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Flood Vulnerability Assessment in Ungauged Watersheds: a Simple Approach Using Regional Functions and 1D Hydraulic Modelling

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A B S T R A C T

Proper flood risk management is essential to guarantee population safety and decrease economic losses. Hydrologic and hydraulic modeling, which enable the creation of flood maps, urge as an important tool to support decision-makers. In this sense, this work aims to map urban areas vulnerable to floods in Lavras, Minas Gerais, Brazil. Considering that many urban watersheds in Brazil lack in streamflow monitoring, as is the case of Lavras, regional functions are an alternative to adequately estimate maximum streamflow. We compared two maximum streamflow regional functions developed for the Grande River Basin, where Lavras is located. Design floods of 2, 5, 10, 20, 50, 100, 500 and 1000-year return periods were estimated by 3-parameter Log-Normal probability density function and the regional functions. The percent error and Nash-Sutcliffe coefficient of natural, logarithmically transformed streamflow showed that the regional function developed by index flood and regional growth curve is more adequate for Lavras as opposed to the regional function based on the best-fitted PDF. Finally, flood maps for 5, 10, 50 and 100-year return periods were created using the software HEC-RAS. The identified flooding areas may support decision-makers of the city to improve the urban drainage system and propose effective soft and hard control measures for vulnerable areas in Lavras.

Keywords: Flood maps. Flood management. Inundation. Flood risk. Grande River Basin.

Avaliação da Vulnerabilidade a Inundações em Bacias Hidrográficas Não Monitoradas: uma Abordagem Simples Utilizando Funções Regionais e Modelagem Hidráulica Unidimensional (1D)

R E S U M O

O gerenciamento do risco de inundações é essencial para garantir a segurança da população e reduzir perdas econômicas. Modelagens hidrológicas e hidráulicas, que possibilitam a criação de mapas de inundação, são ferramentas relevantes para apoiar os tomadores de decisão. Este trabalho visa mapear áreas urbanas vulneráveis a inundações em Lavras, Minas Gerais, Brasil. Devido à falta de monitoramento de vazões em muitas bacias urbanas do Brasil, como em Lavras, as funções regionais apresentam-se como uma alternativa para estimar vazões máximas. Duas funções regionais de vazão máxima desenvolvidas para a Bacia do Rio Grande, onde está situada Lavras, foram comparadas. As cheias de projeto com períodos de retorno de 2, 5, 10, 20, 50, 100, 500 e 1000 anos foram estimadas utilizando a função densidade de probabilidade Log-Normal de 3 parâmetros e as funções regionais. O erro percentual e o coeficiente de Nash-Sutcliffe da vazão natural transformada logaritmicamente indicaram que a função regional desenvolvida com base na inundação de índice e na curva de crescimento regional é mais adequada para Lavras, em comparação com a função regional baseada na densidade de probabilidade de melhor ajuste. Por fim, mapas de inundação para períodos de retorno de 5, 10, 50 e 100 anos foram criados utilizando o software HEC-RAS. As áreas identificadas como sujeitas a inundações podem apoiar os tomadores de decisão na cidade a melhorar o sistema de drenagem urbana e propor medidas de controle eficazes, tanto estruturais quanto não estruturais, para as áreas vulneráveis em Lavras.

Palavras-Chave: Mapas de inundação. Gestão de inundações. Alagamento. Risco de inundação. Bacia Hidrográfica do Rio Grande.

Introduction

Appropriate design of urban drainage systems and studies aiming to assess and reduce the risks and damages caused by inundations are essential to maintain population safety and quality of life. With urban populations expected to grow substantially in the next years, the expansion of impervious surfaces and built environments is anticipated to rise proportionally, significantly amplifying flood risks in urban areas. Rapid and unplanned urbanization often leads to extensive soil sealing, impeding natural infiltration processes and increasing surface runoff (Öztürk et al., 2024). This results in overwhelming existing drainage infrastructure and amplifying flood events (Moraes et al., 2018; Zhao et al., 2023). Furthermore, inadequate urban planning, particularly in regions prone to floods, creates vulnerabilities that threaten both immediate safety and the long-term sustainability of urban ecosystems (Oteng-Ababio et al., 2024).

Moreover, extreme rainfall events are expected to be more frequent and intense due to climate changes, increasing runoff and raising inundation risks (Medeiros et al., 2022; Veiga et al., 2023). This is because climate change disrupts the hydrological cycle, causing shifts in rainfall patterns and intensities, as well as affecting the timing and magnitude of seasonal streamflow (Utsumi and Kim, 2022; Gao, et al., 2023; Ho et al., 2023;). The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2015) predicts a rise in the intensity and frequency of heavy precipitation, particularly in mid-latitude and tropical humid regions, leading to more frequent flooding disasters.

Floods are predominantly triggered by rainfall, but their severity is influenced by various factors such as the timing, intensity, and spatial distribution of precipitation, along with the specific characteristics of the drainage basin, such as soil permeability, land use, vegetation cover, and topography (Basri et al., 2021). These complexities highlight the need for nuanced approaches to manage the escalating impacts of climate change on hydrological systems (Xu and Chen, 2022; Basri et al., 2021).

Flood events have widespread and devastating impacts across the globe. According to The Emergency Events Database (EM-DAT, 2024), floods accounted for nearly half of all-natural disaster on a global scale between 2000 and 2023, affecting regions including Africa, the Americas, Europe and Oceania). South America is identified as the second most impacted continent by floods, , behind Asia (CRED, 2022), the scale of flooding has dramatically increased, with the number of affected individuals rising from an average of 560,000 annually between 1995 and 2004, to 2.2 million annually from 2005 to 2014 (CRED and UNDRR, 2015).

In Brazil, 2023 marked a record year for hydro-geological disasters, including floods, landslides, and wave actions, as reported by the National Center for Monitoring and Early Warning of Natural Disasters (Cemaden, 2024). According to the Brazilian Institute of Geography and Statistics (IBGE, 2018) and Cemaden (2024), more than 8 million Brazilians live in areas vulnerable to floods, landslides, and other climate-related hazards. Over 870 municipalities are designated as high-risk zones, with approximately 18% of the population in these areas being especially vulnerable, including children under five and elderly individuals. For instance, in 2024, the state of Rio Grande do Sul experienced severe flooding due to intense rainfall, which caused rivers and streams to overflow, displacing thousands and causing significant damage to homes and infrastructure. These catastrophic events underscore the growing threat of climate-induced disasters and emphasize the urgent need for a comprehensive reevaluation of national disaster management strategies (Martins-Filho et al., 2024; Pillar and Overbeck, 2024).

Economic losses from flooding encompass both direct impacts, such as damage to properties and infrastructure, and indirect costs, including disruptions to economic activities and essential services. Globally, extreme precipitation events result in economic damages exceeding $30 billion annually (Ren et al., 2023). However, the ramifications of flooding extend beyond material destruction, posing significant public health challenges. Contaminated floodwaters, often laden with fecal matter and rodent urine, facilitate the spread of diseases such as hepatitis A, typhoid fever, and leptospirosis. Moreover, disruptions to sanitation systems frequently contaminate water and food supplies, exacerbating outbreaks of illnesses like diarrhea, particularly among vulnerable populations such as the elderly, severely dehydrated individuals, and those from lower socioeconomic backgrounds (Adelodun et al., 2021).

Flood conditions also increase exposure to tetanus through wounds and promote mosquito proliferation, though the links to diseases like dengue and malaria remain underexplored (Martins-Filho et al., 2024; Ziliotto et al., 2024). Tragically, floods often result in loss of human lives (Pillar and Overbeck, 2024) As highlighted by Oda et al. (2024), gaps in public administration compound these challenges by delaying effective response and recovery efforts.

In this sense, aiming to avoid or reduce negative impacts caused by extreme events, decision-makers should consider an integrated and sustainable flood management. While large-scale structural measures, such as dams and levees, are commonly used to control flood risks, they can create a false sense of security, and their failure can worsen flooding and economic damage (Ridolfi et al., 2020; Osberghaus and Hinrichs, 2021). Conversely, non-structural measures like land-use planning and early warning systems offer more cost-effective and adaptable solutions (Zang et al., 2022). Effective urban drainage planning is key to this strategy, which involves comprehensive approaches that consider both preventive and corrective measures. This includes sustainable urban occupation and infrastructure design that accounts for natural water management systems and limits impervious surfaces, reducing flood risks (Xu and Chen, 2022).

Hence, hydrologic and hydraulic modelling rise as important tools, since they allow simulation of different scenarios to perform flood events studies, flood risk management and urban drainage design (Nkwunonwo et al., 2020; Zhao et al., 2023). These tools are essential for water management and policy-making regarding urban drainage planning (Souza, et al., 2012). The integration of advanced technologies provides a proactive approach to guide policy decisions to reduce vulnerability, managing and mitigating the impacts of floods mainly in urban areas (Dharmarathne et al., 2024).

One such suite of tools is the Hydrologic Engineering Center (HEC) package, developed by the United States Army Corps of Engineers (USACE), which offers a comprehensive set of software designed for hydrological engineering and process planning analysis. This suite supports the study of surface and groundwater hydrology, fluvial hydraulics, sediment transport, and real-time water quality management, alongside hydrological statistics, risk analysis, and reservoir system management. Among the software in the HEC package, HEC-HMS (Hydrologic Modeling System) and HEC-RAS (River Analysis System) are particularly well-known for their application in flood management and urban drainage modeling (Souza et al., 2012; Moraes et al., 2018; El Bilali et al., 2021; Peker et al., 2024).

HEC-HMS specializes in simulating hydrological processes, particularly in dendritic basins, and incorporates various procedures such as infiltration, unit hydrographs, and continuous simulations for processes like evapotranspiration, snowmelt, and soil moisture. It also includes additional tools for model optimization, flow prediction, and uncertainty analysis, as well as the study of erosion, sediment transport, and water quality (Scharffenberg et al., 2018). On the other hand, HEC-RAS focuses on hydraulic modeling, primarily for rivers and channels. It supports simulations of both permanent and non-permanent flows and allows for modeling sediment transport, water quality, and temperature (Brunner and CEIWR-HEC, 2016; Demir, Beden and Ülke Keskin, 2021). HEC-RAS is indispensable for assessing flood risks, planning urban drainage systems, and formulating environmental protection strategies.

Accurate hydrologic and hydraulic modeling relies heavily on streamflow data, which are often limited, especially in small or remote watersheds where gauging stations are sparse (Beskow et al., 2016; Huang et al., 2020). To overcome these challenges, regionalization techniques are employed, using statistical relationships from nearby gauging stations to estimate streamflow in ungauged areas. These methods help produce more reliable streamflow estimates, which are crucial for creating flood hazard maps and performing hydraulic modeling (Baidya et al., 2020; Lelis et al., 2020; Abreu et al., 2022). This regional approach aids in improving flood risk assessments, which are vital for flood mitigation strategies (Mishra et al., 2022).

In urban areas, modeling becomes more complex due to the distinct hydrological processes in built environments. The presence of impervious surfaces, complex drainage systems, and the interaction between surface runoff and sewer networks make it difficult to predict flood behavior As urbanization increases, accurately capturing these complexities in models is essential for improving urban flood management and drainage planning. Thus, advanced regionalization methods and tailored modeling approaches are necessary to address the unique challenges posed by urban environments and ensure more effective flood risk management strategies (Zhao et al., 2023; Sarkar and Gayen, 2024).

In developing countries, the challenges of flood risk management are exacerbated by poorly integrated public policies that fail to align urban expansion with efficient water resource management strategies (Nkwunonwo et al., 2020; Oteng-Ababio et al., 2024). These nations are often the most affected by extreme flood events, yet policymakers struggle to implement effective flood risk management due to multiple obstacles. Key among these are limited financial and human resources, which hinder the collection and analysis of crucial data for flood forecasting and planning. Moreover, there is often a lack of technical expertise, which makes it difficult to predict the impacts of floods and devise appropriate mitigation strategies (Egbinola et al., 2017; Nkwunonwo et al., 2020; Membele et al., 2022).

This lack of resources and expertise results in poorly informed decision-making, leading to increased vulnerability of urban populations to flood disasters. Additionally, the scarcity of reliable data and infrastructure for monitoring exacerbate the difficulty of predicting and addressing flood risks effectively (Mishra et al., 2022). This makes it challenging to develop and implement long-term, sustainable flood risk management plans. As urban populations continue to grow, these challenges are likely to intensify, making it crucial for governments and stakeholders to invest in capacity-building and better data collection systems to improve flood resilience (Egbinola et al., 2017, Dharmarathne et al., 2024).

In Brazil, the lack of streamflow monitoring significantly hinders effective flood risk management, particularly in small and medium-sized cities. Regionalization studies and the comparison of various methodologies have become crucial to address this gap in hydrological data (Lelis et al., 2020). Without adequate monitoring, accurate flood hazard mapping becomes challenging, undermining city management efforts, including disaster prevention, drainage planning, and land-use policies in municipalities that frequently experience flood events (Brites et al., 2019; Mudashiru et al., 2021). Moreover, rapid urbanization and land use changes, compounded by climate change, are exacerbating the frequency of flooding in many regions across the country (Nkwunonwo et al., 2020; Membele et al., 2022).

The situation is particularly dire in smaller municipalities, where there is not only a lack of streamflow monitoring but also insufficient data on inundation boundaries during flood events (Beden and Ülke Keskin, 2021). This data deficiency, coupled with a shortage of technical expertise and resources, creates significant gaps in flood assessment and risk management practices. As a result, these cities struggle to implement effective flood mitigation strategies, leaving populations vulnerable to increasing flood risks (Egbinola et al., 2017; Nkwunonwo et al., 2020). Addressing these challenges requires strengthening monitoring systems, investing in technical capacity, and developing better flood forecasting and risk assessment frameworks.

Flood risk assessment plays a crucial role in urban planning and the implementation of policies for environmental protection and regulation (Cea and Costali, 2022). However, the effectiveness of these assessments depends heavily on reliable data, particularly streamflow data, which remains insufficient or unavailable in many regions of Brazil (Tucci, 2016, Egbinola et al., 2017; Ferreira et al., 2021; Abreu et al., 2022). The frequent mismanagement of urban drainage systems and flood risk planning in Brazilian cities, as noted by Tucci (2016), highlights the urgent need to enhance flood risk assessment methodologies.

In response, this study hypothesizes that simple techniques using secondary and satellite data can aid in effective flood risk management in resource-limited cities by enabling informed decision-making and supporting the development of targeted strategies. This research seeks to generate flood maps for an ungauged watershed in Lavras, MG, Brazil, to enhance flood risk management. Additionally, the study evaluates the predictive performance of two maximum streamflow regional functions developed for the Grande River Basin, aiming to identify the most suitable function for accurate flood mapping in Lavras.

Materials and methods

Study area

The Grande River basin, located in the states of Minas Gerais and São Paulo, in the southeastern region of Brazil, has gone through severe flood events. According to the Brazilian National System of Water Resources Information (ANA, 2019a), 96 of the 434 cities located in the Grande River Basin faced at least one inundation event between 2003 and 2015. In addition, 502 rivers sections were identified as highly vulnerable to floods with high impact and frequency (ANA, 2019b).

Lavras, in the South of Minas Gerais, is located in the upper region of Grande River and in the drainage area of Funil Hydropower plant. Although there are no large rivers in the most urbanized part of the city, residents often experience inundation problems in the urban streams. The city presents a population of 104,761 inhabitants (IBGE, 2024), 95,6% living in urban areas (IBGE, 2010); demographic density 185.5 inh.km-2, urbanized area of 24.15 km² and the urbanization/impervious of roadways correspond to 37.4% (IBGE, 2024). The climate in this region is Cwb in Köppen classification, with dry winter and rainy summer (Alvares et al., 2013). Regarding the water resources, Lavras is located in the Grande River Basin, more specifically into two Water Resources Planning and Management Units (UPGRH): the “Alto Rio Grande” (GD1), which comprises an area of 8,758 km² with 106,906 inhabitants in 32 cities; and the “Vertentes do Rio Grande” (GD2) with a drainage area of 10,533 km² including 42 municipalities and a population of 562,476 inhabitants, of which 88% live in urban areas (IBGE, 2024).

The Vermelho Creek is one of the main urban watercourses in Lavras, a tributary of the Grande River, and often faces inundation events. The software HEC-HMS and HEC-RAS have been widely applied to hydrologic and hydraulic modelling focused on flood management and urban drainage (Souza et al., 2012; Brunner and CEIWR-HEC, 2016; Moraes et al., 2018; Scharffenberg et al., 2018). Considering the most urbanized area of the Vermelho Creek watershed, a subbasin was delineated using the add-in HEC-GeoHMS in ArcGIS 10.5, with area 29.24 km² and perimeter 35.37 km. Then, reaches that constantly deal with flood impacts were selected for generating inundation boundaries for streamflow of 5, 10, 50 and 100-year return periods in the software HEC-RAS 5.0.7 (Figure 1).

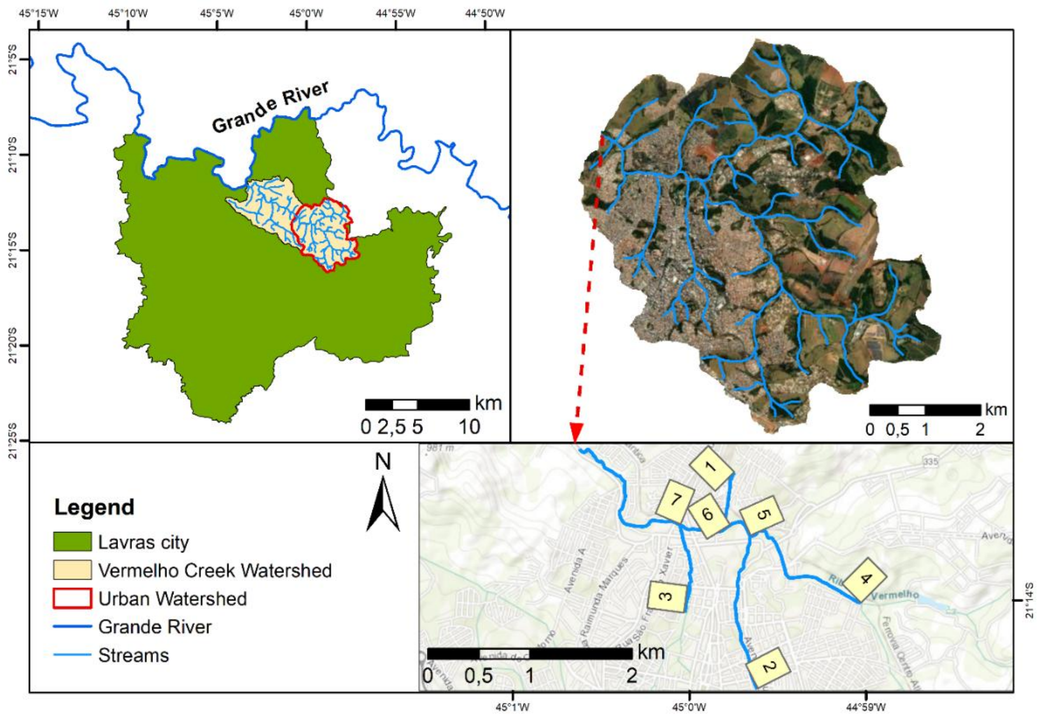


Figure 1. Urban watershed of the Vermelho Creek located in Lavras, MG, Brazil, and selected reaches (1 to 7) for flood mapping.

For the delineation of the urban watershed in ArcGIS and further the hydraulic modelling in HEC-RAS, we used:

• a DEM with spatial resolution of 3x3 m created from contour lines spaced by 1 m, provided by the Secretary of Public Works of the municipality of Lavras;

• aerial images from 2014, provided by the Secretary of Public Works of the municipality of Lavras, with a spatial resolution of 0.07 m;

• a stream area threshold of 1 km² to delineate streams in HEC-GeoHMS.

Maximum streamflow estimates

As the urban watershed studied is ungauged, selecting the most appropriated estimates for maximum streamflow is an important step to guarantee the reliability of the flood maps. Table 1 presents the regional functions developed by Amorim et al. (2020) (RFA) and Souza et al. (2021) (RFS), that applied different methodologies and streamflow observations from different gauge stations (Figure 2).

Table 1. Maximum streamflow regional functions developed for the Grande River Basin by Souza et al. (2021) and Amorim et al. (2020).

Regional function developed by Souza et al. (2021) (RFS)	Regional function developed by Amorim et al. (2020) (RFA)
$Q_R = Q_{mc}\,[0.5133\ln(RP) + 0.5016]$ In which, for ungauged sites: $Q_{mc} = 0.0937A + 20.6312$	$Q_R(2) = 0.17A^{0.92}$ $Q_R(5) = 0.51A^{0.83}$ $Q_R(10) = 0.76A^{0.80}$ $Q_R(20) = 0.98A^{0.79}$ $Q_R(50) = 1.22A^{0.79}$ $Q_R(100) = 1.38A^{0.79}$ $Q_R(500) = 1.71A^{0.8}$ $Q_R(1000) = 1.86A^{0.8}$

Q_R: regionalized streamflow (m³/s); Q_{mc}: index flood, taken as the mean of the AMS series (m³/s) for gauged sites; RP: return period (years); A: drainage area (km²).

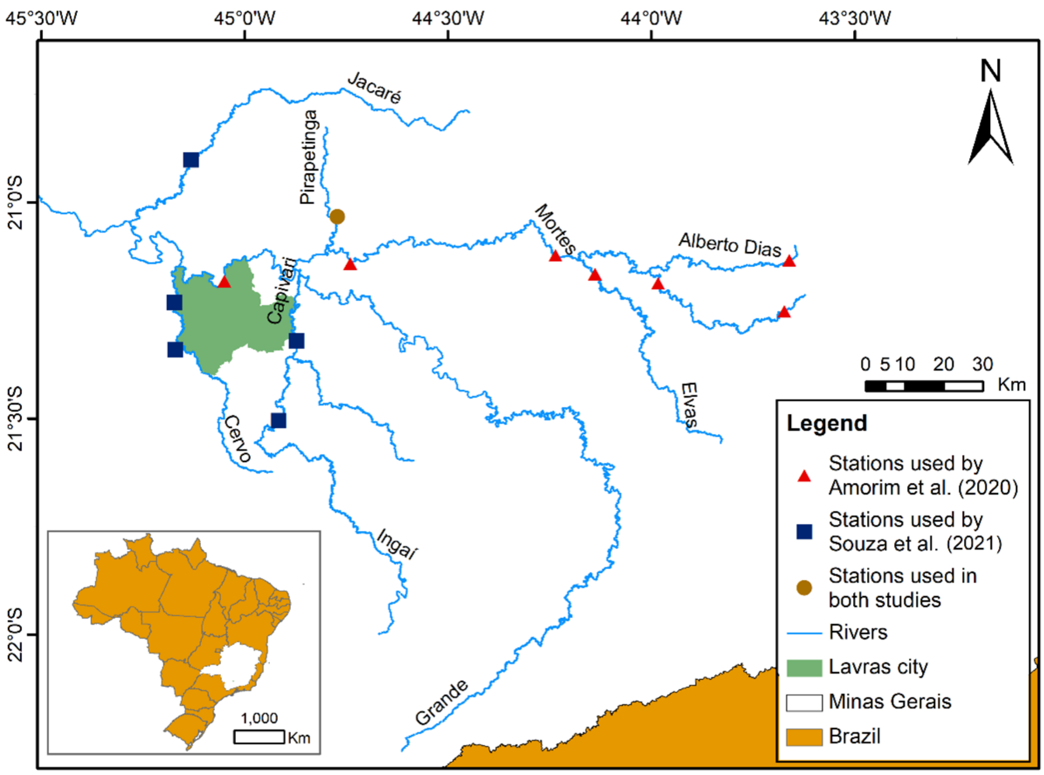


Figure 2. Location of the streamflow gauge stations regionalized by Amorim et al. (2020) and Souza et al. (2021).

The authors of the two previous studies verified adequate performance of the regional functions for estimating maximum streamflow in the Grande River Basin (Amorim et al., 2020; Souza et al., 2021). The comparison of two maximum streamflow regional functions showed that estimates by Souza et al. (2021), using data transfer for the index flood, produced better results, despite it was generated regionalizing drainage areas larger than the analyzed watershed. The estimates by the regional function enabled the construction of flood maps in the ungauged urban watershed and the assessment of population vulnerability considering the ongoing and regulated land use.

For this study, in order to select the most adequate estimates, we compared the regional functions RFA and RFS using the annual maximum streamflow (AMS) series from Bom Sucesso (A = 351.22 km²) and Alfredo Vasconcelos (A = 20.04 km²). These two watersheds were chosen for the following reasons: (a) data from the Bom Sucesso gauge station were applied by both studies in the regionalization, and it presents the smallest area among those studied by Souza et al. (2021); (b) Alfredo Vasconcelos presents a drainage area similar to that of the urban watershed in the city of Lavras (29.24 km²), even though its data were used exclusively in the study by Amorim et al. (2020).

The selected AMS series were adjusted to the probability density function (PDF) 3-parameter Log-Normal (LN-3P) and goodness-of-fit was assessed by the Anderson-Darling test. We estimated the PDF quantiles for 2, 5, 10, 20, 50, 100, 500 and 1000-year return periods and the confidence intervals were constructed by Monte Carlo Simulation (Naghettini, 2017).

Next, the quantiles were also estimated by the regional functions. For RFS, as Bom Sucesso series were used in the regionalization, the Qmc was the observed mean annual maximum streamflow of 71.03 m³/s. Alfredo Vasconcelos was considered as ungauged, then, the index flood was calculated as a function of the drainage area (Qmc = 0.0937A + 20.6312). The index flood for this site was also estimated considering data-transfer from a hydrologically similar site in order to enhance the streamflow predictions (Institute of Hydrology 1999; Kjeldsen and Jones 2007; Kjeldsen and Jones 2010). The Institute of Hydrology (1999) recommends using data from a gauged site (donor site) ideally situated just upstream or downstream of the site of interest; or a similar sized watershed on an adjacent tributary with similar physiography and land use; or a more distant site considered sufficiently similar to the ungauged site. Then, the index flood considering data-transfer from a donor site is estimated by Equation (1).

$$Q_{mc\text{-}adj} = Q_{mc\text{-}est} \frac{q_{d\text{-}obs}}{q_{d\text{-}est}} \quad (1)$$

Where: $q_{d\text{-}obs}$ is the observed index flood at the gauged site; $q_{d\text{-}est}$ is the index flood at the gauged site estimated by the linear function; $Q_{mc\text{-}est}$ is the estimated index flood at the ungauged site and $Q_{mc\text{-}adj}$ is the adjusted index flood at the ungauged site.

To identify the donor site, a homogeneity analysis was performed by adding Alfredo Vasconcelos AMS series into the homogeneous region formed by the six stations regionalized by Souza et al. (2021). This step was necessary, as one of the conditions to apply regional functions is that the sites are part of a homogeneous hydrologic region. We followed the same procedures of these authors to calculate the heterogeneity measure (H) and the discordancy measure (Di) (Hosking and Wallis, 1993; 1995). An acceptably homogenous region would show H < 1. The Di is complementary and identifies a discordant site in comparison to others. Hosking and Wallis (1995) presented threshold values for Di, which depend on N (number of sites) to identify a discordant site i in comparison to the other (N − 1) sites (Table 2).

Table 2. Critical values for the discordancy measure (Di).

Number of sites in the region	Critical value
5	1.333
6	1.648
7	1.917
8	2.140
9	2.329
10	2.491
11	2.632
12	2.757
13	2.869
14	2.971
≥ 15	3

Source: Hosking and Wallis (1995).

By analyzing the drainage area and the discordancy measure, the most similar site was chosen as donor to data-transfer for index flood estimation when considering Alfredo Vasconcelos as ungauged. Finally, the maximum streamflow for an ungauged site were estimated by RFA, RFS and using index flood adjusted by data-transfer for the regional function developed by Souza et al. (2021), so called RFS-a.

The performances of the regional functions were evaluated by the percent error from PDF estimates for all regional estimates and the mean percent error for each basin, and Nash-Sutcliffe coefficient of natural, logarithmically transformed (NSE-LN) streamflow. The NSE-LN was chosen as performance metric because the Nash-Sutcliffe coefficient can be highly sensitive to outliers and skewed data, since the differences between observed and estimated values are squared and an arithmetic mean is implied. Then, to avoid this problem and provide a coefficient that is more evenly affected by the predictions, an alternative is to consider the NSE of the natural logarithms, although it is unable to handle zero data (Gupta and Kling, 2011; Farmer et al., 2015).

Hydraulic modelling and flood maps for the urban ungauged watershed

One-dimensional hydraulic modelling, such as HEC-RAS, are considered the simplest flood models, as they don't necessarily require distributed topographic and friction data, and are computationally efficient (Nkwunonwo et al., 2020). The hydraulic modelling was performed in the software HEC-RAS 5.0.7, in order to assess flood prone areas in the urban watershed in Lavras, MG, Brazil. The software allows carrying on all the simulation pre-processing and post-processing steps to create the inundation profiles.

From the urban watershed delineated and analyzing the aerial images, we drew the geometry layers: river centerline, bank lines, flowpaths and cross-sections. The aerial images were used to identify the land use and then to attribute Manning's n values for the floodplain and river channels. We considered n values of 0.035, 0.025 and 0.020 for the floodplain, channels with vegetation and constructed channels, respectively (Butler and Davies, 2004). Bridges and culverts, and their geometry, were also identified through the aerial images. The simulations were proceeded considering one-dimensional and steady flow, and normal depth as boundary condition.

Figure 3 shows the hydraulic model created on HEC-RAS using the aerial images and the DEM with resolution 3x3 m. The software extracts all the necessary information for the flow computations, as the distance between cross-sections and river length. Figure 4 shows an example of a cross-section in the Vermelho Creek, after computing the delineated geometry and the DEM information on HEC-RAS.

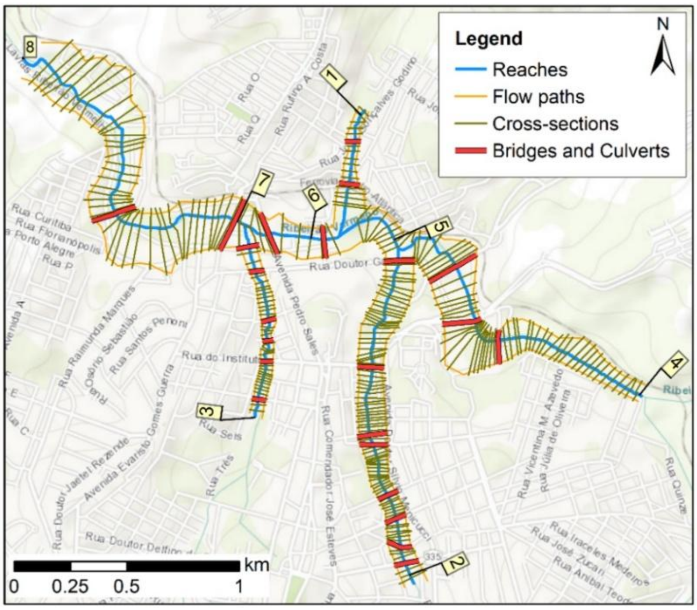


Figure 3. HEC-RAS geometry for the selected reaches in the urban part of Vermelho Creek watershed in Lavras, MG, Brazil.

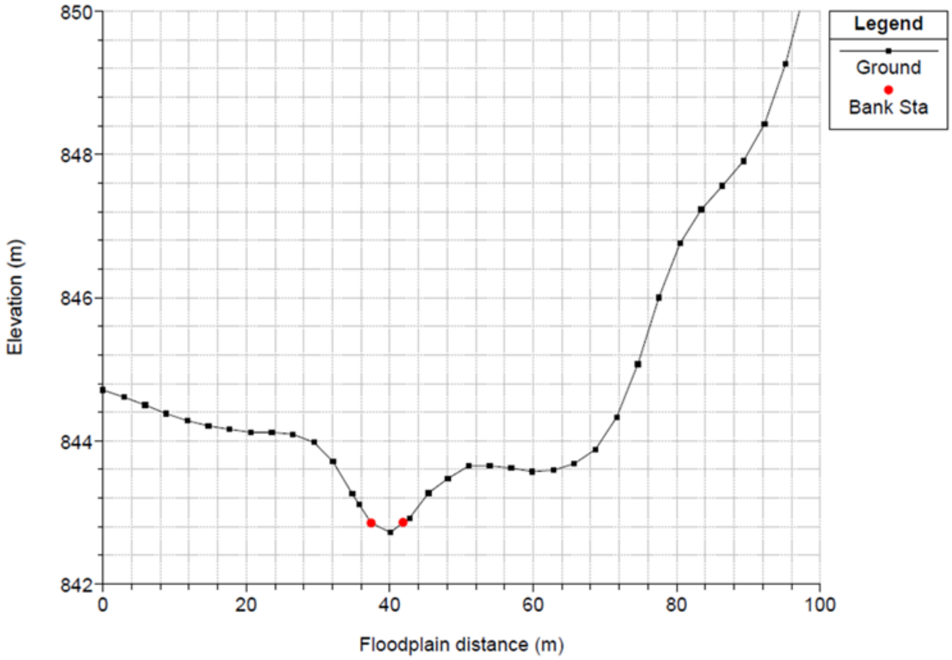


Figure 4. First cross-section of the Vermelho Creek (reach 4) obtained from HEC-RAS using the DEM with 3 meters resolution. Bank Sta: bank station, i.e., the margins of the river.

Following the pre-processing simulation, the discharge values were implemented for each reach. The streamflow was estimated by the regional function that yielded the most adequate predictions in the performance analysis described previously. Hence, the HEC-RAS simulation resulted in water surface profiles that, upon integration with the DEM, enabled the generation of flood extension and depth layers. Finally, flood maps were elaborated for the urban watershed of Vermelho Creek, considering return periods 5, 10,50 and 100-year.

Assessment of the areas affected by the design floods

Evaluating areas affected by the design floods, the current land use, and the city occupation policies is essential for effective urban drainage planning. The land use and occupation were assessed by manually classifying the aerial images of the urban watershed using ArcGIS 10.5. We defined 5 classes of land use: buildings; sparse vegetation; vegetation; roads and railways; and channels. The regulated land use was assessed by the urban zones described in the Soil Use Directive Plan of Lavras (Lavras, 2019; 2020), which establishes land use regulation policies for the city.

Therefore, using the flood maps created, we analyzed the ongoing and the regulated land use within the inundation areas simulated. Thus, a comparison between the impacted areas by the floods in each of the land use cases was possible. In addition, we estimated the population likely to be affected by the design floods of 5, 10, 50 and 100-year return periods, taking into account the area of buildings affected in each return period and the urban population density of 4,147 inh.km-2, which was calculated by the urban population and the urbanized area of Lavras (IBGE, 2024).

Results and discussion

Flood estimates by the regional functions

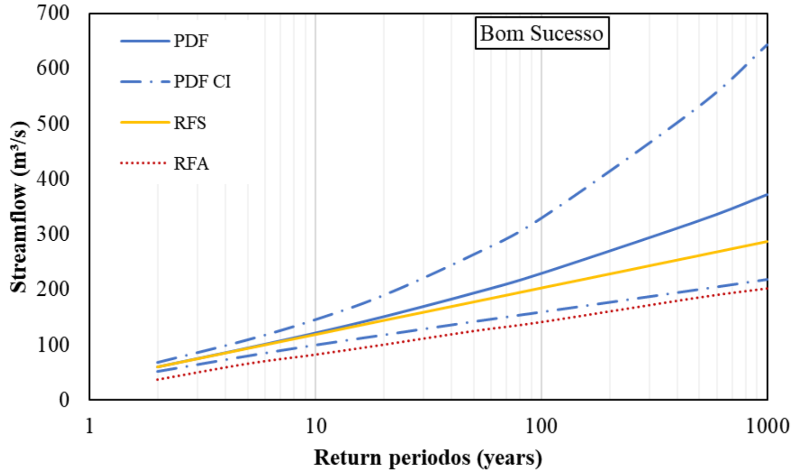
The homogeneity analysis showed that Alfredo Vasconcelos can be include to the region identified by (Souza et al., 2021) since the heterogeneity measure was lower than one (H = 0.9245), which characterizes a homogeneous region (Hosking and Wallis, 1995; 1993). Then, to calculate the index flood for Alfredo Vasconcelos applying the data-transfer scheme, we selected the gauge station Couro do Cervo, since these two stations presented closer Di and drainage areas in comparison with the others (Table 3).

Table 3. Discordancy measure (Di) and drainage areas of the streamflow gauge stations regionalized by Souza et al. (2021) and the gauge station Alfredo Vasconcelos.

Station	Discordancy Measure (Di)	Drainage Area (km²)
Alfredo Vasconcelos	1.3331	20.21
Couro do Cervo	1.6905	387.86
Bom Sucesso	0.5930	351.22
Itumirim	0.6770	1825.44
Luminárias	0.8944	1003.91
Marechal Mascarenhas	1.1876	1049.96
Santana do Jacaré	0.6245	1439.14

Figure 5 shows the streamflow estimates and confidence intervals of PDF for Bom Sucesso and Alfredo Vasconcelos, respectively. Figure 6 shows the distribution of the percent errors of the streamflow estimates using RFA and RFS for Couro do Cervo (gauged basin), and using RFA, RFS and RFS-a for Alfredo Vasconcelos (considered as ungauged).

(a)



(b)

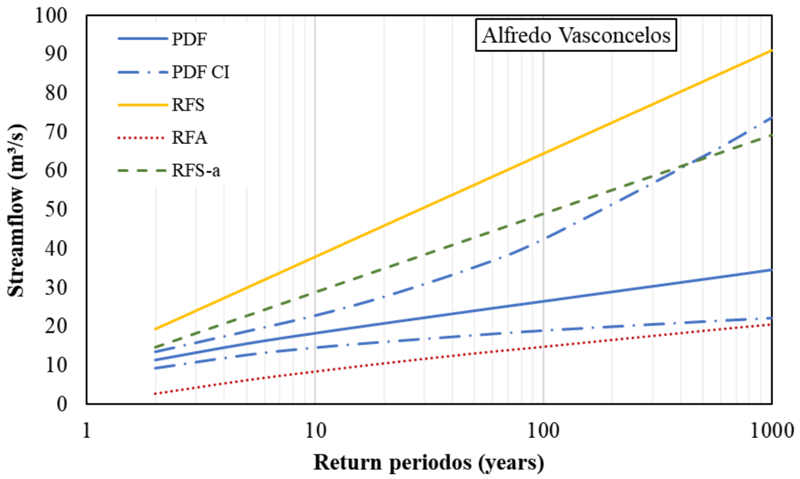


Figure 5. Streamflow quantiles estimated by the LN-3P probability density function (PDF) with confidence intervals (PDF CI) and estimated by the regional functions by Souza et al. (2021) (RFS), with data-transfer for the index flood (RFS-a) and by Amorim et al. (2020) (RFA) for the station Bom Sucesso (a) and Alfredo Vasconcelos when considered as ungauged (b).

RFA underestimated the streamflow in Bom Sucesso out of the confidence interval of the PDF estimates, and presented mean percent error around -37% and NSE-LN of 0.353 (Table 4). For lower return periods (until 50-years), RFS resulted in very close estimates to the PDF's values and all estimates were within the lower confidence interval.

RFS presented a high NSE-LN (0.951), confirming the good performance of this regional function to estimate floods in Bom Sucesso gauge (Table 4). Figure 6a shows that the RFA highly underestimates the streamflow in comparison to the RFS.

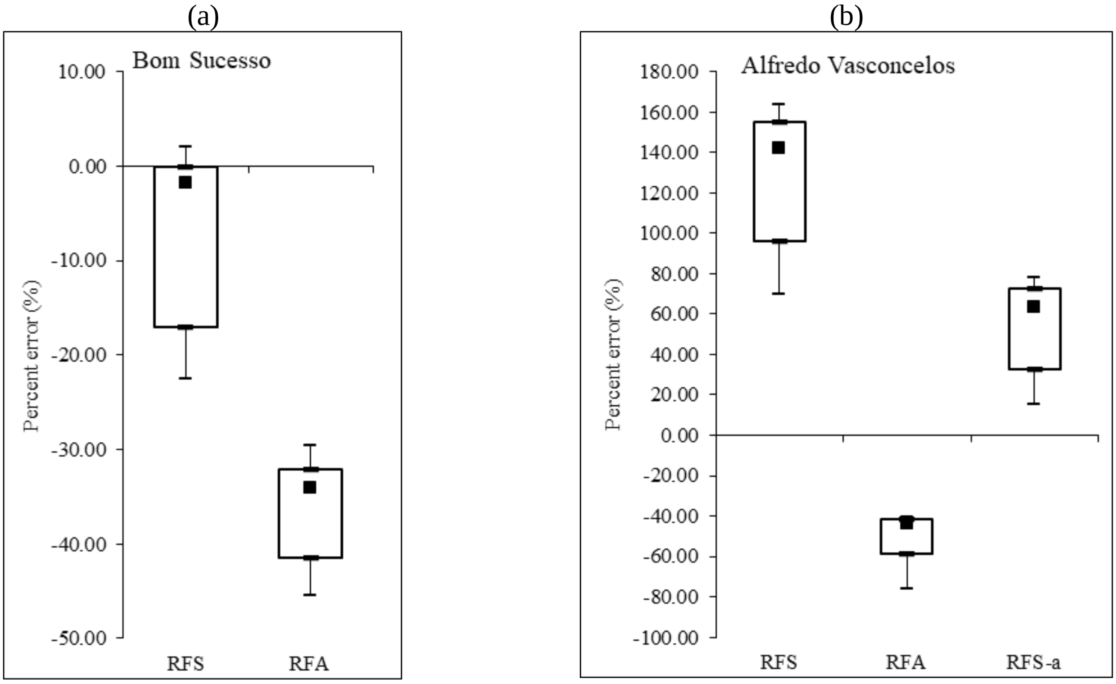


Figure 6. Distribution of percent errors of streamflow estimates for each regional function at the gauge stations Bom Sucesso (a) and Alfredo Vasconcelos (b).

Table 4. Performance of the regional estimates by Souza et al. (2021) and Amorim et al. (2020) evaluated by the mean percent error (MPE), Nash-Sutcliffe of natural-logarithm data (NSE-LN).

Station	Regional estimate	MPE (%)	NSE-LN
Bom Sucesso	RFA	-36.675	0.353
	RFS	-7.870	0.951
Alfredo Vasconcelos	RFA	-51.297	-4.314
	RFS	123.984	-4.333
	RFS-a	51.480	-0.503

For Alfredo Vasconcelos station, when considered as ungauged, RFA underestimates in average -51% the streamflow values comparing to LN-3P estimates (Table 4) and all estimates are out of the confidence interval bound, with NSE-LN of -4.314. RFS overestimates in average 124% the streamflow and are also out of the confidence interval bound (NSE-LN = -4.333). In spite of the estimates by the regional function developed by Souza et al. (2021) with data-transfer for the index flood (RFS-a) still overestimates the streamflow (+51%) and are out of the confidence interval, the NSE-LN has improved considerably (-0.503). The percent errors of RFS-a estimates have also dropped considerably (Figure 6b).

The index flood approach showed lower errors for lower return periods (2 and 5-years), whereas RFA resulted in lower errors for superior return periods (Figure 5b). Baidya et al. (2020) analyzed streamflow estimates by three methods of flood frequency analysis in the Mahanadi River basin, India: direct interpolation of flood quantiles, interpolation of L-moments and flood index procedure. These authors also observed better predictions using index flood for lower frequencies. Although regional functions should not be extrapolated to basins with areas out of the regionalized range (Naghettini, 2017; Fasipe and Izinyon, 2021), RFS-a resulted in better predictions for Alfredo Vasconcelos.

Amorim et al. (2020) regionalized the maximum streamflow by the selected values method, in which, the streamflow values are determined for fixed return periods by using the best adjusted PDF for each time series (Tucci, 2002). Thus, the regression model is produced based on estimates by the best-fitted PDF, which transfer uncertainties related to the adjustment. On the other hand, the regression model developed by Souza et al. (2021) is based on the observed streamflow values, therefore, decreasing inherent errors.

However, hydrological modeling may lead to the underestimation of streamflow, particularly in representing peak flows regions, (Liu et al., 2023). As highlighted by Souza et al. (2021), underestimates of streamflow can represent great risks for population safety when planning flood control measures. Otherwise, overestimates may imply higher costs of structural measures. Thus, balancing these two overviews is essential in flood risk management. Considering that and the performance of the regional functions analyzed for Alfredo Vasconcelos, these findings suggest that RFS-a is more suitable for flood predictions in ungauged watersheds in the city of Lavras.

The design floods for each reach in the Vermelho Creek urban watershed were estimated by the RFS-a, using Couro do Cervo as donor site for index flood data-transfer (Table 5). It is important to mention that Souza et al. (2021) regionalized maximum streamflow from drainage areas varying from 351.22 to 1825.44 km²; extrapolating the index flood to the urban watersheds (0.98 to 29.24 km²) may result in inaccurate estimates. In addition, the linear regression used to estimate the index flood (Q_{mc}) for ungauged sites, implies that when the watershed area is zero, the Q_{mc} is equal to the linear coefficient of the equation (20.6132 m^3s^{-1}). Thus, design floods in smaller drainage areas are highly influenced by the Q_{mc} estimates, resulting in small differences in the regionalized streamflow, as is observed in Table 5.

As highlighted by Ferreira et al. (2021), linear regression is characterized by its applicability, simplicity and good performance. But it should be applied to hydrologically similar regions, as these methods are limited to modeling linear responses (Filipova, 2022). However, as aforementioned, this method better predicted streamflow in Alfredo Vasconcelos, justifying its application. Further analysis, adding this gauged site to the regional function developed by Souza et al. (2021), might improve the estimates.

Table 5. Streamflow estimates for the urban reaches studied in Lavras by the regional function developed by Souza et al. (2021) with data-transfer for the index flood that were used to performing the hydraulic modelling in HEC-RAS.

Reach	n.	Area (km²)	Upstream flow (m³/s)							
			2-year	5-year	10-year	20-year	50-year	100-year	500-year	1000-year
Stream 1	1	0.98	12.0	18.6	23.6	28.6	35.2	40.2	51.7	56.7
Stream 2	2	2.15	12.1	18.7	23.7	28.7	35.4	40.4	52.0	57.0
Stream 3	3	1.04	12.0	18.6	23.6	28.6	35.2	40.2	51.8	56.7
Vermelho Creek	4	12.39	12.6	19.6	24.8	30.1	37.0	42.2	54.4	59.6
Vermelho Creek	5	19.98	13.0	20.2	25.6	31.0	38.2	43.6	56.2	61.6
Vermelho Creek	6	24.51	13.3	20.6	26.1	31.6	38.9	44.4	57.2	62.8
Vermelho Creek	7	26.00	13.4	20.7	26.3	31.8	39.2	44.7	57.6	63.1
Vermelho Creek (estuary)	8	29.24	13.6	21.0	26.6	32.2	39.7	45.3	58.3	64.0

Flood maps in the urban ungauged watershed

Hydraulic modelling and simulation can develop reliable flood assessments based on digital data, satellite images and field observations (Tariq et al., 2021; Al-Hussein, 2022; Schumann et al., 2023; Peker et al., 2024). Despite their limitations on representing hydrological processes, 1D flood modelling remains an important tool in the context of small and medium-sized cities with scarcity of resources and data (Nkwunonwo et al., 2020). Table 6 presents the inundation areas simulated for the streamflow estimates of the Vermelho Creek Watershed (shown on Table 5) and Figure 7 shows the flood extents for design floods of 5, 10, 50 and 100-year return periods.

Table 6. Inundation areas for the urban reaches studied in Lavras, simulated using the streamflow estimates of the regional function developed by Souza et al. (2021) with data-transfer for the index flood.

Return period (years)	Inundation area (km²)
2	0,36
5	0,40
10	0,44
20	0,47
50	0,50
100	0,52
500	0,59
1000	0,62

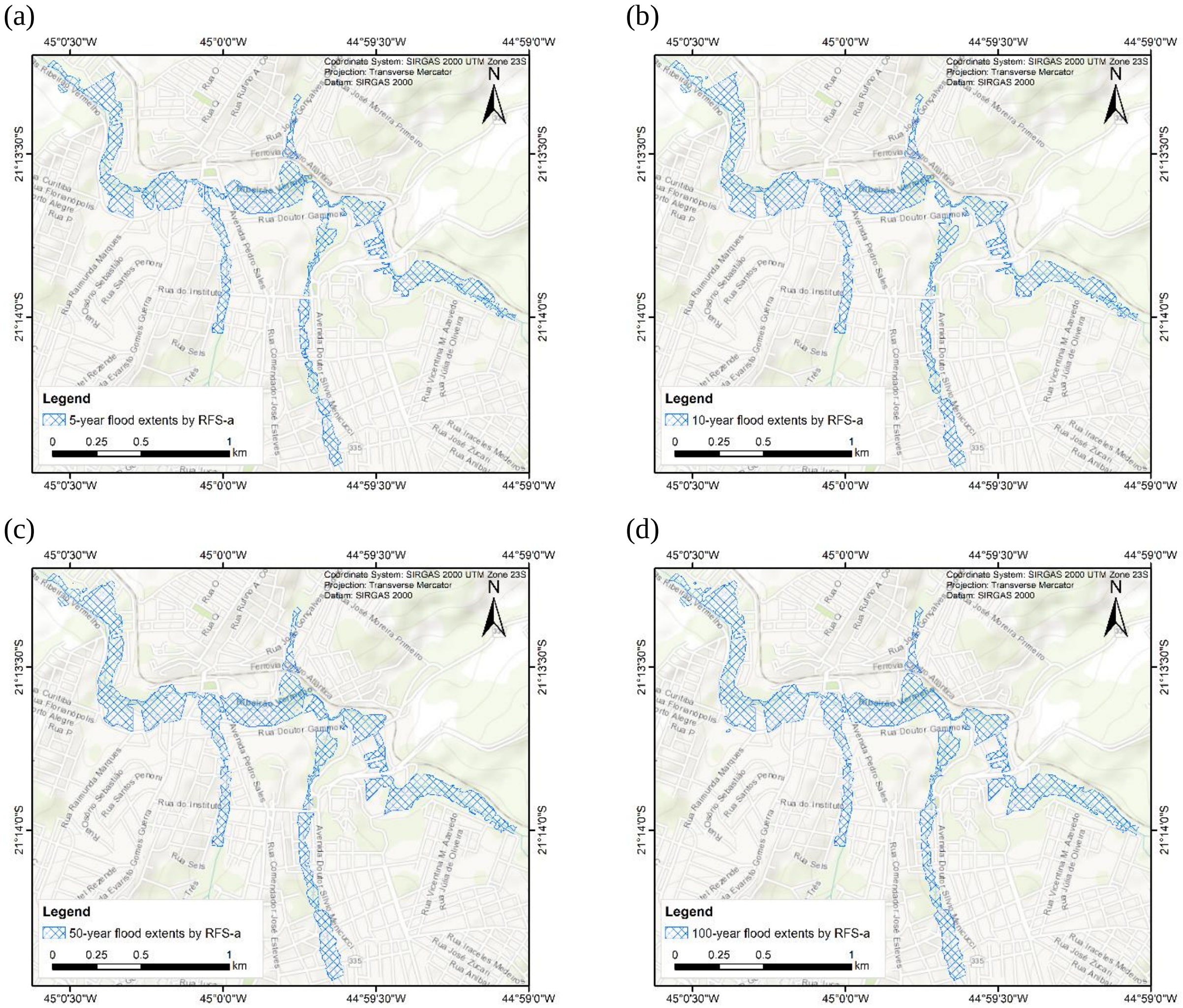


Figure 7. Flood extents in the selected urban area of Lavras for 5-year (a); 10-year (b); 50-year (c) and 100-year (d) return periods with streamflow estimated by the adjusted index flood and regional growth curve developed by Souza et al. (2021).

Tariq et al. (2021) compared the extent of inundated areas simulated by HEC-RAS for a flood event occurred in 2014 in Indus River with MODIS satellite images. These authors used DEM of 30x30 m resolution, still, the flood extents simulated matched closely the satellite images. However, they observed several islands and reservoirs produced by the hydraulic simulation, which may be attributed to the fact that water surface generation assumes continuous values of elevation whereas the DEM has intervals of 1 meter. Some disconnections were also observed in the simulated maps for Lavras that may be more accurate by calibrating channel roughness values and performing a more detailed field assessment of the geometry of reaches (Jafarzadegan, Merwade, and Saksena, 2018; Shaikh et al., 2023).

Al-Hussein et al. (2022) evaluated the floodplain of a reach of Khazir River in Northern Iraq, integrating hydrological and hydraulic analyses through HEC-HMS and HEC-RAS with geographic information systems. Hydraulic modelling by HEC-RAS enables the diagnosis of the hydrodynamic behavior of the watercourse and drainage channel, serving as a basis for urban drainage projects and the establishment of effective environmental, social and economic protection strategies.

Along with that, considering future changes in the hydrological behavior of an area is important to an effective flood management, as it can increase the areas vulnerable to floods. As discussed previously, the regional function overestimated the design floods for Alfredo Vasconcelos. In consequence, it suggests that the inundation areas produced by the hydraulic modelling for Lavras may also be overdesigned. Therefore, the flood maps created may comprise future increases in runoff in the urban area of Lavras due to LULCC and or climate changes.

Urban occupation of the areas affected by the designed floods

Along with the Environmental and Sanitation Plan, the Soil Use Directive Plan (also known as City Master Plan) comprises land use regulation policies and a minimum permeability rate for new buildings and constructions (Lavras, 2016; 2020). In Lavras, there are 18 zones that consider the availability of infrastructure and densification capacity, as well as the discomfort degree of the population and the environmental pollution. For the design floods studied, we identified 8 urban zones that would be affected (Figure 8), which the regulated uses are:

- Reference use – lands that are not regulated by the city council, as universities and colleges;
- ZAE – Economic Activity Zone, which corresponds to areas suitable for large-scale diversified economic use which conflicts with residential use in general and are suitable for installation along the main access routes to the city;
- ZEIS – Special Zone of Social Interest, where there is public interest in organizing occupancy through urbanization and land regularization, or in establishing social housing developments with the possibility of creating local commercial units;
- ZEIUA – Special Zone of Urbanistic-Environmental Interest, which corresponds to degraded urban areas, not adequate to be occupied by residences and/or buildings;
- ZMA – Densified Mixed Zone, occupied by residences, commercial buildings, services and institutions, where is allowed a medium density verticalization process;
- ZMC – Controlled Mixed Zone, where commerce, services and public facilities are concentrated, with predominance of low-density single family and multifamily residential occupation, making it possible to install commercial uses and local care services, compatible with residential use;
- ZMI – Mixed Zone, where predominates residences, but it is also possible to install commerce and local assistant services, admitting a low density verticalization process;
- ZPA – Environmental Protection Zone defined by the Brazilian Environmental Legislation, such as areas around springs and water courses that should be vegetated.

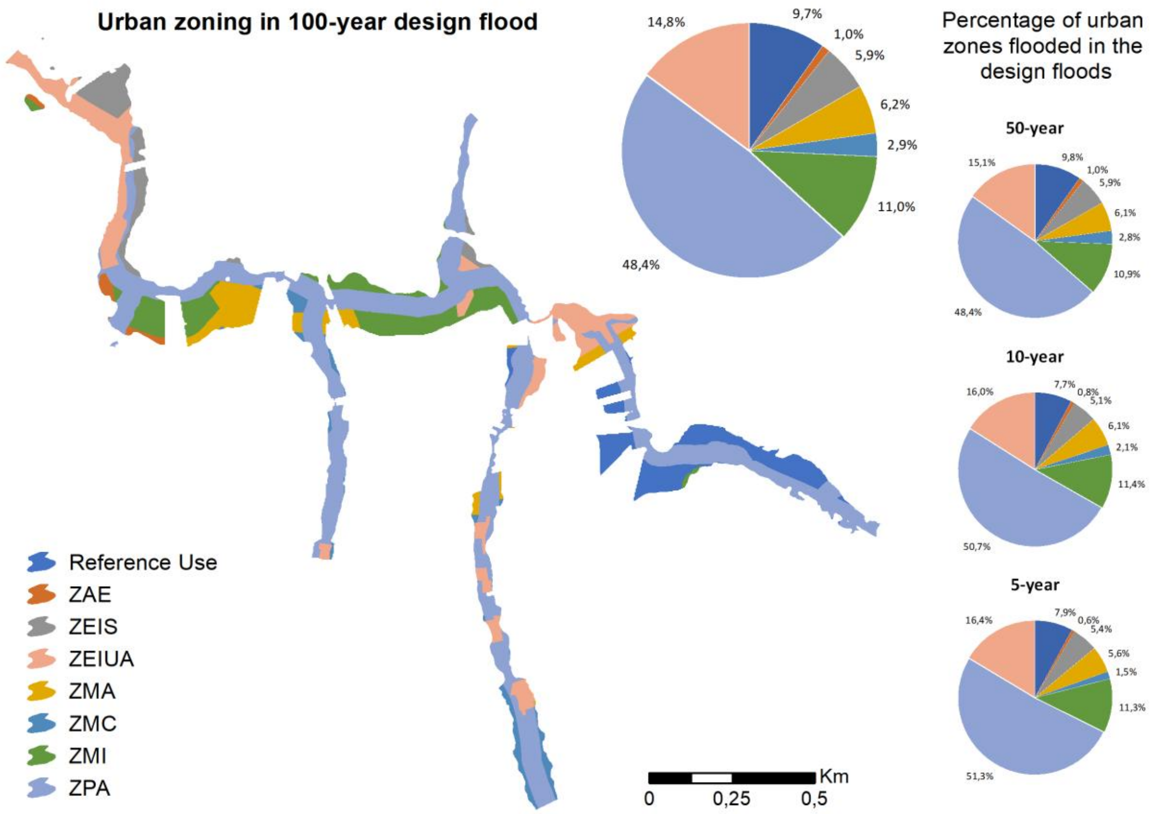


Figure 8. Assessment of the urban zoning of the areas inundated by the 100-year design flood in the urban reaches of Vermelho Creek Watershed and percentage of zones inundated by the design floods of 5, 10 and 50-year return periods.

As show in Figure 8, on average, 65% of the inundated areas are within ZPA and ZEIUA, where urbanization is mostly prohibited. We can also verify, by assessing the current land use, that the majority of the inundated areas would be vegetation (Table 7). However, as the return period increases, the percentage of affected buildings also increases, which in turn reflects on raising the population likely to be affected – estimated considering the urban population density of 4,147 inh.km^{-2} and the area classified as buildings.

Table 7. Assessment of land use and occupation of the areas inundated by the design floods in the urban reaches of Vermelho Creek Watershed.

Design flood	Inundated area by land use (m²)					Population likely affected (ihn)
	Vegetation	Sparse vegetation	Buildings	Roads and railways	Channels	
5-year	174853 (43.6%)	54685 (13.6%)	137829 (34.3%)	27875 (6.9%)	6045 (1.5%)	572
10-year	183855 (42.3%)	57899 (13.3%)	153231 (35.2%)	33780 (7.8%)	6032 (1.4%)	635
50-year	199138 (40.0%)	66901 (13.4%)	182062 (36.6%)	43062 (8.7%)	6336 (1.3%)	755
100-year	205715 (39.8%)	70201 (13.6%)	188409 (36.5%)	45800 (8.9%)	6620 (1.3%)	781

Nevertheless, the uses established on the Soil Use Directive Plan are not completely followed. By assessing the areas affected by the 100-year design flood, Figure 9 shows that 17.7% of the classified land use are not in accordance with the use regulated by the municipal legislation, which corresponds to an area of 0.1 km². In addition, 2.7% of the 100-year flooded area consists of constructions within ZEIUA zone.

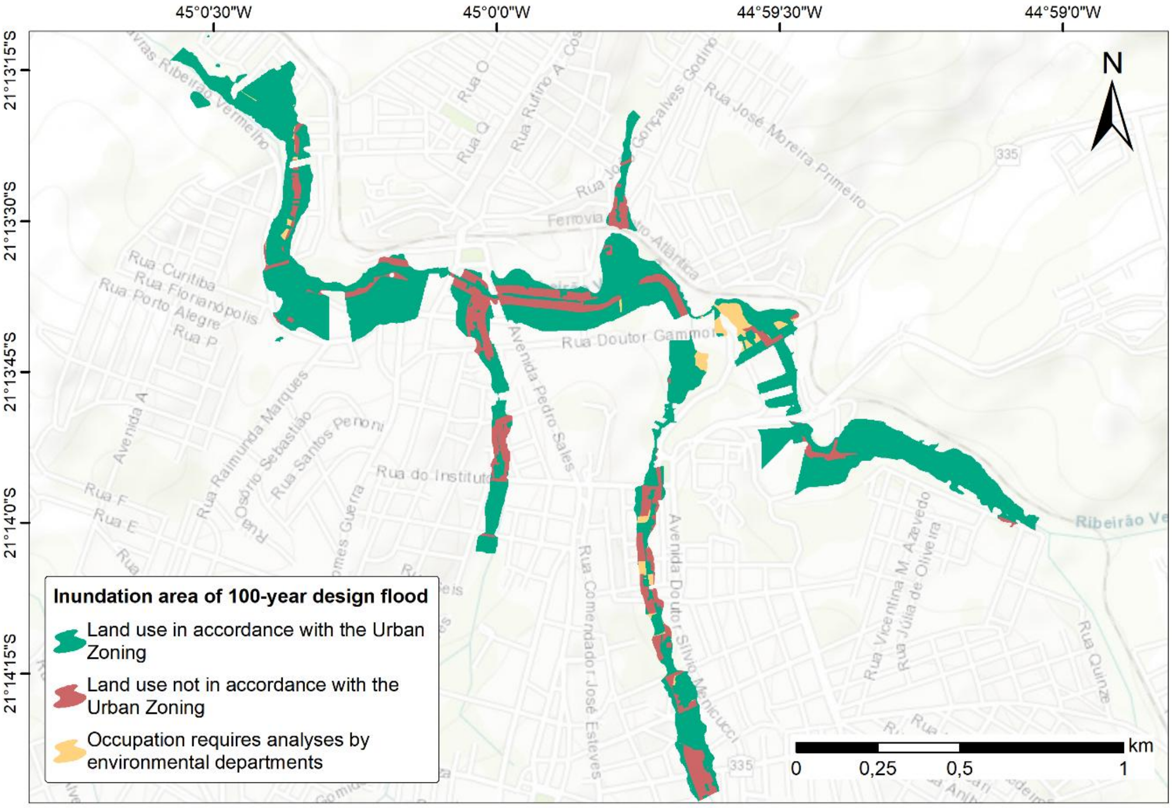


Figure 9. Comparison of the current land use and the regulated use by the Lavras Directive Plan for the inundation area of 100-year return period in the urban reaches of Vermelho Creek Watershed.

According to the Directive Plan, the occupation in ZEIUA requires analyses by environmental departments due to the risks associated with inhabiting these areas, as well as the importance for protecting and/or recovering ecosystems; and ZPA must be an area completely protected.

Therefore, adhering strictly to the land use regulation for Lavras could potentially reduce the affected population by 30%, considering that ZMA, ZMI, ZEIS and ZMC are zones that allows residential occupation (Table 8).

Table 8. Assessment of the residential urban zones of the areas inundated by the design floods in the Vermelho Creek Watershed.

Design flood	Area inundated by urban zones (m²)				Population likely affected (ihn)
	ZEIS	**ZMA**	**ZMC**	**ZMI**	
5-year	21613 (5.4%)	22399 (5.6%)	6169 (1.5%)	45379 (11.3%)	396
10-year	22387 (5.1%)	26619 (6.1%)	9049 (2.1%)	49384 (11.4%)	446
50-year	29596 (5.9%)	30565 (6.1%)	13781 (2.8%)	54130 (10.9%)	531
100-year	30520 (5.9%)	31938 (6.2%)	15127 (2.9%)	57096 (11.0%)	559

The flood maps created for Lavras are an important tool to support urban drainage planning. (Brites et al., 2019) in a study performed in the Jacu River Basin in São Paulo, suggested to employ non-structural measures (e.g. land regulation policies) to areas affected by 100-year flood, since to build structural flood control measures would be necessary an investment 21% higher than considering the 25-year floods in this watershed. Floods of smaller return periods, as 5, 10 and 50-year, should be considered for designing urban drainage systems (Zhang et al., 2024).

According to Tucci (2016), the implementation of an urban drainage directive plan is essential to guarantee population safety, controlling future impacts of floods by means of regulation policies and present impacts with structural and non-structural measures. Currently, there is no urban drainage plan implemented in Lavras, which lacks in flood management directives. The city published the Environmental and Sanitation Municipal Plan in 2018 (Lavras, 2018) that is a mandatory documentation for Brazilian cities (Brazil, 2007). However, the plan describes briefly the present drainage system and has not stablished any goals for improving flood risk management.

As highlighted by Oda et al. (2024), existing laws regulating land use are insufficient to prevent and mitigate the impacts of hydrological disasters. In addition, many governments fail to effectively address the population's flood vulnerability, particularly in informal settlements that are neglected because they are considered illegal, and because flood data are often nonexistent (Membele et al., 2022). It is imperative that government authorities not only implement soil use regulations policies but also collaborate with society to create resilient spaces, studying the development of new structural and non-structural measures. In this sense, a city planning for Lavras more focused in urban drainage and flood risk management is necessary to decrease the population vulnerability to floods and to guide the urbanization increasing. Thus, the flood maps provide fundamental knowledge for decision-makers in order to prioritize high risk areas and to choose the best approach for implementing flood control measures.

Conclusion

In this study, flood risk areas were identified through streamflow estimates by regional functions and 1D hydraulic modelling for an urban ungauged watershed located in Lavras, Minas Gerais, Brazil. The strategy adopted in this work focused on implementing simple techniques to support flood risk management in areas that lack hydrological and hydraulic field data, and often lack technical expertise.

The analysis of land use for the simulated design floods in this study showed that regulatory policies are not being followed, regardless of the recent review of Lavras' Master Plan. Consequently, the population's vulnerability to flood risks from these simulated design floods would considerably decrease if soil use regulations were strictly followed. This study demonstrates the lack in following regulation policies and moreover in adapting it in order to adequate with the society. Therefore, the findings of this study serve as a basis for new revisions of the city's regulations and action plans regarding land occupation and flood risk management.

The flood maps created are an important tool for city management and decision-making regarding the planning of structural and nonstructural flood control measures, i.e. identifying priority areas. To enhance these initial findings, future work should focus on assessing the accuracy of the hydrological and hydraulic simulations performed in this study. Conducting sensitivity analysis of the models is essential to evaluate uncertainties and ensure the reliability of the flood maps, thereby guiding action prioritization effectively. Additionally, the results of flood modelling should be carefully interpreted and communicated to avoid causing exacerbated alarm in the population regarding simulated flood areas, especially those that may be overestimated. It is important to mention that the studied area lacks historical hydrological data. Therefore, efforts to monitor the urban watershed should be considered.

Moreover, this study shows that applying and adapting available data using simple modelling can be a pathway for cities with limited resources to begin to better understand the potential risks associated with floods and to proactively build and ensure more resilient cities, especially in the context of climate change. Our results represent a crucial advancement in the context of Lavras and ungauged urban watersheds, guiding future works and supporting government decisions in investments in flood management and actions plans. These actions may include the definition of priority areas to install low-cost sensors for monitoring flood and conducting participatory socio-environmental diagnoses, thereby enhancing the population awareness of floods risks and their role in urban resilience.

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