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ORIGINAL ARTICLE – Conservation of Nature

Height Above the Nearest Drainage to Predict Flooding Areas in São Luiz do Paraitinga, São Paulo

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Abstract

Natural events associated to environmental disasters has increased with climate changes. Understanding the watershed behavior allows the managers to execute an efficient land use planning. By using as a study area the municipality of São Luiz do Paraitinga, the study's goal was apply the Height Above the Nearest Drainage Model, which allows categorizing areas based on simulations of water level variations, to evaluate flooding risks at the municipality. The data were processed using ArcGIS Desktop v. 10.3, System for Automated Geoscientific Analysis and TerraHidro. The flood susceptibility map was generated with spatial resolution of 30 m. It was simulated water level variations of 7, 9, 12 and 15 meters and, according to the model, areas with high or very high flood susceptibility cover approximately 13% of the study area (81 km^2). In general, the methods used afforded coherent results given the resolution of source data and available information.

Keywords: Climate changes, land use, flooding risks, HAND model.

1. INTRODUCTION

The rivers are directly associated with various societal activities, such as locomotion, agriculture, and trade, thereby contributing to the development of civilization. However, hydrological impacts caused by disordered urban growth are recurrent. According to Andrade et al. (2014), soil waterproofing, especially in areas with high slopes, increases flow peaks and, consequently, the frequency and aggressiveness of flood episodes. The flood damage mitigation depends on the management of land use and protection of water resources.

Nobre et al. (2016) stated that, although it is mandatory in many countries, high resolution flood mapping only covers few flood susceptible areas. Nowadays, the application of hydrodynamics models is widely used in hydric behavior studies allowing a precisely evaluation of flood extension areas (Dimitriadis et al., 2016). However, the hydrodynamics model application requires an advanced knowledge about the fluvial channel geometry and the features of flow drainage (Nobre et al., 2016), besides a high effort both in computational terms and input data acquisition (Momo et al., 2016).

As an alternative, cheaper and simpler methods can be used to enable flood risk mapping. Andrade et al. (2014) used the Analytic Hierarchy Process (AHP), reproduced by Saaty (1977), hierarchizing morphometric variables and applying map algebra to obtain a flood risk map of a Minas Gerais urban watershed. Righi e Robaina (2012) also used map algebra to elaborate a flood risk study, including as key factors the flood return time and the urban features such as infrastructure and population density, besides using the AutoCAD software to get the 3D projection of flood points of the study area.

Extreme flood events are hydroclimatological phenomena that alter the distribution of water in watersheds, influencing the flow response of drainage channels and increasing the risk of floods (Oliveira & Cunha, 2014). Natural factors can determine the magnitude and frequency of floods, including rainfall intensity and distribution, infiltration rate, degree of water saturation in soils, basin morphometry and morphology,

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river network structure, surface topography, slope gradient, geology, and vegetation (Amaral & Ribeiro, 2015).

The municipality of São Luiz do Paraitinga, the target region of the present study, has a history of flood events, which are intensified in rainy periods. At the beginning of 2010, after continuous rainfall, the water level of the Paraitinga River increased extraordinarily, causing severe damage from landslides, cut slope failures, sinkholes, and undermining (Oliveira et al., 2018). Soil compaction by livestock and the regular practice of agricultural burning have led to soil impoverishment, contributing to increased erosion and constant river siltation. In addition, riversides are poorly protected because of the scarcity of riparian vegetation (Soares & Soares, 2010 apud Arguello, 2017). Understanding the factors that increase the risk of floods is fundamental to improve land use planning and minimize damage caused to the environment and urban structure.

This study aimed to identify flood susceptible areas in São Luiz do Paraitinga municipality, which is included at the Paraitinga and Paraibuna watersheds. The selection of the municipality to focus the discussion was firstly due the large size of watersheds, and the absence of representative and well distributes data for all this area. In other hand, the partnership with the São Paulo Forestry Institute allowed a more detailed analysis at the municipality of São Luiz do Paraitinga. In this sense, the results obtained will contribute to disaster risk reduction, damage mitigation, and environmental preservation at the local level and, thus, support the planning of land use and occupation. To attend the goals, the Height Above the Nearest Drainage (HAND) model and geoprocessing tools were applied to characterized morphometrically the study area and developed a flood susceptibility map.

2. MATERIALS AND METHODS

2.1. Study area

The municipality of São Luiz do Paraitinga comprises an area of about 617 km^2 (IBGE, 2010) in the Paraitinga/Paraibuna microregion, eastern São Paulo State, Brazil (Mello, 2017).

Geologically, São Luiz do Paraitinga is located within the Ribeira belt, along the Paraíba do Sul transcurrent fault belt, which encompasses the Coastal and Embu complexes. The study area is composed of Paleozoic peraluminous S-type granites, Precambrian calc-alkaline I-type granites, and peraluminous S-type foliated granitoids. The Coastal complex is represented by quartzite, orthogneiss, and peraluminous gneiss map units. The Embu complex, in contrast, is dominated by schist and paragneiss units (Fig. 1) (Hasui, 2012).

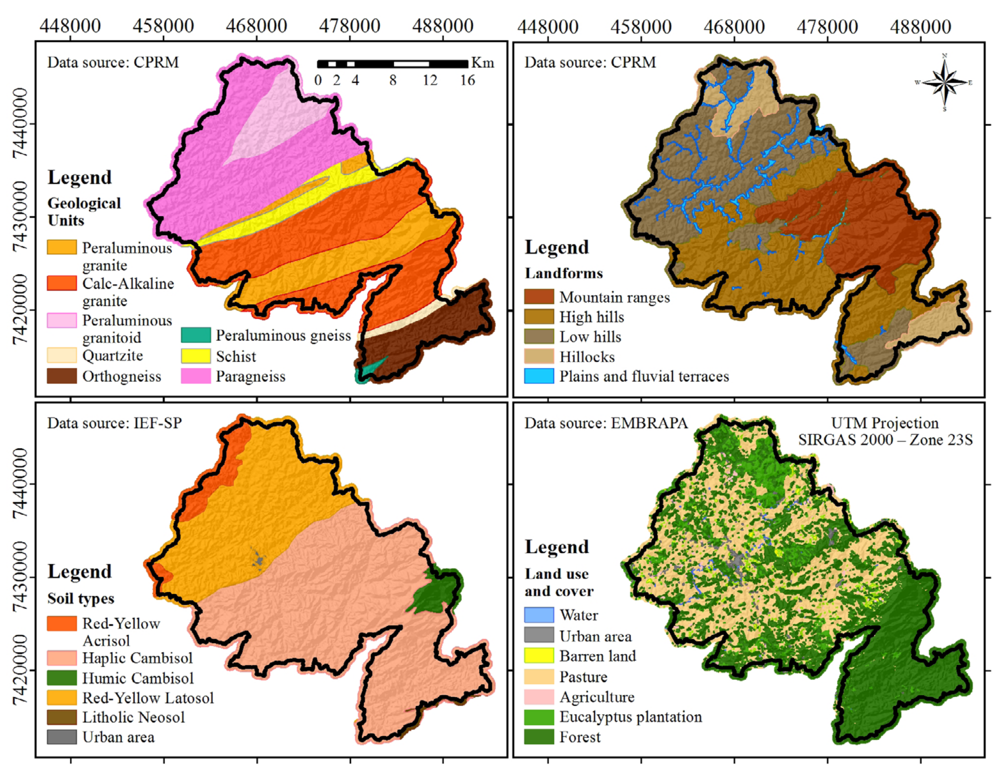

Figure 1. Geological map units (upper left), landforms (upper right), soil types (lower left), and land uses and cover (lower right) in 2015, in São Luiz do Paraitinga.

The municipality sits on the Paraitinga/Paraibuna Plateau, a geomorphological unit of the Atlantic Plateau (Ross & Moroz, 1996). Almeida (2018) described the Paraitinga/Paraibuna Plateau as a structurally complex and maturely dissected crystalline plateau with long longitudinal mountains characterizing it as '*Mar de Morros*' relief. Its morphosculpture is characterized by tall, elongated, convex hills extending to elevations of 700 to 1200 m (Ross & Moroz, 1996). According to a mapping study conducted by the Geological Service of Brazil (CPRM), the area is a mosaic of mountain ranges, high hills, low hills, hillocks, plains, and fluvial terraces. Elevation and slope values classification for the terrain is detailed in Bitar, 2014.

The landscape of the study area is a complex, heterogeneous mosaic dominated by pastures, forests and eucalyptus plantation (about 97% of the territory). Although forests are one of the predominant classes of soil cover (37%), they consist of isolated, poorly connected fragments (EMBRAPA, 2015). A dense and well-preserved forest area occurs in the south, where there is an extensive environmental conservation unit, the Serra do Mar State Park. Table 1 presents the area occupied by each class of land use and cover in São Luiz do Paraitinga (EMBRAPA, 2015). The mapping work carried out by EMBRAPA was on the scale of 1:250 000.

The original vegetation was Montane Dense Ombrophilous Forest, found at elevations of 500 to 1500 m (IBGE, 2012), it is highlighted that the Paraitinga watershed which range from 2000 to 700 m (TOPODATA, 2011). The umbrothermal requirements of this vegetation type include high averages temperatures (25 °C) and abundant, well-distributed rainfall. Thereby, even in low-rainfall years, the region does not suffer from dry periods.

Table 1. Description of land uses and cover in São Luiz do Paraitinga, São Paulo, in 2015.

Class	Area (km^2)	Area (%)
Agriculture	1.77	0.29
Water	1.92	0.31
Urban area	4.56	0.74
Eucalyptus plantation	61.49	10.00
Forest	230.36	37.30
Pasture	306.70	49.70
Exposed soil	10.00	1.63

2.2. Hydrological characteristics

The municipality of São Luiz do Paraitinga is geographically close to the outfall of the Paraitinga and Paraibuna watersheds, a factor that may favor the occurrence of floods. Although the municipality contains two basins, each one of them contributes differently to the drainage of the study region. The Paraitinga watershed occupies about 80% of the municipal territory, including the urban center and much of the economically active rural areas (cropping and livestock systems). The high population density and intensive land use increase the risk of socioenvironmental disasters associated with extreme flood events.

The Paraitinga watershed is located in the Paraíba do Sul Water Resources Management Unit (UGRHI-02) (Arguello, 2017). The basin covers an area of 2430 km^2 (between UTM coordinates 7 487 427 and 7 417 382S 451 060 and 536 166W) and is composed of 38 tributaries that feed the main river from the source to the mouth in the Paraibuna reservoir (Fig. 2). According to EMBRAPA (2015), agriculture and pasture are the major land uses (66%) in the Paraitinga watershed. Although native forest occurs across 25% of the watershed area, it is very fragmented and dispersed, preventing the development of dense vegetation capable of minimizing the erosive effects of rainfall.

Morphometric analysis can be used for a preliminary evaluation of flood likelihood. In the current study, we calculated morphometric parameters to evaluate the Paraitinga and Paraibuna watersheds using the formulae proposed by Villela & Mattos (1975) and Cardoso et al. (2006), as presented below.

Compactness coefficient (*C*c):

$$C_c = 0.28 \frac{p}{\sqrt{A}} \quad \text{(eq. 1)}$$

Where, P is the basin perimeter (km), and A is the basin area (km^2).

Form ratio (F_f):

$$F_f = \frac{A}{L^2} \quad \text{(eq. 2)}$$

Where, *A* is the basin area (km^2), and *L* is the basin length (km).

Circularity ratio (*R*c):

$$R_c = \frac{12.57A}{p^2} \quad \text{(eq. 3)}$$

Where, *A* is the basin area (km^2), and *P* is the basin perimeter (km).

Drainage density (*D*d)

$$D_d = \frac{L}{A} \quad \text{(eq. 4)}$$

Where, L is the total stream length (km), and A is the basin area (km^2).

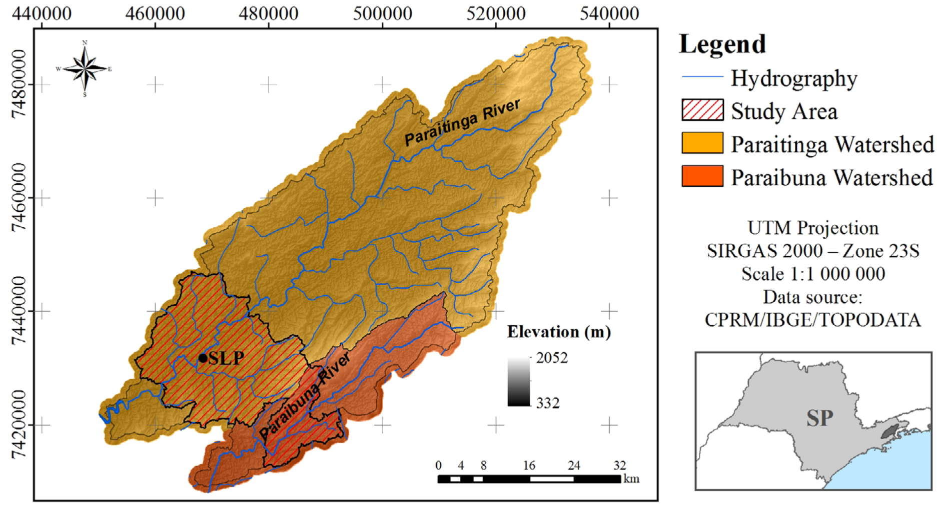

Figure 2. Location map showing the Paraitinga and Paraibuna watersheds, and the study area, São Luiz do Paraitinga municipality (SLP).

Drainage, on the other hand, is a geomorphologically sensitive property, reflecting the relief shape and the structural characteristics of the rocks that compose it. Drainage channels in the Paraitinga watershed are young and highly adapted to geological and geomorphological structures (Almeida, 2018). The basin has a very extensive contributing area, which hinders a detailed study of its hydrographic characteristics. Thus, we chose to focus our attention on the part of the basin located in São Luiz do Paraitinga (Fig. 3). The theoretical basis for the drainage patterns classification was proposed by Howard (1967) in a study assessing the usefulness of fluvial features for the interpretation of geological and geomorphological structures.

The rainfall map of Figure 3 shows the mean annual precipitation in São Luiz do Paraitinga over the period of 1977 to 2006. It was generated by interpolation of isohyets provided by CPRM. The rainfall regime of the region is controlled by Tropical and Equatorial air masses. According to Soares et al. (2008), the annual accumulated rainfall in areas close to Serra da Mantiqueira and Serra do Mar can reach 2200 to 2800 mm, contrasting greatly with annual rainfall values for the Paraíba Valley, which do not exceed 1300 mm.

The climate is warm subtropical, with the mean annual temperature ranging from 18 to 24 °C. The highest rainfall occurs in December, January, and February, a period with increased risk of landslides and floods. The driest months are June, July, and August (Mello, 2017). In the Köppen–Geiger system (Kottek et al., 2006), the climate is designated as Cfb or temperate oceanic with mild summers.

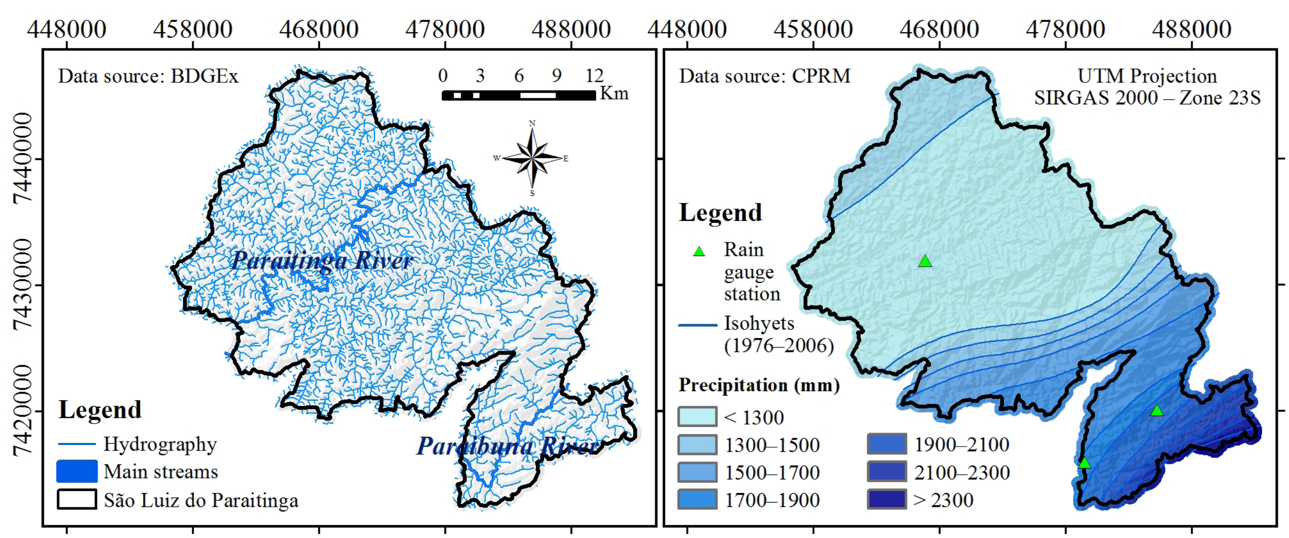

Figure 3. Hydrographic (left) and mean annual precipitation (right) maps of São Luiz do Paraitinga, São Paulo, Brazil.

2.3. Source data and software

The development of this research required the acquisition of data for thematic characterization of the study area and the use of different software tools for processing and analyzing the data before interpretation. The following source data were used:

- Soil map of São Paulo State in vector format, elaborated by Rossi (2017) and provided, at the original scale (1:100 000), by the São Paulo Forestry Institute (IEF-SP);
- Base map of contour lines, elevations points, drainage channels, and water masses for topographical charts SF-23-Y-D-III-1, SF-23-Y-D-III-2, SF-23-Y-D-III-3, and SF-23-Y-D-III-4, at a scale of 1:50 000, provided by Brazilian Army Geographical Database (BDGEx);
- Boundaries of the municipality, rainfall gauge stations, isohyets, structural lineaments, and relief of São Luiz do Paraitinga, at a scale of 1:25 000, provided by CPRM;
- Geological map and hydrography of the state of São Paulo, at a scale of 1:750 000, provided by CPRM;
- Georeferenced database from municipal, state, and national boundaries and railroads in Brazil, at a scale of 1:250 000, provided by IBGE;
- Land use and cover map of Paraíba do Sul Valley in 2015, scale 1:250 000, prepared by EMBRAPA and available from the GEOINFO website; and
- Elevation data from the topographical charts 22S465, 22S45_, 23S45_ and 23S465, at a scale of 1:250 000, available from Topodata website.

The data were processed using ArcGIS Desktop v. 10.3 (ESRI, 2014), System for Automated Geoscientific Analyses (SAGA-GIS) v. 7.2.0, and the TerraHidro extension of TerraView v. 4.2.1.

All source data and generated products were converted to the UTM coordinate system using SIRGAS 2000 Zone 23S as horizontal datum, in accordance with Brazilian Resolution No. 1/2005 (IBGE, 2005).

The digital elevation model (DEM) used in this study has a spatial resolution of 30 m and was generated using the Topo to Raster interpolation method, developed specifically for obtaining hydrologically consistent DEM (HCDEM) (Marcuzzo et al., 2011). After correction for spurious depressions, an HCDEM was generated and elevation continuous model was ready to be used as input to the HAND model.

2.4. Assessment of flood susceptibility

Flood susceptibility mapping requires the identification and evaluation of the determining factors for the target area. In the current study, we selected and characterized, on the basis of case studies and research related to the theme, some of the most important morphometric parameters implicated in flood processes.

The HAND model was used for flood susceptibility mapping. The model generates a normalized terrain topography that can be categorized according to differences in elevation from that of the nearest watercourse (Momo et al., 2016). Thus, it is possible to estimate which areas are more likely to be covered by water in a flood event (Nobre et al., 2016; Mengue et al., 2016).

The HAND model consists of two procedural steps (Nobre et al., 2011) and uses a HCDEM as the main source data. Having the model in hand, the first step is to define local drain directions and identify drainage channels, which are used to generate a nearest drainage map and a normalized topography map. Subsequently, sites are classified according to their flood susceptibility using historical records and simulations. The integration of the HAND map with flood data allows predicting which areas would be flooded for each rise in the water table. This valuable information can be used to guide land use planning decisions in flood-prone river basins.

For interpretation of HAND models, each regular grid cell containing a drainage channel should be assigned a value of zero. This means that the gravitational flow potential along the length of the river is assumed to be null. The definition of the drainage network requires a minimum channel initiation threshold to be established. This value is important for model accuracy and depends on the correct identification of channel initiation and drainage density. The drainage network is composed of all grid cells that have a contributing area greater than the threshold (Rennó et al., 2008); that is, the higher the threshold value, the lower the drainage density and, therefore, the smaller the predicted floodable area. For defining consistent thresholds, it is necessary to assess the hydrological and geomorphological characteristics of the study area through, for instance, field studies or examination of data from previous observations (Rennó et al., 2008).

From the drainage maps, it was possible to generate elevation maps based on HAND model. The HAND model was developed using the TerraHidro extension of TerraView v. 4.2.1. The drainage threshold used in this study was 100. This value was defined by comparing hydrographic vector data of the municipality with the drainage networks generated using thresholds of 50, 100, and 500.

According to Brollo et al. (2011), in and near the urban area of São Luiz do Paraitinga, the Paraitinga River has portions ranging from 1 to 2 m deep and 20 to 30 m wide. The main river is 40–50 m wide and 3–5 m deep. Past records of flood events (in 1996, 2000, and 2006) state that the water level reached 2–4 m in residential areas 12 m far from the main river (Brollo et al., 2011). During the 2010 flood, the water level of the Paraitinga River reached about 15 m (Civil Defense). On the basis of data from the referred studies and considering morphological data, water levels during past floods, and frequency of flood events, five susceptibility classes were determined: very high, high, medium, low, and very low (Tab. 2).

Table 2. Classes of flood susceptibility estimated by the High Above the Nearest Drainage model.

Susceptibility class	HAND (m)
Very high	0–3
High	3–7
Medium	7–12
Low	12–15
Very low	>15

3. RESULTS AND DISCUSSIONS

3.1. Morphometric characterization of the Paraitinga and Paraibuna watersheds

Table 3 shows the morphometric indices calculated for Paraitinga and Paraibuna watersheds.

Table 3. Morphometric parameters of the Paraitinga and Paraibuna watersheds.

Parameter	Paraitinga watershed	Paraibuna watershed
Area	2430 km^2	454 km^2
Perimeter	328 km	152 km
Compactness coefficient (C_c)	1.860	1.997
Form ratio (F_f)	0.208	0.150
Circularity ratio (R_c)	0.284	0.247
Drainage density (D_d)	2.830 km/km^2	2.337 km/km^2

Both watersheds have morphometric features relatively similar, thus, only the most relevant for the study was presented below, the Paraitinga watershed. According to Villela & Mattos (1975), circular basins ($C_C = 1$) tend to generate water overflow in small stretches of the main river, increasing flood susceptibility. The Paraitinga watershed had a compactness coefficient of 1.860 indicating an irregular shape, therefore is not susceptible to flooding. The form ratio determines how similar the shape of the basin is to that of a rectangle. It is defined as the ratio of the mean basin width to the axial length (Cardoso et al., 2006). The analyzed watershed had a relatively low form ratio (F_f = 0.208), indicating a low tendency toward flooding. Similar to the compactness coefficient, the circularity ratio indicates the similarity of the watershed shape to that of a circle; values close to 1 indicate circularity and values greater than 1, elongation (Cardoso et al., 2006). The circularity ratio obtained (R_c = 0.284) also characterize a low probability of flooding.

Drainage density indicates the time that rainfall takes to leave the basin; that is, it indicates the efficiency of the drainage system. According to Villela & Mattos (1975), a poorly drained basin has a drainage density of about 0.5 km/km^2, whereas well-drained basins show values close to or greater than 3.5 km/km^2. The Paraitinga watershed was shown to have a moderate drainage capacity (D_d = 2.830 km/km^2).

Regarding hydrographic characteristics, four predominant drainage patterns were observed: dendritic, subdendritic, parallel, and subtrellis. In areas near the Paraitinga River, where relief variation is insignificant, the main patterns are dendritic and subdendritic. The parallel pattern occurs mainly in the eastern portion of the area and is probably controlled by ruptured parallel structures in a preferential southwest–northeast direction. The subtrellis pattern takes shape as the relief becomes steeper and more active. This pattern has parallel and relatively short drainage segments, which group together and enter the main river at about 90° angle. Trellis drainage occurs on sedimentary, low-grade metamorphic and volcanic rocks with steep or folded layers. It can be formed in areas with parallel fractures, wide relief angles, or fold systems where drainage fits into synclinal folds.

Figure 4 shows the elevation map of São Luiz do Paraitinga (plotted at 100 m intervals) and other terrain attributes obtained by derivation of DEM, such as slope, aspect, and topographic wetness index (TWI). Slope and aspect values were generated using the Slope and Aspect functions, respectively, of the Spatial Analyst Tools: Surface module of ArcGIS Desktop v. 10.3. TWI was obtained with SAGA, using the Topographic Wetness Index function of the Terrain Analysis: Hydrology tool.

The elevation map of the municipality shows the elevation divide between the Paraitinga and Paraibuna watershed, represented by cold colors (Fig. 4). Brown colors represent low elevations, indicating river valleys and areas where the mainstem flows.

The slope refers to the terrain's degree related to the plane (Oliveira et al., 2017). It directly influences water level in soil, pedogenesis, erosion potential, rate of sediment deposition (Silva et al., 2018), and other processes that are fundamental for hydrological, geomorphological, and geotechnical studies. The slope map of the municipality was classified according to the values obtained by Oliveira et al. (2018).

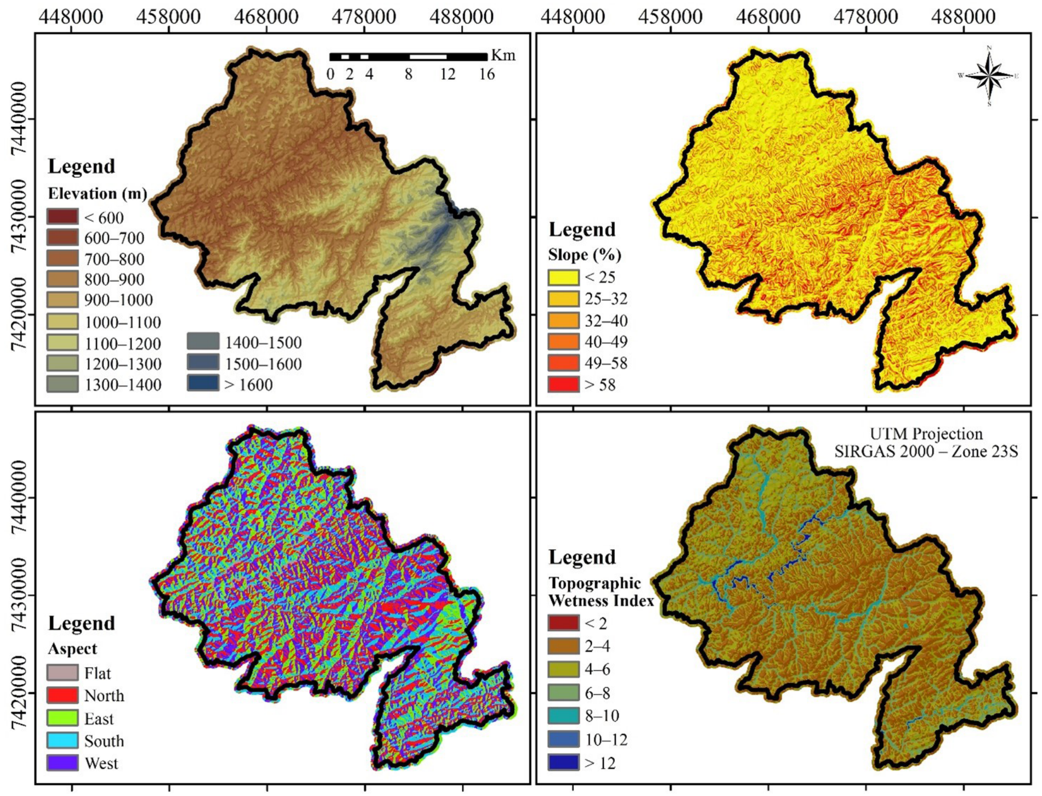

Figure 4. Elevation (upper left), slope (upper right), aspect (lower left), and topographic wetness index (lower right) maps of São Luiz do Paraitinga, São Paulo, Brazil.

Aspect is mainly related to solar radiation and, therefore, indirectly to rainfall distribution, vegetation type, and soil thickness and moisture, among others (Ferreira, 2013).

TWI measures the soil's water distribution, which is directly influenced by topography (Radula et al., 2018). A high TWI indicates that soil has a high tendency to saturate, characterizing extensive contributing areas, low slopes, and flatter reliefs, as observed in regions near main river channels. On the other hand, low TWI values can be found in areas with high slopes and shallow soils, usually near groundwater recharge sites (Lopes, 2012).

3.2. Flood susceptibility areas in São Luiz do Paraitinga

The flood susceptibility map, generated using the HAND Model, consists of a regular grid with a spatial resolution of 30 m, with values of 00 (minimum), 605.9 (maximum), 42 (medium) and 40.2 (standard deviation). The value of each cell indicates the vertical distance to the nearest drainage. Identification of the areas most affected by the increase in water level was performed using the altimetric classification of the normalized topographic model as shown previously in Table 2.

The threshold value adopted in the HAND model is a fundamental parameter for defining flood susceptible areas. An excessively high threshold would imply a representation of only the main drains, possibly omitting areas susceptible to the increase in water level. The use of a low threshold would lead to the identification of a very dense drainage network (Momo et al., 2016), thereby overestimating the susceptibility to flooding. The drainage network obtained using a threshold of 100 was visually consistent with the area hydrography, but no field evaluations were carried out to validate the results.

There are three main flood susceptible areas (Fig. 5). In the northern, central, and southern regions, the confluence of flood-prone zones draws attention, both for their orientation (east–northeast) toward geological structures and for the concentration of highly susceptible areas. On the other hand, the rugged relief does not allow a very extensive floodplain.

According to the results, the flood susceptibility in the county ranges from very high (37 km^2), high (44 km^2), medium (43km^2), low (22km^2) and very low (429km^2), beyond level water (42 km^2). When comparing the susceptibility results and the land occupation, it follows that approximately 1,1 km^2 of urban area (24%) is present in high or very high susceptibility zones, located on the Paraitinga riversides. Furthermore, about 44 km^2 (14%)

of pasture and exposed soil areas, composed mainly for Haplic Cambisol and Red-Yellow Latosol (Rossi, 2017), are in zones where the flood frequency is high or very high, subsidizing erosive process and river siltation.

In the flood susceptibility map presented here, areas with a HAND value lower than 7 m were considered to have a high to very high flood potential, supported by data of flood events that reached water levels close to this value in a relatively short recurrence interval. However, the lack of municipal data on floods hindered obtaining a more representative definition of susceptibility classes based on water level and recurrence interval. The difficulty in acquiring high-resolution data and the lack of field information also limited the quality of the results obtained. Nevertheless, the results allow a preliminary view of flood susceptible areas. A better understanding of the factors that condition and trigger flood events, as well as greater knowledge of new techniques to identify flood hazard areas, can support future research and contribute to municipal land use planning.

Figure 6 shows an overview of São Luiz do Paraitinga and historical houses built on slopes and floodplains.

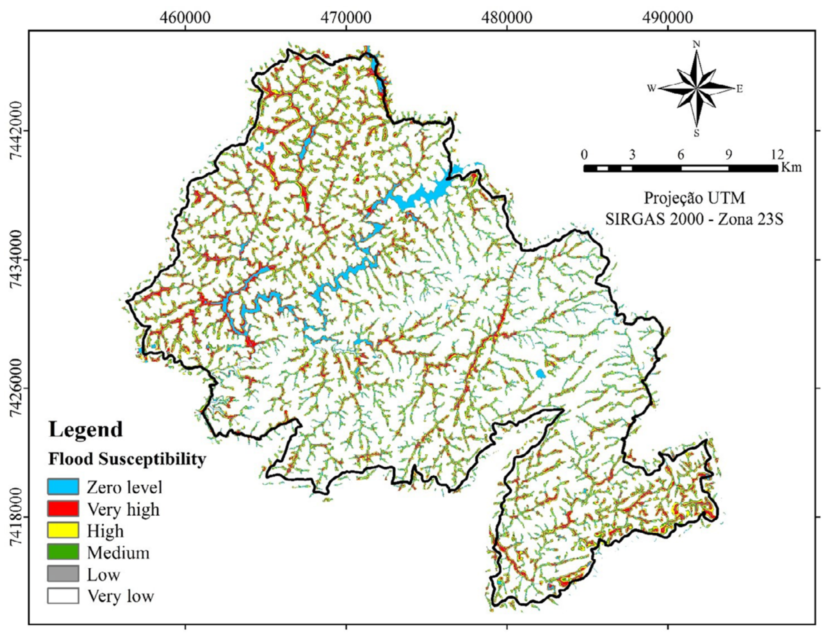

Figure 5. Flood susceptibility map simulating the height above the nearest drainage of 3, 7, 12, and 15 m, represented by red, yellow, green, and grey colors. The blue color indicates the normal water level (zero level).

Figure 6. (a) Overview of São Luiz do Paraitinga. Historical center, (b) '*Mar de Morros*' relief overview; (c) Paraitinga River's water level monitoring station located near to the urban center.

Given the vulnerability to natural disasters, application of hazard mapping techniques is extremely important, and could aid land use planning at this susceptible areas. Reis et al. (2020) developed a comparative study between land use and morphometric parameters, showing that although the watershed is not floodable from the morphometric point of view the large pastures areas can accelerate erosive processes needing more attention. On the other hand, Capoane and Silva (2020) present a study case showing the importance of a high quality data for a land use planning in an urban context comparing elevation models of three different sources and resolution. The authors used geoprocessing tools and geographic information system environments to create morphometric parameters to map possible flood hazard, demonstrating the importance to apply computational techniques to an efficient land use management and occupation of the watershed area.

4. CONCLUSIONS

The morphometric parameters of the Paraitinga watershed showed that the hydrographic region has low susceptibility to flooding. However, as the urban center is located near to the basin outfall and riverside, the occurrence of river overflow upstream of the municipality is favored during severe rainfall events.

The HAND model simulated water level variations and afforded a coherent flood susceptibility map, showing the importance to use geoprocessing tools in preliminary studies. However, there was a lack of field control points and high resolution data, which should be addressed at the future studies to achieve more detailed analysis.

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