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FLOOD MAPPING AND RISK ASSESSMENT OF THE PARAÍBA RIVER BASIN, ALAGOAS, BRAZIL: CASE STUDY

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ABSTRACT

Flood maps are an important instrument in the prevention, control and management of floods, as they can define areas of risk. Thus, the present study aimed to map potential flood risk areas in the urban area of Quebrangulo, a municipality located in the state of Alagoas. The mapping was based on population and households data, obtained from IBGE demographic census of 2010, and hydrodynamic modeling performed by the IBER two-dimensional computational model, which provided the floodwater levels that occurred for each locality. Then, with the use of the ArcMap program, we elaborated a risk map with flood spots for the recurrence periods of 5, 10, 25, 50 and 100 years, for two different scenarios. The areas identified with biggest problems in relation to floods are the areas located near the Paraíba River, where the riverine populations are inserted, mainly due to their vulnerability and disordered occupation.

Key words: Hydrodynamic modeling, flood risk and risk map.

1. INTRODUCTION

The occurrence of floods has intensified and become more frequent each year. Floods are a concern for many populations, as they cause disastrous impacts on affected areas, causing economic, social and environmental damage, and, in more critical cases, can lead to loss of human life. According to Hora *et* Gomes (2009), 164,662,775 people were affected by flood events around the world in 2007, causing also the death of 8,382 individuals.

Flooding events occur due to the natural river regime or are provoked and/or amplified by changes in the soil surface of a river basin, mainly due to the urbanization process, which causes waterproofing and channeling of river surfaces (Tucci *et* Bertoni, 2003).

The application of the GIS tool in the identification and diagnosis of risk areas has been widely explored in several Brazilian cities and currently provides an important role in risk management, since we can elaborate maps from it, associating physical, environmental and social knowledge. Thus, the map of flood risk areas is a relevant instrument in the prevention, control and management of floods.

1.1 Motivation and goal

This work is motivated by the intense rains that occurred in the Paraíba and Mundaú river basins, located in the states of Pernambuco and Alagoas, in June 2010, which affected 15 municipalities in Alagoas and 14 in Pernambuco, and left approximately 80,000 people homeless.

In the municipality of Quebrangulo, on the border of the states of Alagoas and Pernambuco, approximately 80% of the city was devastated by the flood of 2010[1] and about five thousand people lost their homes. According to the Fire Department, 60% of the residences were destroyed.

Thus, the main objective of this study is to map the flood risk areas in the urban area of the city of Quebrangulo, for

1 http://gazetaweb.globo.com/noticia.php?c=207259&e=14, 04/mar/2015.

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two different scenarios: with and without river dams/barriers in the upstream of the municipality. In order to achieve the main goal of this work it is necessary that the following specific objectives are conducted:

- To evaluate and use, for the recurrence times of 5, 10, 25, 50 and 100 years, the affluent hydrograms, elaborated by the company COHIDRO, for the scenarios with and without river dams;
- To determine population and housing densities;
- To characterize land Usage and Occupation;
- To determine the flood spots in the municipality for the recurrence periods of 5, 10, 25, 50 and 100 years for the scenarios with and without the dam.

2. LITERATURE REVIEW

2.1 Risk

The concept of risk may vary according to the context in which it is embedded. According to Zonensein (2007), the definition of a single concept for risk is not advisable, since an approach focused on distinct and specific perspectives is complex. Thus, several areas of science and branches of knowledge have used the concepts of risk as being social, environmental or economic.

The term risk may be associated with vulnerability, sensitiveness, susceptibility or potential harm. In the engineering field, the risk is related both to the probability of an event occurring and to the expectation of losses caused by it.

According to the International Strategy for Disaster Reduction (ISDR), risk is the likelihood of harmful consequences or expected losses (deaths, injuries, disrupted economic activities or environmental damage) resulting from interactions between natural or man-induced hazards and vulnerable conditions.

As explained by CIRIA (2010), the United States Department of Homeland Security (DHS) considers risk based on the threat, vulnerability and consequence of an event.

$$Risk=f(T,V,C)$$

Where T is the threat of an event with potential to cause harm (danger); V is vulnerability, that is, the level of susceptibility to disturbance and C is the consequence, which can be explained by the social, economic and environmental impacts of an event.

2.1.1 Flood risk mapping

In their study, Hora *et* Gomes (2009) aimed to recognize and map the physical and environmental aspects of a section of the Cachoeira river, in Itabuna-BA, which includes the sub-clusters Bananeira, Rua Beira Rio and Jaçanã, due to the analysis of these in the phenomenon of flooding and emphasizing the definition of potential risk areas, drawing a risk map with flood spots for different recurrence periods.

Guimarães *et* Penha (2009) used hydrodynamic models to determine the areas subject to flooding and, based on the comparison with the mapping records of the city, mapped flood risk areas in the municipality of Muriaé-MG.

Silva Junior (2010) provided tools in his study for the management and improvement of public government actions, after analyzing the flood risk in the city of Alenquer-PA.

Sarlas (2010) had as the main goal of his study to elaborate flood spots for the urban area of Santa Rita do Sapucaí / MG, through the SPRING software.

For the mapping of flood risk areas in Guaçuí-ES, Magalhães *et al*. (2011) had as goal the comparison between two different methods through the use of geotechnologies.

Cunha *et* Pinto (2011) used the HEC-FDA software to map and analyze the risks caused by flooding in the riverside area of the city of Peso da Régua, in Portugal.

A flood risk assessment was made by Simões *et al*. (2012), which indicated vulnerability and susceptibility variables at Avenida Cristiano Machado, in the city of Belo Horizonte / MG.

Goerl *et al*. (2012) had as study goal to propose and apply a methodology for mapping flood risk areas in the study area, which covered the municipality of Rio Negrinho, in Santa Catarina.

By cross-referencing hypsometry, declivity and land usage and occupation information, Andrade *et al*. (2014) developed a flood risk map for the urban area of the São Pedro creek basin, Uberlândia-MG.

2.2 Maximum flows

The project “Basic, Feasibility Studies and Master Plan of Works and Interventions for Mitigation of the Effects of Flooding on the Paraíba and Mundaú river basins – AL” of Hydrological Studies, prepared by Cohidro (2013), establishes the maximum flows referring to recurrence times of 5, 10, 25, 50 and 100 years, as presented in **Table 1** below.

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Table 1. Maximum flows.

Recurrence time (years)	Flow (m^3/s)		
	P1	P2	Quebrangulo
5	143,8	71,5	188,0
10	181,3	108,5	237,0
25	228,7	160,4	299,0
50	263,9	203,8	345,0
100	299,1	249,8	391,0

Source: Cohidro (2013).

3. METHODOLOGY

In this chapter, we discuss the methodology used to carry out flood risk mapping in the urban area of the city of Quebrangulo, with the proposal of two dams (P1 and P2), both in the Paraíba river basin.

3.1 Paraíba river basin

3.1.1 General considerations

The Paraíba river basin lies between the parallels 08º 44 'and 09º 39' south latitude and between the 35º 45 'and 36º 45' west longitude of the Greenwich meridians. It is limited to the north by the basin of the Ipanema River, to the south by the basins of the rivers São Miguel and Sumaúma, to the east by the basin of the river Mundaú and to the west by the basins of the rivers Traipú and Coruripe.

Located in the states of Pernambuco and Alagoas, the watershed of the Paraíba River is located in the Eastern Northeast Atlantic Hydrographic Region, according to the ANA division for the Brazilian Hydrographic Regions, as shown Figure 1.

Its drainage area is approximately 3,147 km² long, with 1,989 km² (63%) in the state of Alagoas and 1,158 km² (37%) in the state of Pernambuco. With its source in the municipality of Saloá, in Pernambuco, the Paraíba River runs a distance of approximately 177 km, flowing into the Manguaba lagoon, in the state of Alagoas (Cotec, 2001). According to Rocha (2011), its main tributaries are the rivers Seco and Bálsamo, in Pernambuco, and the rivers Quebrangulinho, Riachão, Caçamba, Paraibinha and Porangaba, in Alagoas.

Its characteristic relief is undulated, being more pronounced in the headwaters region, gradually decreasing the relief slopes along the course of the Paraíba river, which flows NW/SE towards the flat region of the sedimentary basin in its lower course, in the state of Alagoas.

3.1.2 Case study

The studied area is located on the Paraíba river basin, in the municipality of Quebrangulo, located in the state of Alagoas and bordering the state of Pernambuco. As already mentioned, the study aims to evaluate the effects of a flood in the urban area of the municipality, in the scenarios with and without the P1 and P2 dams. Figure 2 below shows the location of the proposed buses, the municipality of Quebrangulo and its urban area, which is downstream of P1 and P2.

3.2 Land usage and occupation

The identification of the main uses of the land, aiming at the elaboration of a diagnosis of land usage in the study area, was made through *Google Earth Street View* feature.

Land uses were sorted by categories of residential use, square parks and leisure area, transport routes, green areas and exposed soil, as observed in **Figure 3**.

The transport routes category was split in two subcategories, as paved and dirt roads.

Squares and leisure areas are the places identified as the leisure area of the population, as playgrounds for children in general.

The green areas were divided and categorized as vegetation/pasture and woods.

3.3 Population and household density

In order to evaluate the population and domiciliary density in the area under study, we used data from the 2010 IBGE demographic census divided by census tracts.

The census tracts established by IBGE are the smallest territorial units and are used for the purpose of collecting the census data. The demarcation of the census tracts is done in accordance with the data collection operationalization criteria, in such a way that they cover an area that can be traversed by a single enumerator in a month and that has around 250 to 350 households (in urban areas).

The municipality of Quebrangulo was divided into 18 census tracts by IBGE. For the present study, we considered the 9 census tracts that are totally or partially contained in the project area. From the information of each of these census tracts we calculated the population density (**Figure 4**), which is the ratio of the total population comprised in the sector by the total area of the census tract in km². We performed the

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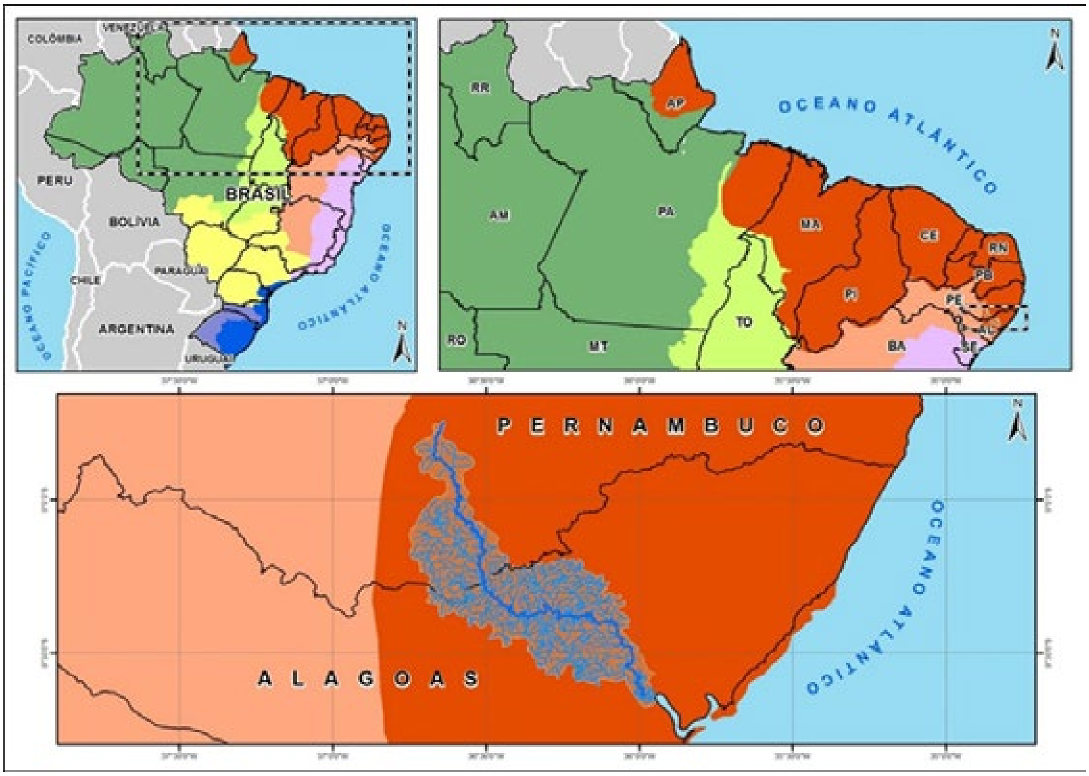

Figure 1. Location of the Paraíba River basin.

Source: Authors' study.

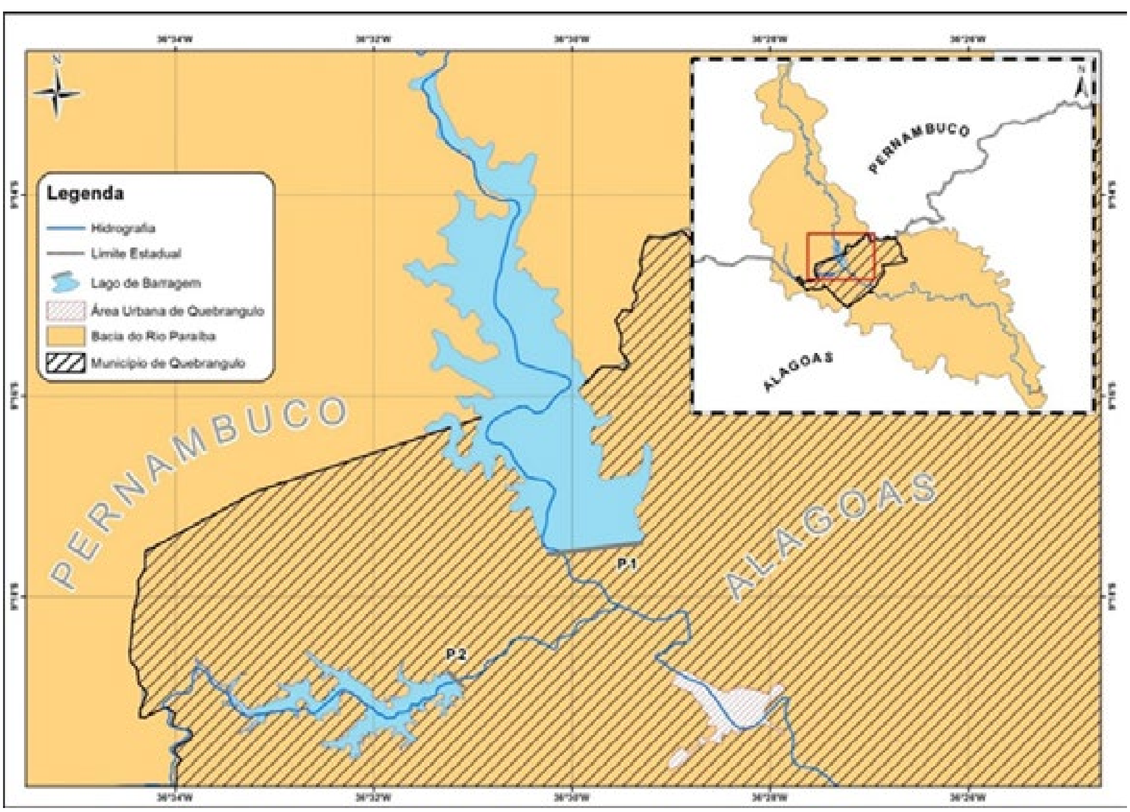

Figure 2. Location of the dams P1, P2 and the municipality of Quebrangulo.

Source: Authors' study

Legend: Hidrography; State border; Lake dam; Quebrangulo urban area; Paraiba River Basin; Quebrangulo municipality.

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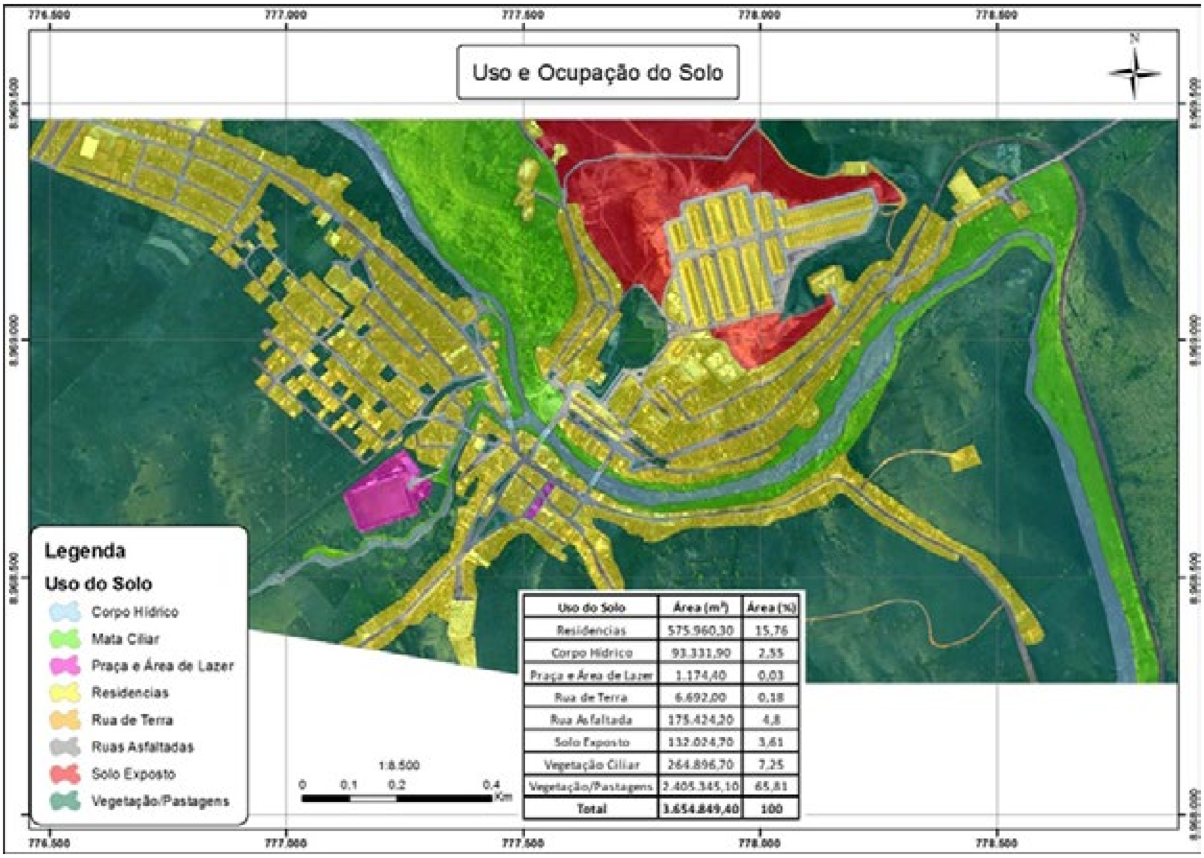

Figure 3. Land usage and occupation

Source: Authors' study.

Legend: Land Usage; Water; Riparian forest; Squares and leisure area; Households; Dirt roads; Paved roads; Exposed soil; Vagetation/pasture

same calculation for the households in the study area, thus obtaining the household density (**Figure 5**).

We also made an estimate of the total number of inhabitants and households in the area of the present project, resulting in a total of 5,834 inhabitants and 1,771 households. To do so, we needed to recalculate the area of the census tracts that was not completely covered by the study area. After this was done, we multiplied the population density and the household density previously calculated, by the area in square kilometers of the sector within the target region of this study.

3.4 Hydrodynamic modeling

Hydrodynamic models use the physical laws of fluid mechanics that govern the behavior of a given water flow.

The correct representation of the physical reality of the flow through the model is, according to Miguez (1994), a function of two levels of the process of its construction, called topological discretization and hydraulic discretization. Topological discretization refers to the way of representing the nature of the flow. Hydraulic discretization refers to the details that involve the topographical and hydraulic descriptions of the model elements.

The topological discretization begins in the definition of the type of the model to be used in the flow, as a single, bi or tridimensional one. The single-dimensional models consider the direction of flow in only one direction along a channel, and make use of the equations of continuity and dynamics, better known as Saint-Venant's equations. Two-dimensional models do not consider a preferred direction for flow. According to Miguez (1994), two-dimensional modeling can be performed using the Navier-Stokes equations vertically integrated, or we can consider a complex network of cells, defined according to the topography of the study site, taking into account the Flow exchange laws between them, in the flow plane. According to Rosman (2012), the Navier-Stokes equations, which represent the principle of conservation of momentum, together with the continuity equation, the state equation and the transport equation for each constituent of the state equation, comprise the three-dimensional mathematical model for any water body.

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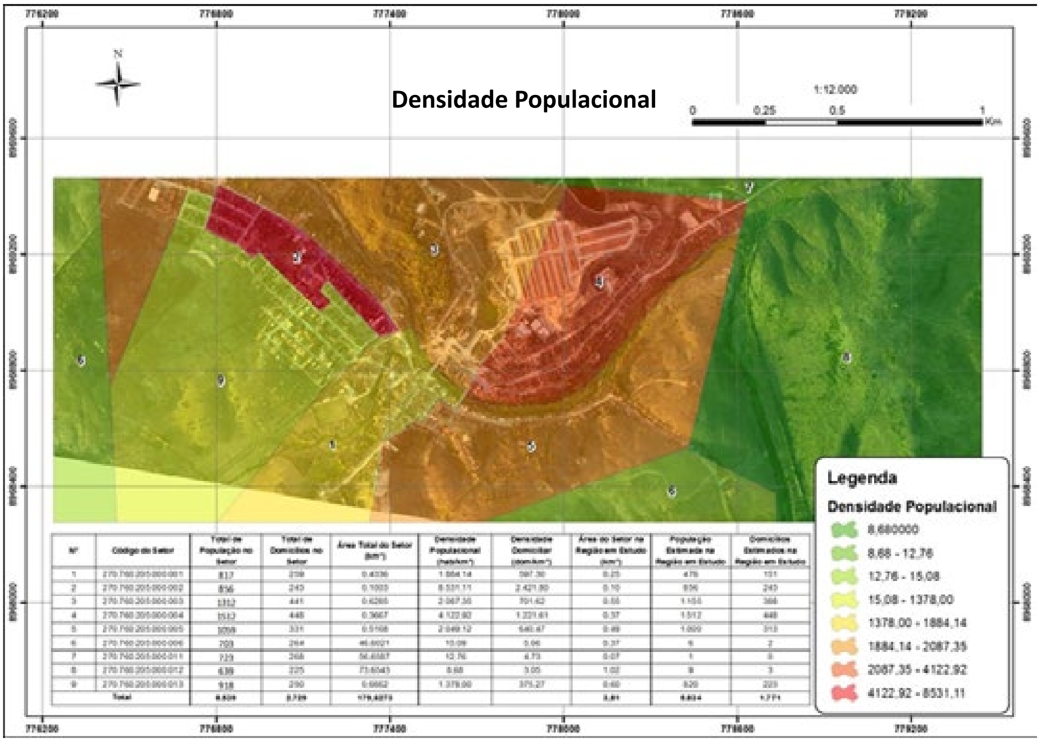

Figure 4. Population density.
Source: Authors' study.

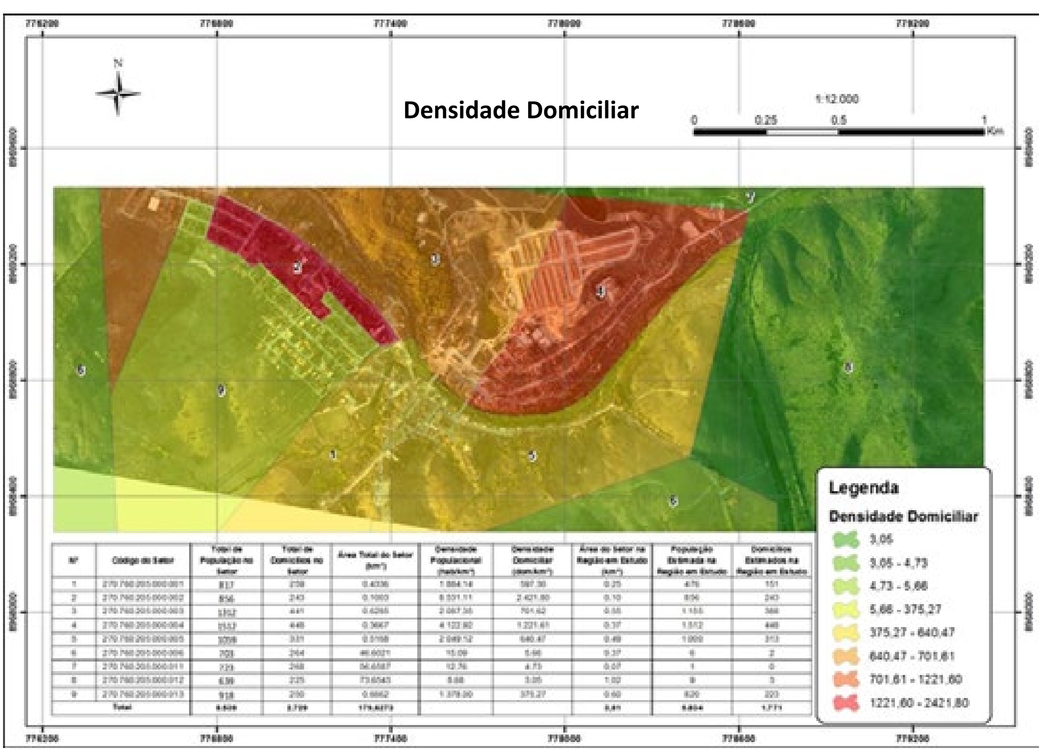

Figure 5. Household density.
Source: Authors' study.

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In this study, we chose to use the IBER two-dimensional hydrodynamic model to determine the flood spots in the urban area of the city of Quebrangulo, based on flow rates associated with recurrence times of 5, 10, 25, 50 and 100 years.

3.4.1 IBER 2.2 input data

To simulate the hydrodynamics of a water body using IBER, we need to provide specific input data to the software, such as the Digital Elevation Model (MDE) of the terrain, the bathymetry of the studied water body and the Manning coefficients. IBER also needs boundary conditions data, which serve to consolidate the hydrodynamic modeling of the study area.

The MDE was conceived from topobatimetric and aerophotogrammetric surveys carried out in the basin, under the project "Basic Studies, Feasibility Studies and Master Plan of Works and Interventions to Mitigate the Effects of Floods in the Paraíba and Mundaú Hydrographic Basins – AL", Topographic Studies, in 2013. The data of the surveys were processed and, thus, generated a relief contour file of 1 by 1 meter of the area under study. With this file, we used Civil 3D software to create a surface of the region of interest for modeling. After this, the generated file was exported to ArcGis 10.0 and from this software we created an MDE file compatible with the IBER model.

The Manning coefficients can be obtained from Chow (1973), which presents the Manning number for different characteristics in stretches in natural rivers, as the case under study.

The first contour condition to be added to the model is the flow, which must be inserted in the upstream stretch from the area to be studied, so that the flood hydrograph propagates downstream. Another condition that must be added is the location of the basin exudate, so that the IBER model understands where the water will exit the model.

For the present study, the flow data inserted in the model, for the scenario without dam, were those obtained in the statistical study of the fluvial post of Quebrangulo. For the dam scenario, we needed to calculate the incremental flow of the basin formed between the exudates of the dams and the Quebrangulo fluviometric station, and add it to the flow normalized by the reservoir.

The method used to calculate the incremental flow is shown in Equation 1 as follows:

$$Q_{inc} = \left(\frac{Q_{P1} + Q_{P2}}{A_{dP1} + A_{dP2}}\right) * A_{dinc} \quad (1)$$

where:

Q_{inc} is the flow generated by the incremental basin ($m^3.s^{-1}$);

Q_{P1} and Q_{P2} are the tributary flows of the P1 and P2 dams ($m^3.s^{-1}$);

A_{dP1} and A_{dP2} are the drainage areas of the dams (km^2);

A_{dinc} is the drainage area of the incremental basin (km^2).

Finally, it is necessary to provide the modeling data to the model, ie, the timeframes the model will use to simulate the flow and present the results.

3.5 Vulnerability of typology of land use

The vulnerability categorization of the typologies was made taking into account the values proposed by Hora *et* Gomes (2009), which assigned values of vulnerability to each type of land use and occupation. The values vary from 0 to 1, and greater values represent the situation of greater vulnerability to damages caused by the phenomenon of flood. **Table 2** lists the vulnerability values attributed to the land uses in this study.

Table 2. Vulnerability values attributed to land uses.

Land Use	Vulnerability Level
Households	1,00
Squares and leisure areas	0,50
Dirt Road	0,05
Paved road	0,00
Exposed soil	0,05
Ciliary Vegetation	0,10
Vegetation/Pasture	0,10

Source: Elaborated based on studies by HORA *et* GOMES (2009)

3.6 Risk mapping

According to Hora *et* Gomes (2009), flood risk can be defined by Equation 2, as follows:

$$Risco = \sum (TR) * \left\{ Vuln * \frac{[(h * P_1) + (Dens\ Pop * P_2) + (Dens\ Dom * P_3)]}{\sum P} \right\} \quad (2)$$

Where:

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TR is the recurrence time (years) of the floods, being represented by the following probability rates:

Vuln is the vulnerability typology (values between 0 to 1);

h is the flood height (m);

Dens are the population and household densities;

P_1,P_2 e P_3 are the weights attributed to the risk calculation, respectively, 2, 5 and 3.

This way, risk maps were produced using ArcGIS software, using the risk equation presented in this sub item, which crosses the vulnerability information of current land use, flood height, and the population and household densities. The classification of the degree of risk occurred in the very high, high, medium and low classes, as shown in **Table 3** below.

Table 3. Vulnerability values attributed to land uses.

Probability Level	Description
Very High Risk	Drainage or drainage compartments subject to processes with high potential to cause damages, mainly social, high frequency of occurrence (at least 3 significant events in 5 years) and involving high vulnerable households.
High Risk	Drainage or drainage compartments subject to processes with high potential to cause damages, average frequency of occurrence (1 significant occurrence registered in the last 5 years) and involving high vulnerable households.
Medium Risk	Drainage or drainage compartments subject to processes with average potential to cause damages, average frequency of occurrence (1 significant occurrence registered in the last 5 years).
Low Risk	Drainage or drainage compartments subject to processes with low potential to cause damages, low frequency of occurrence (no occurrence registered in the last 5 years).

Source: Brazil, 2007.

4. RESULTS AND DISCUSSION

4.1 Hydrodinamic model

The results presented here were obtained using the IBER hydrodynamic model, which aimed to simulate flood spots in the municipality of Quebrangulo, in the State of Alagoas, for events with recurrence times of 5, 10, 25, 50 and 100 years, considering two different scenarios, with and without the P1 and P2 dams.

We considered the urban stretch of the municipality of Quebrangulo in hydrodynamic modeling, taking into account that the goal of this work is to map the risk areas as a function of the flood effects in the municipality. For safety reasons, we used the maximum flows in the simulations, which are summarized in **Table 4** below.

Table 4. Flow rates used to determine flood spots.

Recurrence time (years)	Flow rate (m³/s) for scenarios	
	With dams	Without dams
5	28,1	188,0
10	36,9	237,0
25	85,9	299,0
50	112,6	345,0
100	145,0	391,0

Source: Authors' study.

The results obtained in the hydrodynamic modeling are summarized in **Table 5**. It is possible to observe that the flooded area for the scenario with the dams, for the flood rate related to the 100 year recurrence time was 185,348.46m², which meant an estimated number of 341 inhabitants and 108 households directly affected by the flood. For the scenario without buses, we can observe that, for the same recurrence time, the flooded area was 413,481.27m², which resulted in an estimate of 883 people and 273 households affected by the flood.

In addition, it's relevant to mention that the number of residences and inhabitants estimated in the studied area to be affected by the floods, referring to the recurrence times of 5, 10, 25, 50 and 100 years, are much higher for the scenario without the P1 and P2 dams, surpassing up to 3.3 times the scenario with dams, as can be observed in the 10-year recurrence time.

The population and households affected by the floods were estimated multiplying the flooded area, obtained through the hydrodynamic model, by the population and household densities, determined for each census sector, as presented in sub-item 3.3.

Figure 6 and **Figure 7** present a synthesis map with the flood spots generated by the IBER hydrodynamic model, for the flow rates corresponding to the Recurrence Times of 5, 10, 25, 50 and 100 years, in the scenario with and without the P1 and P2 dams, respectively.

4.2 Risk maps

The risk maps were developed with the purpose of

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identifying the sites that present flood risk for the urban population of the municipality of Quebrangulo. To do so, we designed the risk maps for two different scenarios, as presented below.

The results obtained using the flood risk formula in the study area are presented in **Figure 8** and **Figure 9**. The values found for the risk were divided into four categories, as shown in **Table 6**, which shows the affected area for each risk level.

We can observe that much of the mapped area was classified as low risk of flooding for both scenarios. The area to be affected was higher in the scenario without the dams, being 6.79 and 1.53% for the “high” and “very high” risk levels, respectively.

We also verified that the area identified with risk of flooding, for the scenario without the P1 and P2 dams was almost three times bigger than the results found for the scenario with the dams. The areas classified with high and very high risk levels of flooding were much superior in the scenario without dams, surpassing in more than ten times the area of the other.

We were able to estimate the number of people and households that are included in the sites categorized as flood risk areas based on the cross-referencing of population density and household information with the risk map,

We can observe that in the scenario with no dams, the number of people and households estimated to be within the area classified as at flooding risk was 382 and 121, respectively. For the scenario with the dams, it was estimated that 138 people and 45 households are in areas categorized as flood risk.

Of this total, we can see that, for the scenario with dams, 99% of the estimated population is located in the area classified as low risk. In the scenario without the dams, this total was approximately 92%.

The number of inhabitants estimated in areas marked as with high and very high risk of flood were, in the scenario without P1 and P2, of 22 and 10 inhabitants respectively, whereas, for the scenario with the dams, for both risk levels, was only 1 inhabitant.

5. CONCLUSION

The digital elevation model elaborated based on 1-by-1-meter level curves was considered a great option for the construction of the topobathimetric mesh and, later, for the modeling proposed in this study, due to the lack of more precise data about the studied area.

The IBER hydrodynamic model, used in this study to simulate flood spots, was efficient, considering that it is two-dimensional and uses the complete equations of Saint-Venan. However, We recommend fieldwork to be carried out in order to determine the flows and water level in known sections to calibrate the hydrodynamic model.

The hydrodynamic simulations showed that the Paraíba riverbed is not prepared to withstand floodflows, since the flood spots generated by the model reached regions with residences, thus bringing risk to the resident population of such area. As expected, larger flood spots occurred for the flow rates associated with longer recurrence times.

The analysis of land usage by images of high resolution and *Google Earth* software proved an efficient solution. However, fieldwork is recommended, as it is possible to identify with it areas where recent changes have been made, such as housing construction.

The methodology used to determine the flood risk area was a good tool for municipal management, since it considered the height of the water table, the vulnerability and the population and household densities in its calculation to estimate the risk level in each site.

Table 5. Results obtained by modelling.

Recurrence time (years)	With P1 and P2 dams			Without P1 and P2 dams		
	Area (m2)	Population	Households	Area (m2)	Population	Households
5	84.700,81	141	44	215.255,37	395	124
10	91.588,47	153	48	256.282,25	510	160
25	143.768,73	254	81	341.879,61	715	222
50	160.335,29	287	91	373.831,78	782	243
100	185.348,46	341	108	413.481,27	883	273

Source: Authors’ study.

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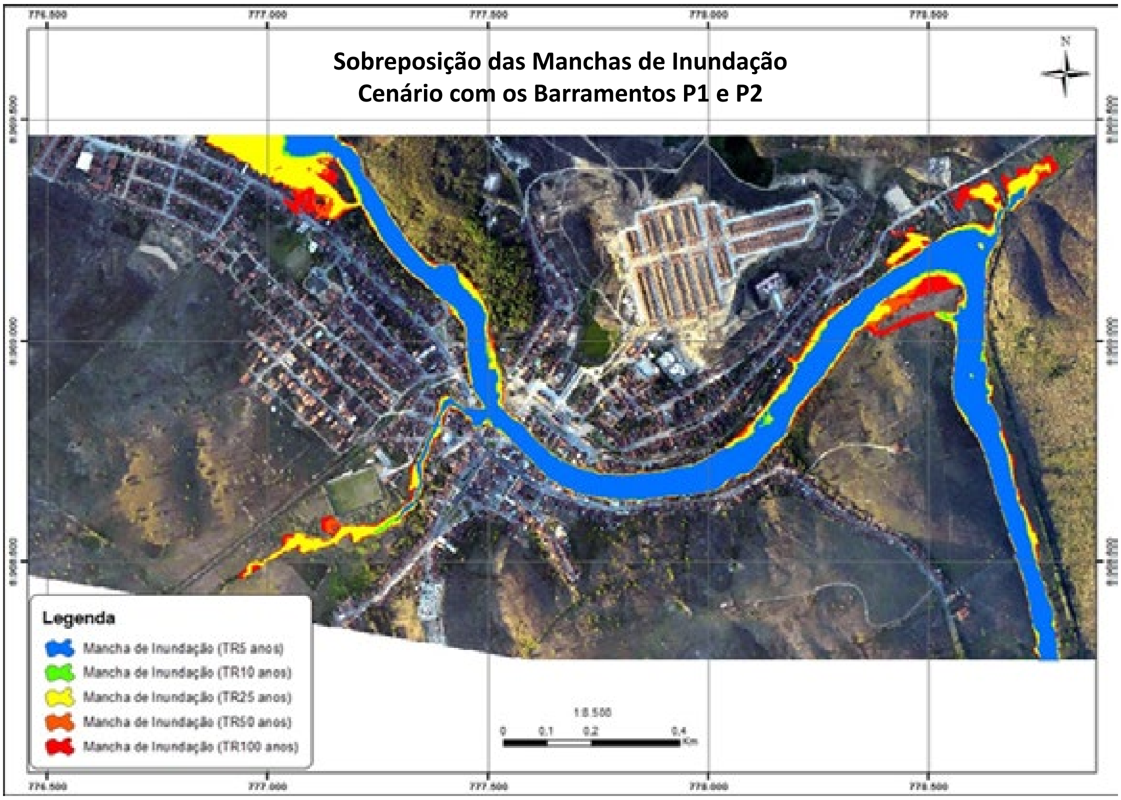

Figure 6. Flood spots for flow rates corresponding to several Recurrence Times, scenario with dams.

Source: Authors' study

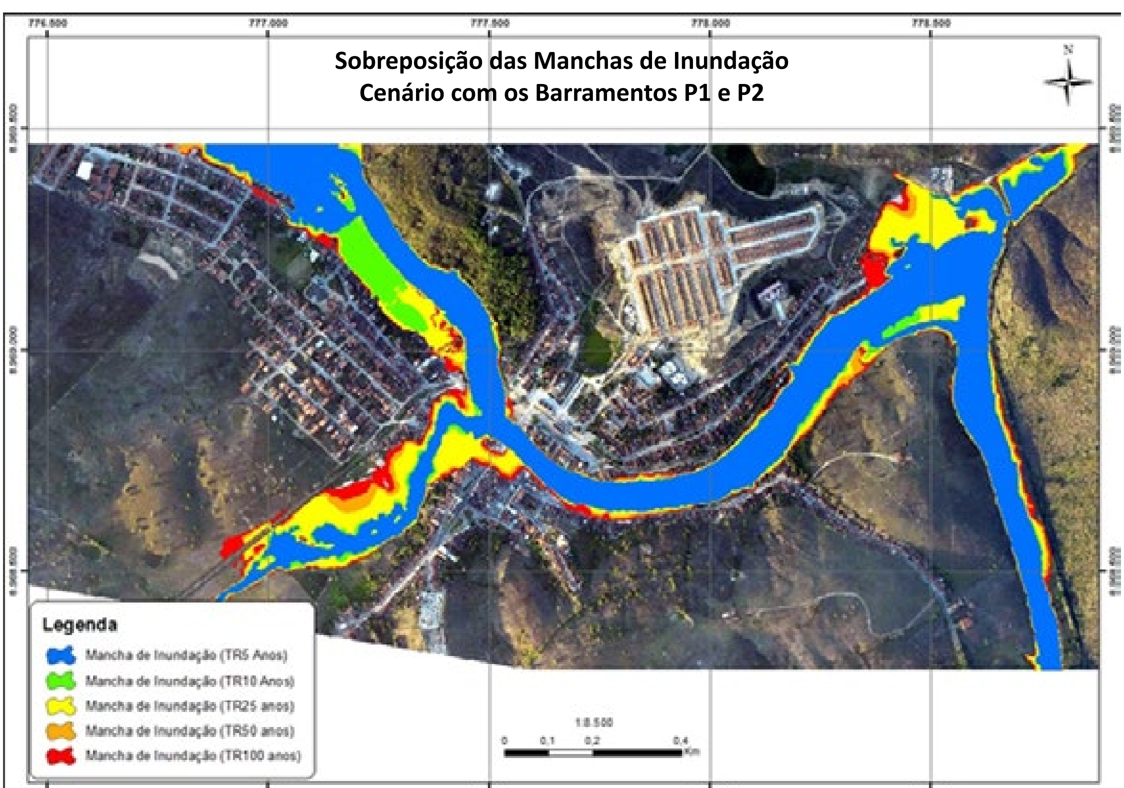

Figure 7. Flood spots for flow rates corresponding to several Recurrence Times, scenario without dams.

Source: Authors' study.

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We were able to confirm with the risk mapping that the riverine population is the most affected group by flood problems, mainly due their location on the banks of the Paraíba river, in the areas that riparian forests should exist.

We concluded that the dams are important tools to mitigate the effects of floods in the urban area of the municipality, because, as shown, the risk area for the scenario with the dams was almost three times lower than the areas categorized as risky in the other. In addition, we can conclude that the number of people and households in the flood risk areas for the scenario without the dams was significantly higher.

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Table 6. Flood risk level and estimates of people and households in the area at risk.

Risk level	Values	With dams			Without dams		
		Area (m²)	Population	Households	Area (m²)	Population	Households
Low	0 – 187	56,714.35	136	43	147,022.91	350	111
Medium	187 - 375	0.00	0	0	46.58	0	0
High	375 - 750	717.73	1	1	10,896.77	22	7
Very High	> 750	292.62	1	1	2,447.60	10	3
Total		57,724.69	138	45	160,413.87	382	121

Source: Authors' study

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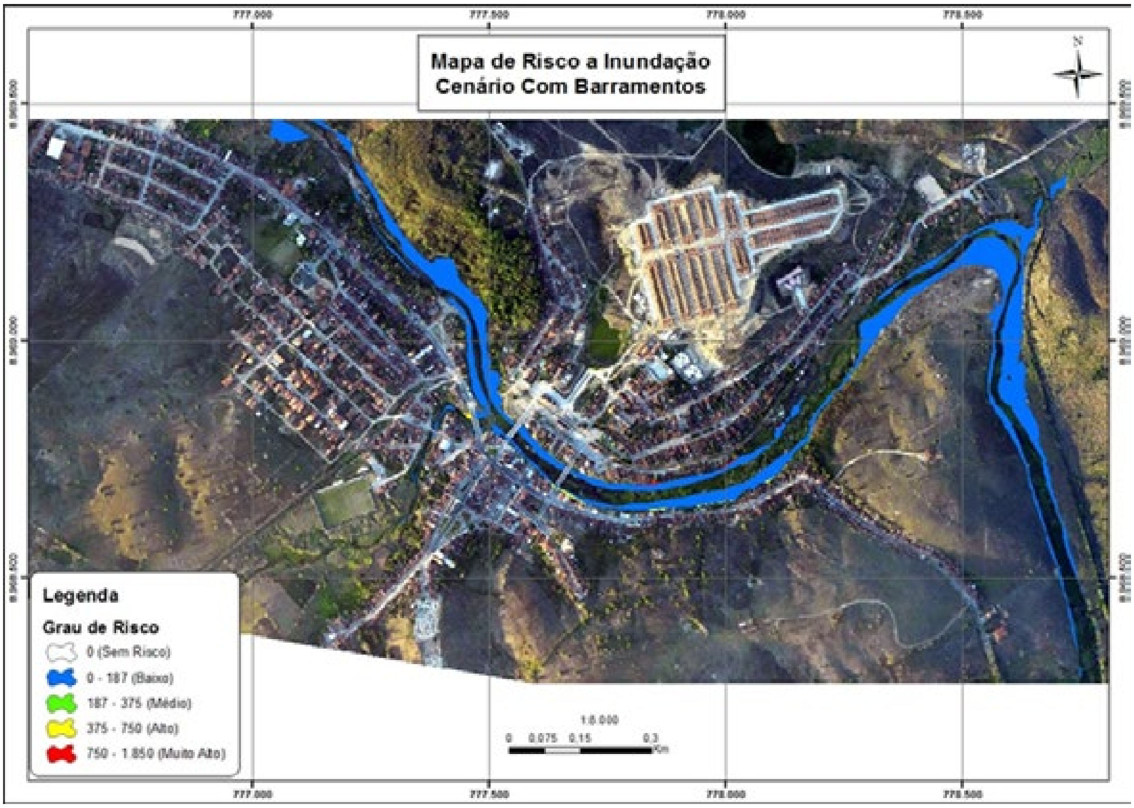

Figure 8. Flood risk mapping for the dam scenario.

Source: Authors' study.

Legend: Risk level: 0 (none); 0 – 187 (low); 187 – 375 (medium); 375 – 750 (high); 750 – 1850 (very high).

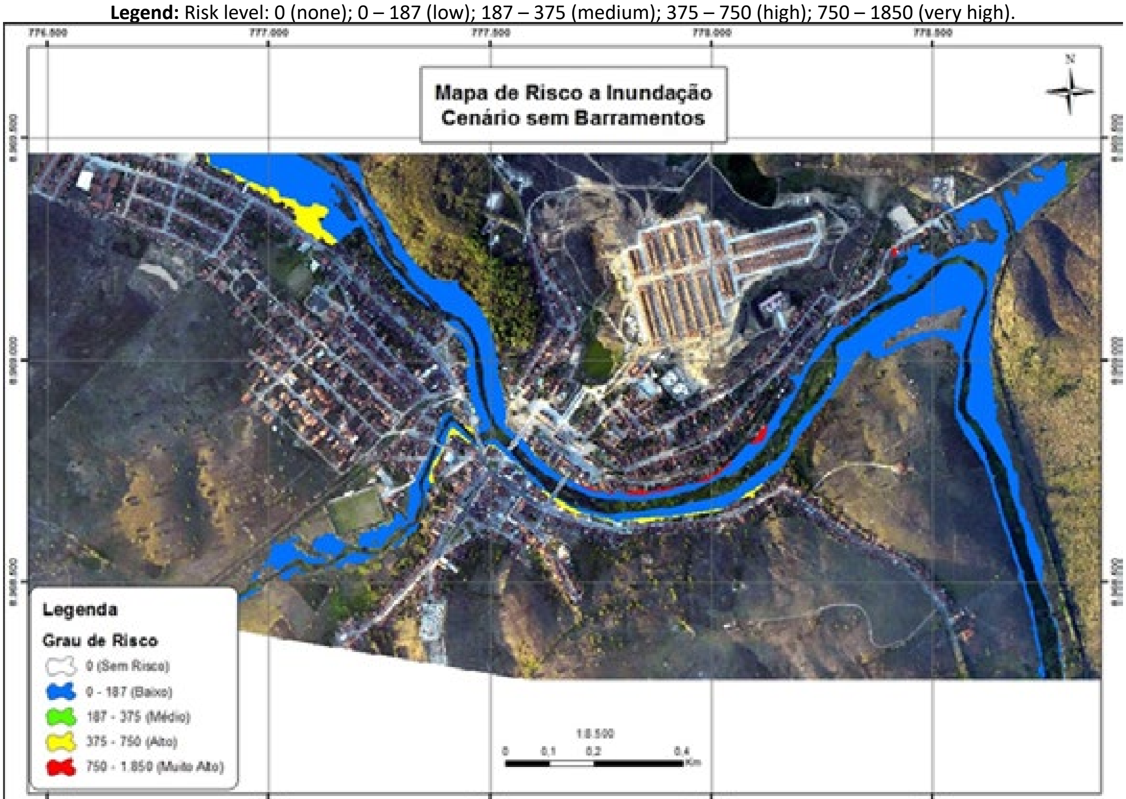

Figure 9. Flood risk mapping for the scenario without dams.

Source: Authors' study.

Legend: Risk level: 0 (none); 0 – 187 (low); 187 – 375 (medium); 375 – 750 (high); 750 – 1850 (very high)

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