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Flood dynamics: A geoecological approach using historical cartography and giscience in the city of petrópolis (Brazil)

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Abstract

Dynamics, structure and function are geoecological characteristics that define landscapes. These characteristics help explain landscape processes, such as floods. This article analyses geoecological variables to understand flood dynamics in the original historical district of Petrópolis City (Brazil). Concepts and techniques of historical cartography and GIScience were used to analyse geoecological variables in three river basins (Quitandinha, Palatino and Piabanha) within the study area. Each basin had a river island which was excavated and removed. The Quitandinha River Basin had the largest river island (965 m2), the highest Edification Index (44.12%) and the most favourable geomorphological indices for the occurrence of floods. Hence, the basin recorded 93% of flood events within the three basins. Multiple geoecological variables influence flood dynamics. In this urban landscape, changes in the drainage network, intensified by disorderly urbanization and geomorphological processes, are extremely important in understanding flooding processes.

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1. INTRODUCTION

Floods are an integral part of human history and occur at multiple spatio-temporal scales. They are the product of different forces that act on landscapes. Climatological, geomorphological, land-use and surface cover (associated with deforestation and urbanization) are some of the factors that contribute to flooding. Floods are responsible for the second-highest number of deaths caused by natural disasters in the world, totalling 686,741 deaths from 1900-2015 (EMDAT, 2020). In recent years, the number of occurrences and people affected by natural disasters, including floods, has markedly increased. The increased incidence and severity of flooding can be associated with climate change, the increase of anomalous rainfall (Blunden and Arndt, 2016) and human actions. These actions include land-use changes (especially deforestation) and changes in the urban fabric (e.g. the construction of high-density urban areas, especially in areas of high flood-risk, such as flood-plains).

In Brazil, the population has increasing concentred in urban areas, especially since the second half of the 20th Century. Urbanization can cause serious socio-environmental problems that influence the occurrence of natural disasters, such as landslides and floods. Often, episodes of heavy rainfall, which are part of natural climate variability in tropical areas, threaten life and property in many Brazilian cities. In 2010, 8.94% of the population of the 207 Brazilian municipalities analysed lived in high-risk areas (IBGE, 2018). Petrópolis City is the 18th largest municipality in Brazil, out of a total of 5,570. Many inhabitants reside in areas at risk from natural disasters (72,070 inhabitants; some 24.4% of the total population of the Municipality).

Floods are very common in Brazilian cities. Flood frequency and magnitude are being increased by dense urbanization and haphazard land occupation patterns. Deforestation, the channelling of rivers and irregular land occupation patterns increase flood risk. One of the most common types of recurrent flooding in Brazil is flash floods. Flash floods are sudden floods produced by short-duration intense rainfall over a small area (Kron, 2005; NWS/NOAA, 2009). Gregory and Walling (1973) associated flash floods with rapid responses of drainage channels to intense rainfall and urban sealing within the drainage basin. These processes modify the structure and thus the functionality of drainage basins and so increase the magnitude and frequency of floods.

Understanding flooding involves analysing the structure, dynamics and functionality of landscapes. Floods can be evaluated as geoecological phenomena that are a function of changes in the structure and functionality of landscapes within specific spatio-temporal scales (Fernandes et al., 2013). Geoecology is a science that seeks to understand the landscape as a product of biotic, abiotic and socio-political-economic processes over time (Troll, 1939; Klink, 1974; Huggett, 1995). Thus, landscapes are considered to be the product of historical processes. Therefore, the landscape is the focus of geoecological analysis and is considered a result of the dynamic combination of biotic, abiotic and human factors that interact dialectically with each other, becoming a unique and inseparable whole of continuous evolution (Turner, 1989; Bertrand, 1982). Geoecological analysis investigates changes in the behaviour of landscapes over time, which can be used to predict landscape structure and functionality (Forman and Godron, 1986; Guofan and Wu, 2008; Mougiakou and Photis, 2014). The geoecological approach is summarized in Figure 1.

For the analysis of geoecological characteristics, the use of historical cartography and geographical information science (GIScience) are spatial analysis elements that are increasingly important in understanding landscape dynamics, especially in urban environments. Geoecological analysis uses multiple tools, including cartographic maps, remote sensing images, historical maps and census surveys. Collier (2013) and Menezes et al. (2015) demonstrated the importance of historical cartography in studies of landscape dynamics. Goodchild (1992) viewed GIScience as a scientific discipline that studies data structures and computational techniques to capture, represent, process and analyse geographic information.

The approach adopted in this study is to analyse the landscape in relation to floods. This approach leads to a central question of understanding how different landscape structures collaborate for produce floods and how landscape dynamics can assist our understanding of the spatio-temporal attributes of floods. This article analyses inter-relationships between geoecological variables and flood dynamics in the 'genesis area' (orginal historical district) of Petrópolis City (Brazil). Geoecology, historical cartography and GIScience were used to identify and compare landscape changes within three river basins (Quitandinha, Palatino and Piabanha) within the genesis area of Petrópolis City (Figure 2).

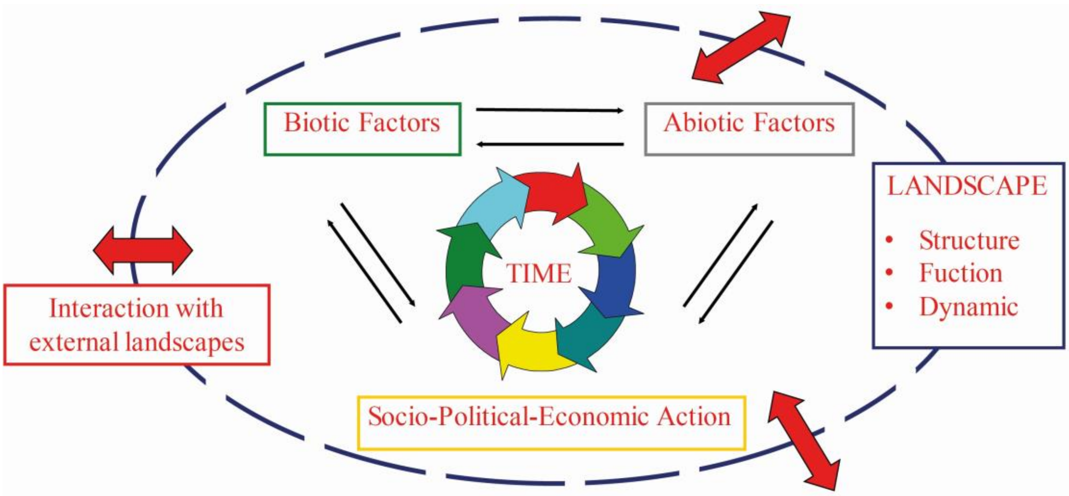

Figure 1. Components and characteristics of the geoecological approach.

2. METHODOLOGICAL FRAMEWORK

The article was developed in three steps. In each step, various materials and methods were used, including surveying and structuring cartographical data, remote sensing images, census surveys, pluvio-fluviometric data, data structuring and manipulating methods, and spatial analysis (Figure 3). All stages were based on concepts and techniques used in geoecological analysis, historical cartography and GIScience.

2.1 Input material

Stage 1 consisted of a survey of all data necessary for the identification of the relevant geoecological variables. The cartographic base used as a mapping and analysis guide for the study was the most recent cartographic base of Petrópolis City (1999) at the scale of 1:10,000. It uses the projected coordinate system UTM zone 23S, SIRGAS 2000 datum. All geoecological variables listed in the second methodological stage, and all resultant maps, were based on this cartographic data-base. The hypsometry and drainage characteristics were abstracted from the cartographic base. These characteristics are essential for the delimitation of the analysed drainage basins, calculation of relevant morphometric indices and analysis of demographic data.

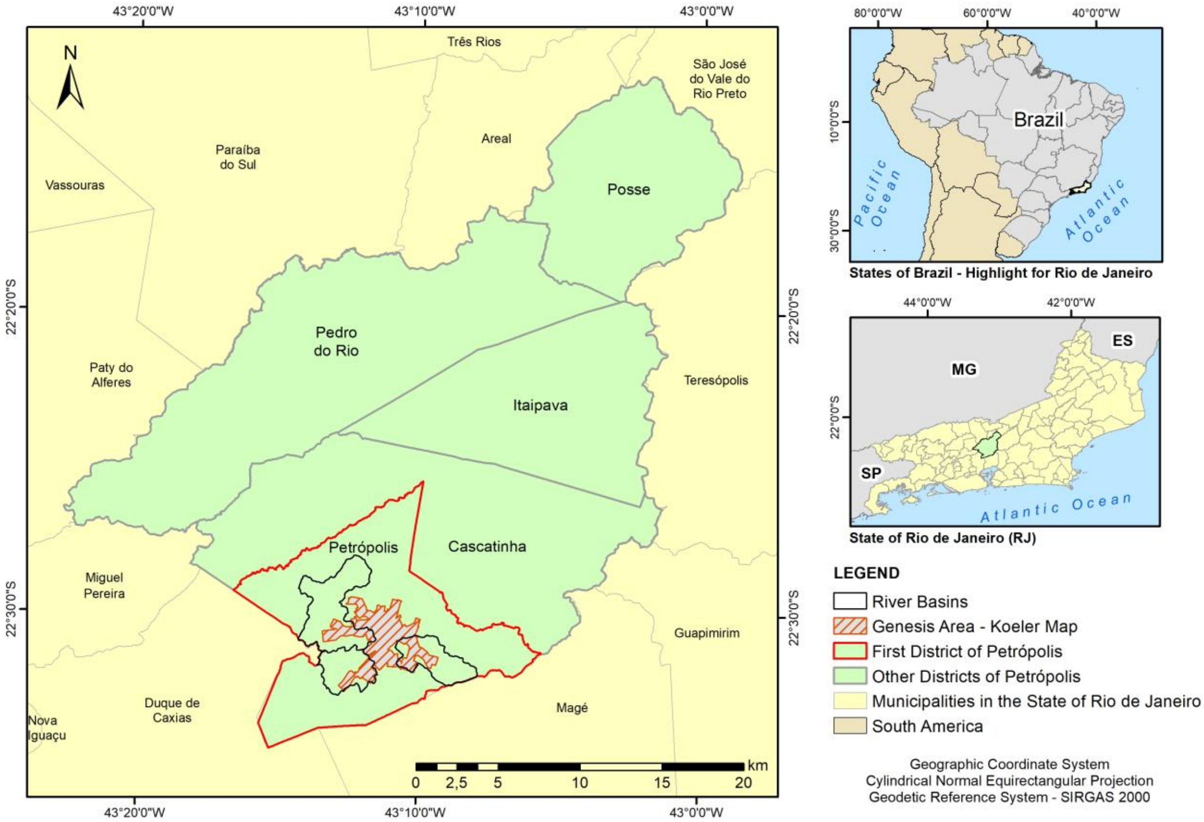

Figure 2. Study area: The First District of Petrópolis, genesis area and river basins.

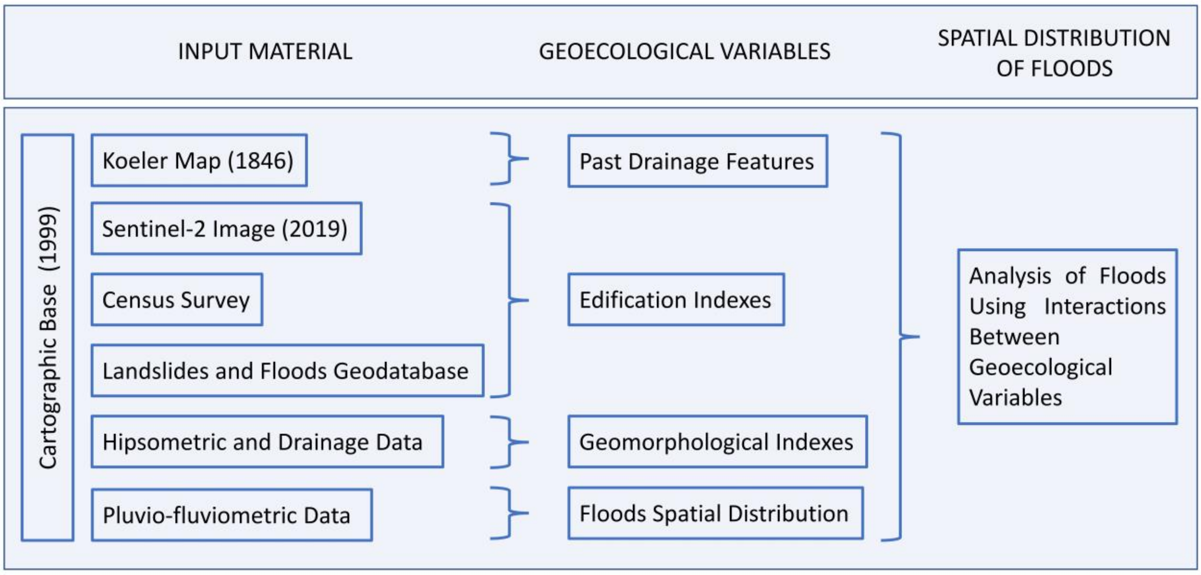

Figure 3. Methodological flowchart adopted for geoecological analysis of floods in Petrópolis City (Brazil).

Hypsometry and drainage features also formed the building elements of a DEM, based on TIN (Triangulated Irregular Network), to obtain readings on a modelled surface (Fernandes et al., 2013). The modelled surface readings were used to develop several measures, including morphometric and building indices. These indices incorporate both linear and area measurements and are also sensitive to readings on the modelled surface, which is particularly relevant to the steep topography within the studied drainage basins. Fernandes et al. (2017) showed a significant increase in basin area and drainage length for the modelled surface in relation to the planimetric surface of 18.8% and 5.31%, respectively, in an area with very similar slope characteristics to the three Petrópolis basins. Fernandes et al. (2012) also showed a 9.55% decrease in population density in areas of rugged relief, with slopes similar to those of the analysis area.

The cartographic base also served as a reference for georeferencing the Koeler Map (1846), the geospatialization of the Edification Index, and flood distribution. The Koeler Map (1846) is the first cartographic record of the Municipality. It contains several cartographical elements, including hydrography, streets, public parks and land lots. The actual physical map was at an advanced stage of degradation and was restored in 2016 (Neves and Zanatta, 2016) (Figure 4). This map was projected on a scale of 1:5,000 (Fernandes et al., 2017) and shows planned urban occupation following the drainage network, with the streets and avenues running parallel to the rivers.

Koeler Map - "Planta de Petrópolis - 1846" Some details of the Koeler Map

Figure 4. Koeler Map (1846) and inset details.

Aiming to map land cover and quantify the Edification Index in the basin area, an image of 29 February 2019 was acquired from the USGS Land Explorer site, taken with an MSI instrument by the Sentinel-2 mission. The visible and near-infrared bands with a spatial resolution of 10 m were used. These were merged into ArcGis®10.2 software and subsequently segmented and classified in the eCognition®9.3 software, using the

Geographic Object-Based Image Analysis-GEOBIA (Blaschke et al., 2008). This classification followed only the spectral parameters, with weights equal to all bands, after analysing the segment samples for each class. It resulted in a mapping of land cover with classes of vegetated area, built area, rock outcrops and water. The mapping underwent rigorous validation from 631 checkpoints, evaluated using field data and high-resolution images. These checkpoints were submitted to the Kappa Index and global accuracy assessment, following the criteria of Colgaton and Green (2009); and Landis and Koch (1977).

Census surveys by IBGE (Brazilian Institute of Geography and Statistics) formed another important source of information (IBGE, 2020). The number of inhabitants at the census dates 1940, 1950, 1960, 1970, 1980, 1991, 2000 and 2010 were used to analyse the population distribution within the landscape. The Petrópolis landslides and floods geodatabase (1932-2015) of the Laboratory of Cartography, Federal University of Rio do Janeiro (UFRJ) (GEOCART, 2015) was also used to correlate the population distribution with natural events. This geodatabase consists of geospecialized surveys of landslides and floods from 1932-2015. The last input material was the pluvio-fluviometric data for 2011-2018 from three stations located at the outlets of the analysed drainage basins. These data were made available by INEA/RJ (State Environmental Institute of the State of Rio de Janeiro). Data from other pluviometric stations provided by CEMADEN/BRAZIL (National Center for Monitoring and Early Warning of Disasters) were used to support rainfall analysis. All stages of representation, processing and analysis of geographic information were performed using ArcGis®10.2 software.

2.2 Geoecological variables

All maps and surveys of the geoecological variables were developed from the input data. The Koeler Map was georeferenced using 106 control points and the adjust interpolator, available in ArcGis®10.2 software. This process achieved an accuracy compatible with the 1:50,000 scale (BRASIL, 1984). Subsequently, the Koeler Map features were vectorized, making it possible to delimit and quantify the 'genesis area' (initial historical core) of Petrópolis City and past drainage features, such as river islands. Thus, it was possible to measure the size of the genesis area, the current dimensions of the Municipality and elements that explain the population distribution within the Municipality.

The Edification Index (Ei) was calculated based on the percentage of the built area within a drainage basin (Table 1). The built area was classified as all areas that have construction (e.g. houses, buildings, warehouses, industries, and soil sealing areas, such as paved areas).

Table 1. Edification Index parameters

INDEX	EQUATION	MEANING OF VARIABLES
Edification Index (Ei)	$Ei = \frac{\Sigma Ba * 100}{A}$	ΣBa = Sum of the basin's built area (km) A = Basin area (km^2)

The population distribution in the Municipality was analysed to try to understand the correlation between the number of inhabitants in the entire Municipality and the population in the First District. The First District includes the Municipality's genesis area and analysed basins. The data made available by IBGE do not specifically address the genesis area or the basins, which is why this analysis was restricted to the districts. Districts are the political and administrative units that can be analysed from the Brazilian census data. However, of the available census data, only those from 1980, 1991, 2000 and 2010 contain individual data for the First District. Concomitant with this survey, other analyses of landslides and floods in the Municipality were completed, based on the Petrópolis landslides and floods geodatabase (1932-2015) (GEOCART, 2015).

For the geomorphological analysis, three morphometric indices were used to quantitatively evaluate flood risk. These were the drainage density (Dd), Compactness Coefficient (Cc), and the Circularity Ratio (Cr). The drainage density was obtained by measuring drainage length and basin area (Strahler, 1952). The Compactness Coefficient (or Gravellus Index), is an index that quantifies the geometric irregularity of the drainage basin (Bendjoudi and Hubert, 2002). The Circularity Ratio (Cr) is a measure of how close the basin is to a circular shape (Miller, 1953). A summary with the indices and their respective equations is presented in Table 2.

Table 2. Summary of the morphometric indices

INDEX	EQUATION	MEANING OF VARIABLES
Drainage Density (Dd), dimensionless	$Dd = \Sigma Cc/A$	ΣCc = Sum of drainage lengths of the basin (km) A = Basin area (km^2)
Compactness Coefficient (Cc), dimensionless	$Cc = 0.28 * \frac{P}{\sqrt{A}}$	P = Basin perimeter (km) A = Basin area (km^2)
Circularity Ratio (Cr), dimensionless	$Cr = \frac{12.57 * A}{P^2}$	P = Perímeter of the basin (km) A = Basin area (km^2)

Analysis of the spatial distribution of floods was based on flood level data recorded at three pluvio-fluviometric stations, one in each analysed basin. These data also contain the rainfall totals that were used to analyse rainfall patterns. The pluvio-fluviometric stations were also important to delimit the drainage basins. These stations were defined as the outlet of the basins, to ensure greater precision in the analysis of the recorded floods.

2.3 Flood analysis

The flood analysis was based on the collected data and the geoecological variables. As the variables do not obey one space-time unit, an analysis of the integration of their layers cannot be performed. Furthermore, the variables considered have different attributes. Some are related to a specific location (such as flood data) and others are associated with information of a specific unit (such as census data). Thus, the analysis of the floods followed a multiscale space-time interpretation, with the integration of a series of interpretations combining the different space-time units that made it possible to understand flood attributes. All elements and spatial units are presented in Figure 5.

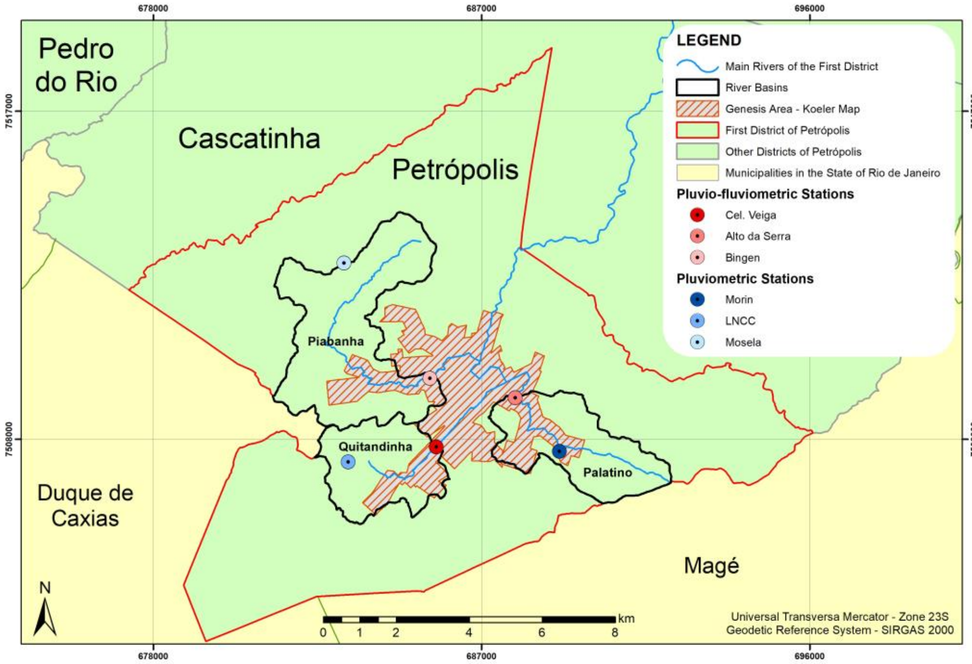

Figure 5. Spatial units and elements used in the geoecological analysis of Petrópolis.

3. THE KOELER MAP: A HISTORICAL MILESTONE IN THE DEVELOPMENT OF PETRÓPOLIS

To understand the flooding situation in the genesis area of the Municipality of Petrópolis, it is necessary to analyse the City's creation, urban code and environmental characteristics. This includes analysis of past river features within each basin. The City of Petrópolis is located in the mountain region of Rio de Janeiro (RJ) State and throughout its historical development has experienced environmental problems, such as landslides and recurring floods, mainly flash floods. Petrópolis is the ninth Brazilian municipality and the first in RJ State in terms of the highest percentage of inhabitants in areas at risk from natural disasters (IBGE, 2018). This framework is directly linked to the city occupation as whole, but mainly in the First District, which was the initial area to be developed in the 19th Century. However, this framework does not agree with one of the main guides of the City's development plan (Koeler Plan). Koeler was extremely concerned with environmental issues.

Petrópolis City was founded on 16 March 1843 by an Imperial Decree of Emperor Pedro II and registered in the Book of Administration under Nº. 155. The Imperial Decree approved the plan suggested by the Imperial House Butler, Paulo Barbosa. The plan decreed the leasing of the Imperial Farm (formerly known as Córrego Seco Farm) and Concórdia Farm, to Major Julio Frederico Koeler, a German immigrant who had joined the military engineering sector of the Brazilian Army. The Decree was the guide for another document (signed on 26 July 1843) which defined the plan for the development of the City. This document became known as the 'Village-Summer Palace' Plan, or the 'Koeler Plan.'

Koeler was requested to prepare the future map of Petrópolis, the Emperor's Palace, and its outbuildings, dividing the Imperial lands into lots, or spots, numbered for the granting of privileges. The map contains many cartographic elements, including hydrography, streets, public parks, lots of lands in which the blocks were divided, and land reserved for public and religious buildings. These spots were distributed to Germanic tenant farmers, who later erected the main buildings of the City of Petrópolis, such as the Imperial Palace.

The Koeler Plan and the Koeler Map was a project which showed due regard for responsible environmental use (Rabaço, 1985). The plan and map was the first Code of Works of Petrópolis, prohibiting buildings on hilltops and the subdivision of lots horizontally (that is, parallel to their front line) (Rabaço, 1985; Neves and Zanatta, 2016; Fernandes et al., 2017). The Koeler Plan was an urban plan whose spatial reference element is the Koeler Map, which functioned as a guide for handling and minimizing the effects of landslides and floods.

The Plan specified that the front of all houses should face the rivers, and sewage should be directed to tanks at the rear of the lots. This style is considered one of the most original characteristics in the Koeler Plan, as it waived the traditional colonial style wherein houses had their rear elevations facing rivers. The Map shows a planned occupation following the drainage network, with the streets and avenues parallel to the rivers (Piabanha, Palatino and Quitandinha). Another very characteristic feature, which corroborates the idea of minimizing flood risk presented in the Koeler Map, is the project to widen and channel the rivers near the future installation of the Imperial Palace.

The Koeler Map graphic scale is in braças (an old Portuguese unit present in many 19th Century Brazilian and Portuguese maps). The area covered by the genesis area in the map (15.96 km^2), calculated using the modelled surface, represented 10.39% of the current First District of Petrópolis and 1.74% of the entire current City. In the projections drawn in the Koeler Map (1846), the straight segmentation of the three main rivers that cross the city was proposed as a way of facilitating urban development. The rivers Piabanha, Palatino and Quitandinha have undergone changes in their courses, such as a decrease in sinuosity (Santos et al., 2019). Other notable modifications included the excavation and removal of three river islands in the drainage basins. These were a 965 m^2 island in the Quitandinha Basin, another in the Palatino Basin (210 m^2) and a third island in the Piabanha Basin (187 m^2).

Santos et al. (2019) found slightly different values for the size of the islands, as they used a different georeferencing interpolator and 72% fewer points. Despite this difference, the results are similar. There is, however, a change in the size hierarchy. In this analysis, the island in the Palatino Basin was larger than the one in the Piabanha Basin. It was possible to identify that the Quitandinha Basin, in relation to the removal of the river islands, underwent the greatest decrease in area, followed by the Palatino Basin and then the Piabanha Basin. Statements about absolute measurements in historical maps should be put into perspective, as the accuracy of maps is now much greater, largely because of new cartographic technologies. Nevertheless, it is possible to infer from relative values that the Quitandinha Basin had the greatest decrease in island areas (70.85%), followed by the Palatino Basin (15.45%) and the Piabanha Basin (13.70%).

The Koeler Map shows that there were four islands in these rivers that no longer exist. The fourth island (162 m^2) was in the Quitandinha River. However, it was not considered, since it was outside the Quitandinha Basin delimited for this study. The removal of the islands was an important element of the landscape dynamics (Figure 6).

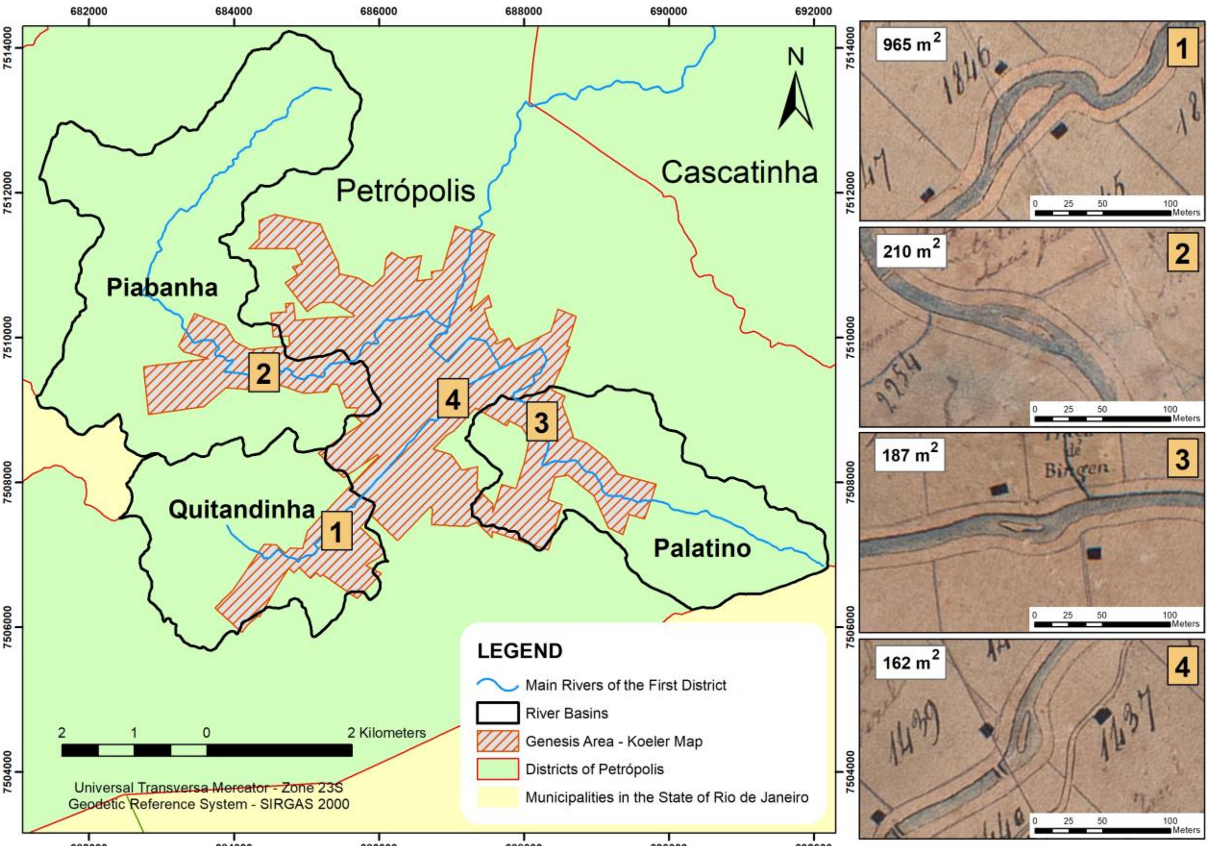

Figure 6. The spatial distribution of excavated and removed islands.

4. POPULATION DISTRIBUTION AND EDIFICATION INDEX

Following the centrality pattern of medium-sized Brazilian cities, Petrópolis City has its highest population density in the First District of the Municipality. However, unlike other Brazilian municipalities, the population of Petrópolis City has been mainly urban since the inception of the City. Although originally an agricultural colony, the rugged relief impeded agricultural development. Therefore, by 1858 industry had replaced agriculture as the main economic activity, some 15 years after the City's foundation (Gonçalves and Guerra, 2009).

The changing economic structure is reflected in the population distribution. From the first available information on rural and urban populations in 1960, 81.92% of the population in Petrópolis was urban, and in 2010 this percentage reached 95.06%. Since industrial activity began and later expanded in the First District, the urban population is mainly concentrated there. It was only by the mid-20th Century that some industrial activity developed outside this area, especially in the Second District. The total city population has continuously grown, from 2,293 inhabitants in 1846; 295,917 in 2010 and an estimated population of 306,191 in 2019 (IHP, 2015; IBGE, 2020).

Even with such continuous growth, the population is still mainly concentrated in the First District of Petrópolis, with the genesis area defined by the Koeler Map and its surroundings forming the core of this growth. Figure 7 shows the percentage ratio of population between the First District and the sum of all other districts in the IBGE Census between 1980-2010. The population concentration in the First District has a mean value of 63.90% (1980-2010) in only 16.77% of the area of the Municipality. In 2010, it was estimated that the population residing in the genesis area was 20.86% of the total population of the Municipality and 33.22% of the population of the First District. Figure 7 also highlights the periods when the population density of the First District was greater than the density of the other districts combined. Figure 7 also shows that the percentage population in the First District has progressively decreased, probably related to population and services saturation, in addition to environmental improvements, which have become more evident in Brazil since the beginning of this Century.

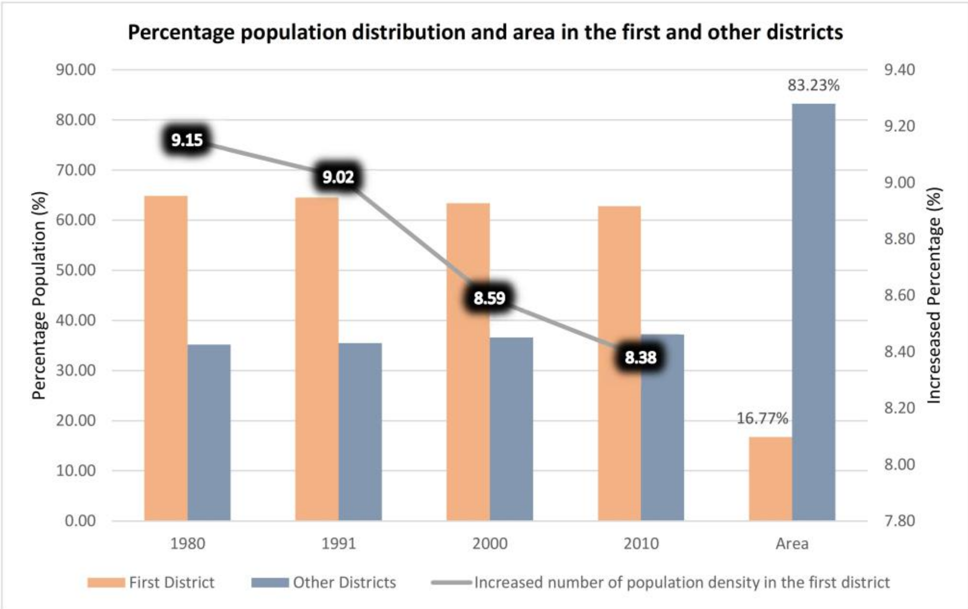

Figure 7. Population distribution and area in the First and other districts of Petrópolis.

A landmark in the dynamics of urban occupation in Petrópolis was the 1960 Building Code. The Code broke with the initial proposal of the Koeler Plan, allowing the construction of buildings where they were previously forbidden (Gonçalves and Guerra, 2009). Thus, there was indiscriminate parcelling of the lots upslope, towards the hill top, with the occupation of slopes adjacent to the already urbanized areas. Here the land is steep and unstable and thus extremely dangerous for building construction. The mean slope of the First District is 55.8º. This urban pressure led to marked landscape changes, including deforestation, channelling and silting of rivers, and haphazard occupation, especially on the steeper slopes (Figure 8).

The changed occupation pattern led to considerable increases in the number of landslides and floods in the Municipality. According to data available from 1932-2015, 83.81% of these events were in the First District (GEOCART, 2015). Thus, the high population density in the First District, more specifically in the genesis area of the Municipality and in the hydrographic basins (Quitandinha, Piabanha and Palatino), is one of the geoecological variables that explains the high incidence of landslides and floods. Of the 1315 (83.81%) landslides and floods in the First District, 472 (35.9%) occurred within the Koeler Map area.

Figure 8. Haphazard occupation on steep slopes in Petrópolis.

These numbers corroborate the focus on the First District, since it occupies only 16.77% of the Municipality area, but had 83.81% of the events. Some 35.9% of these events occurred in the genesis area, which occupies only 10.39% of the area of the First District. In terms of the occurrence of floods, the genesis area is particularly important, as 55.17% of floods occurred in the First District. This flood risk was identified in the Koeler Plan, which advised urban development of the Municipality along the valley bottoms of the main rivers (Table 3). The geodatabase does not have sufficient spatial resolution for the analysis of floods within individual drainage basins. However, the geodatabase is sufficiently accurate for spatial analysis at the district and genesis area level, as suggested by Neves (2017).

Based on the aim of improving the quantification and spatialization of urban occupation within the hydrographic basins, the Edification Index (Ei) was used to quantify the occurrence of construction structures. Construction seals soil surfaces beneath urban areas and so decreases water infiltration rates and capacity, promoting surface runoff and the more rapid arrival of water in the rivers (Dunne and Leopold, 1978).

Ei was based on maps of land cover and its validity was checked through analysis of the Kappa Index (KI) and global accuracy (Colgaton and Green, 2009). KI was 0.81, classified as 'excellent' according to Landis and Koch (1977), and global accuracy was 93.8%. This mapping showed that the drainage basins are predominantly covered by vegetatation (73.53%), followed by built areas (25.55%), rock outcrops (0.84%) and water (0.08%). For the definition of Ei, the areas of vegetated areas, rock outcrops and water classes were combined to creat a new class designated as 'not built.' Thus, the built class is the occurrence of Ei and the three basins have a combined Ei of 25.55% (Figure 9).

Table 3. Distribution of landslides and floods in different units in Petrópolis City (1932-2015)

SPATIAL DIMENSION	NUMBER OF EVENTS	%
LANDSLIDES AND FLOODS		
All Municipality	1569	100
Other Districts	254	16.19
First District	1315	83.81
LANDSLIDES AND FLOODS		
First District	1315	100
First District without Genesis Area	843	64.1
Genesis Area	472	35.9
FLOODS		
First District	145	100
First District without Genesis Area	65	44.83
Genesis Area	80	55.17

Source: Petrópolis Landslides and Floods Geodatabase (1932-2015), (GEOCART, 2015).

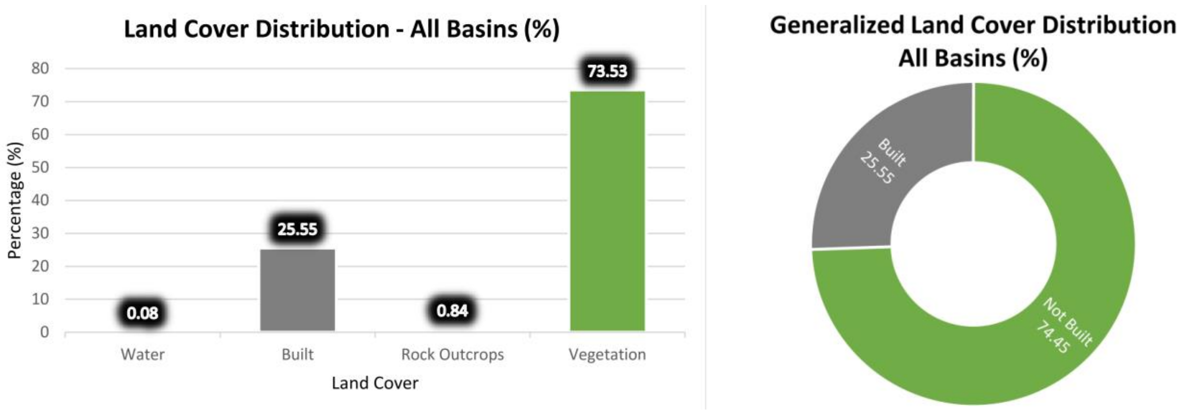

Figure 9. Land cover and distribution of the Edification Index within the three basins.

The spatial distribution of the generalized land cover classes follows a pattern which is repeated in each of the three drainage basins. The 'not built' areas are at higher altitudes and on steep slopes. In contrast, the 'built class' is preferentially located in valley bottoms on gentler slopes (Table 4). Analysis of each basin shows that the Quitandinha Basin has the highest Ei (44.12%), followed by the Palatino Basin (21.50%) and the Piabanha Basin (17.73%). These values indicate greater urban pressure in the Quitandinha Basin, and consequently, greater urban sealing. The consequent increased runoff and faster flow responses means the Quitandinha Basin is more susceptible to flooding. The Palatino and Piabanha basins have higher percentages of 'not built' area, which suggests they have potentially lower flood risks (Figure 10).

Table 4. Relief characteristics of land cover generalized class distribution in the drainage basins

LAND COVER	MEAN ELEVATION (m)	MEAN SLOPE (°)
Not built	886.90	28.16
Built	1345.02	17.54

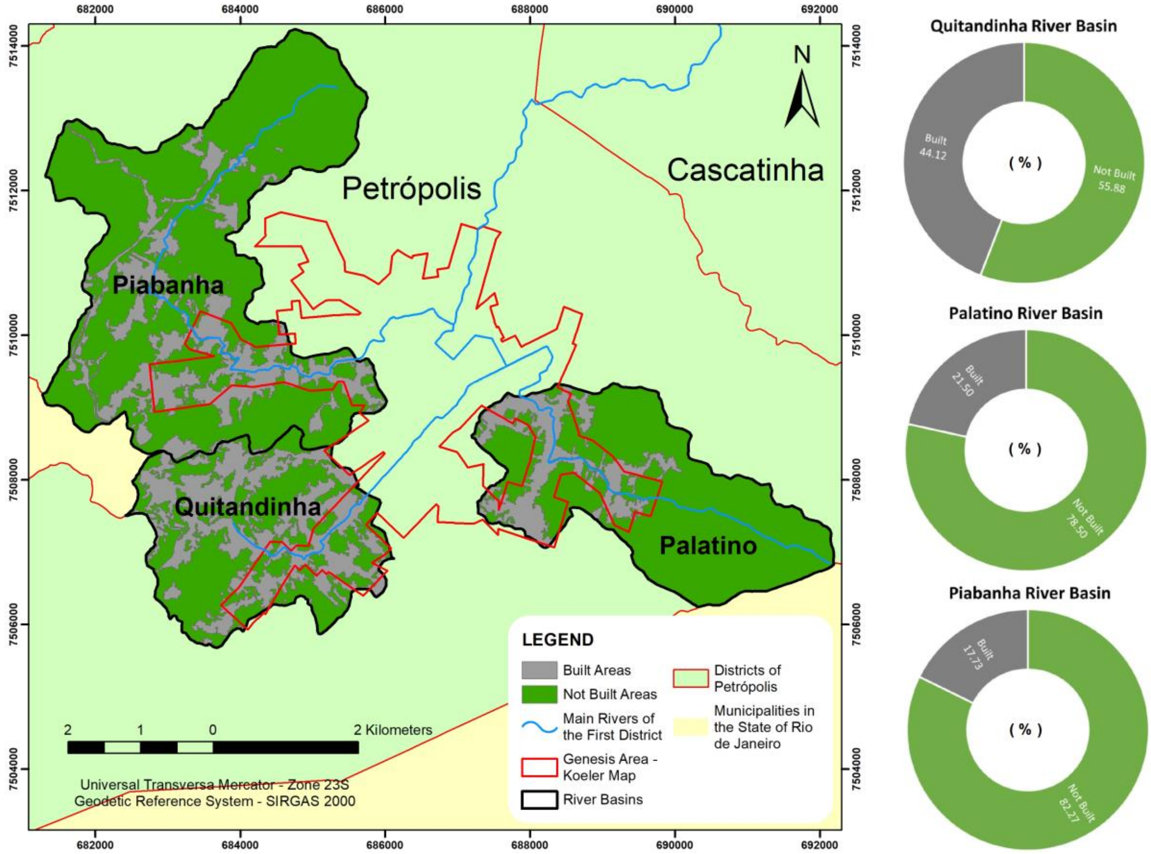

Figure 10. Edification Index for each of the three drainage basins.

5. MORPHOMETRIC INDICES OF THE DRAINAGE BASINS

The study area is located in a mountainous region, with steep slopes and a landscape sculptured by regional tectonic activity and successive erosion phases. The relief reflects these geological conditions and controls the occurrence of elongated valleys, rectilinear drainage segments, granitic massifs, ridges and parallel ridges, upland relief and steep escarpments.

The tropical climate encourages a climax vegetation of dense ombrophilous forest. However, this forest is in a very advanced stage of degradation, due to urban pressure. The soils are also an expression of these geomorphological characteristics, with the occurrence of young and shallow soils on the highest and steepest parts of the landscape, in contrast to more mature and deeper soils in the valley bottoms. The climatic conditions in the study area are very homogeneous. Rainfall was analysed using data from the three pluvio-fluviometric stations within the basins. The mean annual rainfall is 1,750 mm (standard deviation ±47.8 mm, n = 8 years, 2011-2018). Rainfall is concentrated in summer (November-March), which is thus the peak time of landslides and floods.

Despite the high degree of climatological, geological and soil homogeneity, the analysed basins have distinct geomorphological characteristics in terms of flood behaviour. Analysing the basins in terms of their Drainage Density (Dd), Compactness Coefficient (Cc) and Circularity Ratio (Cr), different geomorphological patterns influence the susceptibility of the basins to floods (Figure 11).

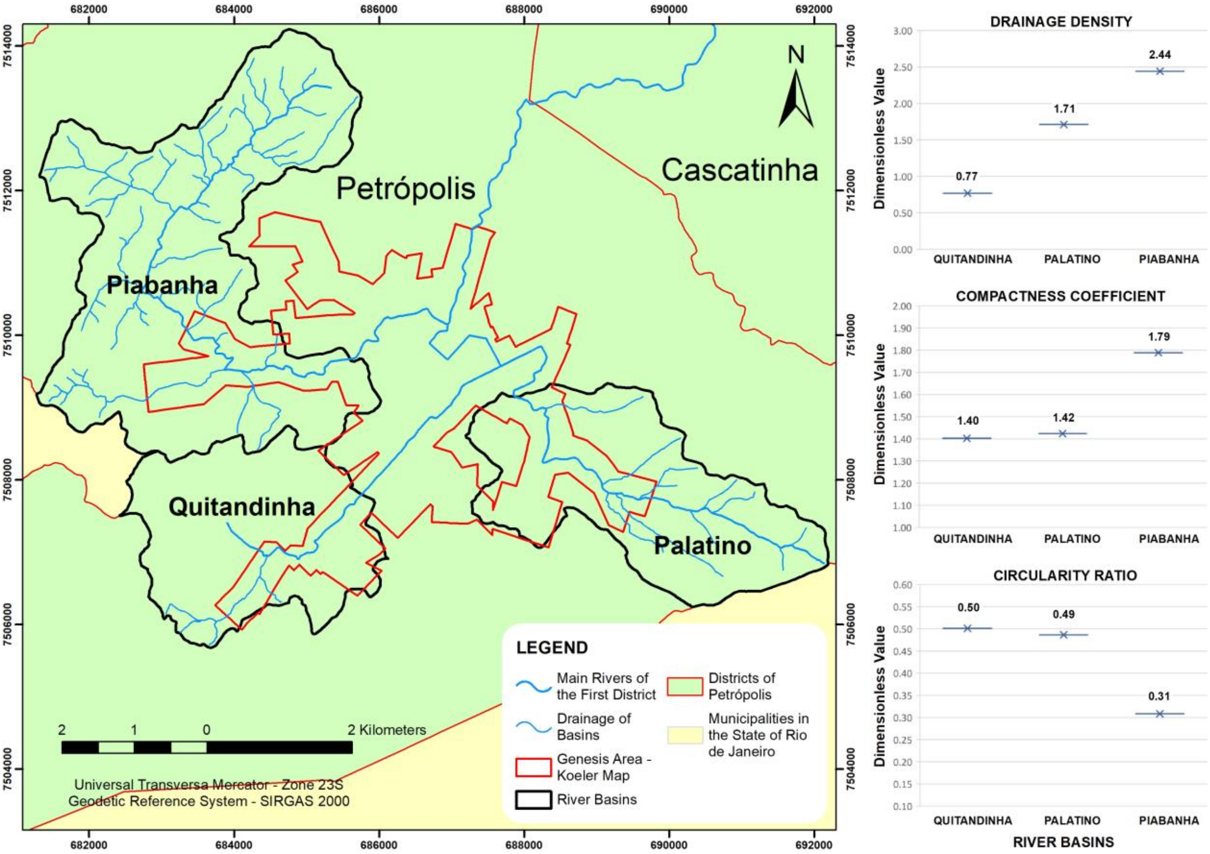

Figure 11. Analysed geomorphological indexes within the three basins.

The lower the drainage density within a basin, the lower its capacity to drain surface water, increasing the susceptibility to flooding (Strahler, 1952). The Quitandinha Basin has the lowest drainage density, followed by the Palatino Basin and finally the Piabanha Basin. The Coefficient Compactness (Gravellus Index) measures the irregularity of the basin shape, that is, the more irregular the basin, the greater the Cc value (Bendjoudi and Hubert, 2002). Thus, the closer Cc is to 1, the more susceptible the basin is to flooding. Cc also showed the greater susceptibility of the Quitandinha Basin to flooding, followed by the Palatino and then the Piabanha basins. The same scenario of susceptibility to the occurrence of floods occurs when analysing the Circularity Rratio (Cr). This Index is the measure of how close the basin is to a circular shape (Miller, 1953). In this ratio, the closer the value to 1, the more circular the basin is and the greater its propensity to flood. Analysis of these three morphometric indices shows the greater susceptibility of the Quitandinha Basin to floods. The Palatino Basin is intermediate in all indices and the Piabanha Basin has least susceptibility to flooding.

6. FLOOD ANALYSIS: A LANDSCAPE READING

The floods recorded in the three drainage basins are directly related to the major rainfall events. In the Quitandinha Basin, it was observed that a flood occurred with a minimum rainfall of 23.45 mm in one hour. This basin registers floods with less rainfall than the other two basins. Flow capacity is an important factor, since the channels have similar widths, but different depths. Currently, the depth that defines the flood level in the pluvio-fluviometric stations is 2.3 m at the Cel. Veiga station (Quitandinha Basin), 3.35 m at the Bingen station (Piabanha Basin), and 4.2 m at the Alto da Serra station (Palatino Basin). This flood behaviour can be classified as flash floods (Kron, 2005; NWS/NOAA, 2009). In these basins, flash floods occur between 15-60 minutes from the onset of rain, with a mean rainfall of 34.38 mm and a mean basin area of 11.77 km^2. In the period 2011-2018 most floods occurred in the Quitandinha Basin, which had 80 floods, equivalent to 90.3% of the total registered floods. In the Palatino Basin, five floods (5.81%) were recorded, and only one (1.16%) in the Piabanha Basin (Figure 12).

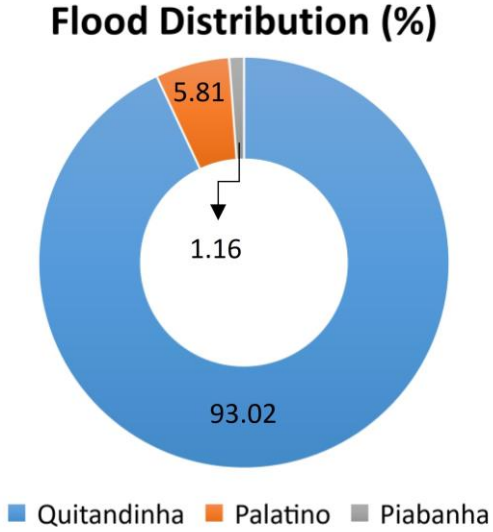

Figure 12. Percentage distribution of floods in the three basins.

The temporal distribution of floods follows the pluviometric pattern, with more floods occurring during summer (November-March), which is the main period of intense rainfall (Figure 13). There is a strong correlation between the total monthly rainfall and the number of floods ($r = 0.974$, $P < 0.001$, $n = 12$). Few floods are recorded in winter (April-October), which is generally drier. This rainfall pattern is common in this area, due to the interactions between atmospheric circulation and relief. However, some short-duration intense rainfalls do occur in the months of April and October. In these two transitional months, floods are also recorded, as occurred in the months April 2013, 2014, 2017 and 2018 with two floods each year.

The flood distributions closely reflect the geoecological variables. All variables influence the greater susceptibility of the Quitandinha Basin to floods, followed by the Palatino and then the Piabanha basins (Table 5). Thus, the geoecological variables in the Quitandinha Basin lead to a 'very high' susceptibility to floods. These variables in the other two basins correspond to their lower susceptibility to floods, classified as 'low' (Palatino Basin) and 'very low' (Piabanha Basin). Based on this interpretation, it is possible to create scenarios to mitigate flood risks. The Quitandinha Basin urgently needs interventions to decrease flood-risk, such as stabilizing and/or decreasing Edification Index (Ei), in conjunction with reforestation and engineering works. The other basins must also be the target of interventions, to prevent repeating the situation in the Quitandinha Basin, especially in the Palatino Basin, which has similar geomorphological characteristics to the Quitandinha Basin.

Overall, the flood risk categorization is quite subjective, but it has several quantitative elements that support the classification. Analysing inter-relationships between geoecological variables, rainfall data and flood frequency and magnitude shows consistent patterns and enabled the prioritization of basins for remedial actions. The framework is being further developed with the incorporation of additional geoecological variables.

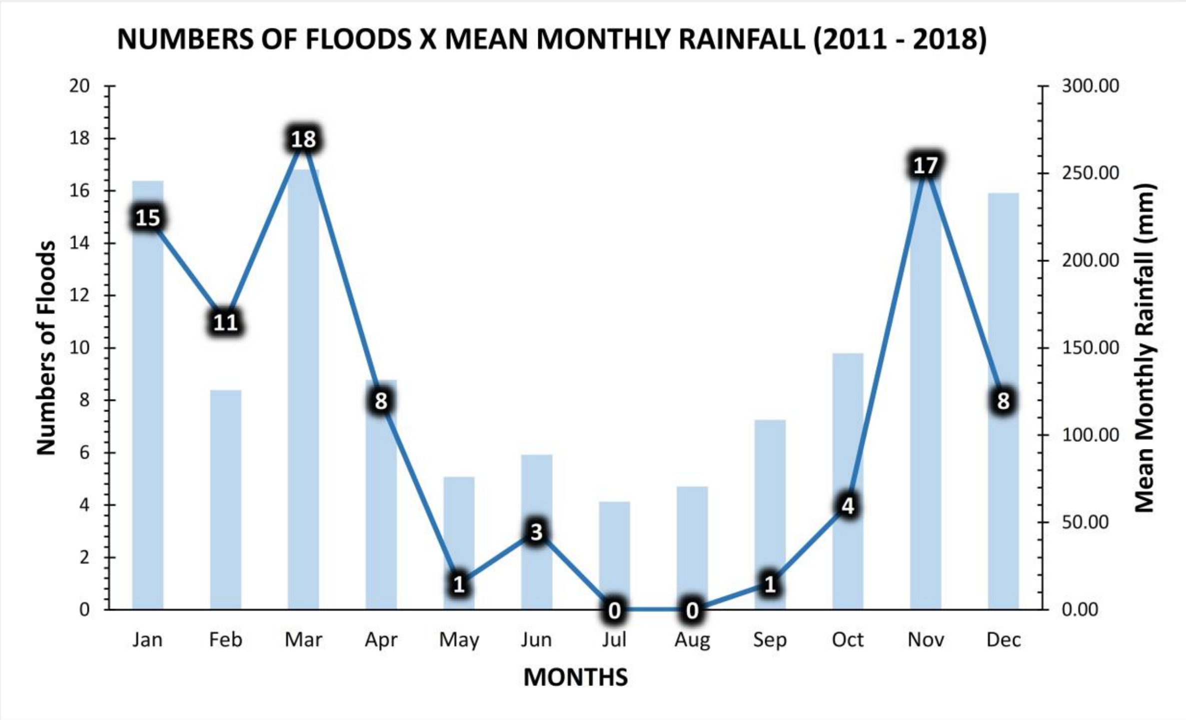

Figure 13. Distribution of floods and mean monthly rainfall.

Table 5. Qualitative synthesis of flood susceptibility levels

		RIVER BASINS		
GEOECOLOGICAL VARIABLES		**QUITANDINHA**	**PALATINO**	**PIABANHA**
Past Drainage Features	Island excavation and removal (%)	70.85	15.45	13.70
Edification Index	Built Area (%)	44.12	21.50	17.73
Geomorphological Indexes	Drainage Density	0.77	1.71	2.44
	Compactness Coefficient	1.40	1.79	1.42
	Circularity Ratio	0.50	0.49	0.31
Pluvio-fluviometric Data	Spatial Distribution of floods (%)	93.02	5.81	1.16
FLOOD SUSCEPTIBILITY		HIGH	LOW	VERY LOW

7. CONCLUSIONS

The occurrence of intense and high-volume rainfall is characteristic of tropical regions. Such rains, together with the increase in urban surfaces in areas of rugged topography and modifications of river morphology, create the conditions necessary for the occurrence of floods in the Municipality of Petrópolis. Flooding is particularly problematic in the First District of the Municipality.

The three river basins that transect the First District area have different structures, functionalities and landscape dynamics and thus have different susceptibilities to flooding. Quitandinha Basin has undergone most changes in the landscape in the historical period. This basin has the highest Edification Index (44.12%) and most removal of river islands (965 m²) of the three analysed basins. These geoecological variables, together with the most favourable geomorphological indices of flood risk, explain why this river basin had the vast majority (93.02%) of recorded floods.

Landscape dynamics are interpreted in this study as the knowledge of the formation and historical evolution of the urban space. The interpretation of urban space parcelling and occupation patterns offers a dynamic perspective, as it allows us to understand how the landscape reached its current structure. Thus, the recent landscape structure, evaluated from the geoecological variables of the Edification Index, several geomorphological indices and pluvio-fluviometric behaviour, aided our understanding of the functionality of flash floods in the urban landscapes of Petrópolis. The approach also enables prioritization of components of the landscape for remedial measures. Petrópolis offers an informative case study of the value of integrating geoecological analysis, historical cartography and GIScience in improving our understanding of landcape dynamics.

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More information about this research and further geospatial references can be found at: https://uploads.knightlab.com/storymapjs/ace1deb1ea5d6cc3a277fd8895b6334b/koeler-lost-island/index.html

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