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ANALYSIS OF THE TENDENCY FOR URBAN FLASH FLOODING TO OCCUR, ON A LOCAL SCALE, BASED ON
MORPHOMETRY AND LAND USE: A CASE STUDY IN THE CITY OF SÃO JOÃO DEL-REI, MINAS GERAIS (BRAZIL)*

ANÁLISE DA TENDÊNCIA À FORMAÇÃO DE ENXURRADAS URBANAS, NA ESCALA LOCAL, A PARTIR DA MORFOMETRIA E
DO USO DA TERRA: ESTUDO DA CIDADE DE SÃO JOÃO DEL-REI, MINAS GERAIS (BRASIL)

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ABSTRACT

Flash floods are processes formed from concentrated surface runoff, which usually occurs during intense rain events and in basins with rugged relief. In cities, torrential floods are further aggravated by excessive waterproofing and the common lack of micro- and macro-drainage systems. The water can therefore flow over the roads and, depending on the volume and energy, it can cause a range of material and social damage. Considering the rapid urbanization process in Brazil and the recurrence of natural hydrological and hydrogeomorphological disasters, this article contributes with a methodology that aims to identify trends in flash flood formation in urban areas, through morphometry and the impermeable percentage. The study takes the city of São João del-Rei (Minas Gerais) as a geographical scale for application of the model. The results showed compatibility with the dynamics of the study area, indicating high tendencies in drainage units conducive to the occurrence of strong flash floods.

Keywords: Disasters, waterproofing, surface runoff.

RESUMO

As enxurradas são processos formados a partir do escoamento superficial concentrado, o qual ocorre, geralmente, durante eventos chuvosos intensos e em bacias de relevo acidentado. Nas cidades, as enxurradas possuem, ainda, agravantes, como a impermeabilização exacerbada e a comum insuficiência do sistema de microdrenagem e macrodrenagem. Desse modo, o caudal escoar sobre as vias e, dependendo do volume e energia, pode causar uma série de danos materiais e sociais. Considerando o acelerado processo de urbanização brasileira e a recorrência de desastres naturais hidrológicos e hidrogeomorfológicos, este artigo contribui com uma metodologia que busca identificar tendência à formação de enxurradas, no espaço urbano, por meio da morfometria e percentual de impermeabilização. O estudo adota como escala geográfica a cidade de São João del-Rei (Minas Gerais) para a aplicação do modelo. Os resultados apresentaram compatibilidade com a dinâmica da área de estudo, indicando tendências elevadas em unidades de drenagem propícias à ocorrência de fortes enxurradas.

Palavras-chave: Desastres, impermeabilização, escoamento superficial.

* O texto deste artigo foi submetido em 06-10-2023, sujeito a revisão por pares a 17-11-2023 e aceite para publicação em 23-02-2024.

Este artigo é parte integrante da Revista *Territorium*, n.º 32 (N.º Especial), 2025, © Riscos, ISSN: 0872-8941.

Introduction

Flash floods result from or correspond to concentrated surface runoff with high transport energy, which may or may not be associated with areas in the domain of fluvial processes (Amaral e Ribeiro, 2009). According to Bertoni e Lombardi Neto (1990), Tominaga *et al.* (2009), and Reis (2011), the speed and volume of this process depends directly on slope gradient. If the gradient of the land increases fourfold, flow speed of the runoff tends to increase twofold, while erosive capacity is four times higher. In addition to the relief, Pruski *et al.* (2003) complement that the factors influencing the rate of water infiltration in the soil also increase or decrease surface runoff. Thus, it is understood that in urban environments floods can be intensified due to an increase in impermeable areas due to constructions and paving without the management of rainwaters (Reis, 2011), that is, an efficient system of micro- and macro-drainage.

During a rain event on a constructed landscape, it is common for the flow of surface runoff to find its direction on the urban thoroughfares, especially those which are impermeable. When these roads have an efficient drainage system, they capture the flow and distribute it internally. However, when this system is lacking and not duly maintained, the water flow tends to be greater on the surface, creating genuine “road rivers”.

This phenomenon is capable of causing serious structural problems through its dragging potential, among others. In addition, when affecting the lowest parts of the relief, flooding can occur and downstream inundations can be intensified, strengthened by the substantial volume of water released over a short period into fluvial channels, which become the final part of the macro drainage system. Thus, flash floods can lead to environmental, economic, and social damage.

Given the reduced infiltration capacity associated with unplanned urbanization, flash floods are becoming more frequent and are often associated with generalized flooding (Centro de Estudos e Pesquisas em Engenharia e Defesa Civil - CEPED (Center for Studies and Research on Engineering and Civil Defense), 2013a). According to CEPED (2013a), of the disasters that affected the Brazilian population between 1991 and 2012, 21% are related to flash floods. During this period, all the Brazilian states have at least one record of the process, especially in coastal locations, such as Pernambuco, Alagoas, Espírito Santo, Rio de Janeiro, and Santa Catarina.

In the state of Minas Gerais, during the abovementioned period, 1,155 official records of severe flash floods characterized as disasters were computed, the majority occurring in the east of the state, in the Zona da Mata (Forest Area) Mesoregion. However, of the 853 municipalities in the state, 520 have at least one record

of a flash flood disaster. In the Campo das Vertentes Mesoregion, 52% (19) of the municipalities also have records of flash floods, with São João del-Rei and Prados standing out, as both have four records between 1990 and 2000 (CEPED, 2013b). In the case of São João del-Rei, the numbers may be significantly higher when analyzing the Observation Reports of the Defesa Civil Municipal (Municipal Civil Defense) (Defesa Civil, 2018, 2019, 2020) and the news on local sites and in local newspapers, as presented by Ferreira *et al.* (2022).

Given this situation and the complexity of the local relief, with accentuated slopes and an altitude range of 142m in an area of 17.5 km², the urban area of São João del-Rei was chosen as the study area for the application of the methodology proposed by Corsi *et al.* (2015). These authors suggest that the altitude range of the drainage units are predictors of the tendency to form flash floods. In addition, this study also aimed to associate the morphometry with the impermeable percentage of the drainage units to generate primary evidence to support environmental planning and territorial management, and to understand the phenomenon on a local scale.

Characterization of the study area

The municipality of São João del-Rei is located in the Central-South region of the state of Minas Gerais/ Brazil, with its municipal headquarters located at the geographical coordinates 44°15'00''W and 21°7'30''S (fig. 1). According to the Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics) (IBGE, 2021) the estimated population of 90,897 inhabitants is mostly urban. The formation history of the population nucleus dates from the end of the 17th century and is related to the mineral prospecting and exploration of the period (IBGE, 2021).

The peculiar geomorphology of São João del-Rei influenced the initial historical formation of the city, described by various authors as being inserted between valleys and slopes, which are referential elements for the formation of the urban nucleus (Brasilero *et al.*, 2013). Currently, the urban area extends between the slopes of the Serra do Lenheiro, part of the Serra de São José, and the flood plains of the Lenheiro, Água Limpa and Rio das Mortes streams. The altitude range between these slopes and valley floors is approximately 142 m (1,025 m and 883 m).

The geographical position, the rainfall characteristics of summer rains with mean precipitation of 750 mm (Baruqui *et al.*, 2006), the disordered land use, and the lack of effective policies and regulations are factors favorable to the occurrence of disasters, such as those that have happened in the form of inundations, mass movements, and flash floods.

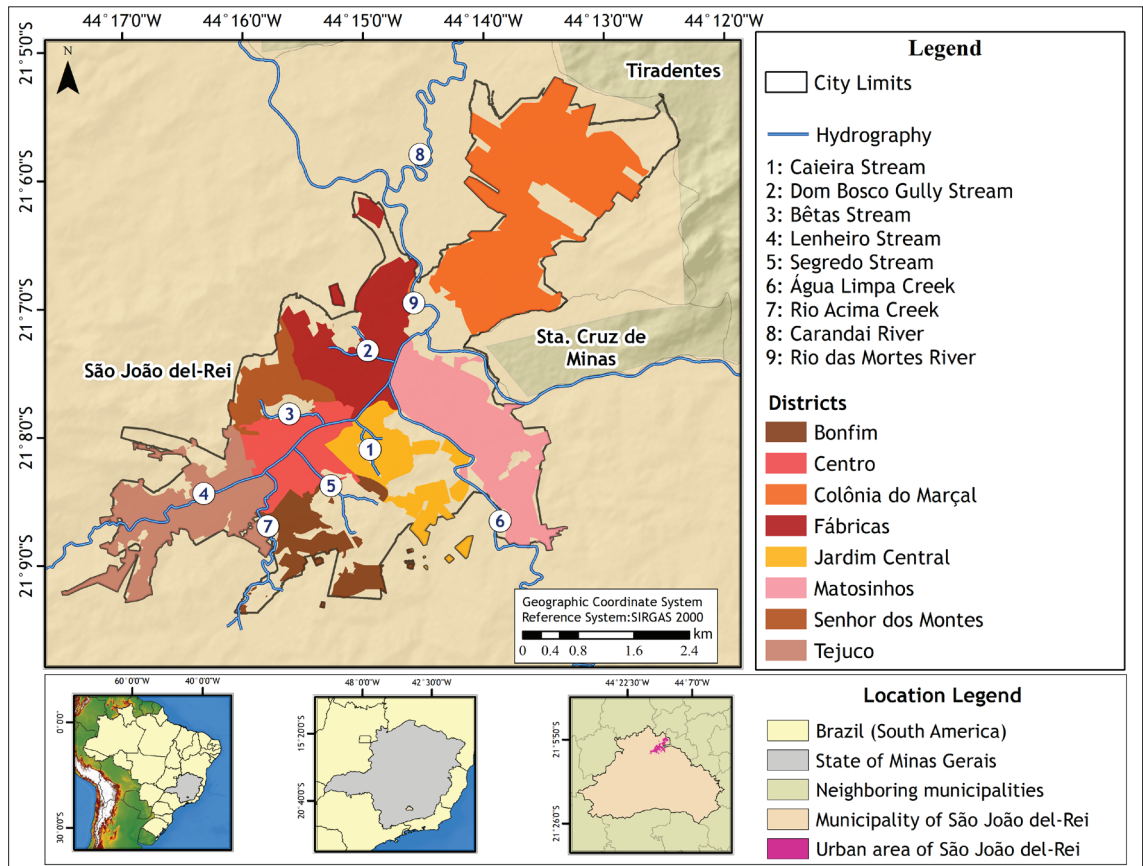


Fig. 1 - Location map of the study area.

Fig. 1 - Mapa de localização da área de estudo.

Methodology

The model of the tendency towards flash flood formation was developed based on the methodology proposed by Corsi *et al.* (2015). The proposal uses the altitude range of the drainage unit as reference under the logic that the greater the range, the greater the energy of the surface runoff.

The vectors of the drainage units, or Ottobasins, made available by the Agência Nacional de Águas (National Waters Agency) (ANA, 2018), and the Digital Terrain Model (DTM), with a spatial resolution of 5 m, were used for model development. The products were added to a GIS using ArcMap, which enabled the extraction and association of the altitude ranges with the referred drainage units.

According to Corsi *et al.* (2015), basins with a range above 300 meters are classified as susceptible to flash floods. In the case of São João del-Rei, as the maximum range does not reach this value, it was decided to represent the result on a sloping scale of maximum, minimum, and intermediate values. These can indicate areas with a greater or lesser tendency towards flash flood formation considering local topography.

Associated with the natural tendency, flash floods can be intensified according to occupation of the area, as the waterproofing of the soil for the most varied urban purposes such as buildings and the implanting of thoroughfares, increases surface runoff and, consequently, flash floods. Based on this principle, previously mapped classes of Land Use and Land Cover (LULC) with references in the Ikonos image (spatial resolution of 1m), were used to identify the impermeable percentage of the drainage units under analysis.

Image classification was carried out manually on *Ecognition* software (advanced analysis software for geospatial applications) based on automatic segmentation, using scale parameter 10 and spectral difference 3, which enabled the separation and/or clustering of the polygons, according to their similarities and differences in spectral response. Eleven LULC classes were classified, which were subsequently grouped into two classes: impermeable and permeable (TABLE I).

Subsequently, the polygons corresponding to the impermeable class were associated with the *shapefile* of the drainage units to represent the impermeable percentage of each unit. In the attributes table, a column

TABLE I - Land use and land cover (LULC) class clustering.

QUADRO I - Agrupamento de classes de UCT.

| LULC | Characteristic |
|------------------------------|----------------|
| Outcrop | < Permeability |
| Asphalt | |
| Buildings | |
| Bridges | |
| Water | |
| Bush/Tree | > Permeability |
| Landslide scar | |
| Grass | |
| Exposed Soil | |
| Semi-permeable thoroughfares | |
| Vegetated gullies | |

Below, the files for tendency towards flash floods and potential for increased surface runoff were converted into raster with a spatial resolution of 5m, as per the reference DTM, and normalized between 0 and 1. Based on this, map algebra was used between the bases (Equation 2), which enabled the acquisition of the integrated potential for flash flood formation.

Tendency towards flash flood formation X Potential for increased runoff

Results

denominated potential for increased runoff was created, which was defined based on the conception of Tucci (2000). According to this author (Op.cit), the greater the percentage of impermeable area, the greater the surface runoff of the section. As an example, in an area in which the impermeable percentage is 20%, the surface runoff volume tends to be 2.15 times greater (Tucci, 2000).

Considering this understanding, the potential for increased surface runoff was defined using the Field Calculator function of ArcMap, to obtain a runoff proportion in each unit (Equation 1).

Runoff proportion in each unit = impermeable % * 2,15 / 20

The proposed methodology presented in the previous section resulted in a set and maps that may help support the Municipal Public Authority in decision making related to urban planning and the reduction of damage arising from flash floods in the city of São João del-Rei. Among the results, first, the LULC map and the clustering of classes with greater or lesser permeability are highlighted (fig. 2). Both representations favor the comprehension and spatiality of the area and the drainage units that make up the integrated tendency towards flash flood formation, associating the altitude range with the impermeable percentage of the area. In the case of São João del-Rei, 39.42% of the urban area is impermeable.

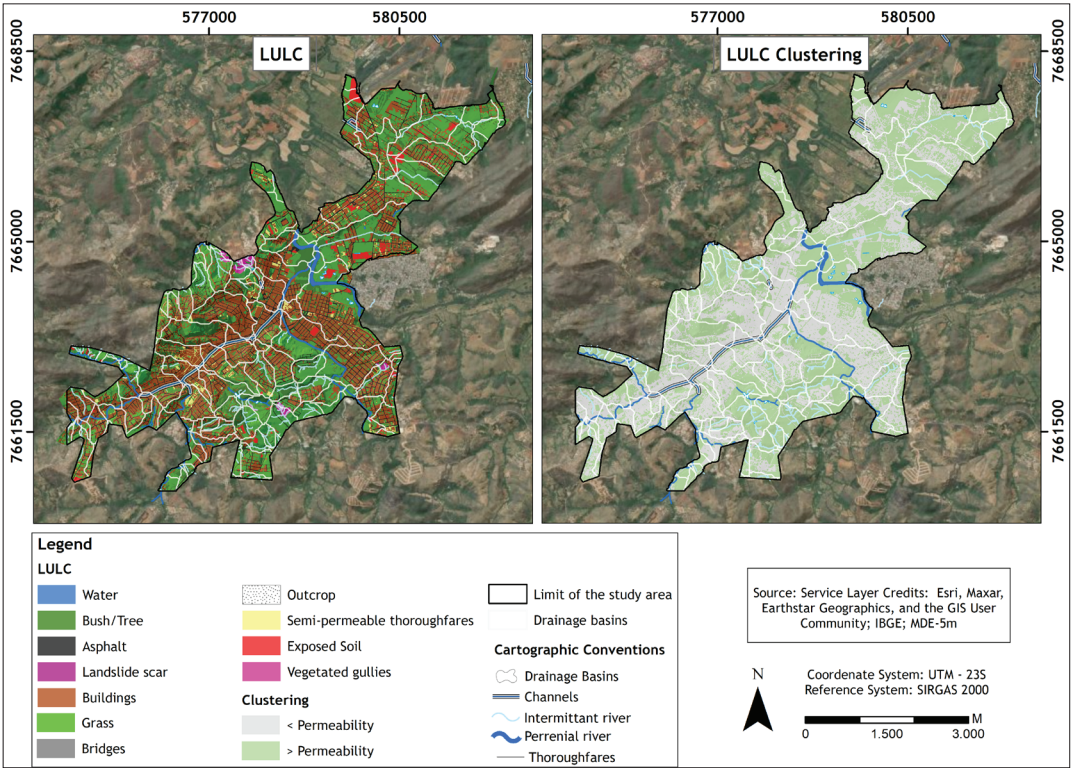


Fig. 2 - Land Use and Land Cover (LULC) and class clusters.

Fig. 2 - Uso e Cobertura da Terra (UCT) e agrupamento de classes.

According to the methodology proposed by Corsi *et al.* (2015), the drainage units with the highest altitude range present the strongest tendency towards flash flood formation. Therefore, by using the technique in the study area, it can be noted that, in the city of São João del-Rei, the basins with the strongest tendency towards flash flood formation are located in the extreme southwest and have an altitude range between 167 and 285 meters.

However, although these basins partially compose the study area, they have this altitude range due to the abrupt ruptures in the relief (presence of the steep rocky walls of the Serra do Lenheiro), where the slope gradient is above 45%. Due to these particularities, the study considered these units as outliers, and they were therefore not analyzed in detail.

The urbanized basins inserted predominantly in the area of analysis that demonstrated a more accentuated tendency towards flash flood formation are situated in the Colônia do Marçal, Fábricas, and Senhor dos Montes districts (fig. 3).

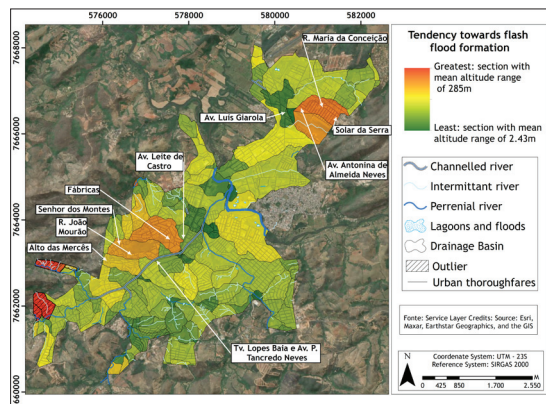


Fig. 3 - Tendency for flash flood formation.

Fig. 3 - Tendência à formação de enxurradas.

In the Colônia do Marçal district, two drainage units indicated medium to high potential for flash flood formation. Both units have their highest part in the Serra de São José and a respective altitude gain of 132 m and 144 m. While the unit with the lower altitude range has lower levels of occupation, influenced by the significant presence of drainage channels and marshy soil, the unit with the higher altitude range has an impermeable percentage of 35%, in addition to a deficient drainage system of asphalted thoroughfares positioned in the direction of the slope. These roads, especially Avenida Antonina de Almeida Neves and Rua Maria da Conceição Resende, become collectors for the entire flow of surface runoff from the basin and direct this flow of flash floods to Avenida Luís Giarola. Thus, the road on the valley floor concentrates all the flow of flash floods in the area, also causing flooding in the most lowered sections (photo 1).



Photo 1 - Flash floods in Colônia do Marçal - Av. Luís Giarola (Source: Cardozo, 2022).

Fot. 1 - Enxurradas na Colônia do Marçal - Av. Luís Giarola (Fonte: Cardozo, 2022).

The central basin, with a medium tendency, corresponds to the area of the Fábricas sector districts, such as Bela Vista, Araçá, São Geraldo, and Fábricas itself. The unit has an altitude range of 132 m and an area of 1.3 km², which mostly drains the flow of surface runoff into Avenida Leite de Castro and its vicinity. This road has gradients lower than 3% and is parallel to the foothill of the slope, collecting the flow of the entire upstream section. Thus, during rain events, there is the common occurrence of floods on this road and in the vicinity (photo 2).

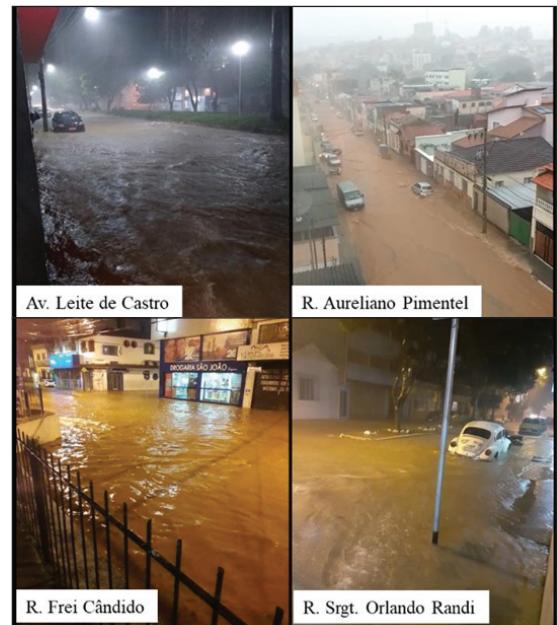


Photo 2 - Flash floods in the Fábricas sector/district (Photography by Ferreira *et al.*, 2023; Civil Defense Finding Report, taken on 07/12/2018)).

Fot. 2 - Enxurradas no Setor/Bairro Fábricas (Fotografia de Ferreira *et al.*, 2023; Relatório de Constatação Defesa Civil, tiara a 07/12/2018).5).

There is a similar situation in the drainage unit of the Senhor dos Montes region. The altitude range in this basin is 126 m and the main focus of the problem

in this area is Rua João Mourão. This road, between the Mercado Municipal (Municipal Market) and Praça Eduardo Rodrigues Vale, receives all the flow from the flash floods in the area, which is 0.47 km², being 39% impermeable. Its extension between the two mentioned points is approximately 630 m, with an altitude range of 78 m, no depressions, asphalt paving, and only three drains. As such, during rain events, the flow of the flash flood is expressive and capable of generating flooding on the roads below, especially Travessa Lopes Bahia and Avenida Presidente Tancredo Neves (photo 3).



Photo 3 - Flash floods in the Senhor dos Montes/Centro region (Photography by Raquel Ramos and Pop News, taken on 12/12/2020).
Fot. 3 - Enxurradas na região Senhor dos Montes/Centro (Fotografia de Raquel Ramos e Pop News, tiara a 12/12/2020).

The neighboring micro-basin in the region of Alto das Mercês has a medium tendency towards flash flood formation. In this area, the altitude range is only 106 m and the impermeable percentage is 56%. As such, the occurrence of this process in the area is not very representative when compared to the other regions. It occurs because, despite the medium altitude range, the area of the basin is very small (0.2 km²) and the urban layout is composed of winding, irregular roads, and rock paving, or cobbles, which favor a reduction in surface flow of approximately 1/3, when compared to asphalt (Maus *et al.*, 2007).

The remaining drainage units have a low to medium tendency towards flash flood formation. However, it is important to emphasize that exacerbated waterproofing, occupation without adequate planning, and the lack of an efficient micro-drainage system can increase surface flow and, thus, flash floods.

Thus, Tucci (2000) reiterates that the greater the impermeable percentage of an area, the greater the volume of surface flow. Quantitatively, an impermeable percentage of 20% is capable of increasing the normal surface flow volume by 2.15 times (Tucci, 2000). Given this understanding and considering that 39.42% of the study area is impermeable, it can be assumed that in São João del-Rei, the surface flow volume can be approximately 4.23 times greater due to the characteristics of the LULC. Among the units with higher potential for increasing surface flow, those standing out are located in the central area of the city of São João del-Rei, where the density of buildings tends to be higher. In the suburban areas, or those in expansion, this potential is lower due to the presence of green areas (fig. 4).

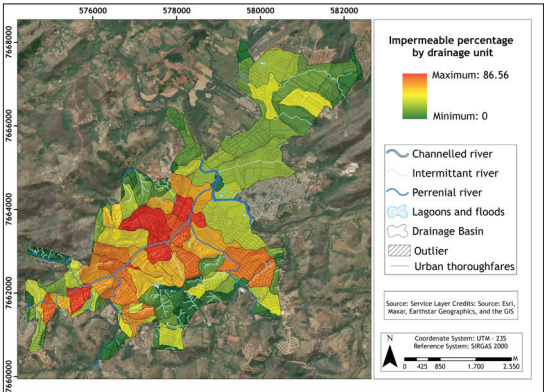


Fig. 4 - Impermeable percentage by drainage unit.
Fig. 4 - Percentual de impermeabilização por unidade de drenagem.

Based on this parameter, the morphometric propensity of each basin to form flash floods was related to the expected potential increase in surface runoff (fig. 5), with the aim of integrating natural characteristics and anthropic-spatial influences.

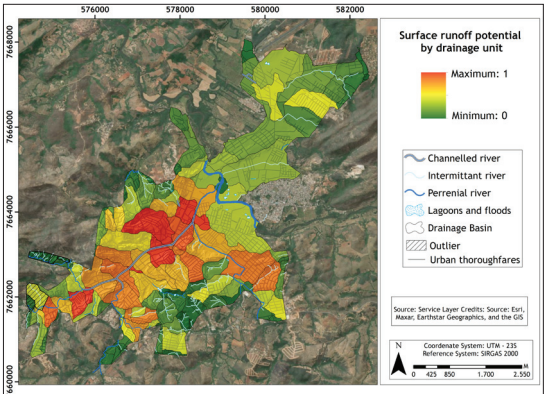


Fig. 5 - Surface runoff potential by drainage unit
Fig. 5 - Potencial de escoamento superficial por unidade de drenagem.

Through this juxtaposition, the increase in the tendency towards flash floods was obtained (fig. 6). Thus, it

can be noted that the drainage units described above with greater propensity to form flash floods, had the process enhanced. Among the units, the drainage unit that includes the Fábricas Sector and Alto das Mercês districts stands out, given the impermeable percentages above 70% and 56%, respectively. In general, it can be observed that the integration between the tendency towards flash floods and the potential increase in surface runoff indicated an increase of the areas with medium propensity to form flash floods in the central region. On the other hand, in the suburban areas, where the population density is lower and there is less housing, there is a decrease in the tendency due to the lower impermeable percentage, with the exception of the Solar da Serra drainage unit. Despite being around 35% impermeable, this unit had its tendency increased because the natural tendency between medium and high was associated with a medium impermeable percentage.

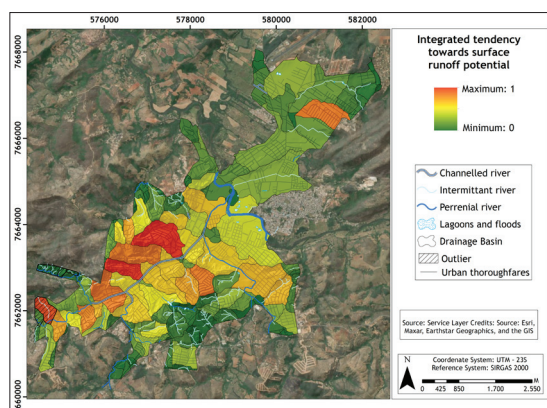


Fig. 6 - Integrated trend for surface runoff potential.

Fig. 6 - Tendência integrada ao potencial de escoamento superficial.

In general, the developed products correspond to spatial analysis tools that could support urban planning and reduce the damage caused by flash floods and flooding. Based on these materials, future zoning and standards for urban soil division, a waterproofing coefficient, an increase of urban green areas, and projects that aim to improve micro- and macro-drainage systems could be established.

Final considerations

Analyzing and understanding the dynamics of natural processes that influence the security and quality of life of the population has become a measure of security and disaster prevention, and, above all, planning. Therefore, this study used a methodology to identify the tendency towards flash flood formation that is already used by national and international institutions of reference, such as the Serviço Geológico Brasileiro (Brazilian Geological Service) and the Instituto de Pesquisas Tecnológicas do Estado de São Paulo (Institute of Technological research of the state of São Paulo).

Considering the natural tendency of the flash flood formation process, a complement was used that associated altitude range of the drainage units with the potential for increased surface runoff, obtained through the impermeable percentage. As such, it was possible to identify urban basins with a greater or lesser integrated tendency towards flash flood formation, observing the phenomenon on a local scale.

It is noted that the methodological complement, as well as the results, integrates natural landscape variables with the horizontal characteristics, which correspond to compartmented land use in impermeable and permeable areas.

The investigation and analysis can support planning organs and public works in the adaptation of infrastructure, such as paving, road position, micro-drainage, and bridges, among others, to the characteristics of the drainage unit. This will involve establishing lower percentages of impermeable areas in basins with a greater tendency towards flash flood formation. In addition, the study can provide support in decision-making priority regarding the urban drainage system, such as expansion of the micro-drainage system and promotion of green areas as a non-structural measure to reduce the damage caused by urban waters.

Acknowledgements

Processes n.º: 2022/15464-1, Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP); This work was carried out with support from Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq, processo 151431/2025-6. The opinions, hypotheses and conclusions or recommendations expressed in this material are the responsibility of the authors and do not necessarily reflect the views of FAPESP.

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