

Methodologies for generation of hazard indicator maps and flood prone areas: municipality of Ipojuca/PE.

Metodologias para Geração de Mapa de Indicadores de Perigo e Áreas Inundáveis: Município de Ipojuca/PE

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ABSTRACT

Studies focusing on urban vulnerabilities due to river floods need the construction of hazard maps and definition of potential flood areas. The objective of this article is to describe the development of a methodology for hazard mapping of river floods and to map areas susceptible to inundation on a municipal scale. The study area is the municipality of Ipojuca – Pernambuco State with area of 527.11 km² and population of 80,637 inhabitants. The first methodology uses the hydrologic-hydraulic simulation for the lower course of the Ipojuca River using the HEC-HMS and HEC-RAS models. The streamflow calculated in the rainfall-runoff model is used as input for the hydraulic model, to simulate the water surface profile in the river. This makes it possible to calculate the water depth and flow velocity, the key elements for the definition of hazard indicators. The results of the hydraulic model were used to generate the hazard indicators: water depth, flow velocity, combination of depth and velocity, energy head, flow force and intensity (flow velocity × water depth). The other methodology seeks to identify areas with potential for inundation considering the entire territory of the municipality. Topographic index of the region and a distance cost matrix (which uses slope and drainage) are the auxiliary variables for determination of this map. Both variables use the digital terrain model. Analysis of risk is essential for planning and intervention in areas susceptible to inundation. Both characterizations of hazard and vulnerability are needed to evaluate risk. The results of the study in Ipojuca can be used for hazard characterization.

Keywords: Natural disasters. Hazard map. Hydrological modelling.

RESUMO

Estudos envolvendo vulnerabilidade de cidades à inundações necessitam do mapeamento de perigo e das áreas com potencial para inundação. O objetivo do artigo é desenvolver metodologia para mapeamento de indicadores de perigo e áreas inundáveis na escala de município. A área de estudo é o município de Ipojuca no Estado de Pernambuco com área de 527,11 km² e uma população de 80.637 habitantes. A primeira metodologia consiste na simulação hidrológica-hidráulica para o baixo curso do rio Ipojuca com uso dos modelos HEC-HMS e HEC-RAS. A vazão gerada no modelo hidrológico do tipo chuva-vazão é utilizada como entrada do modelo hidráulico que simula o perfil da linha d'água no rio para a região de interesse. Com o perfil da linha da água, pode-se determinar a profundidade e a velocidade da água, que são elementos chave para a definição de indicadores de perigo. Com os resultados do modelo hidráulico, geraram-se seis indicadores de perigo: profundidade da água, velocidade do fluxo, combinação profundidade e velocidade, carga de energia, força do escoamento e intensidade (velocidade × profundidade). A outra metodologia procura identificar as áreas inundáveis de todo o território do município. Para isso, faz-se uso do índice topográfico da região e de uma matriz de custo de distância (que utiliza declividade e hidrografia), todos calculados com o modelo digital do terreno. A análise de risco é essencial para o planejamento e intervenção em áreas sujeitas a inundações. Para se avaliar risco, é necessária a caracterização do perigo e da vulnerabilidade. Os resultados do estudo em Ipojuca podem ser utilizados para a caracterização do perigo principalmente.

Palavras Chave: Desastres naturais. Mapa de perigo. Modelagem hidrológica.

INTRODUCTION

The proximity to watercourses determines the location of numerous human settlements evolving into the cities of today. Water supply, irrigation and transport are only some examples of benefits (TURRERO et al., 2013). Proximity to watercourses as well as other more modern risk factors, such as unplanned urbanization, ends up highlighting and maximizing the risks and disasters (VIGLIONE et al., 2014).

The theoretical basis on the theme of natural disasters is vast and diverse, consisting of numerous concepts and methodological practices. But even if there is no universal standard, it is possible to identify some guidelines to qualitative and quantitative categories of disasters and their components. The starting point is the disaster itself, which is characterized by changes originating from the interaction between hazardous natural phenomena and the characteristic conditions of a community, resulting in negative impacts on people, the economy, the environment, the municipal infrastructure, and public health, among other factors. The possibility of occurrence of this kind of situation creates the risk (LAVELL et al., 2012), repeatedly defined by the association between hazard and vulnerability (BIRKMANN, 2006; BIRKMANN et al., 2013; MERZ et al., 2010; GOERL et al., 2012). For Stephenson (2002), hazard is obtained by the product of water depth and flow velocity; and risk is the probability associated to hazard occurrence. In the risk analysis, the Intergovernmental Panel on Climate Change (IPCC) also adds the exposure factor to vulnerability and hazard (LAVELL et al., 2012).

The extent of losses that an element might suffer due to geographic location defines its exposure. The danger is defined by the presence of an extreme natural and potentially hazardous event (flood in the case of this study). For the classification of hazard, in addition to occurrence, the possibility of injury, loss and damage must also be taken into account (LAVELL et al., 2012). Vulnerability, in turn, is determined by the profile of the affected population.

According to Merz et al. (2010), vulnerability is described as the result of the sum of exposure, susceptibility and capacity for response. Birkman et al. (2013) also defined this structure and highlighted the multidimensional, dynamic, complex and broad nature of the concept and components of vulnerability. This is evidenced by the intrinsic character of vulnerability in the composition of the community. Adger (2006) states that these components are translated into the skills of dealing with, recovering from, or resisting hazard situations, together with an understanding developed by the United Nations for what can be called resilience (UNISDR, 2009). Given this vast quantity of components, ranging from individuals to whole communities, Zhou et al. (2014) justify the lack of uniformity in defining the concept of vulnerability and the difficulty in establishing measurement methods in analyses of different scales.

An important aspect in mapping hazard and vulnerability is the definition of the physical indicators. With regard to hazard indicators, more specifically, might include water depth, flow velocity, duration, flood routing, water rising rate and ex-

tent of the flooded area (the most common in map generation) (MOEL et al., 2009).

Kreibich et al. (2009) and Thielen et al. (2005) applied hazard indicators in a huge flood that occurred in the Elba and Danube rivers in August 2002. Return periods even exceeded 500 years at some tributaries of the Elbe River (THIEKEN et al., 2005). The study by Kreibich et al. (2009) sought to define the relevance of the parameters of impact for the losses derived from the flood. Data sets were collected from interviews and post-event field surveys. 2D hydraulic simulations for the events of 20, 50 and 100 years of return period were designed to provide information about water depth and velocity used in risk mapping and cost-benefit analyses. On the other hand, the study by Thielen et al. (2005) examined the damage to properties with data obtained from interviews collected after the 2002 flood event. The survey investigated a number of indicators, with emphasis on hazard, but also covering vulnerability. These indicators were water depth, velocity, duration, water contamination, warning systems, emergency measures, forecasting measures, experience from previous events and the socioeconomic status of the population.

Merz et al. (2007) propose a methodology that divides vulnerability into exposure and susceptibility. The study includes key elements for risk classification. The first component, exposure, is quantified by the number of exposed elements, that is, the quantity of buildings in the flood prone area. The second item, susceptibility, is characterized by relative damage functions, answering the question "How will the affected elements be damaged?" The estimated degree of damage to buildings is based on analysis of financial loss associated with the use of the building and flood depth, translated into depth-damage curves.

In Brazil, it is worth mentioning the studies by Goerl et al. (2012), who used census data to define a vulnerability index; Monteiro and Kobiyama (2013), who used hydrological and hydraulic models to estimate the hazard in the Braço do Baú basin in Santa Catarina; Machado et al. (2005) with the development of a damage x depth function for the municipality of Itajubá in Minas Gerais; and Zonensein (2007), who proposed a flood risk index applied to the Joana River basin in Rio de Janeiro, based on indicators such as inadequate sanitation, traffic, income and household density.

The objective of our study was to develop a methodology for mapping hazard indicators and flood prone areas on a municipal scale. The methodologies were applied to the study of floods in the municipality of Ipojuca in Pernambuco state. The first methodology consisted of hydrological-hydraulic simulation of the lower course of the Ipojuca River using the HEC-HMS and HEC-RAS models of the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE). The other methodology was designed to identify the flood prone areas throughout the municipality. To do this, a topographic index of the region and a distance cost matrix (which uses slope and drainage) were used, both calculated using the digital terrain model. The main aspects that differentiate this study are the assessment of five indicators for hazard map generation and the presentation of a technique that permits mapping of flood

prone areas on a municipal scale. This information can be used in the planning of the land occupation expansion in documents such as geotechnical charts and urban drainage master plans, especially in municipalities under pressure due to the process of population growth and urbanization, as in the case of Ipojuca.

This study was developed under an agreement between the Ministry of Cities and GEGEP/UFPE in the project “Development of geotechnical charts of suitability to urbanization in municipality of Ipojuca in the Metropolitan Region of Recife, Pernambuco state” (COUTINHO, 2014).

METHODOLOGY

Study area

The municipality of Ipojuca in the Metropolitan Region of Recife covers an area of 527.11 km², has a population of 80,637 (IBGE, 2010), is located 49 km from the state capital, and within its boundaries contains the estuary of the Ipojuca River. Ipojuca has an outstanding tourist and economic potential, including some of the most popular beaches on the southern coast of Pernambuco and the Suape industrial and port complex.

With respect to the municipality’s environmental and physical aspects, it has a wet tropical climate with dry summers and a rainy season beginning in the autumn and winter months (April-August), with an annual average rainfall of more than

1300 mm. The relief terrain with reworked surfaces of deep valleys consists basically of hills in the coastal region (MASCARENHAS et al., 2005). Figure 1 shows the location of Ipojuca municipality in Pernambuco and the boundary of the Ipojuca River basin covering an area of 3,435.34 km². Figure 2 highlights the drainage basin of the Ipojuca River considered in the hydrological simulation, covering an area of 474.23 km².

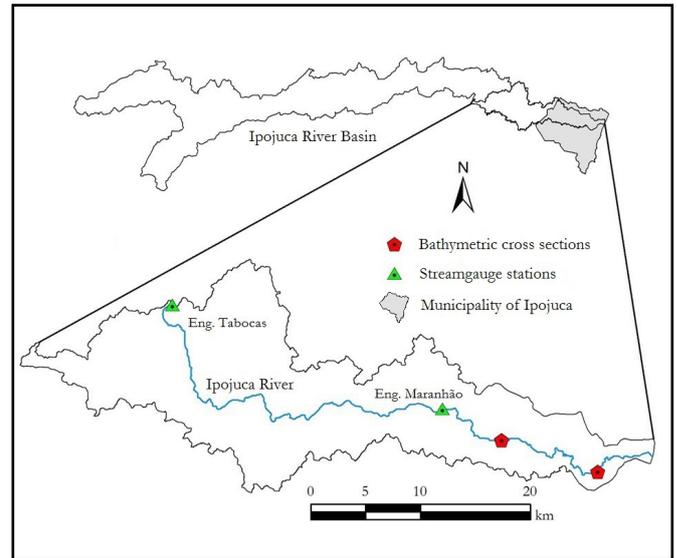


Figure 2 – Area of the Ipojuca river basin simulated by the models

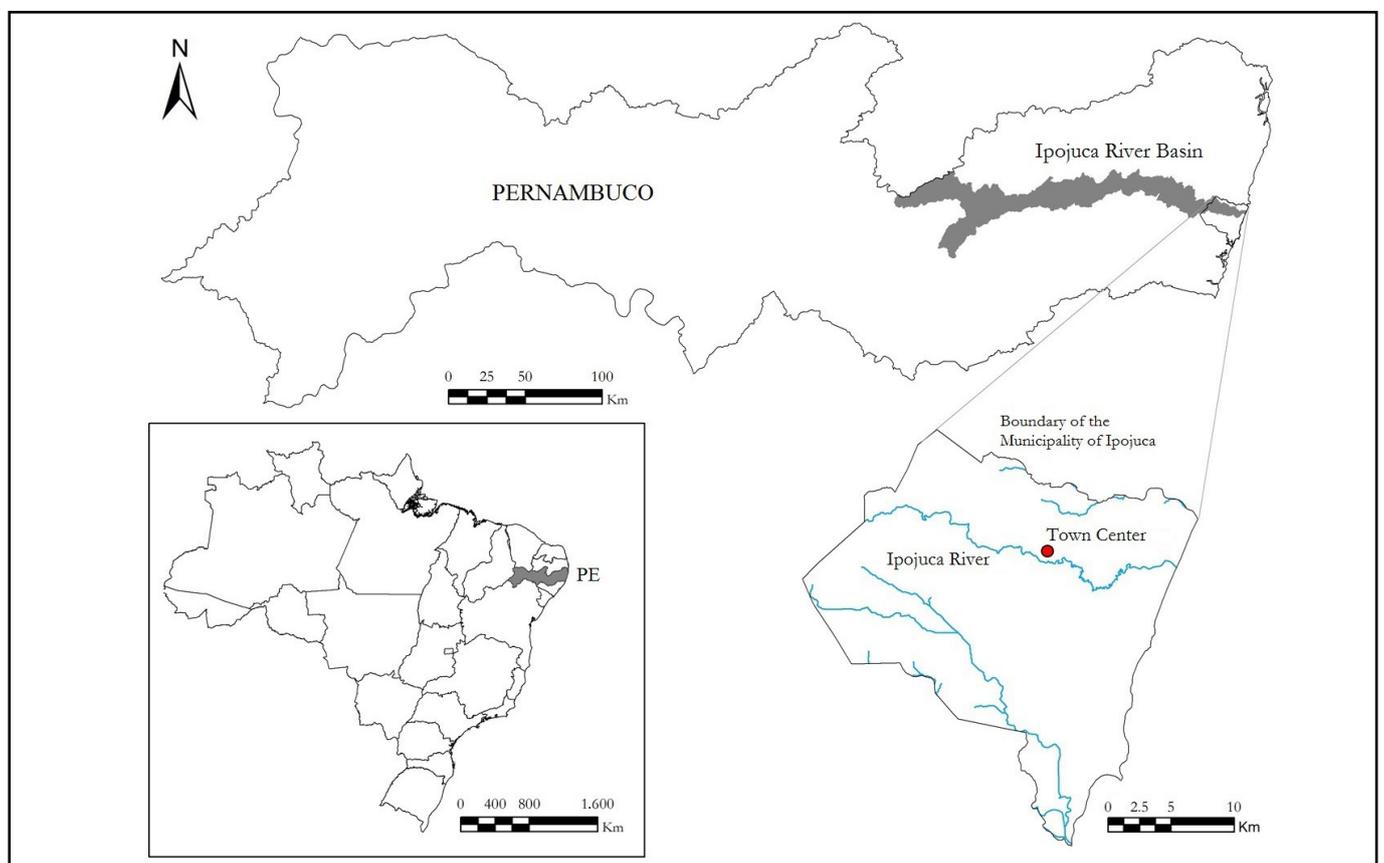


Figure 1 –Location of Ipojuca municipality and Ipojuca river basin

Digital Terrain Model (DTM)

The altimetry of the study area is necessary to delineate the sub-basins for hydrological modeling, to characterize the geometry of the Ipojuca River and to generate a map of the flood prone areas. Two types of altimetry data were used.

Characterization of the geometry of the Ipojuca River was based on the DTM, produced with data from Condepe/Fidem on a scale of 1/25,000, together with field surveys. The resulting DTM has a spatial resolution of five meters.

The other DTM is the result of the Shuttle Radar Topography Mission (SRTM) project. The Brazilian National Institute for Space Research (INPE) accomplished corrective and standardizing work of the SRTM data, eliminating “NoData” pixels, shadows and distortions. The data corrected by INPE, called Topodata, were also resampled to a 30-meter resolution, allowing a better use of the information (VALERIANO et al., 2009). The Topodata DTM was used as input for the discretization of the sub-basins and calculation of the slope and topographic index.

Hydrological simulation

The HEC-HMS (Hydrologic Modeling System) (FELDMAN, 2000) simulates the transformation of rainfall into runoff and natural and controlled propagation processes (e.g. rivers and canals with hydraulic structures). The HEC-HMS model consists of the following components: i) calculation of losses (interception in vegetation and soil surface); ii) separation of the flow; iii) baseflow, and iv) river flow propagation. The parameters related to these methods are the sub-basin area, time of concentration, loss factors through infiltration, evapotranspiration and river cross sections. The HEC-HMS model uses the Curve Number and the triangular unit hydrograph, developed by the U.S. National Resources Conservation Center, to determine the design hydrograph in the reach under study.

The pre-processing activities of the input data for the

HEC-HMS hydrological model consist of discretisation and delineation of the area into sub-basins, determining the length of the longest watercourse, length of the main river and difference in elevation between the farthest point from the largest watercourse and the outlet of the sub-basin. This information is used to calculate the time of concentration of each sub-basin using the Kirpich equation (TUCCI, 1998):

$$t_c = 57 \cdot \left(\frac{L^3}{H} \right)^{0,385} \tag{1}$$

where

t_c is the time of concentration in min

L is the length of the largest watercourse in km

H is the difference in level between the highest and lowest points of the basin in meters

For the process of watershed delineation, the Topodata was used with a 30-meter resolution. In the operations, the ge-processing package ArcGIS 10.1 was used together with the ArcHydro 2.0 extension (MAIDMENT, 2002). Figure 3 shows the area simulated with discretisation in sub-basins (whose areas are shown in brackets). These simulations need the design rainfall as an input for the selected return period, which, for this study, was 100 years.

Hydraulic simulation

The hydrodynamic model HEC-RAS (USACE, 2012) facilitates the simulation of streamflows in natural (rivers) or artificial (e.g. irrigation canals) channels. This software enables the calculation and hydraulic analysis of one-dimensional steady and unsteady flow. In the unsteady flow simulation, the model applies complete Saint-Venant equations and the Preissmann’s four point implicit finite difference scheme (BRUNNER, 2010). In the steady flow simulation, the model calculates the profile of the water surface, solving the energy equation by using the

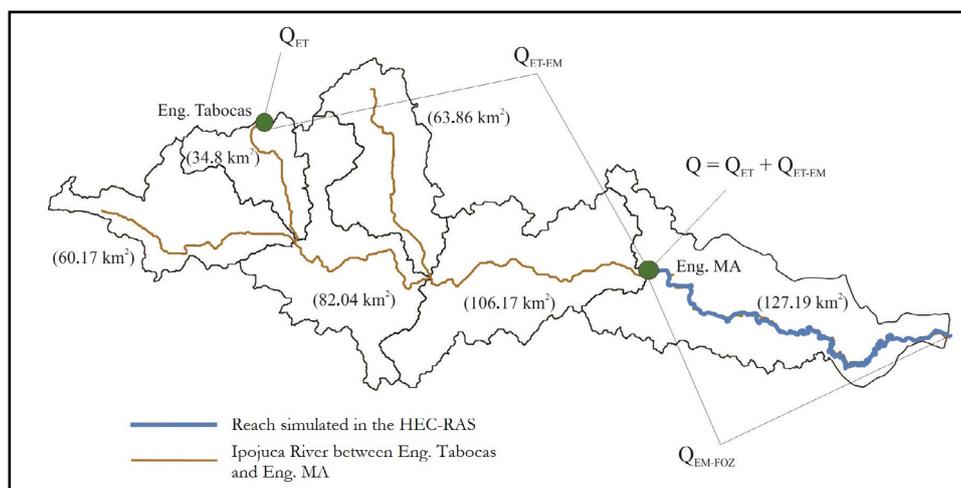


Figure 3 – Input streamflows scheme in the HEC-RAS: Q_{ET} is the maximum flow obtained from the statistical analysis of the Eng. Tabocas series; Q_{ET-EM} is the maximum incremental streamflow of the area between Eng. Tabocas and Eng. Maranhão obtained from HEC-HMS and Q_{EM-FOZ} is the maximum incremental streamflow of the area between Eng. Maranhão and the mouth, obtained with the HEC-HMS

Standard Step method. The simulation in this study was done in steady flow and the downstream boundary condition is the option “Normal Depth” calculated by the Manning equation. Since this is a one-dimensional model, the hydraulic variables such as water depth and velocity refer to average conditions in the cross section.

The input data of the HEC-RAS model is pre-processed in the package ArcGIS 10.1. The HEC-GeoRAS extension, also developed by USACE, permits representation of the main river channel and river banks, in addition to the cross sections from which the geometric characteristics will be taken using DTM.

The HEC-RAS hydrodynamic model was simulated in the reach between the Engenho Maranhão streamgauge and the mouth of the river (~30 km). The upstream boundary condition must be the streamflow in the Engenho Tabocas station (39360000) plus the lateral contribution between Eng. Tabocas and Eng. Maranhão (see Figure 3). Moreover, the incremental discharge in the reach between Eng. Maranhão and the mouth also had to be determined. In both cases, the incremental discharge was calculated with the HEC-HMS model.

The series of streamflow data of the Engenho Tabocas streamgauge was used to define the annual maximum discharge in this section for different return periods. The series, available in the Brazilian National Water Agency database, from January 1967 to December 2006 was used. The series provides 38 annual values of daily maximum streamflow. Gumbel’s distribution function was fit to calculate the streamflow corresponding to the 100-year return period. This was not done for Engenho

Maranhão because its series is too short for a statistical analysis. Table 1 shows the streamflow values of Figure 3 referring to the 100-year recurrence.

Table 1 – Input streamflows in the HEC-RAS model

Streamflow	Value (m ³ /s)
Q_{ET}	413.73
Q_{ET-EM}	873.00
$Q_{ET} + Q_{ET-EM}$	1286.73
Q_{EM-FOZ}	340.50

After the steady flow simulation with the HEC-RAS model, flooded area maps were prepared for the 100-year return period. To assess whether the maps produced are consistent with past events, a field survey was made to identify different points referring to the boundaries of the area affected by the flood event in June 2010. Eighteen points were surveyed along the Ipojuca River, with greatest emphasis on the region of the city of Ipojuca. The points were identified with the help of the residents in the affected places.

Using the time series of the Engenho Tabocas streamflow, we confirmed that the June 2010 flood event had a return period of approximately 150 years, with recorded flow of 441

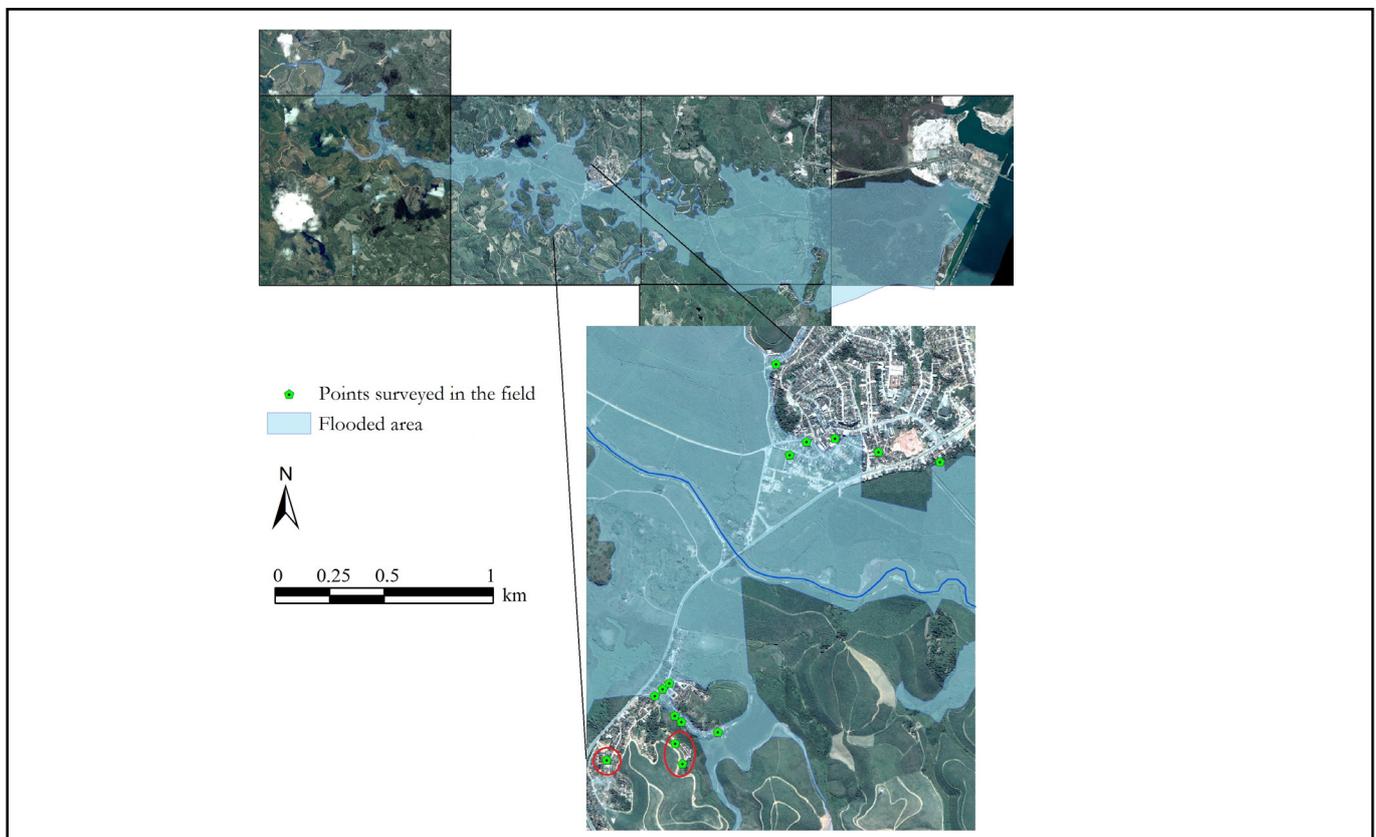


Figure 4 – Points identified as boundary of the flooded area in June 2010 event (in green) and the map produced in ArcGIS corresponding to $Tr = 100$ years

m³/s. The points surveyed in the field were compared to the map produced, based on the HEC-RAS simulation with the 100-year return period. The distance between each point and the boundary delineated by the map was regarded as an error. The average error of the 18 points was 48.11 meters long on the plane. There are some points where it is not clear if the flood came from the main channel of the Ipojuca River or from its small tributaries. The points highlighted in the Figure 4 are examples of this situation (red circle). If these points are removed from the calculation, the average error decreases to 18.59 meters.

Cross sections

Hydraulic modeling requires bathymetric information about the cross sections of the river with an altimetric reference, to enable the determination of not only the area and wet perimeter, but also the longitudinal gradient of the riverbed. For this reason, an altimetric survey was carried out to determine the reference level of the Engenho Maranhão streamgauge station (shown in Figure 3). The elevation of the zero level in the streamgauge is able to be determined and, consequently, the elevation of the cross section in relation to sea level.

In addition to the Engenho Maranhão station, it was necessary to survey two other cross sections for better representation of the geometry and the bottom river slope, as shown in Figure 2.

Design storm

Instead of using a set of raingauge data, the design storm was defined using the intensity-duration-frequency equation determined by Ramos (2010), with pluviographic data from Recife airport. The equation is as follows.

$$i = \frac{1423,97 \cdot T^{0,1124}}{(t + 21)^{0,7721}} \quad (2)$$

where

- i is rainfall intensity in mm/h
- T is return period in years
- t is duration of the rainfall in minutes

This equation was used to calculate the design storm. According to Porto Alegre (2005), a design storm is the critical event generated artificially based on the statistical characteristics of natural rainfall and on the parameters of response of the catchment area. These elements are represented by the return period of the design storm in years and the critical duration of the event (adopted here as twice the time of concentration). The time distribution of the rainfall was based on the methodology described by Porto Alegre (2005). The so-called alternating block method distributes the precipitation over time to find a critical rainfall scenario. This scenario is based on slight and medium precipitation at the beginning and end of the time and heavy precipitation in the middle of the duration, producing high peak flow hydrographs.

Parameter CN

The parameter CN of the Curve Number method is a function of land use and soil type in the catchment area. Land use was obtained from Landsat images. The satellite image was classified using SPRING software, where the maximum likelihood method was used. From the classification result, the following land use classes were identified: water, forest, bare soil/urban area and pasture combined with crops.

The soil type, the other information required to define the parameter CN, was obtained from the map on a scale 1:100,000, produced by the Pernambuco State Agro-Ecological Zoning project (ZAPE). The soil group classification was carried out based on the method presented by Sartori et al. (2005), in which the hydrological group of the soil is defined based on the soil type.

The next step was to combine the land use and soil group maps to define the value of the parameter CN. The U.S. Department of Agriculture's Technical Release 55 (USDA, 1986) presents tables that relate the values of CN with classes resulting from the combination of the land use and soil group maps.

In the water and mangrove areas, the value of CN is 100, assuming that in these classes all rainfall causes surface runoff. The area of the classes is used as a weighting factor to reach the final CN in each sub-basin (the values vary between 58.5 and 68.5).

Hazard areas mapping

According to UNISDR (2009), hazard is described as the frequency of occurrence of different intensities for different areas based on historical data. Tominaga et al. (2009) state that hazard refers to the probability of a potentially damaging natural phenomenon or process occurring in a certain place over a specified time. Considering these concepts, the idea is to generate a hazard map for the areas adjacent to the Ipojuca River, using indicators based on water depth and flow velocity provided by the HEC-GeoRAS (extension of pre and post-processing of the HEC-RAS model).

Alternatively, we defined indicators that could represent or are related to water energy. Kreibich et al. (2009) argue for the use of other variables derived from the water depth and flow velocity to relate to the structural damage to houses, roads, financial losses and business interruption. The suggested indicators are as follows:

$$\text{Energy head} = y + v^2/2g \quad (3)$$

$$\text{Indicator for flow force} = y \cdot v^2 \quad (4)$$

$$\text{Intensity} = v \cdot y \quad (5)$$

where

- y is water depth (m)
- v is flow velocity (m/s)
- g is acceleration of gravity = 9.81 m/s²

Table 2 shows which indicator has the strongest influence on damages caused to different types of land use (KREIBICH et al., 2009).

According to Wright (2008), floods with water depth more than 0.60 meters or flow velocity over 1.2 m/s result in definitive hazard for people. These values were used for Ipojuca River as a basis for defining three levels of severity of the flood related to water depth and flow velocity. Figure 5 shows the histograms with simulated values for water depth and flow velocity in the study area, together with the thresholds values:

0.6 and 1.2 meters and 0.6 and 1.2 m/s. The two maps were reclassified attributing a value of 1, 2 and 3 for depths of 0-0.6 m, 0.6-1.2 m and over 1.2m, respectively, and for flow velocities of 0-0.6 m/s, 0.6-1.2 m/s and over 1.2 m/s, respectively. For water depth, the value (0.60 m) and the double of this value were adopted as thresholds for defining the classes. In the case of flow velocity, it was decided to use the threshold (1.2 m/s) and its half. These thresholds constitute a class with a well-balanced frequency distribution, as shown in Figure 5.

A similar procedure was adopted to define the threshol-

Table 2 – Influence of the different hazard indicator son the flood damages(adapted from Kreibich et al, 2009)

Impact parameters	Damage types				
	Structural damage of residential buildings	Structural damage to roads	Monetary losses to residential buildings	Monetary losses to road infrastructure	Business interruption and duration
Flow velocity	No	Strong	Weak	No	No
Water depth	Strong	Medium	Medium	No	Medium
Energy head	Strong	Medium	Medium	No	Weak
Flow force	Weak	Strong	Weak	No	No
Intensity	Weak	Strong	Weak	No	Weak

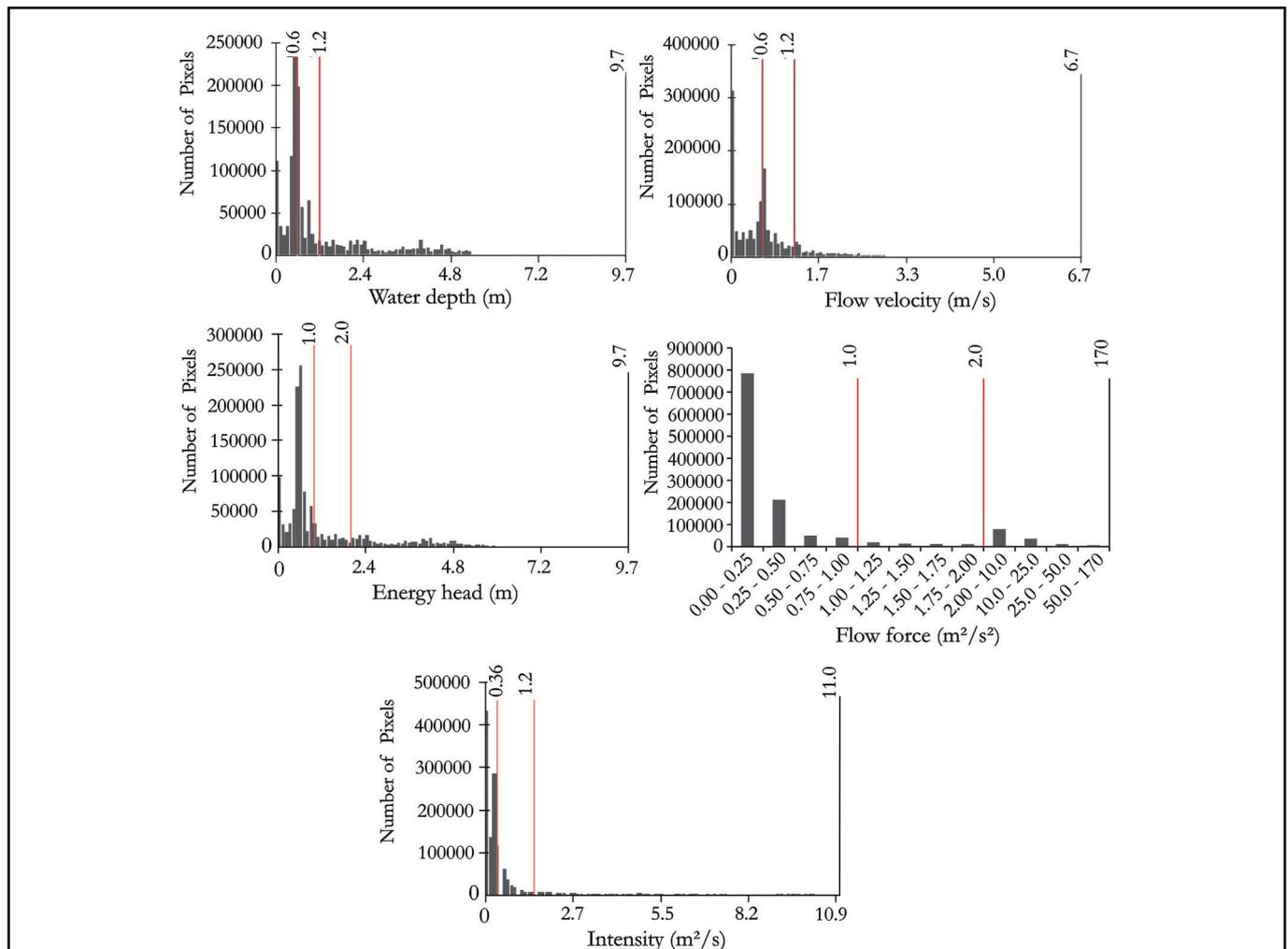


Figure 5 – Histograms with indicator values

ds of the other indicators in Figure 5. According to Kreibich et al. (2009), the values representing a significant increase in damage in the region affected by the flood are two meters for the energy head (Eq. 3), 2 m³/s² for the flow force (Eq. 4) and 1.5 m²/s for the intensity (Eq. 5). Table 3 shows the thresholds used to define the low, medium and high hazard classes for the adopted indicators.

Table 3 – Thresholds of indicators to build a hazard map

Indicator	Low	Medium	High
Water depth (m)	0-0.60	0.60-1.20	> 1.20
Flow velocity (m/s)	0-0.60	0.60-1.20	> 1.20
Energy head (m)	0-1.0	1.0-2.0	> 2.0
Flow force (m ³ /s ²)	0-1.0	1.0-2.0	> 2.0
Intensity (m ² /s)	0-0.36	0.36-1.50	> 1.50

Definition of the flood prone areas

The second methodology adopted provides an overview of the Ipojuca municipality with regard to its susceptibility to flooding. Physical indicators are used to help explain in numerical terms the extent of this degree of susceptibility. Studies carried out in other countries have been taken as a reference, with indicators such as land use, soil type, land cover, slope, proximity to watercourses, flow accumulation and land elevation (PRADHAN, 2009; SANTANGELO et al., 2011; MORAES et al., 2014).

In the application to the municipality of Ipojuca, the flood prone areas were defined with two maps:

- topographic index
- distance cost matrix.

The topographic index of the hydrological Topmodel (BEVEN et al., 2012) represents the potential of a point in the basin to saturate. This is a function of the flow accumulation and slope in the point.

$$IT = \ln \left(\frac{a_i}{tg\beta_i} \right) \tag{6}$$

where

- IT is the topographic index;
- a_i is accumulated drainage area upstream in m²,
- tgβ_i is the topographic gradient given by the slope of the terrain in degrees.

The second map used - the distance cost matrix - gives to each pixel a displacement cost value to the hydrography and weighs it with the value of the slope terrain. The cost has a direct relation with the terrain slope and with the distance to the river or canal. The cost may represent the susceptibility to flooding because the lower the cost, the easier to accumulate water. The result of the operation will be a matrix in which each cell contains the value of the lowest distance cost between the point and the watercourse. This operation was made in the package ArcGIS 10.1. Details about the calculation of the distance cost

matrix can be obtained in ESRI (2016).

The maps used to identify flood prone areas have different ranges of variation in the values. To overcome this characteristic and permit the later combination of these maps, they were normalized so that the final scale indicates that the closer the pixel is to 1, the more susceptible the area is to flooding, and the closer to 0 the less susceptible.

Equation 7 is used to normalize the values of the topographic index (increase in value of the original variable indicates more susceptible to flooding).

$$Cell_{norm} = (Cell - MinValue) / (MaxValue - MinValue) \tag{7}$$

Equation 8 is used to normalize the values of the distance cost matrix (the increase in value of the original variable indicates less susceptibility).

$$Cell_{norm} = (Max Value - Cell) / (Max Value - MinValue) \tag{8}$$

where

- Cell_{norm} is the normalized value
- Cell is the original value of the pixel
- Max Value is the pixel with highest value
- Min Value is the pixel with lowest value

Equal weights were used to match the two normalized maps.

RESULTS AND DISCUSSION

Hazard map

Six hazard indicators were used: water depth, flow velocity, combination of depth and velocity, energy head, flow force and intensity. Figure 6 shows a map with the water depth indicator.

The indicator defined by the combination of the water depth and flow velocity is a raster with pixels that vary from 1 to 9. A new reclassification was made to have a map with values 1, 2 and 3. The value is reached by taking the arithmetic mean of the depth and velocity classes. When the result is fractioned (e.g., (3 + 2 ÷ 2 = 2.5), the value immediately above is adopted (in this example, the resulting value would be 3). Table 4 shows how the result of the combination is defined to generate the hazard indicator map as can be seen in Figure 7.

Table4 – Combination of water depth and flow velocity maps

Depth	Velocity	Combination	Hazard
1	1	1	Low
2	1	2	Medium
3	1	2	Medium
1	2	2	Medium
2	2	2	Medium
3	2	3	High
1	3	2	Medium
2	3	3	High
3	3	3	High

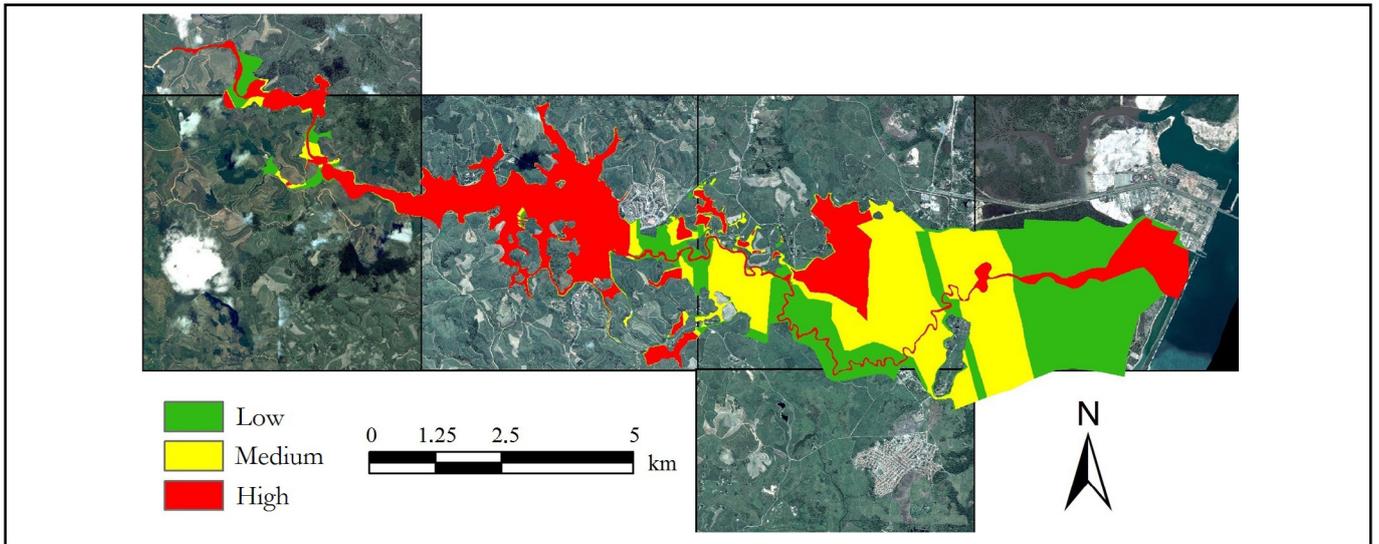


Figure 6 – Hazard indicator map as a result of flooding for the 100-year return period: water depth at low (0-0.60 m), medium (0.60-1.2 m) and high (> 1.2 m) levels

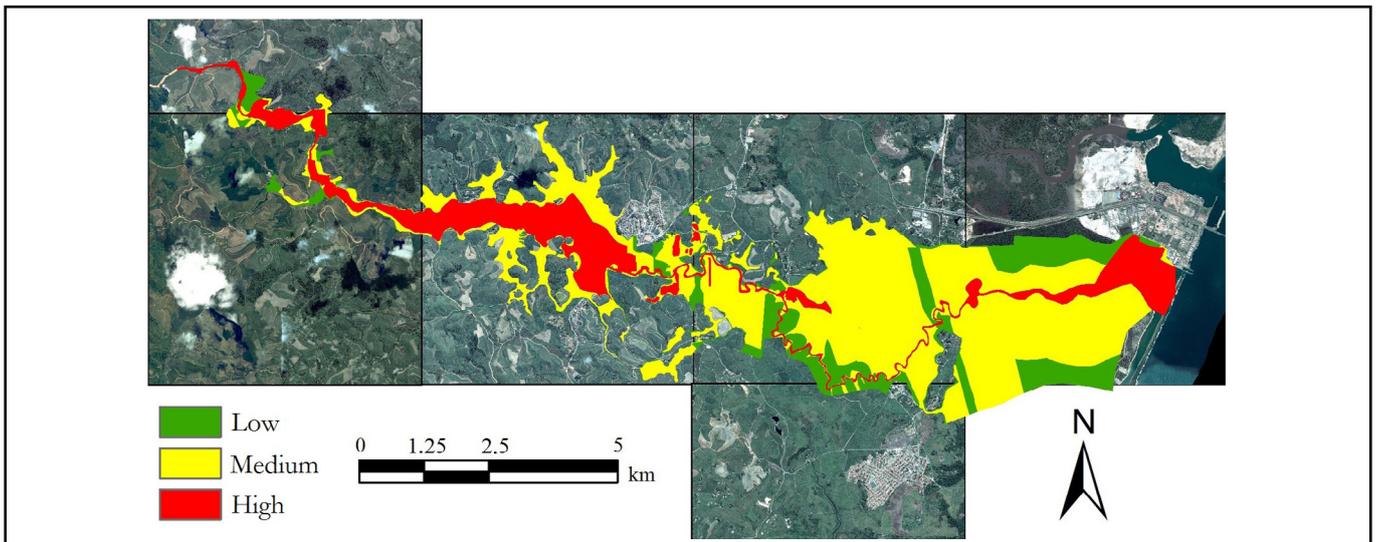


Figure 7 – Hazard indicator map as a result of flooding for the 100-year return period: combination of depth and flow velocity

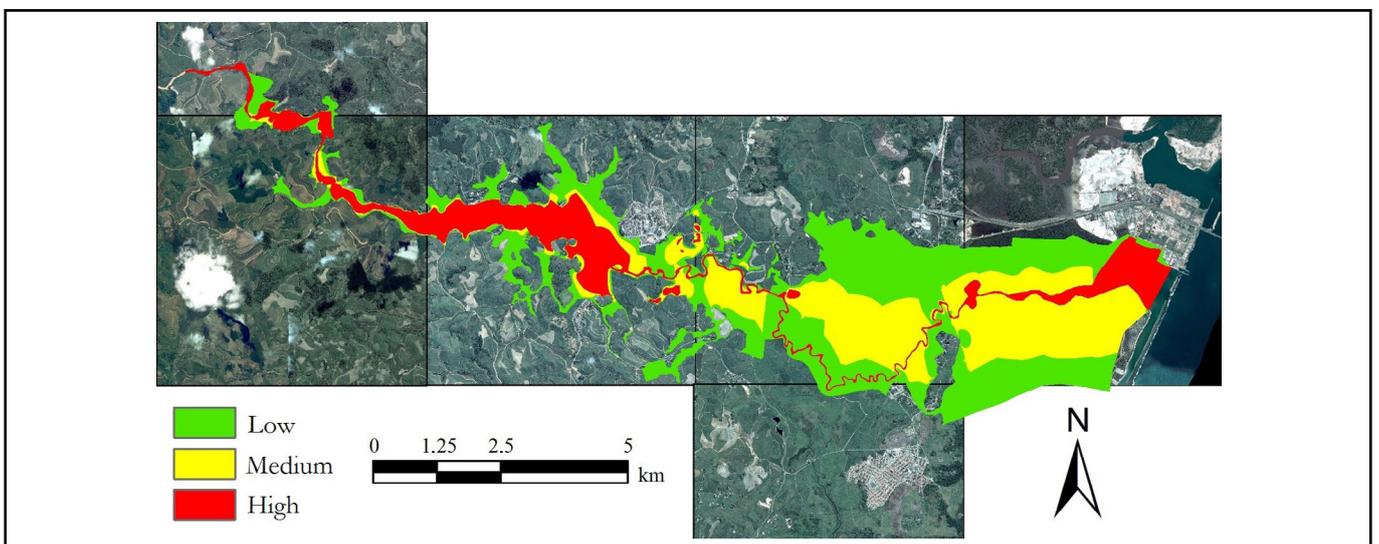


Figure 8 - Hazard indicator map as a result of flooding for the 100-year return period: indicator Intensity

For the last three indicators, map algebra was used to reach the desired result. As in the first hazard indicators, three classes were defined according to the indicator value as shown in Table 3. The map resulting of the indicator “intensity” (Eq. 5) is provided in Figure 8.

Definition of flood prone areas

The topographic index was normalized according to

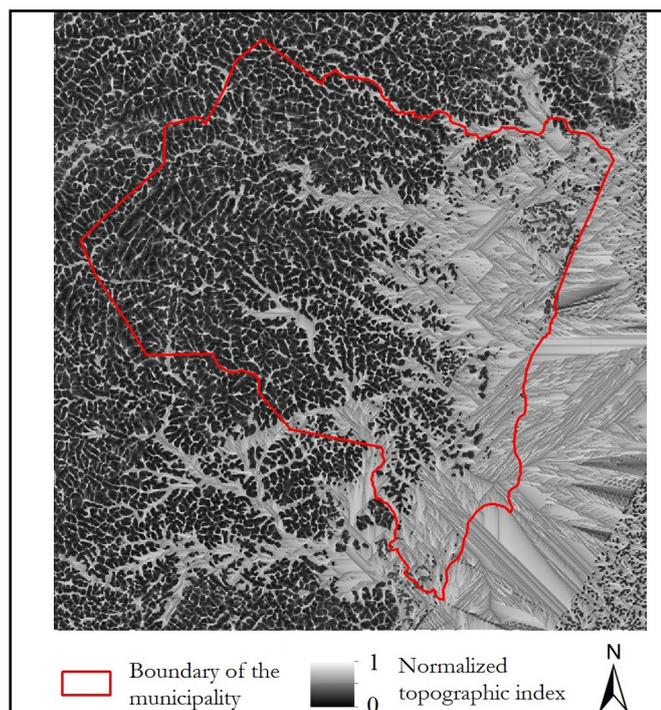


Figure 9 – Normalized topographic index

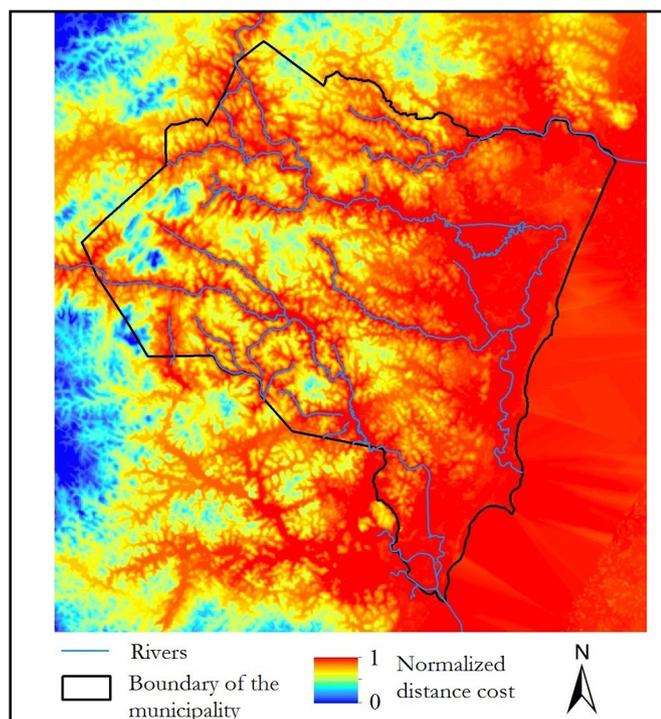


Figure 10 – Normalized distance cost

Equation 7, where the increase in value of the original variable indicates an increase in flood prone level (Figure 9).

For the distance cost matrix, the method used as variables the terrain slope and proximity to watercourses. The distance cost was normalized by applying Equation 8, where the decrease in value of the original variable indicates higher flood prone level (Figure 10).

Finally, the map of flood prone areas was obtained by adopting a weighted average of the normalized values of the topographic index and distance cost matrix. Both values had weight equal to 0.5. The resulting values were grouped into three flood prone classes with an equal variation interval: low, medium and high. Figure 11 illustrates the map with the adopted method where the low and medium classes are combined (white) to differentiate from the high flood prone class (green).

DISCUSSION OF THE RESULTS

The results of mapping the hazard indicators have helped to identify on the Ipojuca River floodplain the areas with highest potential damage to the population. In the area near to the town center of the municipality, for example, the map with the water depth indicator shows a high hazard level. In all indicators evaluated, the high hazard level predominates in the reach of the river upstream from the town center of Ipojuca, mainly due to the high slopes of the riverbed resulting in high flow velocity and water depth. Areas with a medium and low hazard downstream from the town center prevail due to the low slopes of the riverbed. This analysis is only possible thanks to the capacity of the HEC-RAS model to produce maps of water depth and flow velocity in addition to flooded area mapping.

The area corresponding to the class of high hazard is found to be very similar in the different maps produced with the indicators. However, a significant difference is found between the medium and low hazard classes. This is due to the choice of the lower threshold that defines the separation of these two classes. Tests can be performed with other threshold values for water depth and flow velocity.

A reasonable similarity is also found between four maps of hazard indicators: water depth, flow velocity, combined depth-velocity, and intensity. The choice of one or other indicator can follow the instructions provided by Kreibich et al. (2009), which relate types of damage (building and road structures, financial damage, business interruption and so on) to the hazard indicators. In this analysis of the Ipojuca municipality, the water depth indicator is a good choice because the land use is predominantly residential, associated with a road infrastructure. Water depth was also the indicator adopted by Monteiro and Kobiyama (2013) when areas of flooding hazards in the municipality of Ilhota (Santa Catarina state) and by Masood and Takeuchi (2012) and Gain et al. (2015) to determine risk indices in Dhaka, capital of Bangladesh.

The result of mapping the flood prone areas throughout the municipality shows the positive potential of the method to identify places that might suffer flood damage. Together with the flood prone areas, Figure 11 illustrates the boundary of the

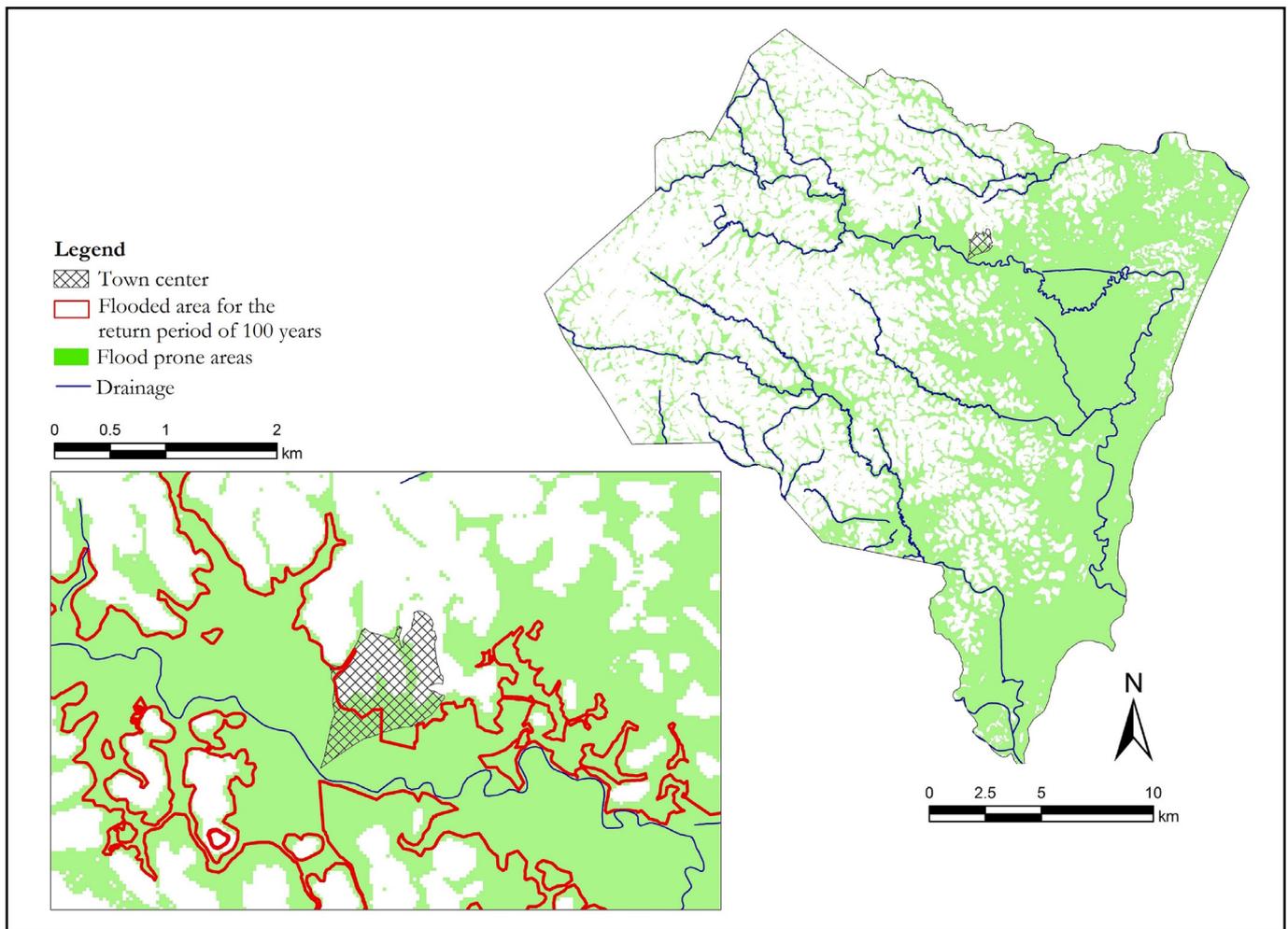


Figure 11 – Map resulting from applying the method of identifying flood prone areas in Ipojuca municipality

Ipojuca River flooded area for a 100-year return period ($T_r = 100$ years) obtained from the HEC-RAS model. A reasonable proximity is noted between the result of the hydraulic model and flood prone area. Like other approaches, the methodology applied to Ipojuca proved effective in identifying flood prone areas using DTM as basic information. Moraes et al. (2014) tested calculation techniques for flow accumulation and associated this to the potential flooding of the terrain. The HAND model, developed by Nobre et al. (2011) to define classes related to the groundwater level, has been used to identify areas susceptible to flooding (NOBRE et al., 2016; SCHLAFFER et al., 2012; SILVA et al., 2013).

CONCLUSIONS

Risk analysis is essential for planning and intervention in flood prone areas. As previously emphasized, for risk assessment it is necessary to characterize both hazard and vulnerability. The results of the Ipojuca study can be used mainly to characterize hazard. This could help, for example, in preparing geotechnical charts to identify areas more suitable to occupation in the municipality. Geotechnical charts are essential for

planning land occupation expansion, aiming to reduce damage and losses for the population and public authorities as a result of natural disasters (COUTINHO, 2014). In cases where the areas are already occupied, e.g., in part of the town center of Ipojuca municipality, the result could be useful for defining the necessary measures to address potentially damaging events.

In Brazil, few studies involve mapping to assess potential flood damage. Spatial details of the hazard indicators are a valuable tool for flood risk management since the map provides a more direct and speedy assessment than other methods.

In the study, the simulated peak flow in the study area attracted our attention when compared with the flow generated in the upper and middle Ipojuca River. To reduce uncertainties, we would need to make a more detailed assessment of the intense rainfall regime in the upper, middle and lower courses of the Ipojuca River to verify the influence of climate on the magnitudes of rainfall events. Moreover, the suitability of the methods used in the HEC-HMS model need to be evaluated with respect to their application in nearby river basins that have streamflows series for comparison.

Nevertheless, the comparison between the flooded area and a field survey has shown a suitable performance of both models used to represent the hydrological and hydraulic processes.

It is worth mentioning that the methodologies developed and applied in the Ipojuca municipality are able to be reproduced in other municipalities in Brazil. The mapping methodology of flood prone areas could be particularly useful for regions with lack of streamgauge data (water level, streamflow, bathymetry), where the use of hydrodynamic modeling is difficult. In general, the most limiting factor that can be considered for adopting the methods are currently the availability of an altimetric survey for characterizing the relief in rivers impacted by flood events.

These results are the first step to reach a flood risk analysis, which requires hazard, exposure and vulnerability mapping. Efforts should be made to characterize vulnerability by assessing susceptibility (damage-depth curves) and resilience (elements such as warning systems, Civil Defense actions, rebuilding operations, among others).

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Larissa Ferreira David Romão Batista: pre e post-processing input data of the models HEC-HMS and HEC-RAS; model simulation; mapping of flooded area, water depth, flow velocity and hazard indicators; literature review; text writing.

Roberto Quental Coutinho: mapping of flooded area, water depth, flow velocity, hazard indicators and flood prone areas; literature review; text writing; coordination of the project.