UNIVERSIDADE FEDERAL DE LAVRAS

GABRIELA REZENDE DE SOUZA

REGIONAL FLOOD FREQUENCY ANALYSIS AS A MEDIUM FOR FLOOD MAPPING IN AN UNGAUGED URBAN WATERSHED

LAVRAS - MG
2021

GABRIELA REZENDE DE SOUZA

REGIONAL FLOOD FREQUENCY ANALYSIS AS A MEDIUM FOR FLOOD MAPPING IN AN UNGAUGED URBAN WATERSHED

Thesis presented to Federal University of Lavras, as part of the requirements of Water Resources Post-Graduate Program, concentration field in Hydrology, to obtain the PhD degree.

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Hidrologia, para a obtenção do título de Doutora.

Prof. Dr. Luiz Fernando Coutinho de Oliveira
Advisor
Orientador

LAVRAS - MG
2021

Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Souza, Gabriela Rezende de.
Regional Flood Frequency Analysis as a Medium for Flood Mapping in a Ungauged Urban Watershed / Gabriela Rezende de Souza. - 2021.
104 p. : il.

Orientador(a): Luiz Fernando Coutinho de Oliveira.

Tese (doutorado) - Universidade Federal de Lavras, 2021.
Bibliografia.

1. urban drainage. 2. hydrological modeling. 3. hydraulic modeling. I. Oliveira, Luiz Fernando Coutinho de. II. Título.

GABRIELA REZENDE DE SOUZA

REGIONAL FLOOD FREQUENCY ANALYSIS AS A MEDIUM FOR FLOOD MAPPING IN AN UNGAUGED URBAN WATERSHED

REGIONALIZAÇÃO DE VAZÕES MÁXIMAS COMO UM MEIO PARA A GERAÇÃO DE MAPAS DE INUNDAÇÃO EM UMA BACIA URBANA NÃO-MONITORADA

Thesis presented to Federal University of Lavras, as part of the requirements of Water Resources Post-Graduate Program, concentration field in Hydrology, to obtain the PhD degree.

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Hidrologia, para a obtenção do título de Doutora.

Approved in 30th April, 2021
Dr. Luiz Fernando Coutinho de Oliveira UFLA
Dr. Gilberto Coelho
Dr. Michael Silveira Thebaldi
Dr. Samuel Beskow
Dra. Isis Stacanelli Pires Chagas Scott

Prof. Dr. Luiz Fernando Coutinho de Oliveira
Advisor
Orientador

LAVRAS - MG
2021

A minha mãe Sebastiana, sempre meu maior exemplo e incentivo,
quem só soube ser amor.
A minha irmã Simone, por todo apoio e cuidado desde a infância.
A minha amiga querida Ana Beatriz (Dizanda), que seus sonhos e
seu amor continuem vivos em nós.
A esses meus três anjos no céu, dedico.
"Metade de mim agora é assim
De um lado a poesia, o verbo, a saudade
Do outro a luta, a força e a coragem pra chegar no fim"
(O anjo mais velho – Teatro Mágico)

AGRADECIMENTOS

Antes de tudo e todos os dias agradeço a Deus, por me proteger e iluminar na caminhada, por todas as pessoas que colocou em minha vida. Agradeço a nossa Mãe Maria por me carregar em seu colo tantas vezes.

À minha família, por todo amor, incentivo e confiança que sempre tive. Meu pai, Quito, por não medir esforços junto de minha mãe, Tianinha (*in memorian*), para que eu tivesse uma educação de qualidade e pudesse seguir meus sonhos. Minha mãe em especial, por me ensinar, todos os dias que estivemos juntas nesse plano, a ser uma mulher forte, independente, mas sem perder o amor e cuidado pelas pessoas, obrigada por ser meu exemplo de dedicação, fé e perseverança. Às minhas "irmães", Sô e Ma (*in memorian)*, por todo amor e apoio que sempre me deram, por acreditarem em mim, por sempre estarem presentes nessa caminhada. Aos meus sobrinhos Mayara, Matheus, Vitória e Álvaro, pela amizade que construímos a cada dia e por me inspirarem a ser exemplo para vocês.

Ao meu orientador, Prof. Coutinho, que desde o início do curso de Engenharia Ambiental e Sanitária me acompanhou. Obrigada, Coutinho, por ser exemplo de docente, por me incentivar e acreditar no meu trabalho, sempre deixando as portas abertas para que eu trabalhasse com o que tinha mais afinidade. Obrigada pela confiança que deposita em mim e conte comigo sempre!

Ao Emaús, por se tornar mais uma família em Lavras, por ser meu refúgio e minha íntima ligação com Deus, por me fazer buscar forças onde achava que não tinha. Essa comunidade que me presenteou com os melhores amigos na fé e em que eu fui capaz de trazer antigos amigos para também fazer parte.

De tantos amigos, agradeço: à Mari e Bruna C. por serem pra sempre meu apoio, por nos detalhes me mostrarem amor e compaixão e me manterem firme na fé sem nem perceber. Ana, Laís, Pena, Jess e Rabello, obrigada por estarem presentes desde quando defendi meu mestrado, cada uma com um jeito diferente, mas com um carinho e amor sem medidas, e que nunca abandonamos, afinal "ainda bem que a gente é a gente". Thiago, Biscoito e Robson por serem entusiasmo e calmaria ao mesmo tempo, serem refúgio e conselho, risadas e palhaçadas. Renan, Rodolfo, Allan, Leo, Lukão, Jas, Pets, Fernando, obrigada por toda companhia, por sempre estarem por perto mesmo que longe, obrigada pelas cervejinhas, pelos lanches, pelas conversas e por toda troca. Renan, obrigada por toda chatice, amizade sincera (às vezes até demais) e por ser tão cuidadoso com todos nós. Rabello, ainda bem que Deus não faz a gente brigar sempre, obrigada por ser minha dupla dinâmica, por estar sempre do meu lado e por eu ter certeza que sempre vai estar.

À Casa de Bamba, o melhor lar que eu poderia ter tido aqui: Maria, Dizanda (Ana Beatriz), Hérica, Thata e Yara. Diza cuida da gente daí desse lugar bem melhor que você está. Obrigada pelos momentos de conversa, por me aguentarem nos momentos de braveza e quando estava com o ego lá nas alturas, por me incentivarem e aumentarem ainda mais meu ego quando elogiam o que eu faço bem. Obrigada por acreditarem em mim e continuarem presentes mesmo cada uma em um canto, com vidas tomando novos rumos, amo vocês. À Flavinha e Lucas (esse menino aí que é seu marido) que mesmo do outro lado do oceano estão sempre por perto, garantindo boas risadas e muita saudade.

À Julinha por ter sido uma ótima escolha pra dividir o AmareLAR, por ter se tornado uma ótima amiga que chora as pitangas da pós-graduação e da vida, aconselha e toma cervejinha junto, e o mesmo digo pra Jéssica que veio no pacote. Obrigada a minha cãopanheira Lany e a Felícia por serem nossas alegrias nessa casa.

À Preserva Jr. que é a responsável pelo meu crescimento profissional, por eu entender onde eu deveria estar e qual é o meu propósito, por me fazer ser mais eco e menos ego. Obrigada por ainda se fazerem presentes nas minhas atividades e pelo orgulho de ser mais Preserva! À Zetta, por me mostrar como é possível unir todo conhecimento da academia com soluções para a sociedade, obrigada pela oportunidade de estar fazendo a diferença. Bruna: migs, obrigada por ser a ponte, por acreditar no que eu era capaz e me dar esse presente. Lu, obrigada por ser mais do que um colega de trabalho, mas um amigo tão especial em tão pouco tempo.

Aos professores do Núcleo de Engenharia Ambiental e Sanitária, por todo apoio e disponibilidade de sempre, desde a graduação. Em especial aos Profs. Camila, André e Marcelo, por me permitirem ser docente voluntária por duas vezes com tanta liberdade na sala de aula, por me incentivarem e acreditarem no meu trabalho como uma professora aprendiz. Agradeço especialmente ao professor Marcelo por ter me auxiliado e incentivado em buscar oportunidades para o Doutorado Sanduíche!

Ao Programa de Pós-Graduação em Recursos Hídricos e ao Departamento de Recursos Hídricos por permitir o desenvolvimento deste trabalho, e por toda dedicação do corpo docente e técnico. Aos membros da banca Ísis, Profs. Samuel, Coelho e Michael, por aceitarem fazer parte deste trabalho e por toda contribuição. Ísis, um obrigada especial pelos tempos de Purdue!

À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) pelo fomento concedido durante a pós-graduação contribuindo para o desenvolvimento desta pesquisa, pela Bolsa de Doutorado Sanduíche (PDSE-88881.362120/2019-01) que permitiu meu crescimento profissional e que este trabalho fosse realizado com excelência, e também durante a graduação por meio do Programa Ciência sem Fronteiras. Viva a ciência! Viva a educação! O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Código de Financiamento 001.

Thanks to Professor Venkatesh Merwade for accepting me as a visiting scholar at Lyles School of Civil Engineering, giving all the opportunities to develop my research; Joane Lax for all the knowledge shared in the workshops, her caring for us and the joy that she shows teaching. A great thanks to Purdue University for all the support to international students, for the pleasure of studying in such a great campus, I will never forget my special moments there: BOILER UP! Also thanks to Lorna, a special and caring property owner.

A todos que cruzaram meu caminho, aos tantos especiais que não sou capaz de citar aqui, cada um deixou um ensinamento, cada um deixou uma história que faz parte de mim. Nunca nos esqueçamos de quem realmente somos, de que sucesso não é apenas medido pelas nossas carreiras, pelo que produzimos, mas o porquê fazemos e como fazemos.

GENERAL ABSTRACT

Disorganized urbanization generates several negative impacts on the urban environment, such as the occurrence of intensified floods. Thus, an adequate urban planning as well as the understanding of the hydrological regime of a region are essential to (1) minimize human and economic losses caused by floods, and (2) guarantee an effective management of water resources. The main objective of this work is to evaluate simulated inundation boundaries for different design floods in Vermelho Creek Watershed in Lavras, Minas Gerais (MG), Brazil. In view of the lack of streamflow monitoring in the watershed, a study of regionalization of maximum streamflow was performed. A regional function of maximum streamflow was generated by the dimensionless curve method using data from six gauging stations in Lavras region, all located in the Grande River Basin. The gauging stations for the study were selected considering the analyses of stationarity and trends by Mann-Kendall test, and the homogeneity of the region by the heterogeneity (H) and discordancy (D_i) measures. The applicability of the regional function to estimate design floods in ungauged watersheds was verified through (1) performance analysis, using the Camargo and Sentelhas coefficient and (2) uncertainty analysis through bootstrapping and Monte Carlo simulations. The maximum streamflow regional function developed in this work can be used to estimate design floods in ungauged basins in the region, e.g., Vermelho Creek. This method is a simple alternative for maximum streamflow estimates and can be used in flood risk management. To calculate the design floods in Vermelho Creek Watershed, two regional functions developed for the Grande River Basin were compared, also considering data-transfer technique to adjust the estimated values. Two monitored basins were selected for analyses: basin X was used in both regionalization studies, and basin Y had drainage area similar to the urban watershed of Lavras. The performances were evaluated using the percentage error and the Nash-Sutcliffe coefficient between the values estimated by the regional functions and calculated by the most adequate probability density function for each studied station. The regional function developed in this work proved to be more adequate for the estimation of design floods in the Vermelho Creek Watershed. Then, flood maps were generated for return periods of 5, 10, 50 and 100 years using the HEC-RAS software. The areas affected by the design floods were compared with the current land use and the Soil Use Directive Plan of the city of Lavras. Considering the current scenario, the results showed that the areas affected in by the simulated inundation boundaries would decrease by 75% if the municipality's use and occupation guidelines were followed correctly. Therefore, this work reinforces the importance of adequate urban planning and compliance with the proposed guidelines, in order to guarantee the safety of the population and the environment.

Keywords: urban drainage; hydrological modeling; hydraulic modeling; risk management; urban hydrology.

RESUMO GERAL

A urbanização desorganizada gera diversos impactos negativos no ambiente urbano, dentre eles a ocorrência de inundações intensificadas. Assim, um adequado planejamento urbano, bem como o entendimento do regime hidrológico da região, são essenciais para (1) minimizar os prejuízos humanos e econômicos causados por enchentes e (2) garantir a efetiva gestão dos recursos hídricos. Portanto, o principal objetivo deste trabalho é avaliar manchas de inundação simuladas para diferentes vazões de projeto na Bacia do Ribeirão Vermelho em Lavras – MG. Diante da inexistência de monitoramento de vazões na bacia, primeiramente foi realizado um estudo de regionalização de vazões máximas. Uma função regional de vazões máximas foi gerada por meio do método da curva adimensional a partir de dados de seis estações de monitoramento na região de Lavras, pertencentes à Bacia do Rio Grande. As estações para o estudo foram selecionadas considerando-se as análises de estacionariedade e tendência por meio do teste de Mann-Kendall, e de homogeneidade da região pelas medidas de heterogeneidade (H) e de discordância (D_i). A adequada aplicabilidade da função regional para estimar vazões de projeto em bacias não monitoradas foi verificada por meio das análises de performance, pelo coeficiente de Camargo e Sentelhas, e de incertezas, por meio da técnica de *bootstrapping* e simulações de Monte Carlo. A função de vazões máximas desenvolvida pode ser utilizada para estimar vazões de projeto em bacias não monitoradas da região, como é o caso do Ribeirão Vermelho, sendo uma alternativa simples e capaz de auxiliar no gerenciamento de riscos de enchentes. Para o cálculo das vazões de projeto, foram comparadas duas funções regionais desenvolvidas para a Bacia do Rio Grande, também levando em consideração a técnica de transferência de dados para correção dos valores estimados. Duas bacias monitoradas foram selecionadas para a análise, uma a qual foi utilizada em ambos estudos de regionalização e outra em que a área de drenagem é similar à bacia urbana de Lavras. As performances foram avaliadas por meio do erro percentual e do coeficiente de Nash-Sutcliffe entre os valores estimados pelas funções regionais e calculados pelas distribuições de probabilidade mais adequadas para cada estação estudada. A função regional desenvolvida neste trabalho mostrou-se mais adequada para a estimativa de vazões de projeto na Bacia do Ribeirão Vermelho. Assim, foram gerados mapas de inundação para os tempos de retorno de 5, 10, 50 e 100 anos utilizando-se o *software* HEC-RAS. Dessa maneira, foi possível avaliar as manchas de inundação simuladas com o uso e ocupação do solo atual e o Plano Diretor da cidade de Lavras. Os resultados demonstraram que, considerando o cenário atual, as áreas afetadas pelas manchas simuladas seria 75% menor caso as diretrizes de uso e ocupação do município fossem seguidas corretamente. Portanto, este trabalho reforça a importância do adequado planejamento urbano e do cumprimento das diretrizes propostas, a fim de garantir a segurança da população e do meio ambiente.

Palavras-chave: drenagem urbana; modelagem hidrológica; modelagem hidráulica; gerenciamento de riscos; hidrologia urbana.

FIGURES LIST

TABLES LIST

LIST OF ACRONYMS AND ABBREVIATIONS

AMS	Annual maximum streamflow
ANA	Brazilian National Agency of Water and Sanitation
BCa	Bias Corrected and Accelerated
CI	Confidence intervals
CRED	Centre for Research on the Epidemiology of Disasters
DEM	Digital elevation model
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
IDF	Intensity-duration-frequency
LN-3P	3-parameter Log-Normal
MK	Mann Kendall test
PDF	Probability density function
PMSB	Municipal Sanitation Plan
RAS	River Analysis System
RFFA	Regional flood frequency analysis
RGC	Regional growth curve
RHN	Brazilian Hydrometeorological Network (Rede Hidrometeorológica Nacional)
SCS-CN	Soil Conservation Service Curve Number Method
SNRH	Brazilian National System of Water Resources Information
SYHDA	System of Hydrological Data Acquisition and Analysis
UFLA	Federal University of Lavras
USACE	United States Army Corps of Engineers
WHO	World Health Organization

LIST OF SYMBOLS

A	Drainage area
C	Runoff coefficient
c	Performance coefficient of Camargo and Sentelhas (1997)
CN	Curve number
D_i	Discordancy measure
H	Heterogeneity measure
I	Rainfall intensity
Ia	Initial abstraction
P	Rainfall/Precipitation
Q	Streamflow/design flood
Q_{mc}	Index flood
Q_R	Regionalized streamflow
RP	Return period
S	Storage capacity
t_c	Time of concentration
t_d	Time of duration
X	Dimensionless flood variable
Z	Statistics of Mann Kendall test

CONTENTS

FIRST PART

1 GENERAL INTRODUCTION

The accelerated urbanization of Brazilian cities has happened in great part without planning, causing severe impacts on water resources, such as water pollution, changes in river channels and in flood regime. Impervious surfaces associated with urbanization reduce infiltration and increase surface runoff, consequently increasing flood risk. Besides that, climate change may also be influencing the intensity and frequency of extreme rainfall events and surface runoff, leading to higher inundation risks.

The traditional approach to avoid urban flood is to adopt flood protection systems (e.g., engineered levees and dams), constructions that demand high economic investments and may cause environmental and social impacts. Other solutions include the channelization of water bodies to drain the exceedance volume rapidly; however, this is simply a relocation approach, transferring the problem to a downstream area.

Effective flood management must be based on hydrological studies capable to estimate design floods adequately. Thus, streamflow monitoring in watersheds is essential to properly design flood control measures. However, there is a lack of streamflow data in urban watersheds and/or with small drainage areas. To overcome this issue, regionalization techniques can be useful to estimate maximum streamflow (i.e., design floods).

Moreover, understanding flood patterns and analyzing the efficiency of control measures are primordial to an adequate planning of urban drainage. Hence, hydraulic modeling allows the simulation of different scenarios, making possible the study of flood events, flood risk management and urban drainage planning. The software HEC-RAS has been widely applied for creating flood maps, which supports decision making regarding flood management (BODOQUE et al., 2016; MORAES et al., 2018; PAES; BRANDÃO, 2013; SOUZA; CRISPIM; FORMIGA, 2012).

According to the Brazilian National System of Water Resources Information (SNIRH – which stands for *Sistema Nacional de Informações Sobre Recursos Hídricos* in Portuguese), between 2003 and 2015, at least one flood event was registered in 96 of the 434 cities located at the Grande River Basin (ANA, 2019a). Further, 502 river stretches in the basin are classified as highly vulnerable to floods, with high impact and frequency (ANA, 2019a). The Grande River Basin is located in the states of Minas Gerais and São Paulo, in the southeastern of Brazil. This basin is subdivided in 14 Water Resources Planning and Management Units (UPGRH), eight in the state of Minas Gerais and six in São Paulo (IGAM; CBH, 2013). Grande River basin drains an area of 143,437.79 km² (39.80% in the state of São Paulo and 60.20% in Minas Gerais) and have 287 streamflow gauge stations registered in the *Hidroweb* system (ANA, 2019b). The climate is predominantly Cwb in Köppen classification, with dry winter and rainy summer (ALVARES et al., 2013).

Lavras, a city in the south of Minas Gerais, has its area located into two UPGRH: the "Alto Rio Grande" (GD1) and the "Vertentes do Rio Grande" (GD2). GD2, with a drainage area of 10,533 km², includes 42 municipalities and a population of 562,476 inhabitants, of which 88% live in urban areas (IBGE, 2019). GD1 comprises an area of 8,758 km² with 106,906 inhabitants in 32 cities. The estimated population for Lavras in 2019 was 103,773 inhabitants (IBGE, 2019); and according to the demographic census of 2010, the demographic density was 163.26 $inh.km^{-2}$ and the urbanization/impervious roadways corresponded to 37.4% (IBGE, 2010). The Vermelho Creek, a tributary of Grande River, is one of the main urban watercourses in Lavras and constantly faces inundation events. The municipality's Contingency Plan of Lavras, elaborated in 2018, classifies four river stretches as high flood risk and one as high risk of fluvial erosion in the Vermelho Creek Watershed (COORDENADORIA MUNICIPAL DE GESTÃO E PROTEÇÃO CIVIL, 2018).

Given the abovementioned and the current situation of Lavras, where there is intense residential occupation in the Vermelho Creek Watershed, the evaluation of inundation boundaries aims to support decision makers to plan and design flood control measures. Hence, generating flood maps for the city might improve population safety and decrease economic losses, as well as provide an adequate urban planning, supporting the Soil Use and Urban Drainage Directive Plans and the Contingency Plan.

Thus, the main objective of this thesis was to evaluate simulated inundation boundaries of various design floods in the Vermelho Creek Watershed, Lavras, MG, Brazil. In addition, the study also aims to:

- Develop a maximum streamflow regional function for the region of Lavras;
- Evaluate the estimates generated by the regional function;
- Estimate design floods for the Vermelho Creek Watershed by using the regionalization technique;
- Create flood maps for an urbanized area of the Vermelho Creek Watershed for return periods of 5, 10, 50 and 100 years;
- Assess the Soil Use Directive Plan of Lavras and current land use and occupation in the simulated flooded areas based on the streamflow estimates.

The first part of this thesis presents the theoretical framework on floods and urban drainage, estimation of design floods in sites with scarcity of monitoring, and the creation of flood maps. The second part presents the articles resulting from this research. The maximum streamflow regional function developed for the region of Lavras is show in article 1, which also includes (1) an analysis of the predictive capacity of the function and the uncertainties related to the estimation, and (2) the applicability of the used methods to improve the estimation of design floods in ungauged or poorly monitored basins. Article 2 presents an evaluation of the developed regional function in comparison to other work, aiming to (1) identify the most adequate estimate for the elaboration of flood maps in an urban section of the Vermelho Creek Watershed, and (2) evaluate the use and occupation policies in the current scenario.

2 THEORETICAL FRAMEWORK

Historically, urbanization took place around watercourses, both due to the ease of water supply and water transport, as well as the flat relief that facilitated the construction of buildings. However, the occupation of river plains has always been associated with the occurrence of floods. According to the Centre for Research on the Epidemiology of Disasters (CRED; UNDRR, 2015), part of the World Health Organization (WHO), inundation events corresponded to 47% of all natural disasters related to climate between 1995 and 2015, affecting 2.3 billion of people, mainly in low-income countries. In South America, on average, 560 thousand people per year were affected by floods between 1995 and 2004, and in the following decade (2005-2014), this average increased to 2.2 million people per year (CRED; UNDRR, 2015).

The international classification proposed by CRED defines hydrological disasters as processes that result in flood, landslide or wave action. In Brazil, hydrological disasters are the second most common natural disasters, and happens all around the country. Between January 1st of 2000 and July 31st, 2017, 6,164 emergencies related to hydrological disasters were registered in 2,872 municipalities, which corresponds to 51.5% of all Brazilian cities (MINISTÉRIO DA SAÚDE, 2018).

Hydrological disasters can impact population health, since there is a direct relationship between the environment and the quality of life. In addition to the material and infrastructure damage caused by hydrological disasters, physical and psychological traumas, deaths and illnesses can occur. Effects on food production, water quality, social processes and behavior of vectors and infectious agents may also occur, consequently reducing quality of life (MINISTÉRIO DA SAÚDE, 2018).

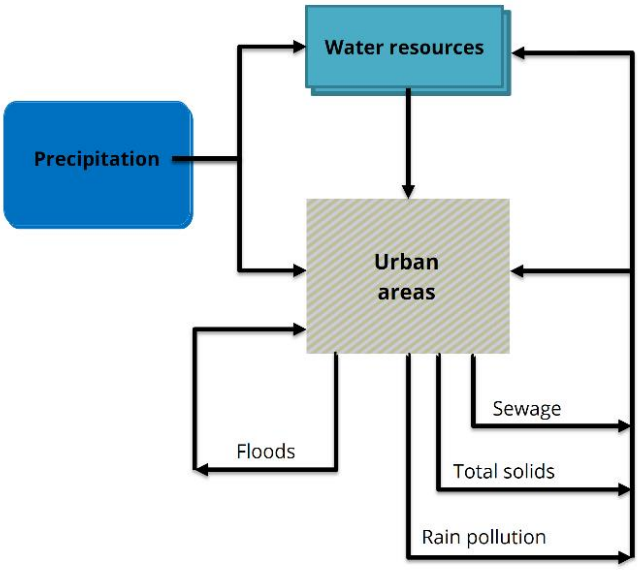
Additionally, the nature of floods has changed in the last years: flash floods and the intensification of riverine and coastal floods are occurring more often. Many of these changes are related to the direct influence of urbanization on the rise of runoff (GAO et al., 2018; MORAES et al., 2018). Moreover, climate change can also play an important role in changing the hydrological cycle, accelerating and intensifying the occurrence of extreme rainfall events and consequently the magnitude and frequency of floods (AHN; MERWADE, 2014; KVOČKA; FALCONER; BRAY, 2015). Thus, the appropriate design of urban drainage systems and the elaboration of studies aiming to reduce the risks and damages caused by these hydrological events are essential to maintain the population's quality of life and well-being (BODOQUE et al., 2016; MERWADE, 2018).

2.1 Urbanization and water resources

According to Tucci (2016), lack of urbanization planning in developing countries results in a cycle of urban waters contamination (FIGURE 1), because of these main causes:

- Contamination of water bodies due to urban growth and lack of sanitation;
- Expansion of impermeable areas, with consequent increase of floods and reduction of aquifer recharge, also increasing sediment transport and causing contamination of run-off water in urban and/or agricultural areas;
- Occupation of areas subject to floods and landslides.

Figure 1 – Cycle of urban waters contamination in developing countries.

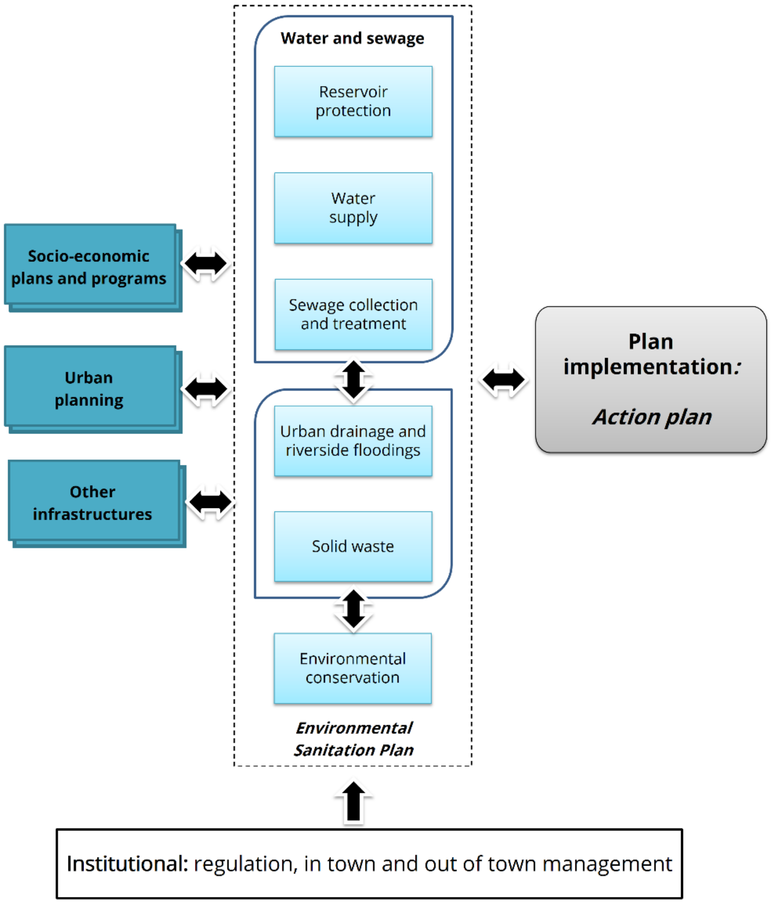


Source: Adapted from Tucci (2016).

Pahl-Wostl et al. (2012) state that the main challenge of the water crisis relies on water governance, which should consider the different stakeholders to support the formulation and implementation of public policies, i.e., the rules for the management of water resources. However, water governance has major flaws, especially in developing countries. Consequently, it leads to ineffective water resources management, comprised of analysis, monitoring, development and implementation of measures that guarantee water resources quantity and quality. One of the gaps pointed out by Pahl-Wostl et al. (2012) is the generalization of rules in water resources planning, without considering the heterogeneity and specificities of different watersheds. Another important aspect is that the development of public policies related to water security is not always executed concurrently with economic development, causing degradation of the environment.

According to Tucci (2016), urban waters planning must be thought of in an integrated way. In other words, the decision-makers must consider land use, the provision of urban services (i.e., water supply, water and sewage treatment, solid waste treatment, and urban drainage), and the objectives of environmental conservation and population health. In Brazil, Law no. 11445/2007, which establishes the National Sanitation Policy, obligated cities to formulate the Municipal Sanitation Plan (PMSB, in Portuguese) (BRASIL, 2007). The plan should include basic services for drinking water supply, sewage, solid waste management, and stormwater drainage and management in urban areas. In this sense, the Municipal Sanitation Plan must align all these work fronts, seeking solutions that reduce costs related to water in the urban environment (FIGURE 2).

Figure 2 – Components of integrated management of environmental sanitation.



Source: Adapted from Tucci (2016).

Nonetheless, urban water management is still generally conducted in a fragmented way, resulting in negative environmental impacts and serious risks to urban sustainability (GHANBARPOUR; SARAVI; SALIMI, 2014; PAHL-WOSTL et al., 2012; TUCCI, 2016). For each of the work fronts of the PMSB, specific objectives and goals must be outlined, as well as a detailed diagnosis of the systems, and actions of short, medium and long term to adapt the municipal environmental management. Tucci (2016) reports the specific characteristics of the plans according to the urban system (TABLE 1).

Table 1 – Characteristics of the city plan's contents.

System	Action	Objective	Entity
Urban Development	Soil Use Directive Plan	Regulation of the occupation of the city	Municipality or Federal District
Water supply	Water Supply Directive Plan	Increase the water supply up to its total coverage	Municipality or State
Sanitation	Sanitation Directive Plan	Built a sewage collecting network and treatment plants aiming at improving the water quality and reduction of diseases	Municipality or State
Urban drainage and erosion	Urban Drainage or Rain Water Directive Plan	Regulate the properties discharge and consequent erosion increase; control the impact of degraded and subject to flooding areas	Municipality
Solid waste	Solid Waste Directive Plan	System of household collection, streets cleaning and final deposition of the solid waste	Municipality
Environment	Environment Directive Plan	Recovery of degraded areas, conservation and planning of spaces	Municipality

Source: Tucci (2016).

Even so, the existence of laws, policies and plans for water resources and sanitation does not guarantee the effectiveness of management (PAHL-WOSTL et al., 2012; PETELET-GIRAUD et al., 2018). In Brazil, the Law 9433 from 1997 established the National Policy of Water Resources (*Política Nacional de Recursos Hídricos*) and created the National System of Water Resources Management (*Sistema Nacional de Gerenciamento de Recursos Hídricos – SINGREH*) (BRASIL, 1997). Nevertheless, Silva, Pereira and Vieira (2020) highlight that the instruments of integrated water resources management, despite being well established in this law for more than 20 years, have not yet been properly implemented in order to balance the various problems that exist in Brazil, both in quantitative and qualitative terms. Petelet-Giraud et al. (2018) also bring up the question of the "real country" *versus* "legal country", i.e., the illegitimacy of the State. From this perspective, many laws and regulations are established merely to meet external requirements (e.g., eligibility for funding); thus, sanctions for violators and the effective policies implementation are not carried out.

2.2 Urban Drainage

Urban drainage can be understood as a group of measures that aim to drain the water present in the urban environment (DECINA; BRANDÃO, 2016) and it is one of the four pillars of the Brazilian National Sanitation Policy, established by Law n. 11445/2007 (BRASIL, 2007). This sanitation policy describes urban drainage management as the set of activities, infrastructures and operational installations for urban stormwater drainage, transportation, detention or retention for the mitigation of floods, treatment and final disposal of rainwater drained in urban areas (BRASIL, 2007).

Floods are the result of two processes, which may occur concurrently or not: floods in areas of land adjacent to a river or stream, and floods due to urbanization (TUCCI, 2004, 2005). The former is a natural phenomenon, which occurs due to increasing water volume in the river that starts to occupy its larger bed or floodplain. The impacts related to this type of flood are linked to the inadequate occupation of the floodplain. Floods due to urbanization, on the other hand, are caused mainly due to impervious surfaces, altering the flowpath and increasing runoff, because the volume of water that would be infiltrated into the soil and retained by vegetation quickly flows to the watercourse (TUCCI, 2004).

Consequently, urban planning must consider strategies to minimize flood impacts. Flood control strategies are classified into soft and hard measures, according to their approach. Hard or structural measures are engineering constructions that modify the fluvial system in order to avoid water overflowing into the larger bed of the river (TUCCI, 2005). Hard measures are classified as extensive (watershed-scale) and intensive (river-scale). Extensive hard measures seeks to modify the relationship between precipitation and runoff, such as altering the vegetation cover of the soil, which reduces and delays flood peaks and controls basin erosion (TUCCI, 2005). Intensive measures, according to the objective, can be of four types:

- Flow acceleration: channeling and related structures;

- Flow retardation: reservoirs (detention/retention basins), restoration of natural channels;
- Flow diversion: bypass tunnels (i.e., culverts) and diversion channels;
- Individual actions, including the construction of flood-proof buildings (CANHOLI, 2005).

Differently, soft or non-structural measures seek to reduce the damage caused by floods through standards, regulations and programs. These measures include, for example, disciplining land use and occupation, implementing warning systems, and raising public awareness for the maintenance of drainage constructions. In other words, soft measures are essentially actions to regulate land use and occupation, and to offer environmental education focused on the control of diffuse pollution, erosion and solid waste, flood insurance and systems of flood warning and forecast (CANHOLI, 2005).

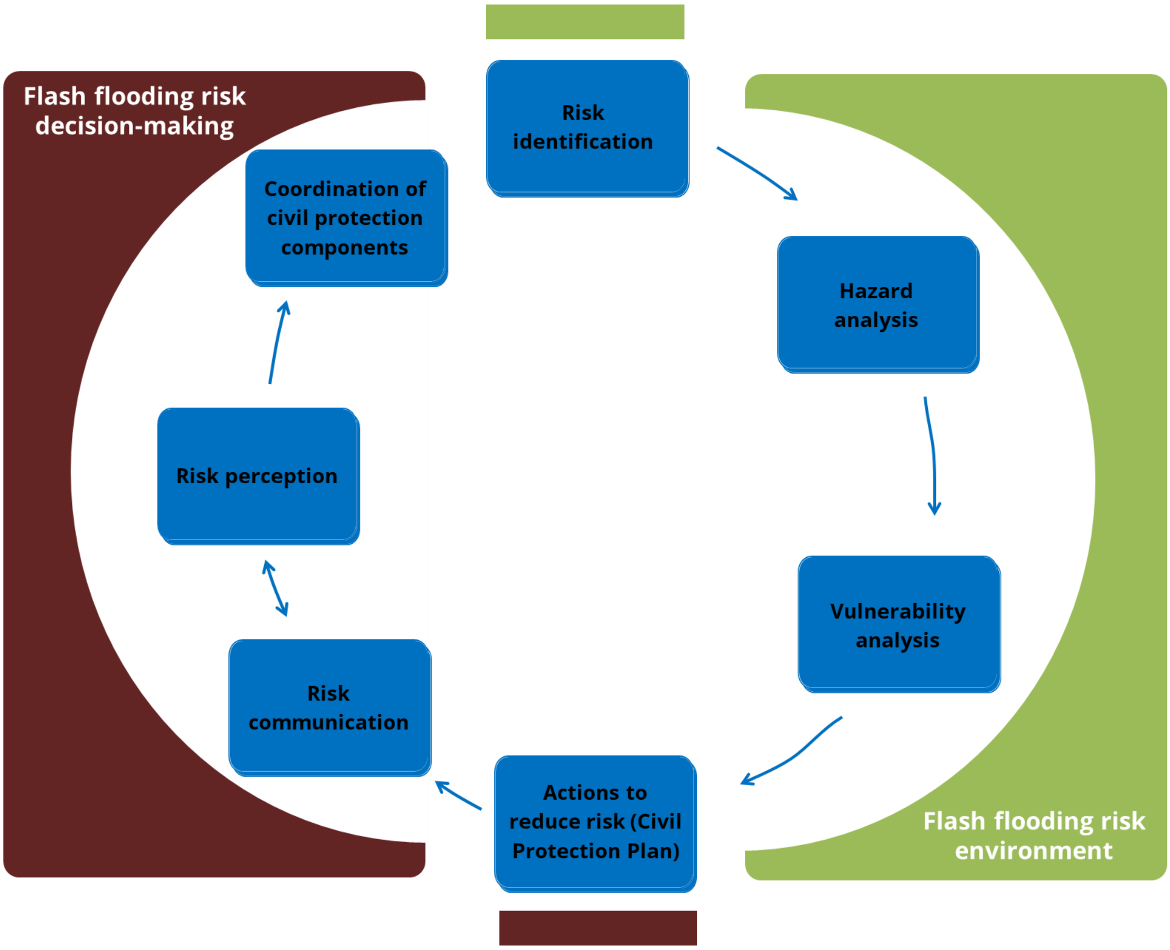
According to Merwade (2018), big engineering structures give the false sense of security and the application of hard measures has led to immense problems of floods and economic losses. For instance, Ardaya, Evers and Ribbe (2017) studied the flood risk perception of the population living in flood-prone areas in the state of Rio de Janeiro, Brazil. The authors showed that both population and government see hard measures as the best solution to prevent flood impacts. Structural control measures are placed as more effective because they are easily detectable by the population, and perceived as accomplishments of public administration (ARDAYA; EVERS; RIBBE, 2017).

However, non-structural measures can be effective at lower costs and with longer horizons of action (CANHOLI, 2005). Ridolfi, Albrecht and Di Baldassarre (2020) showed that soft measures are linked to significant decrease in flood losses, mainly with bottom-up decision-making, in which the population plays an important role in flood awareness. Likewise, Brites et al. (2019) estimated that construction costs of structural measures designed for 100-year return period to protect the Jacu River Basin in São Paulo would be U$44 million higher when compared to 25-year design flood.

Thus, proper planning of urban drainage implies an integrated vision of preventive and corrective measures, involving the planning of urban occupation and the design of structures that are necessary (DECINA; BRANDÃO, 2016). Therefore, the Urban Drainage Directive Plan along with the Land Use and Occupation Directive Plan are essential instruments to minimize future and current impacts of flooding, through regulation and flood control measures, respectively (TUCCI, 2016).

Moreover, adequately assessing risk areas, identifying vulnerabilities, and changing the traditional mindset from top-down to bottom-up decision-making are crucial for effective flood management. Bodoque et al. (2016), in studying the social perception of the Civil Protection Plan in Navaluenga, Central, Spain, developed a systematic approach for conducting flash flood risk management (FIGURE 3). The authors highlighted that one of the main problems of protection plans is their inability of linking the social risk perception in the emergency plans with an effective communication of the actions that should be taken in a risk situation.

Figure 3 – Framework approach for managing flash flood risk at local scale.



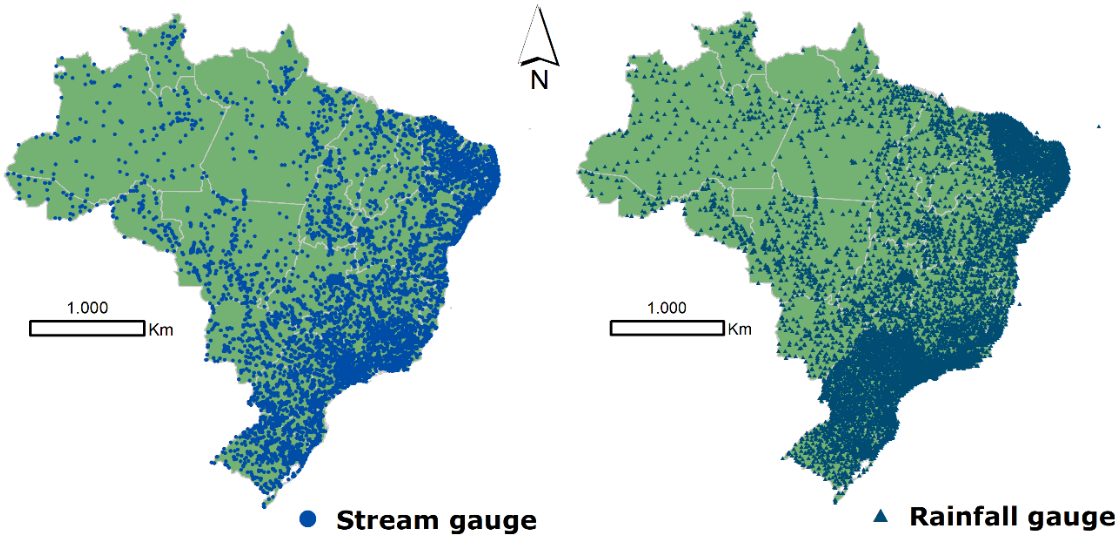
Source: Adapted from Bodoque et al. (2016).

2.3 Streamflow monitoring and design flood estimates

Monitoring water quality, quantity, distribution, and utilization is essential to describe the characteristics of watersheds, and provide adequate information to hydrological and hydraulic modeling (MELO et al., 2020). Historical data allow the identification of trends and the simulation of future scenarios. A robust hydrometeorological monitoring network supports decision-making regarding water resources management (MELO et al., 2020).

The Brazilian Hydrometeorological Network (RHN – which stands for *Rede Hidrometeorológica Nacional* in Portuguese) is constituted by a total of 4,641 monitoring locations, with 1,874 stations that monitor river parameters such as water level, streamflow, water quality, and sediment transport, and 2,767 that mainly monitor rainfall (ANA, 2019b). Despite the large numbers, Brazil is a country with continental dimensions, and therefore, much of the water system still lacks hydrological monitoring, specially related to streamflow. In addition, the gauging stations are not homogeneously distributed in the territory (FIGURE 4).

Figure 4 – Gauge stations of the Brazilian National Hydrometeorological Network.



Source: ANA (2019b) produced by Author (2021).

The lack of streamflow information is enhanced in small and medium watersheds, which hinders adequate urban waters planning. Reliable streamflow data and estimates are crucial for properly designing flood control measures and implementing urban drainage programs (ALAM; MUZZAMMIL; KHAN, 2016; CASSALHO et al., 2017, 2019). Thus, to overcome the scarcity of historical data, many techniques are applied to estimate streamflow in ungauged basins, using other variables or parameters.

In Brazil, urban drainage projects usually adopt rainfall-runoff models to estimate design floods using extreme rainfall events obtained from intensity-duration-frequency (IDF) curves (CABRAL et al., 2014; DECINA; BRANDÃO, 2016). In this approach, a design rainfall is estimated considering the intensity of the extreme event and the concentration time of the watershed (EQUATION 1). Ideally, IDF curves should be adjusted using data from rainfall recording gauges, selecting maximum intensities of different rainfall duration times (OLIVEIRA, 2019). However, because of their poor distribution in Brazilian territory, the alternative is to apply disaggregation of daily rainfall (SOUZA et al., 2019). As an example, Equation 2 shows the IDF curve fitted for the city of Lavras by Oliveira (2019) using the disaggregation technique. For estimating design rainfalls in drainage projects, Tucci (2005) recommends adopting return periods from 2 to 10 years for micro drainage, 10 to 25 years for macro drainage, and 100 years for floodplain zoning projects. Also, the total duration of the event is usually the concentration time of the watershed, and the temporal distribution of the precipitation is developed using the alternating block method (TUCCI, 2005).

$$P = I \times t_c \tag{1}$$

$$I = \frac{803.20557 \times RP^{0.17002}}{(t_d + 9.78654)^{0.72426}} \tag{2}$$

Where:

- P: design rainfall (mm);
- t_c: concentration time of the watershed (h);
- I: average maximum rainfall intensity (mm h^{-1});
- RP: return period (years);
- t_d: rainfall duration (minutes).

One of the simplest models for estimating streamflow from rainfall data is the rational method, commonly used by drainage designers in Brazil (EQUATION 3). This method assumes a runoff coefficient for accounting for the initial and continuing flow losses due to infiltration, which varies according to the soil cover (BUTLER; DAVIES, 2004). Tucci (2005) recommends using design floods estimated by the rational method for micro-drainage projects. In addition, Melo and Silva (2013) states that the method is adequate for watersheds with areas up to 2 km^2.

$$Q = 0.278 \times C \times I \times A \tag{3}$$

Where:

- Q: design flood/streamflow (m^3 s^{-1});

- C: runoff coefficient;
- I: average maximum rainfall intensity (mm h^{-1});
- A: drainage area (km^2).

The Soil Conservation Service Curve Number Method (SCS-CN) is a more robust rainfall-runoff method, still simple and easy to apply (EQUATION 4). Besides the water retention in the soil (infiltration), the SCS-CN also takes into account flow losses due to terrain depressions and vegetal cover, called initial abstraction (Ia) (MELO; SILVA, 2013). As a recommendation of the method, the initial abstraction corresponds to 20% of the maximum storage capacity of the soil (S), then, runoff can be estimated by Equation 5 (MELO; SILVA, 2013). The SCS-CN method also assumes that runoff only occurs if the rainfall is higher than the initial abstraction. Storage capacity is obtained based on the Curve Number (CN, EQUATION 6), a runoff coefficient that varies from 1 to 100 and is related to soil type, cover and antecedent moisture content.

$$Q=\frac{(P - Ia)^2}{(P - Ia + S)} \tag{4}$$

$$Q = \frac{(P - 0{,}20 \times S)^2}{(P + 0{,}80 \times S)} \tag{5}$$

$$S = \frac{25400}{CN} - 254 \tag{6}$$

Where:

- Q: design flood/streamflow (m^3 s^{-1});
- P: design rainfall (mm);
- Ia: initial abstraction (mm);
- S: storage capacity of the soil (mm)
- CN: curve number (1-100).

Although these approaches are highly widespread for calculating design floods for urban drainage structures and projects, we can point out some issues:

- The assumed RP is related to maximum rainfall series and may not reflect the real extreme streamflow (NAGHETTINI, 2017);

- Because of the lack of recording rainfall gauges in Brazil, IDF curves are estimated by disaggregation of daily rainfall (SOUZA et al., 2019);
- Soil and land use information required in rainfall-runoff models sometimes are not easily available and/nor accurate (BESKOW et al., 2016b);
- Calibration of rainfall-runoff models is an important step and still a challenge in ungauged basins (POOL; VIVIROLI; SEIBERT, 2017).

2.4 Maximum streamflow regionalization

Statistical approaches are a potential alternative to estimate extreme flood events, since they overcome the calibration challenge in ungauged watersheds and are built from observed streamflow data from gauged sites (SWAIN; PATRA, 2017). In that way, regional flood frequency analysis (RFFA) emerges as an important tool for the poor hydrological monitoring, as it can add information to existing series in gauged sites and transfer it to ungauged watersheds (CASSALHO et al., 2017, 2018). According to Tucci (2002), the main methods to develop a regional function to estimate maximum streamflow are:

- Selected values method: streamflow values are determined for fixed RPs derived from the best fitted probability density function (PDF) for each time series, producing regional regression functions for each predetermined RP;
- Regionalization of probability distribution parameters: a representative PDF is determined for all series contained in a hydrological homogeneous region, based on goodness-of-fit statistical tests. Then the regionalization of its parameters is conducted, yielding a single function applicable for different RPs;
- Dimensionless curve method: this method comprises two steps: (1) determining the dimensionless curve and (2) establishing the average maximum streamflow function. This method enables the consideration of peak streamflows of different magnitudes, since the streamflow values are non-dimensionalized for each historical series.

The regionalization of hydrological variables requires two conditions: 1) all analyzed sites are part of a homogeneous hydrologic region; 2) the series are stationary (BESKOW et al., 2016a; CUNNANE, 1987; JINGYI; HALL, 2004). Mann-Kendall trend test is commonly used to verify series stationarity (EQUATIONS 7-8), since the non-existence of trends implies that the series are stationary, as both are directly related in hydrological data sets (CASSALHO et al., 2018). If the absolute value $|Z| \leq Z_{1-\alpha/2}$ at a significance level α, there is no trend in the data and the series hypothesis of stationarity is valid (WANG et al., 2015).

$$Z = \begin{cases} \frac{(S - 1)}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{(S + 1)}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \tag{7}$$

$$S = \sum_{k-1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \quad , \quad sgn(x_j - x_k) = \begin{cases} +1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \tag{8}$$

Where:

- Z: statistic of the test;
- sgn: signum function;
- x: hydrological variable;
- n: length of the historical series;
- j and k: time indices.

Regarding the homogeneity of the sites, Hosking and Wallis (1993) presented the heterogeneity measure (H). The heterogeneity measure is based on the analysis of the statistical variability of the series set in comparison to what would be expected from a truly homogeneous region, through L-moments analysis (EQUATIONS 9-11). According to Hosking and Wallis (1993), an acceptably homogenous region would show $H < 1$, $1 \leq H < 2$ for a possibly heterogeneous region, and $H \geq 2$ for definitely heterogeneous region.

$$H = \frac{(V - \mu_v)}{\sigma_v} \tag{9}$$

$$V = \left\{ \frac{\sum_{i=1}^{N} n_i \left[t^{(i)} - t^R \right]^2}{\sum_{i=1}^{N} n_i} \right\}^{\frac{1}{2}} \tag{10}$$

$$t^R = \frac{\sum_{i=1}^{N} n_i t^{(i)}}{\sum_{i=1}^{N} n_i} \tag{11}$$

Where:

- H: heterogeneity measure;
- μ_V: mean of simulations for a region with N sites;
- σ_V: standard deviation of simulations for a region with N sites;
- V: weighted standard deviation of the coefficient of L-variation calculated for each simulated region;
- i: represents a site with a record length n_i and sample coefficient of L-variation $t^{(i)}$, L-skewness $t_3^{(i)}$ and L-kurtosis $t_4^{(i)}$;
- t^R: corresponds to the regional average coefficient of L-variation.

Complementary to the heterogeneity measure, Hosking and Wallis (1993) proposed the measure of discordancy (D_i) which identifies a discordant site in comparison to others, also through L-moments analysis (EQUATIONS 12-14). Hosking and Wallis (1995) presented threshold values for D_i, which depend on N (number of sites) to identify a discordant site i in comparison to the other (N − 1) sites (TABLE 2).

$$D_i = \frac{1}{3} N \left(u_i - \bar{u}\right)^T A^{-1} \left(u_i - \bar{u}\right) \tag{12}$$

$$A = \sum_{i=1}^{N} \left(u_i - \bar{u}\right)\left(u_i - \bar{u}\right)^T \tag{13}$$

$$\bar{u} = N^{-1} \sum_{i=1}^{N} u_i \tag{14}$$

Where:

- D_i: discordancy measure for a site i;
- N: number of sites in the proposed region;
- u_i: a vector formed by the sample coefficients of L-variation and sample L-skewness and L-kurtosis;
- T: transpose of a vector or matrix;
- A: matrix of sums of squares and cross-products;
- $\bar{u}$: the regional average of the vector u_i.

Table 2 – Critical values for the discordancy measure (D_i).

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).

Many studies have been trying to improve regionalization techniques in order to facilitate and provide more reliability in maximum streamflow estimates. Jingyi and Hall (2004) compared the geographical approach with multivariate techniques based on watershed characteristics. In their work, the regional frequency curves for ungauged sites were constructed using regional L-moment analysis and compared with alternative approaches based on artificial neural networks and fuzzy logic. Besaw et al. (2010) and Atieh et al. (2017) applied artificial neural networks for the prediction of flow duration curves including different explanatory variables. Cassalho et al. (2017) and Atieh et al. (2017) pointed out the importance of selecting explanatory variables that represent the processes with less errors and the evaluation of the predictive capacity of the generated regional function.

2.5 Dimensionless curve method

The dimensionless curve method is the simplest procedure to generate a regional function for estimating streamflow (CUNNANE, 1987). In this method, the streamflow (Q_R) is estimated through a dimensionless flood variable (X) and a scaling factor, the index flood (Q_{mc}), as show in Equation 15.

$$Q_R = X \times Q_{mc} \tag{15}$$

The X values (EQUATION 16) are the relation between the analyzed variable, i.e., annual maximum streamflow observed values, and the index flood (Q_{mc}). Usually the Q_{mc} is the mean or median of the series, e.g., the average maximum streamflow in case of annual maximum streamflow (NAGHETTINI, 2017).

$$X = \frac{Q}{Q_{mc}} \tag{16}$$

From the series of X values, a regional growth curve is usually generated by a logarithmic regression between the X values series and their corresponding return periods (Equation 17), which is common to every site in a hydrologic homogeneous region.

$$X = RGC = [a \times \ln(RP) + b] \tag{17}$$

The index flood is a scaling factor that can be related to explanatory variables of the watershed, as the drainage area, drainage density, length and steepness of main river, average annual rainfall, land cover, and so on (CUNNANE, 1987). Then, regression models can be used to estimate the Q_{mc} in ungauged watersheds (EQUATION 18).

$$Q_{mc} = k \times Z^{z} \times Y^{y} \times W^{w} \ldots \tag{18}$$

Where:

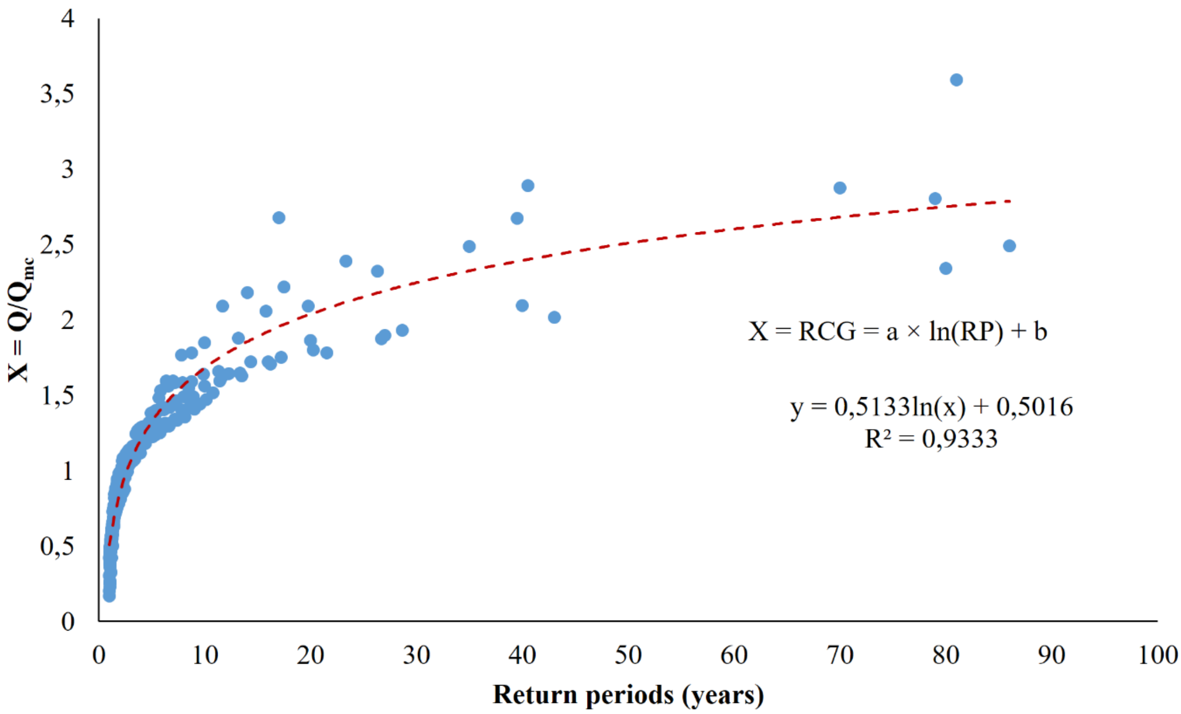
- Q_R: regionalized streamflow ($m^3\ s^{-1}$);
- X: dimensionless flood variable;
- Q_{mc}: index flood as mean or median maximum streamflow of the series ($m^3\ s^{-1}$);
- Q: annual maximum streamflow values ($m^3\ s^{-1}$);
- RGC: regional growth curve;
- RP: return period (years);
- a, b: adjustment parameters of the logarithmic regression between X and RP;
- k, Z, z, Y, y, W, w: adjustment parameters of the relation between the Q_{mc} and the watershed characteristics;

In summary, the steps to generate a maximum streamflow regional function are:

1) Select gauged basins that may be part of a hydrologic homogeneous region;
2) Construct the annual maximum streamflow series;
3) Verify the series stationarity through Mann-Kendall test;

4) Verify the homogeneity of the series through the heterogeneity measure (H) and the discordancy measure (D_i);
5) Calculate the index flood (Q_{mc}) of each gauged site as the mean or median of the observed annual maximum streamflow values;
6) For each series, calculate the dimensionless flood variable (X) and their corresponding return periods;
7) Generate the logarithmic regression model of the values of RP vs. X for all the sites in the homogeneous region (FIGURE 5);

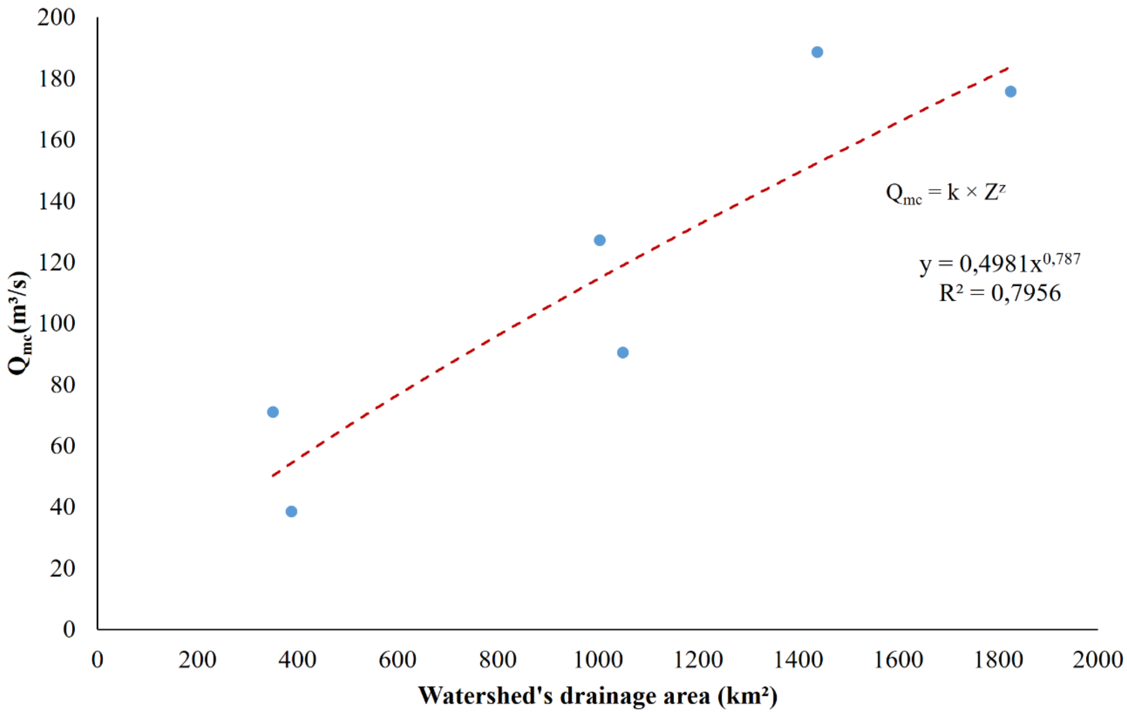
Figure 5 – Regional growth curve fitted by logarithmic regression of the values of return periods (RP) and correspondent dimensionless flood variable (X).



Source: from Author (2021).

8) Select the explanatory variables for the index flood;
9) Generate the regression model for the index flood, for example, a potential regression between the Q_{mc} and drainage area (FIGURE 6);

Figure 6 – Index flood generated by potential regression of the observed Q_{mc} values and drainage area of gauged watersheds.



Source: from Author (2021).

10) Write the maximum streamflow regional function as the product of the regional growth curve and the index flood, for example:

$$Q_R = [a \times \ln(RP) + b] \times [k \times Z^z] = [0.5133 \times \ln(RP) + 0.5016] \times [0.4981 \times Area^{0.787}].$$

Cassalho et al. (2017) developed a regional function for estimating maximum streamflow in the Mirim-Gonçalo Basin in Rio Grande do Sul, Brazil. The homogenous region identified by the authors had seven streamflow gauge stations, and the annual maximum streamflow was regionalized through the dimensionless curve method. The index flood was estimated using the drainage area as explanatory variable, in order to follow the parsimony principle that stands that a phenomenon should be explained with a minimum of explanatory variables. The authors compared the estimates from the regional approach with multiparameter PDFs and reached optimum performance according to the c coefficient proposed by Camargo and Sentelhas (1997). Cassalho et al. (2017) highlighted the easy applicability of the regional function to design hydraulic structures and flood risk management.

2.6 Flood mapping

Hydraulic modeling produces maps of inundation boundaries or flood risk maps in defined conditions. These maps became essential tools for the management of water resources and decision-making regarding public policies and urban drainage planning, in addition to supporting emergency actions in flood disasters (MERWADE, 2018).

The Hydrologic Engineering Center (HEC) package, developed by the United States Army Corps of Engineers (USACE), is a suite of software for hydrological engineering and process planning analysis. This package enables the study of surface and groundwater hydrology, fluvial hydraulics and sediment transport, hydrological statistics and risk analysis, analysis of reservoir systems, planning analysis, and water quality management in real time. In particular, HEC-HMS (Hydrologic Modeling System) and HEC-RAS (River Analysis System) software have been widely used in hydrological and hydraulic modeling applied to flood management and urban drainage (SOUZA et al., 2012; PAES; BRANDÃO, 2013; BODOQUE et al., 2016; MORAES et al., 2018).

The HEC-HMS simulates hydrological processes in dendritic basins. The software includes traditional hydrological analysis procedures, such as infiltration and unit hydrographs, as well as processes for continuous simulation, including evapotranspiration, snow melt and soil moisture. Supplementary analysis tools are also available for model optimization, flow prediction, assessment of model uncertainty, erosion and sediment transport and water quality (SCHARFFENBERG et al., 2018). The HEC-RAS performs one-dimensional hydraulic modeling for a network of rivers or channels, and can be used for permanent flow, non-permanent flow, sediment transport modeling and quality analysis and water temperature (BRUNNER; CEIWR-HEC, 2016).

HEC-RAS proceed calculations of water surface profiles flowing in channels, thus, it is possible to analyze the consequences of flood events in an urban area. The newest software version (HEC-RAS 5.0.7) allows carrying on all the simulation pre-processing and post-processing steps to create the inundation profiles. In the previously versions were necessary to use the HEC-GeoRAS extension in ArcGIS™ to digitize and extract geometry and topology information from the Digital Elevation Model (DEM) and aerial images, and then from the hydraulic model to the water surface generation.

The pre-processing steps include the creation of geometry layers: river channel, riverbanks, flowpaths, cross-sections, bridges, ineffective areas, buildings, levees, assign Manning’s n values for channels and floodplains, and so on. Either using HEC-RAS 5.0.7 or

HEC-GeoRAS, the software extracts all the necessary information for the flow computations, as the distance between cross-sections and river length. However, hydrologist expertise and field measures may be necessary to edit information concerning bridges, levees, and correct banks width. Hence, once discharge values are implemented for each reach to be modeled, the HEC-RAS simulation results give water surface profiles, that integrated to the DEM, creates flood extension and depth layers.

Gao et al. (2018) in a study performed in the Qinhuai River Basin, China, verified that the simulation of floods by HEC-RAS was satisfactory in the lower and middle reaches of the river through calibration of Manning’s n values with observed water levels. The authors evaluated the impacts of urban agglomeration polders in the streamflow of Qinhuai River and their relationship with urbanization. The presence of polders in the watershed increases the streamflow in Qinhuai River, and there is a linear relationship between urbanization rates in the polders and water level increasing. The authors also pointed out that minor floods are more sensitive to the polders urbanization, and their distribution and operation are important factors in flood control of the basin.

Hydraulic modeling and simulation can develop reliable flood assessments based on digital data, satellite images and field observations (COOK; MERWADE, 2009; HASANI, 2013; CABRAL et al., 2014). Oliveira et al. (2016) highlights that the use of hydraulic modeling by HEC-RAS allows the diagnosis of the hydrodynamic behavior of the watercourse and drainage channel, serving as a basis for urban drainage projects and for the establishment of effective environmental, social and economic protection strategies.

3 GENERAL CONSIDERATIONS

Brazilian cities often face inundation events that cause great damage to urban infrastructure and population safety. Many problems are due to inadequate design of flood control structures that are often planned without considering future expansion of cities. In addition, the former approach of urban drainage was to channelize and rectify urban watercourses, hiding the real problem by forcing water to flow rapidly downstream. One recent example was the floods that occurred in Belo Horizonte, in the state of Minas Gerais, in January 2020, where many infrastructures collapsed due to the great volume of water.

Although Brazilian law established clear rules for urban planning and water resources management for over 20 years, cities lack effective actions to improve urban infrastructure and regulation, mainly in medium and small municipalities. Especially regarding urban drainage, flood control measures are commonly adopted based on the “common sense” of city planners, a “try and error” approach, in which infrastructures are improved as a damage was caused. Along with that, the gap in hydrologic monitoring in urban watersheds leads to difficulties in estimating reliable design floods.

Regarding urban drainage planning in Lavras, the city holds the Environmental and Sanitation Plan, which describes the current urban drainage system and some guidelines for its maintenance (LAVRAS, 2018), the Soil Use Directive Plan (LAVRAS, 2008, 2016), which establishes land use regulation policies for the city, and the Contingency Plan published in 2018 that identifies inundation risk areas. Still, this documentation shows some issues:

- The Environmental and Sanitation Plan does not specify any foreseen activities in order to improve the drainage system and flood management;
- Urban zoning established by the Soil Use Directive Plan is not fully obeyed, since some areas that should be protected areas were formerly occupied by urbanization;
- The Contingency Plan were elaborated based on population recollections about the water level in past events of extreme rainfall;
- The drainage management of Lavras is carried out without any standard methodology of design flood estimation;
- A specific Urban Drainage Directive Plan is not implemented in the city, which is essential to protect areas susceptible to floods.

In this sense, the first article “Regional Flood Frequency Analysis and Uncertainties: Maximum Streamflow Estimates in Ungauged Basins in the Region of Lavras, MG, Brazil” provides reliable and robust estimates of design peak flows for the region, using a combination of statistical methods. Besides supporting decision-makers of Lavras planning flood control measures, the regional function was developed through a simple methodology that may be applied in other regions. The adequate performance of the regional function justifies its application. Moreover, this is an effective approach for improving the accuracy of streamflow estimates throughout Brazil, consequently reducing the negative impacts of floods.

The urban streams in Lavras are relatively small, but population often faces inundation problems. Therefore, the article “Flood Maps Using Maximum Streamflow Regional Functions in Ungauged Watersheds: How to Improve the Flood Management in Lavras, MG, Brazil” presents a relevant tool for proper urban drainage planning. The article simulated inundation boundaries of different design floods and compared the areas affected in current land use with the regulation proposed by the Soil Use Directive Plan of Lavras. The results showed the importance of focusing on flood risk management to decrease the population vulnerability and to guide the urbanization, as a significant damage prevention would be reached just by following the urban zoning guidelines.

This work brings initial and crucial contributions for an effective water resources management, primarily for flood control planning, aiming to support decision-making in a region that lacks in adequate urban planning and monitoring of urban streams. Some topics that should be considered in future works to enhance this research are:

- Application of more robust regionalization techniques, studying the influence of other explanatory variables in index flood, and other methods for the regional growth curve development;
- Evaluation of the performance of multi-parameter probability density functions to estimate design streamflow in the region of Lavras;
- Incorporation of field data into the hydraulic model to provide detailed information about the rivers’ geometry and structures (e.g. bridges);
- Monitoring of streamflow, even for short periods or individual measures, to enable the calibration of Manning’s coefficient for a more reliable hydraulic simulation.

REFERENCES

AHN, K. H.; MERWADE, V. Quantifying the relative impact of climate and human activities on streamflow. **Journal of Hydrology**, [s. l.], v. 515, p. 257–266, 2014. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2014.04.062>

ALAM, J.; MUZZAMMIL, M.; KHAN, M. K. Regional flood frequency analysis: comparison of L-moment and conventional approaches for an Indian catchment. **ISH Journal of Hydraulic Engineering**, [s. l.], v. 22, n. 3, 2016.

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, [s. l.], v. 22, n. 6, p. 711–728, 2013.

ANA. **Vulnerabilidade a Inundações do Brasil | Agência Nacional de Águas**. 2019a. Disponível em: <http://dadosabertos.ana.gov.br/datasets/4b7b20091fb940d492a1ebc85dfa88bb_0/data>. Acesso em: 13 jan. 2020.

ANA. **Rede Hidrometeorológica Nacional**. 2019b. Disponível em: <https://portal1.snirh.gov.br/ana/apps/webappviewer/index.html?id=8e97da1658c54bdbb87b402343433dca>.

ARDAYA, A. B.; EVERS, M.; RIBBE, L. What influences disaster risk perception? Intervention measures, flood and landslide risk perception of the population living in flood risk areas in Rio de Janeiro state, Brazil. **International Journal of Disaster Risk Reduction**, [s. l.], v. 25, n. August, p. 227–237, 2017. Disponível em: <http://dx.doi.org/10.1016/j.ijdrr.2017.09.006>

ATIEH, M. et al. Prediction of flow duration curves for ungauged basins. **Journal of Hydrology**, [s. l.], v. 545, p. 383–394, 2017. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2016.12.048>

BESAW, L. E. et al. Advances in ungauged streamflow prediction using artificial neural networks. **Journal of Hydrology**, [s. l.], 2010.

BESKOW, S. et al. Artificial intelligence techniques coupled with seasonality measures for hydrological regionalization of Q90 under Brazilian conditions. **Journal of Hydrology**, [s. l.], v. 541, p. 1406–1419, 2016. a. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2016.08.046>

BESKOW, S. et al. Potential of the LASH model for water resources management in data-scarce basins: a case study of the Fragata River basin, southern Brazil. **Hydrological Sciences Journal**, [s. l.], v. 61, n. 14, p. 2567–2578, 2016. b. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/02626667.2015.1133912>. Acesso em: 12 jan. 2020.

BODOQUE, J. M. et al. Improvement of resilience of urban areas by integrating social perception in flash-flood risk management. **Journal of Hydrology**, [s. l.], v. 541, p. 665–676, 2016.

BRASIL. **Lei nº 9.433 de 8 de janeiro de 1997**. Institui a Política Nacional de Recursos Hídricos, cria o Sistema Nacional de Gerenciamento de Recursos Hídricos, regulamenta o inciso XIX do art. 21 da Constituição Federal, e altera o art. 1º da Lei nº 8.001, de 13 de março de 1990, que modificou a Lei nº 7.990, de 28 de dezembro de 1989. Brasília: Presidência da República, 1997. Disponível em: <http://www.planalto.gov.br/ccivil_03/leis/l9433.htm>. Acesso em: 20 jul. 2020.

BRASIL. **Lei nº 11.445 de 5 de janeiro de 2007**. Estabelece as diretrizes nacionais para o saneamento básico; cria o Comitê Interministerial de Saneamento Básico; altera as Leis nos 6.766, de 19 de dezembro de 1979, 8.666, de 21 de junho de 1993, e 8.987, de 13 de fevereiro de 1995; e revoga a Lei nº 6.528, de 11 de maio de 1978. (Redação pela Lei nº 14.026, de 2020). Brasília: Presidência da República, 2007. Disponível em: < planalto.gov.br/ccivil_03/_ato2007-2010/2007/lei/l11445.htm>. Acesso em: 20 jul. 2020.

BRITES, A. P. Z. et al. Flood Zoning in Urban Planning and Runoff Control. In: WORLD ENVIRONMENTAL AND WATER RESOURCES CONGRESS 2019 2019, Reston, VA. **Anais**... Reston, VA: American Society of Civil Engineers, 2019. Disponível em: <http://ascelibrary.org/doi/10.1061/9780784482339.022>. Acesso em: 2 jul. 2020.

BRUNNER, G. W.; CEIWR-HEC. **HEC-RAS River Analysis System User's Manual Version 5.0**. Davis, CA. Disponível em: <www.hec.usace.army.mil>. Acesso em: 2 jul. 2020.

BUTLER, D.; DAVIES, J. W. **Urban Drainage**. 2nd. ed. New York: Spon Press, 2004. v. 53

CABRAL, S. L. et al. Hydrologic and hydraulic modelling integrated with GIS: A study of the Acaraú River Basin – CE. **Journal of Urban and Environmental Engineering**, [s. l.], v. 8, n. 2, p. 167–174, 2014.

CAMARGO, A. P.; SENTELHAS, P. C. Performance Evaluation of Different Potential Evapotranspiration Estimating Methods in the State of São Paulo, Brazil. **Revista Brasileira de Agrometeorologia**, [s. l.], v. 5, n. 1, p. 89–97, 1997.

CANHOLI, A. **Drenagem urbana e controle de enchentes (Urban Drainage and flood control)**. Sao Paulo.

CASSALHO, F. et al. Hydrological regionalization of maximum stream flows using an approach based on L-moments. **Revista Brasileira de Recursos Hídricos**, [s. l.], v. 22, n. 0, 2017.

CASSALHO, F. et al. At-Site Flood Frequency Analysis Coupled with Multiparameter Probability Distributions. **Water Resources Management**, [s. l.], v. 32, n. 1, p. 285–300, 2018.

CASSALHO, F. et al. Regional flood frequency analysis using L-moments for geographically defined regions: An assessment in Brazil. **Journal of Flood Risk Management**, [s. l.], v. 12, n. 2, p. 1–13, 2019.

CRED, C. for R. on the E. of D.; UNDRR, U. N. O. for D. R. R. **The human cost of weather-related disasters, 1995–2015.** Geneva.

CUNNANE, C. Review of statistical models for flood frequency estimation. [s. l.], n. (ed.), Dordrecht, The Netherlands, D. Reidel Publishing Co., 1987, Section 1, p.49- 95. (ISBN 90-277-, 1987.

DECINA, T. G. T.; BRANDÃO, J. L. B. Análise de desempenho de medidas estruturais e não estruturais de controle de inundações em uma bacia urbana. **Engenharia Sanitaria e Ambiental**, [s. l.], v. 21, n. 1, p. 207–217, 2016.

GAO, Y. et al. Analysis of impacts of polders on flood processes in Qinhuai River Basin, China, using the HEC-RAS model. **Water Science and Technology: Water Supply**, [s. l.], v. 18, n. 5, p. 1852–1860, 2018.

GHANBARPOUR, M. R.; SARAVI, M. M.; SALIMI, S. Floodplain Inundation Analysis Combined with Contingent Valuation: Implications for Sustainable Flood Risk Management. **Water Resources Management**, [s. l.], v. 28, n. 9, p. 2491–2505, 2014.

HOSKING, J. R. M.; WALLIS, J. R. Some statistics useful in regional frequency analysis. **Water Resources Research**, [s. l.], v. 29, n. 2, p. 271–281, 1993. Disponível em: <http://doi.wiley.com/10.1029/92WR01980>. Acesso em: 20 fev. 2021.

HOSKING, J. R. M.; WALLIS, J. R. Correction to "Some Statistics Useful in Regional Frequency Analysis". **Water Resources Research**, [s. l.], v. 31, n. 1, p. 251–251, 1995. Disponível em: <http://doi.wiley.com/10.1029/94WR02510>. Acesso em: 11 jan. 2020.

IBGE. **Censo Demográfico 2010**. Brasilia: Imprensa Nacional/Diário Oficial da União, nº 211, Seção 1, 2010.

IBGE. **Estimativas da população residente com data de referência 1° de julho de 2018**. Rio de Janeiro.

IGAM, I. M. de G. das Á.; CBH, C. da B. H. do R. G. Plano Diretor de Recursos Hídricos da Bacia do Rio das Mortes. [s. l.], p. 70, 2013.

JINGYI, Z.; HALL, M. J. Regional flood frequency analysis for the Gan-Ming River basin in China. **Journal of Hydrology**, [s. l.], v. 296, n. 1–4, p. 98–117, 2004.

KVOČKA, D.; FALCONER, R. A.; BRAY, M. Appropriate model use for predicting elevations and inundation extent for extreme flood events. **Natural Hazards**, [s. l.], v. 79, n. 3, p. 1791–1808, 2015.

LAVRAS. **Lei Complementar nº 156 de 22 de setembro de 2008**. Dispõe sobre o zoneamento e regulamenta o uso e a ocupação do solo urbano do município de Lavras e dá outras providências. Lavras: Assessoria Junrídica do Município, 2008. Disponível em: <https://sapl.lavras.mg.leg.br/media/sapl/public/normajuridica/2008/2581/2581_texto_integral.pdf>. Acesso em: 10 mar. 2020.

LAVRAS. **Lei Complementar nº 347 de 23 de fevereiro de 2016**. Altera a Lei Complementar nº 156, de 22 de setembro de 2008, que dispõe sobre o zoneamento e regulamenta o uso e a ocupação do solo urbano do município de Lavras e dá outras providências. Lavras: Câmara Municipal de Lavras, 2016. Disponível em: < https://sapl.lavras.mg.leg.br/media/sapl/public/normajuridica/2016/2806/2806_texto_integral.pdf>. Acesso em: 10 mar. 2020.

LAVRAS. **Lei Ordinária nº 4445 de 20 de março de 2018**. Aprova o Plano Municipal de Saneamento Básico do Município de Lavras - PMSB-Lavras, e o Plano Municipal de Gestão Integrada de Resíduos Sólidos de Lavras - PMGIRS-Lavras. Lavras: Procuradoria Geral do Município, 2018. Disponível em: < https://sapl.lavras.mg.leg.br/media/sapl/public/normajuridica/2018/6923/6923_texto_integral.pdf>. Acesso em: 10 mar. 2020.

MELO, D. C. D. et al. The big picture of field hydrology studies in Brazil. **Hydrological Sciences Journal**, [s. l.], v. 65, n. 8, p. 1262–1280, 2020. Disponível em: <https://doi.org/10.1080/02626667.2020.1747618>

MELO, C. R. De; SILVA, A. M. Da. **Hidrologia: Princípios e Aplicações em Sistemas Agrícolas**. 1. ed. Lavras: Editora UFLA, 2013.

MERWADE, V. Flood Modeling Within the Context of Sustainable Water Resources Management. **Sustainable Solution With Appropriate Technological Development and Innovation (SWADIN) Conference**, [s. l.], 2018. Disponível em: <https://docs.lib.purdue.edu/swadin/2013/presentations/14>. Acesso em: 8 out. 2020.

MINISTÉRIO DA SAÚDE. Desastres naturais e saúde: análise do cenário de eventos hidrológicos no Brasil e seus potenciais impactos sobre o Sistema Único de Saúde. **Boletim Epidemiológico da Secretaria de Vigilância em Saúde**, [s. l.], v. 49, n. 10, p. 13, 2018. Disponível em: <http://portalarquivos2.saude.gov.br/images/pdf/2018/marco/22/2017-032-Publicacao.pdf>

MORAES, T. C. et al. Effects on runoff caused by changes in land cover in a Brazilian southeast basin: evaluation by HEC-HMS and HEC-GEOHMS. **Environmental Earth Sciences**, [s. l.], v. 77, n. 6, p. 1–14, 2018. Disponível em: <https://doi.org/10.1007/s12665-018-7430-6>

NAGHETTINI, M. **Fundamental of statistical hydrology**. Switzerland: Springer International, 2017.

OLIVEIRA, L. F. C. De. **Chuvas extremas no Brasil: modelos e aplicações**. 1. ed. Lavras: Editora UFLA, 2019. Disponível em: <http://www.livraria.editora.ufla.br/chuvas-extremas-no-brasil-modelos-e-aplicacoes.html>. Acesso em: 25 nov. 2020.

PAES, R. P.; BRANDÃO, J. L. B. Flood Control in the Cuiabá River Basin, Brazil, with Multipurpose Reservoir Operation. **Water Resources Management**, [s. l.], v. 27, n. 11, p. 3929–3944, 2013.

PAHL-WOSTL, C. et al. From applying panaceas to mastering complexity: Toward adaptive water governance in river basins. **Environmental Science and Policy**, [s. l.], v. 23, p. 24–34, 2012. Disponível em: <http://dx.doi.org/10.1016/j.envsci.2012.07.014>

PETELET-GIRAUD, E. et al. Multi-layered water resources, management, and uses under the impacts of global changes in a southern coastal metropolis: When will it be already too late? Crossed analysis in Recife, NE Brazil. **Science of the Total Environment**, [s. l.], v. 618, p. 645–657, 2018.

POOL, S.; VIVIROLI, D.; SEIBERT, J. Prediction of hydrographs and flow-duration curves in almost ungauged catchments: Which runoff measurements are most informative for model calibration? **Journal of Hydrology**, [s. l.], v. 554, p. 613–622, 2017. Disponível em: <https://doi.org/10.1016/j.jhydrol.2017.09.037>

RIDOLFI, E.; ALBRECHT, F.; DI BALDASSARRE, G. Exploring the role of risk perception in influencing flood losses over time. **Hydrological Sciences Journal**, [s. l.], v. 65, n. 1, p. 12–20, 2020. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/02626667.2019.1677907>. Acesso em: 2 jul. 2020.

SCHARFFENBERG, B. et al. **Hydrologic Modeling System HEC-HMS - User's Manual**. Davis, CA.

SILVA, D. D. Da; PEREIRA, S. B.; VIEIRA, E. de O. Integrated Water Resources Management in Brazil. In: **Integrated Water Resource Management**. Cham: Springer International Publishing, 2020. p. 13–26.

SOUZA, G. R. De et al. Heavy rainfall maps in Brazil to 5 year return period. **Revista Ambiente e Agua**, [s. l.], v. 14, n. 3, p. 445–458, 2019. Disponível em: <www.ambi-agua.net>. Acesso em: 11 jan. 2020.

SOUZA, R. M.; CRISPIM, D. C.; FORMIGA, K. Estudo comparativo entre os modelos SWMM e HEC-HMS para simulação de escoamento superficial – caso de estudo bacia do Córrego Samambaia. **REEC - Revista Eletrônica de Engenharia Civil**, [s. l.], v. 5, n. 2, p. 1–11, 2012.

SWAIN, J. B.; PATRA, K. C. Streamflow estimation in ungauged catchments using regionalization techniques. **Journal of Hydrology**, [s. l.], v. 554, p. 420–433, 2017. Disponível em: <https://doi.org/10.1016/j.jhydrol.2017.08.054>

TUCCI, C. E. M. **Regionalização de vazões**. Porto Alegre: Ed. Universidade/UFRGS, 2002.

TUCCI, C. E. M. **Hidrologia: Ciência e Aplicação, 3ª edição**. 3. ed. Porto Alegre: Ed. Universidade/ UFRGS; ABRH, 2004.

TUCCI, C. E. M. **Gestão de Águas Pluviais UrbanasMinistério das Cidades – Global Water Partnership - Wolrd Bank – Unesco 2005**. Brasilia.

TUCCI, C. E. M. Urbanization and water resources. In: **Waters of Brazil: Strategic Analysis**. [s.l.] : Springer International Publishing, 2016. p. 89–104.

WANG, Y. et al. A Time-Dependent Drought Index for Non-Stationary Precipitation Series. **Water Resources Management**, [s. l.], 2015.

SECOND PART – JOURNAL ARTICLES

ARTICLE 1 - REGIONAL FLOOD FREQUENCY ANALYSIS AND UNCERTAINTIES: MAXIMUM STREAMFLOW ESTIMATES IN UNGAUGED BASINS IN THE REGION OF LAVRAS, MG, BRAZIL

Article published on the journal CATENA – ISSN: 0341-8162, Impact Factor: 4.333, Qualis-CAPES: A2, presented according to its publication standards.

Gabriela Rezende de Souza [a,b,*]; Venkatesh Merwade [a]; Luiz Fernando Coutinho de Oliveira [b]; Marcelo Ribeiro Viola [b]; Matheus de Sá Farias [b]

[a] Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana, 47907-2051, USA

[b] Department of Water Resources and Sanitation, Federal University of Lavras (UFLA), Campus Universitário, Lavras, Minas Gerais, 37200-900, Brazil

* Corresponding author at: gabriela.souza2@estudante.ufla.br. Present Address: Federal University of Lavras, Department of Water Resources and Sanitation, Lavras, MG, Brazil

HIGHLIGHTS

- Regional function is an important alternative for ungauged sites in Lavras region;
- Monte Carlo and bootstrapping are used to evaluate uncertainties;
- Flood estimates in ungauged sites in the region of Lavras show large uncertainties;
- Assessing uncertainty is essential for appropriate and safe flood risk management;
- Simple methods help decision-makers throughout places with globally available data.

ABSTRACT

Regionalization techniques are an important alternative to overcome the scarcity of streamflow data and to provide adequate estimates for flood management. This work aims to generate a maximum streamflow regional function and evaluate the uncertainties in estimates for a basin in the South of Minas Gerais, Brazil. Six streamflow gauging stations, that presented stationarity and no trends according to the Mann-Kendal test, were used to develop the regional function by the dimensionless curve method. The annual maximum streamflow series were adjusted to the probability density functions (PDFs) 2-parameter Log-Normal, 3-paramenter Log-Normal, Gumbel, and Gamma. Then, the goodness-of-fit of the PDFs was verified by the Anderson-Darling test. For the regional analysis, heterogeneity and discordancy measures verified the homogeneity of the region, and the jack-knifing technique evaluated the predictive performance of the regional function by the coefficient c of Camargo and Sentelhas. The uncertainty analysis for at-site and regional function estimates was assessed by Monte Carlo simulations and bootstrapping. The performance of the regional function was classified as optimum for most of the watersheds, but as good when considering the prediction in certain return periods. The uncertainties were larger in ungauged basins, especially for greater return periods and drainage areas. The regional function developed can be employed in ungauged sites, but also to improve data in poorly monitored watersheds. Thus, this study demonstrates the adequate applicability of regionalization in ungauged watersheds and provides a simple alternative for maximum streamflow estimates in order to promote sustainable flood risk management.

Keywords: design floods; flood management; dimensionless curve method; regionalization; extreme events, bootstrapping.

1 INTRODUCTION

Urbanization can negatively impact the environment, especially in developing countries, where the growth of the cities is not always planned. One of the major issues related to urbanization without planning is the impact due to extreme flood events. To overcome this problem, sustainable water resources planning and flood risk management are essential. Therefore, streamflow monitoring is crucial to provide data for the design of structures (e.g. levees and dams) and other flood control measures (e.g. land regulation policies). However, there is a lack of adequate streamflow gauging stations in developing and undeveloped countries, mainly in medium and small watersheds (BESKOW et al., 2016b; JINGYI; HALL, 2004; SWAIN; PATRA, 2017). This gap in streamflow information compromises studies and the application of flood mitigation measures, that can cause property damages and even lead to fatalities.

Estimating design streamflow in regions with a lack of hydrologic monitoring requires the implementation of techniques that allow the inference of the site streamflow from other variables or parameters. Rainfall-runoff models are widely used to estimate the streamflow, but calibrating these models in ungauged catchments is a challenge (POOL; VIVIROLI; SEIBERT, 2017)**.** Some techniques exist that can provide reliable streamflow information with less or no calibration of a hydrologic model. For example, Basu et al. (2010) developed a model called the Threshold Exceedance Lagrangian Model (TELM) for generating hydrographs at the watershed outlet without parameter calibration. The TELM assumes that the streamflow generation is a threshold driven process by the field capacity of the soil, depending on the travel time to route the water through the landscape in relation to its area. Yet, the application of this model without calibration was only possible because it was applied in intensely managed and engineered watersheds that present dominance and persistence of short-circuiting flow paths.

Another approach for estimating streamflow information in ungauged basins is through regionalization techniques. Regionalization transfers parameter sets of rainfall-runoff models or hydrological information from one or more gauged basins to an ungauged one (ATIEH et al., 2017; GARAMBOIS et al., 2015; PETROSELLI; VOJTEK; VOJTEKOVÁ, 2019; SWAIN; PATRA, 2017). Three regionalization approaches can be highlighted: regression based methods, geographical proximity and similarity methods (GARAMBOIS et al., 2015).

Regardless of the regionalization method chosen, it is essential that all the sites analyzed are part of a homogeneous hydrologic region and that the streamflow time series demonstrate stationarity (BESKOW et al., 2016a; CUNNANE, 1987; JINGYI; HALL, 2004), which can be verified through the Mann-Kendall test (CASSALHO et al., 2018). For testing the homogeneity of the sites, Hosking and Wallis (1997) presented the heterogeneity measure H, based on the analysis of the statistical variability of the streamflow time series in comparison to what would be expected from a truly homogeneous region.

Regression analysis is one of the most commonly used regionalization methods because it overcomes the calibration issue in ungauged catchments (SWAIN; PATRA, 2017). Regional flood frequency analysis, which is an important tool for estimating design flows in ungauged basins, can add information to the existing time series in gauged sites and also transfer them to ungauged catchments (CASSALHO et al., 2017, 2018).

Tucci (2002) describes three main methods to develop a regional frequency function. The first one is the selected values method, in which streamflow values are determined for fixed return periods by using the best adjusted probability density function (PDF) for each time series. This method gives regional regression functions for each predetermined return period. The second method is the regionalization of probability distribution parameters to provide a representative PDF for all the time series in a hydrological homogeneous region, based on goodness-of-fit statistical tests. The regionalization of PDF parameters yields a single function applicable for different return periods. The third method, the dimensionless curve method, estimates a dimensionless flow curve, also named as regional growth curve (RGC), and an average maximum streamflow function. This method enables consideration of peak streamflow values of different magnitudes since the streamflow values are non-dimensionalized for each historical series.

Considering the availability and quality of data used in regionalization or any other statistical methods, it is critical to assess the uncertainty associated with their application in order to reduce economic and health damages caused by flood events (CHOUBIN et al., 2019; HAILEGEORGIS; ALFREDSEN, 2017a). According to Hailegeorgis and Alfredsen (2017a), major sources of uncertainty in flood frequency analysis include the data quality, probability distribution fit, and the heterogeneity of basins included in the regional analysis. Monte Carlo simulations are widely applied for the construction of confidence intervals of PDFs and models parameters (POOL; VIVIROLI; SEIBERT, 2017; RUIZ-VILLANUEVA et al., 2013). However, Monte Carlo simulations assume that the parameters or variables analyzed follow a known probability distribution. Thus, many studies use non-parametric bootstrap sampling in uncertainty analysis, because it allows accounting for the influence of sampling on estimations (ARSENAULT; BRISSETTE, 2014; FAGHIH et al., 2017; HAILEGEORGIS; ALFREDSEN, 2017a, 2017b; MÉLÈSE; BLANCHET; MOLINIÉ, 2018).

Given the theory and development related to regionalization techniques, the primary objective of this study is to apply these techniques to estimate design flows for urban areas in Brazil. The federal law n. 11445 (BRAZIL, 2007) obligated the municipalities to elaborate the Environmental and Sanitation Plan, which must include guidelines for urban drainage and flood management (TUCCI, 2016). However, lacks of streamflow information and underestimation of design peak flows have led to inadequate flood risk management in many Brazilian cities, and consequently to a lot of damage. In Lavras, Minas Gerais, Brazil, the Environmental and Sanitation Plan describes the current urban drainage system and some guidelines for its maintenance (LAVRAS, 2018). Nevertheless, the plan does not specify any foreseen activities in order to improve the drainage system and flood management. Moreover, an Urban Drainage Directive Plan was not implemented in the city, which is essential to protect areas susceptible to floods (TUCCI, 2016). Hence, the aim of this study is to generate a maximum streamflow regional function and evaluate the uncertainties associated to it for estimating design streamflow in ungauged basins in the region of Lavras, Minas Gerais, Brazil. The novelty of this study lies in estimation of reliable and robust design peak flows in data scarce regions by using a combination of statistical techniques.

2 MATERIALS AND METHODS

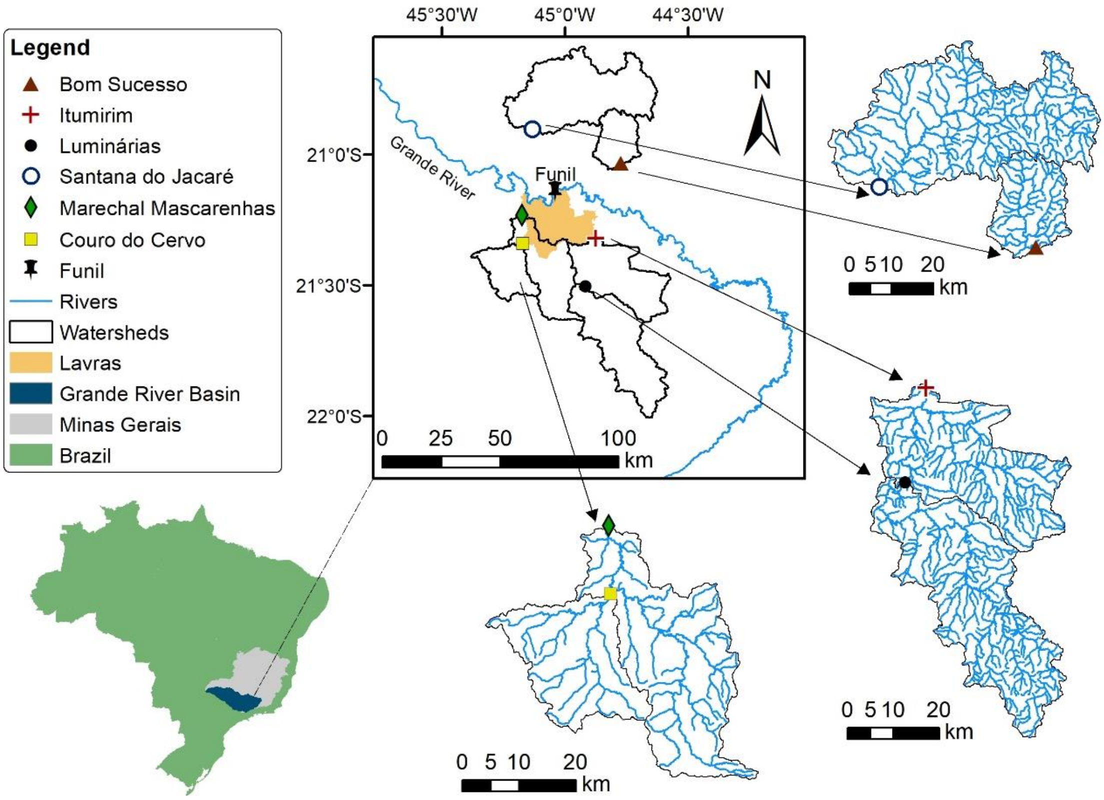
2.1 Study area and streamflow data

The Grande River Basin is located in the states of Minas Gerais and São Paulo, in the southeastern region of Brazil. This basin is subdivided in 14 Water Resources Planning and Management Units (UPGRH), eight in the state of Minas Gerais and six in São Paulo (IGAM; CBH, 2013). These UPGRH were established in order to implement the Water Resources State Politics of Minas Gerais and the decentralized management.

The city of Lavras (FIGURE 1), in the south of Minas Gerais, has its area located into two UPGRH: the "Alto Rio Grande" (GD1) and the "Vertentes do Rio Grande" (GD2). The climate in this region is predominantly Cwb in Köppen classification, with dry winter and rainy summer (ALVARES et al., 2013). GD2, with a drainage area of 10,533 km², includes 42 municipalities and a population of 562,476 inhabitants, of which 88% live in urban areas. GD1 comprises an area of 8,758 km² with 106,906 inhabitants in 32 cities. The estimated population for Lavras in 2019 was 103,773 inhabitants (IBGE, 2019); and according to the demographic census of 2010, the demographic density was 163.26 inh.km^{-2} and the urbanization/impervious roadways corresponded to 37.4% (IBGE, 2010).

Hydrologic time series are available from the Brazilian Water Resources National Agency (ANA) through *Hidroweb*, a web platform that assembles streamflow and rainfall data from different sources. For the GD1 and GD2 region, there are 77 streamflow gauging stations, but some of them have less than 10 years of data and some are not even available through *Hidroweb*. Hydrologic studies require at least 10 years of continuous record, and that the time series is stationary with no significant trends (Beskow et al., 2016a; Cassalho et al., 2019, 2017; Souza et al., 2019). For this study, six streamflow gauging stations (FIGURE 1 and TABLE 1) were selected in the region of Lavras. From the hydrologic data of these stations, the annual maximum streamflow series were constructed, and their stationarity was analyzed using the Mann-Kendall test (CASSALHO et al. 2017).

Figure 1 – Location of the watersheds near Lavras used in the regional flood frequency analysis in the Grande River basin, and the Funil Hydropower Plant, with the detailed drainage network.



Source: from Author (2021).

Table 1 – Streamflow gauging stations studied and length of the annual maximum streamflow (AMS) series.

Gauging station	Station number	Drainage area (km²)	Length of the AMS series
Bom Sucesso	61140000	351.22	69
Couro do Cervo	61173000	387.86	85
Itumirim	61078000	1825.44	80
Luminárias	61075000	1003.91	78
Marechal Mascarenhas	61176000	1049.96	16
Santana do Jacaré	61202000	1439.14	79

Source: from Author (2021).

2.2 Homogeneous regions identification

Verifying the homogeneity of the region is essential for regional flood frequency analysis. The homogeneity of the study region was verified using the heterogeneity measure, H (HOSKING; WALLIS, 1997), which takes into account the magnitude of L-moments of the samples in relation to what is expected for a truly homogeneous region (Equations 1, 2 and 3). According to Hosking and Wallis (1997), an acceptably homogenous region would present H < 1, a possibly heterogeneous 1 ≤ H < 2 and definitely heterogeneous H > 2. More information about the L-moments can be obtained from Hosking and Wallis (1997) and Naghettini (2017).

$$H = \frac{(V - \mu_V)}{\sigma_V} \tag{1}$$

$$V = \left\{ \frac{\sum_{i=1}^{N} n_i \left[t^{(i)} - t^R \right]^2}{\sum_{i=1}^{N} n_i} \right\}^{\frac{1}{2}} \tag{2}$$

$$t^R = \frac{\sum_{i=1}^{N} n_i t^{(i)}}{\sum_{i=1}^{N} n_i} \tag{3}$$

Where:

- H: heterogeneity measure;
- μ_V: mean of simulations for a region with N sites;
- σ_V: standard deviation of simulations for a region with N sites;
- V: weighted standard deviation of the coefficient of L-variation calculated for each simulated region;
- i: represents a site with a record length n_i and sample coefficient of L-variation $t^{(i)}$, L-skewness $t_3^{(i)}$ and L-kurtosis $t_4^{(i)}$;
- t^R corresponds to the regional average coefficient of L-variation.

Complementary to the heterogeneity measure, Hosking and Wallis (1995) proposed the measure of discordancy (D_i, equations 4-6). Hosking and Wallis (1997) presented threshold values for D_i, which depend on N (number of sites) to identify a discordant site i in comparison to the other (N − 1) sites.

$$D_i = \frac{1}{3} N \, (u_i - \bar{u})^T A^{-1} (u_i - \bar{u}) \tag{4}$$

$$A = \sum_{i=1}^{N} (u_i - \bar{u})(u_i - \bar{u})^T \quad (5)$$

$$\bar{u} = N^{-1} \sum_{i=1}^{N} u_i \quad (6)$$

Where:

- D_i: discordancy measure for a site i;
- N: number of sites in the proposed region;
- u_i: a vector formed by the sample coefficients of L-variation and sample L-skewness and L-kurtosis;
- T: transpose of a vector or matrix;
- A: matrix of sums of squares and cross-products;
- $\bar{u}$: the regional average of the vector u_i.

Ribeiro et al. (2005) recommended the utilization of at least 6 stations for performing a regional flood frequency analysis, based on the evaluation of homogeneous regions in the Doce River Basin (Brazil), which was followed by Beskow et al. (2016b) and Cassalho et al. (2017).

2.3 Probability density functions

The probability density functions (PDFs) 2-parameter Log-Normal (LN-2P), 3-parameter Log-Normal (LN-3P), Gamma and Gumbel were adjusted to the annual maximum streamflow series by the L-moments method (NAGHETTINI, 2017). According to Franco et al. (2014), the L-moments method seems to be more appropriate for the estimation of PDF parameters.

The performance of PDFs was evaluated using the Anderson-Darling goodness-of-fit test as described by Franco et al. (2014). Series of maximum streamflow tend to present asymptotic behavior (BESKOW et al., 2015). The Anderson-Darling test is considered superior and more adequate to asymptotic distributions, as it gives more importance to the extremes of the probability functions (CASSALHO et al., 2018).

2.4 Regional Flood Frequency Analysis

According to Cunnane (1987), the index flood method is the simplest procedure to generate a regional function. This method calculates a dimensionless flood variable (X) that allows the estimation of a regional growth curve. The estimated curve is common to every site in a region, but each site has a specific scaling factor, the index flood. In this study, the X values correspond to the dimensionless annual maximum streamflow series in relation to the average maximum streamflow (Equation 7).

For gauged basins, the index flood (Q_{mc}) is taken as the mean or median values of the series (NAGHETTINI, 2017). In this study, the index flood for each one of the six monitored watersheds is the mean of annual maximum series. In that way, the streamflow regional function is generated using Equation 8 (CUNNANE, 1987; TUCCI, 2002).

$$X = \frac{Q}{Q_{mc}} \tag{7}$$

$$Q_R = X \times Q_{mc} \tag{8}$$

Where:

- X: dimensionless flood variable;
- Q: annual maximum streamflow values (m^3/s);
- Q_{mc}: mean of annual maximum series (m^3/s);
- Q_R: regionalized streamflow (m^3/s).

In ungauged sites, the index flood (Q_{mc}) is determined relating the average annual maximum streamflow to explanatory variables of the monitored watersheds in a region. The explanatory variables to describe this relationship could be the drainage area, drainage density, length and steepness of the main river, average annual rainfall, land cover, and so on. Cassalho et al. (2017, 2019) highlight the parsimony principle, which means that a phenomenon should be explained with the lowest number of explanatory variables. To accomplish this, the index flood for ungauged basins was determined by a linear regression between the Q_{mc} values and drainage areas of the six study watersheds (Equation 9), as presented by Hailegeorgis and Alfredsen (2017a). The regional growth curve (RGC) was determined by a logarithmic regression between the X values and their corresponding return periods (Equation 10). Then, Equation 11 gives the regionalized streamflow for this study.

$$Q_{mc} = a \times A + b \tag{9}$$

$$RGC = [a' \times \ln(RP) + b'] \tag{10}$$

$$Q_R\ (RP, A) = [a \times A + b] \times [a' \times \ln(RP) + b'] \tag{11}$$

Where:

- A: watershed drainage area (km^2);
- RGC: regional growth curve;
- RP: return period (years);
- a, b, a', b': adjustment parameters of the equations;
- Q_R (RP, A): regionalized streamflow (m^3/s).

2.5 Performance of the regional function

The performance of the regional function was assessed by the jack-knifing method as described by Merz and Bloschl (2005), which simulates the case of ungauged watersheds. In this assessment, one of the analyzed watersheds is treated as ungauged. First, the flood quantiles of 10, 20, 50 and 100 years of return period were estimated by a regional function based only in the data of the others watersheds in the region. Then, the flood quantiles estimated by this regional function were compared with the quantiles estimated by the best-fitted PDF for the at-site analysis. This procedure was repeated for each one of the six streamflow gauging stations. The performance of the regionalization was evaluated through the coefficient c (Equation 12), where r is the Person correlation coefficient and d, the accuracy coefficient (Equation 13) (CAMARGO; SENTELHAS, 1997). Camargo and Sentelhas (1997) proposed the following classification of c values: c > 0.85, optimum; 0.76 to 0.85, very good; 0.66 to 0.75, good; 0.61 to 0.65, median; 0.51 to 0.60, tolerable; 0.41 to 0.50, bad and c ≤ 0.40, terrible.

$$c = r \times d \tag{12}$$

$$d = 1 - \frac{\sum\left(Qr_i - Qe_i\right)^2}{\sum\left(\left|Qr_i - \overline{Qe}\right| + \left|Qe_i - \overline{Qe}\right|\right)^2} \tag{13}$$

Where:

- c: coefficient c of Camargo and Sentelhas (1997);
- r: Pearson correlation coefficient;
- d: accuracy coefficient;
- Qr_i: regionalized streamflow values;
- Qe_i: PDF estimated streamflow values;
- $\overline{Qe}$: mean of PDF estimated streamflow values.

2.6 Uncertainty analysis

The uncertainty associated with the estimates both from the PDFs and the regional function was assessed by applying Monte Carlo simulations and bootstrap technique. The construction of the confidence intervals for the PDFs quantiles of 10, 20, 50 and 100-years return period followed the steps proposed by Naghettini (2017) in applying Monte Carlo simulation method. Monte Carlo simulation was also utilized for estimating the confidence intervals of the linear regression parameters of the index flood.

The bootstrap technique was utilized for evaluating the uncertainty related to the regional growth curve. This method consists of obtaining new samples from resampling the original data with replacement, giving new parameters estimates for each resample. Then, the approximate confidence intervals (1-α) are obtained empirically, as the interval bounded by the empirical quantiles of order α/2 for the lower confidence interval and (1-α/2) for the upper one (EFRON, 1987). The Bias Corrected and Accelerated (BCa) method was used, as it adjusts bias and skewness in the distribution for producing more accurate confidence intervals (ARSENAULT; BRISSETTE, 2014; DICICCIO; EFRON, 1996).

In this work, 5000 Monte Carlo Simulations and bootstrap resampling were conducted to construct the 95% confidence intervals.

2.7 Computer software used

The System of Hydrological Data Acquisition and Analysis (SYHDA) was used to create the annual maximum streamflow series and compute the discordancy and heterogeneity measures (VARGAS et al., 2019). The stationarity test, adjustment of PDF's parameters, regressions for generating the regional function, the uncertainty and performance analyses were performed on the software R version 3.6.0 (R TEAM, 2019), with the aid of the packages: trend

(POHLERT, 2020); lmomco (ASQUITH, 2018); nsRFA (VIGLIONE, 2018); goftest (FARAWAY et al., 2019); and boot (CANTY; RIPLEY, 2019). ArcGIS version 10.5 was used to delineate the watersheds from each gauging station.

3 RESULTS AND DISCUSSION

3.1 Trend, stationarity and homogeneity tests

Change in streamflow regime, mainly due to anthropogenic interventions, can introduce non-stationarity in hydrological data sets (CASSALHO et al., 2019). Results from the six stations included in the study (as presented in Table 2) show that data are stationary and present no trends ($p > 0.05$).

The calculated value for the heterogeneity measure ($H = 0.6974$) was lower than one; consequently, all the six watersheds analyzed are part of a homogeneous hydrologic region. Hosking and Wallis (1995) established the critical value for the discordancy measure Di as 1.648 for a region with 6 sites. Likewise, none of the studied watersheds overcame this limit. As a result, this study follows the minimum of 6 sites recommended by Ribeiro et al. (2005) to perform a regional analysis.

Table 2 – Mean of maximum streamflow series (Qmc), Mann-Kendall test and discordance measure (D_i) of the annual maximum streamflow series studied.

Gauging station	Q_{mc} (m³/s)	Mann-Kendall p-value	D_i
Bom Sucesso	71.03	0.221	0.726
Couro do Cervo	38.53	0.654	0.870
Itumirim	175.77	0.116	1.532
Luminárias	127.03	0.651	0.544
Marechal Mascarenhas	90.35	0.857	1.635
Santana do Jacaré	188.61	0.356	0.694

Source: from Author (2021).

Beskow et al. (2016a) found 6 homogeneous regions for 78 watersheds analyzed in the Rio Grande do Sul State. Drissia et al. (2019) developed regional flood frequency curves for the Kerala State in India, grouping 41 sites into 5 homogenous regions that were not spatially continuous. In this study, two watersheds are located in the north of Lavras, displaced from the other four that constitute the region. However, all of them are within the Grande River Basin, which may imply similar characteristics.

3.2 Selection of the probability density functions

The PDFs parameters estimated by the L-moments method, as well as the results for the Anderson-Darling tests, are presented in Table 3. The distribution LN-3P showed to be the best-fitted PDF for the majority of the series analyzed in this study. LN-2P distribution best described one of the annual maximum streamflow series and Gumbel distribution another one. Cassalho et al. (2018) applied L-moments method for estimations of two-parameter and multiparameter PDFs in 106 streamflow series in Rio Grande do Sul. The authors noted that, however LN-2P, LN-3P, Gumbel, and Gamma PDFs adequately described more than 70 of the studied series, multiparameter distributions showed superior performance in adjusting the time series. Drissia et al. (2019) also found that multiparameter distributions Generalized Extreme Value, Generalized Pareto and Generalized Logistic were the best fitted for the 43 time series studied. Considering that, future evaluations of multiparameter PDFs in the region of Lavras could improve the estimates of design streamflow.

Table 3 – PDFs parameters estimated by the L-moments method and Anderson-Darling (AD) test values appropriated at 5% of significance.

Gauge Station	LN-2P	LN-3P	Gumbel	Gamma
Bom Sucesso	μ = 4.134 σ = 0.502 AD = 0.546	β = 14.200 μ = 3.818 σ = 0.667 AD = 0.266*	not appropriate	not appropriate
Couro do Cervo	not appropriate	β = -65.714 μ = 4.636 σ = 0.148 AD = 0.517*	not appropriate	not appropriate
Itumirim	μ = 5.080 σ = 0.403 AD = 0.608*	β = 39.931 μ = 4.758 σ = 0.554 AD = 0.682	not appropriate	not appropriate
Luminárias	μ = 4.727 σ = 0.488 AD = 0.223	β = 11.523 μ = 4.598 σ = 0.550 AD = 0.163*	μ = 97.927 α = 0.020 AD = 0.541	υ = 3.948 β = 32.172 AD = 0.577
Marechal Mascarenhas	μ = 4.341 σ = 0.619 AD = 0.340	β = -31.861 μ = 4.717 σ = 0.422 AD = 0.256	μ = 66.451 α = 0.024 AD = 0.248*	υ = 2.895 β = 31.214 AD = 0.266
Santana do Jacaré	μ = 5.148 σ = 0.443 AD = 0.369	β = -85.236 μ = 5.572 σ = 0.286 AD = 0.166*	μ = 152.077 α = 0.016 AD = 0.189	υ = 5.628 β = 33.512 AD = 0.180

*Lowest AD values.

Source: from Author (2021).

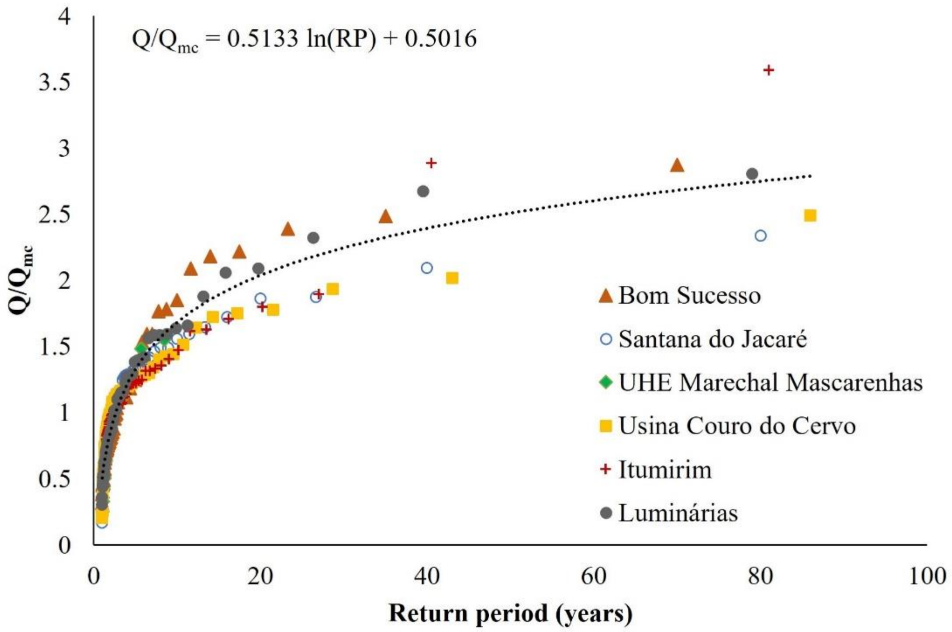
3.3 Regional flood frequency analysis and its performance

The regional growth curve was generated correlating the dimensionless flood variable ($X = Q/Q_{mc}$) with their return periods (RP) by a logarithm relationship with R^2 equal to 0.93 (FIGURE 2). Figure 3 shows the linear regression for the Q_{mc} using the drainage area as explanatory variable, and the fit with R^2 equal to 0.83 suggests adequate performance. Then, the product between these two relationships generated the regional function for ungauged basins in the region of Lavras (Equation 14).

The adequate adjustment of the regional growth curve by the logarithm regression between return period and Q/Q_{mc} was also verified by Cassalho et al. (2017). These authors obtained an optimum performance of an equation developed for 7 watersheds in the Rio Grande do Sul State in Brazil. Concerning the index flood, Hailegeorgis and Alfredsen (2017a) reported a R^2 of 0.95 using linear relationship between the drainage area and index flood, considerably superior when using the power law ($R^2 = 0.80$).

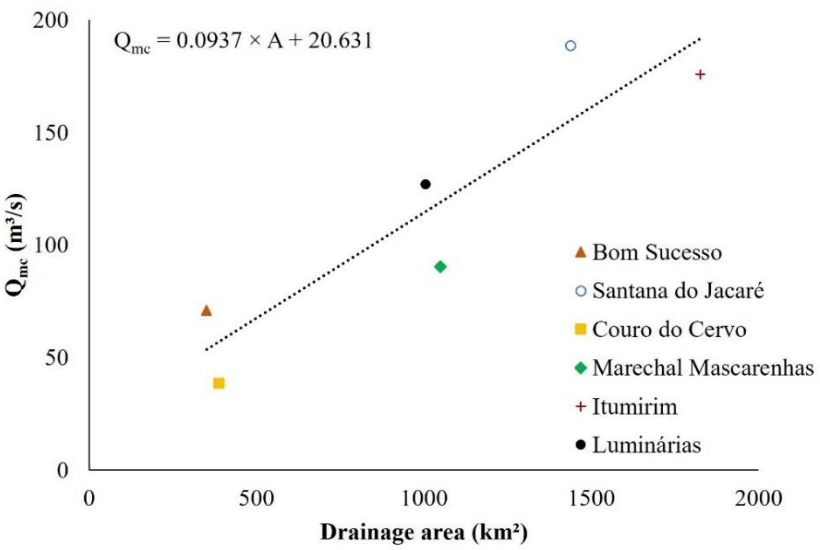
$$Q_R = [0.0937 \times A + 20.6312] \times [0.5133 \times \ln(RP) + 0.5016] \tag{14}$$

Figure 2 – Relationship between dimensionless flood variable and corresponding return period (RP) in the studied watersheds.



Source: from Author (2021).

Figure 3 – Relationship between average maximum streamflow and drainage area in the studied watersheds.



Source: from Author (2021).

Considering the best-fitted PDFs for each annual maximum streamflow series, the performance of the regional function were evaluated by the jack-knifing method (MERZ; BLÖSCHL, 2005). In the first analysis, the coefficient c for each station was calculated comparing the maximum streamflow values estimated by the jack-knifed regional function with the best-fitted PDF estimates at return periods of 10, 20, 50 and 100 years (TABLE 4). According to the classification proposed by Camargo and Sentelhas (1997), the majority of the sites exhibited optimum predictive performance ($c > 0.85$) and two of them had the performance classified as very good ($0.76 \leq c \leq 0.85$). The relatively low performances of Couro do Cervo and Itumirim might be due to PDF fitting and not the predictive capacity of the regional function. Both series presented the highest values of Anderson-Darling test, in addition, Couro do Cervo series was fitted only by LN-3P.

Table 4 – Performance of the regional function for each gauging station when considered as ungauged.

Gauging station	**c**	**Classification**
Bom Sucesso	0.88	Optimum
Couro do Cervo	0.77	Very good
Itumirim	0.84	Very good
Luminárias	0.98	Optimum
Marechal Mascarenhas	0.87	Optimum
Santana do Jacaré	0.98	Optimum

Source: from Author (2021).

In addition, the coefficient c was calculated considering the estimates at all sites at return periods of 10, 20, 50 and 100 years, one at a time (TABLE 5). In this analysis, the predictive performance of the regional function was classified as very good ($0.76 \leq c \leq 0.85$) for the estimates at 10 and 20-year return period, and as good ($0.66 \leq c \leq 0.75$) for 50 and 100-year (CAMARGO; SENTELHAS, 1997). The series length varied from 16 to 85 years, thus, uncertainties related to the estimation of higher return periods might have influenced the regional function and PDFs performances. Likewise, Drissia et al. (2019) evaluated the correlation between observed and estimated flood quantiles by at-site and regional frequency analysis. In both cases, the correlation decreased as the return period increased. Despite of the correlation between regional function and observed values were lower, the authors mentioned that regional flood frequency analysis has estimated flood quantiles similar to at-site estimates, being an important contribution for ungauged sites.

Table 5 – Performance of the regional function for different return periods.

Return period	c	Classification
10	0.78	Very good
20	0.76	Very good
50	0.73	Good
100	0.70	Good

Source: from Author (2021).

In this study, the watersheds' areas varied from 351.22 to 1825.44 km², in that way the extrapolation of the regional function to drainage areas out of this range may result in inaccurate estimates (JUNIOR et al., 2003; NAGHETTINI, 2017). Regarding the adequate performance and taking as reference the return periods, it demonstrates the applicability of the regional function for different assumed risks in flood management. Likewise, Cassalho et al. (2017) found adequate applicability when they performed a maximum streamflow regionalization with 7 watersheds in the South of Brazil.

Many studies also verified the drainage area as appropriate explanatory variable for the index flood, agreeing with the parsimony principle (ALAM; MUZZAMMIL; KHAN, 2016; CASSALHO et al., 2017, 2019; DE MICHELE; ROSSO, 2002). Other studies sought to improve the performance of the regional function when correlating more explanatory variables (CASSALHO et al., 2019; DRISSIA et al., 2019; JINGYI; HALL, 2004; NOTO; LA LOGGIA, 2009; PETROSELLI; VOJTEK; VOJTEKOVÁ, 2019). However, Drissia et al. (2019) mentioned that including more parameters in the index flood requires deeper statistical understanding of their influence in the function's behavior. Therefore, further analysis in the region of Lavras, applying other characteristics to describe the index flood, may improve the determination coefficient of the linear regression and the performance of the regional function in predicting flood quantiles.

3.4 Flood quantiles, regional growth curve and index flood uncertainty

The confidence intervals (CI) for the best-fitted PDF, i.e., at-site quantiles estimates, for the 6 annual maximum streamflow series varied considerably. Couro do Cervo produced the narrowest CI, with a maximum variation of streamflow estimates of -0.12% and 0.17% at 100-year due to relatively longer period of data at this gauging station. On the other hand, Marechal Mascarenhas (-0.32% and 0.42%) and Bom Sucesso (-0.30% and 0.46%) produced widest CI. Marechal Mascarenhas is the series with smaller length, so it was expected, since the estimates of higher return periods extrapolates the observed frequency of exceedance. Regarding Bom

Sucesso series, it showed the second lowest p-value for the MK test, what is an indication that the series is slightly leaning to present non-stationarity and it may have influenced this result.

For the regional growth curve, the lower and upper CI estimated by the BCa bootstrap at 95% for parameter a' were 0.4875 and 0.5463; and for parameter b' were 0.4771 and 0.5221. Therefore, the regional growth curve lower (RCG_L) and upper (RCG_U) bounds are given by equations 15 and 16, respectively.

$$RGC_L = 0.4875 \times \ln(RP) + 0.4771 \quad (15)$$

$$RGC_U = 0.5463 \times \ln(RP) + 0.5221 \quad (16)$$

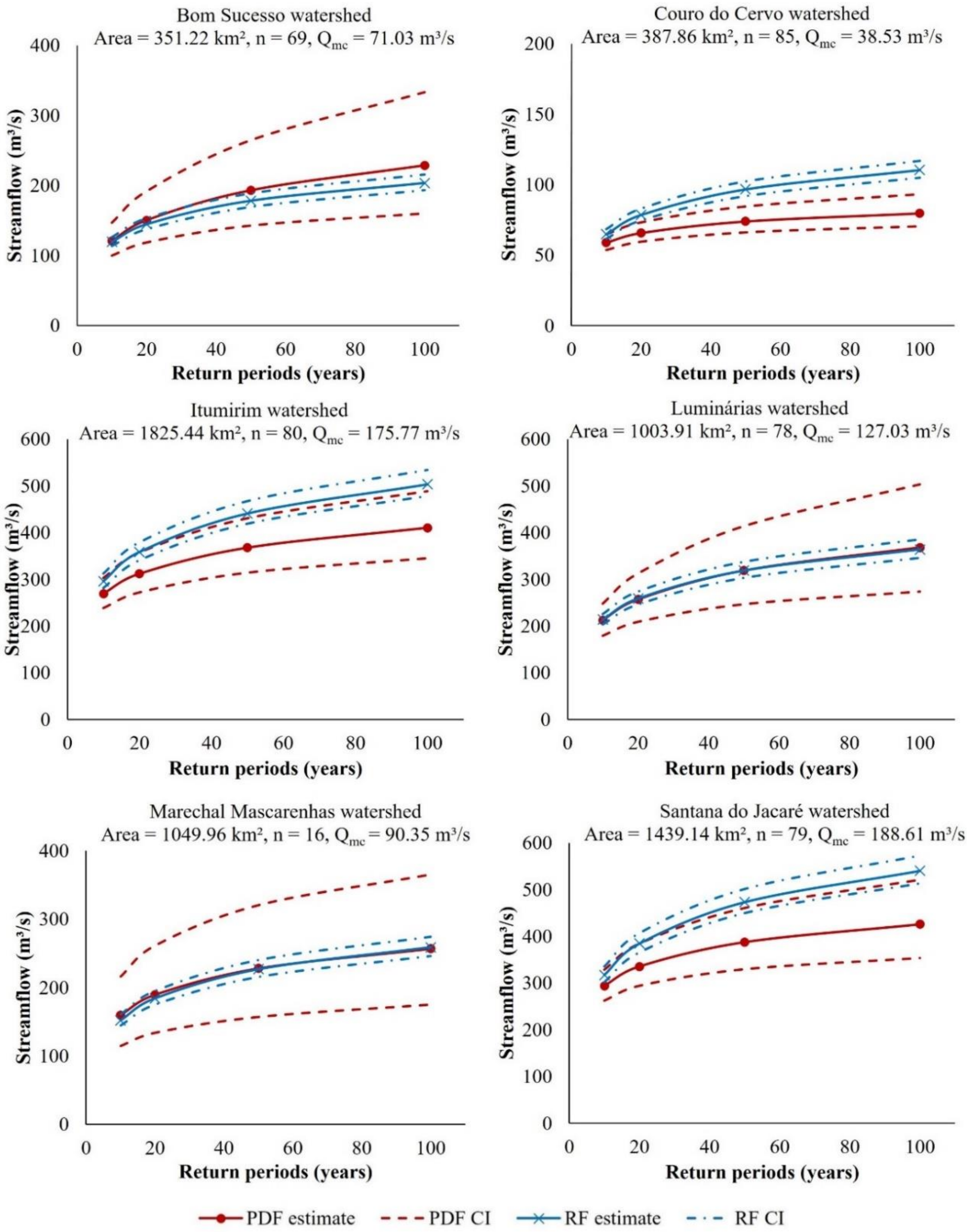
As mentioned on Section 2.4, in gauged basins, the index flood is the average maximum streamflow of the series. Hence, the bounds of the quantiles estimates from regional function (RF) and at-site (PDF) analysis for each one of the six stations are compared in Figure 4. Higher return periods presented wider uncertainty for predicted streamflow, as was expected, since these estimates extrapolate the observed events, for either at-site or regional analysis.

Bom Sucesso flood quantiles were under-estimated by the regional function in comparison with at-site analysis, even displaying upper confidence interval values lower than the PDF estimate. This case may represent great risks, because it can imply under-design of flood control measures, affecting population safety. However, it is important to note that the estimates and uncertainty bounds of the regional function still are within the PDF confidence intervals.

The regional function estimates for Couro do Cervo, Santana do Jacaré, and Itumirim were higher than at-site estimates, even higher than at-site upper confidence interval. Hailegeorgis and Alfredsen (2017a) also verified this behavior in two of the 20 watersheds regionalized in Mid-Norway. In these sites, considering a certain return period adequate for a structure, the streamflow estimates by the regional function would surpass the necessary safety standards for flood control measures. Nevertheless, overestimation of design floods increases the construction costs of structural measures.

Luminárias and Marechal Mascarenhas showed very close values from both predictions. These sites present similar drainage areas with values near to the median (1026.9 km²). It might indicate a better performance of the regional function for basins with drainage areas distant from the boundary values of the analyzed sites. Consequently, the application of the regional function can improve the quality of Marechal Mascarenhas series, since it holds only 16 years of streamflow data. According to Hailegeorgis and Alfredsen (2017a), these differences between estimates from at-site and regional flood frequency analysis indicate the importance of comparative evaluation of the results for each case individually.

Figure 4 – Estimated at-site and regional quantiles with uncertainty bounds for the watersheds in the region studied at 95% of confidence.



Q_{mc}: average maximum streamflow; n: length of the series; PDF: probability density function; RF: regional function; CI: confidence interval.

Source: from Author (2021).

Changes in climate and land use can considerably affect extreme floods in the future and influence flood risk management. Some recent studies assessed the impacts of possible changes in the Grande River Basin hydrology. Nóbrega et al. (2011) showed that a dangerous climate change scenario, increasing 2°C in the global mean temperature, could result in 18% increase in maximum streamflows for the entire Grande River Basin. Viola et al. (2015) indicated that maximum streamflow in the headwaters of Grande River basin could increase by 37%; whereas Oliveira et al. (2017) suggested that peak discharges upstream the Funil Hydropower Plant could increase by up to 22.6% from the RCP 8.5 climate scenario.

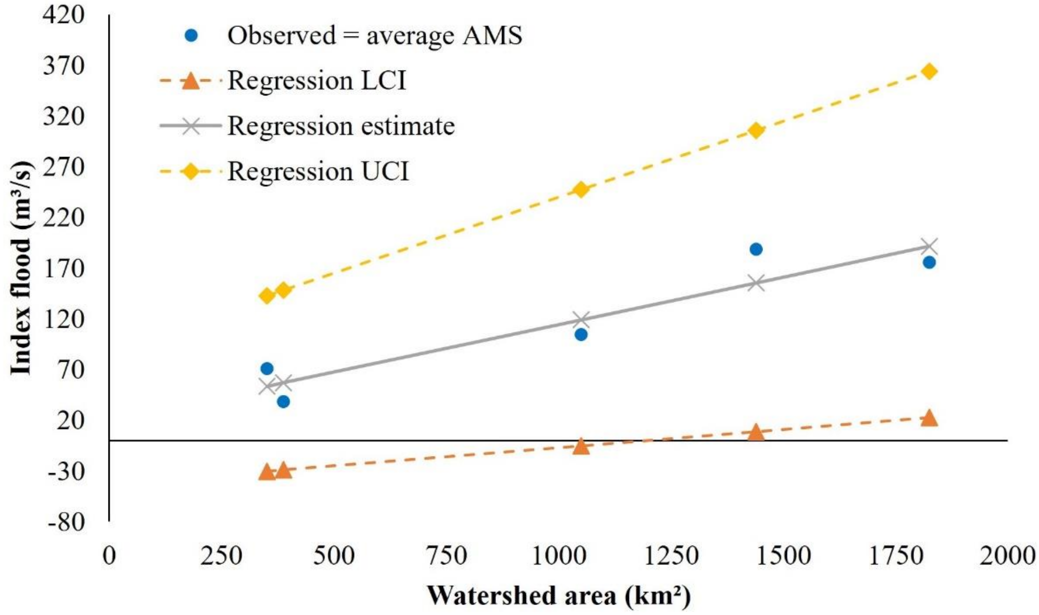
Regarding future land use changes, Viola et al. (2014) estimated that maximum streamflow could increase by 15% and 43% with 30% and 70% of deforestation, respectively in Grande River headwater basins. Oliveira et al. (2018), however, estimated a very slight increase of 1.6 and 1.9 m^3/s for 20% and 50% deforestation, respectively, at Funil Hydropower Plant. Higher alterations in headwaters regime are explained because there is no reservoirs or streamflow regulations in this portion of the basin (VIOLA et al., 2015).

To assess the validity of the at-site estimates and regional functions in Figure 4, we compared the streamflow estimates with published possible increases in streamflow from future projections of climate and land use studies. For 10-years return period, the upper bound of the regional function would cover a streamflow increase of 16.40% for Couro do Cervo and 16.14% for Itumirim. Increases in streamflow of 26.4% for Couro do Cervo, 21.68% for Itumirim and 21.37% for Santana do Jacaré would be covered by the upper limit for 20-years return period. For 50 and 100-years, the upper limits of Itumirim and Santana do Jacaré comprise the 22.6% streamflow increasing estimated by Oliveira et al. (2017). Finally, higher alterations due to climate changes estimated by Viola et al. (2015) would be captured in Couro do Cervo estimates for 50 and 100-years return periods. Overall, the regional estimates and their uncertainty bound capture the range published by different studies.

Considering these future streamflow changes in present flood risk planning will be important. Kundzewicz et al. (2018) highlight that as predictions of water resources alteration due to climate changes highly differ, the decision-making process, which becomes hard under uncertain conditions, often neglect those future scenarios. According to Viola et al. (2014), Grande River headwaters are actually going through a reforestation process due to the expansion of eucalyptus. In this case, eucalyptus reforestation in substitution of grassland may result in 5.17% decrease in peak flows (VIOLA et al., 2014).

The linear regression adjusted for the index flood resulted in a residual standard error of 27.25 m^3/s. Monte Carlo simulations estimated lower confidence interval (LCI) and upper confidence interval (UCI) for index flood parameters of 0.036 and 0.150 for a, and of -42.913 and 89.768 for b. Figure 5 shows the uncertainty bounds of the index flood equation for the six watersheds in this region. As discussed by Hailegeorgis and Alfredsen (2017a), the uncertainty of the index flood prediction is higher for larger drainage areas. It is worth to mention that the wide parameters range produced negative values of index flood for smaller watersheds, which is not physically feasible. Then, for basins with drainage area lower than 1191.25 km², the lower confidence interval of the index flood has no physical meaning.

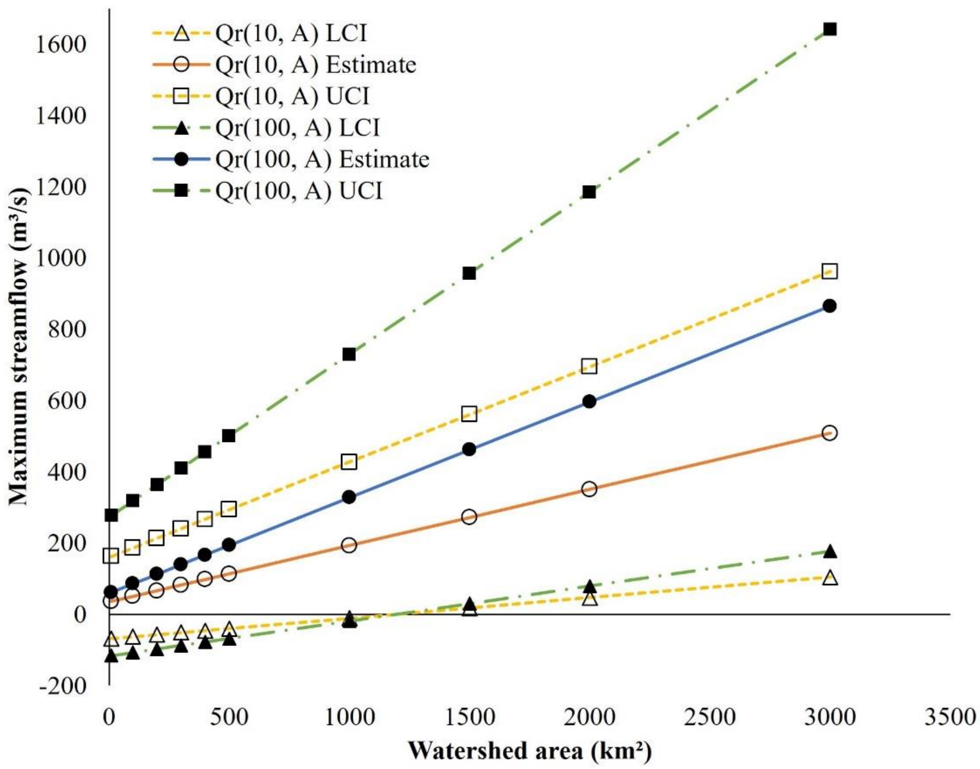
Figure 5 – Average maximum streamflow and linear regressions related to the watersheds' areas in the region.



Source: from Author (2021).

The uncertainty of predictions in ungauged basins presented wide ranges, which increases with the watershed area and return period (FIGURE 6), as was observed by Hailegeorgis and Alfredsen (2017a). Again, because of negative index flood estimates for the lower bound, the maximum streamflow estimates presented negative values for smaller watersheds that are not feasible. However, for flood control measures, it is of high importance to consider the upper bound. The upper bound shows the maximum value that the streamflow estimate can reach and protect from under-design of structures. Thus, the lower confidence interval can be neglected for this approach.

Figure 6 – Predicted flood quantiles as a function of watershed area in ungauged basins for 10- and 100-years return period.



Q_R: regionalized streamflow; A: drainage area; LCI: lower confidence interval; UCI: upper confidence interval.

Source: from Author (2021).

3.5 Applicability of the regional function

Dealing with the uncertainty of the regional function in ungauged sites is a challenge, as the confidence intervals highly differ from the estimates. Kundzewicz et al. (2017) state that uncertainties in flood predictions should be used to inform decision-makers about adaptive design of control measures. Adaptation pathways are a set of strategies, which should be implemented in the drainage system in order to meet future changes in streamflow, e.g., improving porous pavements, green roofs, reservoirs, and the diameter of sewers (BABOVIC; MIJIC, 2019). Babovic and Mijic (2019) evaluated different future scenarios of rising storm water coupled with adaptation pathways of flood risk management, and found that the order in which the solutions are implemented is crucial for population safety along with economic benefits. In this sense, iterative policy revision and implementing diversity strategies, i.e. combining soft and hard flood control measures, are essential for the success of flood risk management (KUNDZEWICZ et al., 2017; MERZ et al., 2015).

Despite the large uncertainty bounds related to the predictions in ungauged basins, the regional function generated for Lavras region is an important tool for water resources and flood risk management. Design floods in Brazil are generally estimated by considering rainfall IDF curves and rainfall-runoff models (CABRAL et al., 2014; DECINA; BRANDÃO, 2016; TUCCI, 2005). For this approach, we highlight some issues that may enhance uncertainty: IDF curves are estimated by disaggregation of daily rainfall, since there is a lack recording gauges in Brazil (Souza et al., 2019); even simpler rainfall-runoff models require soil and land use information, that sometimes are not easily available and/nor accurate (BESKOW et al., 2016b); calibration of rainfall-runoff models is an important step and still a challenge in ungauged basins (POOL; VIVIROLI; SEIBERT, 2017). Hence, the regional function developed in this study, besides being a simpler approach, decreases the uncertainty of the modeling process. The model is based on streamflow observations and observes the parsimony principle by using only the watershed area as explanatory variable (BASU et al., 2010; CASSALHO et al., 2017, 2019).

Developing a regional function for other sites through the methodology applied in this work is a task that does not require high programming or GIS skills, since it was built through simple regression models. Hydrological data in Brazil are easily available in *Hidroweb*, with streamflow observations reaching 100 years and information about drainage area of more than 4,000 stations, thus GIS skills are not necessary to delineate the analyzed watersheds. For nonprofessionals, the most challenging task would be organizing streamflow data, proving its stationarity and defining a homogeneous region. However, SYHDA simplifies these steps by enabling hydrologic analyses, including non-parametric tests for stationarity and homogeneity tests (VARGAS et al., 2019). Therefore, these simple methods can be applied worldwide anywhere hydrological data are available.

Finally, this work supports urban planning of Lavras. Currently, the drainage management of Lavras is carried out without any standard methodology for design flood estimation. The Contingency Plan published in 2018 identified inundation risk areas based only on what is called historical information, i.e., residents' memories about the water level in past events of extreme rainfall (COORDENADORIA MUNICIPAL DE GESTÃO E PROTEÇÃO CIVIL, 2018). We contacted some current and former officials of the Secretariat of Public Works, Urban Regulation and Civil Defense of Lavras to assess the importance of this study. All argued that the regional function would provide more reliability for planning and designing flood control measures. In their view, considering the uncertainties would be important to prioritize risk areas, once the majority is already occupied.

4 CONCLUSION

A maximum streamflow regional function was developed in this study for the region of Lavras, in the south of Minas Gerais, Brazil, through the dimensionless curve method. The index flood, based only on the drainage area, is a simple approach and easy to employ in ungauged sites. The R^2 equal to 0.83 of the linear regression between the average maximum streamflow and the drainage area of the monitored watersheds suggested a good fit. Likewise, the regional growth curve, obtained by a logarithm relationship between the dimensionless flood variable, i.e., the ratio between annual maximum streamflow and the series mean, and return periods, satisfactorily described the studied watersheds with R^2 equal to 0.93.

At-site analysis showed that 3-parameter Log-Normal distribution best described four of the studied annual maximum streamflow series, 2-parameter Log-Normal best described one and Gumbel the other one. The values of coefficient c of Camargo and Sentelhas, comparing at-site to regional analysis estimates by jack-knifing, proved the good performance of the regional function ($c > 0.70$ in all cases). Thus, the maximum streamflow regional function is an interesting alternative for flood estimates in gauged and ungauged sites in this region. However, it is important to mention the possible inaccuracy of applying the function in watersheds with areas out of the boundary of the studied sites (351.22 to 1825.44 km^2).

Monte Carlo simulations and bootstrapping resulted in the evaluation of the estimates uncertainties. At-site analysis showed wide confidence intervals, with Bom Sucesso presenting the widest range (-0.30% to 0.46%) and Couro do Cervo the narrowest range (-0.12% to 0.17%). The confidence intervals of the regional function were narrower than the PDFs, however, in some cases they did not overlap. Regional analysis under-estimated the streamflow in one of the gauged watersheds, over-estimated it in three sites and showed very close values in two sites. Hence, it is important to consider these variations and evaluate the best approach for each site in the region.

Regardless of the large confidence intervals for prediction in ungauged basins, the consideration of uncertainty bounds is an important step for appropriate flood risk management. In order to improve the adequacy of estimates in ungauged watersheds, future studies should consider the utilization of more robust regionalization techniques, including improved statistical analyses, different hydrological grouping, and a larger number of explanatory variables.

The regional function developed for the region of Lavras will support the decision-makers planning flood control measures, as the city lacks adequate urban drainage management. Further, the simple methodology applied in this work may assist the development of regional functions for other regions, improving the adequacy of streamflow estimates throughout Brazil and consequently reducing the negative impacts of floods.

ACKOWNLEDGMENTS

The authors would like to acknowledge CAPES (Coordination for the Improvement of Higher Education Personnel in Brazil) for the scholarship PDSE-88881.362120/2019-01. Also, acknowledge Purdue University for hosting the research scholar; UFLA (Federal University of Lavras) for educational support; and the Research Group on Hydrology and Hydrological Modeling in Watersheds/CNPq of the Federal University of Pelotas for providing the full version of the software SYHDA. And grateful thank Ms. Joanne Lax, Graduate Technical Communications & Professional Development Specialist of Purdue University College of Engineering, for the technical writing support.

Funding: This work was supported by the Coordination for the Improvement of Higher Education Personnel in Brazil (CAPES) [grant number PDSE-88881.362120/2019-01]. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001

REFERENCES

ALAM, J.; MUZZAMMIL, M.; KHAN, M. K. Regional flood frequency analysis: comparison of L-moment and conventional approaches for an Indian catchment. **ISH Journal of Hydraulic Engineering**, [s. l.], v. 22, n. 3, 2016.

ALVARES, C. A. et al. Köppen’s climate classification map for Brazil. **Meteorologische Zeitschrift**, [s. l.], v. 22, n. 6, p. 711–728, 2013.

ARSENAULT, R.; BRISSETTE, F. P. Continuous streamflow prediction in ungauged basins: The effects of equifinality and parameter set selection on uncertainty in regionalization approaches. **Water Resources Research**, [s. l.], v. 50, n. 7, p. 6135–6153, 2014.

ASQUITH, W. . **lmomco---L-moments, censored L-moments, trimmed L-moments, L-comoments, and many distributions.**, Texas Tech University, 2018.

ATIEH, M. et al. Prediction of flow duration curves for ungauged basins. **Journal of Hydrology**, [s. l.], v. 545, p. 383–394, 2017. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2016.12.048>

BABOVIC, F.; MIJIC, A. Economic evaluation of adaptation pathways for an urban drainage system experiencing deep uncertainty. **Water (Switzerland)**, [s. l.], v. 11, n. 3, 2019.

BASU, N. B. et al. Parsimonious modeling of hydrologic responses in engineered watersheds: Structural heterogeneity versus functional homogeneity. **Water Resources Research**, [s. l.], v. 46, n. 4, 2010. Disponível em: <http://doi.wiley.com/10.1029/2009WR007803>. Acesso em: 12 jan. 2020.

BESKOW, S. et al. Multiparameter probability distributions for heavy rainfall modeling in extreme southern Brazil. **Journal of Hydrology: Regional Studies**, [s. l.], v. 4, n. PB, p. 123–133, 2015.

BESKOW, S. et al. Artificial intelligence techniques coupled with seasonality measures for hydrological regionalization of Q90 under Brazilian conditions. **Journal of Hydrology**, [s. l.], v. 541, p. 1406–1419, 2016. a. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2016.08.046>

BESKOW, S. et al. Potential of the LASH model for water resources management in data-scarce basins: a case study of the Fragata River basin, southern Brazil. **Hydrological Sciences Journal**, [s. l.], v. 61, n. 14, p. 2567–2578, 2016. b. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/02626667.2015.1133912>. Acesso em: 12 jan. 2020.

BRAZIL. Law n. 11445, January 5th of 2007.Brazil, 2007.

CABRAL, S. L. et al. Hydrologic and hydraulic modelling integrated with GIS: A study of the Acaraú River Basin – CE. **Journal of Urban and Environmental Engineering**, [s. l.], v. 8, n. 2, p. 167–174, 2014.

CAMARGO, A. P.; SENTELHAS, P. C. Performance Evaluation of Different Potential Evapotranspiration Estimating Methods in the State of São Paulo, Brazil. **Revista Brasileira de Agrometeorologia**, [s. l.], v. 5, n. 1, p. 89–97, 1997.

CANTY, A.; RIPLEY, B. **boot: Bootstrap R (S-Plus) Functions**, 2019.

CASSALHO, F. et al. Hydrological regionalization of maximum stream flows using an approach based on L-moments. **Revista Brasileira de Recursos Hídricos**, [s. l.], v. 22, n. 0, 2017.

CASSALHO, F. et al. At-Site Flood Frequency Analysis Coupled with Multiparameter Probability Distributions. **Water Resources Management**, [s. l.], v. 32, n. 1, p. 285–300, 2018.

CASSALHO, F. et al. Regional flood frequency analysis using L-moments for geographically defined regions: An assessment in Brazil. **Journal of Flood Risk Management**, [s. l.], v. 12, n. 2, p. 1–13, 2019.

CHOUBIN, B. et al. Streamflow regionalization using a similarity approach in ungauged basins: Application of the geo-environmental signatures in the Karkheh River Basin, Iran. **Catena**, [s. l.], v. 182, p. 104128, 2019.

COORDENADORIA MUNICIPAL DE GESTÃO E PROTEÇÃO CIVIL. Plano de Contingência - Lavras - MG. . 2018.

CUNNANE, C. Review of statistical models for flood frequency estimation. [s. l.], n. (ed.), Dordrecht, The Netherlands, D. Reidel Publishing Co., 1987, Section 1, p.49- 95. (ISBN 90-277-, 1987.

DE MICHELE, C.; ROSSO, R. A multi-level approach to flood frequency regionalisation. **Hydrology and Earth System Sciences**, [s. l.], v. 6, n. 2, p. 185–194, 2002.

DECINA, T. G. T.; BRANDÃO, J. L. B. Análise de desempenho de medidas estruturais e não estruturais de controle de inundações em uma bacia urbana. **Engenharia Sanitaria e Ambiental**, [s. l.], v. 21, n. 1, p. 207–217, 2016.

DICICCIO, T. J.; EFRON, B. **Bootstrap Confidence IntervalsStatistical Science**. [s.l: s.n.].

DRISSIA, T. K. et al. Flood Frequency Analysis Using L Moments: a Comparison between At-Site and Regional Approach. **Water Resources Management**, [s. l.], v. 33, n. 3, p. 1013–1037, 2019. Disponível em: <https://doi.org/10.1007/s11269-018-2162-7>. Acesso em: 16 jan. 2020.

EFRON, B. Better bootstrap confidence intervals. **Journal of the American Statistical Association**, [s. l.], v. 82, n. 397, p. 171–185, 1987.

FAGHIH, M. et al. Uncertainty Estimation in Flood Inundation Mapping: An Application of Non-parametric Bootstrapping. **River Research and Applications**, [s. l.], v. 33, n. 4, p. 611–619, 2017.

FARAWAY, J. et al. **goftest: Classical Goodness-of-Fit Tests for Univariate Distributions.**, 2019. Disponível em: <https://cran.r-project.org/package=goftest>

FRANCO, C. S. et al. Distribuição de probabilidades para precipitação máxima diária na Bacia Hidrográfica do Rio Verde, Minas Gerais. **Revista Brasileira de Engenharia Agrícola e Ambiental**, [s. l.], v. 18, n. 7, p. 735–741, 2014.

GARAMBOIS, P. A. et al. Parameter regionalization for a process-oriented distributed model dedicated to flash floods. **Journal of Hydrology**, [s. l.], v. 525, p. 383–399, 2015. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2015.03.052>

HAILEGEORGIS, T. T.; ALFREDSEN, K. Regional flood frequency analysis and prediction in ungauged basins including estimation of major uncertainties for mid-Norway. **Journal of Hydrology: Regional Studies**, [s. l.], v. 9, p. 104–126, 2017. a.

HAILEGEORGIS, T. T.; ALFREDSEN, K. Analyses of extreme precipitation and runoff events including uncertainties and reliability in design and management of urban water infrastructure. **Journal of Hydrology**, [s. l.], 2017. b.

HOSKING, J. R. M.; WALLIS, J. R. Correction to “Some Statistics Useful in Regional Frequency Analysis”. **Water Resources Research**, [s. l.], v. 31, n. 1, p. 251–251, 1995. Disponível em: <http://doi.wiley.com/10.1029/94WR02510>. Acesso em: 11 jan. 2020.

HOSKING, J. R. M.; WALLIS, J. R. **Regional frequency analysis: an approach based on L-moments**. Cambridge: Cambridge University Press, 1997.

IBGE. **Censo Demográfico 2010**. Brasilia: Imprensa Nacional/Diário Oficial da União, nº 211, Seção 1, 2010.

IBGE. **Estimativas da população residente com data de referência 1° de julho de 2018**. Rio de Janeiro.

IGAM, I. M. de G. das Á.; CBH, C. da B. H. do R. G. Plano Diretor de Recursos Hídricos da Bacia do Rio das Mortes. [s. l.], p. 70, 2013.

JINGYI, Z.; HALL, M. J. Regional flood frequency analysis for the Gan-Ming River basin in China. **Journal of Hydrology**, [s. l.], v. 296, n. 1–4, p. 98–117, 2004.

JUNIOR, O. B. D. S. et al. Extrapolação Espacial na Regionalização da Vazão. **Revista Brasileira de Recursos Hídricos**, [s. l.], v. 8, n. 1, p. 21–37, 2003.

KUNDZEWICZ, Z. W. et al. Differences in flood hazard projections in Europe–their causes and consequences for decision making. **Hydrological Sciences Journal**, [s. l.], v. 62, n. 1, p. 1–14, 2017.

KUNDZEWICZ, Z. W. et al. Uncertainty in climate change impacts on water resources. **Environmental Science and Policy**, [s. l.], v. 79, n. October 2017, p. 1–8, 2018.

LAVRAS. Lei 4.445 - Plano Municipal de Saneamento Básico do Município de LavrasLavras, Brazil, 2018.

MÉLÈSE, V.; BLANCHET, J.; MOLINIÉ, G. Uncertainty estimation of Intensity–Duration–Frequency relationships: A regional analysis. **Journal of Hydrology**, [s. l.], v. 558, p. 579–591, 2018.

MERZ, B. et al. Charting unknown waters-On the role of surprise in flood risk assessment and management. **Water Resources Research**, [s. l.], v. 51, n. 8, p. 6399–6416, 2015. Disponível em: <http://doi.wiley.com/10.1002/2015WR017464>. Acesso em: 13 jul. 2020.

MERZ, R.; BLÖSCHL, G. Flood frequency regionalisation - Spatial proximity vs. catchment attributes. **Journal of Hydrology**, [s. l.], 2005.

MERZ, R.; BLOSCHL, G.; BLÖSCHL, G. Flood frequency regionalisation — spatial proximity vs . catchment attributes. **Journal of Hydrology**, [s. l.], v. 302, p. 283–306, 2005.

NAGHETTINI, M. **Fundamental of statistical hydrology**. Switzerland: Springer International, 2017.

NÓBREGA, M. T. et al. Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil. **Hydrology and Earth System Sciences**, [s. l.], v. 15, n. 2, p. 585–595, 2011.

NOTO, L. V.; LA LOGGIA, G. Use of L-Moments Approach for Regional Flood Frequency Analysis in Sicily, Italy. **Water Resour Manage**, [s. l.], v. 23, p. 2207–2229, 2009. Disponível em: <https://www.researchgate.net/publication/225584750>. Acesso em: 13 jan. 2020.

OLIVEIRA, V. A. et al. Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande river basin, Southeastern Brazil. **International Journal of Climatology**, [s. l.], v. 37, n. 15, p. 5005–5023, 2017.

OLIVEIRA, V. A. et al. Land-use change impacts on the hydrology of the upper grande River Basin, Brazil. **Cerne**, [s. l.], v. 24, n. 4, p. 334–343, 2018.

PETROSELLI, A.; VOJTEK, M.; VOJTEKOVÁ, J. Flood mapping in small ungauged basins: A comparison of different approaches for two case studies in Slovakia. **Hydrology Research**, [s. l.], v. 50, n. 1, p. 379–392, 2019.

POHLERT, T. **trend: Non-Parametric Trend Tests and Change-Point Detection**, 2020. Disponível em: <https://cran.r-project.org/package=trend>

POOL, S.; VIVIROLI, D.; SEIBERT, J. Prediction of hydrographs and flow-duration curves in almost ungauged catchments: Which runoff measurements are most informative for model calibration? **Journal of Hydrology**, [s. l.], v. 554, p. 613–622, 2017. Disponível em: <https://doi.org/10.1016/j.jhydrol.2017.09.037>

RIBEIRO, C. et al. Estimativa e regionalização de vazões mínimas de referência para a bacia do rio Doce. **Revista Engenharia Agrícola**, [s. l.], v. 13, p. 103–107, 2005.

RUIZ-VILLANUEVA, V. et al. Characterisation of flash floods in small ungauged mountain basins of Central Spain using an integrated approach. **Catena**, [s. l.], v. 110, p. 32–43, 2013.

SOUZA, G. R. De et al. Heavy rainfall maps in Brazil to 5 year return period. **Revista Ambiente e Agua**, [s. l.], v. 14, n. 3, p. 445–458, 2019. a. Disponível em: <www.ambi-agua.net>. Acesso em: 11 jan. 2020.

SOUZA, G. R. et al. Heavy rainfall maps in Brazil to 5 year return period. **Revista Ambiente e Agua**, [s. l.], v. 14, n. 5, 2019. b.

SWAIN, J. B.; PATRA, K. C. Streamflow estimation in ungauged catchments using regionalization techniques. **Journal of Hydrology**, [s. l.], v. 554, p. 420–433, 2017. Disponível em: <https://doi.org/10.1016/j.jhydrol.2017.08.054>

TEAM, R. C. **R: A language and environment for statistical computing**, R Foundation for Statistical Computing, 2019. Disponível em: <https://www.r-project.org/>

TUCCI, C. E. M. **Regionalização de vazões**. Porto Alegre: Ed. Universidade/UFRGS, 2002.

TUCCI, C. E. M. **Gestão de Águas Pluviais UrbanasMinistério das Cidades – Global Water Partnership - Wolrd Bank – Unesco 2005**. Brasilia.

TUCCI, C. E. M. Urbanization and water resources. In: **Waters of Brazil: Strategic Analysis**. [s.l.] : Springer International Publishing, 2016. p. 89–104.

VARGAS, M. M. et al. SYHDA – System of hydrological data acquisition and analysis. **Revista Brasileira de Recursos Hidricos**, [s. l.], v. 24, 2019.

VIGLIONE, A. **nsRFA: Non-Supervised Regional Frequency Analysis**, 2018. Disponível em: <https://cran.r-project.org/package=nsRFA>

VIOLA, M. R. et al. Impacts of Land-use Changes on the Hydrology of the Grande River Basin Headwaters, Southeastern Brazil. **Water Resources Management**, [s. l.], v. 28, n. 13, p. 4537–4550, 2014.

VIOLA, M. R. et al. Assessing climate change impacts on Upper Grande River Basin hydrology, Southeast Brazil. **International Journal of Climatology**, [s. l.], v. 35, n. 6, p. 1054–1068, 2015.

ARTICLE 2 - FLOOD MAPS USING MAXIMUM STREAMFLOW REGIONAL FUNCTIONS IN UNGAUGED WATERSHEDS: HOW TO IMPROVE THE FLOOD MANAGEMENT IN LAVRAS, MG, BRAZIL

Article submitted on the journal Environment, Development and Sustainability – ISSN: 1573-2975, Impact Factor: 2.191, Qualis-CAPES: B1, presented according to its publication standards.

Gabriela Rezende de Souza [a*]; Jhones da Silva Amorim[a]; Luiz Fernando Coutinho de Oliveira [a]; Gilberto Coelho [a]; Marcelo Ribeiro Viola [a]

[a] Department of Water Resources, Federal University of Lavras (UFLA), Campus Universitário, Lavras, Minas Gerais, 37200-900, Brazil

* Corresponding author at: gabriela.souza2@estudante.ufla.br
Present Address: Federal University of Lavras, Department of Water Resources, Lavras, MG, Brazil

ABSTRACT

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. Two gauged watersheds were selected to evaluate the performance of the regional functions, one that was used to develop both regional functions and one with drainage area similar to the ungauged urban watershed in Lavras. 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: hydraulic modelling; inundation; flood risk; Grande River Basin.

1 INTRODUCTION

Accelerated urbanization without planning causes severe impacts in water resources, such as water pollution, changes in river channels and flood regime. Impervious surfaces lead to decreased infiltration in the floodplain, which increases the runoff, consequently rising the flood risk (MORAES et al., 2018). Besides that, climate changes may also be influencing the rise of extreme rainfall events and runoff, leading to higher inundation risks (AHN; MERWADE, 2014). Therefore, appropriate design of urban drainage systems, and studies aiming to reduce the risks and damages caused by these events are essential to maintain population safety and quality of life (BODOQUE et al., 2016; SPECKHANN et al., 2018).

According to the Centre for Research on the Epidemiology of Disasters (CRED; UNDRR, 2015), part of the World Health Organization (WHO), inundation events corresponded to 47% of all natural disasters related to climate occurred between 1995 and 2015, affecting 2.3 billion of people, mainly in lower income countries. In South America, on average, 560,000 people per year were affected by floods between 1995 and 2004, and in the following decade (2005-2014), this average rose to 2.2 million people per year (CRED; UNDRR, 2015). In Brazil, hydrological disasters (i.e., flood, landslide, and wave action) are the second greatest occurrence of natural disasters and occur throughout the country. Between January 1st of 2000 and July 31st 2017, 6,164 emergencies related to hydrological disasters were registered in 2,872 municipalities, which corresponds to 51.5% of all Brazilian cities (Brazilian Ministry of Health 2018).

Aiming to avoid or reduce negative impacts caused by extreme events, decision-makers should consider an integrated and sustainable flood management. Large construction projects, as dams and levees, gives a false sense of security, and failures in structural (hard) flood control measures can lead to higher flood problems and economical injuries (ARDAYA; EVERS; RIBBE, 2017; RIDOLFI; ALBRECHT; DI BALDASSARRE, 2020). On the other hand, non-structural (soft) measures can be effective with lower costs and in a longer planning horizon (CANHOLI, 2005; CARRICK et al., 2019). In this sense, proper planning of urban drainage systems implies a broad view of preventive and corrective measures, involving urban occupation planning and built infrastructure that may be necessary (DECINA; BRANDÃO, 2016).

Hence, hydrologic and hydraulic modeling rise as important tools, since they allow simulation of different scenarios to perform flood events studies, flood risk management and urban drainage design (CABRAL et al., 2014; QUIROGAA et al., 2016). These tools are essential for water management and public policy decision-making regarding urban drainage planning (SOUZA; CRISPIM; FORMIGA, 2012). The software applications HEC-HMS and HEC-RAS have been widely applied to hydrologic and hydraulic modeling focused on flood management and urban drainage (BODOQUE et al., 2016; BRUNNER; CEIWR-HEC, 2016; MORAES et al., 2018; PAES; BRANDÃO, 2013; SCHARFFENBERG et al., 2018; SOUZA; CRISPIM; FORMIGA, 2012).

Cabral et al. (2014) evaluated the floodplain of a reach of Aracaú River Basin, Ceará, Brazil, integrating hydrological and hydraulics analyses through HEC-HMS and HEC-RAS with geographic information systems. This approach allowed developing reliable flood assessments based on digital data, satellite images and field observations (CABRAL et al., 2014; COOK; MERWADE, 2009; HASANI, 2013). Hydraulic modeling 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.

Proper hydrologic and hydraulic modeling rely on adequate streamflow estimates, which in turn, depend on satisfactory hydrological monitoring. However, many countries face a lack of streamflow gauging stations, especially in small watersheds (BESKOW et al., 2016; SWAIN; PATRA, 2017). To overcome this issue, a common alternative is to implement regionalization techniques to estimate streamflow in ungauged or poorly monitored sites (BAIDYA; SINGH; PANDA, 2020; CASSALHO et al., 2017; LELIS et al., 2020). In this sense, regional functions to predict maximum streamflow can produce estimates that are more reliable, and support the creation of flood hazard maps by means of hydraulic modeling.

As pointed by Lelis et al. (2020), because of the gap in streamflow monitoring in Brazil, regionalization studies and the comparison of different methodologies are an important topic in hydrology. Along with that, flood hazard mapping is essential to guide effective city management involving disaster prevention, drainage planning, and land use and occupation policies in Brazilian municipalities that constantly face flood impacts (BRITES et al., 2019; SPECKHANN et al., 2018).

The Grande River basin, located in the states of Minas Gerais and São Paulo, in the southeastern region of Brazil, has undergone 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 river sections were identified as highly vulnerable to floods with high impact and frequency (ANA, 2019b).

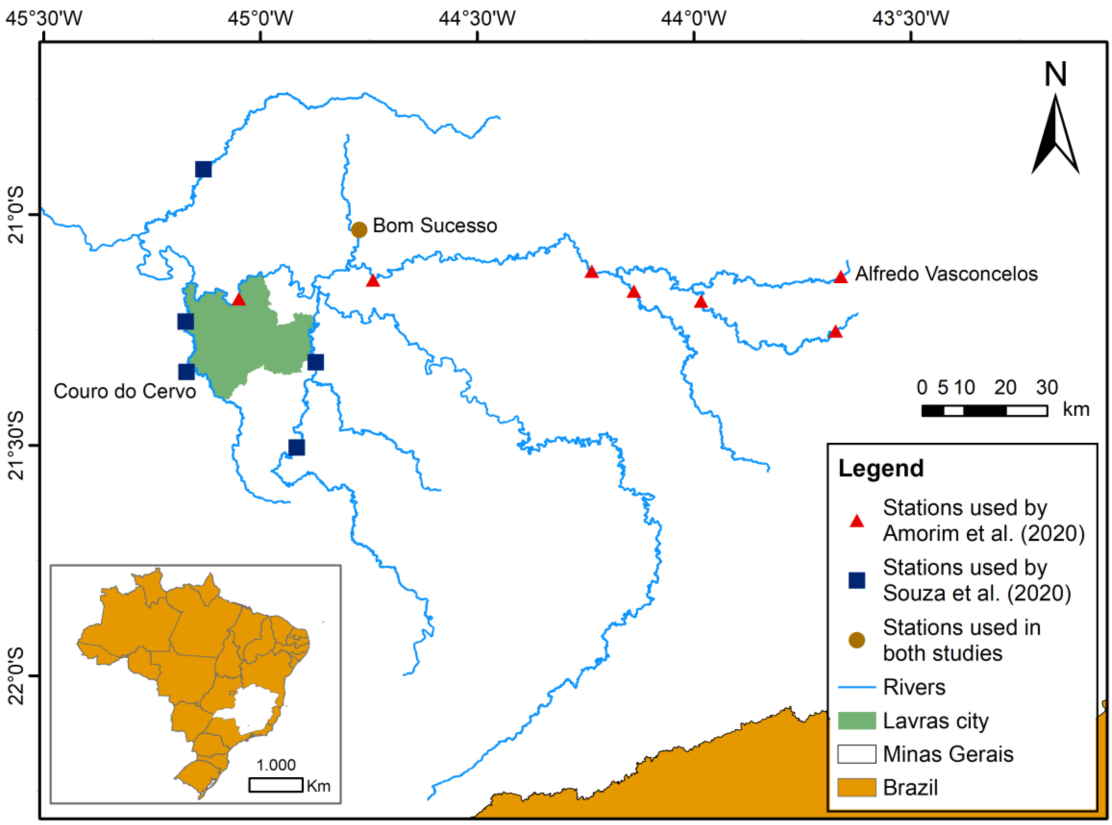
Lavras, in the South of Minas Gerais, is located in the upper region of Grande River and in the drainage area of Funil Hydropower plant. There are no large rivers in the most urbanized areas of the city, but residents often face inundation problems in the urban streams. To avoid negative impacts on the economy and population safety, Tucci (2016) highlighted the importance of proper city planning regarding urban drainage and flood management that is commonly misled in Brazilian cities.

Given the abovementioned, the main objective of this study is to create flood maps for an ungauged watershed located in Lavras, MG, Brazil, aiming to support effective flood risk management. In addition, this work aims to evaluate the predictive capacity of two maximum streamflow regional functions developed for the Grande River Basin and identify the one more adequate to support the creation of flood maps for Lavras.

2 MATERIALS AND METHODS

This study was performed based on maximum streamflow regional functions developed by Amorim et al. (2020) and Souza et al. (2021). Both works regionalized maximum streamflow in the Grande River Basin, Brazil, applying different methodologies and streamflow observations from different gauge stations (FIGURE 1). The estimates from both regional functions were compared in order to define the most appropriate approach to estimate streamflow in an ungauged urban watershed located in Lavras city, MG, Brazil, and then create flood maps.

Figure 1 – Location of the streamflow gauge stations regionalized by Amorim et al. (2020) and Souza et al. (2021).



Source: from Author (2021).

2.1 Maximum streamflow regional functions

Amorim et al. (2020) adjusted regional models (RFA) based on the drainage areas, applying the best-fitted PDF for each series, for return periods of 2, 5, 10, 20, 50, 100, 500 and 1000 years. These authors identified the hydrological homogenous region based on statistical criteria, comparing the observed frequencies of the dimensionless flood variable, i.e., the ratio between the observed streamflow and the mean of the annual maximum streamflow series.

Souza et al. (2021) identified the homogenous region according to the heterogeneity measure (H) and the discordancy measure (D_i), proposed by (HOSKING; WALLIS, 1995, 1997). The regional function developed by Souza et al. (2021) (RFS) was based on the dimensionless curve method, considering an index flood that is specific for each location and a regional growth curve that is common for every site in a region. For gauged basins, the index flood is the mean of the annual maximum streamflow (AMS) series. For ungauged basins, it was estimated by a linear regression between the mean annual maximum streamflow and the drainage area. The regional growth curve is common to every site in the region and was determined by a logarithmic regression between the dimensionless flood variable and their corresponding return periods. Table 1 shows the regional functions developed by these studies.

Table 1 – Maximum streamflow regional functions developed by Souza et al. (2021) (RFS) and Amorim et al. (2020) (RFA).

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

Q_R: regionalized streamflow (m^3s^{-1}); Q_{mc}: index flood, taken as the mean of the AMS series (m^3s^{-1}) for gauged sites; RP: return period (years); A: drainage area (km²).

Source: from Author (2021).

2.2 Flood estimates by the regional functions

In order to compare the regional functions developed by Amorim et al. (2020) and Souza et al. (2021), we selected the AMS series from Bom Sucesso (A = 351.22 km²), which was regionalized by both studies and from Alfredo Vasconcelos (A = 20.04 km²), regionalized by Amorim et al. (2020). The last station was chosen because the area of the urban watershed in the city of Lavras is similar (29.24 km²).

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 Q_{mc} was the observed mean annual maximum streamflow of 71.03 m^3s^{-1} (SOUZA et al., 2021). Alfredo Vasconcelos was considered ungauged, then, the index flood was calculated as a function of the drainage area (Q_{mc} = 0.0937 × A + 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; JONES, 2007, 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 data-transferred index flood is estimated by Equation (1).

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

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 new homogeneity analysis was performed adding Alfredo Vasconcelos AMS series to the homogeneous region composed by the six stations regionalized by Souza et al. (2021). We followed the same procedures of this paper to calculate the heterogeneity measure (H) and the discordancy measure (D_i) (HOSKING; WALLIS, 1995, 1997). 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), henceforth referred as RFS-a.

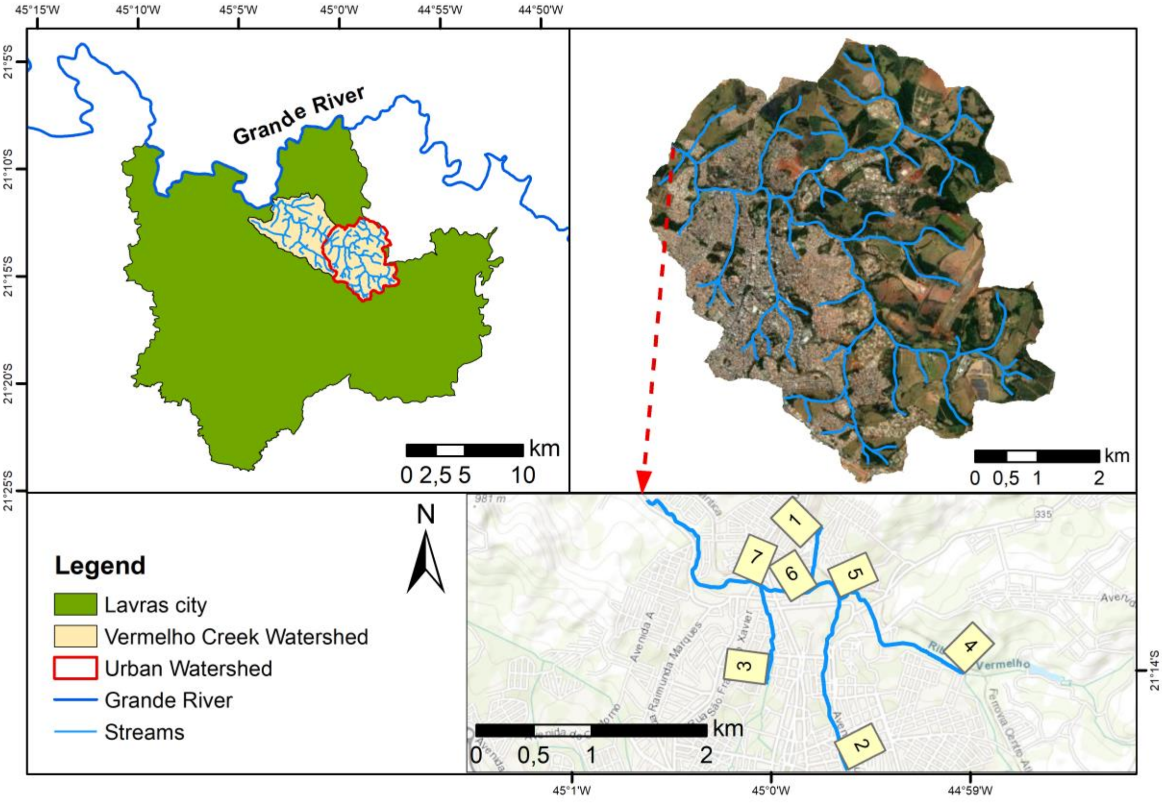
The performances of the regional functions were evaluated by the percent error from PDF estimates for all regional estimates and the mean percent error for each basin, and Nash-Sutcliffe coefficient of natural, logarithmically transformed (NSE-LN) streamflow. The NSE-LN was chosen as performance metric 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 (FARMER et al., 2015; GUPTA; KLING, 2011).

2.3 Flood maps in an urban ungauged watershed

The city of Lavras is located in the South of Minas Gerais State with a population of 103,773 inhabitants (IBGE, 2019); demographic density 163.26 inh.km^2 and the urbanization/impervious roadways correspond to 37.4% (IBGE, 2010). The climate in this region is Cwb in Köppen classification, with dry winter and rainy summer (ALVARES et al., 2013). 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 face flood impacts were selected for generating inundation boundaries of 5, 10, 50 and 100-year return periods in the software HEC-RAS 5.0.7 (FIGURE 2).

Figure 2 – Urban watershed located in Lavras, MG, Brazil, and selected reaches (1 to 7) for flood map.



Source: from Author (2021).

The contribution areas of each reach were calculated using the GeoHMS add-in and the streamflow estimated applying the regional function that produced the most adequate predictions in the performance analysis described on Section 2.2.

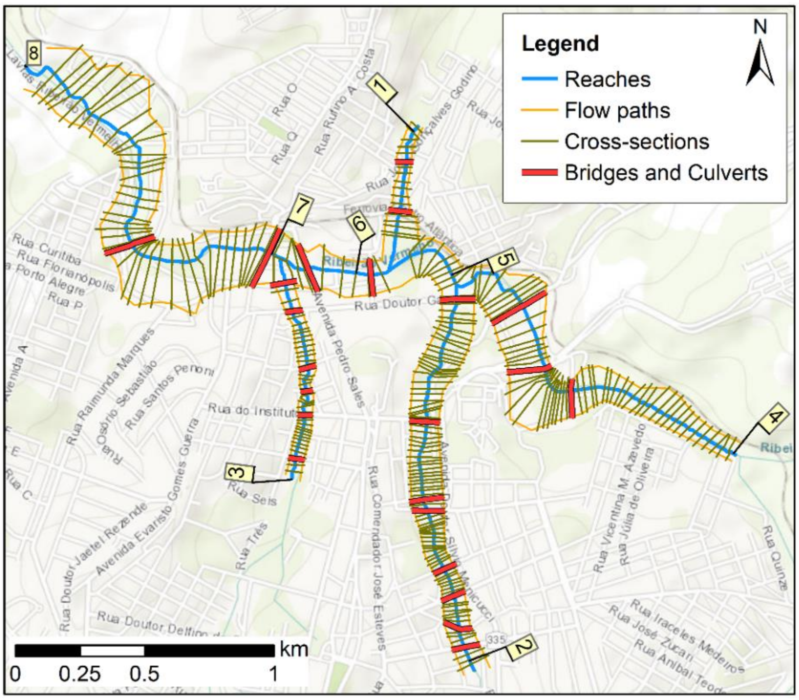
For the delineation of the urban watershed in ArcGIS and the creation of flood maps in HEC-RAS, we used:

- 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 meters.

This version of HEC-RAS allows the construction of the geometry data on the software itself. Analyzing the DEM and aerial images, we drew the 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. For the floodplain, channels with vegetation and constructed channels we considered *n* values of 0.035, 0.025 and 0.02, respectively (BUTLER; 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.

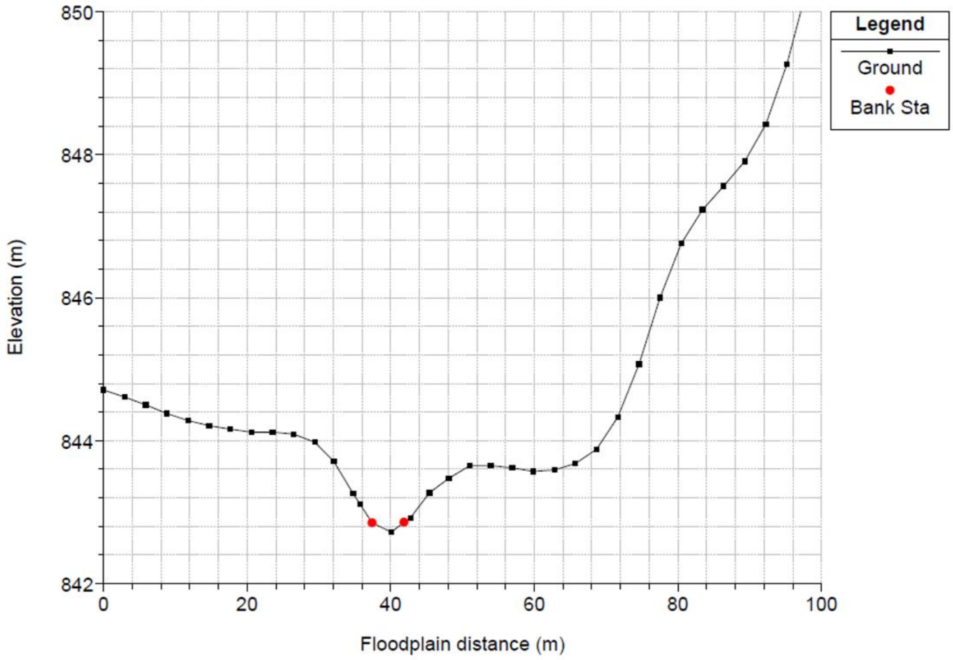
Figure 3 shows the hydraulic model created on HEC-RAS using the aerial images and the DEM with resolution 3x3 m. Figure 4 shows an example of a cross-section in the Vermelho Creek, after computing the delineated geometry and the DEM information on HEC-RAS.

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



Source: from Author (2021).

Figure 4 – First cross-section of the Vermelho Creek (reach 4) obtained from HEC-RAS using the DEM with 3 meter resolution.



Bank Sta: bank station, i.e., the margins of the river.

Source: from Author (2021).

2.4 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/streams.

The regulated land use was assessed by the urban zones described in the Soil Use Directive Plan of Lavras (LAVRAS, 2008, 2016), which establishes land use regulation policies for the city. In Lavras, there are 14 zones that consider the availability of infrastructure and densification capacity, as well as the discomfort degree of the population and the environmental pollution. However, for the design floods studied, we identified 7 urban zones that would be affected, which the regulated uses are:

- Reference use – lands that are not regulated by the city council, as universities and colleges;
- ZPA – Environmental Protection Zone defined by the Brazilian Environmental Legislation, such as areas around springs and water courses that should be vegetated;
- ZEIA – Special Zone of Environmental Interest, where interventions should be made to implement recreational and environmental recovery areas;
- 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 and services, 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.

Therefore, using the flood maps created, we analyzed the current and the regulated land use of the designed inundation areas. Thus, a comparison between the impacted areas by the floods in each of the land use cases was possible.

3 RESULTS AND DISCUSSION

3.1 Flood estimates by the regional functions

The homogeneity analysis showed that Alfredo Vasconcelos can be included in 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; WALLIS, 1997). 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 D_i and drainage areas in comparison with the others (TABLE 2).

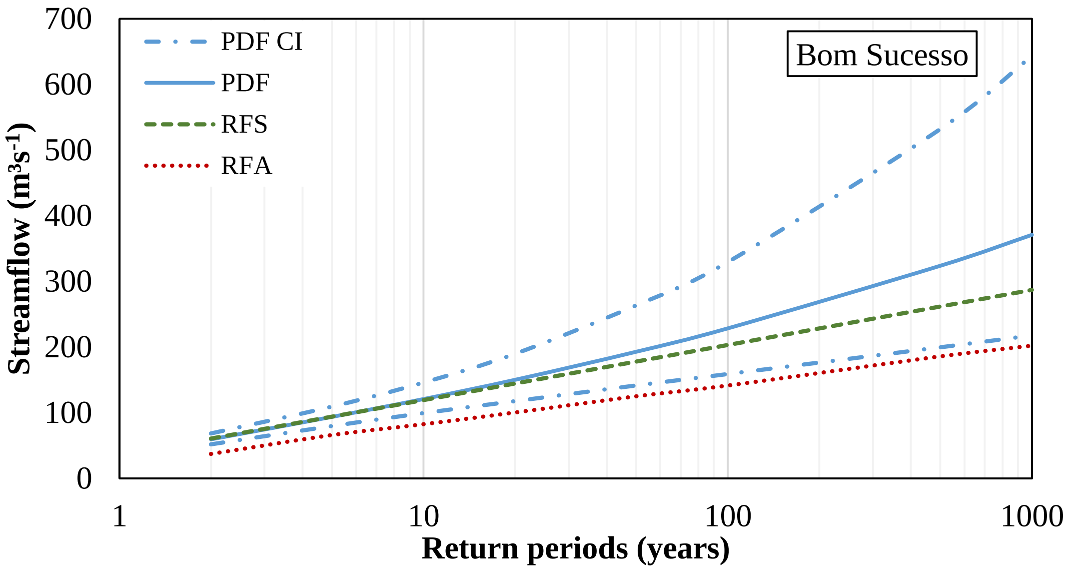
Table 2 – Discordancy measure (D_i) and drainage areas of the streamflow gauge stations regionalized by Souza et al. (2021) and the gauge station Alfredo Vasconcelos.

Station	Discordancy Measure (D_i)	Drainage Area (km²)
Alfredo Vasconcelos	1.3331	20.21
Couro do Cervo	1.6905	387.86
Bom Sucesso	0.593	351.22
Itumirim	0.677	1825.44
Luminárias	0.8944	1003.91
Marechal Mascarenhas	1.1876	1049.96
Santana do Jacaré	0.6245	1439.14

Source: from Author (2021).

Figure 5 and 6 show the streamflow estimates and confidence intervals of PDF for Bom Sucesso and Alfredo Vasconcelos, respectively. Figure 7 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).

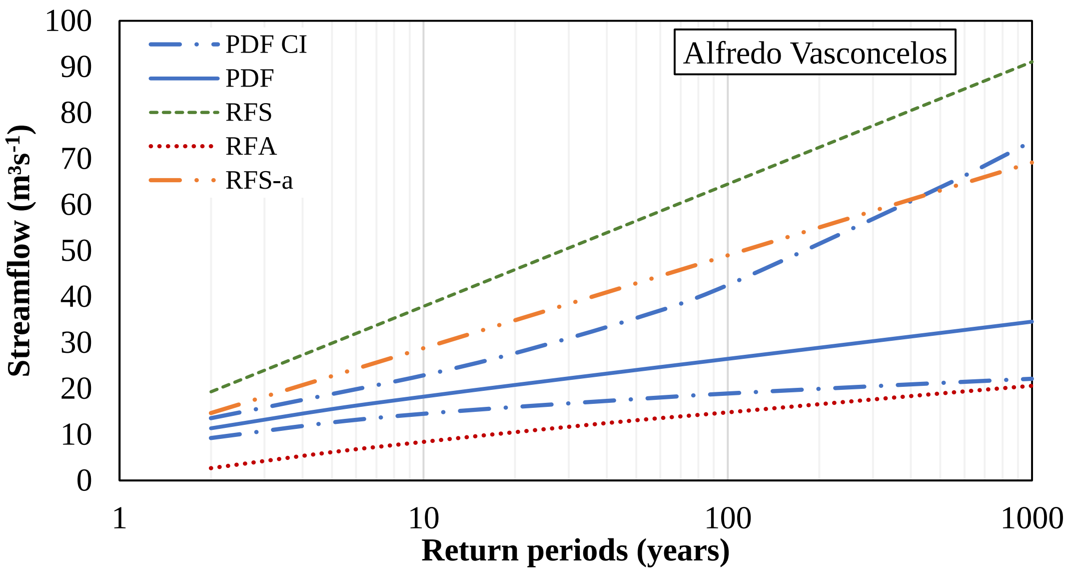
Figure 5 – Streamflow quantiles estimated by the LN-3P probability density function with confidence intervals and estimated by the regional functions for the station Bom Sucesso.



PDF: probability density function; CI: confidence interval; RFS: regional function by Souza et al. (2021); RFA: regional function by Amorim et al. (2020).

Source: from Author (2021).

Figure 6 – Streamflow quantiles estimated by the LN-3P probability density function with confidence intervals and estimated by the regional functions for the station Alfredo Vasconcelos when considered as ungauged.

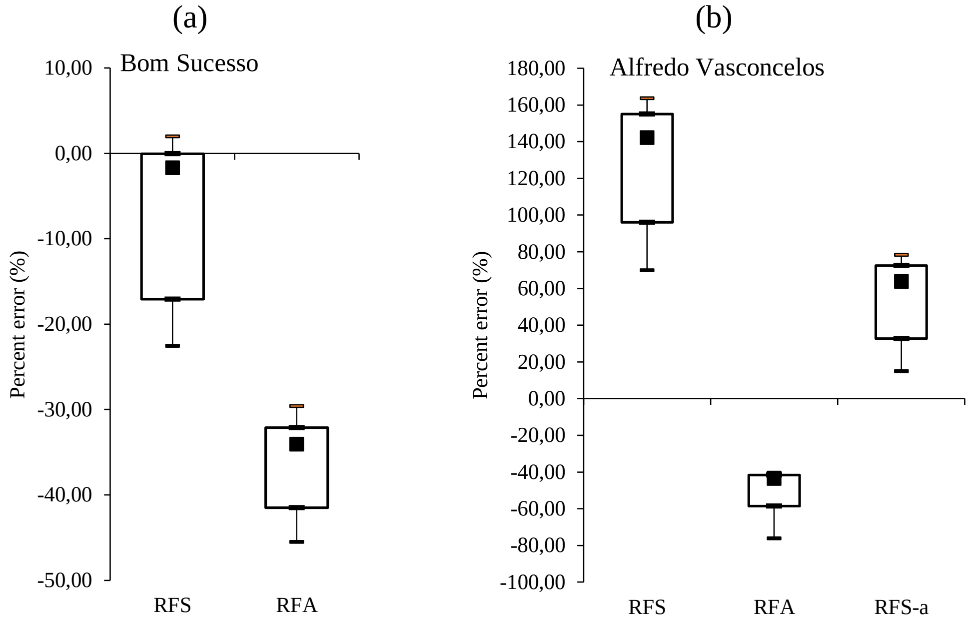


PDF: probability density function; CI: confidence interval; RFS: regional function by Souza et al. (2021); RFA: regional function by Amorim et al. (2020); RFS-a: regional function by Souza et al. (2021) with data-transfer for the index flood.

Source: from Author (2021).

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 comparing to the PDF estimates (TABLE 3). For return periods lower than 50-years, RFS resulted in estimates closer to the PDF's values, and all estimates were within the lower limit of the 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 3). The good performance for Bom Sucesso was expected since the Q_{mc} was the mean of observed AMS series. Figure 7a shows that the RFA highly underestimates the streamflow in comparison to the RFS.

Figure 7 – Distribution of percent errors of streamflow estimates in comparison with PDF estimates for each regional function at the gauge stations Bom Sucesso (a) and Alfredo Vasconcelos (b).



Source: from Author (2021).

Table 3 – 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

Source: from Author (2021).

For Alfredo Vasconcelos station, when considered as ungauged, RFA underestimates on average -51% the streamflow values comparing to LN-3P estimates (TABLE 3) 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). Although 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 7b). The lower performance of RFS and RFS-a for Alfredo Vasconcelos when compared to Bom Sucesso is explained by the estimation of the index flood and its smaller drainage area, since the regional function by Souza et al. (2021) was developed from watersheds from 351.22 to 1825.44 km². 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 6).

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 may 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, the wide range of AMS series length (16 to 85 years) regionalized by Souza et al. (2021) also produces uncertainties that influences the adequacy of the estimates.

As highlighted by Souza et al. (2021), underestimates of streamflow can represent great risks for population safety when planning flood control measures. On the other hand, overestimates may imply higher costs of structural measures. Thus, balancing these two scenarios 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 region of Lavras.

3.2 Flood maps in an urban ungauged watershed

The design floods for each reach were estimated by the RFS-a, using Couro do Cervo as donor site for index flood data-transfer (TABLE 4). 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) that may imply in inaccurate estimates. In addition, the linear regression used to estimate the index flood (Qmc) for ungauged sites, implies that when the watershed area is zero, the Qmc 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 Qmc estimates, resulting in small differences in the regionalized streamflow, as is observed in Table 4. 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 4 – 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.

Reach	**n.**	**Area (km^2)**	**Upstream flow (m^3s^{-1})**							
			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

Source: from Author (2021).

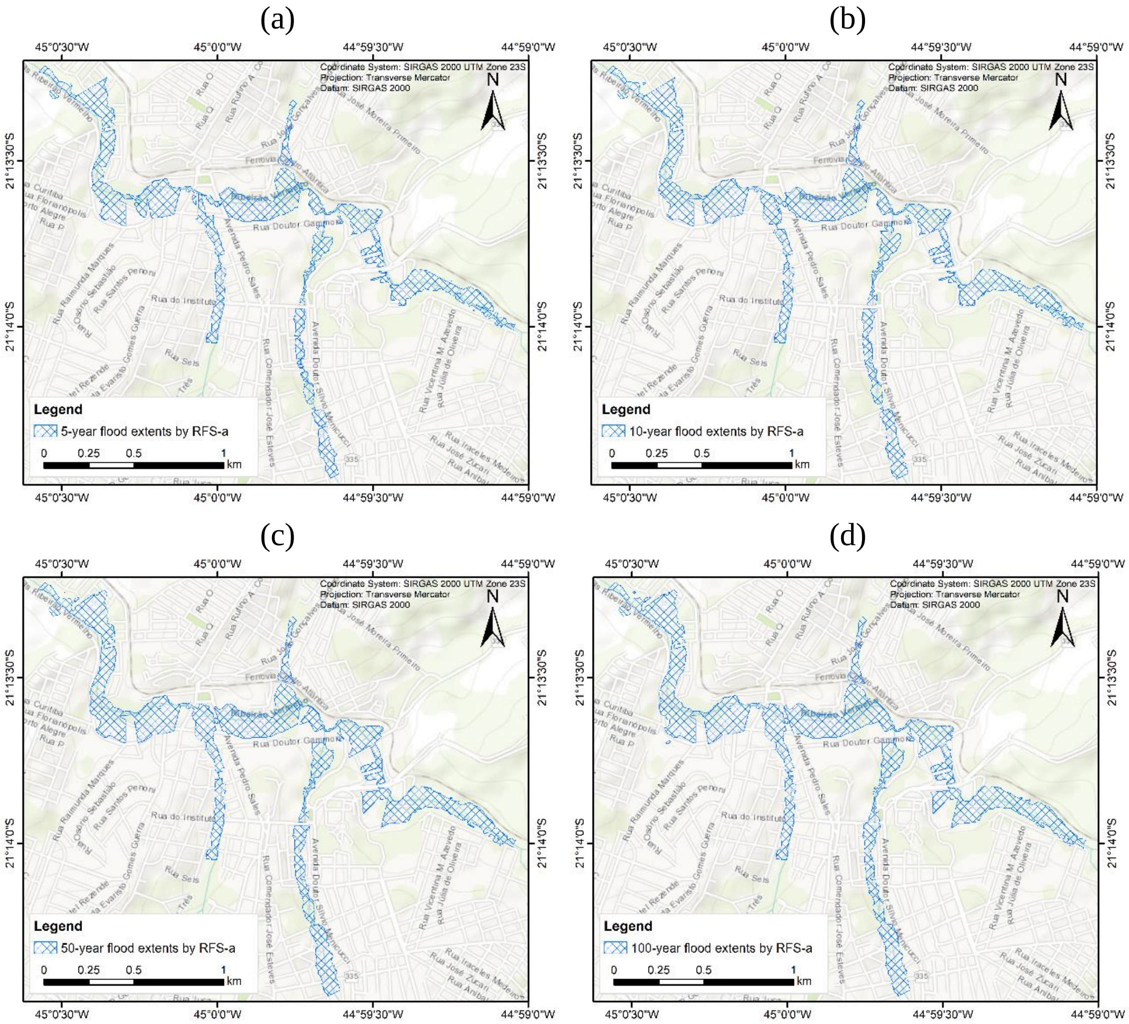
Finally, Table 5 presents the inundation areas simulated for the streamflow estimates shown on Table 4 and Figure 8 shows the flood extents for design floods of 5, 10, 50 and 100-year return periods. Brites et al. (2019), in a study performed in the Jacu River Basin in São Paulo, suggested to employ non-structural measures (e.g. land regulation policies) to areas affected by 100-year flood, otherwise, building structural flood control measures would require an investment 21% higher than 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 (BUTLER; DAVIES, 2004; MIGUEZ et al., 2007).

Table 5 – 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	36.29
5	40.34
10	43.74
20	47.34
50	50.06
100	51.86
500	58.69
1000	62.04

Source: from Author (2021).

Figure 8 – 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).



Source: from Author (2021).

Khattak et al. (2015) compared the extent of inundated areas simulated by HEC-RAS with a flood event occurred in 2010 in Kabul River with MODIS satellite images. Although these authors used DEM of 30x30 m resolution, the simulated flood extents still closely matched 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 addressed by calibrating channel roughness values and performing a more detailed field assessment of the reaches geometry (JAFARZADEGAN; MERWADE; SAKSENA, 2018; KHATTAK et al., 2015).

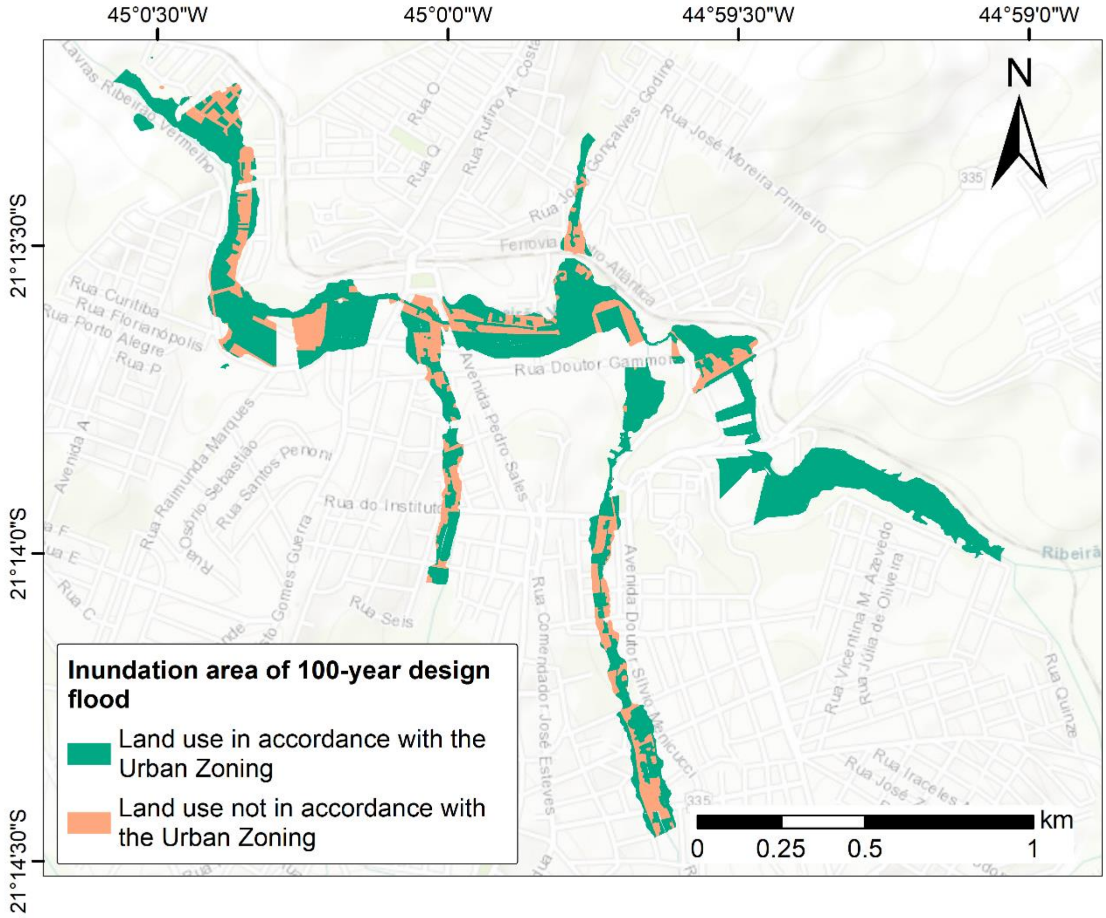
Considering future changes in land use is important to an effective flood management, as it can increase the vulnerable areas to floods. As discussed on Section 3.1, the regional function overestimated the design floods for Alfredo Vasconcelos. In consequence, it suggests that the inundation areas produced 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.

The flood maps created for Lavras are an important tool to support urban drainage planning. 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 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 presents a brief description of the present drainage system and none established goals for improving flood risk management.

3.3 Urban occupation of the areas affected by the designed floods

Along with the Environmental and Sanitation Plan, the Soil Use Directive Plan (LAVRAS, 2008, 2016) comprises land use regulation policies and a minimum permeability rate for new buildings and constructions. Nevertheless, the uses established by the plan are not completely followed. By assessing the areas affected by the 100-year design flood, Figure 9 shows that 24% of the current land use are not in accordance with the use regulated by the municipal legislation.

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.



Source: from Author (2021).

By assessing the current land use and the urban zoning of Lavras, we identified the percentage of areas affected by the design floods of 5, 10, 50 and 100-year return period. Table 6 shows the inundated percentage of area considering the land use classes defined for the region. For all return periods, the majority of the inundated areas would be vegetated. However, as the return period increases, the percentage of buildings affected also increases. Table 7 shows the percentage of area inundated according to the urban zones.

Table 6 – Assessment of the current land use of the inundated areas by the design floods in the urban reaches of Vermelho Creek Watershed.

Design flood	**Percentage of inundated area by land use (%)**				
	Vegetation	**Sparse vegetation**	**Buildings**	**Roads and railways**	**Channels**
5-year	44.61	16.51	30.43	6.95	1.51
10-year	43.31	16.16	31.38	7.76	1.39
50-year	40.96	16.22	32.92	8.63	1.27
100-year	40.76	16.23	32.87	8.85	1.28

Source: from Author (2021).

Table 7 – Assessment of the urban zoning of the inundated areas by the design floods in the urban reaches of Vermelho Creek Watershed.

Design flood	**Percentage of inundated area by urban zones (%)**						
	Reference use	**ZPA**	**ZEIA**	**ZEIUA**	**ZMA**	**ZMC**	**ZMI**
5-year	16.88	64.26	4.25	0.01	5.24	1.26	7.90
10-year	16.36	63.77	4.60	0.02	5.27	1.82	7.85
50-year	18.75	61.69	4.42	0.03	4.88	2.53	7.37
100-year	18.77	61.54	4.37	0.03	4.92	2.68	7.33

Source: from Author (2021).

As mentioned in Section 2.4, residences, commercial and services buildings are not allowed in the zones ZPA, ZEIA and ZEIUA. Thus, by comparing the inundated areas considering the current land use and the urban zoning, we verified that simply by following the regulation policies, the percentage of buildings affected by the designed floods would decrease 75%.

In this sense, a city planning 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.

4 CONCLUSION

In this study, the predictions of maximum streamflow regional functions developed by Amorim et al. (2020) and Souza et al. (2021) were compared in order to perform flood studies in ungauged basins in Lavras, MG, Brazil. Estimates by Souza et al. (2021), using data transfer for the index flood, showed better results, despite it was generated regionalizing drainage areas

(351.22 to 1825.44 km²) bigger than the gauged watershed that was analyzed, Alfredo Vasconcelos (20.04 km²).

The estimates by the regional function generated by Souza et al. (2021) enabled the construction of flood maps in the ungauged urban watershed located in Lavras. These maps are an important tool for city management and decision-making regarding the planning of structural flood control measures and land occupation policies. The comparison between the current and regulated land use showed that the urbanized areas affected by floods would decrease 75% by following the urban zones established by the Soil Use Directive Plan of Lavras.

ACKNOWLEDGMENTS

The authors would like to acknowledge CAPES (Coordination for the Improvement of Higher Education Personnel in Brazil) for the scholarship PDSE-88881.362120/2019-01. Also, acknowledge Purdue University for hosting the research scholar; UFLA (Federal University of Lavras) for educational support; the Research Group on Hydrology and Hydrological Modeling in Watersheds/CNPq of the Federal University of Pelotas for providing the full version of the software SYHDA; and the Secretary of Public Works of the municipality of Lavras for providing research data.

DECLARATIONS

Funding This work was supported by the Coordination for the Improvement of Higher Education Personnel in Brazil (CAPES) [grant number PDSE-88881.362120/2019-01]. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

Conflicts of interest The authors declare that they have no conflict of interest.

Availability of data and material Not applicable.

Code availability (software application or custom code) Not applicable.

REFERENCES

AHN, K. H.; MERWADE, V. Quantifying the relative impact of climate and human activities on streamflow. **Journal of Hydrology**, [s. l.], v. 515, p. 257–266, 2014. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2014.04.062>

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, [s. l.], v. 22, n. 6, p. 711–728, 2013.

AMORIM, J. da S. et al. Streamflow regionalization for the Mortes River Basin upstream from the Funil Hydropower Plant, MG. **Revista Ambiente e Agua**, [s. l.], v. 15, n. 3, 2020.

ANA. **Municípios Atingidos por Eventos de Inundação em 2015 | Agência Nacional de Águas**. 2019a. Disponível em: <http://dadosabertos.ana.gov.br/datasets/9df7783fe63745d7a813e2d61c0b4b3d_0>. Acesso em: 13 jan. 2020.

ANA. **Vulnerabilidade a Inundações do Brasil | Agência Nacional de Águas**. 2019b. Disponível em: <http://dadosabertos.ana.gov.br/datasets/4b7b20091fb940d492a1ebc85dfa88bb_0/data>. Acesso em: 13 jan. 2020.

ARDAYA, A. B.; EVERS, M.; RIBBE, L. What influences disaster risk perception? Intervention measures, flood and landslide risk perception of the population living in flood risk areas in Rio de Janeiro state, Brazil. **International Journal of Disaster Risk Reduction**, [s. l.], v. 25, n. August, p. 227–237, 2017. Disponível em: <http://dx.doi.org/10.1016/j.ijdrr.2017.09.006>

BAIDYA, S.; SINGH, A.; PANDA, S. N. Flood frequency analysis. **Natural Hazards**, [s. l.], v. 100, n. 3, 2020.

BESKOW, S. et al. Potential of the LASH model for water resources management in data-scarce basins: a case study of the Fragata River basin, southern Brazil. **Hydrological Sciences Journal**, [s. l.], v. 61, n. 14, p. 2567–2578, 2016. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/02626667.2015.1133912>. Acesso em: 12 jan. 2020.

BODOQUE, J. M. et al. Improvement of resilience of urban areas by integrating social perception in flash-flood risk management. **Journal of Hydrology**, [s. l.], v. 541, p. 665–676, 2016.

BRAZIL. Law n. 11445, January 5th of 2007.Brazil, 2007.

BRITES, A. P. Z. et al. Flood Zoning in Urban Planning and Runoff Control. In: WORLD ENVIRONMENTAL AND WATER RESOURCES CONGRESS 2019 2019, Reston, VA. **Anais**... Reston, VA: American Society of Civil Engineers, 2019. Disponível em: <http://ascelibrary.org/doi/10.1061/9780784482339.022>. Acesso em: 2 jul. 2020.

BRUNNER, G. W.; CEIWR-HEC. **HEC-RAS River Analysis System User's Manual Version 5.0**. Davis, CA. Disponível em: <www.hec.usace.army.mil>. Acesso em: 2 jul. 2020.

BUTLER, D.; DAVIES, J. W. **Urban Drainage**. 2nd. ed. New York: Spon Press, 2004. v. 53

CABRAL, S. L. et al. Hydrologic and hydraulic modelling integrated with GIS: A study of the Acaraú River Basin – CE. **Journal of Urban and Environmental Engineering**, [s. l.], v. 8, n. 2, p. 167–174, 2014.

CANHOLI, A. **Drenagem urbana e controle de enchentes (Urban Drainage and flood control)**. Sao Paulo.

CARRICK, J. et al. Is planting trees the solution to reducing flood risks? **Journal of Flood Risk Management**, [s. l.], v. 12, n. S2, 2019. Disponível em: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jfr3.12484>. Acesso em: 2 jul. 2020.

CASSALHO, F. et al. Hydrological regionalization of maximum stream flows using an approach based on L-moments. **Revista Brasileira de Recursos Hídricos**, [s. l.], v. 22, n. 0, 2017.

COOK, A.; MERWADE, V. Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. **Journal of Hydrology**, [s. l.], v. 377, n. 1–2, p. 131–142, 2009. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2009.08.015>

CRED, C. for R. on the E. of D.; UNDRR, U. N. O. for D. R. R. **The human cost of weather-related disasters, 1995–2015.** Geneva.

DECINA, T. G. T.; BRANDÃO, J. L. B. Análise de desempenho de medidas estruturais e não estruturais de controle de inundações em uma bacia urbana. **Engenharia Sanitaria e Ambiental**, [s. l.], v. 21, n. 1, p. 207–217, 2016.

FARMER, W. H. et al. A comparison of methods to predict historical daily streamflow time series in the southeastern United States. [s. l.], 2015.

GUPTA, H. V.; KLING, H. On typical range, sensitivity, and normalization of Mean Squared Error and Nash-Sutcliffe Efficiency type metrics. **Water Resources Research**, [s. l.], v. 47, n. 10, p. 2–4, 2011.

HASANI, H. Determination of Flood Plain Zoning in Zarigol River Using the Hydraulic Model of HEC-RAS. **International Research Journal of Applied and Basic Sciences**, [s. l.], v. 4, n. 12, p. 4300–4304, 2013.

HOSKING, J. R. M.; WALLIS, J. R. Correction to “Some Statistics Useful in Regional Frequency Analysis”. **Water Resources Research**, [s. l.], v. 31, n. 1, p. 251–251, 1995. Disponível em: <http://doi.wiley.com/10.1029/94WR02510>. Acesso em: 11 jan. 2020.

HOSKING, J. R. M.; WALLIS, J. R. **Regional frequency analysis: an approach based on L-moments**. Cambridge: Cambridge University Press, 1997.

INSTITUTE OF HYDROLOGY. **Flood Estimation Handbook**. Wallingford, UK: IH, 1999.

JAFARZADEGAN, K.; MERWADE, V.; SAKSENA, S. A geomorphic approach to 100-year floodplain mapping for the Conterminous United States. **Journal of Hydrology**, [s. l.], v. 561, n. March, p. 43–58, 2018. Disponível em: <https://doi.org/10.1016/j.jhydrol.2018.03.061>

KHATTAK, M. S. et al. Floodplain Mapping Using HEC-RAS and ArcGIS: A Case Study of Kabul River. **Arabian Journal for Science and Engineering**, [s. l.], v. 41, n. 4, p. 1375–1390, 2015.

KJELDSEN, T. R.; JONES, D. Estimation of an index flood using data transfer in the UK. **Hydrological Sciences Journal**, [s. l.], v. 52, n. 1, p. 86–98, 2007.

KJELDSEN, T. R.; JONES, D. A. Predicting the index flood in ungauged UK catchments: On the link between data-transfer and spatial model error structure. **Journal of Hydrology**, [s. l.], v. 387, n. 1–2, p. 1–9, 2010. Disponível em: <http://dx.doi.org/10.1016/j.jhydrol.2010.03.024>

LAVRAS. Complementary Law n. 156 of September 22th of 2008. . 2008.

LAVRAS. Complementary Law n. 347 of February 23th of 2016. . 2016.

LAVRAS. Lei 4.445 - Plano Municipal de Saneamento Básico do Município de LavrasLavras, Brazil, 2018.

LELIS, L. C. da S. et al. Assessment of hydrological regionalization methodologies for the upper Jaguari River basin. **Journal of South American Earth Sciences**, [s. l.], v. 97, n. October 2019, 2020.

MIGUEZ, M. G. et al. Simulating floods in urban watersheds: hydrodynamic modelling of macro, micro-drainage and flows over streets. **Transactions on Ecology and the Environment**, [s. l.], v. 103, p. 1743–3541, 2007. Disponível em: <www.witpress.com,>. Acesso em: 3 jul. 2020.

MORAES, T. C. et al. Effects on runoff caused by changes in land cover in a Brazilian southeast basin: evaluation by HEC-HMS and HEC-GEOHMS. **Environmental Earth Sciences**, [s. l.], v. 77, n. 6, p. 1–14, 2018. Disponível em: <https://doi.org/10.1007/s12665-018-7430-6>

NAGHETTINI, M. **Fundamental of statistical hydrology**. Switzerland: Springer International, 2017.

PAES, R. P.; BRANDÃO, J. L. B. Flood Control in the Cuiabá River Basin, Brazil, with Multipurpose Reservoir Operation. **Water Resources Management**, [s. l.], v. 27, n. 11, p. 3929–3944, 2013.

QUIROGAA, V. M. et al. Application of 2D numerical simulation for the analysis of the February 2014 Bolivian Amazonia flood: Application of the new HEC-RAS version 5. **Ribagua**, [s. l.], v. 3, n. 1, p. 25–33, 2016. Disponível em: <http://dx.doi.org/10.1016/j.riba.2015.12.001>

RIDOLFI, E.; ALBRECHT, F.; DI BALDASSARRE, G. Exploring the role of risk perception in influencing flood losses over time. **Hydrological Sciences Journal**, [s. l.], v. 65, n. 1, p. 12–20, 2020. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/02626667.2019.1677907>. Acesso em: 2 jul. 2020.

SCHARFFENBERG, B. et al. **Hydrologic Modeling System HEC-HMS - User’s Manual**. Davis, CA.

SOUZA, G. R. De et al. Regional flood frequency analysis and uncertainties: Maximum streamflow estimates in ungauged basins in the region of Lavras, MG, Brazil. **Catena**, Lavras-BR, West Lafayette-USA, v. 197, n. September 2020, p. 104970, 2021. Disponível em: <https://doi.org/10.1016/j.catena.2020.104970>

SOUZA, R. M.; CRISPIM, D. C.; FORMIGA, K. Estudo comparativo entre os modelos SWMM e HEC-HMS para simulação de escoamento superficial – caso de estudo bacia do

Córrego Samambaia. **REEC - Revista Eletrônica de Engenharia Civil**, [s. l.], v. 5, n. 2, p. 1–11, 2012.

SPECKHANN, G. A. et al. Flood hazard mapping in Southern Brazil: a combination of flow frequency analysis and the HAND model. **Hydrological Sciences Journal**, [s. l.], v. 63, n. 1, p. 87–100, 2018. Disponível em: <https://doi.org/10.1080/02626667.2017.1409896>

SWAIN, J. B.; PATRA, K. C. Streamflow estimation in ungauged catchments using regionalization techniques. **Journal of Hydrology**, [s. l.], v. 554, p. 420–433, 2017. Disponível em: <https://doi.org/10.1016/j.jhydrol.2017.08.054>

TUCCI, C. E. M. **Regionalização de vazões**. Porto Alegre: Ed. Universidade/UFRGS, 2002.

TUCCI, C. E. M. Urbanization and water resources. In: **Waters of Brazil: Strategic Analysis**. [s.l.] : Springer International Publishing, 2016. p. 89–104.