Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Hydrologic and hydraulic modeling to assess the efficiency of structural flood control measures: case study of Audi-União District in the city of Curitiba, Brazil

ARTICLES doi:10.4136/ambi-agua.2894

Received: 28 Sep. 2022; Accepted: 26 Jan. 2023

Letícia Giese de Andrade Cruz[1*]; Fernando Oliveira de Andrade[2,3];
Márcia Ferreira Prestes[4]; Stella Maris da Cruz Bezerra[5];
Simone Aparecida Polli[6]

[1]Programa de Pós-Graduação em Engenharia de Recursos Hídricos e Ambiental. Universidade Federal do Paraná (UFPR), Avenida Coronel Francisco Heráclito dos Santos, n° 100, CEP: 81531-980, Curitiba, PR, Brazil.
[2]Departamento Acadêmico de Construção Civil. Universidade Tecnológica Federal do Paraná (UTFPR), Rua Deputado Heitor Alencar Furtado, n° 5000, CEP: 81280-340, Curitiba, PR, Brazil.
E-mail: fandrade@utfpr.edu.br
[3]Programa de Pós-graduação em Engenharia de Recursos Hídricos e Ambiental. Departamento de Hidráulica e Saneamento. Universidade Federal do Paraná (UFPR), Avenida Coronel Francisco Heráclito dos Santos, n° 100, Caixa postal 19011, CEP: 81531-980, Curitiba, PR, Brazil. E-mail: fandrade@utfpr.edu.br
[4]Laboratório de Urbanismo, Planejamento e Paisagem. Departamento Acadêmico de Arquitetura e Urbanismo. Universidade Tecnológica Federal do Paraná (UTFPR), Rua Deputado Heitor Alencar Furtado, n° 5000, CEP: 81280-340, Curitiba, PR, Brazil. E-mail: marciaprestes@utfpr.edu.br
[5]Laboratório de Urbanismo, Planejamento e Paisagem. Departamento Acadêmico de Arquitetura e Urbanismo. Universidade Tecnológica Federal do Paraná (UTFPR), Rua Deputado Heitor Alencar Furtado, n° 5000, CEP: 81280-340, Curitiba, PR, Brazil. E-mail: stella.utfpr@gmail.com
[6]Programa de Pós-graduação em Planejamento e Governança Pública. Laboratório de Urbanismo, Planejamento e Paisagem. Departamento Acadêmico de Arquitetura e Urbanismo. Universidade Tecnológica Federal do Paraná (UTFPR), Rua Deputado Heitor Alencar Furtado, n° 5000, CEP: 81280-340, Curitiba, PR, Brazil.
E-mail: simonep@utfpr.edu.br
[*]Corresponding author. E-mail: leticiacruz@alunos.utfpr.edu.br

ABSTRACT

The objective of this study is to assess the efficiency of flood control measures implemented in the Audi-União District, located on the Iguaçu River floodplain in the city of Curitiba, Brazil, by the application of hydrological-hydraulic modeling using HEC-HMS and HEC-RAS software packages. The scenarios of the years of 2014, 2024 and 2034 with return periods of 10, 25, 50 and 100 years were analyzed. It was observed that the set of hydraulic structures located upstream of Audi-União District can reduce the peak flow at the beginning of the Iguaçu River by 31.4% and the flood area by 35.1%, considering the period of return of 100 years and the land use of 2014. Regarding the measures implemented directly by the Audi-União District, it was observed that the built levee can control floods in the area, except for a small area that is not protected by the levee, in both 2014 and future scenarios. The creation of the Iguaçu Environmental Protection Area and the relocation of families, which were non-structural measures implemented in the region, also proved to be efficient, considering that these areas would suffer from flooding even for rainfall events with a period of return of 10 years.

Keywords: Flood control, HEC-HMS, HEC-RAS.

Modelagem hidrológica-hidráulica para avaliação da eficiência de medidas de contenção de cheias: estudo de caso do Bolsão Audi-União em Curitiba, Brasil

RESUMO

Este estudo teve como objetivo avaliar a eficiência das medidas implementadas para contenção de cheias na região denominada Bolsão Audi-União, localizada na planície de inundação do rio Iguaçu em Curitiba-PR, mediante a aplicação de modelagem hidrológica-hidráulica utilizando os programas HEC-HMS e HEC-RAS. Foram analisados os cenários referentes aos anos de 2014, 2024 e 2034, com tempos de recorrência de 10, 25, 50 e 100 anos. Verificou-se que o conjunto de obras realizadas a montante do Bolsão Audi-União conseguem reduzir em 31,4% a vazão de pico no início do rio Iguaçu e em 35,1% da mancha de inundação ao considerar o tempo de retorno de 100 anos, considerando uso e ocupação do solo do ano de 2014. No que se refere às medidas implementadas diretamente no Bolsão Audi-União, constatou-se que o dique construído consegue conter as inundações ocorridas no local, com exceção de uma pequena área que não é protegida pelo dique, tanto no cenário de 2014 como em cenários futuros. A criação da Área de Proteção Ambiental do Iguaçu e a realocação de famílias, que foram medidas não estruturais implementadas na região, também se mostraram eficientes, tendo em vista que estas áreas sofreriam com inundações até mesmo para eventos com tempo de retorno de 10 anos.

Palavras-chave: contenção de cheias, HEC-HMS, HEC-RAS.

1. INTRODUCTION

The fast Brazilian population growth over the last decades has occurred mostly without a proper urban plan and in a social-inequality scenario. The combination of these two factors has led to the arising of many irregular occupations, especially in major cities. The city of Curitiba, located in the south of the country, is the eighth largest city in Brazil (IBGE, 2021) and has faced the increase of irregular occupations, notably in the 1990s. One of the most impacted areas was the east side of the city which is delimited by the Iguaçu River (IR). Thus, many of the occupations emerged by the riverside, an inappropriate place, since these areas often experience floods (Lima, 2000). One of the most remarkable floods occurred in 1995 when, within seven days, 361.8 mm of precipitation was registered, approximately 15,000 people were displaced and the financial losses reached around 43.7 million dollars at that time (Lima, 2000; Zanella, 2014).

Regarding flood control, the reduction of flood risk can be obtained by implementing non-structural measures, structural measures or the combination of both. Non-structural measures refer to procedures such as flood zoning, evacuation policies, land-use planning, insurance, etc., measures that do not involve engineering actions (Hansson *et al.*, 2008). Structural measures are usually divided in four categories: (a) storage reservoirs to decrease the downstream flow of a channel; (b) enlargement of the channel section to increase the channel capacity; (c) diversions to reduce the flow in the main channel; and (d) levees to protect the areas close to the channel (Tang *et al.*, 2020; Tucci, 2001). The application of structural measures is widely observed in big cities around the world (Gül *et al.*, 2010; Abdel-Fattah *et al.*, 2021), where non-structural measures alone are not able to mitigate flow hazards, since urban areas have expanded to the riverine floodplains.

The effectiveness of the non-structural and structural measures on flood controlling can be evaluated by a combination of hydrologic and hydraulic modeling. Some studies have used

Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) and Hydrologic Engineering Center - River Analysis System (HEC-RAS) modeling tools integrated with Geographic Information Systems (GIS) tools to accomplish this objective. Gül *et al.* (2010) have used these software packages to assess the efficiency of a planned dam in reducing river flows and flood areas in a densely urbanized city in Turkey. The use of these computational programs is also observed in the study of Tang *et al.* (2020), that sought to determine the better location and size of wetlands in a watershed in Houston-Texas to reduce the flood hazards. In Brazil, Decina and Brandão (2016) have studied the combination of non-structural and structural measures proposed by the local government, in a watershed of an urban area in the city of São Carlos in the state of São Paulo, considering seven possible sets and the future increase of urbanization.

Recent worldwide studies have shown the capability of HEC-HMS and HEC-RAS implementations, either integrated or separately, to perform flood predictions for open river basins and urban areas. Natarajan and Radhakrishnan (2020) analyzed several flood-modeling methods widely used for major- and medium-sized cities. The advantages and disadvantages of each method were discussed, and parameters were also identified by means of an integrated flood-modeling approach for a medium-sized ungauged urban catchment area. The chosen case study was Tiruchirappalli City in India. It was concluded that HEC-HMS and HEC-RAS were ideal tools for obtaining an accurate flood risk assessment for the medium-sized ungauged catchment area taken up in this study. Ongdas *et al.* (2020) used a two-dimensional HEC-RAS model in order to simulate different flood scenarios for the Yesil River, located in the metropolitan region of Nur-Sultan, the capital city of the Republic of Kazakhstan. Hazard classification of the flood generated by modeling indicated that the settlements of Zhibek-Zholy and Arnasay were flooded in all the simulated events. Volgodonovka village experienced flooding when a 100-year flood event was simulated. On the other hand, settlement No. 42 did not experience any flooding in any of the scenarios. Madhuri *et al.* (2021) applied a two-dimensional HEC-RAS model to estimate submerged areas, flood depths, and building risk for extreme events in the Greater Hyderabad Municipal Corporation (GHMC), India. Percentages of buildings in GHMC under high, medium, and low flood risks were determined by the modeling, and correlated flood proofing strategies were proposed for attenuating building risk along with the required capital costs. Tamiru and Dinka (2021) employed Artificial Neural Networks (ANN) together with HEC-RAS, by a multi-layered feed-forward neural network trained with backpropagation using a gradient descent training algorithm. The objective of ANN-HEC-RAS integration model was to improve the accuracy of flood inundation prediction in the lower Baro Akobo River Basin, Ethiopia, and also to provide new hydrological insights for the region. AL-Hussein *et al.* (2022) employed HEC-HMS and HEC-RAS in order to analyze the behavior of flooding events that frequently impact villages near the Khazir River's floodplains, Iraq, causing crop losses and threatening residential areas. HEC-HMS was used to calculate hydrographs of torrential flows and estimate flow rates on the surface for different return periods of 2, 5, 10, 20, 50, and 100 years. The HEC-RAS model was combined with the HEC-GeoRAS extension in ArcGIS. Final modeling results indicated that the areas of flood risk varied from low to very low (80.31%), medium (16.03%), and high to very high (3.8%).

In the case of the city of Curitiba in Brazil, the local government has implemented some non-structural and structural measures to reduce flood risks. Primarily, after the event of 1995, a 20 km diversion channel (DC) was built along IR with resources from the World Bank. In addition, two storage reservoirs used for water supply were built upstream of IR, reducing the total flow on the river. Nevertheless, these measures gave the population the wrong idea that it was safe to live on riverine areas and some irregular occupations have emerged closer to IR banks (Zanella, 2014; Tucci, 2002).

One of these occupations has received the name of Audi-União District and, even after the first structural measures were implemented, this area kept facing flooding problems. Trying to prevent more settlements close to IR, in 2000 the government of Curitiba implemented a law establishing the Protected Areas (PA), that states that the minimum strips of 100 meters along the IR must be preserved or recovered (Curitiba, 2000). Considering this new situation, some houses of the Audi-União District were relocated to other regions.

In 2007, this district was selected to be part of a national program, named "Programa de Aceleração do Crescimento" (PAC), or, Growth Acceleration Program, that aimed to invest in infrastructures to improve urban and social development in the country (Teixeira, 2019). Part of the infrastructure improvements at Audi-União District was a flood-control project that included the construction of a 2 km levee and the elevation of the land level at some areas close to IR (COHAB, 2017).

The objective of the study is to evaluate the effectiveness of the structural and non-structural measures implemented in Audi-União District considering six different scenarios: (1) all implemented infrastructure measures and land occupation of 2014; (2) a future scenario of year 2024; (3) a future scenario of year 2034; (4) a scenario with no reservoirs; (5) a scenario with no diversion channel; and (6) a scenario with no reservoirs and no diversion channel. To reach these objectives, the software HEC-HMS is primarily used to generate hydrographs for returning periods of simulated flood events of 10, 25, 50 and 100 years. Subsequently, the hydrographs are used as inflow boundary conditions in the software HEC-RAS to calculate the flooding areas through the solution of the 2D-Navier-Stokes equations and then drawing the final inundation maps.

2. MATERIALS AND METHODS

2.1. Study Area

The study area can be separated into two parts: the first one refers to the Audi-União District, which will have its inundation areas determined using HEC-RAS; the second part describes the highest Iguaçu River basin (HIB), that is located upstream of Audi-União District, and contributes to the initial flow in IR and to the flow in the DC that will be determined in HEC-HMS and afterwards will be used as a boundary condition on HEC-RAS. The Audi-União District is located on the border of Curitiba and the neighbor city of São José dos Pinhais. It has an area of 2 km², which is delimited by the IR on the east side, by the railway line on the west side, by the BR 277 highway on the north and by Comendador Franco Avenue on the south. The first settlements in the area emerged in 1990 close to the BR 277 highway and in 2014 the region contained around 3 thousand houses and 12 thousand inhabitants (Teixeira, 2019; Schäfer and Gomide, 2014; Curitiba, 2013).

The highest Iguaçu River Basin lies upstream of the confluence of the Rivers Atuba and Iraí, where the IR is formed. The basin has an area of approximately 694 km² and is located between parallels 25º13’08" S and 25º36’56" S and meridians 48º57’18" W and 49º16’29" W. Regarding the land use and occupation, the HIB is mainly composed of urban areas, but it also has some regions, especially close to its borders, with mixed land use. The population present in the basin was approximately 814.5 thousand inhabitants in 2010 (IBGE, 2010). The location of Audi-União district, HIB, the IR, the DC and three water reservoirs are shown in Figure 1.

The main structural and non-structural measures implemented directly in the Audi - União District are the following: (a) the construction of a drainage channel that collects stormwater from the residential area and carries it out to small reservoirs, reducing the lateral inflow of IR; (b) the ground elevation of an area that had been continuously flooded; (c) the built of a levee along the drainage channel that should have 2 km, but until the beginning of this study had around 1.3 km; and (d) the creation of the PA law that led to the reallocation of some houses and the construction of the Japanese Immigration Centennial Park at the small reservoirs area.

These measures are illustrated in Figure 2.

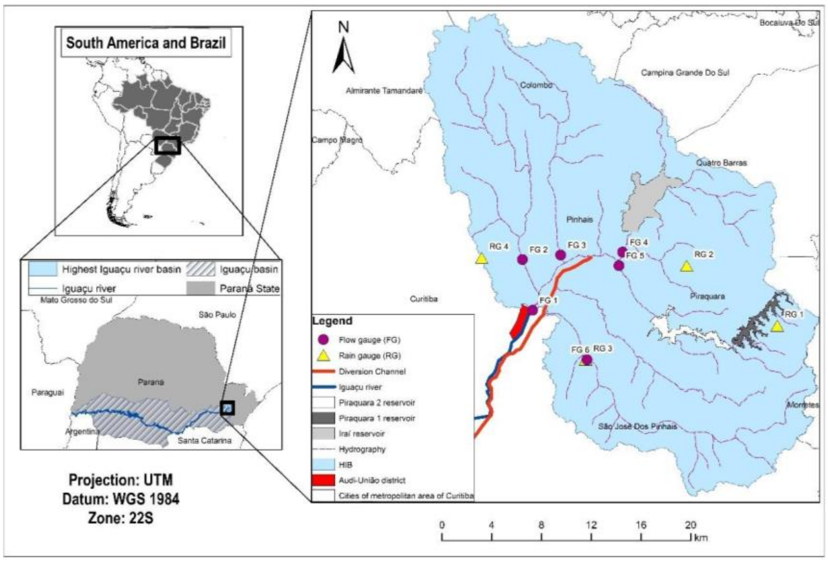

Figure 1. Audi-União District and HIB locations.

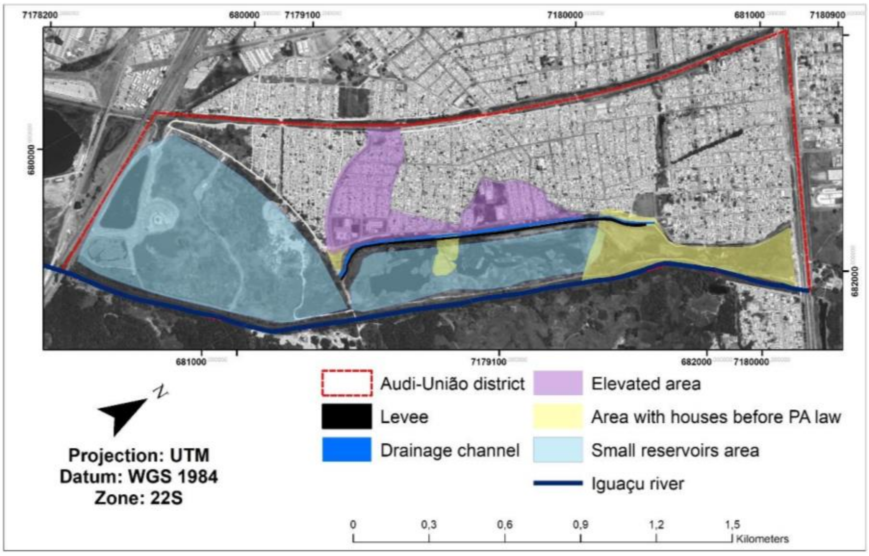

Figure 2. Structural and non-structural measures in Audi-União District.
Source: Adapted by the author from Google Earth Pro (2020).

2.2. Methodology framework

In order to conduct this study several steps were carried out. Initially, some input data were obtained and processed using a Geographic Information System (GIS). Then, the design rain and the scenarios of study were defined. Subsequently, calibration and verification simulations were performed on HEC-HMS. Finally, the study scenarios were simulated on HEC-HMS, the hydrodynamic simulations were performed on HEC-RAS and the inundation maps were developed. The flux of the methodological steps is represented in Figure 3. These steps will be better explained in the next sections.

2.3. Hydrological model topology

In the HEC-HMS program the HIB was represented by 16 sub-basins, which had their physiographic features determined from Digital Elevation Models (DEM) obtained from ALOS-PALSAR. In addition to the 16 sub-basins, 16 reaches were included in the HEC-HMS model, using the routing method Muskingum-Cunge (USACE, 2000), except for reach T9**, which did not have any routing method applied, since the reservoirs P1 and P2 are very close to each other. Two outlets points were considered in the model, one for the IR and the other for the DC. The hydrographs calculated in these points were afterwards used as boundary conditions to the HEC-RAS model. Figure 4 shows the topology used in the HEC-HMS hydrological model.

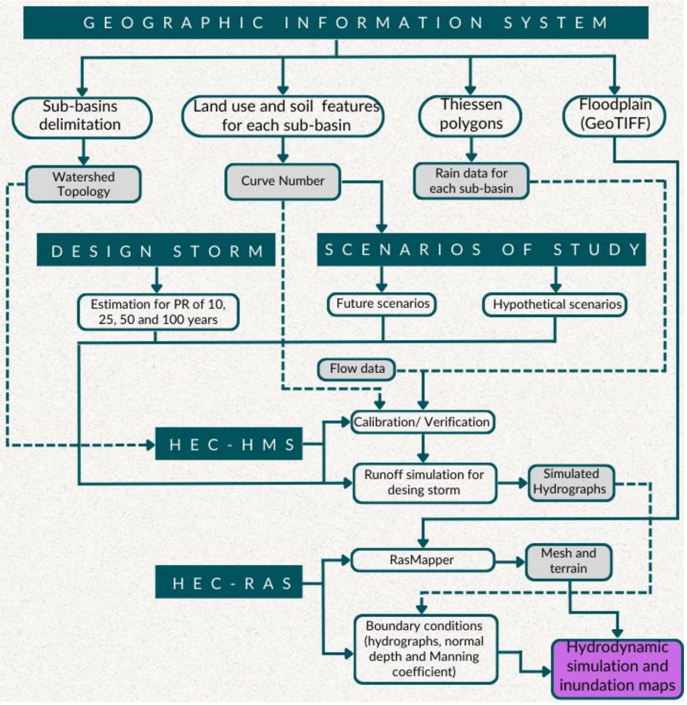

Figure 3. Flux of methodological steps.

The three reservoirs (Iraí, Piraquara 1 and Piraquara 2) and the DC were also included in the HEC-HMS hydrological model topology; the assigned hydraulic operational rules for these structures are described by Cruz (2022).

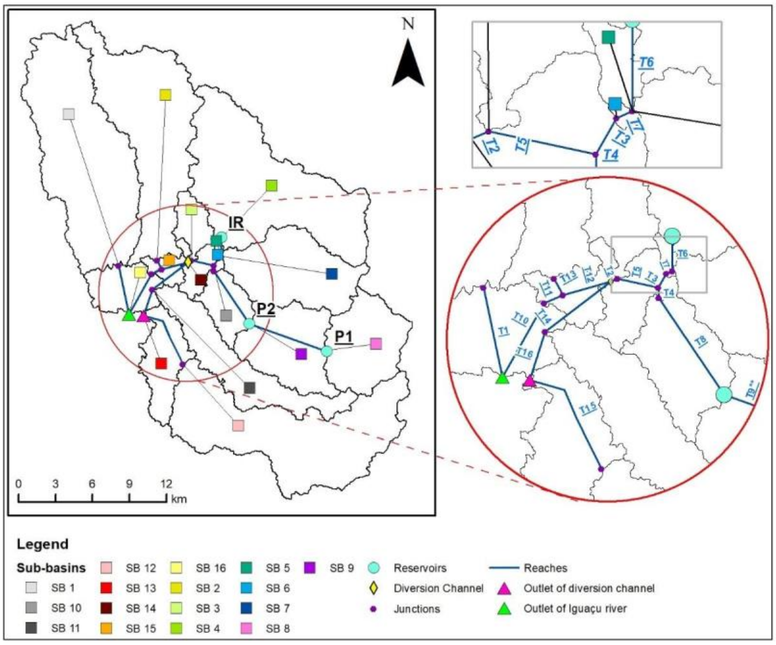

Figure 4. Topology of the hydrological model.

2.4. Input data of hydrological model

In order to perform a calibration of unknown parameters of the hydrological model, observed data of rainfall and flow were required. Thus, daily average flow data and accumulated precipitation data were obtained from six flow gauges and four rain gauges distributed on the watershed area, these gauges are shown in Figure 1. The data were obtained from the Brazilian National Water Agency (ANA-Hidroweb) and hydrological information system of Paraná Water Institute. The location of the gauges and the Hidroweb registration code are described in Table 1.

Table 1. Rain and flow gauges.

Gauge	Latitude	Longitude	Hidro- web Code	Gauge	Latitude	Longitude	Hidro-web Code
FG 1	-25.48	-49.19	65009000	**FG 6**	-25.52	-49.15	65010000
FG 2	-25.45	-49.20	65007046	**RG 1**	-25.49	-49.99	2548041
FG 3	-25.44	-49.17	65056055	**RG 2**	-25.45	-49.07	2549004
FG 4	-25.44	-49.12	65003950	**RG 3**	-25.52	-49.15	2549017
FG 5	-25.45	-49.12	65004995	**RG 4**	-25.45	-49.23	2549006

The flow data were directly used on the calibration process to compare observed flow and simulated runoff. It is worth mentioning that only events with consistent data were selected to perform the calibration. The rain data were weighted using the Thiessen polygons method, which will be explained in Section 2.5.

Also, to accomplish the calibration process, a Curve Number (CN) of each sub-basin was determined. The CN was estimated based on satellite images from Landsat-8 from 2009 that have a 15 m resolution, which were used to determine the land use of the area, and on soil map of Paraná State obtained from ITCG (2008). After the calibration, verification simulations were carried out using the same events of the calibration, as well as events from 2013 to 2015 with CN obtained from satellite images from Landsat-9 from 2014.

Besides the data described previously, the time of concentration (t_c) was also needed as an input data and it was obtained directly from CN, as well as, from physiographic features of each sub-basin, that were obtained from ALOS-PALSAR DEM. The equation for t_c is described in Section 2.6.

2.5. Average rainfall

The average rain data for each sub-basin were obtained by applying Thiessen polygons method. This method consists of estimating a weighted average rain for each sub-basin based on the areas of influence of each rain gauge. Thus, the application of the Thiessen method provides a way of estimating the average rain data by considering the non-uniformity of the distribution of the rain gauges (Tucci, 2001).

According to Tucci (2001), three steps are required to determine the Thiessen polygons:

1) Adjacent gauges must be connected by straight lines;

2) Perpendicular bisectors must be drawn in each traced line;

3) The bisections must be extended until their interception to form the area of influence of each gauge (polygons).

As described in Table 1, in this study rain data from four gauges were used to determine the average rain on each sub-basin. In this way, four Thiessen polygons were obtained at the HIB area using GIS. The polygons are represented in Figure 5.

The average rainfall for each sub-basin could be estimated from Thiessen polygons shown in Figure 5, using the following Equation 1:

$$P_m = \frac{\Sigma P_i * A_i}{A} \tag{1}$$

Where:

P_m – Average precipitation (mm);

P_i – Observed precipitation at rain gauge (mm);

A_i – Area of influence of the rains gauge over the sub-basin (m²);

A – Total area of the sub-basin (m²).

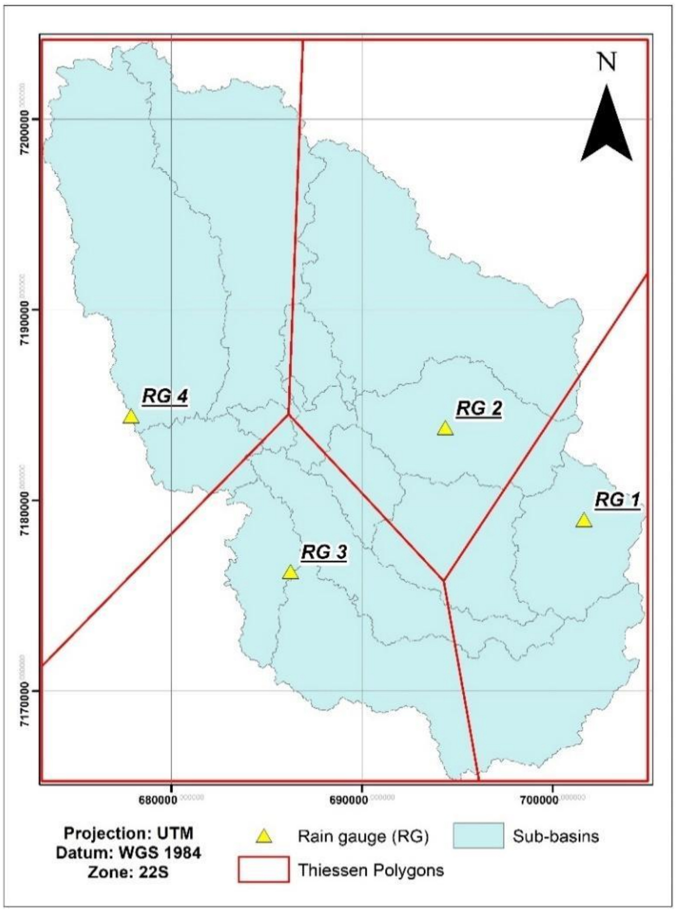

Figure 5. Thiessen polygons on HIB watershed.

2.6. Hydrological methods and calibration

In HEC-HMS software the selected method to compute the runoff volume was the SCS Curve Number method, which uses the parameter Curve Number (CN) to represent the soil type and land use, determining the soil infiltration and the excess precipitation. The transformation of rainfall-runoff was obtained by Clark Unit Hydrograph (HU) Model, that is based on time of concentration and the storage coefficient (R) to estimate the hydrograph from the excess rainfall. The baseflow was estimated by the Exponential Recession Model which is based on an initial flow value (Q_0), an exponential decay constant (k) and a parameter called Ratio to Peak Flow. All these methods are widely described in USACE (2000).

The concentration time was estimated by SCS Lag, Equation 2, according to Silveira (2005):

$$t_c = 0.057(1000/CN - 9)^{0.7} * L^{0.8} * Y^{-0.5} \quad (2)$$

Where:

t_c – Time of concentration (h);

CN – Curve Number;

L – Main river length (km);

Y – Sub-basin average slope (m m-1).

The estimation of the design storm was obtained by the rainfall intensity equation established by Fendrich *et al.* (1989) for the city of Curitiba and represented by Equation 3. The representation of the storm hyetographs was given by the alternating blocks method (Zahed Filho and Marcellini, 1995), with a total duration of eleven hours with interval time of one hour and return periods (PR) of 10, 25, 50 and 100 years.

$$i = (3221.07 * PR^{0.258})/(t_{ch} + 26)^{1.01} \quad (3)$$

Where:

i – Rainfall intensity (mm h-1);

PR – Period of return (years);

t_{ch} – Rainfall duration (min).

A calibration process was carried out aiming to estimate the Clark HU Model storage coefficient, the parameters from Exponential Recession Model for each sub-basin and the Manning roughness coefficient of each reach. The selected events to run the calibration ranged from 2007 to 2011. The objective function used in the calibration process was the Peak Weighted Root Mean Square Error (PWRMSE).

The verification of the calibrated parameters was performed using the same events of the calibration process and events from 2013 to 2015 using the CN determined from 2014 satellite images. The estimation of future CN values was established considering that the urban areas of 2014 will grow at the rate of the projection of population growth, which are approximately 12% and 20% for the years of 2024 and 2034, respectively, for HIB (Cruz, 2022).

2.7. Simulation scenarios

Six scenarios were proposed considering hypothetical conditions and future land occupation: (1) a scenario considering all the implemented measures and the land occupation of 2014 (2014); (2) a future scenario of 2024 (2024); (3) a future scenario of 2034 (2034); (4) a scenario without the reservoirs (SR); (5) a scenario without the DC (SC); (6) a scenario without the reservoirs and DC (SR/SC).

The topology for the scenarios 2014, 2024 and 2034 was the same topology presented in Figure 4, the difference between the scenarios was on the parameter CN and, consequently, on time of concentration. Small changes were made in the topology represented in Figure 4 for the hypothetical scenarios. For the scenarios without the reservoirs (SR and SR/SC) the Muskingum-Cunge method was applied to represent the routing on reach T9**. For the scenarios without the DC (SC and SR/SC), the reaches T14 and T16 were removed and the sub-basins SB 13 and SB 11 were connected to T10 by two reaches that also used Muskingum-Cunge method. The topology for each scenario is represented in Figure 6.

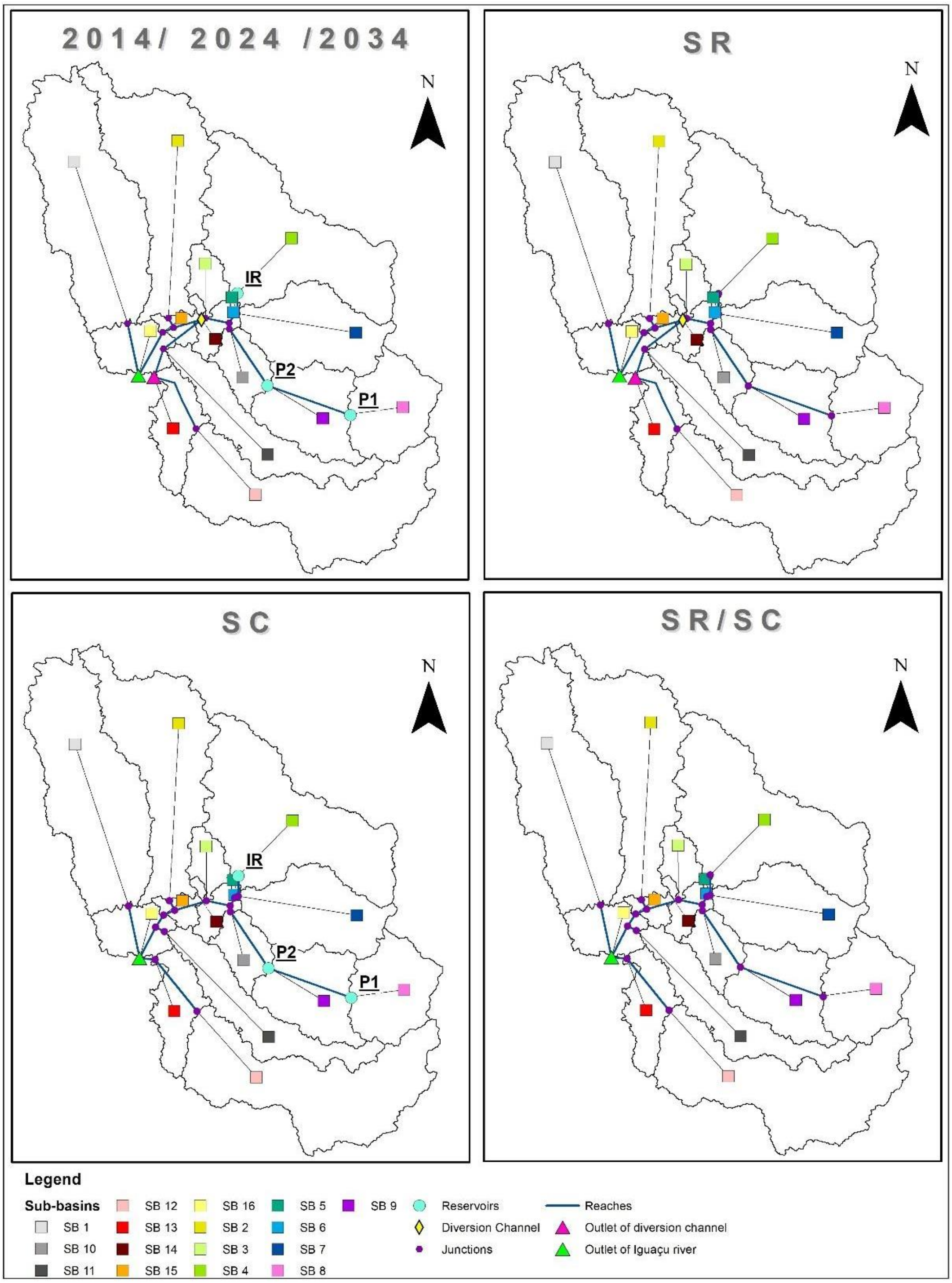

Figure 6. Topology for scenarios of study.

2.8. Hydraulic model methods

The hydraulic model considered the floodplain of IR and the DC between BR 277 highway and Comendador Franco Avenue, where the Audi-União District is located. The representation of the floodplain was performed from a combination of contour line maps from Audi-União area which resulted in a terrain file with 2 m precision. The geometry of the IR was represented by the bathymetric curves that were measured in 1995 in the DC project. These geometries were interpolated and a terrain file was created. The geometry of the DC was approximated by the trapezoid format described in the DC project, which has the upper width of 40 m, the depth of 3 m and the bottom width of 28 m. In order to create a single file to represent the area, the terrain files of the IR and the DC were overlapped on the floodplain terrain (Figure 7 a.).

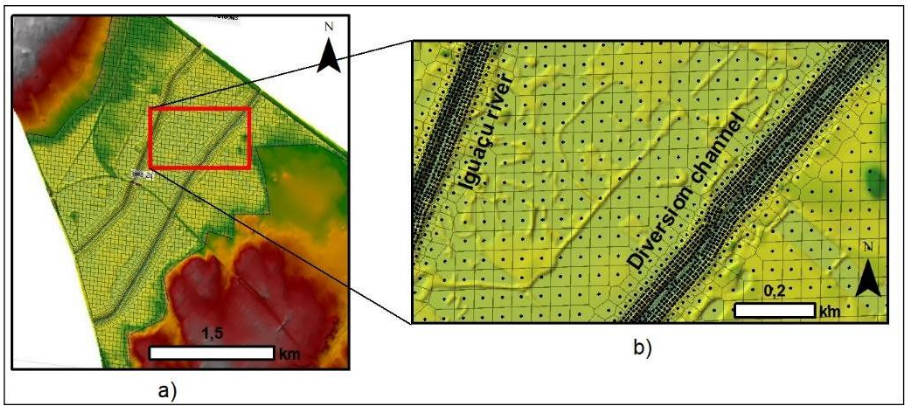

Figure 7. a) Mesh and terrain of hydraulic model; b) Mesh detail.

From the final terrain file, a 2-D computational mesh was created, using computational cells of 50 m on the floodplain and 10 m on IR and DC (Figure 7 b.), and the hydrodynamic model was applied. The bidimensional model solves the complete Navier-Stokes equations that consist of a conservation of mass equation (Equation 4) and the Equations 5 and 6 for momentum conservation in x and y directions, written as:

$$\frac{\partial H}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}+q=0 \tag{4}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial H}{\partial x}+v_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-c_f u+fv \tag{5}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial H}{\partial y}+v_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-c_f v+fu \tag{6}$$

Where:

H – water surface elevation (m);

t – time (s);

x and y – flow direction (m);

h – water depth (m);

u e v – velocity components in x and y directions (m s-1);

q – source/sink flux term (m^3 s-1 m-2).

g – gravity acceleration (m s-2);

v_t– eddy viscosity coefficient (m^2 s-1);

c_f – bottom friction coefficient ($m^{0.5}m-1$);

f – Coriolis parameter (s-1).

The Navier-Stokes equations were solved by a finite difference scheme and finite volume approximations. The boundary conditions used in the hydraulic model were the hydrographs estimated from the HEC-HMS at the upstream inlet and the normal depth of 0.0004 m m-1 and 0.0005 m m-1 for IR and for the DC, respectively, at the downstream outlet. The Manning's roughness coefficient was obtained from the literature and was considered 0.05 on the floodplain and 0.04 on the channel and river (SUDERHSA, 2002).

3. RESULTS AND DISCUSSION

3.1. Hydrological model

The estimated Curve Numbers (CN) and the calibrated parameters of storage coefficient (R), initial flow (Q_0), exponential decay constant (k) and ratio to peak for each sub-basin are represented in Table 2.

Table 2. Sub-basin Parameters.

Sub-basin	CN (2009)	CN (2014)	CN (2024)	CN (2034)	R (h)	Q_0 (m^3/s)	k	Ratio to peak
SB 1	86.93	88.81	89.99	90.74	30.96	6.22	0.69	0.49
SB 2	78.33	80.57	81.59	82.23	29.07	2.27	0.66	0.26
SB 3	82.59	83.53	83.87	84.08	33.85	0.31	0.26	0.28
SB 4	76.29	77.25	77.65	77.90	62.22	1.48	0.31	0.52
SB 5	79.52	79.94	80.08	80.18	28.20	0.46	0.35	0.33
SB 6	81.75	82.22	82.22	82.23	31.93	0.99	0.80	0.58
SB 7	77.30	78.93	79.43	79.74	55.98	1.60	0.70	0.60
SB 8	81.67	81.70	81.72	81.73	113.49	2.71	0.78	0.69
SB 9	73.13	74.91	75.09	75.20	64.92	0.48	0.24	0.08
SB 10	80.95	81.96	82.23	82.40	23.00	0.42	0.27	0.39
SB 11	77.44	80.26	80.90	81.29	90.01	1.89	0.61	0.36
SB 12	76.26	78.57	78.82	78.97	144.20	3.84	0.88	0.55
SB 13	84.71	86.50	87.24	87.70	56.58	1.11	0.39	0.25
SB 14	85.43	86.58	86.93	87.15	48.57	0.59	0.38	0.55
SB 15	90.23	90.95	91.81	92.35	30.11	0.22	0.23	0.22
SB 16	92.31	92.98	93.87	94.00	28.54	0.11	0.42	0.39

Source: Author (2022).

The simulated 100 years hydrographs for the DC and for the IR are represented in Figure 8 (a) and (b), in which it is possible to see that in future scenarios large flow increases are not expected. The peak flows for each simulated scenario are summarized in Table 3.

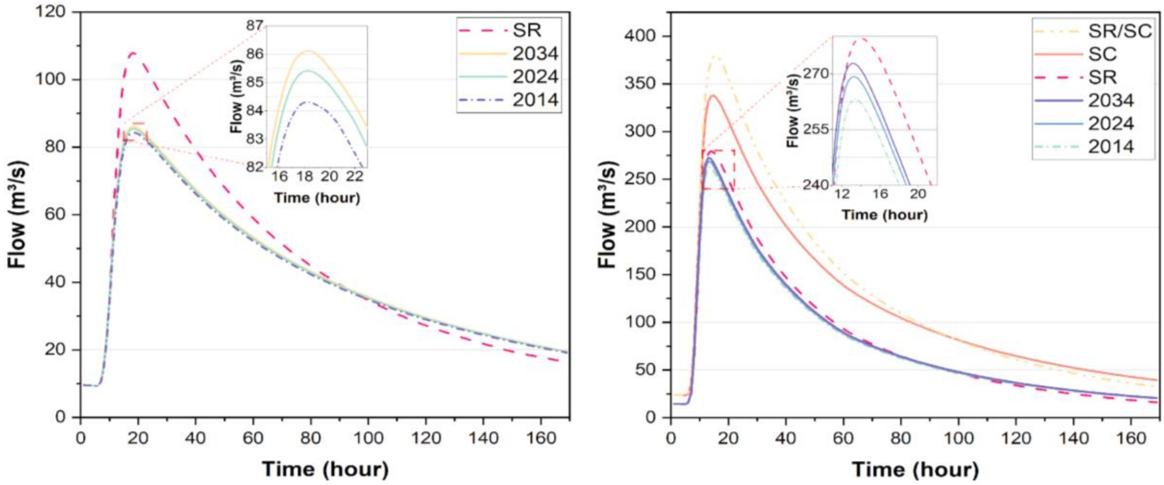

Figure 8. a) DC 100 years hydrograph; b) IR 100 years hydrograph.

Table 3. Peak flows for each scenario (m^3 s-1).

Scenario	IR				DC			
	PR 10	**PR 25**	**PR 50**	**PR 100**	**PR 10**	**PR 25**	**PR 50**	**PR 100**
2014	121.9	165.6	207.5	258.9	36.1	50.1	64.0	81.2
2024	126.5	170.9	213.5	265.3	36.6	50.8	64.7	82.0
2034	129.4	174.1	216.9	269.0	37.0	51.2	65.2	82.5
SR	127.7	175.3	221.2	278.1	45.6	65.0	84.0	107.4
SC	154.2	210.1	264.4	330.9	-	-	-	-
SR/SC	169.3	234.9	298.7	377.3	-	-	-	-

The results from the hydrological model show that in the scenario of 2034 an increase of 6.15% is expected in the 10-year flow and 3.9% in the 100-year flow in IR, demonstrating that the urbanization will affect mostly the flow of more frequent events than the rarer ones. On the other hand, it is possible to notice from Table 3, that the effect of reservoirs in flow reduction is greater in events that are less recurrent than in the more frequent events. Moreover, the effect of the reservoirs is more significant in reducing the flow on the DC than on the IR.

Also, evaluating the SC scenario, it is clear that the DC has a greater impact in the flow reduction in the IR than the reservoirs. Besides, the set of the DC and the reservoirs brings a reduction of 31.4% and 28.0% for 100-year and 10-year flows, respectively.

3.2. Hydraulic model

The representation of the 100-year return period areas of inundation for each scenario are shown in Figure 9 and a summary of the total flow area for each scenario is presented in Table 4. Great differences were not observed between inundation areas of 2014 scenario and future scenarios, the most significant difference was 2.7% in 2034 scenario and a 10-year period of return. The most important result is that the built levee will protect Audi-União District even for future scenarios, except for a small area close to BR 277 that will probably be protected by a planned continuation of the existing levee.

The scenario SR had inundation areas similar to the 2034 scenario and even in this scenario the levee could protect part of Audi-União District, demonstrating that the reservoirs do not have a major importance in the reduction of the flow area. The most remarkable differences in the inundation areas were observed in the scenarios SC and SR/SC, especially the 10-year return period inundation area for the SR/SC scenario which was 79.6% bigger than the 2014 scenario, indicating the right decision of the construction of the DC.

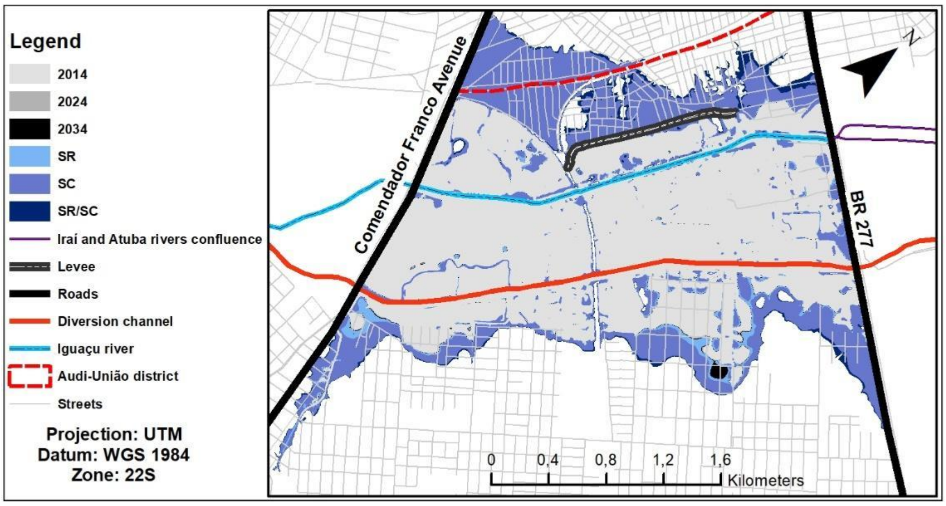

Figure 9. Inundation areas for 100 years period of return.

Table 4. Inundation area for each scenario (km²).

Scenario	Period of return			
	PR 10	PR 25	PR 50	PR 100
2014	2.60	3.13	3.50	4.05
2024	2.63	3.17	3.54	4.08
2034	2.67	3.19	3.56	4.11
SR	2.73	3.29	3.84	4.31
SC	4.40	5.33	5.75	6.06
SR/SC	4.67	5.54	5.92	6.23

Regarding the non-structural measures, the establishment of the PA law, with the creation of the Japanese Immigration Centennial Park and the reallocation of families, demonstrated to be very important measures, since these areas could face frequent inundations (PR of 10 years). The combination of PA law and the levee allowed the clear delimitation of the floodplain on the right bank of IR and the creation of the park allowed the protection of the area against future occupations.

Although the structural and non-structural measures demonstrated mostly good results protecting the right margin of IR floodplain, the left side seemed to be neglected by the government actions. This difference evidenced a lack of integration in the decisions made by governments of the cities that surround the river and a failure to consider the totality of factors involved in urban planning of the area.

4. CONCLUSIONS

This study employed HEC-HMS and HEC-RAS hydrological/hydraulic models to assess the efficiency of non-structural and structural flood control measures implemented at the Audi-União District in the city of Curitiba, Brazil. Some of the significant results demonstrated by the models were: (1) the reservoirs alone located upstream in the watershed did not have a major importance in the reduction of the flooding area; (2) the construction of the diversion channel parallel to the Iguaçu River proved to be one of the most effective flood-control structural measures. It was observed that the combination of the reservoirs and the diversion channel could bring a reduction in the flooding area on the order of 44.3%; (3) the set of structural and non-structural measures presently existing in the study area is capable of protecting against future flooding scenarios, except for a small area close to BR 277 that could probably be protected by the continuation of the existing levee; (4) the creation of the Japanese Immigration Centennial Park proved to be a very important non-structural measure, since this area used to face frequent inundations. The levee constructed in this region allowed delimitation of the floodplain on the right bank of Iguaçu River and the park allowed the protection of the area against future settlements.

Nevertheless, while the right margin of IR floodplain received many flood control measures, the left side of the floodplain is still very susceptible to frequent flooding and residential areas are vulnerable to flood damage. In this way, complementary actions are needed and it is recommended that a cost-benefit study be carried out to determine the best practices to be implemented in the area. In addition, it is recommended that integrated flood-control planning be implemented in the region, integrating the Municipal Governments and the State Government to protect the population living in border regions with floodplain areas. Moreover, the protection of Audi-União District is conditioned on the maintenance of the implemented structure measures. Lastly, it is recommended that, if possible, future studies use updated bathymetry and flow data, as well as other hydrological methods and high-resolution images for land-use determination.

5. ACKNOWLEDGEMENTS

This study was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ), process number 131716/2020-4.

6. REFERENCES

AL-HUSSEIN A. A.M. *et al.* Flood analysis using HEC-RAS and HEC-HMS: a case study of Khazir River (middle east—northern Iraq). **Water,** v. 14, n. 22, p. 3779-3798, 2022. https://www.mdpi.com/2073-4441/14/22/3779

ABDEL-FATTAH, M. *et al.* Evaluation of Structural Measures for Flash Flood Mitigation in Wadi Abadi Region of Egypt. **Journal of Hydrologic Engineering**, v. 26, n. 2, p. 04020062, 2021. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002034

CRUZ, L. G. de A. **Avaliação da eficácia das medidas de urbanização e drenagem implantadas em um assentamento urbano precário mediante modelagem hidrológica-hidráulica: estudo de caso do Bolsão Audi-União em Curitiba-PR**. 2022. 130 p. Dissertação (Mestrado em Engenharia de Recursos Hídricos e Ambiental) — Universidade Federal do Paraná, Curitiba, 2022.

CURITIBA. Decreto nº 192 de 03 de abril de 2000. Regulamenta parcialmente o Art. 5º, inciso IX, da Lei nº 9.800/00, no que diz respeito à Área de Proteção Ambiental do Iguaçu, Parque Municipal do Iguaçu e dá outras providências. **Diário Oficial**, Curitiba, 2000.

CURITIBA. **Projeto de urbanização da Vila Audi concorre a prêmio internacional**. Curitiba, dez. 2013. Available at: https://www.curitiba.pr.gov.br/noticias/projeto-de-urbanizacao-da-vila-audi-concorre-a-premio-internacional/31498. Access: 26 Jan. 2021.

COHAB-CT. **Relatório Final de Avaliação - Bacia do Iguaçu - TC 0226009 - 68/2007**. Curitiba, 2017. 236 p.

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 Sanitária e Ambiental**, v. 21, n. 1, p. 207-217, 2016. https://doi.org/10.1590/S1413-41520201600100116134

FENDRICH, R. *et al.* **Estudo de Chuvas Intensas do Estado do Paraná**. Curitiba: ISAM PUC, 1989.

GOOGLE EARTH PRO V 7.3.3.7699. 2020, October 30. **Curitiba, Brazil. 25°30'00" S, 49°12'00" W**. Available at: http://www.earth.google.com. Access: 30 out. 2020.

GÜL, G. O. *et al.* A combined hydrologic and hydraulic modeling approach for testing efficiency of structural flood control measures. **Natural Hazards**, v. 54, n. 2, p. 245-260, 2010. https://doi.org/10.1007/s11069-009-9464-2

HANSSON, K. *et al.* A framework for evaluation of flood management strategies. **Journal of Environmental Management**, v. 86, n. 3, p. 465–480, 2008. https://doi.org/10.1016/j.jenvman.2006.12.037

IBGE. **Censo 2010**. Rio de Janeiro, 2010. Available at: https://censo2010.ibge.gov.br/. Access: 11 mar. 2021.

IBGE. **Estimativas da população residente no brasil e unidades da federação com data de referência em 1º de julho de 2021**. Rio de Janeiro, 2021. Available at: https://ftp.ibge.gov.br/Estimativas_de_Populacao/Estimativas_2021/estimativa_dou_2021.pdf Access: 11 maio 2022.

ITCG. **Solos**: Estado do Paraná. Curitiba, 2008. Scale 1:2.000.000 Available at: https://www.iat.pr.gov.br/sites/agua-terra/arquivos_restritos/files/documento/2020-07/mapa_solos.pdf. Access: 15 maio 2022.

LIMA, C. d. A. **A ocupação de área de mananciais na região metropolitana de Curitiba: do planejamento à gestão ambiental urbana-metropolitana**. 2000. 425 p. Tese (Doutorado) — Universidade Federal do Paraná, Curitiba, 2000.

MADHURI, R. *et al.* Urban flood risk analysis of buildings using HEC-RAS 2D in climate change framework. **H_2Open Journal,** v. 4, n. 1, p. 262-275, 2021. https://dx.doi.org/10.2166/h2oj.2021.111

NATARAJAN, S.; RADHAKRISHNAN, N. An integrated hydrologic and hydraulic flood modeling study for a medium-sized ungauged urban catchment area: a case study of Tiruchirappalli City using HEC-HMS and HEC-RAS. **Journal of the Institution of Engineers (India) Series A,** v. 101, p. 381–398, 2020. https://doi.org/10.1007/s40030-019-00427-2

ONGDAS N. *et al.* Application of HEC-RAS (2D) for flood hazard maps generation for Yesil (Ishim) river in Kazakhstan. **Water**, v. 12, 2020, p. 2672-2692. https://doi.org/10.3390/w12102672

SILVEIRA, A. L. L. da. Desempenho de fórmulas de tempo de concentração em bacias urbanas e rurais. **Revista Brasileira de Recursos Hídricos**, v. 10, n. 1, p. 05–23, 2005.

SCHÄFER E. F.; GOMIDE F. P. B. Avaliação Pós-ocupação do conjunto habitacional Moradias União Ferroviária Bolsão Audi/União, Curitiba (PR). **Engenharia Sanitária e Ambiental**, v. 19, n. 2, p. 155-164, 2014. https://doi.org/10.1590/S1413-41522014000200006

SUDERHSA. **Plano Diretor de Drenagem para a Bacia do Rio Iguaçu na Região Metropolitana de Curitiba**. Curitiba, 2002. v. 3 e v.4. Tomos 3.3 e 4.16.

TAMIRU H.; DINKA, M. O. Application of ANN and HEC-RAS model for flood inundation mapping in lower Baro Akobo River Basin, Ethiopia. **Journal of Hydrology: Regional Studies**. v. 36, p.100855, 2021. https://doi.org/10.1016/j.ejrh.2021.100855

TANG, Y.*et al.* Impact of size and location of wetlands on watershed-scale flood control. **Water Resources Management**, v. 34, n. 5, p. 1693–1707, 2020. https://doi.org/10.1007/s11269-020-02518-3

TEIXEIRA, L. B. **Da lama ao caos: a urbanização de Curitiba vista do Bolsão Audi-União**. 2019. 296 p. Tese (Doutorado) — Universidade Federal do Paraná, Curitiba, 2019.

TUCCI, C. E. M. **Hidrologia**: Ciência e Aplicação. 2 ed. Porto Alegre: Ed. Universidade/UFRGS; ABRH, 2001. 939 p.

TUCCI, C. E. M. Flood control and urban drainage management in Brazil. **Waterlines**, p. 6-8, 2002.

USACE. **Hydrologic Modeling System - HEC-HMS - Technical Reference Manual**. Davis-CA, 2000. 148 p.

ZAHED FILHO, K.; MARCELLINI, S. Precipitações Máximas. *In*: TUCCI, C. E. M. *et al.* (orgs.). **Drenagem Urbana.** Porto Alegre: ABRH, 1995. p. 37-76.

ZANELLA, M. E. **Inundações em Curitiba**: impactos, risco e vulnerabilidade socioambiental. Fortaleza: Imprensa Universitária, 2014, 197 p.