro-drainage systems are poorly designed or rendered inefficient due to obstructions, surface flows may reach significant velocities and become concentrated in flatter, lower-lying areas, leading to localized flooding.

- Concave, Plano-Concave, and Rectilinear Segments of Upper and Lower Hillslopes

Concave and plano-concave slope elements, whether on upper or lower slopes, are associated with headwaters and drainage channels and therefore exhibit a greater tendency toward concentrated surface runoff, especially in the lower portions of the slopes.

Rectilinear segments, in turn, exhibit hydrodynamic behavior that is directly influenced by slope gradient. Gently sloping segments – generally located in the upper third of the hillslope – tend to promote diffuse surface runoff, whereas more steeply sloping rectilinear segments are prone to concentrated surface flow. As a result, there is a greater tendency for linear erosive processes on middle and upper hillslope segments.

In the absence of vegetation cover—such as in “Exposed Soil / Earthworks” or “Initial Urbanization Phase” areas – concentrated surface runoff tends to intensify in rectilinear segments. In concave features, both surface and subsurface concentrated flows are amplified, leading to the development of linear erosion processes.

In areas characterized as being in the “intermediate phase of urbanization,” when located on concave segments, there is potential for slope instability due to earth cuts and fills, lack of proper management of stormwater and wastewater, and the presence of waste and debris deposits.

Areas in the “final phase of urbanization” also exhibit a tendency toward concentrated surface runoff, with frequent occurrences of flash flooding, especially when urban micro-drainage systems are inefficient.

Landfills or other forms of “Earthworks / Technogenic Deposits” placed in concave segments may result in serious stability issues. Discontinuities between different layers of fill material, and between these and the original deposits, when combined with infiltration and subsurface water flow, may trigger mass movement events.

The changes in hydromorphodynamic processes caused by anthropogenic morphologies have been outlined in general terms, according to the geometry and position of the hillslope segments. However, it is important to highlight significant differences between sedimentary and crystalline terrains – differences which, unsurprisingly, lead to distinct responses to anthropogenic modifications. Given the steeper slopes typically found in crystalline terrains, it is understood that the resulting process changes – due to human-induced alterations in these areas – differ in terms of thresholds, magnitude, and frequency when compared to those previously described.

Thus, it is important to consider that, in crystalline terrains, anthropogenic morphologies associated with “initial” or “intermediate” phases of urbanization, as well as areas classified as “Exposed Soil / Earthworks” or “Mining,” would, in theory, result in highly severe erosive processes—especially when the upper soil horizons have been removed. Under such conditions, these areas effectively become sediment source zones, contributing significantly to the siltation of drainage channels and, consequently, to the increased frequency and magnitude of flooding events.

The steep slopes characteristic of crystalline terrains also increase the likelihood of landslides, particularly in deforested areas with cut-and-fill operations. Additionally, the imperviousness caused by urbanization accelerates surface water flow, generating torrential runoff and contributing to flooding in valley bottoms.

With respect to morphologies associated with fluvial plains, the following changes in forms, materials, and processes have been identified:

- *Fluvial Terraces*

The presence of Holocene organic deposits, as observed by Ab'Sáber (1957), covering terraces as well as portions of floodplains and the footslopes of hills, indicates poor drainage and soil saturation issues in this morphological unit under its original conditions.

When stripped of vegetation or subjected to landfilling, these areas exhibit a strong tendency toward water concentration, with the formation of surface water sheets during rainfall events. Moreover, due to fill operations carried out in adjacent floodplain areas, fluvial terraces increasingly become sites of flooding.

These hydrodynamic characteristics, combined with the properties of the original surface material – composed of unconsolidated sediments and organic matter – can lead to instability issues. Such conditions may hinder the establishment and long-term maintenance of buildings, as well as surface infrastructure (e.g., roadworks) and subsurface infrastructure (e.g., tunnels, pipelines, foundations, among others).

- *Floodplains*

During the rainy season, when discharge exceeds the conveyance capacity of the river channel, overbank flooding occurs and water spreads across the floodplain.

Flood dynamics are responsible for the development, within the floodplain, of various topographic features – such as marginal dikes, meander belts, oxbow lakes, rills, cover deposits, and flood basins – resulting from sedimentation processes. Although these are environments where aggradational processes prevail, erosive activity is also observed, especially along channel margins.

As previously mentioned, floodplains have been significantly altered through channel straightening, landfilling, and surface impermeabilization. The landfills carried out have transformed these surfaces into 'technogenic terraces', often making them free from frequent overflow discharges. These deposits consist of various allochthonous materials which, when not impermeabilized, present issues related to internal drainage and compaction. As floodplains are elevated through landfilling, flood zones

expand their elevation levels, reaching even the fluvial terraces that were previously protected by altimetric differences.

Anthropogenic changes to river channels – such as straightening and culverting – do not eliminate flood risks but rather displace them to other locations. While channel straightening increases flow velocity, culverting promotes sediment accumulation and clogging within confined channels, particularly when maintenance and cleaning operations are limited or rendered unfeasible.

6 FINAL CONSIDERATIONS

The Complex Morphological Units Map, in addition to depicting morphological changes, provides, through its complete legend, a detailed indication of changes in surface materials and hydromorphodynamic processes. It constitutes, above all, an analytical product that expresses the procedural transformations resulting from the superimposition of specific anthropogenic morphologies onto particular characteristics of the original landforms.

While the Map of Anthropogenic Morphologies enables a more general interpretation of how each category of urban morphology influences the hydrogeomorphological processes within the watershed, the Complex Units Map allows for a more detailed analysis at the level of landform elements or slope segments (5th taxon). In this context, it becomes evident that anthropic forms – or forms induced by human activity – are not restricted to the 6th taxon; they can be observed at the 5th or even at higher taxonomic levels, when considering the reference by Ross (1992). Although some anthropogenic morphologies may not result in direct alterations to the original forms, they can significantly affect the processes, which may in turn lead to the formation of landforms at a different spatial scale. Thus, it is not only direct modifications to landforms (such as cuts and fills) that influence slope processes; surface impermeabilization alone can alter hydrogeomorphological dynamics. Even though the landforms have not been completely altered, the processes acting upon them have nonetheless changed and, depending on their magnitude and duration, may give rise to new forms.

In addition to these qualitative and quantitative assessments regarding changes in landform attributes, materials, and processes directly and

indirectly driven by urbanization and its patterns, the complex unit map also enables analyses of spatial trends in hydrogeomorphological processes within each unit – for example: tendencies toward infiltration, subsurface flow through pipes, and both concentrated and diffuse surface runoff. This interpretative potential can be incorporated and tested in hydrological models, as demonstrated in the studies by Veneziani (2014) and Simas (2017; 2023).

Thus, identifying the characteristics and processes associated with each complex morphological unit plays a crucial role in supporting urban physical-territorial planning efforts and, more importantly, in guiding decision-making for the implementation of intervention and impact mitigation measures. This technical tool holds significant potential to complement various others, such as geotechnical maps, risk cartography, fragility assessments (Ross, 1994), degrees of anthropization (Rodrigues, 2008, 1997), environmental mapping, among many others.

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