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Mapping of flood areas of the Sapucaí River in the municipality of Santa Rita do Sapucaí, MG

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Abstract: Urban development in Brazil often lacks adequate infrastructure, leading to disorderly occupations that result in conflicts with nature, such as urban floods causing significant damages to society. In response, the implementation of control measures to prevent or mitigate this problem becomes imperative. The production of flood area maps constitutes a nonstructural measure, a resource of urban planning that utilizes geographic information systems (GIS) tools to extract essential information for decision-making. Flood episodes are part of the history of Santa Rita do Sapucaí municipality, with three major floods occurring in recent decades. Aware of the possibility of these incidents, the population recognizes the importance of the limnimetric ruler as a crucial tool to monitor river levels. Given this scenario, this study aims to apply a methodology for mapping flood-prone areas in the Sapucaí River, especially in the urban area of Santa Rita do Sapucaí, MG. Topographic surveys and river slope analysis were conducted to process flood areas. For comparison and validation of the methodology, historical flood event markers from the years 2000, 2007, and 2011 were used. The flood area mapping methodology demonstrated efficiency in analyzing these events, presenting an average error of 10% in flood height. This positions it as an exceptional tool for municipal urban planning, assisting authorities in decision-making regarding these recurring events.

Key words: flood area; sapucaí river; floods; limnimeter ruler; territorial planning

1 Introduction

Flooding is a natural process of the hydrological cycle that occurs when a sudden or gradual increase in water flow in the smaller bed causes the waters of a watercourse to overflow, exceeding its banks and invading the larger bed (Neves & Tucci, 2008; 2012; Farias & Mendonça, 2022; Maillard et al. 2022). This process results from a combination of several physical characteristics of a given location (Pessôa et al. 2022). Among these characteristics, changes in the precipitation pattern stand out, which include the intensity, quantity, distribution, and frequency of rainfall (Duarte et al. 2021). The presence or absence of vegetation cover also plays a crucial role, since vegetation can reduce surface runoff and increase water infiltration into the soil, leading to its saturation (Toneli, 2022). Furthermore, the geomorphological characteristics of the drainage basin, such as topography and soil composition, significantly influence flood dynamics (Costa et al. 2022;

Prasetyo, 2022).

However, anthropogenic modifications to the natural environment have exacerbated the risks and frequency of floods, especially in urban areas (Zhou et al. 2019; Handayani et al. 2020; Feng et al. 2021; Farias & Mendonça, 2022). Changes in land use and occupation, associated with the urbanization process, manifest themselves through practices such as the channeling and rectification of watercourses, the waterproofing of surrounding areas and the occupation of riverside floodplains (Basri et al. 2022; Silva et al. 2023). Such changes play a direct role in worsening the impacts of urban flooding, generating challenges in several areas of study, including medicine, hydrology, engineering and urban planning (Menezes et al. 2023). Floods contribute to the transmission of infectious diseases through water and vectors, in addition to causing problems related to access to basic sanitation and drinking water (Tin et al. 2024).

It is also worth highlighting that in a context of climate change, extreme meteorological events have become more recurrent, which also implies the intensification of flooding processes (Wing et al. 2020; Tabari, 2020; Tabucanon et al. 2021). In recent decades, a recurrence of these events in short periods of time has been observed, as well as an increase in their severity (Monteiro & Madureira, 2020). As a result, concerns about events of this nature are a topic of debate around the world. According to data from the Emergency Events Database (EM-DAT), from 1995 to 2022, 11,360 disasters were recorded. Of this total, 43.7% (4,969) were hydrological disasters and among the hydrological disasters, the majority were floods (Tin et al. 2024).

The report by the United Nations Office for the Coordination of Humanitarian Affairs - UN-OCHA (2020) highlights that Brazil is among the countries most affected by the effects of floods. In Latin America, the country is considered the most susceptible to this type of disaster, being among the 15 countries with the highest incidence of people affected by river floods. Between 2000 and 2019 alone, around 70 million people were affected by floods in Brazil, according to UN-OCHA (2020).

Based on national records, the Digital Atlas of Disasters database reveals alarming figures. Between 1991 and 2023, 6,183 flooding incidents were recorded, resulting in 644 deaths, 3.99 million homeless and displaced people, and a total of 3.88 million people affected. In economic terms, the damages were estimated at R$25.34 billion and the losses at R$45.25 billion (CEPED, 2024). The North, South and Southeast regions are generally the most affected by this type of disaster (CEPED, 2024).

Recently, the state of Rio Grande do Sul is facing enormous challenges due to floods that have affected more than 300 municipalities (Estadão, 2024). The catastrophe has raised discussions about the state's ability to manage the risks that are intensified by climate change. Urban planning that identifies and considers flood areas is of utmost importance to minimize the impacts suffered by the population (Perrut & Brito, 2022).

Flood risk management can be carried out through both structural and non-structural measures (Decina & Brandão, 2016). Structural measures involve engineering works that modify the river system, such as dikes, dams, and other physical infrastructure (Tucci, 1997; Paixão et al. 2022). On the other hand, non-structural measures consist of public policy actions aimed at land use planning and management. These measures include laws, regulations, decrees, operations, geoenvironmental zoning, preventive civil defense plans, warning and monitoring systems, environmental education, and programs aimed at preventing and living with the problem, seeking to reduce damage and consequences (Carvalho et al. 2019).

According to Sarlas (2010) and Rangel et al. (2021), non-structural measures are based on the study of the basin's hydrological history, allowing the construction of models capable of demonstrating the hydraulic and hydrological behavior of the watercourse. For this, the construction of flood maps and hydraulic characteristics is mainly used. Mapping flood areas is an important tool both for planning land use and occupation and for monitoring regions that are prone to flooding (Silva et al. 2020). Flood maps can be classified in two ways: planning maps and warning maps (Marciano, 2019; Borba, 2020). The planning map defines the areas affected by floods with chosen return times. The warning map is a tool in a decision-making process for implementing a contingency plan (Tucci, 2003). Thus, it is possible for residents to follow the guidelines established by official bodies in extreme events in order to avoid human and material losses.

Silva et al. (2020) used digital elevation models (DEM) and data on the maximum levels of the Uruguay River to map flood areas in Itaquari (RS). The methodology applied was able to adequately represent the relief of the region and identify risk areas and trends in the increase of the maximum levels of the river. By integrating these data with the flood forecasts carried out by the Civil Defense, it is possible to adopt preventive measures, such as the removal of residents from the affected areas. Also in RS, the study by Menezes et al. (2020) for the city of Alegrete determined the probability and spatialization of areas under threat of flooding, considering the relationship between the levels of the Ibirapuitã River and the altimetric levels of the modeled terrain. The work sought to relate return times, severity and degrees of danger, contributing to the identification of susceptible areas and providing support for risk management.

In the Southeast, Urbani et al. (2023) delimited flood spots for return periods of 10, 25, and 100 years, based on hydrological-hydraulic simulations calibrated for the Ipiranga Stream Basin, in São Paulo (SP). The authors found that more than half of the affected residences are of low and popular construction standard, that is, the negative impact of floods is greater in this portion of the population. The simulated spots largely coincided with areas previously mapped as susceptible to flooding, highlighting the relevance of the observed data for model calibration. In Minas Gerais, Faria and Barbosa (2020) identified the flood-prone areas of the Alto Sapucaí Basin in the municipality of Itajubá. The authors observed that approximately 65% of the city's urban area is susceptible to flooding. The use of technologies such as data processing software and Geographic Information Systems (GIS) has enabled the generation of flood maps, important instruments for urban planning and disaster prevention at the municipal level.

The southeast region in particular stands out for the magnitude of damage and losses (Dias et al. 2021), as it accounts for one of the largest percentages of the national GDP (IBGE, 2024). The city of Santa Rita do Sapucaí, located in the south of the state of Minas Gerais, developed in flat areas, occupying the largest bed of the Sapucaí River, without taking into account urban and land use planning. The city is experiencing an intensive urbanization process. The population increase triggers a series of elements, such as the increase in impermeable areas and the urbanization of areas prone to flooding. This has consequences for the hydrodynamics of watercourses, such as the increase in surface runoff velocities, reducing the times of flood peaks.

Historically, the population of the municipality of Santa Rita do Sapucaí has lived with floods, which affect the city from time to time. In recent decades, there have been three major flooding episodes, dating back to 2000, 2007, and 2011 (SEMAD 2013; Servidoni et al. 2021; Santos et al. 2021). The population knows that the Sapucaí River can flood at any time, and therefore there is great concern about monitoring the river, which is observed and monitored by the Civil Defense (Santa Rita do Sapucaí, 2024). Another monitoring tool is the limnimetric ruler, a measuring instrument used to monitor the variation in the volume of water in the reservoirs of water bodies. Installed in the urban perimeter of the municipality, the limnimetric rulers of Santa Rita do Sapucaí are used by the population for individual monitoring.

In this context, with the aim of generating information for both the population and municipal government agencies, this study presents the mapping of flood-prone areas relating the limnimetric ruler to the overflow heights of the Sapucaí River that occurred in the flooding episodes experienced in the city. To achieve this objective, the present study applied the methodology developed in the work of Marciano (2019) to delimit the flood areas and to validate these areas through references to the historical marks of the flood events of the years 2000, 2007 and 2011.

2 Material and methods

2.1 Study area

The municipality of Santa Rita do Sapucaí is located in the southern mesoregion of the state of Minas Gerais, covering a total area of 352.969 km² and housing an estimated population of 40,635 inhabitants (IBGE, 2024). The region of analysis is part of the urban area of the city, built around the course of the Sapucaí River (Figure 1).

Figure 1. Location map of the study area, the municipality of Santa Rita do Sapucaí (MG). Highlighting the section of the Sapucaí River that crosses the city

It is precisely this proximity that exposes the population to the consequences of flooding. According to Sarlas (2010), there is no adequate organization for the orderly occupation of the urban perimeter, since there is a growing number of properties being built in places affected by flooding, even with the risk of economic and social losses.

According to the Flood Contingency Plan (Santa Rita do Sapucaí, 2024), prepared by the Municipal Civil Defense Coordination (COMDEC) of the municipality, up until 2007, more than 14 overflow events of the Sapucaí River were recorded in the last 122 years. The most relevant events that occurred were:

• Event in 2000 affected 70% of the urban area and 15% of the rural area, leaving approximately 10,000 people homeless;

• Event in 2007 affected 50% of the urban area and 10% of the rural area, leaving approximately 4,190 people homeless;

• Event in 2011 affected 30% of the urban area and 5% of the rural area, leaving approximately 2,600 people homeless

The Sapucaí River level is monitored by two fluviometric stations installed in the city, and also by a limnimetric gauge that provides analog readings. The limnimetric gauge is installed on the José de Almeida Neves bridge (Figure 1), and is the main means of accessing information for the population.

COMDEC is responsible for this monitoring and has defined 3 levels of flood vulnerability as per Table 1.

Above 6 m, more than 50% of the city is flooded, blocking some highway entrances and exits, causing some parts of the city to become isolated. The city center and the neighborhoods bordering the Sapucaí River are flooded. In addition, some neighborhoods suffer from drainage problems, increasing the likelihood of flooding.

Table 1. Flood vulnerability levels

Level	Height	Proportion	Neighbourhoods affected
I	5 to 5.5 m	Small	Jardim Beira Rio, Fernandes and Maristela
II	5.5 to 6.0 m	Media	Jardim Beira Rio, Fernandes, Maristela and São João.
III	Above 6.0 m	Great	Jardim Beira Rio, Fernandes, Maristela, São João, Jardim das Palmeiras, Osório Machado, Família Andrade and Centro

2.2 Mapping of flood-prone areas

The mapping of flood-prone areas was conducted following the methodology of Marciano (2019), which consists of subtracting images to create rasters of flood spots. The process occurred in three stages, executed through a Geographic Information System (GIS) program.

Figure 2 illustrates the steps for creating the flood spots. In Step 1, the Digital Elevation Model (DEM) of the study area was generated; in Step 2, the rasters of the slope of the Sapucaí River were generated; and, finally, in Step 3, an algorithm was applied between the DEM and the rasters, resulting in the flood spots.

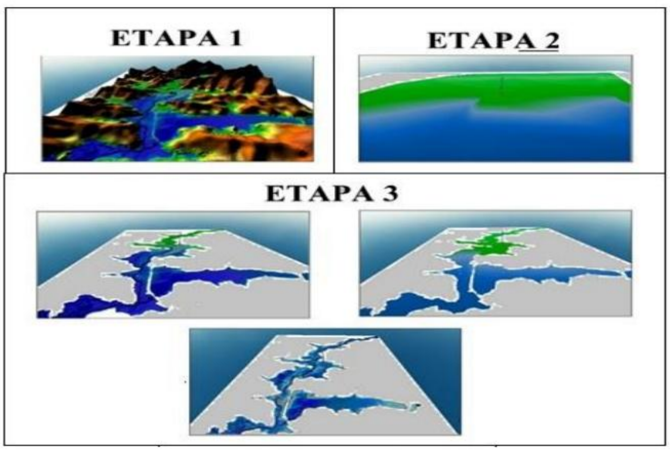

Figure 2. Presentation of the steps for generating a floodplain. Source: Marciano, 2019

2.2.1 Stage 1 - Digital Elevation Model (DEM）

To create the Digital Elevation Model (DEM), a topographic survey had to be carried out between 2011 and 2020, using a Leica TS02 Total Station and Leica CS09 GNSS Receivers. This equipment was used to collect points in the study area. More than 8,000 points were collected and referenced to the Brazilian Geodetic System (SGB).

The points collected in the topobathymetric section surveys followed criteria established by Companhia Energética de Minas Gerais - CEMIG (1997), prioritizing straight stretches with symmetrical margins and avoiding sudden widening or narrowing of the section.

After collection, the points were processed in the Leica Geo Office 7.0 program and orthometrically corrected in the MapGeo 2015 program. The orthometric altitude is related to the geoid, which is a gravitational equipotential surface that coincides with mean sea level and therefore has a more rugged shape that follows the planet's gravitational potential (Severo et al. 2013).

These points were then imported into a GIS program in elevation grid format, resulting in the creation of the MDE for the city of Santa Rita do Sapucaí - MG.

To fill in the areas with the highest elevation, we used the Digital Terrain Model (DTM) from the ALOS PALSAR satellite (Advanced Land Observing Satellite, Phased Array L-band Synthetic Aperture Radar), which are altimetric images with a spatial resolution of 12.5 m, in GEO TIFF (Georeferenced Tagged Image File) format, available free of charge from the ASF/NASA (National Aeronautics and Space Administration) website (Sabino et al. 2020; Marciano, 2024).

2.2.2 Stage 2 - Sapucaí River slope rasters

The slope points of the Sapucaí river stretch were collected using an inflatable boat, sailing from the water collection station (22° 16' 00.8703" S, 45° 41' 38.9097" W) to the sewage treatment plant (22° 14' 37.9054" S, 45° 43' 34.1291" W), with the GNSS receiver switched on in kinematic collection mode, programmed to measure a point every 10 meters to trace the river path. Figure 3 shows the inflatable boat collecting the point on the Sapucaí River.

The points were processed in the same way as in step 1. The collected points were imported into a GIS program as a line vector. Using the "Buffer" tool, two more lines were generated on both sides, respecting the limits of the 823 m contour line of the MDE, the height considered not to be flooded in the simulation. Once these lines had been created, they were saved in a text file in ENZ (East, North, Z-elevation) format.

To create the slope rasters, it was necessary to know the historical flood levels, and evidence was found of the flood events of the years 2000, 2007 and 2011. This evidence was found with the help of COMDEC and referenced to the Brazilian Geodetic System (SGB), and is shown in Table 2. Figure 4 shows evidence of the water level reached in the 2000 flood.

It was then imported into a GIS program, with an elevation grid, creating rasters of the slopes of the floods in the years 2000, 2007 and 2011.

Figure 3. Collection of slope points of the Sapucaí River section

Table 2. Locations with historical evidence

Latitude (m)	Longitude (m)	Height (m)	Quota (m)	Year of the Flood	Neighborhood
22° 15' 49.6125" S	45° 42' 02.7352" W	820,28	2,13	2000	Jardim Santo Antônio
22° 14' 47.0033" S	45° 42' 47.1636" W	820,00	2,37	2000	Fernandes
22° 14' 41.2463" S	45° 42' 47.1636" W	820,00	2,08	2000	Maristela
22° 14' 41.2463" S	45° 42' 38.1777" W	818,96	0,99	2007	Maristela
22° 14' 41.1262" S	45° 42' 30.0025" W	818,96	1,17	2007	Maristela
22° 14' 40.9795" S	45° 42' 30.1703" W	818,15	0,23	2011	Maristela

Figure 4. Water level mark reached in the 2000 flood

2.2.3 Stage 3-Algorithm between the slope map and the DEM

By inserting the DEM and the slope raster into a GIS program, calculations were made to create the flood spot. This operation involved the use of the terrain calculation tool, divided into two stages, as described below:

• Minimum height filtering on DEM and slope raster;

• Filtering the maximum height over the slope raster and DEM.

Based on the results of these filterings, the result of part 1 was subtracted from that of part 2, resulting in the flood spot for each simulated event. With the flood patch, the area and volume flooded for each event were then calculated.

2.3 Comparison and evaluation of flood spots

To evaluate the flood spots, the following were used: the georeferenced locations of the preserved marks of the floods of 2000, 2007 and 2011 (Table 2); the results found in the work of Sarlas (2010) and Fortes (2012); and the 2000/2021 flood contingency plan (Santa Rita do Sapucaí, 2024). Comparisons were made with the results of the methodology of Marciano (2019), which was applied in the city of Itajubá, 50 km from the municipality of Santa Rita do Sapucaí.

In addition, statistical analysis was performed. Equations I, II and III express the comparison between the differences found in the heights of the historical marks with the simulated heights. Equation III calculates the proportion of variation in the observed values compared to the simulated variable (Rangel, 2021; Marciano et al. 2024).

$$SSE = \sum(y - \hat{y})^2 \qquad \text{I}$$
$$SST = \sum(y - \bar{y})^2 \qquad \text{II}$$
$$r^2 = 1 - \frac{SSE}{SST} \qquad \text{III}$$

Where, SSE is the sum squared error; SST is the total sum of squares; y is the observed value; $\bar{y}$ is the average of the observed values; and $\hat{y}$ is the calculated/simulated value.

3 Results and discussion

3.1 Step 1- Digital elevation model

Figure 5 shows the result of creating the DEM of the study area, with a spatial resolution of 1 m. The DEM of the study area was created from topographic data, data from topobathymetric sections, and data on the slope of the Sapucaí River. The aim was to represent the details of the city's topography, as they are important in the study of runoff. The areas with lower altitudes are the areas of dense vegetation and the Sapucaí River channel (Figure 1). These areas have been landfilled in recent years for new developments, due to the population growth, which in the last decade increased by 10% (Sarlas, 2010). It can be seen that the city developed on the banks of the Sapucaí River. The city's growth occurred quickly and these urban areas were not prepared to receive the demand resulting from this urbanization, and the consequences were considerable, since this development was not carried out in a sustainable manner (Sucupira et al. 2022).

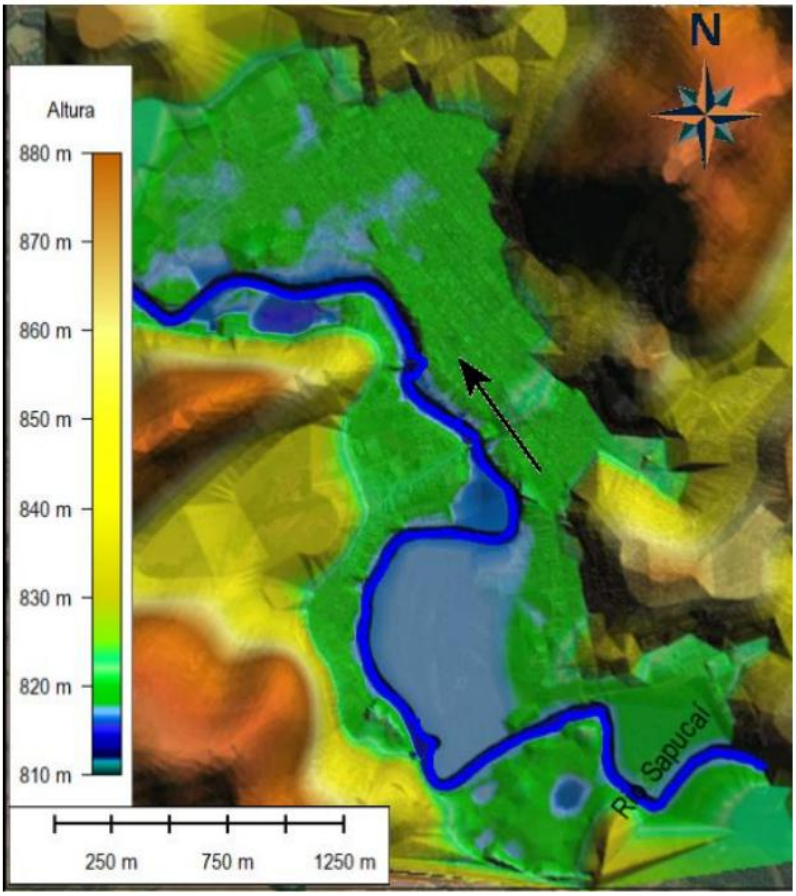

Figure 5. DEM of the study area

3.2 Step 2-Rasters of the slope of the Sapucaí River

On average, the river is 30 m wide, but there may be places where it is wider when it is bordered by non-urbanized areas. The river's water level varies from 813.98 m upstream to 812.53 m downstream, with an average slope of 0.23 m/km, over a distance of 6,220 m.

The river slope values within the study area show that the steepest slopes are found near the city's bridges (Figure 6). Among the bridges, the average slope is 0.46 m/km, causing the flow to be faster than in other locations, making the Sapucaí River more critical in terms of impacts related to flooding.

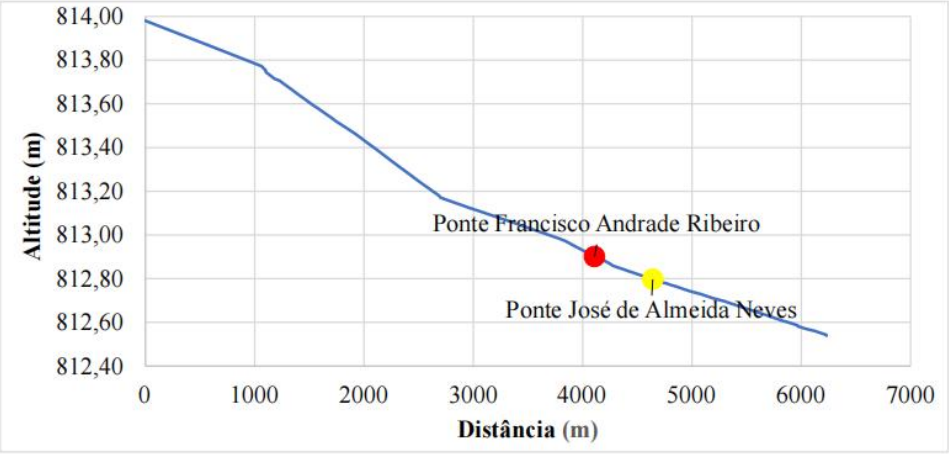

Figure 6. Slope of the Sapucaí River in the study area

Figure 7 shows the result of the "Buffer" process of the Sapucaí River route on both sides, respecting the limits of the 823 m contour line of the DEM, which is the maximum flood limit, which was never reached.

Cross-sections were drawn to follow the points of historical evidence. This procedure was repeated for the years 2000, 2007 and 2011 to generate the 3 slope rasters.

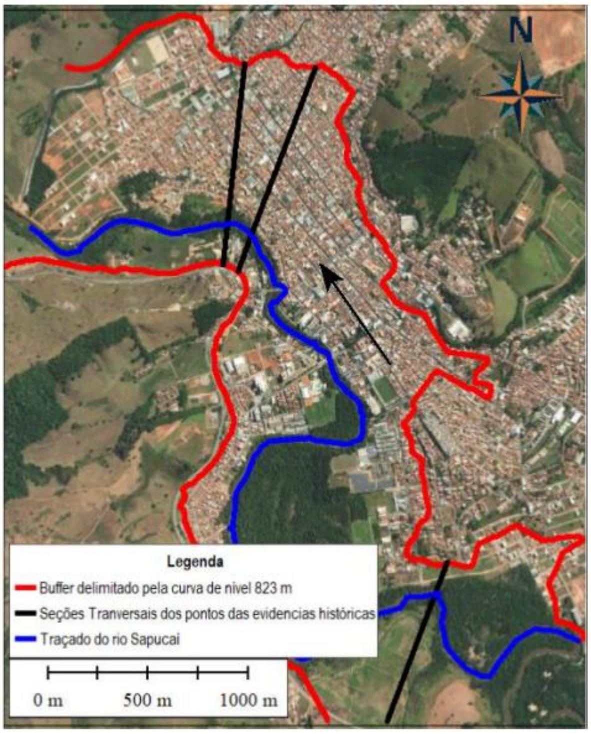

Figure 7. Buffer with delimitation of the 823m contour line with the cross-sections of the study area

After the "Buffer" procedures, the data were imported into a GIS program in elevation grid format, generating rasters of the flood slopes of the years 2000, 2007 and 2011 (Figure 8).

The water level in the 2000 flood was 1.08 m higher than the 2007 flood, and 2.01 m higher than the 2011 flood. The 2000 event is one of the most extreme that has ever occurred in Santa Rita do Sapucaí – MG (Martins et al. 2019).

Sarlas (2010) calculated the flow rate of this 2000 flood event at 3,200 m³/s, with a Return Time (RT) of 16,266 years. The Sapucaí River rose 9.70 m compared to the usual low water level.

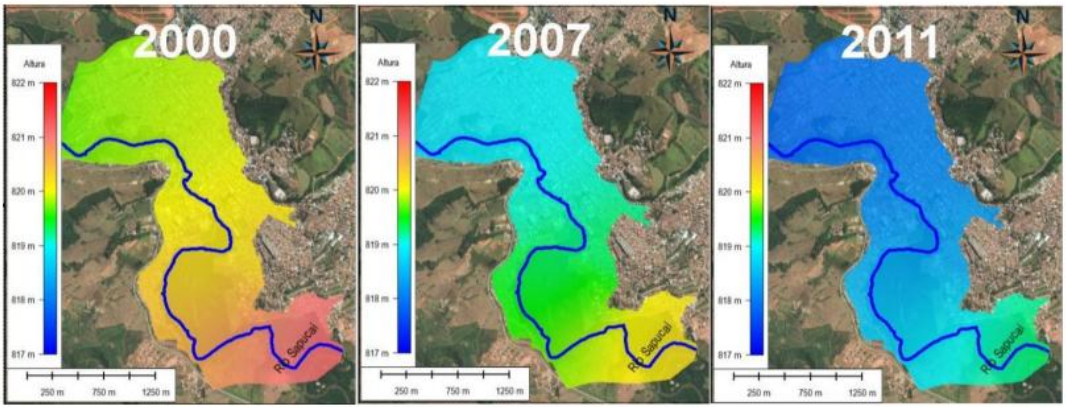

Figure 8. Rasters of the slope of flood events that occurred in the years 2000, 2007 and 2011 in the city of Santa Rita do Sapucaí, MG

3.3 Step 3-Algorithm between slope rasters and DEM

Using the GIS program's terrain calculation, the following procedures were performed:

I - Using the DEM and the slope rasters from the flood events in 2000, 2007 and 2011, the minimum height was filtered, generating rasters with the lowest heights among them.

II - With the slope rasters from the flood events of 2000, 2007 and 2011 and the DEM, the maximum height was filtered, generating rasters with the highest heights among them.

The results of parts I and II were subtracted, generating the flood spots. Figure 9 shows the results of the flood spots for the years 2000, 2007 and 2011.

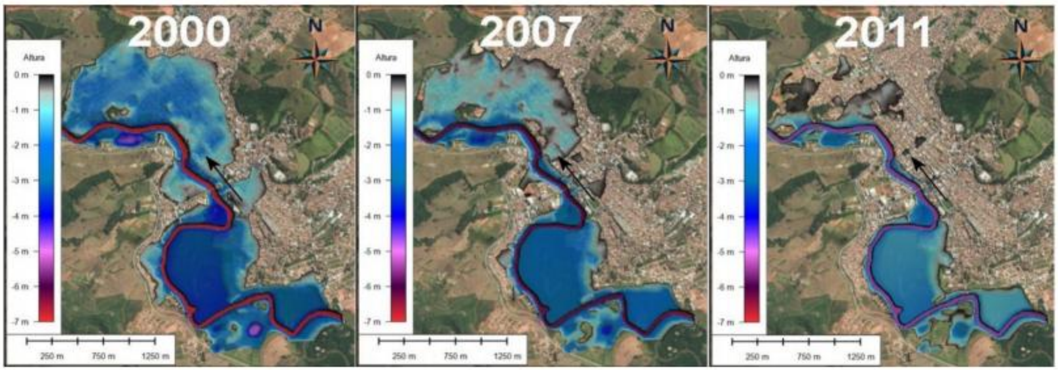

Figure 9. Floodplain from the 2000, 2007 and 2011 flood events in the city of Santa Rita do Sapucaí, MG

Table 3 shows the flooded areas and the volumes occupied by the water from each event. The 2000 event had the largest flooded area. The 2007 and 2011 events had respectively 17% and 46% less flooded areas than the 2000 event.

The volume occupied by flood waters in the events of 2007 and 2011 was 37% and 63% lower than the event in 2000.

The relationship between the area flooded and the volume filled by the flood waters from the 2000 event was delimited by the topography in the higher parts of the city (Figure 5).

The 2000 flood had an Area/Volume ratio of 2.06 m, which means that every 1 m² had a height of 2.06 m of floodwater. The 2011 event had fewer impacts (social damage), while the 2000 and 2007 events had greater flooded areas and volumes.

Table 3. Flood areas and volumes occupied by floodwaters in the events of 2000, 2007 and 2011

Flooding	Flooded area (m²)	Volume (m³)	Volume /Area (m)
2000	3.695.485	7.624.750	2,06
2007	3.053.601	4.780.283	1,57
2011	1.998.518	2.795.919	1,40

3.4 Step 4 - Comparison and evaluation

Table 4 compares the altitudes of the historical evidence with the georeferenced sites.

Table 4 shows the comparison of the altitudes of the historical evidence with the sites. It should be noted that the statistical analysis had an average difference of less than 10%, which is considered small and adequate for representing the floods. However, it is worth noting that there are only a few sites with historical evidence for comparison; more sites would be needed for a more qualified analysis.

The biggest difference (21%) was in the Jardim Santo Antônio neighborhood, which is located near a bend in the Sapucaí River (Figure 10), increasing the complexity of the flood simulation due to the hydrodynamics of the bend (Luz & Rodrigues, 2020; Paiva & Lima, 2023).

Marciano's (2019) flood patch creation methodology proved to be suitable for use in mapping flood areas.

Table 4. Comparison of the heights of the flood spots with the locations of the historical evidence of the 2000, 2007 and 2011 events

Latitude (m)	Longitude (m)	Neighborhood	Height of historical evidence (m)	Simulation Height (m)	Flood Event
22° 15' 49.6125" S	45° 42' 02.7352" W	Santo Antônio	2,13	2,72	2000
22° 14' 47.0033" S	45° 42' 47.1636" W	Fernandes	2,37	2,23	2000
22° 14' 41.2463" S	45° 42' 29.8725" W	Maristela	2,08	1,98	2000
22° 14' 38.4665" S	45° 42' 38.1777" W	Maristela	0,99	0,93	2007
22° 14' 41.1262" S	45° 42' 30.0025" W	Maristela	1,17	1,11	2007
22° 14' 40.9795" S	45° 42' 30.0025" W	Maristela	0,23	0,27	2011

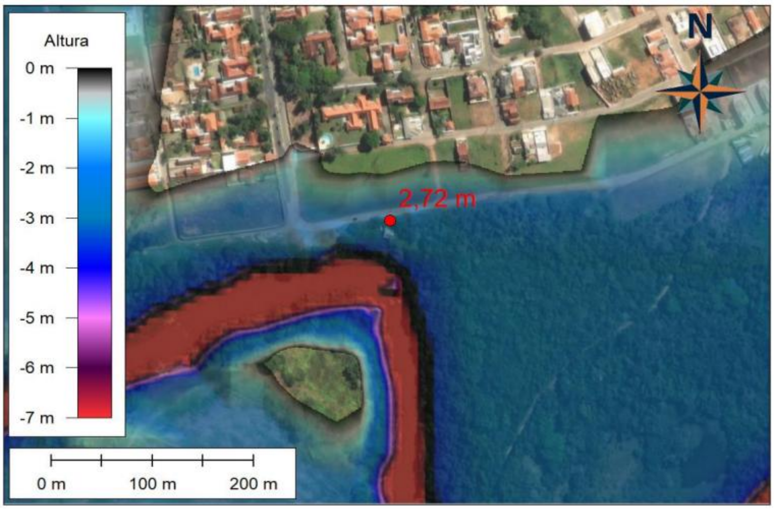

Figure 10. Flood stain from the event that occurred in 2000 with the marking of historical evidence

Table 5 shows a comparison of the results found in the work by Sarlas (2010). The author calculated the flood flow for the 2000 event at 3200 m³/s, considering a return time of 16,266 years, a floodable area of 4,612,827 m² and a flood elevation of 820.28 m.

The flood spot in Sarlas' work (2010) occupies the town's main square, but according to residents who witnessed the 2000 flood, this place was not flooded. It is possible that the flood spot in Sarlas's work (2010) is overestimating the flooding in 2000.

The explanation for the differences in the areas is that the simulated event from the year 2000, in this study, presents a better representation of the city's topography, since it sought to represent all the details and used up-to-date tools to generate the flood spot. This difference was considered high, as it is 20% larger than the area simulated in this study.

Table 5. Comparison with the results of Sarlas' work (2010)

Sarlas (2010)		Simulated		Comparisons	
Area (m²)	Flood altitude (m)	Area (m²)	Flood altitude (m)	Difference in areas (m²)	Altitude difference (m)
4.612.827	820,28	3.695.485	819,95	917.342	0.33

Table 6 shows the comparison between the results obtained in this research and those of the work by Fortes (2012). The aim of Fortes (2012) was to determine the marginal lands in the city of Santa Rita do Sapucaí according to the return times of 2, 3 and 5. He used the altitudes to plot the flood spots, which were made from the topobathymetric section of the water catchment, located at latitude 22° 15' 50.7462" S, and longitude 45° 42' 02.9522" W.

The difference found in the flood areas can be explained by the detail of the topography in this study, since the study by Fortes (2012) did not include the topography of the banks of the Sapucaí River. The difference found in the altitudes: 817m was 2%; 818 m was 13%; and 818.7 was 15%.

Table 6. Comparison with the results found in the work by Fortes (2012)

Altitude (m)	Flooded area (Fortes, 2012) (m^2)	Simulated flooded area (m^2)	Difference (m)
817	1.350.000	1.380.000	30.000
818	1.620.000	1.830.000	210.000
818,70	2.100.000	2.410.000	310.000

In the municipality of Itajubá, which is around 50 km upstream from the municipality of Santa Rita do Sapucaí, Marciano (2019) calculated that the flood event of 2000 reached a height of 847.42 m. This is around 8.40 m above the usual level of the Sapucaí River, with a maximum flow of 390 m³/s.

Table 7 shows the comparison between the results obtained in this research and those of Marciano's work (2019). The area flooded in the city of Itajubá was 65 % larger than the area flooded in Santa Rita do Sapucaí, but the average heights of this event were similar, with a difference of 0.10 m.

The difference found in the areas of flooding can be explained by the size of Itajubá's urban network, which has a population 56% larger than that of Santa Rita do Sapucaí. In addition, the city of Itajubá is crossed by 4 rivers (Sapucaí, José Pereira, Anhumas and Piranguçu), which increases the flooded area.

Table 7. Comparison with the results found in Marciano's work (2019)

Flood event of 2000	Flooded area (m²)	Volume (m³)	Volume /Area (m)
Santa Rita do Sapuca	3.695.485	7.624.750	2,06
Itajubá	10.636.217	20.867.843	1,96

3.5 Limnimetric ruler

According to the 2000/2021 flood contingency plan (Santa Rita do Sapucaí, 2024), level I would start at a height of 5 m, flooding some of the city's neighborhoods. In this study, the flood would start at 7 m, in the Família Andrade, Jardim Beira Rio and Ozório Machado neighborhoods. This difference in the height at which the flooding begins can be explained by the problem of the municipality's urban drainage system, which is unable to cope with the volume of rainfall, flooding some streets in the neighborhoods (Fernandes and Maristela). This flooding is not caused by the waters of the Sapucaí River, but by the waters of precipitation that have not been drained or by another urban watercourse.

Figure 11 shows the graphical representation of the limnimetric ruler on the José de Almeida Neves bridge, the photo was taken on November 11, 2020. From the height of 7 m on the ruler, the water already occupies the secondary channel of the topobathymetric section of the José de Almeida Neves Bridge. The flood from the 2000 event reached a height of 9.98 m, partially covering the bridge.

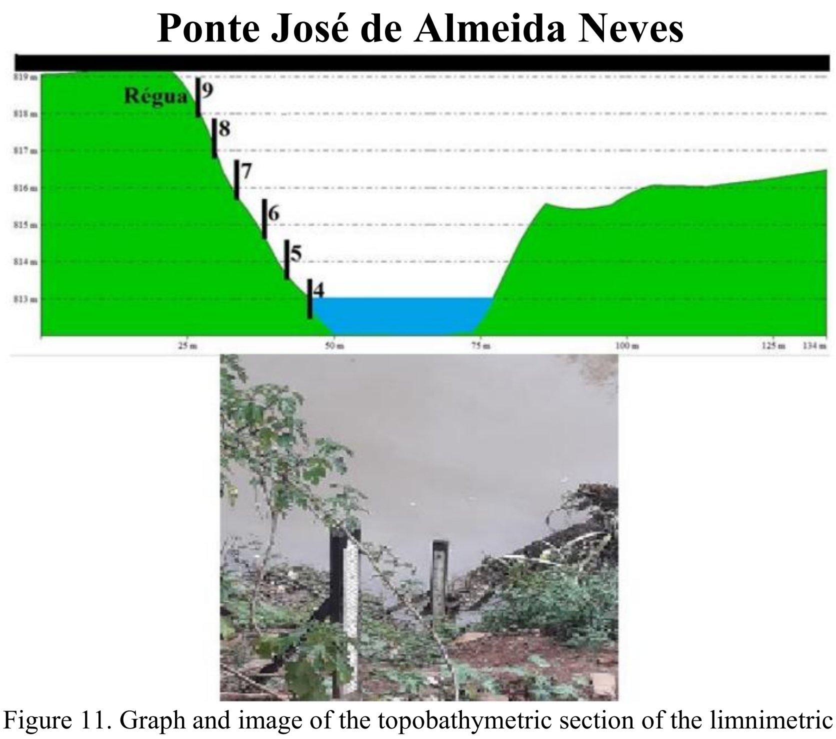

Figure 11. Graph and image of the topobathymetric section of the limnimetric ruler

Figures 12, 13 and 14 show the results of the flood spots and the heights in meters of the limnimetric ruler.

Figure 12 shows the location of the ruler and the flood stain at the height of the 7 m limnimetric ruler. The flood does not reach the houses, in some stretches of the Sapucaí River there is overflow, the city is in a state of alert and alert in case of an increase in the flow of the Sapucaí River.

Figure 13 shows the location of the ruler and the flood area at the height of the 8 m limnimetric ruler. The flooding affects some houses near the Sapucaí River, and the city is in a state of emergency due to the flood event. This flooded area corresponds to a return period of 3 years.

Figure 14 shows the location of the ruler and the flood spot at the height of the 9 m limnimetric ruler. Flooding affects about 30% of the urban area of the study area. The height of this flood spot is 0.98 m below the height recorded by the flood event of the year 2000.

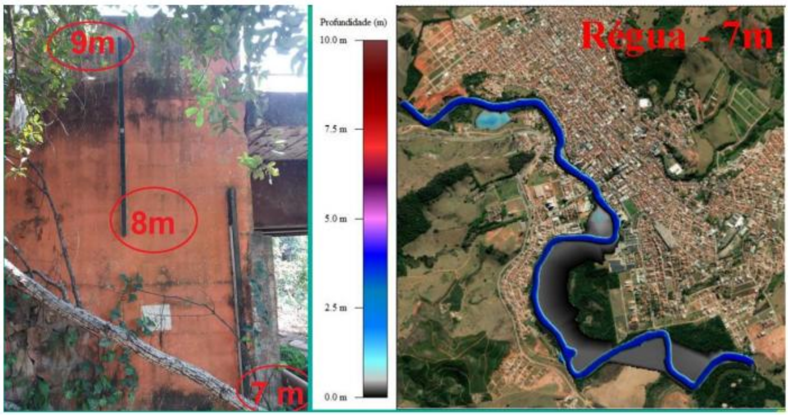

Figure 12. Photo of the limnimetric ruler with the flood stain at a height of 7 m

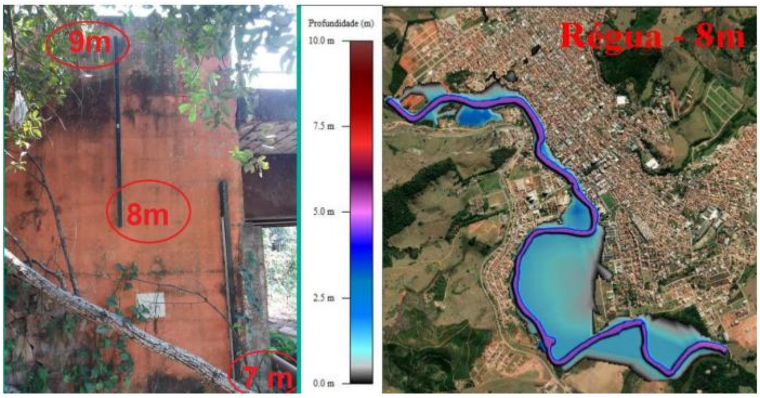

Figure 13. Photo of the limnimetric ruler with the flood stain at a height of 8 m

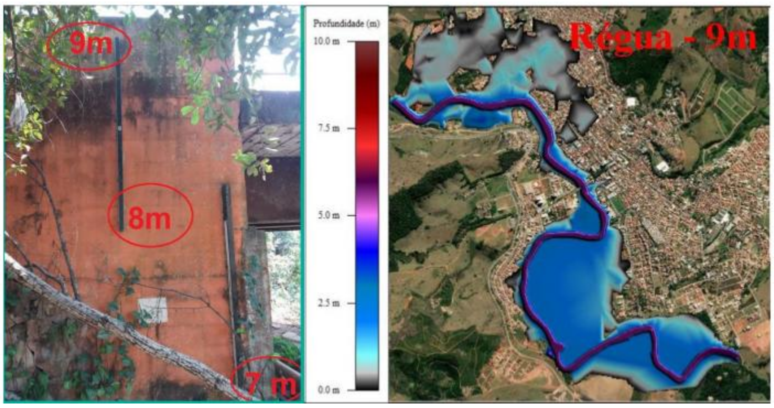

Figure 14. Photo of the limnimetric ruler with the flood stain at a height of 9 m

4 Conclusion

Flood spots generated by a GIS require two types of information to be constructed: topography and watercourse slope. These data are expensive and time-consuming to collect, and are responsible for most simulation errors. Current GIS systems have a high capacity for generating topographic surfaces, but require quality input data and extensive user knowledge to obtain good results.

The floodplain mapping methodology proposed by Marciano (2019) proved to be efficient for analyzing flood events, especially in straight sections of the watercourse. However, for sections characterized by curves, the inaccuracy increases due to the hydrodynamic complexity of the watercourse. The average error was 10% of the height reached by a flood event, which is considered adequate given the size of the study area.

In comparison with other methods of mapping flood-prone areas, it proved to be coherent, since the flooded areas were generated with larger numbers of topographic data, being similar in some aspects to those found in the literature. By comparisons with the marks of historical evidence of floods from the events of the years 2000, 2007 and 2011, they were considered similar, because the average error was only 0.10 m, providing greater credibility in the simulation.

The flood maps generated reveal that the impacts caused by a possible flood, similar to the flood of the year 2000, would have greater impacts. Theoretically, it would affect more than twenty thousand buildings, due to the landfilling in recent years for new developments in areas susceptible to flooding. This is amplified by the low frequency of floods, causing the population to overcome the trauma, gain confidence and disregard the threat.

The limnimetric ruler is an important instrument for the population to monitor the river, even though it is an outdated tool. Nowadays, there are more precise and easily accessible monitoring methods for the population, such as automatic monitoring. However, most of the time this information is not passed on to the population, causing people to resort to old tools, such as the limnimetric ruler.

This study provides a complement to the limnimetric ruler for the population to use in a flood event. However, the objective of this study, which was to generate information for both the population and municipal government agencies, was achieved. With these flood maps relating to the limnimetric ruler, the population of the municipality of Santa Rita do Sapucaí can anticipate the disaster in a given flood event.

The results presented have the potential to indicate stretches of river with a higher probability of flooding. These stretches deserve attention and some intervention from hydraulic engineering, in order to avoid an increase in the impacts in the event of a possible flood.

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Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Basri, H. Syakur, S. Azmeri, A. & Fatimah, E. (2022). Floods and their problems: Land uses and soil types perspectives. In IOP Conference Series: *Earth and Environmental Science* (Vol. 951, No. 1, p. 012111). IOP Publishing. https://doi.org/10.1088/1755- 1315/951/1/012111.

[2] Borba, E. A. (2020). *Análise das áreas de inundação na região sudeste da cidade de Pato Branco-PR*. Trabalho de Conclusão de Curso. Universidade Tecnológica Federal do Paraná. 2020.

http://repositorio.utfpr.edu.br/jspui/handle/1/27 488.

[3] Carvalho Gama, K. N., de Barros, A. J., Laudares, S., Totaro, J. H. R., & de Paula, G. A. (2019). Processos de urbanização: Avaliação dos ricos de inundação de áreas ribeirinhas do rio piracicaba em área do bairro Santa Cruz e centro industrial, município de João Monlevade-mg. *Observatorio de la Economía Latinoamericana*, (7), 21. https://dialnet.unirioja.es/descarga/articulo/8930050.pdf.

[4] CEMIG. Companhia Energetica de Minas Gerais. (1997). Departamento de Planejamento Energético. Especificações técnicas para levantamentos topobatimétricos e cadastro de marcas de cheias. *Potamos Engenharia e Hidrologia Ltda*, 18 p, 1997. https://www.potamos.com.br/.

[5] CEPED - UFSC. (2024). *Atlas Digital de Desastres no Brasil*. http://atlasdigital.mdr.gov.br/#.

[6] Costa, A. M., de Oliveira, N. E. G., de Barros Leal, V. F., Molena, C., Melillo, R. C. S., & Soares, E. R. (2022). Análise das áreas com risco de inundações urbanas e escorregamentos de terra em três bairros do município de Jundiaí/SP. *South American Sciences*, 3(1), e22158-e22158. https://doi.org/10.52755/sas.v3i1.158

[7] Decina, T. G. T., & Brandão, J. L. B. (2016). Análise de desempenho de medidas estruturais e não estruturais de controle de inundações em uma bacia urbana. *Engenharia Sanitária e Ambiental*, 21, 207-217. https://doi.org/10.1590/S1413- 41520201600100116134

[8] Dias, M. B., Galina, N. R., & Alves, C. N. (2021). Mapeamento da suscetibilidade a inundações em áreas urbanas: estudo de caso no município de Marabá, Sudeste do estado do Pará, Região Norte do Brasil. *Revista Ibero-Americana de Ciências Ambientais*, 12(6), 347-359. https://www.sustenere.co/index.php/rica/article /view/5684

[9] Duarte, T. L. S., Santos, G. C., & Castelhano, F. J. (2021). Eventos de chuvas extremas associados aos riscos de inundações e de alagamentos em Aracaju, Sergipe. GEOSABERES: *Revista de estudos geoeducacionais*, 12, 256-273.

https://doi.org/10.26895/geosaberes.v12i0.1089

[10] Estadão. (2024). *Chuvas no RS: entenda a maior tragédia climática do Estado em 5 pontos*. https://www.estadao.com.br/sustentabilidade/chuvas-no-rs-a-maior-tragedia-climatica-doestado-em-5-pontos-nprm/

[11] Faria, C. E. T., & Barbosa, A. A. (2020). Machas de inundação no município de Itajubá-MG. *ForScience*, 8(2), e00594-e00594. https://doi.org/10.29069/forscience.2020v8n2.e 594.

[12] Farias, A., & Mendonça, F. (2022). The Urban Environmental System perspective on socioenvironmental risks of urban flooding. *Sociedade & Natureza*, 34, e63717. https://doi.org/10.14393/SN-v34-2022-63717

[13] Feng, B., Zhang, Y., & Bourke, R. (2021). Urbanization impacts on flood risks based on urban growth data and coupled flood models. *Natural Hazards*, 106(1), 613-627. https://doi.org/10.14393/SN-v34-2022-63717.

[14] Fortes, L. R. (2014). *Delimitação da linha média das enchentes ordinárias e linha limite dos terrenos marginais (Decreto-lei Nº 9760) para a área urbana de Santa Rita do Sapucaí - MG*. Trabalho Final de Graduação do curso de Engenheira Ambiental da Universidade Federal de Itajubá. https://repositorio.unifei.edu.br/xmlui/handle/123456789/63.

[15] Handayani, W., Chigbu, U. E., Rudiarto, I., & Putri, I. H. S. (2020). Urbanization and Increasing flood risk in the Northern Coast of Central Java—Indonesia: *An assessment towards better land use policy and flood management*. Land, 9(10), 343. https://doi.org/10.3390/land9100343.

[16] IBGE. Instituto Brasileiro de Geografia e Estatística. (2024). *Santa Rita do Sapucaí*. https://cidades.ibge.gov.br/brasil/mg/santa-ritado-sapucai/panorama

[17] Luz, R. A., & Rodrigues, C. (2020). O processo histórico de ocupação e de ocorrência de enchentes na planície fluvial do rio Pinheiros de 1930 até os dias atuais. *GEOUSP Espaço e Tempo (Online)*, 24(2), 340-360. https://doi.org/10.11606/ISSN.2179- 0892.GEOUSP.2020.164499.

[18] Maillard, P., Gomes, M. F., Pôssa, É. M., & Paula, R. S. D. (2022). Desafios na delimitação de planície de inundação usando o conceito de "linha média de enchentes ordinárias" usando sensoriamento remoto no Brasil: um estudo de caso no Rio São Francisco. *Revista Brasileira de Recursos Hídricos*, 27, e5. https://doi.org/10.1590/2318- 0331.272220210110

[19] Marciano, A. G. (2019). *Modelagem Hidrodinâmica com a integração do mapeamento das inundações do rio Sapucaí do município de Itajubá/MG*. Dissertação de mestrado, Engenharia Hídrica, Universidade Federal de Itajubá. 2019. https://repositorio.unifei.edu.br/jspui/handle/12 3456789/1968

[20] Marciano, A. G. Assireu, A. T. Azevedo, S. C. D. Silva, B. C. D. Abreu, A. T. D. & Nalini Júnior, H. A. (2024). Mudanças intensas na morfologia da confluência impulsionadas por um pulso hidrológico extremo: impactos na restauração do Rio Doce. *Revista Brasileira de Recursos Hídricos*, 29, e9. https://doi.org/10.1590/2318-0331.292420230139.

[21] Martins, C. M. S., Silva, B. C., & Pons, N. A. D. (2019). Estimativa de cheias em bacias hidrográficas com base em previsões de precipitação por conjunto. *Revista Brasileira de Geografia Física*, 12(5), 1713-1729. https://www.academia.edu/download/69859795/34018.pdf.

[22] Menezes, D. J., de Souza Robaina, L. E., & Trentin, R. (2020). Estudo das inundações na cidade de Alegrete, Rio Grande do Sul: Probabilidade e espacialização do perigo. *Caminhos de Geografia*, 21(74), 213-225. https://doi.org/10.14393/RCG217450113.

[23] Menezes, R. N., Teixeira, V. A. P., & Schröder, L. G. (2023). *Relação entre saneamento básico e saúde pública*. Rede de Ensino Doctum-Dom Orione. Graduação em Engenharia Civil. Unidade Itamar Franco JF. http://hdl.handle.net/123456789/4608

[24] Neves, M. G. F. P. & Tucci, C. E. M. (2008). Resíduos sólidos e drenagem urbana: estudo de caso. *Revista Brasileira de Recursos Hídricos*, v. 13, n.4, p 43-54. https://lume.ufrgs.br/bitstream/handle/10183/2 30265/000714947.pdf?sequence=1&isAllowed=y.

[25] Paiva, R. C. D. D., & Lima, S. G. (2023). Modelo simplificado de atenuação de ondas de cheia. Simpósio Brasileiro de Recursos Hídricos (25.: 2023: Aracaju). Anais (recurso eletrônico). Porto Alegre: *ABRHidro*, 2023. https://lume.ufrgs.br/bitstream/handle/10183/270810/001189532.pdf?sequence=1

[26] Paixão, C. C., Vieira, A. P. D. S. D., & Malutta, S. (2022). Medidas estruturais e não estruturais de drenagem urbana em Paranaguá/PR Structural and not structural methods implanted to contain floods in Paranaguá/PR. *Brazilian Journal of Development*, 8(4), 28728-28748. https://scholar.archive.org/work/djp5yt76vjd5dbyvqeqm6tlvhq/access/wayback/https://www.brazilianjournals.com/index.php/BRJD/article/d ownload/46798/pdf.

[27] Perrut, R. H. P., & Brito, L. A. T. (2022). Cartografia Rápida: uma Abordagem das Principais Variáveis nos Desastres de Inundação e Modelagem Conceitual da Consciência Situacional. *Revista Brasileira de Cartografia*, 74(2). https://seer.ufu.br/index.php/revistabrasileiraca rtografia/article/download/63303/33935

[28] Pessôa, V. M. M., Cecagno, C. F., Camargo, D. M. D., & Marques, M. L. (2022). Contribuição de Aspectos Naturais e Antropogênicos para Análise do Perigo à Inundação em Campinas -SP. *Revista Brasileira de Cartografia*, 74(1), 100-121. https://doi.org/10.14393/revbrascartogr.

[29] Prasetyo, K. (2022). Flash Flood Disaster Mitigation Through Environmental Education. *Geomatics and Environmental Engineering*, 16(4), 119-134. https://doi.org/10.7494/geom.2022.16.4.119.

[30] Rangel, L. C., Junior, J. L., Telles, W. R., Silva, S. V., & da Silva Neto, A. J. (2021). Levantamento das abordagens de modelagem matemática ou modelagem computacional para o estudo e avaliação de mitigação de inundações em áreas urbanas. *Boletim do Observatório Ambiental Alberto Ribeiro Lamego*, 15(2), 03-18. https://doi.org/10.19180/2177- 4560.v15n22021p03-18.

[31] Rangel, B. D. Á. (2021). *Comportamento morfológico no delta do rio Magdalena (Colômbia) devido as variações da vazão em escala intra e interanual*. Tese de doutorado. Programa de engenharia oceânica, Universidade Federal do Rio de Janeiro. https://w1files.solucaoatrio.net.br/atrio/ufrjpeno_upl/THESIS/10002785/doutorado_borisavila_20220304081600403.pdf

[32] Sabino, H., Vasques, G. M., Hermani, L. C., & Dart, R. O. (2020). Morfometria de bacias hidrográficas de primeira ordem em áreas agrícolas sob sistema plantio direto: delimitação e propensão à erosão e inundação. *Revista Brasileira de Geomorfologia*, 21(3). https://doi.org/10.20502/rbg.v21i3.1770.

[33] Santa Rita do Sapucaí. (2024). *Plano de Contingência de Enchentes*, Coordenadoria Municipal de Defesa Civil do municipio de Santa Rita do Sapucai -MG. https://pmsrs.mg.gov.br/category/noticias/obra s/defesa-civil/.

[34] Santos, C. A. Adorno, C. F. D. C. B. & Araujo, R. A. (2021). Análise do Meio Físico como subsídio à definição de diretrizes em Planos Diretores Municipais no Sul de Minas Gerais. *Caderno de Geografia*, v. 31, n. 2, p. 313-313. https://doi.org/10.5752/P.2318- 2962.2021v31nesp2p313

[35] Sarlas, T. L. B. (2010). *Elaboração de Manchas de Inundação para o Município de Santa Rita do Sapucaí / MG, Utilizando SIG*. Dissertação de Mestrado em Engenharia da Energia, Universidade Federal de Itajubá. https://repositorio.unifei.edu.br/jspui/handle/123456789/1499

[36] SEMAD. Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável. (2013). *Atlas de Vulnerabilidade a Inundações*. Belo Horizonte, P. 34. 2013. http://www.meioambiente.mg.gov.br/noticias/1 3-informativo/2284-atlas-de-vulnerabilidade-ainundacoes

[37] Servidoni, L. E. Ayer, J. E. B. Estella, P. V. M. Oliveira, G. H. & Mincato, R. L. (2021). Atributos morfométricos e hidrológicos da Bacia Hidrográfica do Alto Sapucaí, Minas Gerais. *Revista do Departamento de Geografia*, v. 41, p. e169817-e169817. https://doi.org/10.11606/eISSN.2236- 2878.rdg.2021.169817

[38] Severo, T. C., Souza, S. F. D., Matsuoka, M. T., & Gehlen, A. K. (2013). Estudo das correções gravimétricas para altitudes físicas aplicadas aos desníveis da RAAP. *Boletim de Ciências Geodésicas*, 19, 472-497. https://doi.org/10.1590/S1982- 21702013000300008

[39] Silva, R. M, Moreira, V. S, Lopes, A. B., Araújo, P. V. N., & Cortes, A. F. (2020). Proposta Metodológica de Alta Acurácia para Delimitação de Áreas de Inundação Urbana: Um Estudo de Caso em Itaqui-RS, Brasil. *Anuário do Instituto de Geociências*, 43(2). https://www.researchgate.net/profile/PauloAraujo-30/publication/343806628_Proposta_Metodologica_de_Alta_Acuracia_para_Delimitacao_de_Areas_de_Inundacao_Urbana_Um_Estudo_de_Caso_em_ItaquiRS_Brasil/links/5f469fa3a6fdcc14c5c5e120/Proposta-Metodologica-de-Alta-Acuracia-paraDelimitacao-de-Areas-de-Inundacao-UrbanaUm-Estudo-de-Caso-em-Itaqui-RS-Brasil.pdf

[40] Silva, A. M., Pereira, C. E. R. F., & Alves, R. M. (2023). Impacto das inundações nas cidades: Caso do município de Duque de Caxias. *Simpósio Nacional de Gestão e Engenharia Urbana*, v. 4, n. 00. https://doi.org/10.46421/singeurb.v4i00.3619

[41] Sucupira, A. A. M., de Andrea, T. R. L., & Okawa, C. M. P. (2022). Renaturalização de rios: um caminho à sustentabilidade Urbana. *Revista Gestão & Sustentabilidade Ambiental*, 11, 306-322. https://doi.org/10.19177/rgsa.v11e02022306- 322.

[42] Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific reports*, v. 10, n. 1, p. 13768. https://doi.org/10.1038/s41598-020- 70816-2.

[43] Tabucanon, A. Kurisu, K. & Hanaki, K. (2021). Assessment and mitigation of tangible flood damages driven by climate change in a tropical city: Hat Yai Municipality, southern Thailand. *Science of The Total Environment*, v. 789, p. 147983. https://doi.org/10.1016/j.scitotenv.2021.147983 https://doi.org/10.1016/j.scitotenv.2021.147983.

[44] Tin, D., Cheng, L., Le, D., Hata, R., & Ciottone, G. (2024). Natural disasters: A comprehensive study using EMDAT database 1995–2022. *Public health*, 226, 255-260. https://doi.org/10.1016/j.puhe.2023.11.017

[45] Toneli, C. Z. (2022). Mapa de áreas prioritárias para florestas urbanas. In 9° *Congresso Florestal Brasileiro*, Vol.1, No. 1, pp. 675-678. https://doi.org/10.55592/CFB.2022.1981875

[46] Tucci, C. E. (1997). *Água no meio urbano. Águas Doces do Brasil: capital ecológico, uso e conservação*, v. 2, p. 475-508. https://www.academia.edu/download/57731503/aguanomeio_urbano.pdf.

[47] Tucci, C. E. (2003). Drenagem Urbana. *Ciência e Cultura*. São Paulo, v. 55, n. 4. http://cienciaecultura.bvs.br/scielo.php?script= sci_arttext&pid=s0009-67252003000400020

[48] Tucci, C.E. (2012). Hidrologia: Ciência e Aplicação. *Editora da Universidade/UFGRS* Porto Alegre-RS, 943 p. https://scholar.google.com/scholar?cluster=17158111481932112747&hl=en&oi=scholarr

[49] UN OCHA. (2020). *Data Responsibility in Public Private Partnerships. United Nations Office for the Coordination of Humanitarian Affairs*. https://centre.humdata.org/guidance-note-dataresponsibility-in-public-private-partnerships

[50] Urbani, G. L., Graciosa, M. C. P., & Brambila, M. C. V. (2023). Delimitação de manchas de inundação na bacia do Corrego do Ipiranga, São Paulo - SP, Brasil, com modelagem hidrologico-hidraulica utilizando HECHMS/HEC-RAS. *Revista de Gestão de Água da América Latina*, 20. https://dx.doi.org/10.21168/rega.v20e13

[51] Wing, O. E. J. Pinter, N. Bates, P. D. & Kousky, C. (2020). New insights into US flood vulnerability revealed from flood insurance big data. *Nature communications*, v. 11, n. 1, p. 1444. https://doi.org/10.1038/s41467-020- 15264-2.

[52] Zhou, Q. Leng, G. Su, J. & Ren, Y. (2019). Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation. *Science of the Total Environment*, v. 658, p. 24-33. https://doi.org/10.1016/j.scitotenv.2018.12.184