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Nota técnica

Cartography of original and technogenic landform in the Tigre watershed, Erechim, RS

Cartografia das formas de relevo original e tecnogênicas na bacia hidrográfica do rio Tigre, Erechim, RS

André Ricardo Furlan[1], Romario Trentin[2] e Luís Eduardo de Souza Robaina[3]

[1] Universidade Federal de Santa Maria, Departamento de Geociências, Santa Maria, Brasil. E-mail: andre.ricardofurlan@gmail.com
ORCID: https://orcid.org/0000-0003-1927-6114

[2] Universidade Federal de Santa Maria, Departamento de Geociências, Santa Maria, Brasil. E-mail: romario.trentin@gmail.com
ORCID: https://orcid.org/0000-0002-0615-2801

[3] Universidade Federal de Santa Maria, Departamento de Geociências, Santa Maria, Brasil. E-mail: lesrobaina@yahoo.com.br
ORCID: http://orcid.org/0000-0002-2390-6417

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Abstract: This study examines the importance of geomorphological maps in spatial analysis and urban planning, focusing on the representation of anthropogenic landform. The objective is to present methods for mapping morphological changes resulting from urbanization, using cartography of original and technogenic forms over 48 years. The research combines literature review, fieldwork, and the use of Geographic Information Systems (GIS), generating Digital Terrain Models. The results show that urbanization in the Tigre River basin increased from 35.43% in 1975 to 79.22% in 2023. An analysis at scales of 1:25,000 and 1:5,000 revealed substantial changes in the original morphology, with transformations in plain and terraces fluvial as well as the formation of technogenic hillslopes. This process intensified surface runoff due to reduced infiltration. Human interventions intensified erosive processes and altered the natural morphology, creating technogenic surfaces susceptible flooding, flash floods, inundation and erosion. It is concluded that urbanization drastically changed the hydrogeomorphological dynamics, requiring an integrated approach in urban and environmental planning to mitigate these impacts on the population.

Keywords: Geomorphological mapping; Anthropogenic geomorphology; Methodological guidelines; Urban sprawl.

Resumo: Este estudo examina a importância dos mapas geomorfológicos na análise espacial e no planejamento urbano, com foco na representação do relevo antropogênico. O objetivo é apresentar métodos para mapear as mudanças morfológicas decorrentes da urbanização, utilizando cartografia das formas originais e tecnogênicas ao longo de 48 anos. A pesquisa combina revisão bibliográfica, trabalho de campo e uso de Sistemas de Informação Geográfica (SIG), gerando Modelos Digitais de Terreno. Os resultados mostram que a urbanização na bacia do rio Tigre aumentou de 35,43% em 1975 para 79,22% em 2023. Uma análise em escalas de 1:25.000 e 1:5.000 revelou mudanças substanciais na morfologia original, com transformações nas planícies e terraços fluviais, além da formação de vertentes tecnogênicas. Esse processo intensificou o escoamento superficial devido à redução da infiltração. As intervenções humanas intensificaram processos erosivos e alteraram a morfologia natural, criando superfícies tecnogênicas suscetíveis a alagamentos, enxurradas, inundações e erosão. Conclui-se que a urbanização mudou drasticamente a dinâmica hidrogeomorfológica, exigindo uma abordagem integrada no planejamento urbano e ambiental para mitigar esses impactos sobre a população.

Palavras-chave: Mapeamento geomorfológico; Geomorfologia antropogênica; Diretrizes metodológicas; Expansão urbana.

1. Introduction

Geographical science provides various methodological and analytical possibilities for understanding society-nature relations. Geomorphology is one of the specialties of geographical studies, which corresponds to systematizing the organization of landform elements in order to understand the past and current dynamics that constitute and shape relief forms (MARQUES, 2018; SILVA, 2021). Geomorphology of a geographical nature is considered to analyze the genesis of forms, reconstructing past processes, reaching morphogenetic studies and valuing time to understand the present (GUERRA; MARÇAL, 2012; SUERTEGARAY, 2017). Geomorphological cartography has emerged as a prominent discipline, derived from the phylogenesis of classical theories of geomorphology, and is essentially integrated into environmental planning and land-use planning projects, constituting an intrinsic part of geomorphological research (ABREU, 1983; ROSS, 2017; NUNES, 2019).

Geomorphological maps are documents of high scientific value and contain a large amount of information that identifies the spatial relationships established in geographical compartments. They are an analytical and synthesizing tool (SIMON; CUNHA, 2008; MOURA, 2008; VERSTAPPEN, 2011). Nationally and internationally, there is discussion of a standardized system of legends for geomorphological mapping, but some essential elements are standardized: morphometry, morphography, morphodynamics and morphochronology (COLTRINARI, 2011; RĂDOANE; CRISTEA; RĂDOANE, 2011). It is noteworthy that the biggest distinctions between the systems correspond to the colors and symbols adopted by each system (PARONA; CLAESSENS, 2011; SILVEIRA; SILVEIRA, 2021).

From 1971 to 1985, RADAMBRASIL, a program coordinated by the IBGE (Brazilian Institute of Geography and Statistics) carried out extensive systematic mapping of the entire country on a scale of 1:1,000,000. The results presented include geomorphological mapping (BARBOSA et al., 1984; PARONA; CLAESSENS, 2011). The first version of the Geomorphology Technical Manual was published in 1985 (NUNES et al., 1995). In the 21st century, a new version was published (IBGE, 2009), updating the way in which relief is interpreted based on the evolution of Brazilian geomorphological mapping. This version included the use of digital images, geoprocessing and Geographic Information Systems (GIS) in databases, thus seeking to understand the magnitude generally mapped at scales of 1:250,000.

In the early 21st century, discussions emerged in Brazilian geomorphology about the standardization of geomorphological cartography. In this context, the development of the Brazilian Relief Classification System (SBCR) represents an effort in this direction (BOTELHO; PELECH, 2019; PELECH et al., 2019). Based on the SBCR, urbanized landscapes have also become a focus of geomorphological cartography, exploring representation strategies (MARQUES NETO, 2020). Urban landscapes are approached through the prism of anthropogenic geomorphology (GUERRA; LOUREIRO, 2023), or technogenic landforms (MOURA et al., 2023).

Urban geomorphology covers the study of human activities in natural forms, identifying anthropic activities as a physical process of change in geographical settings (COOKE, 1976, COOKE, et al., 1982; DOUGLAS, 1988; DIAO, 1996; JORGE, 2011; MANDARINO et al., 2020). Human beings are constantly increasing their ability to reshape and use nature (NIR, 1983; JÓZSEF; LÓRÁNT; DÉNES, 2010; 5. LUZ; RODRIGUES, 2013, 2020; LI et al., 2017). In this way, human beings are identified as geomorphological agents, and should be considered important in the process of formation and evolution of modern geomorphology (NIR, 1983; RODRIGUES, 2005; SIMON; CUNHA, 2008; THORNBUSH, 2015; LUZ, 2015; PASCHOAL; SIMON; CUNHA, 2015).

Mapping urban landform on a detailed scale is fundamental material for urban planning. These maps are valuable as a reference for current environmental and land-use planning and to guide future improvements in urban management. These documents provide a detailed inventory of the landform and allow for an assessment of the impact of human beings on the landscape, its extent and, especially, the durability of the environmental effects of past human activity (LATOCHA, 2009; DEL MONTE et al., 2016; BRANDOLINI et al., 2020; FACCINI et al., 2020).

Recognizing the original morphology and anthropogenic features (current morphology) requires a spatial scale of great detail, between 1: 25,000 or greater (RODRIGUES, 2005; FACCINI et al., 2020). The time scale helps with a comprehensive retrospective analysis of geomorphological characteristics, and the historical approach to landform allows us to verify the transformations of the earth's surface throughout the urbanization process (MOURA, 2005, 2011; PELFINI et al., 2020). Retrospective landform mapping incorporates the transformations produced in forms, materials and processes as a result of urbanization (RODRIGUES, 2005; MOROZ-CACCIA GOUVEIA; RODRIGUES, 2017; GOMES; MOURA, 2017; MOURA et al., 2023). In this way, the urbanization process directly impacts the hydrogeomorphological system, affecting both river and hillslope systems. Thus, changes in the geometry of these components can affect the dynamics of subsurface and surface processes, modifying their flows into concentrated and dispersed patterns (RODRIGUES, 2010; RODRIGUES; MOROZ–CACCIA GOUVEIA, 2013; RODRIGUES et al., 2019; BRANDOLINI et al., 2021; CHIRICO et al., 2021).

The work uses the definition of landform taxonomy, followed by the fourth, fifth and sixth taxa (ROSS 1992). In this way, the aim is to identify the original morphology (4th and 5th Taxon) and the technogenic landform forms (5th and 6th Taxon), which can be classified into two levels, assigning their Category and Type (MOURA et al, 2023). Anthropogenic landform needs to be dealt with on the basis of the smallest forms, so that the changes that have taken place in the relief can be identified with the advent of new forms, which, as a result of human activities, are capable of conceiving or driving new processes, altering the characteristics of the original forms (PELOGGIA, 2005; PELOGGIA; SILVA; NUNES, 2014).

In this perspective of geomorphological analysis, the work of Fujimoto (2001), who studies the Arroio Dilúvio watershed, and Rehbein (2011), who analyzes the Arroio Feijó watershed, both in the Metropolitan Region of Porto Alegre, stand out. The work of Moroz-Caccia Gouveia (2010), in the Tamanduateí River Basin, in the metropolitan region of São Paulo, Fagundes and Lupinacci (2017), who carried out a study in the Lavapés Stream Basin - Rio Claro (SP). Chirico et al., (2021) carried out a study in the Piney Branch watershed in Vienna, Fairfax County, Virginia, a suburb of Washington, District of Columbia and Barbosa and Furrier (2023) undertook efforts to map the Central Sector of the Metropolitan Region of João Pessoa (PB).

The case study aims to present the methods and tools used to represent the retrospective morphological changes resulting from the urbanization process. To this end, it makes use of cartography of the original forms and the current anthropogenic landform. The aim is to implement an approach in line with recent trends in geomorphological cartography supported by Geographic Information Systems (GIS) technologies in a digital environment, which aims to replace traditional symbols with representations based on total coverage models, using polygons to represent the original relief elements (BISCI; DRAMIS, 1991; DRAMIS; GUIDAB; CESTARIC, 2011). Therefore, the delimitation of the geomorphological element presents a generalized area, with homogeneous form, material and genesis.

The synthesis of this work is expressed in the cartographic products and the legend system, which integrate polygons of total coverage and specific symbologies. A geomorphological cartography model was developed, characterized by the representation of landforms using morphometric procedures. The approach adopted considers the 4th and 5th order on the geomorphological scale of Tricart (1965), the 4th, 5th and 6th taxa of Ross (1992, 2012, 2017) and the Complex of Forms (Level 0) proposed by the SGI (2023), represented at detailed scales (>1:5,000 to 1:25,000), according to the standards of large-scale geomorphological map legends. The research product is easily interpreted by urban planning specialists, making it an essential document for environmental planning and land use planning, following a geomorphological and environmental analysis.

2. Study Area

Erechim is located in the north of the state of Rio Grande do Sul, with central geographic coordinates of 27º 38' 30" South Latitude and 52º 38' 30" West Longitude (Figure 1). The municipality of Erechim is located in the northern part of the state of Rio Grande do Sul, in the Alto Uruguai region and the geographical micro-region of Erechim and has 105,705 inhabitants (IBGE, 2022), 96,087 inhabitants in the 2010 census and 90,552 urban and 5,535 rural (IBGE, 2011).

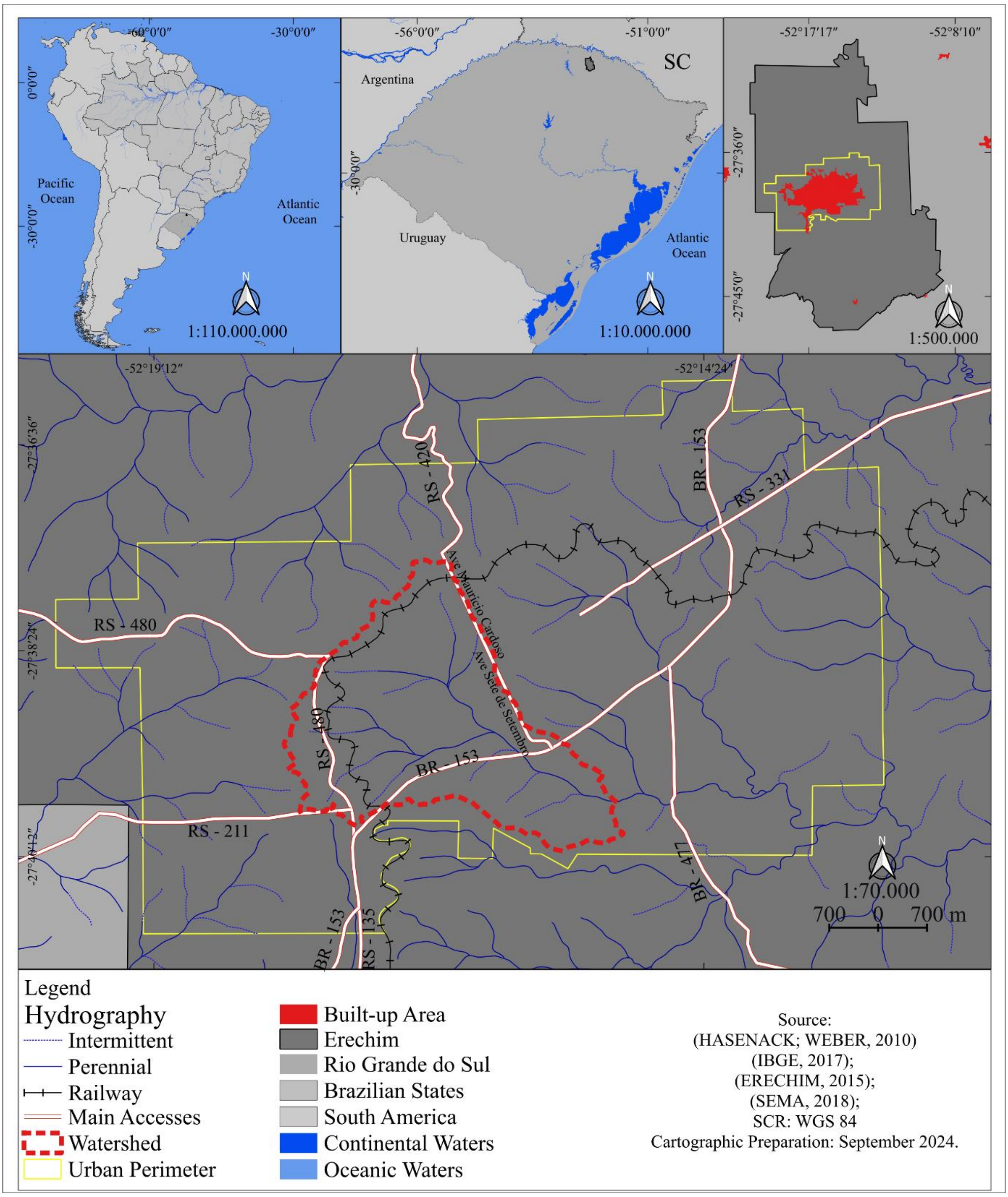


Figure 1. Location of the study area.

In the watershed, areas of urban use, pasture/fallow and tree vegetation are identified, as well as some green areas, parks and Permanent Preservation Areas (APP) (ERECHIM, 2011). Among the basins located on the urban perimeter, this one stands out for having the largest urbanized area (FURLAN; SPINELLI, 2019). The urbanization process has the effect of exposing certain areas to the risk of flooding, thus highlighting the morphodynamic transformations that have taken place in the basin (FURLAN; SPINELLI, 2020).

The study area is located in the *Planalto das Missões* (Missions Plateau), a geomorphological unit within the larger Geomorphological Region of the same name, in southern Brazil, as defined by the RADAMBRASIL Project (IBGE, 2008). The region features altitudes ranging from 200 to 400 meters and is characterized by small, rounded hills locally known as *coxilhas*. The associated valleys have an average depth of 20 to 30 meters, forming a gently undulating landform. In certain areas, planation surfaces can be identified, revealing residual landforms associated with an older plateau (IBGE, 2023).

The geological substrate is made up predominantly of volcanic rocks from the Serra Geral Formation, belonging to the Paranapanema facies (K1 beta pr), covered by deep soils with thicknesses of more than two meters, most of which are classified as Aluminoferric Red Latosol (LVaf). This soil is characterized by a very clayey texture, a prominent surface horizon and gentle undulating to rolling landforms. As a secondary component, there are typical Alumina Red Nitossols, also associated with similar relief conditions. These soils are the product of homogeneous dissection processes in volcanic substrate, which shape the landform uniformly (IBGE, 2003; IBGE, 2023).

The landscape also displays a rectangular hydrographic network, strongly influenced by geological faults and fractures (CPRM, 2007). Peretti (2013) points out that the local landform, formed by volcanic flows on plateaus, is conditioned by the orientation of the fractures, facilitating the process of dissection. Erosive features such as rills, ravines and gullies can be seen on the gentle hillslopes of the hills, as well as in some situations across them, some of which have stabilized over time. These elements show the interaction between lithological, climatic and erosive factors, which shape the current landscape. In addition, the landform is marked by undulating hills with generally flat and convex tops, and by slope breaks generated by faults and geological fractures, which contribute to the formation of valleys.

Annual rainfall ranges from 1,700 to 1,900 mm, concentrated mainly in spring, when between 175 and 215 mm of rain are recorded. The higher altitudes of the Basaltic Plateau, combined with atmospheric patterns, contribute significantly to this volume of rainfall. The characteristics of the local landform play a crucial role in these high rainfall rates, especially due to the position of the Uruguay River valley, located in the north of the state of Rio Grande do Sul. This promotes the rise of air from the directions of Santa Catarina (north) and Rio Grande do Sul (south) (ROSSATO, 2011).

3. Materials and Methods

This study was based on extensive research to gather essential bibliographic and cartographic information. Various theoretical sources and methodologies were consulted to carry out the geomorphological mapping. Numerous field trips played a fundamental role in refining this mapping, taking place simultaneously with sketching and on-site verification. This ensured a faithful representation of reality by allowing direct assessment of the crucial elements for cartographic preparation, as well as the capture of photographic images for documentation.

3.1 Original Geomorphological Cartography

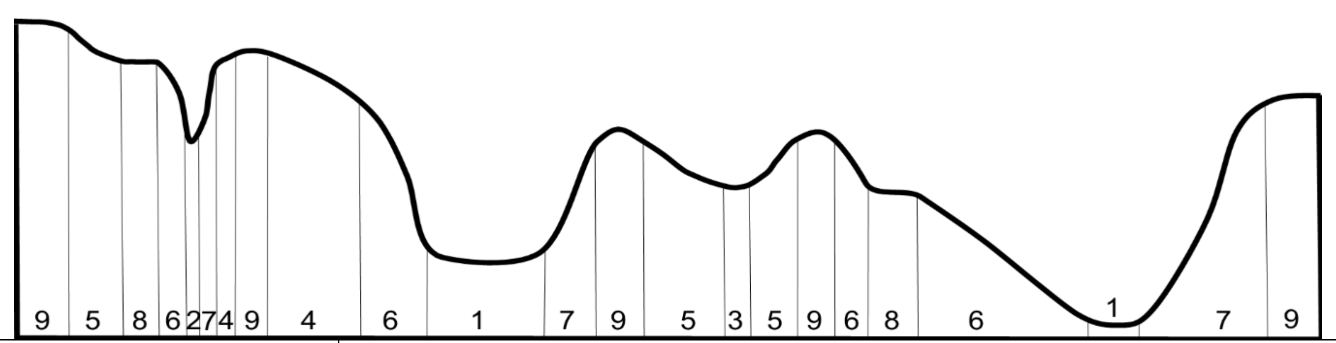
Two cartographic bases were used to analyze the study area on a detailed scale of 1:5,000. To reconstruct the river channels in the central area, we also used a plan on a scale of 1:5,000, which contained contour lines with an equidistance of 5 meters, along with information on the hydrography. For the rest of the watershed, we used 15 topographic maps dating from 1990, which were digitized with a resolution of 900 DPI (dots per inch). These maps, originally in 1:2,000 scale, reached their native resolution after the digitization process.

The Digital Terrain Model (DTM) was developed from vectorial planialtimetric data, which included information on contour lines, datum points and hydrographic details available on topographic maps. The altimetric values of the terrain were extracted, eliminating surface elements such as trees or buildings. For this purpose, the ArcToolbox interpolation tool in ArcGIS® software was used. As a result of this process, an MDT was generated with a cell resolution of 2x2 meters, aligned with the scale of 1:5,000 (SILVEIRA; SILVEIRA, 2015; FURLAN; TRENTIN, 2019).

To achieve this goal, the methodological assumptions indicated by Ross (1992, 2012, 2017) and also used by Fujimoto (2001), Rehbein (2005) and Moroz-Caccia Gouveia (2010) were adopted, together with processing in a GIS environment (FURLAN; TRENTIN; ROBAINA, 2024). The result corresponds to relevant complements at the detailed level, highlighting morphography. To facilitate interpretation, an integrated legend was developed, organized in a table, which presents and includes textual information on the 4th and 5th taxon, as proposed by

Ross (1992, 2012, 2017) and Guerra and Guerra (2018) and the 5th order on the geomorphological scale of Tricart, (1965), focused on the analysis of small forms and different specificities of hillslopes.

Table 1. Patterns of Similar Shapes and the Shapes of Strands



Landform Elements	Geomorphological processes
1 - River Plains and Terraces	River Plains and Terraces The predominant process is that of aggradation, characterized by the continuous deposition of sediments in colluvial-alluvial deposits. This process involves the formation of deposits made up of transported and accumulated sediments from the removal of materials from the slopes. In these areas, there is a tendency for the water table to rise, which favors the creation of wetlands such as marshes.
2 - Incised valleys	Erosion process according to the resistance of the materials.
3 - Drainage Headwaters	Areas of water flow convergence (hollows). Large volume of material (colluvium or talus) to be mobilized.
4 Gently Sloping Convex Hillslopes	Erosion and material loss predominate, with low transport capacity.
5 - Gently Sloping Concave Hillslopes	Surface runoff concentration and sediment deposition predominate.
6 - Steep Convex Hillslopes	Erosion and material loss prevail, with high transport capacity. This leads to material displacement on the hillslopes due to the steep incline.
7 - Steep Concave Hillslopes	Linear or rill erosion predominates; these areas are most prone to shallow landslides, as they are characterized by thick soil layers.
8 - Flat and Convex Terraces	Tendency to diffuse surface runoff, with a propensity for water infiltration into the soil.
9 - Flat, Convex, and Pointed Summits	More stable terrain. There is a greater tendency for water infiltration and percolation into the soil horizons. This also leads to the formation of well-defined soil horizons. Chemical erosion processes through dissolution and leaching, along with material migration, result in the loss of surface soil materials.

Source: Author's organization (2024)

3.2 Cartography of Anthropogenic Geomorphology

To analyze surface cover and current processes, an historical-geographical and cartographic analysis was conducted by interpreting aerial photographs, using new Remote Sensing techniques to measure the Earth's surface, investigate soils, and monitor surface processes (ROCCATI et al., 2020). Transformations in land cover and land use were identified by overlaying aerial photographs from the aerophotogrammetric survey, using photogrammetry to create orthomosaics in the PhotoScan software by Agisoft for the years 1975 and 1989, as well as World View2 satellite images from 2010 and Google© Satellite images from 2023, covering a 48-year period. This allowed the identification of the main areas undergoing anthropogenic transformations resulting from urbanization. Through detailed scans and interpretation of the highlighted elements, it is possible to recognize the particularities of anthropogenic urban land use categories, accompanied by their specific, singular characteristics in each classification.

Technogenic landforms are categorized into two levels, where a Category (1st Level) and a Type (2nd Level) are assigned (MOURA et al., 2023). In the context of this study, two levels of technogenic landforms were identified. In the first level, there are Elevations and Technogenic Superpositions, while in the second level, Accumulation Technoforms are observed, which are expressed on the ground as forms associated with constructed technogenic deposits and the morphogenetic process of direct material accumulation. The Cartographic Representation for this element is characterized by Areolar Forms, such as embankment ramps, which are areas characterized by variable hillslopes, resulting from the direct accumulation of surface materials, and technogenic Floodplains and Terraces, which, in turn, are formed by the deposition of technogenic materials. Hillslope breaks caused by embankment fill are defined as linear elements, representing the upper limit of embankment ramps on the ground. The form's symbolism follows the indications of Rodrigues (2005).

At the first level, Technogenic Scars and Depressions are identified, while at the second level, Excavation Technoforms are observed. These latter features manifest on the landscape as scars resulting from technogenic excavations, characterized by the direct removal of material. Mining scars are cartographically represented as areolar forms (FUJIMOTO, 2001; MOROZ–CACCIA GOUVEIA, 2010). The linear elements known as Hillslope Breaks by Cutting refer to the abrupt interruption of a hillslope due to the creation of cut banks or stepped surfaces, as indicated by Rodrigues (2005). Roadways, which include transportation routes such as streets, avenues, and bridges—as well as railways and similar structures like cut or embankment steps—are represented as linear features on the map. (FUJIMOTO, 2001; RODRIGUES, 2005; PELOGGIA; SILVA; NUNES, 2014)

As formas lineares que correspondem à hidrografia antropogênica Canal Tamponado e Canal Retificado (1:25.000) foram estabelecidas por Moroz–Caccia Gouveia (2010). Na escala 1:5.000 optou-se em classificar Hidrografia em ativa ou modificado ou inativo classificando a morfologia naturais e modificados em Vale de Fundo Côncavo, Vale em "V", Vale de Fundo Chato e Canalizado (DEL MONTE et al., 2016). Para aprimorar a análise da morfologia antropogênica, foram empregados polígonos para representar as áreas de represas e açudes. As simbologias para representação dos açudes foram ancoradas nos trabalhos de Fujimoto (2001) e Moroz–Caccia Gouveia (2010) e Peloggia, Silva e Nunes (2014).

The linear features corresponding to anthropogenic hydrography—Covered Channels and Straightened Channels (1:25,000 scale)—were established by Moroz–Caccia Gouveia (2010). At the 1:5,000 scale, hydrography was classified as active, modified, or inactive, categorizing both natural and altered morphologies into Concave-Bottom Valleys, V-Shaped Valleys, Flat-Bottom Valleys, and Channeled Valleys (DEL MONTE, 2016). To enhance the analysis of anthropogenic morphology, polygons were used to represent the areas of dams and reservoirs. The symbologies for the representation of reservoirs were based on the works of Fujimoto (2001), Moroz–Caccia Gouveia (2010), and Peloggia, Silva, and Nunes (2014).

The representation of Technogenic Equiforms (1st Level) classified in Surface Modification Technogenic Equiforms (2nd Level) are represented in the areolar format. This classification presents characteristics present in the terrain resulting from the presence of technogenic soils that imply a direct or indirect transformation in the composition or physical structure of the Earth's surface (MOURA et al., 2023). However, it is important to emphasize that the implication of this category is related to the characteristic of the form in which it is superimposed, thus causing differentiated morphodynamic processes.

4. Results

The analysis of anthropogenic transformations in the Tigre River watershed seeks to understand the processual relationship between morphological processes and the changes resulting from human occupation. In this context, the natural landscape loses its original characteristics, making it necessary to conduct geomorphological studies to measure the effects of anthropic action on the landform in a broadly geomorphological sense (JORGE, 2011).

Through geomorphological cartography in the urban area, it is possible to identify and understand relevant variables, such as the layout of streets and the urban footprint in relation to the original morphology (MOROZ–CACCIA GOUVEIA; RODRIGUES, 2017). In this way, through human interventions that altered the original morphology into a predominantly anthropogenic configuration, the urban area of Erechim was gradually built and structured. These interventions represent a fundamental aspect of the city's development and played a crucial role in adapting the natural environment to urban needs. During the implementation of the urban layout in Erechim, a series of engineering works was carried out, including the construction of deep underground galleries in the city center. Alongside the construction of these galleries, it was necessary to build embankments and implement drainage systems in wetland areas (banhados) to enable the creation of many streets outlined in the original urban development plan. As a result, through various human interventions that transformed the original landforms into a predominantly anthropogenic configuration, the urban area of Erechim was gradually constructed and organized.

Urbanization within the watershed experienced a significant increase over the four analyzed periods. As shown in Table 1, the data indicate a consistent upward trend in urbanized areas. Notably, between 1975 and 1989, there was a marked expansion of the urbanized area. A similarly relevant increase occurred between 1989 and 2010. Between 2010 and 2023, the smallest increment in urban area over the watershed was observed. An important observation, in addition to the expansion of the urban footprint, is the noticeable increase in the street network layout.

Table 1. Evolution of Urbanized Areas in the Tigre River Watershed

Period	1975	1989	2010	2023
Km^2	4.11	7.44	8.80	9.19
%	35.43	64.14	75.86	79.22

Source: Authors (2024)

Urbanization in 1975 was primarily concentrated in the area corresponding to the central district. By 1989, urban expansion had spread to other parts of the watershed. In 2010, urbanization became more homogeneous throughout the watershed, with the exception of a few small areas. By 2023, urban growth extended into the western and eastern sectors of the watershed, leaving only a few remaining unurbanized spaces. Thus, by 2023, urbanization had reached 79.22% of the watershed area.

4.1 Urbanization over Landform Elements

The overlap of urbanization in relation to landform elements becomes evident (Table S1, Figures S1, S2, S3, and S4 – Supplementary Document 1). This process has led to drastic changes in the watershed's morphology. Notably, Floodplains and Fluvial Terraces had 24.85% of their area altered. Incised Valleys showed 28.14% of their area affected by urbanization, as did Drainage Headwaters, with 29.09% of their area modified. Gently Sloping Convex Hillslopes and Gently Sloping Concave Hillslopes were the hillslope elements under the greatest urbanization pressure, with 36.42% and 39.24% of their areas affected, respectively. Steep Convex Hillslopes had 29.70% and Steep Concave Hillslopes had 27.29% of their areas altered by urban growth. Flat and Convex Terraces were the most affected landform elements, with 59.98% of their area modified by anthropogenic activities. Flat, Convex, and Sharp Hilltops also underwent significant modification due to urbanization, reaching 50.63% of their area.

Urbanization in 1989 resulted in morphological changes to landform elements, as shown in Figure 2. Floodplains and Fluvial Terraces had 57.98% of their area urbanized. Incised Valleys experienced alterations in 51.16% of their area. Drainage Headwaters showed a significant increase, with 58.18% of their area affected. Gently Sloping Convex Hillslopes had 67.96% of their areas modified by urbanization. Gently Sloping Concave Hillslopes also saw an increase, with urbanization reaching 68.86% of their total area. In Steep Convex Hillslopes, urbanization in 1989 impacted 56.15% of the area. Steep Concave Hillslopes had 54.58% of their area affected by urban development. Flat and Convex Terraces were the most significantly altered landform elements in 1989, with 82.07% of their area modified. Flat, Convex, and Sharp Hilltops also experienced a notable increase, with 70.32% of their area urbanized.

The data indicate that by 2010, urbanization had expanded in the Tigre River watershed, as shown in Figure 2. Floodplains and Fluvial Terraces saw an increase in their modified areas, reaching 74.54% of their area urbanized. Incised Valleys also demonstrated an increase in their urbanized area, totaling 63.95%. Drainage Headwaters had 66.11% of their area urbanized. Gently Sloping Convex Hillslopes exhibited 80.87% of their area urbanized, while Gently Sloping Concave Hillslopes reached 79.22%. Steep Convex Hillslopes had 70.19% of their area urbanized, and Steep Concave Hillslopes had 65.50%. Flat and Convex Terraces showed 88.39% of their area urbanized, while Flat, Convex, and Sharp Hilltops had 74.53% of their area urbanized. By examining Figure 2, which represents urbanization in 2023, it is clear that during this period, the area displays a predominantly anthropogenic configuration at the expense of the original morphology.

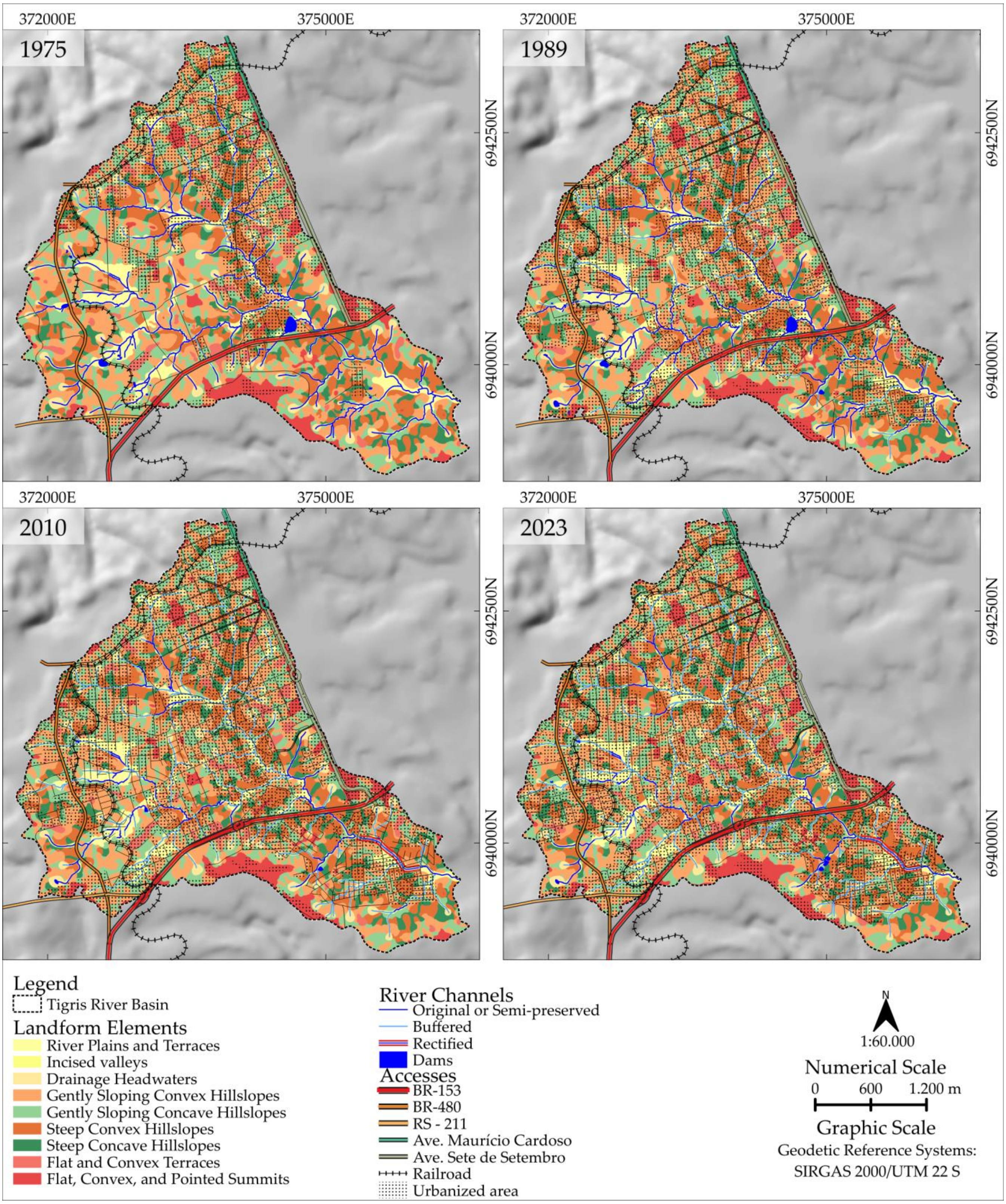


Figure 2. Urban Expansion over the Landforms (1:60.000).

Floodplains and Fluvial Terraces showed an increase in urbanized areas, reaching 81.64% of their total area. Incised Valleys also demonstrated an increase in their area, totaling 66.51% of their urbanized area. Drainage Headwaters had an urbanized area of 71.40%. Gently Sloping Convex Hillslopes showed 84.02% of their area urbanized, while Gently Sloping Concave Hillslopes had 81.81%. Steep Convex Hillslopes exhibited 72.89% of their area urbanized, while Steep Concave Hillslopes showed 67.68%. Flat and Convex Terraces had 94.70% of their area urbanized, while Flat, Convex, and Sharp Hilltops had 78.75% of their area urbanized. These data indicate an expansion of urbanization in the watershed, with impacts on various landforms.

When analyzing the watershed as a hydrogeomorphological study unit, it becomes evident that it exhibits characteristic patterns in its segments. We can observe the compartmentalization of the landforms, which allows us to identify the hillslope elements and their functionality based on both the original and anthropogenic morphology. It is clear that all the landform elements have been altered due to the urbanization process. The data presented show the evolution of urbanized areas in different landform elements over the years of 1975, 1989, 2010, and 2023. There is a significant increase in the urbanized area of the Floodplains and Fluvial Terraces, which went from 24.85% in 1975 to 81.64% in 2023. This urbanization process may have negative impacts on the watershed, such as a decrease in infiltration and subsurface flow, which can lead to an increase in surface runoff. It is important to highlight that urbanization can affect the hydrological processes of a region, leading to the replacement of natural areas with built and impervious environments.

When analyzing the dynamics of urbanization on landform elements, we observe significant increases in the urbanized area across different features. In the V-shaped Valleys, there was a growth from 28.14% in 1975 to 66.51% in 2023. Similarly, in the Drainage Headwaters, an increase from 29.09% in 1975 to 71.40% in 2023 is observed. There was also a substantial increase in the Gently Sloping Concave Hillslopes, rising from 39.24% in 1975 to 81.81% in 2023. In the Steeply Sloping Concave Hillslopes, the urbanized area percentage increased from 27.29% in 1975 to 67.68% in 2023. These data indicate a tendency for the concentration of water flow in concave-sloped areas. As urbanization advances, these elements show an increase in concentrated surface runoff, as the infiltration capacity drastically decreases.

The expansion of the urbanized area on Gently Sloping Convex Hillslopes was significant, rising from 36.42% in 1975 to 84.02% in 2023. An increase in the urbanized area was also observed in the Steeply Sloping Concave Hillslopes, going from 27.29% in 1975 to 67.68% in 2023. Flat and Convex Terraces followed this trend, showing a sharp increase in urban area, from 59.98% in 1975 to 94.7% in 2023. The Flat, Convex, and Sharp Summits also expanded their urbanized area, from 50.63% in 1975 to 78.75% in 2023. When subjected to anthropogenic modifications, these landform elements tend to disperse water flow—even in their original state, which already has limited absorption capacity. However, during the urbanization process, this capacity is drastically reduced, leading to diffuse runoff in some parts of the hillslopes and concentrated flow in others, resulting in changes to the hydro-geomorphological system.

The Floodplains and Fluvial Terraces increased from 24.85% in 1975 to 81.64% in 2023. This urbanization process may have negative impacts on the watershed, such as a reduction in infiltration and subsurface flow, which can lead to an increase in surface runoff. It is important to highlight that urbanization can affect the hydrological processes of a region by replacing natural areas with built and impervious environments.

4.2 Cartographic Representations and Interpretation of Anthropogenic Landforms

The results present the relief elements (4th and 5th Taxon), classified as having a Semi-Preserved Original Morphology. Technogenic landforms are categorized into technogenic elevations and superpositions, as well as technogenic equiforms (1st Level), which are further subdivided into accumulation technoforms and surface modification technoforms (2nd Level).

The spatial organization encompasses floodplains and fluvial terraces (4th Taxon), whose morphography facilitates the understanding of natural processes. The technogenic classification of these landforms corresponds to the accumulation process (2nd Level). In these areas, drainage problems are common due to channelization and embankment, which increase the frequency of sudden flooding events. Additionally, the deposition of technogenic materials contributes to the silting of the riverbed. These locations exhibit modified drainage patterns, often transforming streets into fluvial and pluvial channels during intense rainfall events.

The incised valleys (5th taxon) are characterized by erosive processes. The channelization of river channels and the construction of fills result in technogenic valleys (2nd level), which are more susceptible to flash floods due to alterations to the original morphology. The drainage headwaters (5th taxon), as initial components of the drainage network, play a crucial role in maintaining hydrogeomorphological balance. Technogenic changes, such as the inclusion of fill ramps (2nd level), significantly modify the hydrological and geomorphological dynamics of these areas, increasing their vulnerability to flooding and surface landslides. Further details are provided in Table 2.

Table 2. Landform Elements: Floodplains and Fluvial Terraces, Incised Valleys, and Drainage Headwaters

Floodplains and Fluvial Terraces		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: Gently sloping surfaces toward the thalweg, distributed across different sectors of the watershed. **Morphometry:** Elevation ranges from 660 to 775 meters, amplitude between 6 to 40 meters, slopes of 0 to 5%, and concave profile.	Composed of material eroded from the hillslope margins and deposited as debris in colluvial-alluvial deposits, formed by fluvial sediments at the base. They are affected by fluvial erosion, which deepens the thalweg. They promote the emergence of the water table, giving rise to wetland areas that favor water retention	Morphology is altered by the deposition of materials in embankments, resulting in discontinuous forms and concentrated surface runoff. Deposition of technogenic-origin materials in buffered fluvial channels or induced technogenic-sedimentary deposits near the hillslopes.
Incised Valleys		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: These elements present topographic shapes with gentle hillslopes toward the streambed. **Morphometry:** Characterized by altitudes ranging from 675 to 695 meters, amplitudes from 3 to 54 meters, slopes from 0 to 15%, and a concave profile.	The configuration of these valleys is shaped by the continuous process of erosion, influenced by the resistance of the materials present. The morphodynamics of these valleys are predominantly associated with fluvial erosion processes.	Straightening and damming of river channels and the construction of embankments. Morphology: they create discontinuous forms with embankment ramps with variable hillslopes due to the direct accumulation of surface materials. Laminar concentrated surface runoff process.
Drainage Headwaters		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: These areas are characterized by first-order basins, with a concave shape in plan view and a convergent profile. **Morphometry:** The altitude of these areas ranges from 695 to 810 meters, the amplitude varies between 2 and 23 meters, the slope ranges from 0 to 15%, and the profile curvature is concave.	They are areas of water flow convergence (hollows), accumulating a large volume of residual material, such as colluvium or talus, which is ready to be mobilized. Regressive erosion of the headwaters.	They include embankment ramps in these areas, which makes the laminar and surface flows discontinuous. They present low infiltration and a decrease in subsurface flow, which tends to eliminate the water hillslope.

The sector of the hillslopes (5th Taxon) shows a diversity in terms of morphology and morphodynamics. These technogenic forms represent technogenic equiforms (1st Level) and technogenic equiforms of surface modification (2nd Level). Additional details can be found in Table 3.

Gently sloping convex hillslopes play an essential role in the landform. They connect water divides to valley floors and facilitate the dispersion of surface runoff. Technogenic hillslopes intensify erosion and soil removal. The remobilization of materials is common, and the presence of small terraces, created by the rearrangement of surface materials, is frequent. These terraces can be delimited by cut steps and embankment ramps, depending on the extent and type of intervention carried out. The modified surfaces influence the hydrological and geomorphological behavior of the area, contributing to the lowering of the water table.

The gently sloping concave hillslopes have a specific morphology and variability in morphometry, characterized by concentrated flow. These technogenic hillslopes are altered by human interventions, which intensify erosion and remobilize materials. During rain, streets transform into stormwater channels due to concentrated water runoff. Depositional forms result from technogenic colluvial deposits. Human interventions create scouring scars and cuts, increasing erosion, especially due to urban impermeabilization.

Table 3. Landform Elements: Hillslope Sections

Convex Gently Sloping Hillslopes		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: These hillslopes have gently inclined surfaces and represent the connection between water divides and valley bottoms. **Morphometry:** The altitude of these areas ranges between 670 and 825 meters, with an amplitude varying from 2 to 72 meters. The slope gradients range from 0 to 15%, and the profile curvature is convex**.** .	The morphology facilitates the dispersion of surface runoff. These hillslopes are subject to erosive processes influenced by rainfall factors. Erosion and material loss predominate, although the sediment transport capacity is low.	Morphology is altered by the process of material deposition in embankments and by material removal due to cuttings. Surface and subsurface runoff becomes both diffuse—due to terrain modifications—and concentrated along roadways. There is a tendency for dispersion of surface runoff as well as sediment dynamics.
Gently Inclined Concave Hillslopes		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: Gently sloping surfaces that facilitate the concentration of surface runoff while effectively connecting watershed divides to valley bottoms. **Morphometry:** Altitudes ranging from 670 to 821 meters, and landform amplitudes between 2 and 45 meters, with slopes varying from 0 to 15% and a concave profile.	In the morphodynamics of gently inclined concave slopes, erosive processes predominate, influenced by rainfall factors. These processes are characterized by the concentration of surface runoff and the formation of material deposits in the area.	Discontinuous morphology resulting from terrain cuts leads to steep slopes and slope breaks. Embankment ramps, with their variable inclinations, are formed by the direct accumulation of surface materials. These features increase the concentration of surface flow, generating a large water volume and concentrated surface runoff. .
Strongly Inclined Convex Hillslopes		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: Sloped surfaces that disperse surface runoff while effectively connecting watershed divides to valley bottoms. **Morphometry:** With elevations ranging from 673 to 820 meters and amplitudes between 5 and 52 meters, these hillslopes have slopes from 15% to 35% and a convex profile.	They are highly susceptible to erosive processes influenced by rainfall factors. Erosion and material loss prevail, with a high capacity for sediment transport. This steep slope facilitates the movement of material along the hillslopes, making these areas dynamically active in sediment redistribution or the fall of basalt rock blocks.	Presence of cuts and embankments along these hillslopes results in steep inclines and slope breaks. Small terraces are frequently found; these terraces may be bounded by cut steps and embankment ramps. Modifications in surface and subsurface runoff can be either diffuse or concentrated, depending on the characteristics of the modified terrain.
Steep Concave Hillslopes		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: Sloped surfaces that facilitate the concentration of surface runoff while effectively connecting the watershed divides to the valley bottoms**.** **Morphometry:** Altitudes ranging from 674 to 815 meters, with an elevation amplitude between 3 and 57 meters. The slope in these areas varies from 15% to 38%, and their profile is predominantly concave**.**	They are prone to intensified erosive processes, especially due to rainfall factors. These processes favor linear or gully erosion along the hillslopes. These sectors are particularly susceptible to the occurrence of superficial landslides due to the presence of thick soil layers, which increase instability and the mobility of surface materials.	The inclusion of cut steps and embankment ramps in these areas makes laminar and surface flows discontinuous. There is a considerable increase in water volume and concentration of surface runoff due to infrastructures such as cuts and embankments altering slope stability. Greater sediment transport occurs along the hillslopes, intensifying linear erosion processes and material mobilization.

Steep convex hillslopes exhibit flow dispersion characteristics and undergo modifications due to cuts and embankments, resulting in steep slopes. These alterations facilitate both surface and subsurface runoff, which can be either diffuse or concentrated. They are susceptible to landslides and basalt block falls, as well as intensified erosion, leading to the removal of the soil's surface horizons and compromising its stability. This can cause instability problems affecting adjacent urban areas.

Steep concave hillslopes are prone to landslides and slips. Human interventions worsen the instability, resulting in increased sediment transport and intensified linear erosion. The concentration of water runoff and soil impermeabilization due to urban infrastructure exacerbate drainage problems. Technogenic modifications directly impact the landform dynamics, compromising soil stability and increasing material mobilization.

The terraces and hilltops are fully described in the legend system presented in Table 4. The flat and convex terraces (5th Taxon) are landform elements characterized by relatively flat and slightly elevated surfaces. These terraces are subject to erosive processes influenced by rainfall conditions. Diffuse surface runoff promotes water infiltration into the soil, contributing to the stability and conservation of the landform. In technogenic areas (2nd Level), surface runoff is concentrated on streets and avenues due to urban impermeabilization.

The flat, convex, and sharp hilltops (5th Taxon) stand out for their specific morphographic characteristics. Morphodynamically, these formations are subject to erosive processes influenced by rainfall. In technogenic flat, convex, and sharp hilltops (2nd Level), human interventions modify the morphology and natural dynamics of these formations. During heavy rains, altered drainage patterns turn streets into stormwater channels, increasing the volume and velocity of water runoff. This can intensify erosion and sediment transport, affecting soil stability and the integrity of urban infrastructures.

Table 4. Landform Elements: Terraces and Summits

Flat and Convex Terraces		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: Characterized by flat surfaces that interrupt the continuity of hillslope gradients, forming steps along the slope. **Morphometry:** Altitudes range from 728 to 820 meters, with amplitude varying between 2 and 9 meters, slopes between 0 and 5%, and a convex profile.	Diffuse surface runoff favors water infiltration into the soil, contributing to the stability and preservation of this landform. They are subject to erosive processes influenced by rainfall conditions.	The configuration of lots and roadways is well defined, which favors the removal of surface soil horizons through linear erosion. The presence of an underground water network contributes to the modification of subsurface water flow, affecting hydrological behavior.
Flat, Convex, and Pointed Summits		
Original Semi-Preserved		Technogenic
Morphography	**Materials / Morphogenesis / Morphodynamics**	**Hydromorphology**
Morphology: These are higher areas with gently inclined surfaces. Sharp hilltops, in turn, are associated with small pointed surfaces. **Morphometry:** Altitudes range from 695 to 825 meters, with amplitudes from 0 to 28 meters, slopes not exceeding 5%, and a convex profile.	Subject to erosive processes influenced by rainfall factors. There is a greater tendency for water infiltration and percolation through the soil horizons, which can promote the development of well-defined layers. Chemical erosion processes occur through dissolution and leaching, resulting in the migration of materials and the loss of surface soil components.	Steeply inclined surfaces are observed, resulting from the removal of materials through cuts and embankments, which cause breaks along the form edges. Surface runoff tends to concentrate in well-defined and structured roadways, facilitating the removal of surface soil horizons. These areas are susceptible to linear erosion processes.

For the cartographic representation at a 1:28,000 scale (Figure 3), the distribution of landform elements with Original Semi-Preserved Morphology and those with Technogenic/Anthropogenic Morphology can be observed. At this scale, a legend with simplified symbology was developed, providing less detail.

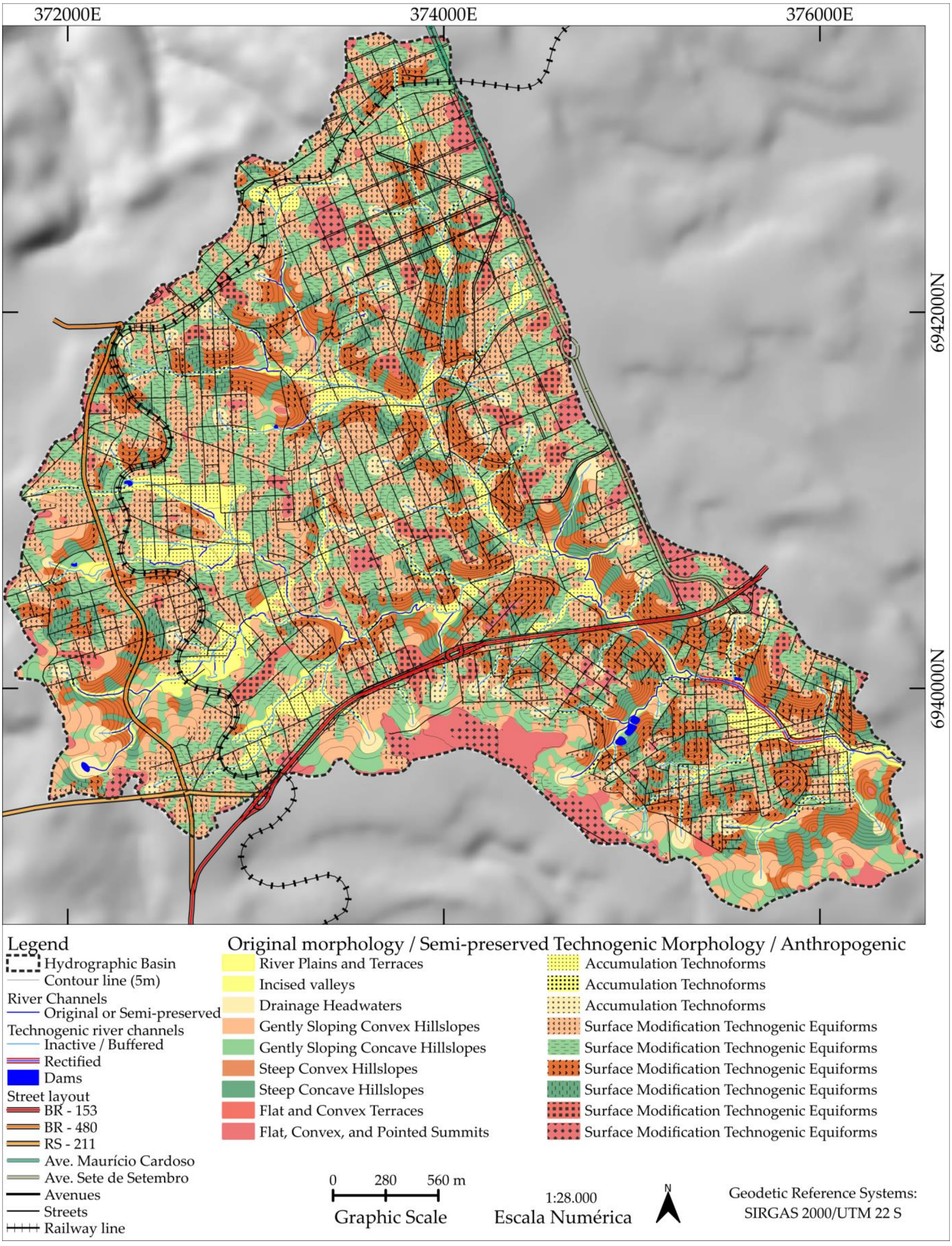


Figure 3. Original and Technogenic Morphology of the Tigre River Basin (1:28,000), Erechim, RS

In a second analysis, examples from various spatial sections of the watershed were examined, using photography as interpretative keys. At the 1:5,000 scale, a greater level of detail in technogenic forms becomes identifiable, with the inclusion of specific symbols representing active, modified, and inactive hydrography, as well as technogenic morphologies (see the A0-sized map at a 1:6,000 scale in Supplementary Document 2). This higher level of detail contributes to a more accurate interpretation of current geomorphological processes. Figure 4 presents four spatial sections of the watershed, complemented by Figure 6, which further illustrates these sections.

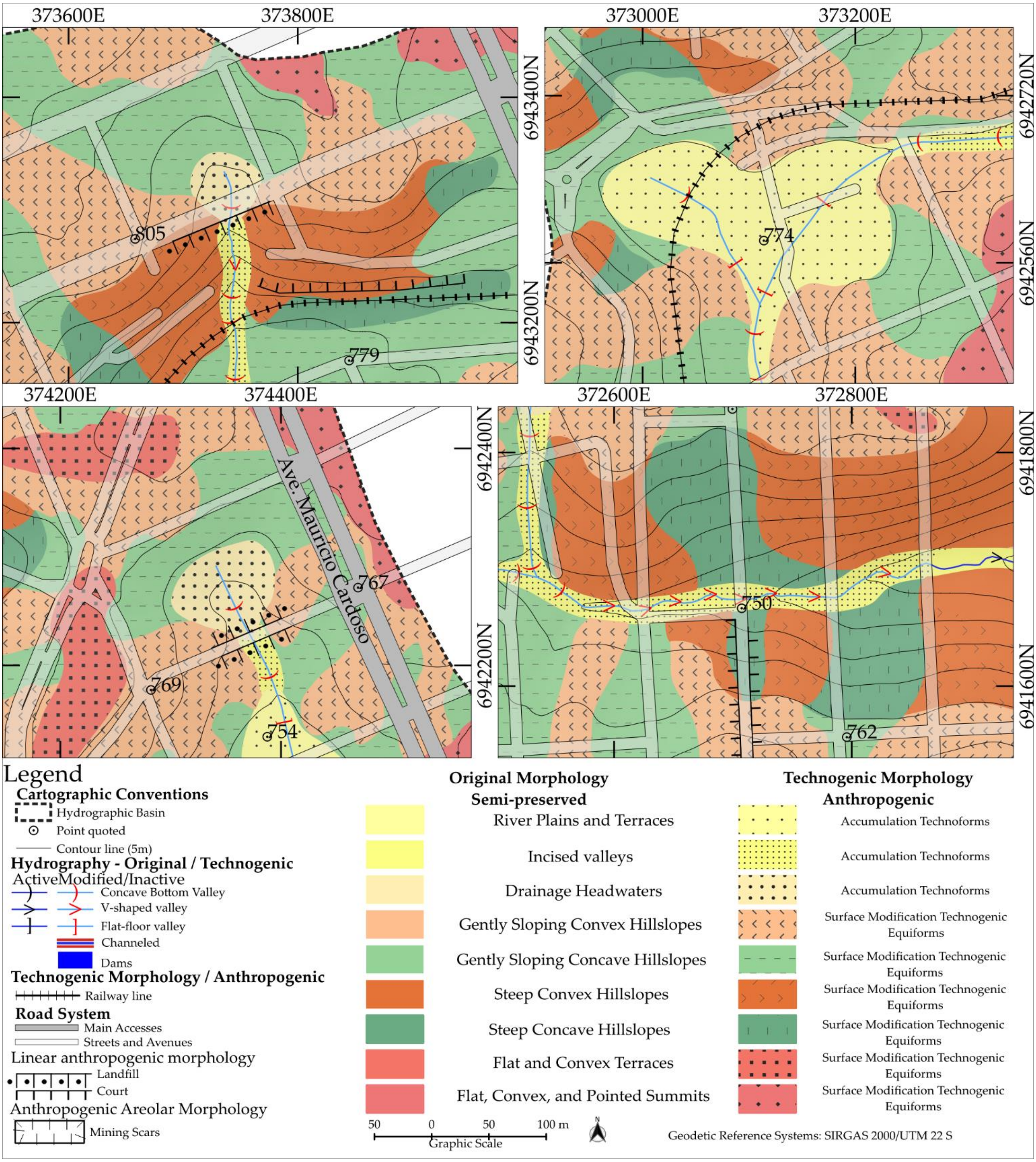


Figure 4. Spatial Section 1 - Original and Technogenic Morphology of the Tigre River Basin, Erechim, RS

The section shown in the upper left corner of Figure 4 represents the area where a drainage head is located, specifically the source of the main channel of the Tigre River. In this section, elements such as cut-and-fill operations, as well as streets and avenues, can be identified, as seen in Figure 6a. The section in the upper right corner of Figure 4 illustrates an area of floodplains and fluvial terraces located in the upper course of the river. Figure 6b shows the layout of this area. Figure 5 displays two sections of this area taken at different times (2014–2024), highlighting the development of two large-scale projects in the right-hand section. These modifications drastically affect the hydrogeomorphological process, as surface impermeabilization in the upper course leads to increased water flow during rainfall events, impacting downstream areas.

Figure 5. Google Earth Sections (2014 – 2024)

In the lower left corner of Figure 4, another section of the upper course is observed, featuring a drainage headwater, gently sloping convex hillslopes, and entrenched valleys. Figure 6b shows the degree of impermeabilization in this area, as well as the densification of infrastructure. For the construction of the road over the entrenched valley area, embankments were necessary along with the channelization of the hydrography, classified here as having a concave bottom. The last section, in the lower right corner of Figure 4, identifies the presence of an entrenched valley with V-shaped hydrography and modified, dammed morphology. Figure 6d presents a panoramic photo of this area, with yellow arrows indicating the direction towards the thalweg and the street where Figure 6e was taken.

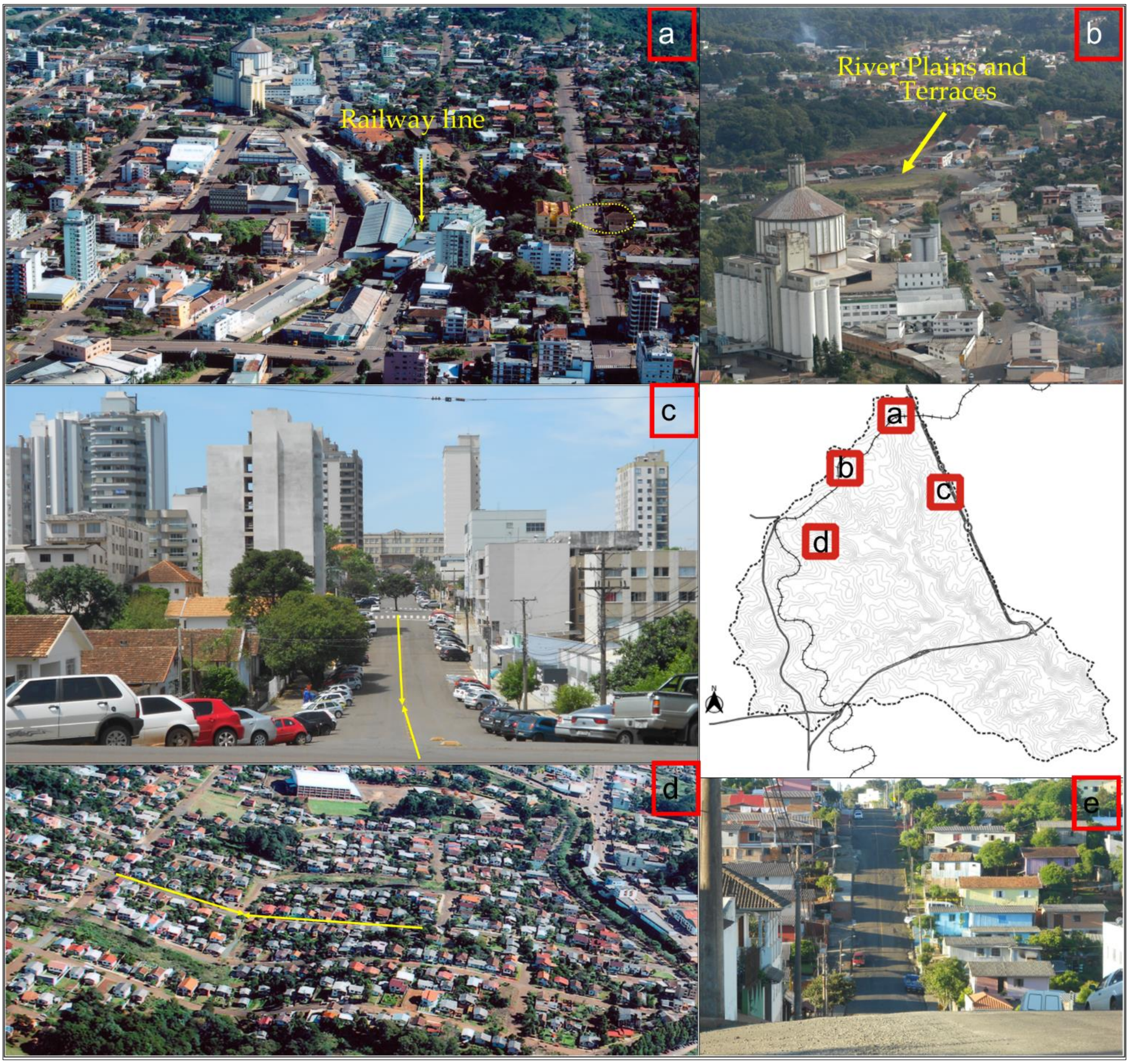


Figure 6. Spatial section 1. (a) Aerial photograph highlighting Drainage Headwater (2007); (b) Aerial photograph highlighting Floodplains and River Terraces (2007); (c) Photograph showing gently sloping convex hillslopes and the entrenched valley (2019); (d) Aerial photograph highlighting entrenched valley and steep hillslopes (2007); (e) Photograph showing V-shaped valley and steep hillslopes (2019).

In Figure 7, spatial sections of the watershed are presented, while Figure 8 complements the illustration of these sections. Within these sections, various elements stand out, with emphasis on floodplains and river terraces, as well as steep hillslopes. Other notable features include cuts, embankments, and mining scars. Observing Figure 8a, the layout of streets and avenues is evident. The highlighted arrows indicate the directions of the photographic shots (Figures 8b and 8c). Figure 8b shows the direction of the larger arrow pointing to José do Patrocínio Street, while Figure 8c (smaller arrow) points to Santos Dumont Street. In these photographs, it is possible to identify the presence of floodplains and river terraces undergoing Accumulation Technoforms. Additionally, there is a transition from floodplains and river terraces to the steep hillslopes, represented as Technogenic Surface Modification Equiforms.

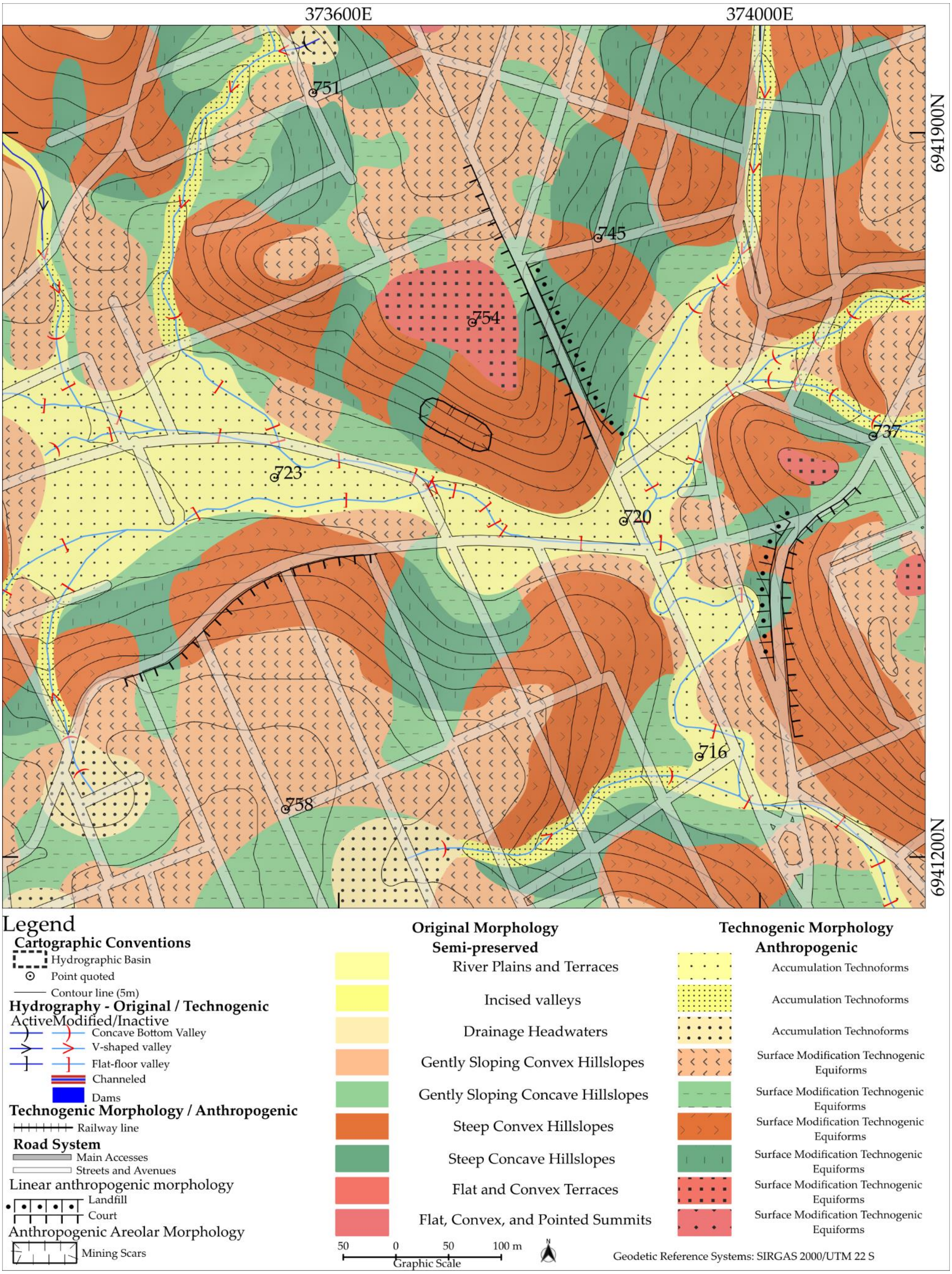


Figure 7. Spatial Section 2 – Original and Technogenic Morphology of the Tigre River Basin, Erechim, RS

Figure 8d shows a section where floodplains and fluvial terraces under the process of Accumulation Technoforms can be observed. Also present are steeply inclined hillslopes, flat and convex terraces, and flat, convex, and sharp hilltops, all classified as Technogenic Surface Modification Equiforms. In this area, a transformation of the floodplain and fluvial terrace elements was identified. Figure 9 illustrates this spatio-temporal section (2014–2024), showing the insertion of a condominium. Previously covered by grass, the area is now impermeabilized, completely altering the hydrogeomorphological system. In addition to impermeabilization, channelization of the local hydrography has been implemented.

Figura 8. Spatial section 2. (a) Aerial photograph (2007); (b) Aerial photograph highlighting Floodplains and Fluvial Terraces (2007); (c) Photograph showing gently inclined convex hillslopes and the Incised Valley (2019); (d) Aerial photograph highlighting Floodplains and Fluvial Terraces (2019); (e) Photograph showing Steeply Inclined Hillslopes and Mining Scar (2019).

Figure 9e represents a section where steeply inclined hillslopes are observed, with the presence of a currently inactive mining scar. This area was used for basalt extraction, likely intended for paving (cobblestones) or construction purposes. Also notable is the presence of a flat, convex bench, classified as a Technogenic Surface Modification Equiform.

Figure 9. Google Earth Sections (2014 – 2024)

Figure 10 represents a spatial section of the middle course of the watershed, while Figure 11a aids in understanding the landform elements located in this area. There is a noticeable concentration of residences on the landform elements. The yellow arrow indicates the point from which the photographs in Figures 11b and 11c were taken.

Figure 11b shows, in the foreground, floodplains and fluvial terraces under the process of Technogenic Accumulation Forms. As identified in Figure 10, this area is a hydrographic junction; however, the hydrography has undergone channelization with the construction of underground galleries extending throughout the spatial section, ending at Figure 12c. In the background (Figure 11b), elements such as steeply inclined hillslopes and flat, convex benches are identified, classified as Technogenic Surface Modification Equiforms.

Figure 11d illustrates another practice of hydrography channelization. It can be seen that this filled river channel runs very close to the densely built residences. Thus, these residences are located on floodplains and fluvial terraces undergoing the process of Technogenic Accumulation Forms.

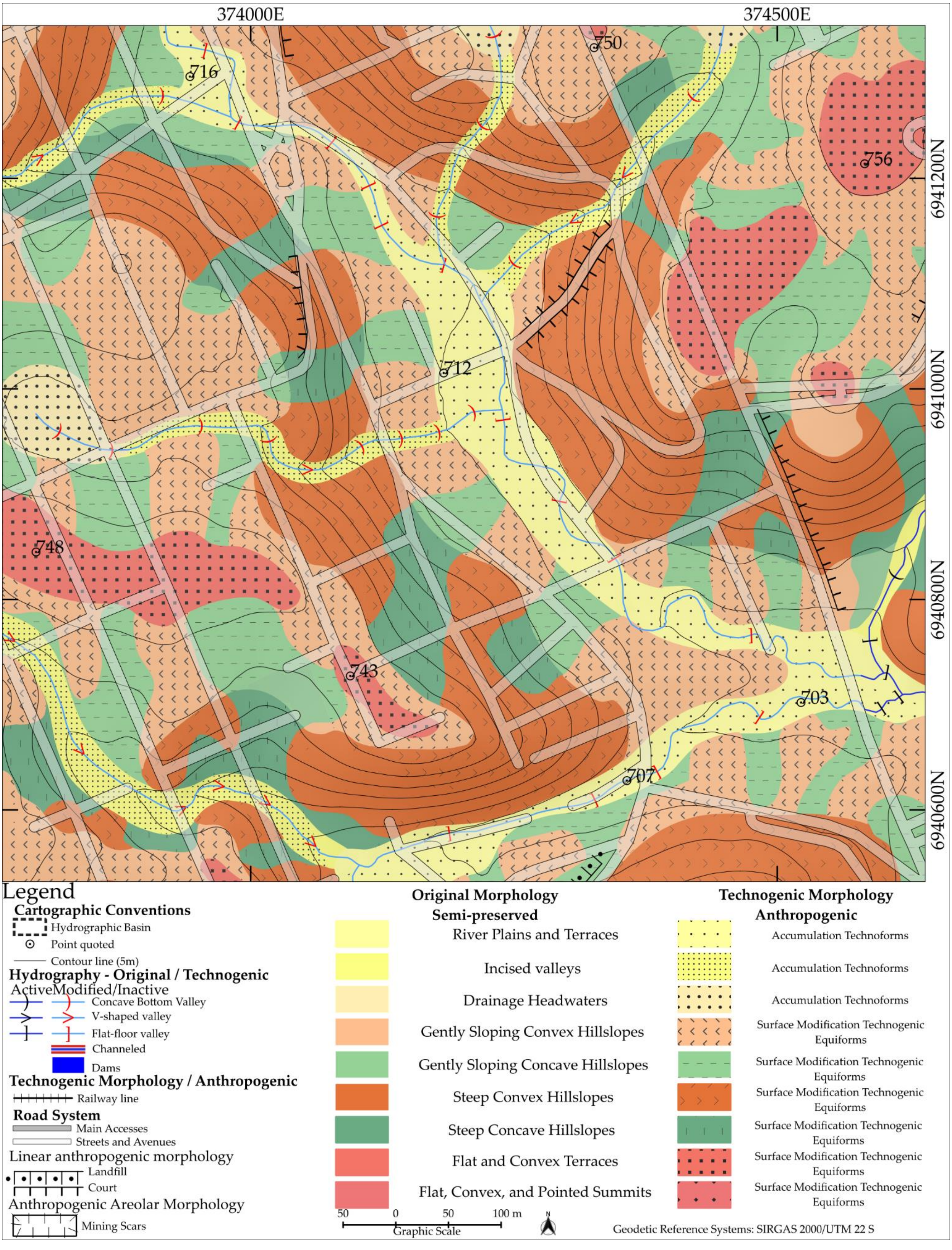


Figure 10. Section 3. Original and Technogenic Morphology of the Tigre River basin, Erechim, RS

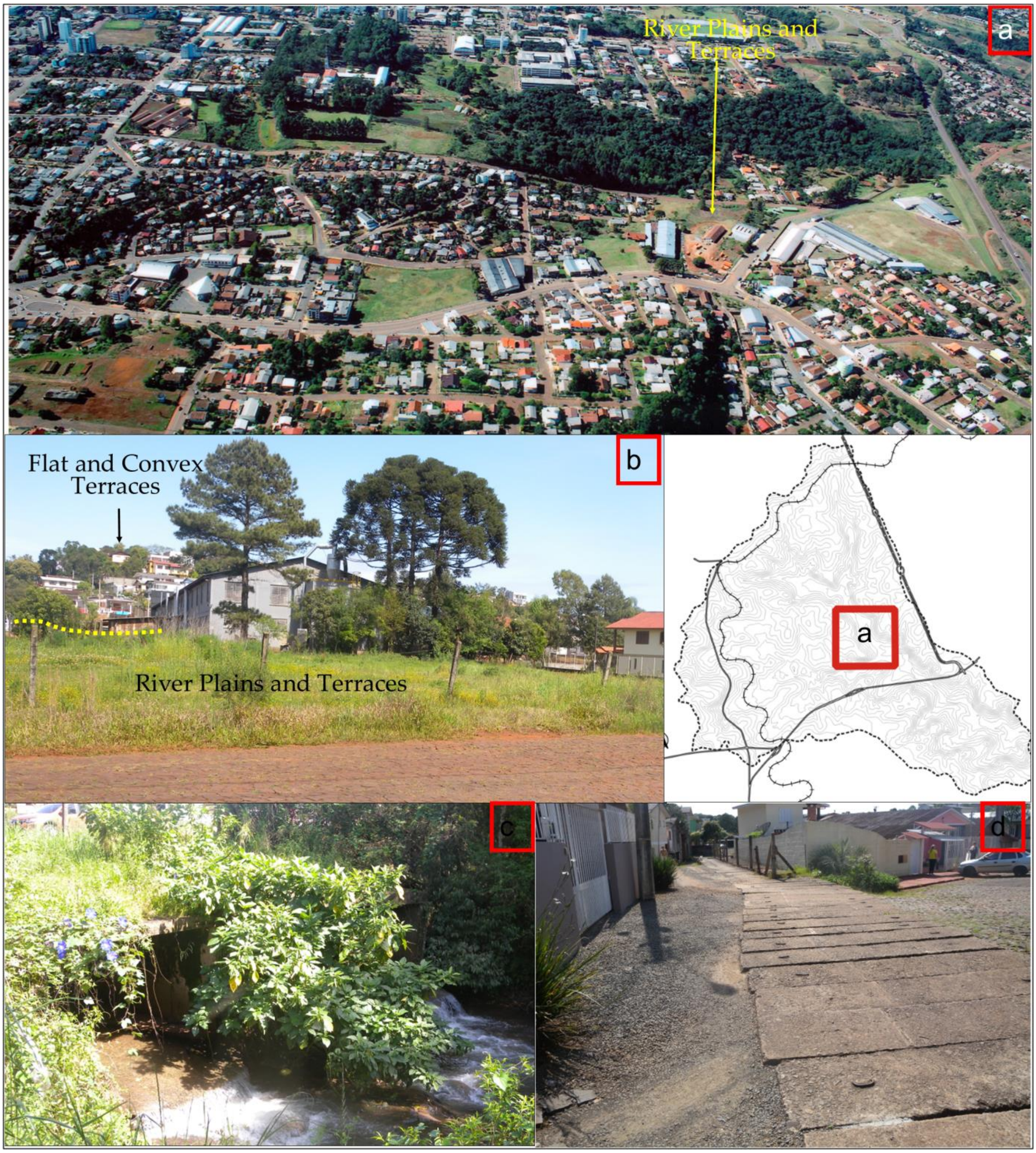


Figure 11. Spatial section 3. (a) Aerial photograph (2007) ;(b) Aerial photograph highlighting Floodplains and Fluvial Terraces (2019); (c) Photograph showing the end of the galleries (Capped Hydrology) (2019); (d) Photograph highlighting galleries (Capped Hydrology) (2019)

The fourth spatial section of the Tigre River basin (Figure 12) highlights morphological changes resulting from the construction of BR-153 and how this highway altered the landform dynamics through the implementation of cuts and embankments. Figures 13a and 13b provide more detailed views through aerial photographs, while Figure 13c shows the full extent of the two spatial sections.

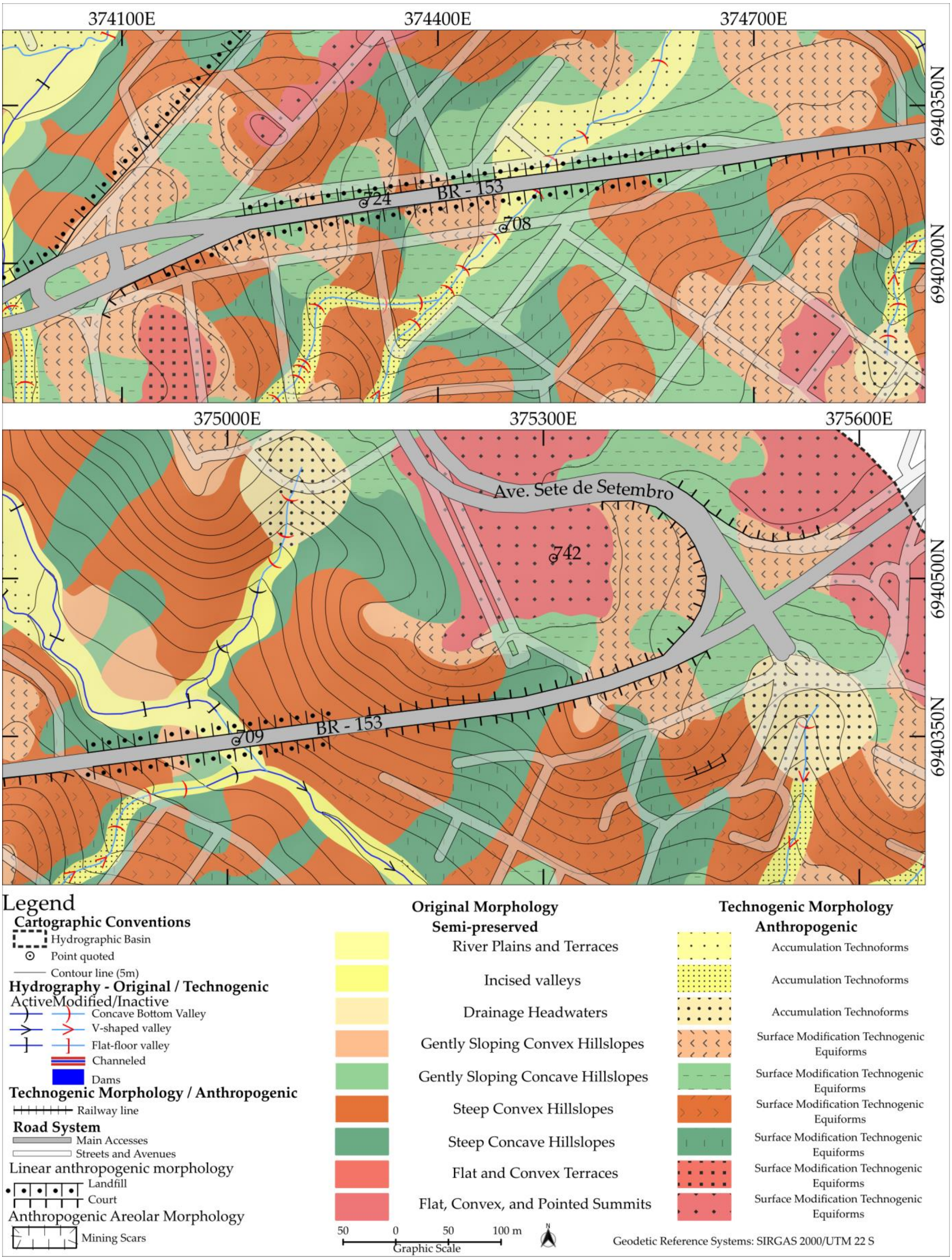


Figure 12. Spatial Section 4. Original and Technogenic Morphology of the Tigre River Basin, Erechim, RS

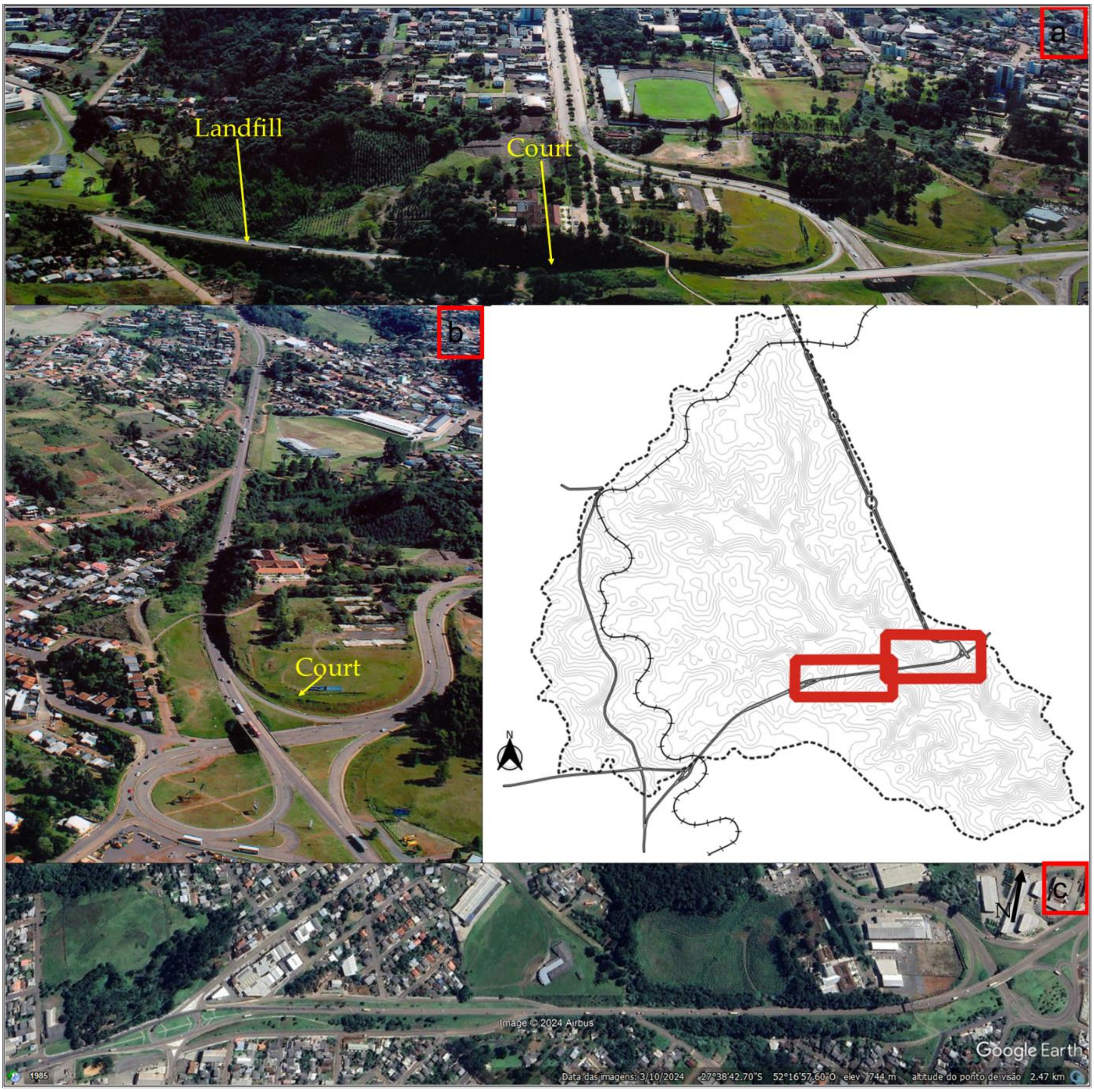


Figure 13. Spatial Section 4. (a) Aerial photograph (2007); (b) Aerial photograph (2007); (c) Google Earth sections (2024)

The last spatial section (Figure 14) presents the dynamics of the lower course of the Tigre river basin. In Figure 15a, it is possible to identify the presence of an entrenched valley, where the hydrography features a concave-bottom channel. Figure 16b highlights the steeply inclined hillslopes and, as a reference, a flat, convex, and sharp summit located at an elevation of 721 meters (Figure 14). In this area, there is significant urban densification, with hillslopes and summit terraces classified as Technogenic Surface Modification Equiforms.

In the foreground of Figure 15b, the floodplains and fluvial terraces undergoing Accumulation Technoforms processes are visible, situated at an elevation of 673 meters (Figure 14). In the background, areas of steep hillslopes can be identified, which still retain their Semi-Preserved form.

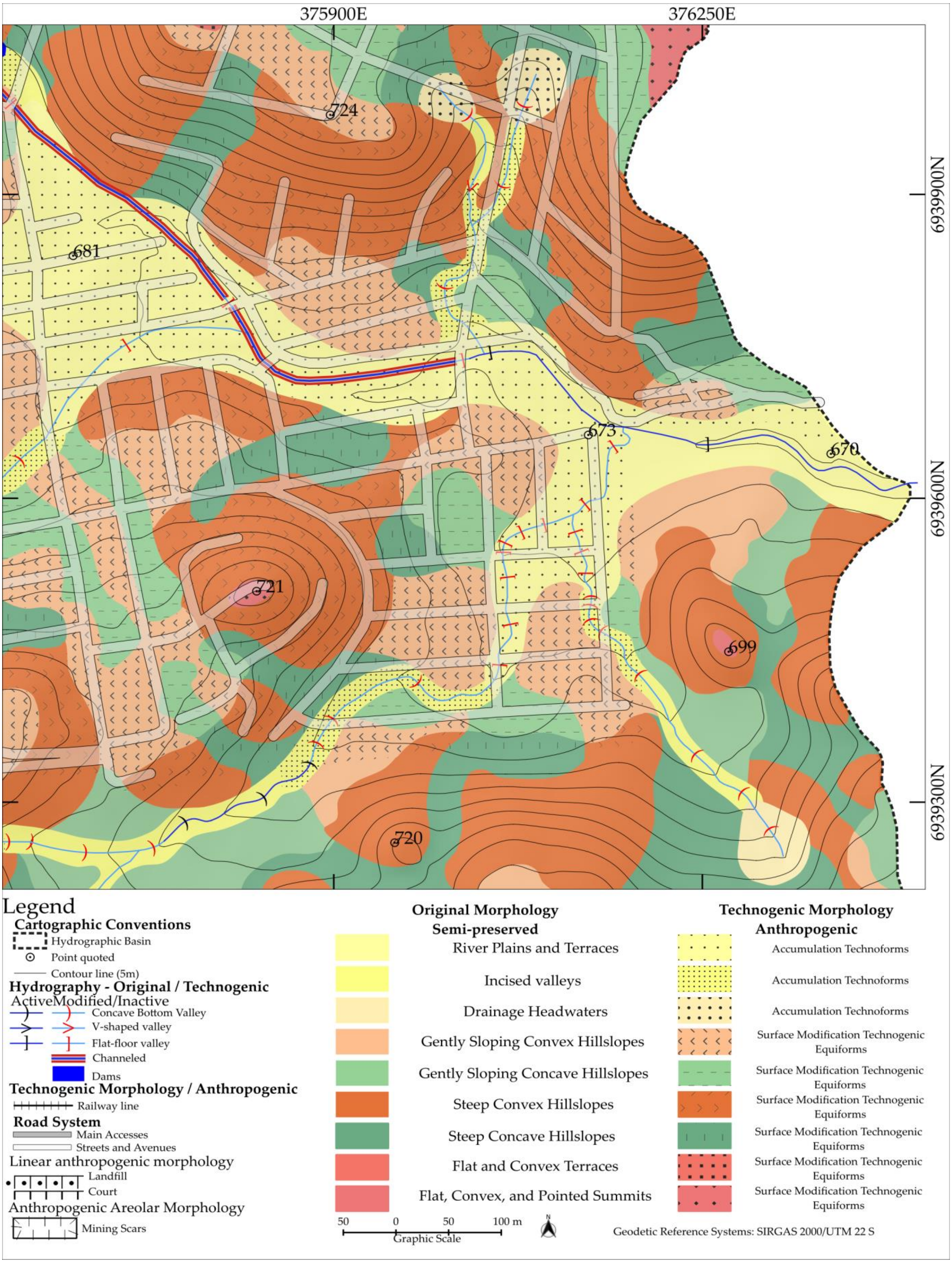


Figure 14. Spatial Section 5. Original and Technogenic Morphology of the Tigre River Basin, Erechim, RS

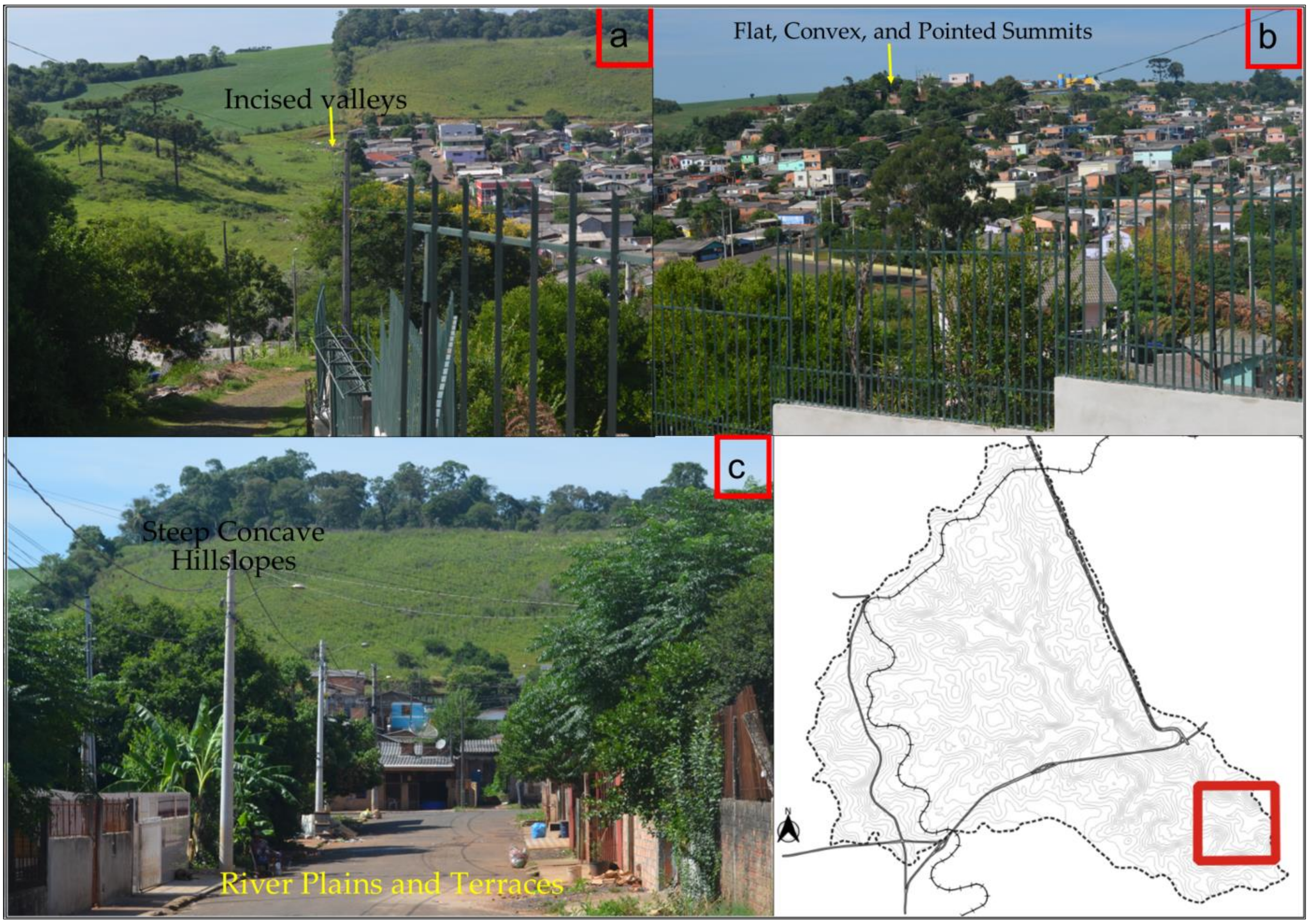


Figure 15. Spatial Section 5. (a) Photograph highlighting fluvial plains and terraces (2019); (b) Photograph showing steeply inclined hillslopes and a flat, convex, and pointed hilltop (2019); (c) Photograph of fluvial plains and terraces (2019).

Figure 16 presents spatial sections of the lower course, illustrating the region's hydric dynamics. In Figure 16a, an area is shown where the fluvial channel was rectified with open-channel canalization. It is important to note that, due to the drought period during the fieldwork, the flow in the fluvial channels was low. Figure 16b shows an area where the hydrography remains preserved; observing the dotted line, the process of margin embankment can be identified. In Figures 16c and 16d, one can identify Accumulation Geotechnoforms that are not visible at the 1:5,000 scale. These forms are associated with induced technogenic deposits, whose morphogenesis results from the induced addition of material.

Figure 16. Spatial Section 5. (a) Photograph highlighting floodplains and fluvial terraces (2019); (b) Photograph of steeply inclined hillslopes and a flat, convex, and pointed hilltop (2019); (c) Photograph of floodplains and fluvial terraces (2019).

Thus, it is understood that the Tigre River watershed is under strong influence of urbanization. Many occupied areas are located on landform elements that should have restricted use. A significant portion of the hydrography has been altered due to urban development, and many residences are situated on or very close to fluvial channels that have been buried, straightened, or are semi-preserved. This increases the susceptibility to processes such as flash floods, flooding, or inundation.

5. Discussion

With the increasing demand for land and the continuous expansion of urban areas—which often impact and transform natural systems—it becomes essential to understand the dynamics of the urban environment and its physical evolution. In this context, the authors presented a methodological and applied approach to investigate the urban environment, with an emphasis on physical processes, especially those of geomorphological, historical, and anthropogenic nature. Geomorphological reconstructions in urban areas prove to be essential tools for analyzing geomorphological dynamics, particularly in contexts where human interventions have substantially altered the natural environment, such as the drainage of watercourses, channelization, and covering of riverbeds.

The growing attention dedicated to urban geomorphology (MOURA et al., 2023) and to geomorphological legend design—a topic widely discussed in Brazil (BOTELHO; PELECH, 2019; PELECH et al., 2019)—reinforces the relevance of studies focused on this area. Based on the studies conducted and the applied methodology, it was possible to identify important issues, including the need to deepen the discussion regarding the adopted scale, considering the diversity of anthropogenic landforms and features, both small and large in extent. In general, Brazilian municipalities lack detailed-scale cartographic bases, and this study aimed to develop a geomorphological assessment using a detailed cartographic base. In this regard, the original morphological classification of landform elements, according to Ross (1992, 2012, 2017), includes: fluvial plains and terraces, entrenched valleys, drainage headwaters, concave and convex hillslopes, benches, and hilltops.

The spatial distribution of these elements was analyzed at different scales — 1:50,000, 1:25,000, and 1:5,000 — which made it possible to identify distinct characteristics and varied hydrogeomorphological processes. This analysis also involved associating landform elements with technogenic features, such as elevations, overlaps in accumulation and excavation technoforms, requiring the use of specific symbols like "V-shaped incision" to represent anthropogenic features.

In addition to the graphical representation, the descriptive tables—which detail morphology, materials, morphogenesis, morphodynamics, and hydromorphology of each element, both original and technogenic—serve as complementary resources to the map. The distribution of this information in supplementary materials, such as reports or layered maps, reduces visual complexity in the main map, ensuring that professionals can access detailed data as needed. It is essential that, beyond meeting scientific requirements, the proposed methodology remains practical and useful for professionals who rely on these maps for urban planning and risk management. The readability and accessibility of cartographic products are priorities, ensuring their applicability across different sectors, such as public administration and urban area management. A good geomorphological map is not defined by the amount of information it contains, but by its practicality and legibility.

The proposed methodology needs to be evaluated and applied by other researchers in different urban areas with various types of landform. Analytical comments and suggestions are essential for broader application and complementary validation. These methodologies are replicable in different contexts and have the potential to contribute to the development of urban zones classified based on measurable risks, even impacting the value of urban properties. To improve readability, the use of differentiated scales may be suggested.

One of the main contributions of this study to landscape reconstruction is the detailed field survey, which allows for understanding the role of anthropogenic activities in reshaping the space. The adoption of an integrated approach to reconstruct urban geomorphology and history is an essential strategy to improve the understanding of the current city's characteristics and to provide a more accurate comprehension of fluvial dynamics, hillslopes, and potential risk scenarios.

The examples presented highlight the importance of considering the interaction between anthropogenic and natural processes in risk assessment. This interaction is particularly significant in urban areas, where high population density and infrastructure are exposed to risks arising from changes in natural dynamics. The reconstruction of geomorphological evolution in urban landscapes can provide valuable support for urban planning and emergency management.

6. Conclusions

The detailed analysis of cartographic representations and the interpretation of anthropogenic landform in the Tigre River basin reveals a complex interaction between original forms and technogenic modifications. At the 1:25,000 scale, the general arrangement of landform elements is observed, both in their original and technogenic forms. This initial representation provides a comprehensive overview of the morphology and spatial distribution of these forms. By increasing the scale to 1:5,000, it becomes possible to identify details of the technogenic forms, including modified hydrography and the details of urban infrastructures that directly impact the local hydrogeomorphological dynamics. This higher resolution reveals how human interventions—such as cuts, fills, and channelizations—not only alter surface morphology but also affect runoff dynamics and susceptibility to extreme events, such as flash floods

The spatial sections complement this analysis by focusing on specific areas of the basin, highlighting how different types of interventions affect the behavior of the landform. For example, in the drainage headwaters, the construction of fills and the channelization of the hydrography modify the landscape, increasing the potential for erosive processes and drainage problems. Thus, the cartographic representation and interpretation of anthropogenic landform in the Tigre River basin emphasize the importance of an integrated approach to environmental planning and territorial management, considering both natural features and human interventions. This approach is essential to mitigate environmental impacts and improve the resilience of urban areas in the face of emerging climatic and hydrological challenges.

This study aimed to provide guidelines for anthropogenic geomorphological mapping, focusing on the detailed mapping of Semi-Preserved and Technogenic hillslopes resulting from the urbanization process. To map these elements, the methodological principles established by Ross (1992, 2012, 2017) were employed, complemented by geoprocessing techniques within GIS. The use of aerial photographs and satellite images, following Rodrigues (2005), Moroz–Caccia Gouveia (2010), and Chirico et al. (2021), assisted in identifying terrain alterations developed throughout the historical occupation process.

The results obtained from the analysis of the Tigre River watershed highlight the influence of urbanization on geomorphological and hydrological dynamics, as indicated by studies in other areas conducted by Fujimoto (2001), Rehbein (2011), and Faccini et al. (2020). Land occupation, combined with intense modification of landforms through cuts, embankments, and urban infrastructure construction, has caused substantial alterations in natural processes of erosion, surface runoff, and sediment transport.

From the conducted analysis, the identification and contribution to the interpretation of anthropogenic landform are evident. The preliminary analysis at a 1:50,000 scale contributes to understanding the urbanization's advance and its impact on the quantitative changes of relief elements, revealing a dynamic of anthropic transformation in the watershed, as applied by Rodrigues (2010). In the second analysis, following the guidelines for mapping technogenic landforms proposed by the Brazilian Relief Classification System (SBCR) (MOURA et al., 2023), an analysis at a 1:25,000 scale was performed. Technogenic Equiforms and Technogenic Elevations and Superpositions (1st Level) were identified, also classified as Technogenic Surface Modification Equiforms and Accumulation Technoforms (2nd Level), using areal forms as the graphic configuration. In a detailed analysis at a 1:5,000 scale, symbologies representing technogenic relief forms, such as cuts and embankments, were explored.

This study provides a detailed analysis of the consequences of urbanization on a specific watershed, integrating geomorphological and hydrological aspects. The results highlight the importance of land-use policies and environmental planning that consider both natural processes and the need for resilient infrastructure. The methodology used can serve as a model for similar studies in other urbanized regions, offering a foundation for developing strategies to mitigate socio-environmental impacts.

In summary, the presented methodology proves to be effective for anthropogenic geomorphological mapping, revealing the complex interaction between urbanization and natural dynamics. This work contributes to understanding the transformations of the relief in urbanized areas and highlights the need for an integrated approach in urban planning. There are several issues to be evaluated when planning this type of mapping, each of which can influence the choice of the most appropriate methodology according to the specific characteristics of the area to be mapped. Methodological adjustments will be inevitable, considering regional and local particularities.

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