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Research paper

Geomorphologic Mapping of Tete Municipality, Mozambique

Mapeamento Geomorfológico do Município de Tete, Moçambique

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Abstract: Geomorphological mapping consists of a set of techniques used to map landforms and the processes acting on the Earth's surface. It is a combination of techniques used in the representation of landforms and a useful tool to support information for integrated environmental analyses, territorial management, and geo-environmental risk assessment. Despite its importance and widespread use in several countries, including Brazil, most African countries do not conduct this type of mapping in their territories. This article aims to present the geomorphological mapping of the municipality of Tete in Mozambique. The methodology employed included the use of a Digital Elevation Model (DEM), high-resolution optical images, and fieldwork. The definition and classification of landforms followed the system proposed by Latrubesse and Carvalho (2006), which is nationally recognized and adaptable to different environments. The results indicate that the municipality's area is dominated by denudational units (~208 km²), which have sculpted large Receding Erosion Zones and Planation Surfaces, exhibiting different evolutionary stages. The aggradational units (~85 km²), in turn, are associated with the current and past dynamics of the Zambezi and Revúboè river systems. This study represents a pioneering product in the region and aims to provide support information for urban planning, environmental management, and hydrogeomorphological risk mitigation actions in the municipality of Tete.

Keywords: Geomorphologic Mapping; Mozambique; Zambezi River; Tete.

Resumo: O mapeamento geomorfológico constitui um conjunto de técnicas empregadas para cartografar as formas de relevo e os processos atuantes na superfície terrestre. Trata-se de uma conjunção de técnicas utilizadas na representação das formas de relevo e que proporciona informação de base para análises ambientais integradas, gestão territorial e avaliação de riscos geoambientais. Apesar de sua importância e ampla utilização em diversos países, incluindo o Brasil, a maioria dos países africanos não realiza esse tipo de mapeamento em seus territórios. Este artigo tem como objetivo realizar o mapeamento geomorfológico do município de Tete, em Moçambique. A metodologia empregada incluiu o uso de Modelo Digital de Elevação (MDE), imagens ópticas de alta resolução e trabalho de campo. A definição e classificação das geoformas seguiram o sistema proposto pelo Latrubesse e Carvalho (2006), reconhecido nacionalmente e adaptável a distintos ambientes. Os resultados indicam que a área do município é dominada por unidades denudacionais (~208 km²), que esculpiram grandes Zonas de Erosão Recuante e superfícies de aplainamentos, os quais exibem diferentes estágios evolutivos. As unidades agradacionais (~85 km²), por sua vez, estão associadas à dinâmica atual e pretérita dos sistemas fluviais dos rios Zambeze e Revúboè. Este estudo constitui um produto pioneiro na região e objetiva proporcionar informações relevantes para planos e ações de planejamento urbano, gestão ambiental e mitigação de riscos hidro-geomorfológicos no município de Tete.

Palavras-chave: Mapeamento Geomorfológico; Moçambique; Rio Zambeze; Tete.

1. Introduction

Geomorphologic mapping can be described as a set of techniques used to map and represent landforms, taking into account their genesis, composition, and structure (Da Silva, 2000; Lee, 2001; Arnaud-Fassetta et al., 2009; Griffiths, Smith, Paron, 2011; Bishop et al., 2012; Cunha, Pinton, 2013; Chelli et al., 2021). Its historical development has evolved through different countries but fundamentally has been derived from European schools (Bishop et al., 2012), each with its own objectives (Griffiths, Smith, Paron, 2011).

Countries such as Germany, Austria, France, Spain, England, Italy, the Netherlands, Poland, and others have a long tradition in geomorphological mapping, and many of them maintain national programs, in addition to sustaining extensive experience in geomorphological scientific research (Klimaszewski, 1956; Tricart, 1965; Lee, 2001; Paron, Claessens, 2011; Coltrinari, 2011; Verstappen, 2011; Otto, Smith, 2011; Wohl, Bierman, Montgomery, 2016; Quesada-Román, Peralta-Reyes, 2023). Unlike Europe, where geomorphological mapping has been carried out systematically even for national agencies, the United States demonstrated less interest in this area, and geomorphic maps have generally been produced at a regional scale (Bishop et al., 2012; Quesada-Román, Peralta-Reyes, 2023). Also, China has made significant progress in the production of articles related to geomorphological mapping (Quesada-Roman, Peralta Reyes, 2023).

In South America, Brazil stands out as one of the countries that has systematically conducted geomorphological mapping in conjunction with governmental agencies. The RADAMBRASIL project, launched in the 1970s and 1980s, developed a system of geomorphological mapping that, with adaptations, led to the mapping system of the Brazilian Institute of Geography and Statistics (IBGE) (Da Silva, 2000; IBGE, 2009; Pelech et al., 2019; Botelho, Pelech, 2019). In Brazil, geomorphological mapping has been applied in large-scale projects as a basic component of integrated environmental analyses Crepani et al. (2001); Valente; Latrubesse (2009); Da Silva (2021), as it provides an important base for territorial management, environmental planning, and environmental impact studies. In addition, various state-level maps have been carried out using different methodologies (Ross, Moroz, 1996; Latrubesse, Carvalho, 2006; Santos et al., 2006; Coelho et al., 2012; Rodrigues et al., 2023). However, this reality contrasts with that of most African countries, where geomorphological mapping is still incipient or even nonexistent. According to Quesada-Román and Peralta-Reyes (2023), African countries have published only 1.5% of articles related to geomorphological mapping over the past 21 years, out of a total of 735 articles analyzed.

In geomorphological mapping, various methodologies support risk assessment and mitigation, landscape-unit identification, and environmental planning strategies (Cooke, Doornkamp, 1990; Dramis, Guida, Cestari, 2011). However, unlike geological mapping, which, despite some variation, follows a consolidated and internationally accepted conceptual logic Florenzano (2008); Da Silva (2021), geomorphic mapping has not yet achieved comparable uniformity, despite ongoing harmonization efforts (Verstappen, 2011; Griffiths, Smith, Paron, 2011; Pelech et al., 2019; Da Silva, 2021).

In this article, we present the first geomorphologic mapping of Tete municipality, Mozambique. We adopted a classification and mapping system proposed by Latrubesse and Carvalho (2006), which has already been tested in extensive areas of Brazil as the official product of the Ecological and Socioeconomic Zoning Project for the states of Mato Grosso and Rondônia; the Geomorphologic map of Goiás and the Federal District by the Goiás State Mining

Superintendency; the Geomorphologic map of the Brazil-Bolivia Ecological-Environmental Zoning (CPRM); as well as the map of the Araguaia basin (Latrubesse, Rodrigues, Mamede, 1998; Latrubesse, 2000; Latrubesse, Carvalho, 2008; Valente, Latrubesse, 2012). This is a methodology already well-established in Brazil and recognized for its efficiency in different environmental contexts. Furthermore, the Brazilian territory, where the mentioned mapping system was originally tested, shares geological and climate similarities with certain regions of Mozambique.

Thus, this work aims to present the geomorphological mapping of Tete Municipality in Mozambique. The Tete municipality faces recurring flooding problems and challenges related to land-use planning. Given that a geomorphological map is a basic component of integrated environmental analysis, its development is considered relevant to help local authorities mitigate geoenvironmental risks and improve land-use management.

2. Description of study area

The municipality of Tete, in the eponymous province, is in the central-western part of Mozambique (figure 1). It lies between latitudes S16°07'12" and S16°15' and longitudes E33°30'58" and E33°36'50", covering an area of ~287 km² and divided into nine neighborhoods. It is bordered to the north and east by the district of Moatize, via the Revúboè River, and to the south and west by the districts of Changara and Marara, respectively.

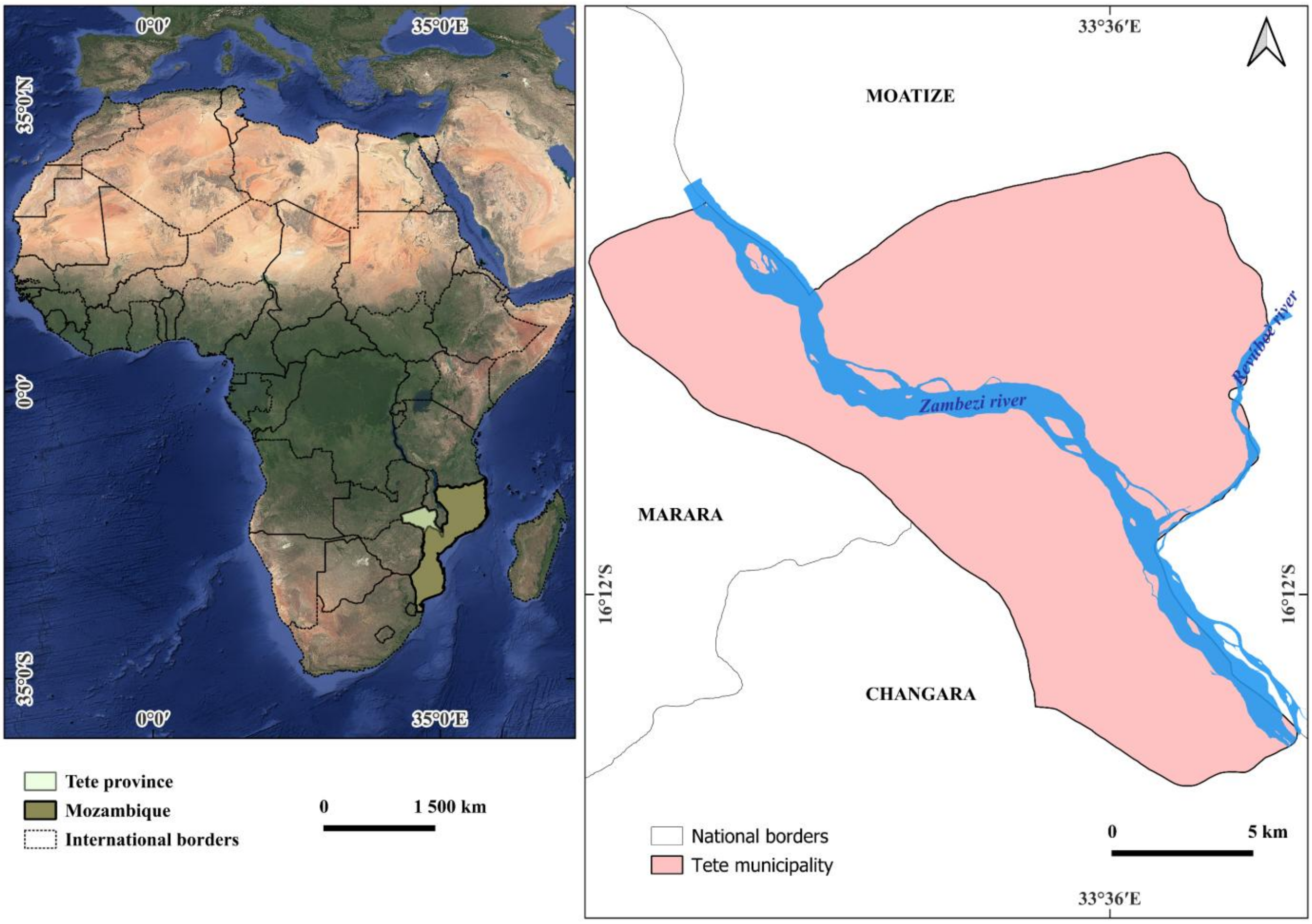

Figure 1. (a) The African continent, highlighting Mozambique and Tete province, and (b) Tete municipality.

The Tete municipality has a population of 307,338 inhabitants (INE, 2017). The climate is semi-arid, with two distinct seasons: a hot, rainy summer, from September to March, and a short dry winter, from May to August. The average annual temperature is about 26.5°C, while average annual rainfall usually does not exceed 600 mm (Figure 2).

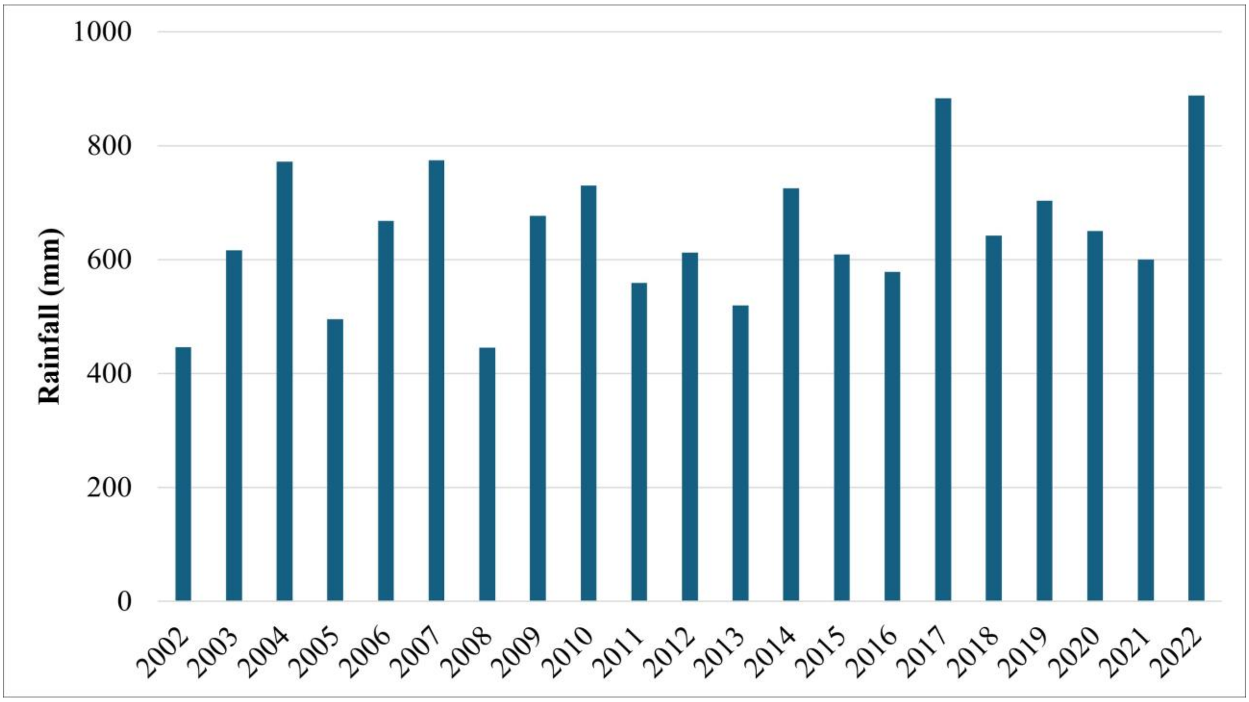

Figure 2. Average annual rainfall in the municipality of Tete. Date source: NASA/CERES/MERRA2.

From a geological perspective, four main lithologies crop out in the Tete municipality (Figure 3). One is the Matinde Formation, dating from the Low Triassic (251.0-201.3 Ma), composed mainly of Sandstones, Claystones, and Marls. This Formation covers ~90% of the municipality's area. Second, Pre-Cambrian rocks (Mesoproterozoic; 1,600-1,000 Ma), covering ~4% of the territory, are composed of anorthositic gabbros of the Tete Suite and Chacocoma Granites (GTK Consortium, 2006).

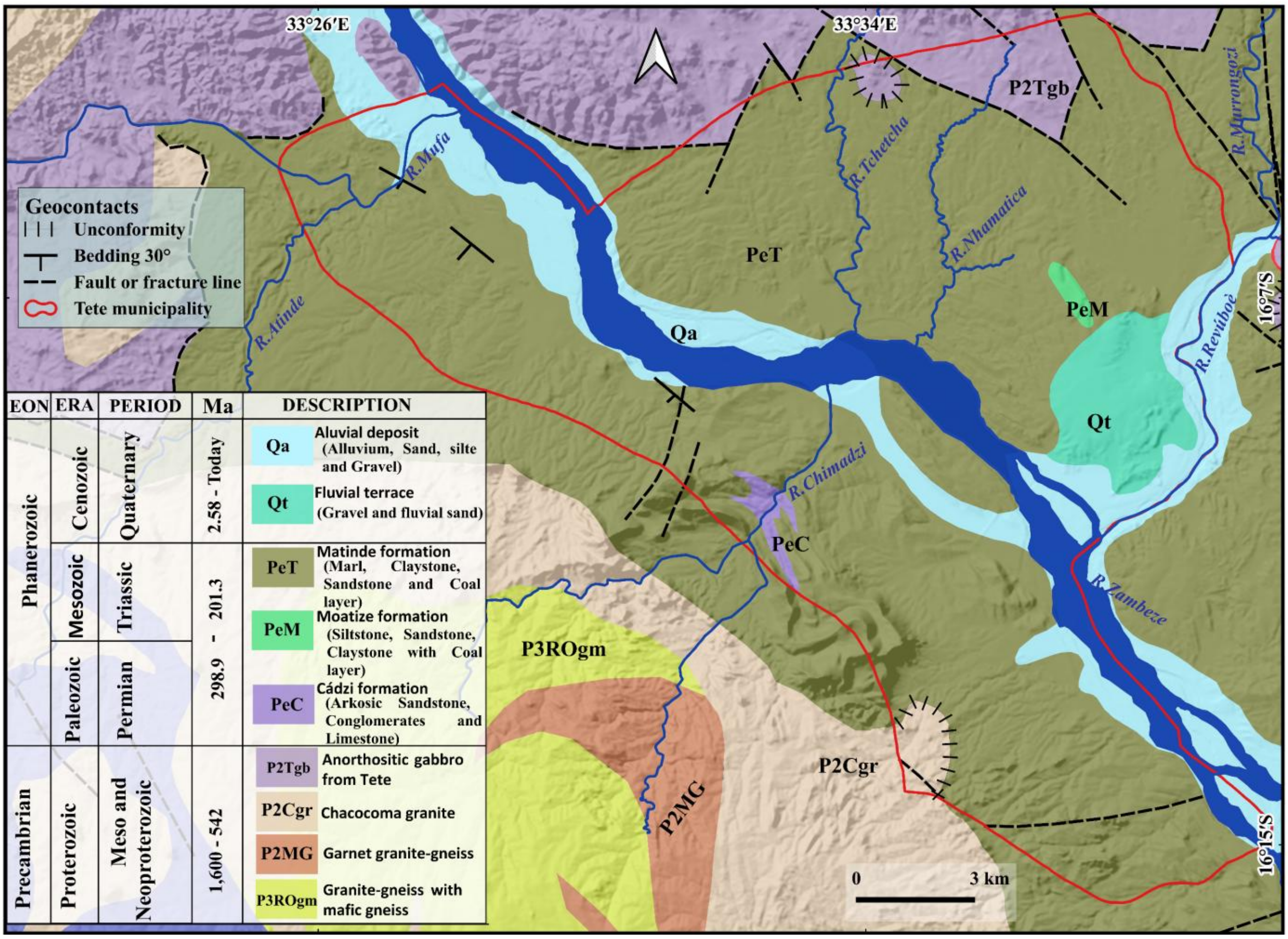

Figure 3. Geological Map of Tete Municipality. Source: adapted from the National Directorate of Geology of Mozambique (2006).

The last two formations occupy a small part of the central region of the municipality and Caloeira Hill. The Cádzi Formation, dating from the Permian (298.9 Ma), consists of Arkose Sandstones, Conglomerates, and Limestone. The Moatize Formation, from the Permian-Triassic (298.9-201.3 Ma), contains Sandstones, Claystones, Siltstones, and coal layers. The Quaternary is represented by fluvial terraces and alluvial deposits along the main river systems and creeks (GTK Consortium, 2006).

2.1 Materials and Methods

For the geomorphological mapping of the municipality of Tete, satellite imagery processing and interpretation were integrated with fieldwork.

2.1.1 Data

Planet images (https://www.planet.com/), the Elevation Digital Model SRTM (Shuttle Radar Topography Mission), obtained using the OpenTopography plugin in QGIS (https://opentopography.org/), and Google Earth Pro images were used as a base for landforms interpretation and digital mapping of geomorphological units (Table 1).

Table 1. Satellite images used for digital geomorphological mapping.

Date purchase	Sensors	Spatial resolution (m)
2000	SAR	30 m
May 2024	Planet	5 m
April 2023	Planet	5 m

2.1.2 Visual interpretation and landform delineation

The regional geology was used as a base to comprehend how different lithologies played a role in shaping the landscape. We also extracted the drainage network from the SRTM 30 m. Subsequently, the drainage network was overlaid onto a previously generated slope map, and the data were integrated to assess the degree of dissection of the terrain. Then, a set of procedures was applied to the DEM in GIS (Geographic Information System). Specific highlight and color palettes were used to enhance topographic variations, along with analytic shading (hillshade) to emphasize the terrain's roughness. Based on prior knowledge of the regional geology, the drainage network, and the area slope, the DEM was imported into the Global Mapper software, where the process of manually delineating landforms was conducted. During the mapping, continuous visual analyses were conducted and complemented with verifications of lithology and optical imagery from Planet and Google Earth Pro. Planet images were processed to adjust color parameters such as brightness, contrast, color, and sharpness to highlight the different geomorphological units, specifically those in the floodplains of the major river systems.

High-resolution images from Google Earth Pro complemented the visual interpretations of landforms across different temporal scales. The geomorphological system employed treats scale as an adjustment variable determined by the interpretation of geomorphological elements at different hierarchical levels (Latrubesse; Carvalho, 2006). Scale is treated as a dynamic parameter, not tied to the scale defined for geomorphological categorizations. Thus, the cartographic product expresses hierarchical geomorphological levels chosen for its representation and not as tied to specific scale ranges.

2.1.3 Fieldwork

Fieldwork was conducted to validate the digital geomorphological mapping. Three field surveys were conducted in August, October, and December 2024. During the surveys, control points for each geomorphological unit were described, photographic images were captured, and expedited topography surveys were conducted. Subsequently, the field control points and photographic images were georeferenced, thus culminating in the final adjustment of the geomorphological map.

2.1.4 Conceptualization of the geomorphological map

The geomorphological map of the Tete municipality followed the conceptual methodology proposed by (Latrubesse; Carvalho, 2006). Its main advantage lies in the fact that it is an open system, based on a genetic, time-evolutionary conceptual framework, which allows for the inclusion of new categories, according to the specific characteristics of each region. This classification system prioritizes the genesis and identification of landforms; it is not based on the mapping of current transformation variables, such as the current morphogenic processes, although these may be partially included when they are dominant in certain areas (Latrubesse; Carvalho, 2006). For example, an old terrace, whose genesis is related to aggradational-erosional processes, containing alluvial deposits and belonging to a specific fluvial zone, continues to be classified as such, even if it is currently undergoing erosional processes. Another fundamental aspect of this system is the treatment of the cartography scale. Unlike other mapping systems, here the scale does not act as a determining classification factor but as an adjustment variable that enables the interpretation of geomorphological elements at different hierarchies. Thus, a landform of an aggradational or denudational origin retains its classification regardless of the scale of representation (Latrubesse; Carvalho, 2006). Figure 4 presents a synthesis of the methodology procedure adopted in this article.

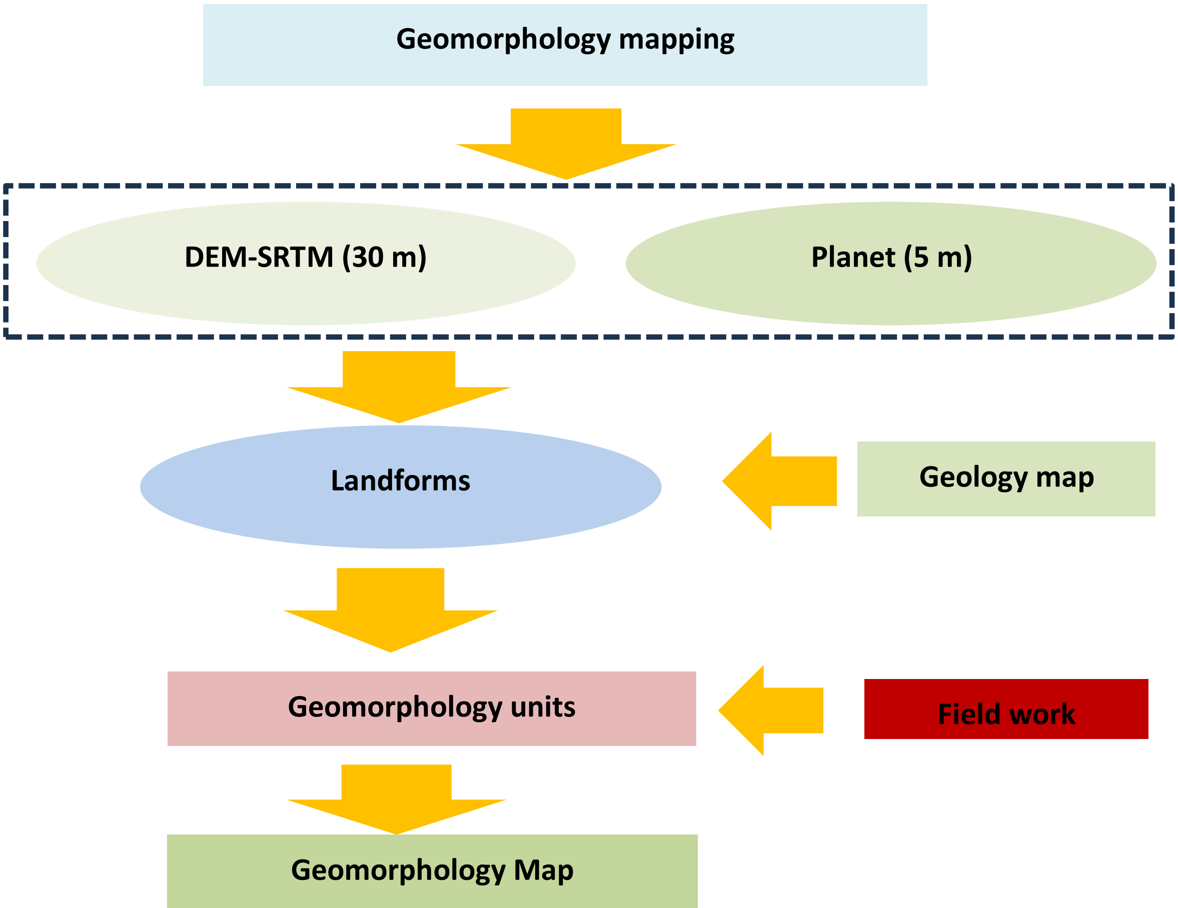

Figure 4: Summary of methodological procedures.

3. Results

Remote sensing techniques, combined with fieldwork, allowed recognition of geomorphological units that develop in the municipality of Tete. These units were categorized into two main groups: aggradational associated units and denudational units. Aggradational units, dominated by sedimentation, occupy an area of ~85.22 km², corresponding to ~29.03% of the mapped area. The aggradational units consist of landforms that develop in the alluvial plain of the region's two main rivers and the tributaries of the Zambeze and Revúboè (Figure 5 and Table 2). Also, we identified lakes and colluvial and alluvial deposits associated with denudational units such as the Receding Erosional Zone, as well as fluvial terraces and tributaries (see section 3.2, subsection a). The second major category is the denudational, associated with dominant erosion, covering ~208.30 km², equivalent to 70.96% of the mapped area. This category consists of the following units: Planation Surfaces of Tete Municipality, which develop on two different levels (PSTMa and PSTMb); the Receding Erosional Zone; Hills with strong structural control; and residual Hills (Figure 5 and Table 2). Dambos were also identified as landforms associated with the Planation Surfaces (PSTMa and PSTMb) and the Receding Erosional Zone (see section 3.5, subsection b). Dambos are seasonally or permanently flooded depressions, commonly located at the headwaters of drainage systems, developed on rocky substrate, and containing regolith (Thomas, 1994) (see more details in section 3.5, subsection b). Information for each unit and landforms mapped in the municipality of Tete are presented below.

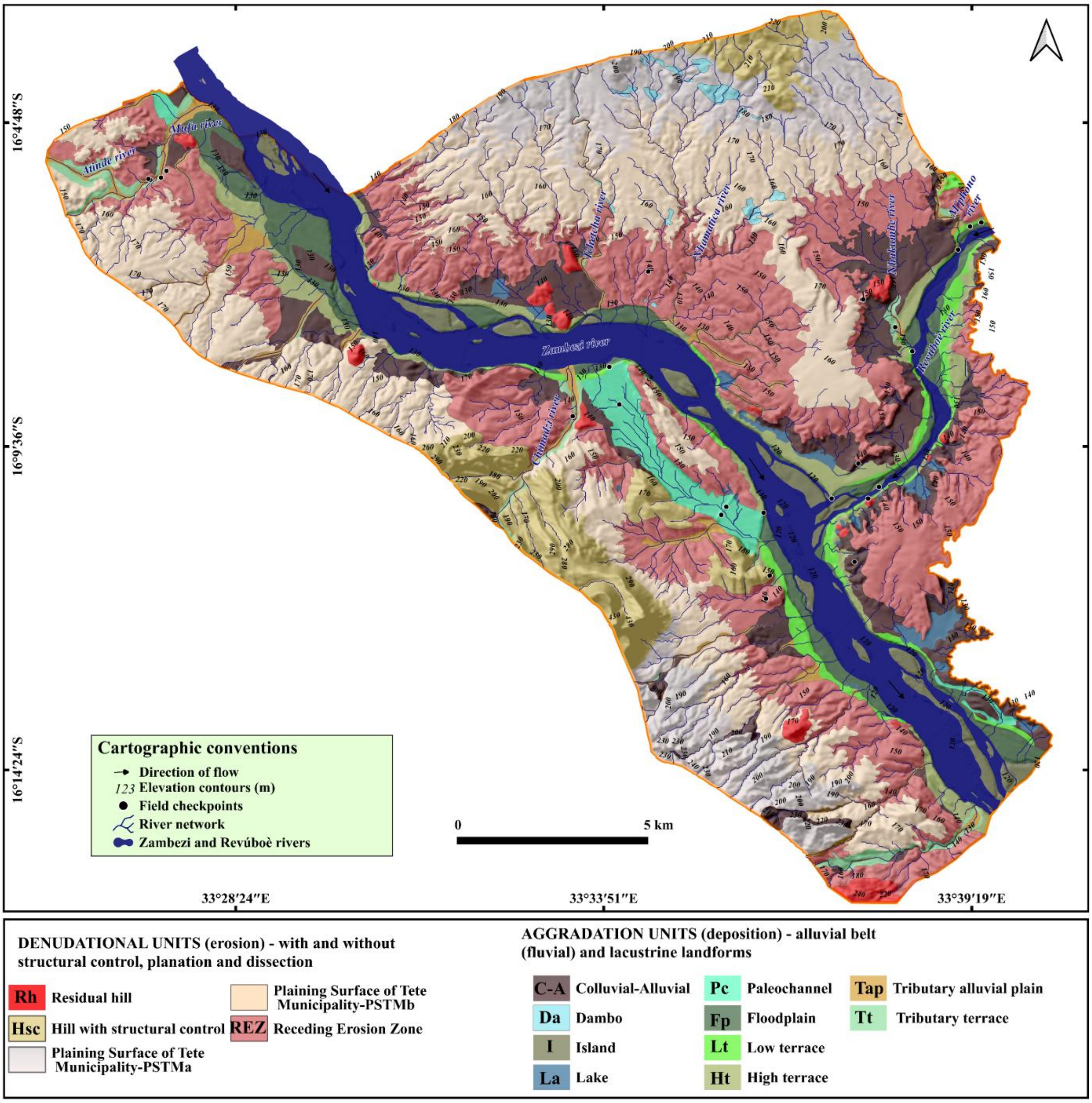

Figure 5. geomorphologic map of Tete municipality

Table 2. Classification system for the geomorphology of the municipality of Tete.

SYSTEM	GEOMORPHOLOGICAL UNITS			Area (km²)	Area (%)
AGGRADATIONAL	Alluvial belt	Fluvial	Tributary terrace	3.00	1.02
			Tributary alluvial plain	8.00	2.73
			Colluvium-Alluvium	29.60	10.08
			Low terrace	4.80	1.64
			High terrace	9.90	3.37
		Lacustrine	Paleochannel	6.00	2.04
			Island	5.70	1.94
			Flood plain	14.30	4.87
			Dambo	1.30	0.44
			Lake	2.62	0.89
DENUDATIONAL	With or without structural control	Planation	Planation Surface of Tete Municipality-PSTMa	30.66	10.44
		Dissection	Planation Surface of Tete Municipality-PSTMa	74.47	25.37
			Receding Erosional Zone - REZ	78.19	26.64
			Residual hill	3.34	1.13
			Hill with strong structural control	21.78	7.42

3.1 Geomorphological units of denudation (associated with erosional processes)

a) Planation Surface of Tete Municipality (PSTMa)

The Planation Surface (PS) results from a process that levels the relief within a specific elevation range, independently of regional geological, lithological, and structural controls estruturais (Latrubesse; Carvalho, 2006). In terms of spatial distribution, the PS can encompass and level different geological units simultaneously, while sectors more resistant to denudation may still emerge above the regional surface as residual hills (inselberg hills).

In the municipality of Tete, we identified this surface developing on two main lithologies: the anorthositic gabbros from the Tete Suite, dating from the Pre-cambrian, and Sandstone and Claystone of the Matinde Formation, of the Phanerozoic age (Figure 6). The SP was identified through visual interpretation and the topographic variation observed in the DEM, in addition to analyses of the regional geology. In general, it appears as a relatively flat surface that locally favors the formation of some local wetlands confined to the headwaters and channel of small tributaries, known locally as *Dambo*, which are very common in various regions of Africa (Boast, 1990; Mandishona e Knight, 2022) (see section 3.5, subsection b). The PS is distributed in two distinct levels, described below.

b) Planation Surface of Tete Municipality – PSTNa

The PSTMa covers an area of ~30.66 km², equivalent to ~10.44% of the total mapped area, and occurs at altitudes ranging from 240 to 180 m. On the northwest and north flanks, PSTMa develops on the anorthositic gabbros of the Tete Suite, intersecting the Sandstones of the Matinde Formation, extending toward the Zambezi River (Figure 5). In this portion, it is relatively flat, favoring the development of Dambos distributed along the Nhamatica River drainage system (Figures 6 and 7). On the southeast bank of the Zambezi River, this unit lies predominantly on Sandstone of the Matinde Formation. In contrast to the northwest and north flanks, here the PSTMa is heavily dissected, with poorly developed and deep valleys, shaped by the lithology. In this sector, the elevation range is between 240 and 200 m.

c) Planation Surface of Tete Municipality-PSTMb

The PSTMb unit lies beneath the PSTMa, distributed between elevations of 180 and 160 m. It occupies an area of ~74.4 km², corresponding to 25.37% of the total mapped area. This unit lies predominantly on Sandstones of the Matinde Formation. On the north flank, near the Nhamatica River, and in the east, along the Tchetcha River, it occurs on anorthositic gabbros of the Tete Suite, where it locally overlies Sandstones and Claystones of the Matinde Formation. On the south and northeastern banks, however, the PSTMb is undergoing an advanced denudational process, characterized by dissected relief and the presence of various residual hills (Figure 5). The Sandstones of the Matinde Formation are tectonically deformed, exhibiting, depending on the sector, dips of ~30° and fold structures. The Planation Surface (PSTMb) plains and levels the regional surface without being constrained by strong structural control (Figure 7c).

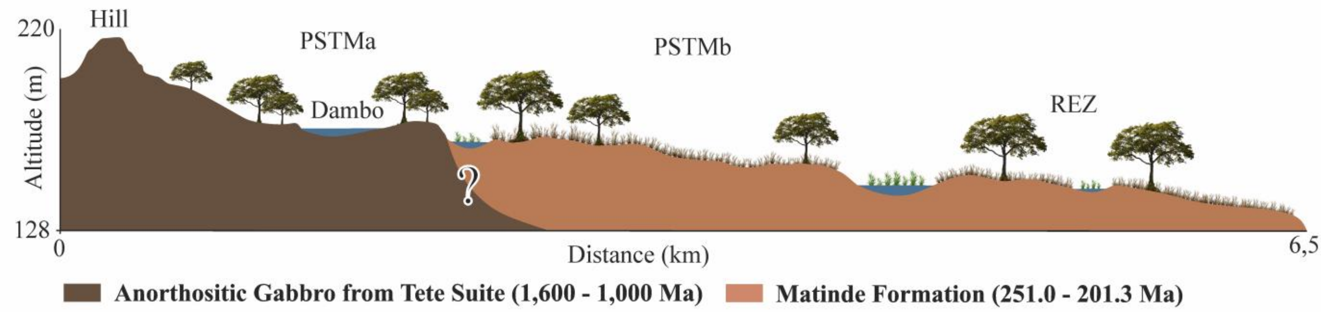

Figure 6. Topography profile and conceptual model highlighting the bedrock and associated geomorphological units.

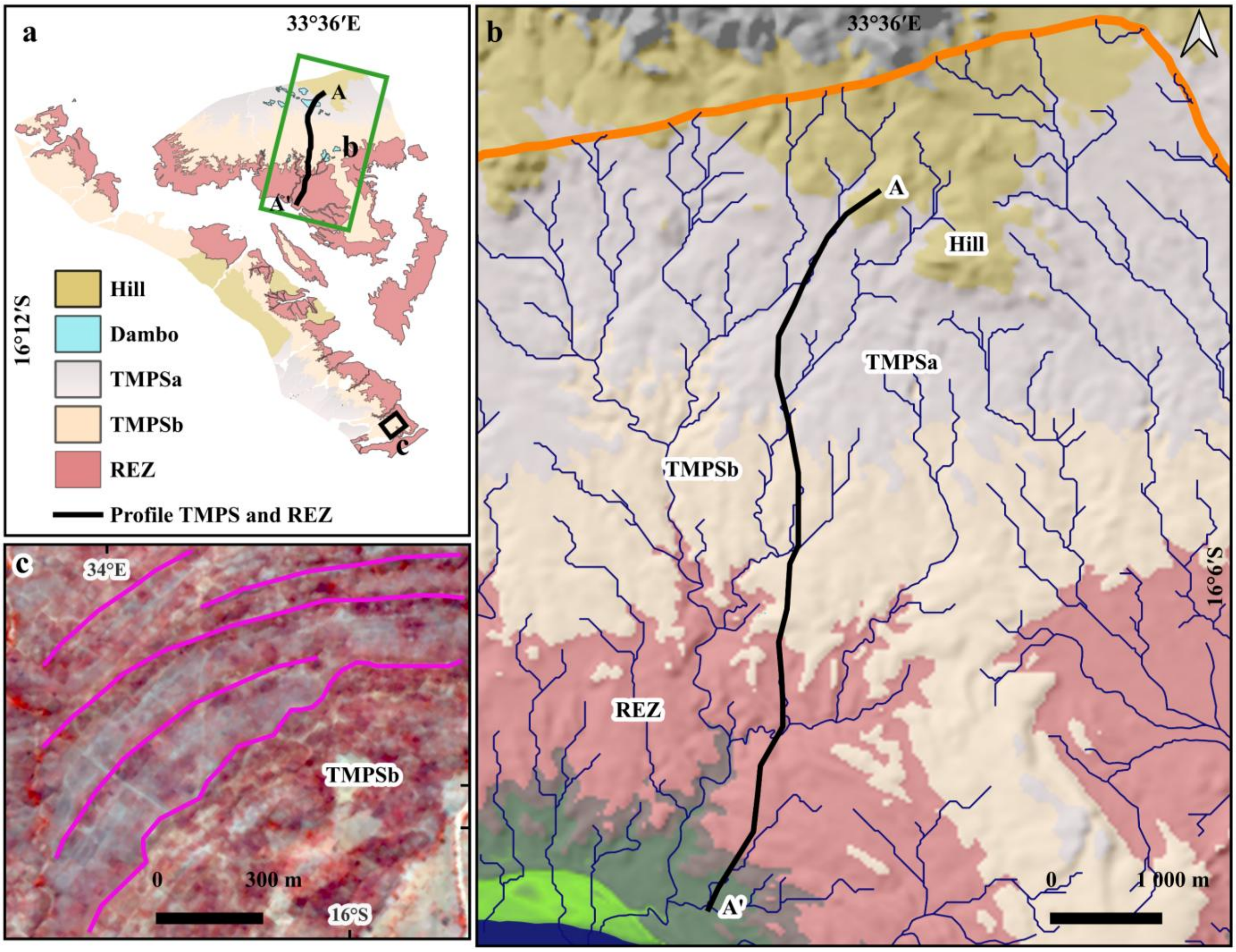

Figure 7. (a) Representation of the STs, ZER, Morros, and Dambos; the A-A' transect corresponds to the topographic profile shown in Figure 6: (b) Example of the use of a color ramp for the digital mapping of geomorphological units; (c) SAMTb, where it levels and flattens different elevations in the southeastern part of the municipality of Tete and has left the sandstones of the Matinde Formation exposed. The lines show the deformations; Background images: Figure 7b: SRTM and 7c: Planet, May 2024.

d) Receding Erosion Zone - REZ

The Receding Erosion Zone (REZ) can connect different Planation Surfaces, extending over large areas, especially when associated with drainage basins. Under these conditions, they may exhibit significant retreats and valley slopes blanketed with colluvial deposits (Latrubesse, Carvalho, 2006). During their retreat, isolated hills may form at their front. In the municipality of Tete, the Receding Erosion Zone (REZ), which develops on the low level of the PSTMb, was recognized cartographically through detailed visual analysis of the DEM and the drainage network and confirmed through fieldwork. This unit exhibits relatively steep slopes, and the drainage network reveals the erosion processes.

REZ occupy an area of ~77.90 km², equivalent to 26.54% of the mapped area, distributed between altitudes of 130 and 160 m (Figure 7). It is developed predominantly on the Sandstones of the Matinde Formation, except on the northwestern flank, near the Tchetcha River, where it lies on the anorthositic gabbros of the Tete Suite. In this area, a moderate to strong dissection pattern is observed, with slopes exceeding 20% (Figure 8b). The re-entrances of the REZ over the PSTMb are a result of headward erosion associated with the drainage network (Figure 8b). In the southern end of the Zambezi River and near the Chimadzi River, dendritic drainage patterns occur, locally controlled by the lithology (Figures 8c and 8e). In sectors such as the confluence of the Zambezi and Mufa Rivers and near Kassuende Bridge, the REZ is associated with intensive erosion processes, particularly in the Sandstones of the Matinde Formation, where weathering-related potholes are observed (Figures 8d and 8f). Residual Hills and Hills with strong structural control are distributed across this unit (Figure 8b). At the lower boundary of the REZ, colluvial deposits eroded from higher elevations (Figures 8a and 8b) and more recent alluvial deposits, accumulated by local tributaries, are observed.

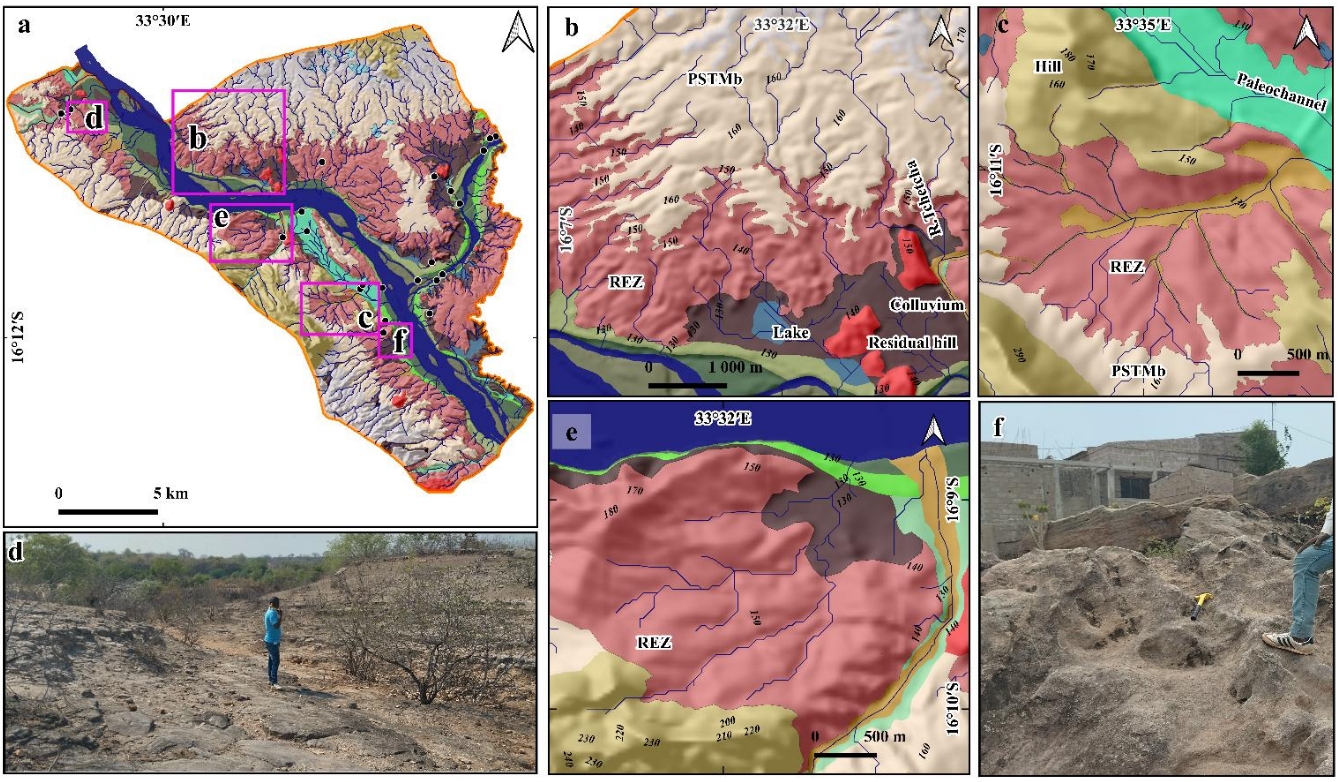

Figure 8. (a) Geomorphological map of the municipality of Tete, REZ near the Tchetcha River, where the REZ indents into the PSTMb; (c) REZ on the southern bank of the Zambezi River, where it exhibits a dendritic drainage pattern with strong local lithological control; (d) REZ near the Mufa River, where an outcrop of the Matinde Formation sandstones is observed, coordinates: S16°5'37.94", E33°27'6.01", altitude: 136 meters; (e) REZ near the Chimadzi River, locally dissected and with strong lithological control and a dendritic drainage pattern; (f) Exposed Sandstone with some potholes resulting from weathering, near the Kassuende Bridge, coordinates: S16°11'51.56", E33°36'15.71", elevation: 140 m.

e) Hills with strong structural control and Residual Hills

The term Hill with strong structural control is defined in various ways in geomorphological literature, depending on the country and the author. In this study, we adopt the concept of Florenzano (2008), according to which a hill is defined as a moderate elevation in the terrain, characterized by rounded summits and altitudes ranging from 100 to 200 m. Although useful, it is, however, an essentially descriptive concept and, therefore, imprecise (Guerra; Guerra, 2003). The hills, in turn, correspond to small, isolated elevations with gentle slopes and are commonly the result of denudational processes and thus constitute residual landforms. As the Receding Erosion Zone expands and slope retreats intensifies, hills and residual hills may emerge as residual landforms (Latrubesse; Carvalho, 2006). In the municipality of Tete, the Residual Hills (Rh) and Hills with strong structural control (Hsc) result from erosive processes associated with REZ and PS.

Most of the hills with strong structural control were identified through visual interpretation of the DEM, with the exception of Caloeira Hill, which is the highest point in the municipality. These elevated landforms form in the most resistant lithologies, as remnants of erosive processes. Isolated Hills such as the one in Figure 9d (~198 m) relate to residual landforms from erosion of the Planation Surface PSTMb, underlain by Sandstones and Claystone of the Matinde Formation. In contrast, Hills such as the one in Figure 9b consist of rocks of the Cádzi Formation (Arkose Sandstone), exhibiting strong structural control by local deformations. The highest point in the study area, known locally as Monte Caoleira (~478 m), Figure 9b, was selected as the illustrative Hill for this mapping.

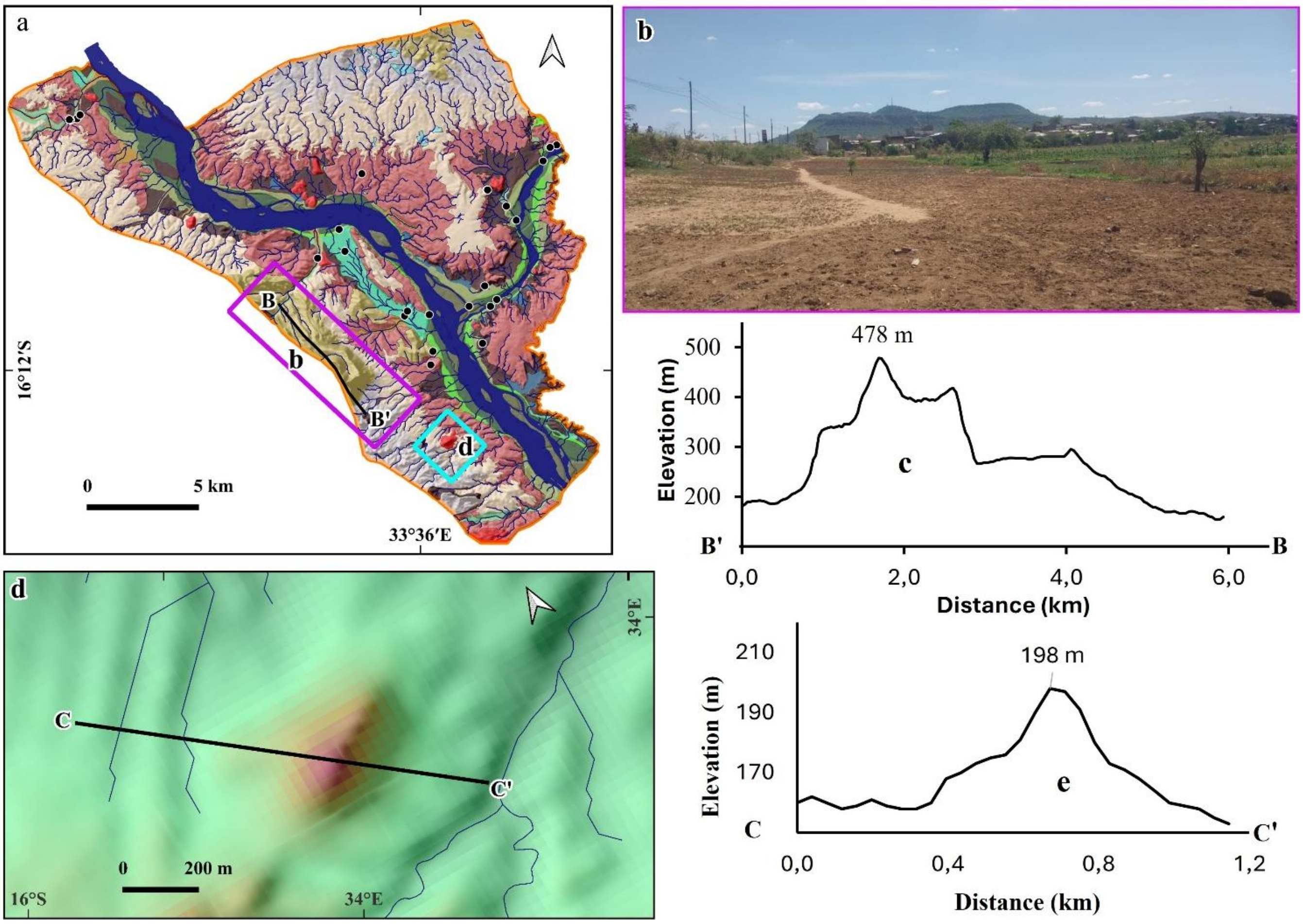

Figure 9. (a) a geomorphological map of the municipality of Tete, showing Caloeira Hill (highlighted in violet) and the residual hill (highlighted in cyan); (b) illustrates Caloeira Hill, which stands out as the highest point in the municipality; (c) an illustrative topographic profile of Caloeira Hill; (d) a representation of the residual hill that extends over the PSTMb; and (e) a topographic profile of the residual hill shown in Figure 9d.

3.2 Aggradational geomorphological units (deposition and sedimentation)

The aggradational geomorphological units cover an area of ~85.22 km², corresponding to ~28.03% of the total mapped area. The main aggradational landforms identified include fluvial terraces, subdivided into Low fluvial terraces (Lft) and High fluvial terraces (Hft); Floodplains (Fp); Paleochannels (Pc); Tributary alluvial plains (Tap); Islands (I); and Lakes (La), associated with the alluvial plains of the Zambezi and Revúboè Rivers; Alluvial-Colluvial deposits (A-C), related to the REZ, to High terraces and tributaries; and Dambos (Da), associated with the PS and REZ. The Tributary alluvial plain (Tap) includes some morphologically indistinguishable terraces that are difficult to map. The most evident one was classified as Tributary terrace (Ta).

The fluvial terrace develops along the main fluvial systems of the Revúboè and Zambezi rivers. Their identification was based on topography variations observed in the DEM and was subsequently confirmed through fieldwork. The Lft has a relatively lower elevation and is younger than the Hft. The latter is morphologically more pronounced, standing out on both banks of the Revúboè River and on the Zambezi River, especially upstream near the Mufa and Tchetcha rivers.

On the Revúboè River, Hft and Lft are located, respectively, ~2 to 4 m and 1 to 3 m above the current riverbed level. Behind the Hft, there is a relatively flat, ramp-shaped area filled with colluvial, and alluvial materials eroded from higher elevations (see more details in section 3.2, subsection a). This area is densely populated and houses the municipality's main socioeconomic infrastructure.

On the Zambezi River, the fluvial terraces are better developed, with heights ranging from 1 to 3 m for the Low terrace and 3 to 5 m for the high terrace above the current riverbed levels. At the lowest level are the floodplain and the river channel. According to Stevaux and Latrubesse (2017), since channel patterns are differentiable by morphogenetic processes and the availability of sediment, it is to be expected that each channel pattern has its own characteristic floodplain. Although this is not a rule, the two fluvial systems mapped here exhibit distinct variations in landforms and channel patterns (Figure 10).

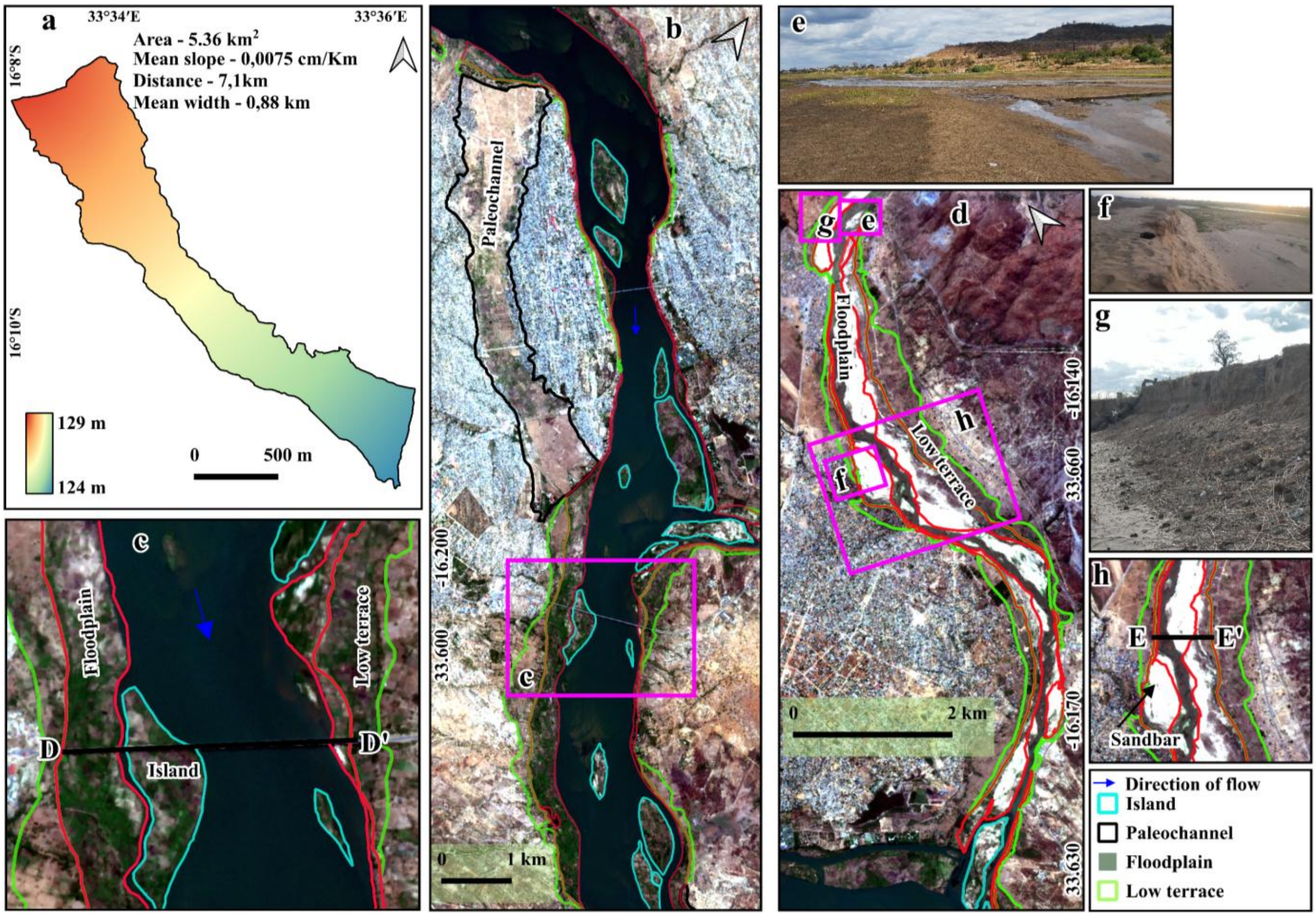

Figure 10. Landforms mapped in the Zambezi and Revúboè river systems. (a) Paleochannel known locally as the Nhartanda Valley; (b) The Zambezi River system with an anabranching pattern, in which the water flows between the islands; (c) Cross-section of the Zambezi River floodplain, where the D–D' transect illustrates the floodplain width of ~1,600 m. (d) Revúboè River system, which exhibits a single-channel pattern with a braided tendency, showing sandbars along its course; (e) Channel of the Revúboè River, which during the dry season forms a network of very shallow channels; Coordinates: S16°6'22.78", E33°39'39.11"; elevation: 131 m; (f) Sandy bar on the Revúboè River, Coordinates: S16°8'11.29", E33°38'25.79"; elevation: 128 m; (g) High terrace on the Revúboè River, Coordinates: S16°6'16.71", E33°39'27.23"; alt.: 135 m; (h) Cross-section of the Revúboè River floodplain, where the E–E' transect illustrates the floodplain width of ~900 m. Background images: Planet (May, 2024).

The Zambezi fluvial system exhibits anabranching channel patterns (Figure 10b), characterized by the dominant presence of the islands and paleochannels along its course. It has a wide alluvial plain, with an average width of ~1,200 m. In contrast, the Revúboè River system exhibits single-channel patterns with a tendency to be weakly braided (Figure 10d), in which several sandbars subdivide the flow into shallow channels (Figures 10d and 10e). Its alluvial plain has an average width of ~550 m. The braided channel pattern is typical of heavily bed-loaded rivers in semiarid environments with unstable and mobile sandbars, and the river is restricted to in-channel processes, having poor development of a wider floodplain (Stevaux; Latrubesse, 2017) (Figure 10f). On the Revúboè

River, for example, the sandbars and main channel constitute the active alluvial plain. During flood periods, the river reworks the entire floodplain, mobilizing the sandbars and promoting them to rearrange. As is characteristic of rivers in semiarid environments, the Revúboè River has a high sediment load, both suspended and bedload, as well as flash floods, in which flooding events rarely last longer than 48 hours.

a) Colluvial – Alluvial

Materials eroded from higher elevations, such as in the REZ, are transported by lower-order watercourses and deposited behind the high fluvial terrace. On the Zambezi River, for example, these tributaries form colluvial deposits with deltaic morphology, located behind the High Terrace, which in some cases cover areas exceeding 1 km². These aggradational forms were classified as colluvial-alluvial deposits (Figure 11d), but the exact boundary was not determined in this mapping. Specific studies may provide further details regarding their chronology and boundaries.

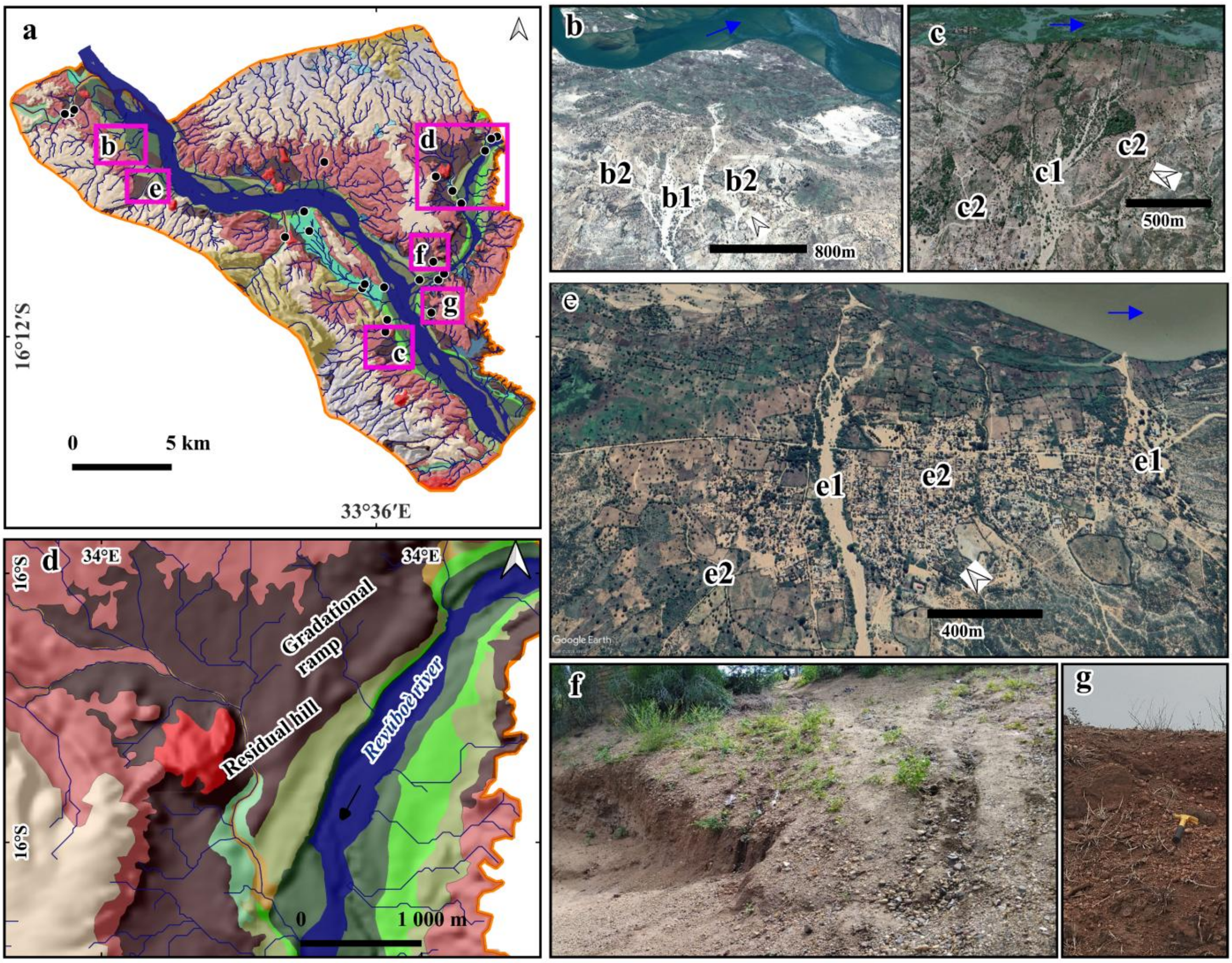

Figure 11. A geomorphological map highlighting colluvial and alluvial deposits; (b), (c) and (e) small tributaries forming alluvial deltas, where b1, c1, and e1 are alluvial plains of the tributaries (Paf), and b2, c2, and e2 are colluvial-alluvial deposits; (d) Gradational ramp near the Revúboè River; no need to put 2 times the same coordinate; (f) colluvial-alluvial deposit near the confluence of the Zambezi and Revúboè Rivers. Coordinates: S16°9'44.68" and E33°37'52.20". Elevation: 144 m; (g) colluvial-alluvial deposit on the right bank of the Zambezi River. Coordinates: S16°11'18.69" and E33°37'34.42". Elevation: 130 m. The arrows indicate the direction of flow. Background images were taken from Google Earth: (b) June 2013; (c) June 2010; and (e) June 2025.

Near the confluence of the Revúboè and Zambezi rivers, significant colluvial deposits are observed, composed predominantly of sand, rounded pebbles, and angular boulders (Figure 11f). On the left bank of the Zambezi River, near the village of Benga, there are deposits characterized by the presence of boulders and pebbles (Figure 11g). On the right bank of the Revúboè River, an aggradational ramp was identified, characterized by a flat and extensive surface where the Tete International Airport and the army barracks are currently located, impeding access authorizations for field control. Subsequent observations on the M'Phono River, which erodes this landform, confirmed the presence of a ~8 m thick mantle of colluvial-alluvial deposits.

3.3 The Zambezi River

The Zambezi River has a drainage basin of ~1,36 million km² and flows for ~2,574 km before emptying into the Indian Ocean in Mozambique, where it forms a delta of ~11,410 km², covering the districts of Chinde, Luabo, Marromeu, Chiringoma, Muanza, Mopeia, Inhassunge, and Nicoadala. The Zambezi basin is traditionally subdivided into three major segments: the Upper, Middle, and Lower Zambezi, each with its own physiographic and climatic characteristics (Figure 12). The Lower Zambezi, where the study area is located, is shared by Mozambique, Malawi, Tanzania, Zimbabwe, and Zambia and has a semiarid climate with an average annual rainfall of around 600 mm. However, the northern portions, located in Tanzania, Malawi, and the Mozambican coastal zone, can reach values close to 1,400 mm annually (Sanchez, 2018). The flow of the Zambezi River is regulated by the Kariba and Cahora Bassa dams, located in the upper and middle reaches, upstream of the study area. Although these infrastructure projects play an important role in mitigating floods, significant flooding still occurs, particularly in the lower Zambezi, often associated with the passage of cyclones and tropical storms (Sanchez, 2018). Due to the regulation imposed by the hydroelectric dams, flood pulses and associated risks have been reduced by human activities.

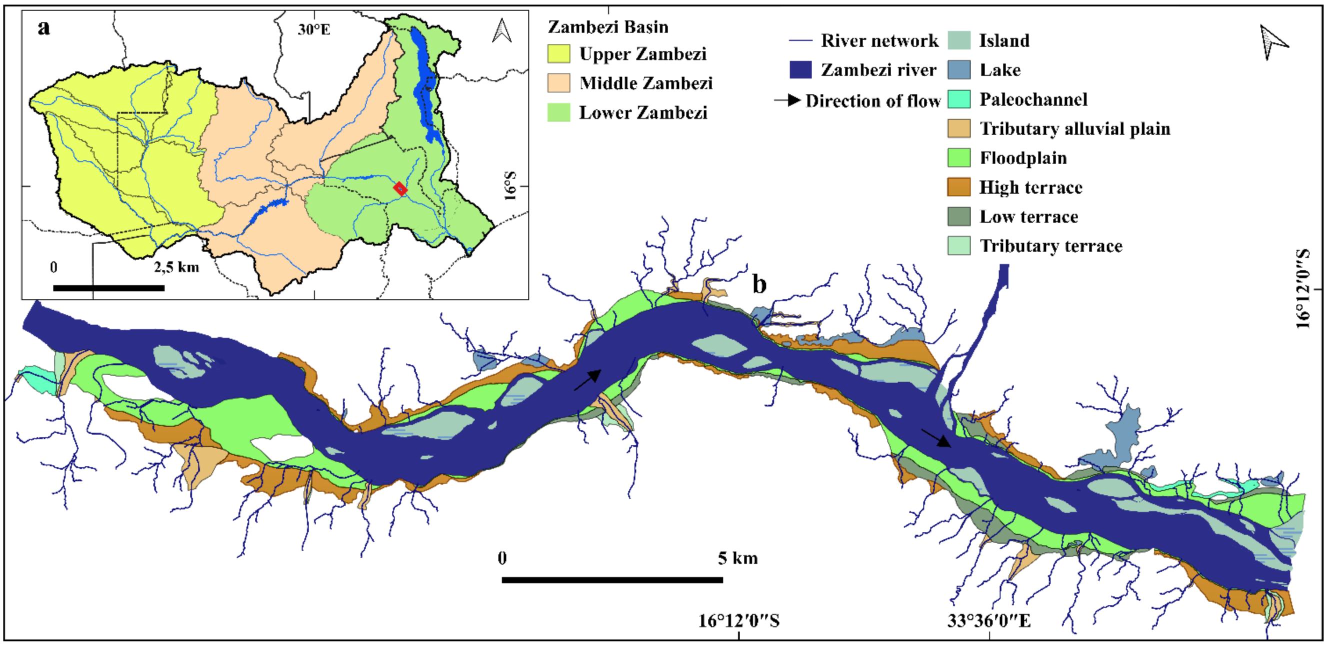

Figure 12. (a) the Zambezi River basin, showing the three sub-basins (upper, middle, and lower Zambezi); the red rectangle highlights the Zambezi River floodplain, located in the municipality of Tete; (b) a section of the Zambezi River floodplain in the municipality of Tete. The arrows indicate the direction of flow.

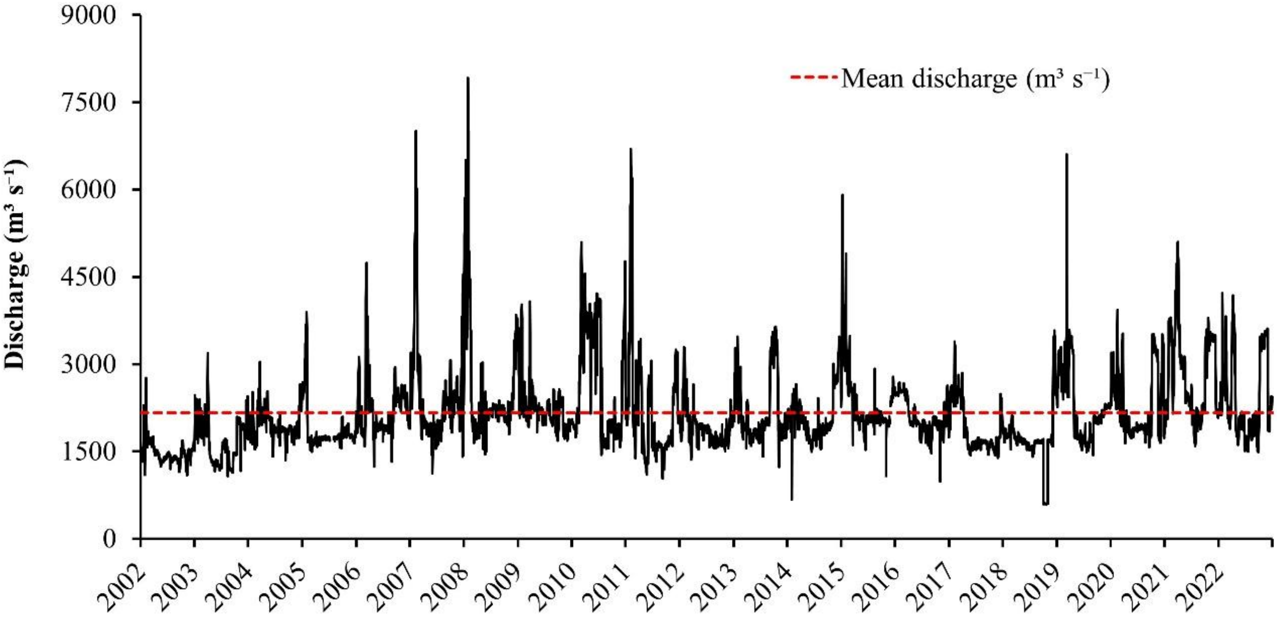

Figure 13. Flow rate of the Zambezi River at station E-302, located in the municipality of Tete, from 2002 to 2022. The average flow rate was 2,164.9 $m^3 s^{-1}$. In 2007 and 2008, the peak flood discharge was approximately 7,003 and 7,918 $m^3 s^{-1}$. Source: ARA-Zambezi (2023).

3.4 The Revúboè River

The Revúboè River is the main tributary of the Zambezi River in the municipality of Tete. The drainage area is ~16,350 km^2, and the headwaters are on the border between Mozambique and Malawi, at an elevation of ~1,460 m. The river flows 304 km before emptying into the left bank of the Zambezi River, marking the natural boundary between the Chingodzi neighborhood in the municipality of Tete and the villages of Benga in the district of Moatize (Figure 14b).

Climatic variation throughout the basin has a direct influence on downstream flood peaks. In the northwest sector and on the eastern flank, where a humid highland tropical climate predominates, the average annual precipitation exceeds 1,000 mm, corresponding to the sub-basins with the highest flow contributions. In the lower section of the basin, where the municipality of Tete is located, a semiarid climate predominates, with average annual precipitation below 600 mm. As a result, the Revúboè River is a perennial watercourse with a tendency toward intermittency, exhibiting lower flows during the dry season (May to November), when the average daily flow is less than 20 $m^3 s^{-1}$.

During the wet season, this average rises to about 130 $m^3 s^{-1}$ (figure 15). However, due to the influence of tropical cyclones and the geomorphological and geological characteristics of the basin, major short-duration floods (flash floods) are recorded, lasting less than 48 hours and with flows that can reach ~7,000 $m^3 s^{-1}$. In 2022, for example, the observed flood level was 9.5 m, with a discharge of ~7,492.2 $m^3 s^{-1}$, which caused partial flooding of the city and the destruction of the bridge connecting the municipality of Tete to the city of Moatize.

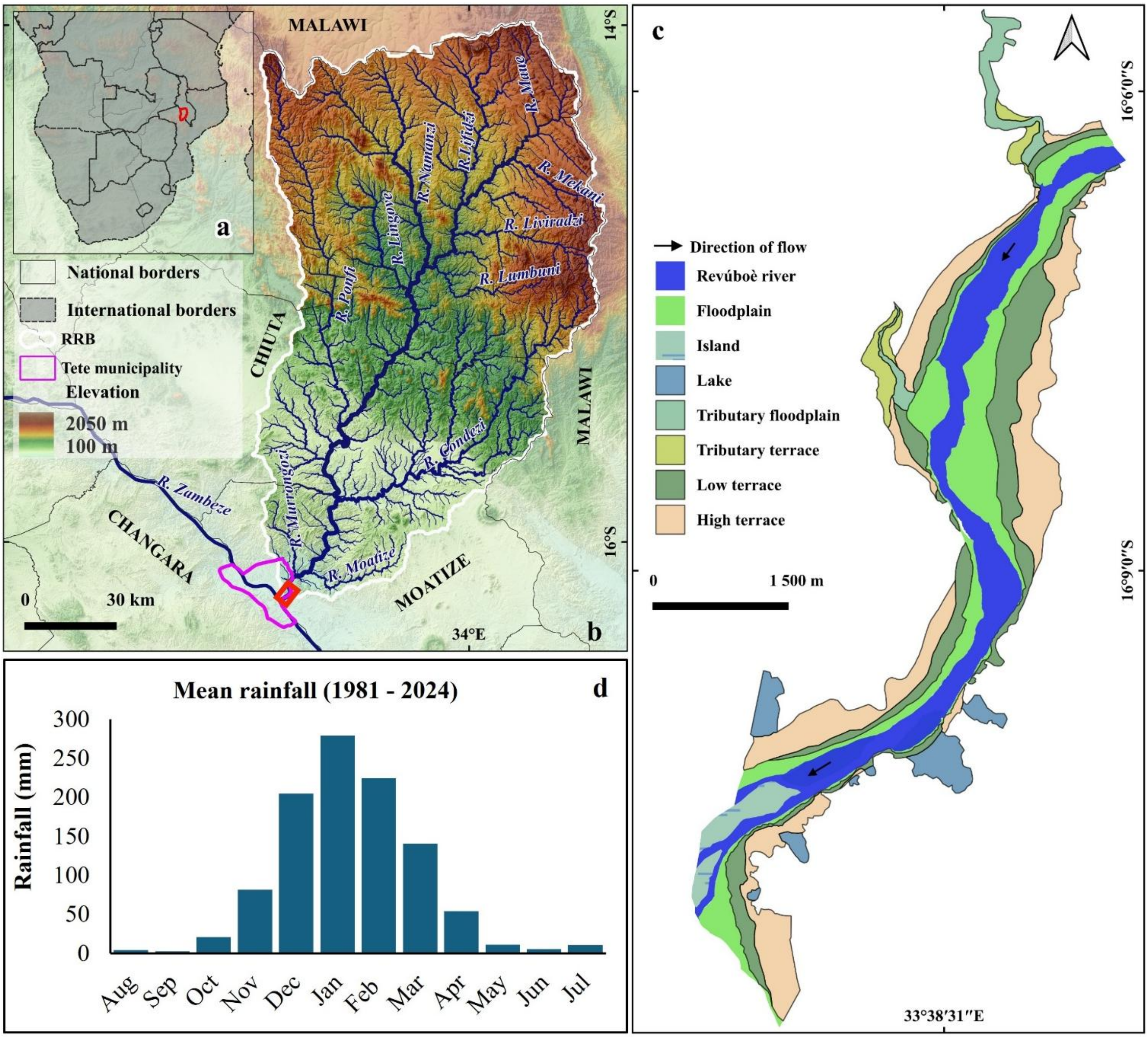

Figure 14. (a) Southern Africa, with the Revúboè basin highlighted in red; (b) Revúboè River Basin (RRB), where the red rectangle highlights the mapped area in the municipality of Tete; (c) Alluvial belt of the Revúboè River, with arrows indicating the direction of flow; and (d) average monthly precipitation in the basin for the period from 1981 to 2024. Source: CHIRPS, 2026. Background Figure 14b: from SRTM.

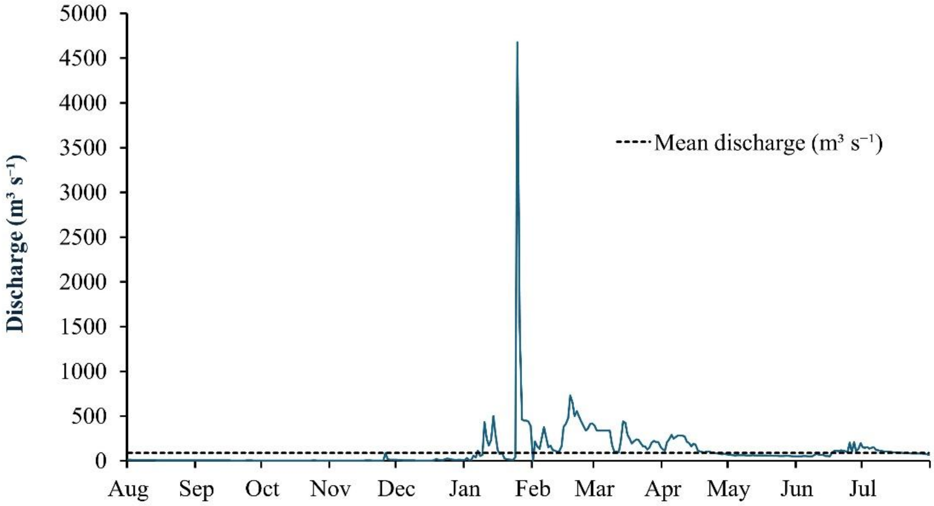

Figure 15. Typical flow rate of the Revúboè River in a wet year (2021–2022). Average flow rate: 113.11 $m^3 s^{-1}$. Data obtained from the Revúboè E-302 gauging station, provided by ARA-Zambeze (2023).

3.5 Lake systems

a) Temporary lakes/ponds

Temporary lakes are found mainly on the upper and lower terraces of the Zambezi and Revúboè rivers. They are relatively oval and elongated in shape (Figure 16) and filled with water during the wet season, generally between December and March. They vary in size but generally do not exceed 1 km^2. Most of them develop in confined areas on the higher and lower terraces and are fed by small tributaries, local rainfall, and major rivers during the flood season. Altogether, the lakes cover an area of ~2.62 km^2, corresponding to 0.89% of the total mapped area.

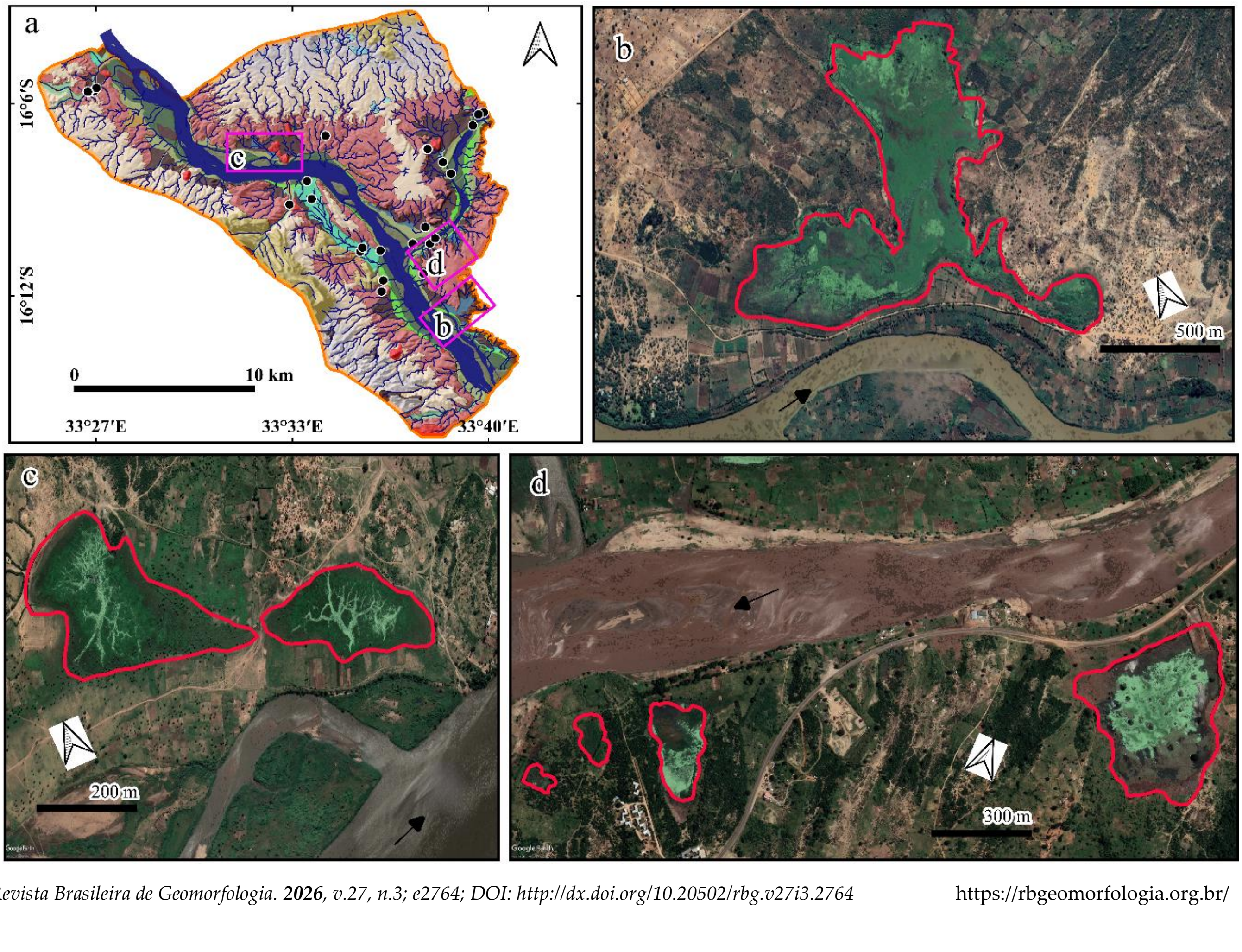

Figure 16. (a) a geomorphological map highlighting the lake systems along the Zambezi and Revúboè rivers; (b) a lake along the Zambezi River, near the village of Benga; (c) lakes on the Zambezi River, located near the Tchetcha River; (d) lakes along the Revúboè River, near the village of Benga. The arrows indicate the direction of flow. Background image: Google Earth, March 2022.

b) Dambos

Although dambos are found in various parts of Africa, the term has Bantu origins and is used in Malawi and Zambia Boast (1990); Mandishona and Knight (2022) to refer to seasonally flooded wetlands, typically located in river headwaters and channels. According to Bullock (1992) and von der Heyden (2004), dambos are low-lying landforms, circular or elongated in shape, corresponding to shallow wetlands that flood seasonally, characteristic of stream headwaters. They commonly develop flat terrain with high annual rainfall. The Dambos mapped in the municipality of Tete occur in the headwaters and channels of the Tchetcha and Nhamatica rivers. They occupy an area of ~1.30 km², which corresponds to about 0.44% of the total mapped area (Figure 17a).

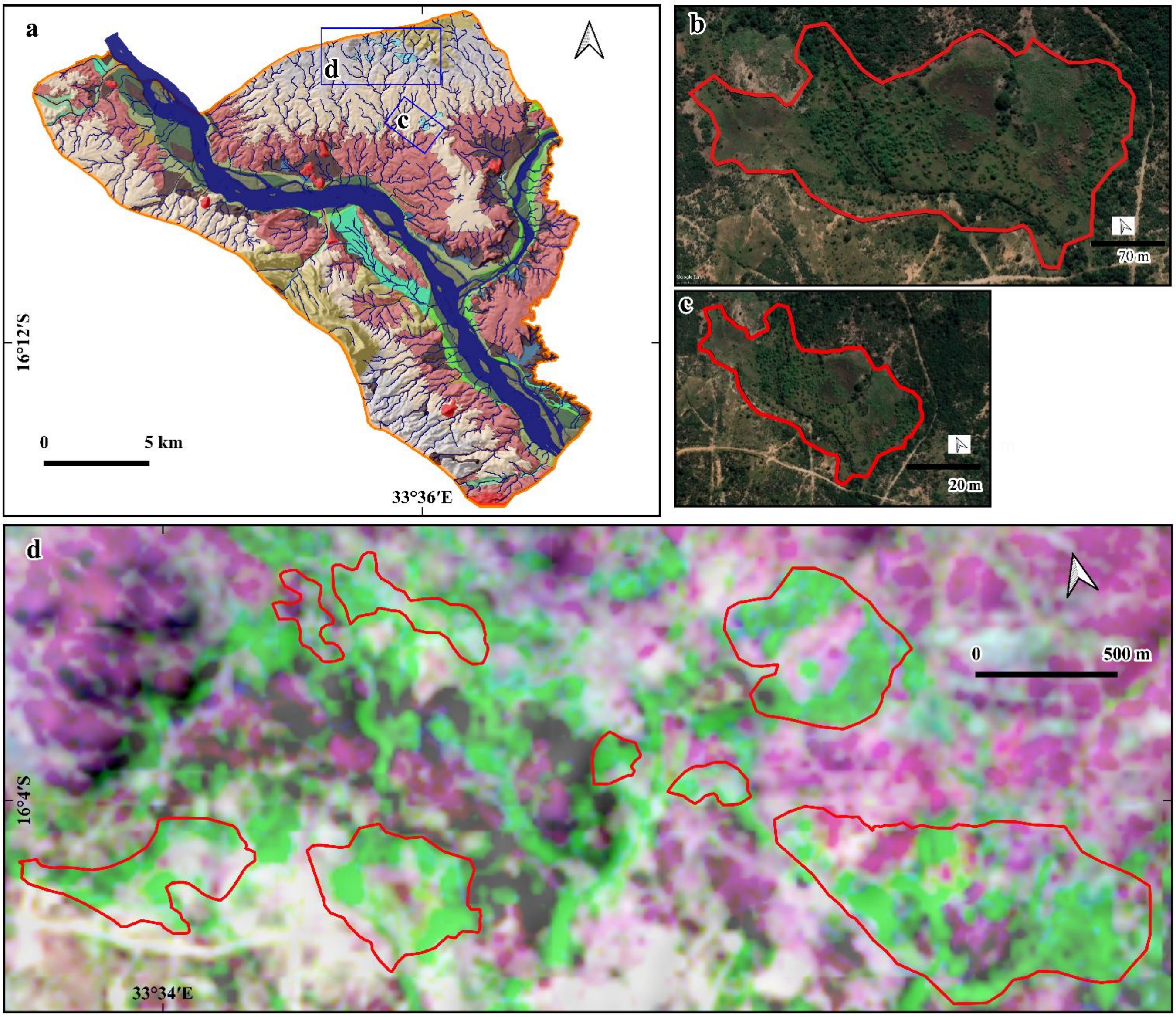

Figure 17. (a) Seasonal wetlands (Dambos) are mapped in the municipality of Tete. Background images (b) and (c): Google Earth, March 2022. (d) Color composite derived from the shortwave infrared (SWIR – B12), near-infrared (NIR – B8A), and red (B4) bands of Sentinel-2, dated June 8, 2022, in which the red polygons highlight the areas where

Dambos occur. The vegetation, predominantly green in color, indicates the Dambos and stream channels, while the brown color represents exposed soil.

Local geology plays a decisive role in the formation of these wetland environments. According to von der Heyden (2004); Bullock (1992), dambos occur predominantly in African crystalline basement complexes. In Zimbabwe, for example, ~90% of these environments are associated with intrusive Granites, Gneisses, Kalahari sediments, and other types of Mafic basement rocks, such as Basalt (von der Heyden, 2004). Similarly, in Malawi, Dambos develop in complexes composed of Schists, Gneisses, and other Metamorphic lithologies (Bullock, 1992). Bullock (1992) also notes that in Nigeria, Cameroon, Uganda, Tanzania, and Zambia, Dambos occur on Granitic basement and Metamorphic rocks, including Schists and quartzites. Similarly, the Dambos in the municipality of Tete develop on the crystalline basement, primarily in plutonic rocks such as the anorthositic gabbros of the Tete Suite, but they also occur on sedimentary rocks, especially the Sandstones of the Matinde Formation, which are associated with the Planation Surfaces (PSTMa and PSTMb) and the Receding Erosion Zone (REZ).

The Dambos were identified solely based on high-resolution images from Google Earth and Sentinel-2 and were not confirmed in the field, since the areas of occurrence belong to a mining company that owns large tracts of land in the region and did not grant access. Furthermore, due to their ephemeral nature, it was not possible to identify them definitively in satellite images using spectral indices such as the NDWI. The color composite derived from the shortwave infrared (SWIR – B12), near-infrared (NIR – B8A), and red (B4) bands of Sentinel-2, dated June 8, 2022, generally highlights vegetation in shades of green in these areas, indicating the prevalence of moisture during the dry season (Figure 17d). In contrast, exposed soil predominates in the adjacent areas, appearing in brown tones. Therefore, caution is advised when interpreting these depressions, and further studies are recommended to confirm their classification with greater precision.

4. Concluding remarks

The geomorphological mapping conducted in the municipality of Tete, covering an area of ~293.52 km², represents the first study of its kind carried out at the municipal level in Mozambique. Two major groups of geomorphological units were mapped: aggradational and denudational units, each group exhibiting distinct characteristics that reveal the processes acting upon them and the evolution of the Tete landscape. Despite the regional significance of the results, the study has some limitations, stemming from the fact that certain geomorphological units could not be confirmed in the field, while others require more specific studies to be fully understood. More detailed studies of each unit will also allow for a better understanding of the composition and evolution of Mozambique's landscapes along the Zambezi Valley. Regarding the Dambos, it is recommended that future research includes more detailed studies to improve the local morphological characterization.

On the other side, in countries such as Brazil, geomorphological mapping is a fundamental component of integrated environmental analyses and a tool used in land-use management projects, environmental planning, and environmental impact studies. In Mozambique, however, regulations and established practices for applying geomorphology in such studies are still lacking. Therefore, these results may help catalyze the importance of geomorphology as a discipline and encourage the development and incorporation of geomorphological mapping in the country. As the first product of its kind in the region, this map has the potential to serve as a primary reference for environmental, hydrogeomorphological risk, and land-use management studies conducted by government agencies, academic institutions, and the private sector.

Contributions: W.M.W.: Conceptualization, Methodology, SIG processing, Writing, and Editing. E.M.L.: Supervision, Methodology, Writing, and Editing. R.B.V.: Fieldwork, Drafting, and Review of the manuscript.

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Declaration on the Use of Artificial Intelligence: The authors declare that no generative artificial intelligence tools were used at any stage of the development of this manuscript (conception, writing, data analysis, or submission).

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