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FLOOD RISK INDEX MAPPING OF AN AREA DOWNSTREAM OF A DAM IN CASE OF A BREAK

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Abstract

We aimed to evaluate the flood risk index due to the hypothetical break of the São Bento dam (SC, Brazil). The risk index was obtained by combining the hazard and vulnerability indices. The hazard index was obtained by multiplying the velocity by the depth of the water, simulated with HEC-RAS 2D. The simulated flood extent was 64.8 km², with a maximum flow of 3586.60 m³·s-1, a depth of up to 2.0 m, and a velocity of up to 2.0 m·s-1 in most of the area. The formation of the breach occurred in 2.85 h, and the peak flow occurred at 1.67 h. The volume that overflowed with the break was 44.75 hm³. The flood wave reached 22.0 km in length, where the municipality of Forquilhinha is located. The risk index map showed that the risk is high up to 6 km from the dam since most people were at least 60 years old and had low incomes. In this location, the people were not safe inside buildings because they had a high probability of being destroyed. Thus, risk mapping may be adopted as a preventive measure to assist in preparing an emergency action plan and serve for environmental education and territorial planning.

Keywords: Dam Break; HEC-RAS 2D; Risk Mapping.

Resumo / Resumen

MAPEAMENTO DE ÍNDICE DE RISCO DE INUNDAÇÃO DE ÁREA A JUSANTE DE UMA BARRAGEM EM CASO DE ROMPIMENTO

Objetivou-se avaliar o índice de risco de inundação, devido ao rompimento hipotético da barragem de São Bento (SC). O índice de risco foi obtido combinando os índices de perigo e de vulnerabilidade. O perigo obteve-se multiplicando a velocidade pela profundidade da água, simuladas com HEC-RAS 2D. A mancha de inundação simulada foi de 64,8 km², a vazão máxima de 3586,60 m³.s-1, profundidade de até 2,0 m e velocidade de até 2,0 m.s-1, na maior parte da área. A formação da brecha aconteceu em 2,85 h e o pico de vazão ocorreu em 1h40 min. O volume extravasado no rompimento foi de 44,75 hm³. A onda de cheia atingiu 22,0 km de extensão onde fica o município de Forquilhinha. O mapa de índice de risco mostrou que até 6 km da barragem o risco é alto, devido a maioria das pessoas terem 60 anos ou mais e serem de baixa renda. Nesse local, as pessoas não estão seguras dentro das edificações, porque têm alta probabilidade de serem destruídas. Assim, o mapeamento de risco pode ser adotado como medida de prevenção, auxiliar na elaboração de um plano de ação emergencial, servir para educação ambiental e para o planejamento territorial.

Palavras-chave: Rompimento de Barragem; HEC-RAS 2D; Mapeamento de Risco.

MAPEO DEL ÍNDICE DE RIESGO DE INUNDACIÓN DE UN ÁREA AGUAS ABAJO DE UNA PRESA EN CASO DE FALLA

El objetivo fue evaluar el índice de riesgo de inundación, debido a la hipotética ruptura de la represa de São Bento (SC). El índice de riesgo se obtuvo combinando los índices de peligrosidad y vulnerabilidad. El peligro se obtuvo multiplicando la velocidad por la profundidad del agua, simulada con HEC-RAS 2D. El punto de inundación simulado fue de 64,8 km², el caudal máximo fue de 3586,60 m³.s-1, profundidad de hasta 2,0 m y velocidad de hasta 2,0 m.s-1, en la mayor parte del área. La brecha se produjo en 2,85 h y el pico de flujo se produjo en 1h40 min. El volumen fugado en la ruptura fue de 44,75 hm³. La ola de inundación alcanzó 22,0 km de longitud donde se ubica el municipio de Forquilhinha. El mapa de índice de riesgo mostró que hasta 6 km de la represa el riesgo es alto, debido a que la mayoría de las personas tienen 60 años o más y son de bajos ingresos. En este lugar, las personas no están seguras dentro de los edificios, debido a que tienen una alta probabilidad de ser destruidos. Así, el mapeo de riesgos puede ser adoptado como medida preventiva, auxiliar en la elaboración de un plan de acción de emergencia, servir para la educación ambiental y la planificación territorial.

Palabras-clave: Falla de Presa; HEC-RAS 2D; Mapeo de Riesgos.

INTRODUCTION

Dams are structures built transversely to the flow direction of a river with the purpose of creating an artificial reservoir for water storage with proper safety. They are important for society because they provide multiple uses for the water (power generation, water supply, flood control, irrigation, leisure, etc.) and lead to the economic and social development of municipalities, regions, and countries (MONTE et al., 2017; ARAUJO et al., 2019). However, dams may have flaws in their structure, thus being a potential risk for the population that occupies the downstream areas (LAURIANO, 2009). At the time of a dam break, the resulting flows and water levels are usually higher than the maximum natural levels of the downstream section, affecting material assets and populations that are considered safe from flooding (COLLHISHONN & TUCCI, 1997; MARANGONI et al., 2017).

In Brazil, for example, an average of eight disasters involving dams occur annually due to partial or total break of the structure and mainly to extreme rainfall events. From 2011 to 2020, 83 accidents were recorded (ANA, 2021). Discussing the magnitude of disasters caused by dam breaks in Brazil and globally, Armada (2021) and Silva (2021) highlighted the environmental impacts, material damage, economic losses, and the severity of these disasters due to the loss of human lives.

Therefore, the evaluation and monitoring of dams are paramount for maintaining the integrity of the structures and operations and ensuring the safety of the downstream population. Thus, the construction of a dam must strictly follow the standards required by law, in addition to the constant monitoring of the structures after their construction (ANA, 2018). In this regard, Law No. 12334/2010, which established the Brazilian National Dam Safety Policy (PNSB), requires an emergency action plan (EAP) for certain dams (BRASIL, 2010). In the preparation of the EAP, hydrological and hydrodynamic models may be used to estimate the areas likely to be flooded due to the flood wave originating in the event of a dam break, affecting the population, facilities, infrastructure, and the downstream valley environment (ANA, 2016). These models allow the characterization of the flooding hazard due to the possible dam breaks. Based on these models, it is possible to draw up an emergency action plan and estimate the depth of the water and the arrival time of the flood wave downstream of the dam (XIONG, 2011).

Currently, there are several hydrodynamic models to simulate a dam break, such as the HEC-RAS (USACE, 2016), FLDWAV (NWS, 1998), and BOSS DAMBRK (BOSS INTERNATIONAL, 1999), among which the River Analysis System (HEC-RAS) is the most used. This model was developed by the Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers (USACE) and allows the numerical simulation of the propagation of one-dimensional and two-dimensional constant flow in river channels using the equations proposed by Saint-Venant for situations of permanent and turbulent flow (USACE, 2016). Several studies have used this model to simulate dam breaks. In the world, HEC-RAS has been used, for example, by Xiong (2011), Jung & Kim (2017), and Leoul & Kassahun (2019). In Brazil, it has been used by Kuhlkamp (2016), Mota (2017), and Ferla (2018), thus being a very useful tool to evaluate dam safety.

The occasional break of a dam can bring catastrophic, often irreparable consequences, such as environmental damage, financial losses, and the loss of human lives (VEIZAGA et al., 2017). Therefore, dams must be classified according to the consequences of a break and the potential damage considering the social, environmental, structural, and economic aspects (BRASIL, 2010).

In this context, risk mapping is an important tool for analyzing areas subject to a flood risk because, through the map, it is possible to establish preventive measures regarding the possible emergency situations that may occur, as well as to carry out planning of the occupation of areas subject to flooding (BRITO, 2017).

The risk represents the possibility of loss to an inhabited region at a given time due to the presence of a hazard. Risk is commonly defined as a function of the hazard and vulnerability (WISNER et al., 2004; UNISDR, 2016; MONTE et al., 2021). Goerl et al. (2012) proposed a method for mapping the flood risk index through the estimated hazard and the vulnerability index. Monte et al. (2017) also used different methodologies to calculate the flood hazard index and, together with the vulnerability index, estimated the risk index of flooding due to the break of the Lomba do Sabão dam in Porto Alegre, RS, Brazil.

The hazard may be defined as the possible action of an event that occurs at known times and regions that may cause serious socioeconomic damage to the exposed communities (UNDP, 2004; UNISDR, 2016; MONTE et al., 2021). The mapping of the flood hazard represents the distribution of potential consequences of a flood, thus being a good alternative to improve the management of floodable areas. Using hazard indicators and categories for more detailed mapping is practical and useful (MONTEIRO et al., 2021). For example, Neto et al. (2016) proposed a hazard mapping methodology using water depth, flow velocity, energy load, flow force, and intensity indicators. In turn, Stephenson (2002) and Smith et al. (2014) used water depth and velocity as indicators for the hazard index, with these typically being used for hazard mapping.

Vulnerability refers to the conditions determined by physical, social, economic, and environmental factors or processes that increase the susceptibility of an individual, community, property, or system to the impacts of hazards (KOHLER et al., 2004; UNISDR, 2016; MONTE et al., 2021). Moreira & Kobiyama (2021) analyzed 21 Brazilian studies on vulnerability indices and found that most studies used the indicators obtained from the 2010 census conducted by the Brazilian Institute of Geography and Statistics (IBGE), with the most used indicators being the per capita income, number of households with bathrooms without sewage, demographic density, number of households with or without water supply in the network, and precarious private households. Andrade et al. (2017) and Debortoli et al. (2017) calculated the vulnerability index on a municipal scale. In turn, Marcelino et al. (2006), Goerl et al. (2012), and Reis et al. (2016) used indicators based on the socioeconomic characteristics of the census tracts of the municipality conducted by IBGE.

The São Bento River Dam is located in the municipality of Siderópolis in the state of Santa Catarina, inserted in the São Bento River basin. In this basin, some studies have already been conducted to evaluate the impacts of the construction of the dam. For example, Ming (2007) developed a computational system for predicting floods in the region downstream of the dam using the HEC-RAS model to simulate three flood scenarios (2006 rainfall event and return periods of 100 and 1000 years). Schwalm (2008) also compared the project volume of the São Bento River Dam reservoir with the volumes obtained in the field using geoprocessing tools.

In this context, the present study aimed to evaluate the flood risk index estimated according to a flood hazard index and a vulnerability index considering the hypothetical break of the São Bento Dam in the south of Santa Catarina.

STUDY AREA

The study area was the downstream section of the São Bento River Dam, located in the São Bento River sub-basin (157.40 km²), which is part of the Araranguá River Basin (3089 km²), in the south of Santa Catarina (Figure 1). The dam receives the contribution of two main rivers: the São Bento River and the Serrinha River. Downstream of the dam are the communities of São Bento Alto (149 inhabitants) and São Bento Baixo (786 inhabitants), which are 6.5 km and 15.5 km away from the dam, respectively. These communities belong to the municipality of Nova Veneza (13309 inhabitants) (IBGE, 2010). Due to the distance from the dam, these two communities are subject to potential damage caused by a possible dam break. Thus, due to the existence of these downstream communities and the large volume of the reservoir (68.10 hm³), the São Bento River Dam was classified, according to ANA (2021), as medium risk, yet with high associated potential damage.

According to the Köppen classification, the basin region has two climatic subtypes: Cfa (humid mesothermal subtropical with hot summers) and Cfb (humid mesothermal subtropical with cool summers) (ALVARES et al., 2014). The average total annual rainfall of this region is 1694 mm, with a total annual average of 115 days of rain, having an average annual relative humidity of 82% (BACK, 2020; BACK & POLETO, 2018).

The native vegetation cover of the São Bento River basin belongs to the Dense Ombrophilous Forest formation (Atlantic Forest Domain). However, according to Costa (2008), the primary native forest was practically replaced by secondary vegetation; the deforestation areas, mainly downstream of the dam, were replaced by rice, bean, tobacco, cassava, and maize crops. This region still has isolated patches of native forest and medium-sized vegetation. In turn, upstream of the dam, on the slopes of the

Serra Geral, the vegetation is predominantly forest, with some areas with low vegetation and temporary crops. The relief of the region upstream of the São Bento River Dam is formed by the foothills of the Serra Geral, with steep shoulders in a "V" shape, presenting large basaltic escarpments cut by deep valleys. The drainage in this region is considered young, with rapids and stretches of a high slope, having a difference of 1280 m between the most elevated part and the dam structure (CASAN, 2004). Downstream of the dam, the relief is an alluvial plain, with formation characteristics in a lake environment, composed of several layers of rolled pebbles (MING, 2007) from the rocks of the Serra Geral.

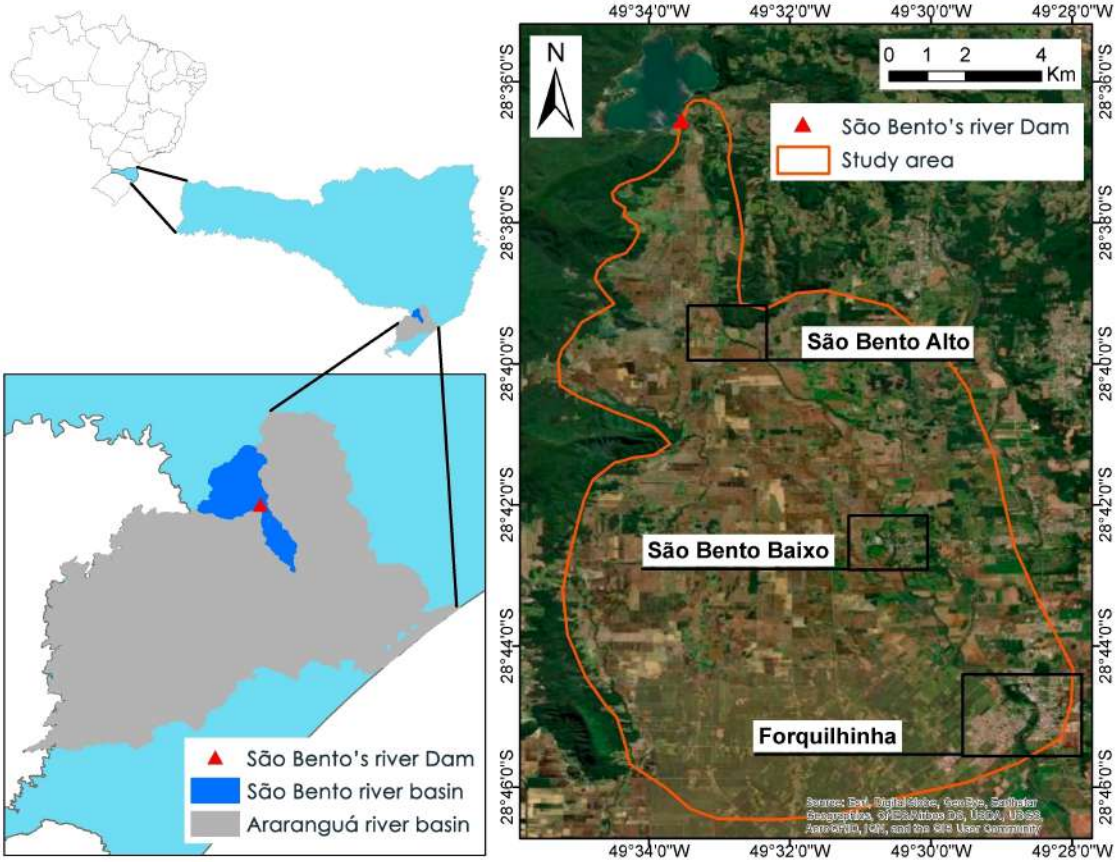

Figure 1 - São Bento's River Dam location in the south of Santa Catarina.

The São Bento River Dam has a total length of 476 m, and the central part is 240 m long and was built of gravity-type roller-compacted concrete. In turn, the shoulders were built with backs in compacted gravel and an impermeable clay core, extending 128 m and 108 m on the left and right banks, respectively (Figure 2). The maximum elevation to the foundation is 49 m, with 38 m over the riverbed (CASAN, 2004).

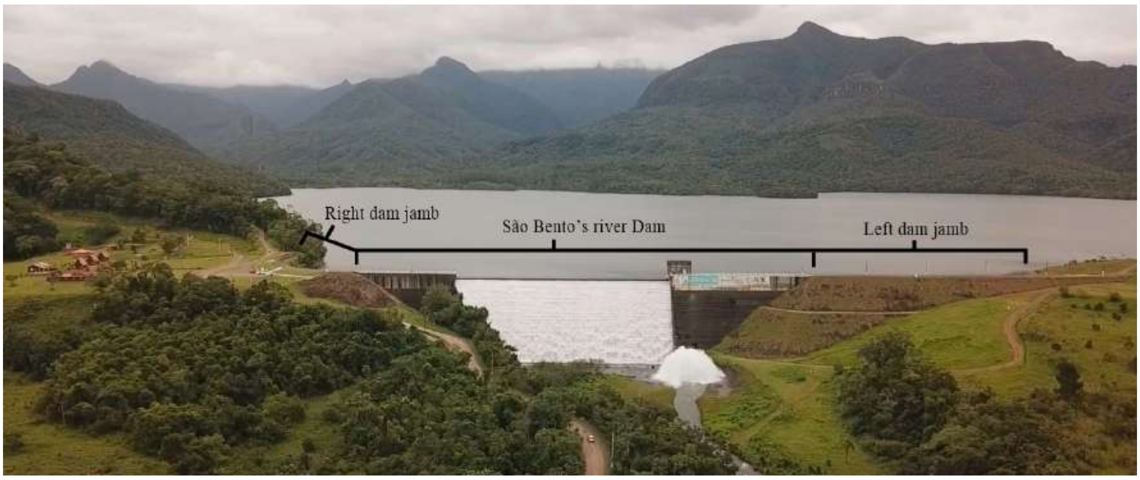

Figure 2 - São Bento River Dam's photo.

MATERIALS AND METHODS

To evaluate the flood risk of the area downstream of the São Bento River Dam, the following were used: (i) the HEC-RAS 2D hydrodynamic model to simulate the dam break due to the formation of the breach and for the propagation of the flood wave; (ii) the hazard index proposed by Stephenson (2002); (iii) the vulnerability index based on the methodology proposed by Goerl et al. (2012).

HYDRODYNAMIC MODEL

For the dam break simulation in the HEC-RAS 2D model, the main input data required (USACE, 2016; TSCHIEDEL, 2017) were: (i) the topography of the area downstream of the dam; (ii) parameters of breach configurations; (iii) hydrological data (reservoir volume and level); (iv) Manning coefficient (n); (v) equation for wave propagation.

For the propagation of the wave downstream of the dam, a Digital Elevation Model (DEM) with a spatial resolution of 1.0 m × 1.0 m from the State Department for Sustainable Economic Development (SDE), obtained in the Geographic Information System (SIGSC) was used as topographic data (SDE, 2013). To simulate the flood wave due to the dam break, the maximum normal reservoir level of 157.5 m was adopted, which corresponds to the threshold of the spillway. This level corresponds to an accumulated volume of 58.2 hm³, a flooded area of 4.5 km², and an initial flow of 29.8 $m^3 \cdot s^{-1}$. These data were obtained from the risk management report of the São Bento Dam provided by the Companhia Catarinense de Águas e Saneamento (CASAN, 2004).

In the propagation of the flood wave, the Saint-Venant 2D equations were used, which, according to USACE (2016), constitute the equations of conservation of mass (Equation 1) and conservation of momentum in the X and y axes (Equation 2 and 3).

$$\frac{\partial H}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} + q = 0$$

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

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

where H is the elevation (altitude) of the water surface (m), h is the water depth (m), u and v are the velocities in the Cartesian directions ($m \cdot s^{-1}$), t is the time (s), q represents the flow contributions or abstractions ($m3 \cdot s^{-1}$), vt is the coefficient of turbulent viscosity ($m^2 \cdot s^{-1}$), cf is the coefficient of friction (dimensionless), f is the Coriolis parameter (s^{-1}), and g is the gravitational acceleration (9.80665 $m \cdot s^{-2}$). These parameters were calculated by the HEC-RAS 2D model as the flood wave advanced towards the valley downstream of the dam.

In the present study, for the propagation of the flood wave in the model, the following parameters were used as boundary conditions: (a) the maximum normal level of 157.5 m and the volume of the reservoir of 58.2 hm^3 for the stretch upstream of the reservoir; (b) an average slope of 0.00448 $m \cdot m^{-1}$ determined in the floodplain of the stretch downstream of the dam. The latter was determined by the DEM through the average of points (altitude) between the dam and the end of the computational mesh.

To propagate the hydrograph of the dam break, a 136.72 km^2 computational mesh with a spatial resolution of 15 m × 15 m was used for the floodplain to cover the communities of São Bento Alto and São Bento Baixo and the central region of the municipality of Forquilhinha, which are 6.6 km, 15.5 km, and 22 km away from the dam, respectively. For the simulation of the flow propagation, a "non-permanent" flow regime was adopted, with a computational time interval of 15 s, which allowed better stability to the simulation. For this computational time, the interval between 1 s and 60 s suggested by USACE (2014) was considered due to the short rise time of the hydrograph and the very fast flood wave velocity.

MANNING COEFFICIENT

In the simulation of the propagation of the flood wave stemming from a dam break event, according to Tschiedel (2017), the calibration and choice of the value of n is a difficult task because there are no measurements of quota and flow of these magnitudes, with it thus being necessary to use values available in the existing literature. Hence, in this study, the values of n were fitted for the entire computational mesh based on the tables proposed by Chow (1959), considering the different land uses and occupations of the floodplain downstream of the São Bento Dam. The land use and occupation map was obtained from Collection 5 of the Annual Mapping of Land Cover and Use in Brazil project (MAPBIOMAS, 2020), referring to 2019. This map was edited to group the different uses and occupations into four categories. Samples (latitude and longitude) of the types of use and occupation of the region were collected in the field with a Garmin ETrex 30x GPS to verify this map. Hence, the n values adopted for each land use were 0.045 for natural rivers, 0.055 for forests, 0.035 for agricultural and pasture areas, and 0.030 for urbanized areas.

BREACH DATA

In the HEC-RAS model, there are two ways to simulate the formation of a breach: (i) through a simplified physical model of breach evolution; (ii) direct input of data related to the evolution of the breach, such as dimensions, formation time, and breach progression, among others (USACE, 2014). The dam of the present study is made of concrete, and according to Vischer & Hager (1997), the most common type of breach to occur is overtopping. This type of breach may occur due to the large volume of water that arrives in the reservoir that the dam spillway is unable to overflow, considerably increasing the water level (USACE, 2014; TSCHIEDEL, 2017).

It is noteworthy that, in Brazil, although the PNSB contemplates hydrodynamic models to simulate the break of concrete dams, there is no information on the parameters of the formation of the breach or the equations that must be used to calculate the dimensions of the breach. Thus, in the present work, the equations proposed by Froehlich (2008), determined based on 74 dam break data, were used to calculate the average width (Equation 4) and formation time (Equation 5) of the breach. These data consisted of the breach height from 3.05 m to 92.96 m and reservoir volume at the time of the breach from 0.0139 × 106 m^3 to 660 × 106 m^3 (USACE, 2014).

$$B_{média} = 0.27 * k_0 * V_w^{0.32} * h_b^{0.04}$$

$$T_f = 63.2 * \sqrt{\frac{V_w}{g * h_b^2}}$$

where Bavg is the average width of the breach (m), Tf is the formation time of the breach (h), k0 is 1.0 for intubation and 1.3 for overtopping, Vw is the volume of the reservoir at the time of the breach (m^3), and hb is the height of the breach (m). The values of these breach parameters are presented in Table 1.

Data	Value adopted
Breacl Breach width at the base	104 m
Breacl Breach width at the top	134 m
Breacl Breach height	15 m
Breacl Breach slope	45°
Breacl Breach formation time	2.85 h

Table 1 - Characteristics adopted for the breach of the São Bento River Dam. Source: Froehlich (2008).

MAPPING OF THE FLOOD RISK INDEX (RI)

In general, the risk may be measured considering the vulnerability and hazard (GOERL et al., 2012). Hence, to determine vulnerability, eight census variables were selected from the demographic census conducted by the IBGE in 2010 and grouped into six (Table 2). The variables were selected based on the study by Goerl et al. (2012) on flood risk mapping in the municipality of Rio Negrinho in northern Santa Catarina. These variables are related to the demographic, education, dependency, and income characteristics of each census tract.

Number	Census Variables	Number	Vulnerability Variables
1	Number of residents in the tract	1	Number of residents in the tract
2	Average number of residents per household	2	Average number of residents per household
3	Population Density	3	Population Density
4	% of population under 12 years old	4	Sum of the percentage of population over 60 and under 12 years old
5	% of population over 60 years old		
6	% of illiterate people over 12 years old	5	% of illiterate people over 12 years old
7	% of responsible persons without income	6	Sum of the percentage of responsible persons without income and with income up to one time the minimum wage
8	% of responsible persons with income up to one time the minimum wage		

Table 2 - Census variables and variables used to measure vulnerability.

For the present study, the indicators of the census tracts of the 2010 Census were used, which correspond to the smallest territorial unit, with physical limits identifiable in the field, defined by the IBGE. In the definition of the census tracts, three municipalities were considered that cover the area downstream of the São Bento Dam: Siderópolis, Nova Veneza, and Forquilhinha. According to IBGE

(2010), these municipalities are divided into 27, 33, and 47 census tracts, respectively. However, the vulnerability analysis considered the area of the tracts delimited by the computational mesh used in the HEC-RAS 2D to simulate the propagation of the flood (Figure 3).

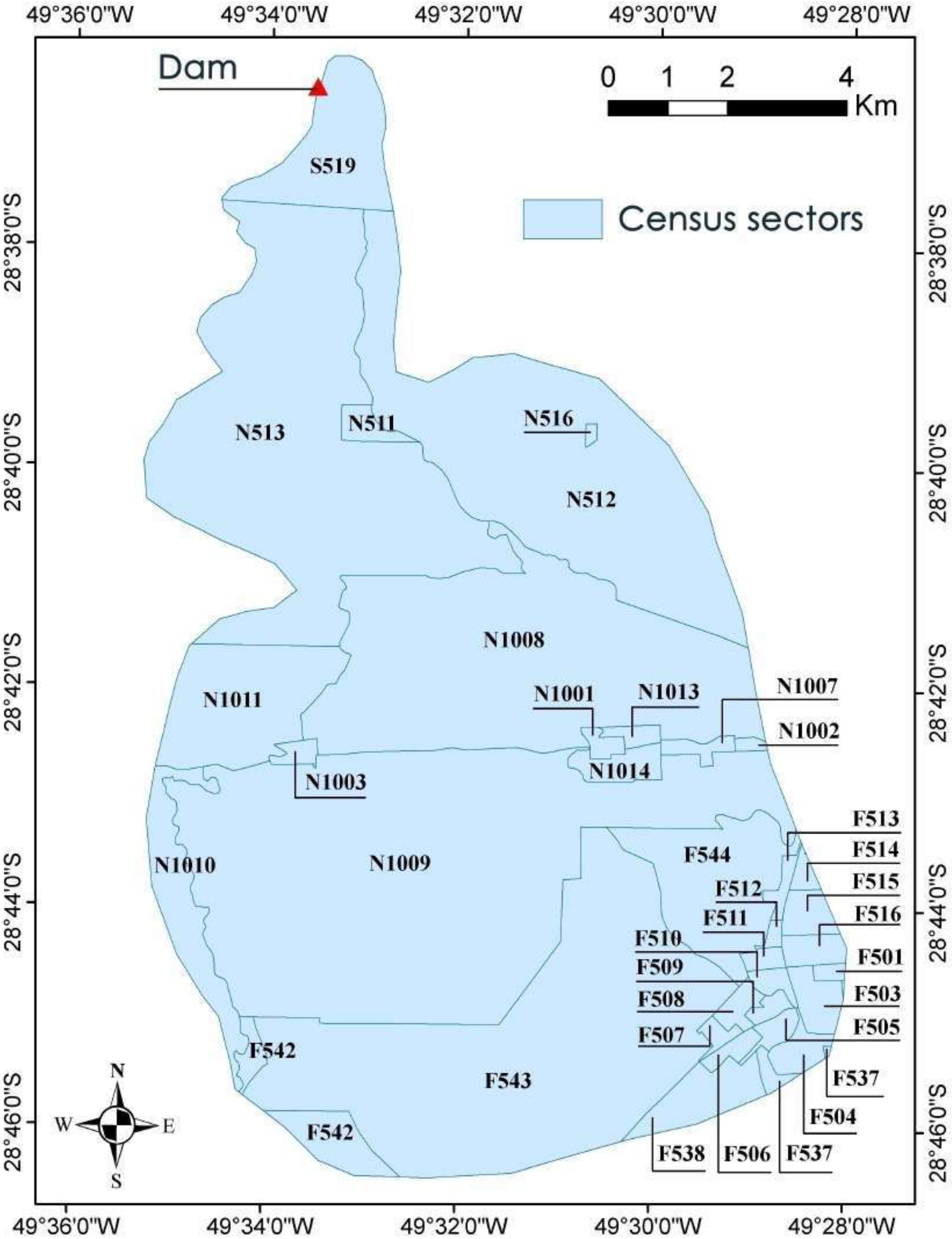

Figure 3 - Census tracts downstream São Bento River's Dam within the computational mesh analyzed in HEC-RAS 2D.

Thus, the vulnerability index (VI) was calculated by Equation (6), proposed by Goerl et al. (2012):

$$VI = \frac{Dd + Nm + Mm + Td + E + R}{MHDI}$$

where Dd is the population density (inhabitants·km^{-2}), Nm is the number of residents in the tract, Mm is the average number of residents per household, Td is the rate of dependence of children (up to 12 years old) and senior citizens (over 60 years old), E is education level (illiterate over 12 years old), R is the income (persons responsible without income or with up to one time the minimum wage), and MHDI is the Municipal Human Development Index.

According to Goerl et al. (2012), vulnerability is inversely proportional to the capacity and preparedness of the municipality to provide a response and support to the hazard event. Thus, the authors point out that, in the face of a disaster, the entire municipality may be affected by a lack of water or electricity, roadblocks, and suspended classes, among other adverse situations. Therefore, the MHDI is considered an index that represents the capacity of the municipality to respond to the disaster that occurred. The MHDI is composed of three indicators: long and healthy life (longevity), access to knowledge (education), and standard of living (income). It is divided into five classes: from 0 to 0.499 (very low), 0.5 to 0.599 (low), 0.6 to 0.699 (medium), 0.7 to 0.799 (high), and 0.8 to 1 (very high) (PNUD, 2013). Hence, the MHDI values of Siderópolis (0.774), Nova Veneza (0.768), and Forquilhinha (0.753) were used as indicators of this capacity for their respective census tracts. In order to standardize the units of the variables in Equation 6, the methodology proposed by Marcelino et al. (2006) was used, in which the value of each variable was calculated as:

$$Ve = \frac{Vo - Vmin}{Vmax - Vmin}$$

where Ve is the staggered value, Vo is the observed value, Vmin is the minimum value, and Vmax is the maximum value. Thus, the values were staggered from 0 to 1, with 1 being the maximum value and 0 being the minimum value.

Hence, the VI was classified into four classes: low, medium, high, and very high. These classes were defined using the Natural Breaks method. This method consists of minimizing the variance within each class, thus creating natural categories of the data within each class that have more homogeneous values (REIS et al., 2016). The hazard index (HI) was calculated by the equation proposed by Stephenson (2002) for a given point in the flooded area:

$$HI = h \cdot v$$

where h is the water depth (m) and v is the flow velocity (m·s^{-1}).

The HI map was generated by the HEC-RAS 2D model with the data obtained by the simulation of the São Bento Dam break This map was characterized using the considerations of Prevene (2001), as shown in Table 3. Thus, the values of the hazard index by Stephenson (2002) were classified as follows: HI from 0.1 m²·s^{-1} to 0.5 m²·s^{-1} for low, HI from 0.5 m²·s^{-1} to 1.0 m²·s^{-1} for the intermediary, and HI over 1.0 m²·s^{-1} for the high.

Hazard Class	Color on the Map	Description
High	Red	People are in danger, whether inside or outside their homes. Buildings have a high chance of being destroyed.
Medium	Orange	People are in danger outside their homes. Buildings may be damaged and destroyed.
Low	Yellow	Low or non-existent possibility of fatalities. Buildings may be damaged.

Table 3 - Flood Hazard Levels.

Finally, based on the indices described above, the risk index (RI) was calculated, expressed by:

$$RI = HI \ x \ VI$$

where HI is the hazard index and VI is the vulnerability index. The final RI map was prepared using the same methodology as the HI map. However, the classes were categorized as high, intermediary, and low using the RI values obtained by Equation 9. The HI, VI, and RI maps were prepared through the ArcGIS 10.8 software using the raster calculator.

RESULTS AND DISCUSSIONS

EXTENT OF THE FLOOD AREA SIMULATED IN THE HEC-RAS 2D

The simulation of the São Bento Dam break with the HEC-RAS 2D resulted in a flood area of 64.8 km², covering several communities downstream of the dam and extensive rice planting areas, as shown in Figure 4. The simulation result shows that the flood wave first reaches the community of São Bento Alto (149 inhabitants), which is 6.5 km from the dam, then São Bento Baixo (786 inhabitants), 15.5 km away, and finally the central region of the municipality of Forquilhinha (22 km away). The first two communities belong to the municipality of Nova Veneza (SC). The following items describe in more detail the vulnerability, hazard, and risk indices that the communities present if the dam breaks.

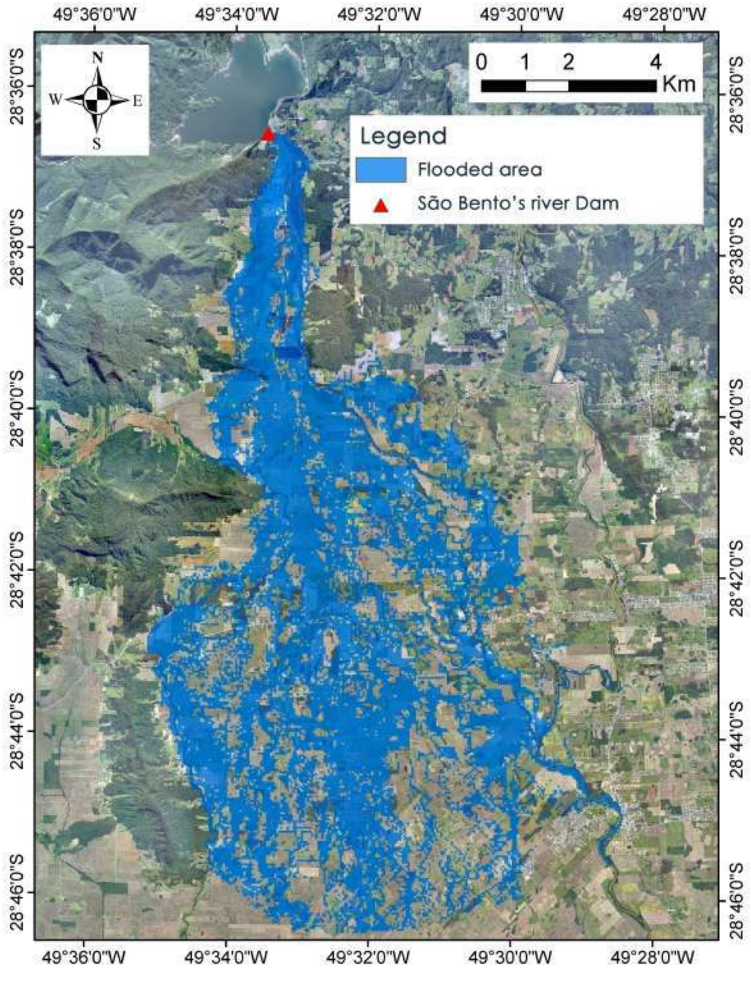

Figure 4 - HEC-RAS 2D simulated flood area.

Figure 5 shows the hydrograph of flow due to the breach simulated in the HEC-RAS 2D, obtained based on the parameters in Table 1. One may observe that the breach formation occurs in an interval of 2.85 hours, and the peak flow, estimated at 3586.60 $m^3 \cdot s^{-1}$ occurred in 1 h and 40 min. The estimated total overflown volume due to the dam break was 44.75 hm³, representing about 79% of the total reservoir volume at the maximum normal level.

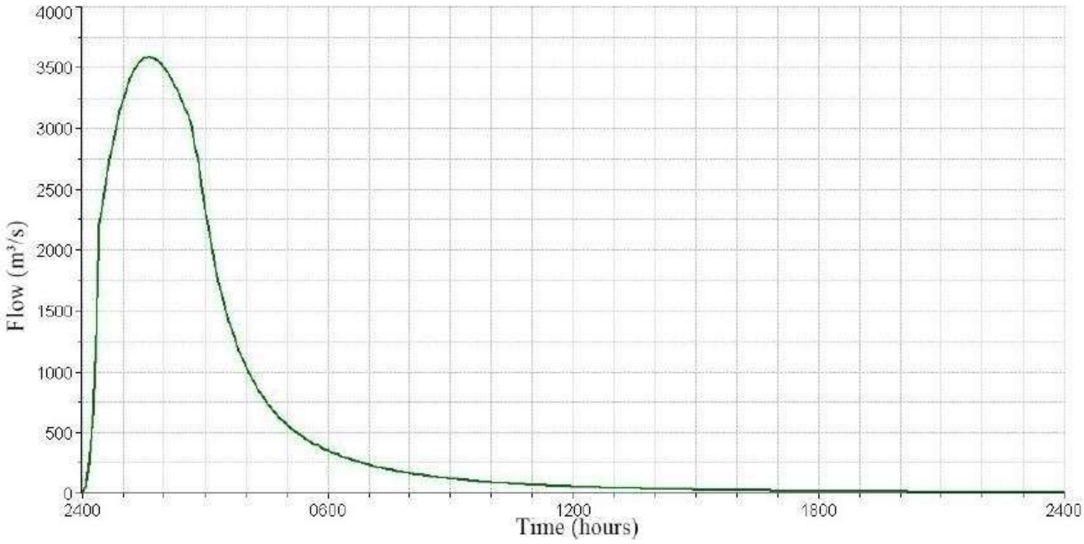

Figure 5 - São Bento's River Dam breach resulting hydrograph simulated in the HEC-RAS 2D.

Figures 6, 7, and 8 show the moment of arrival of the flood wave in the three affected communities. In the community of São Bento Alto, the estimated time of arrival of the flood wave was 55 minutes, with the maximum depth (Figure 6a) and the maximum velocity (Figure 6b) of the water being 0.30 m and 1.7 m·s-1, respectively. In São Bento Baixo, the arrival time of the flood wave was 2 h 45 min, with a maximum depth (Figure 7a) of 0.8 m and a maximum velocity (Figure 7b) of 1.4 m·s-1. In turn, in the central region of the municipality of Forquilhinha, the flood wave arrived in 4 h 30 min with a maximum depth (Figure 8a) of 0.6 m and a maximum velocity (Figure 8b) of 0.8 m·s-1 on the banks of the São Bernardo River.

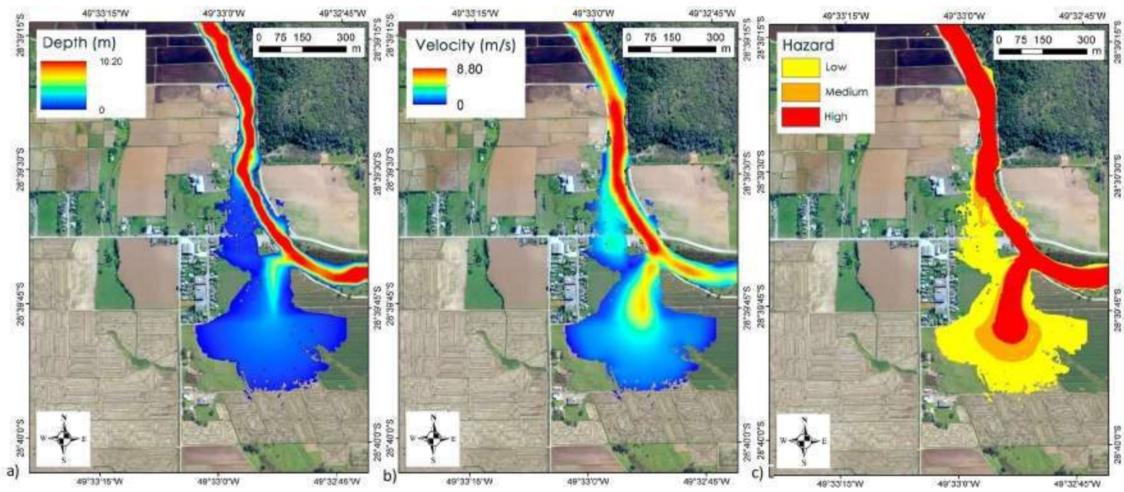

Figure 6 - São Bento Alto's community situation at the wave time arrival: (a) depth; (b) velocity; (c) hazard index.

For the HI calculated at the time of arrival of the flood wave in the communities, obtained by Equation 8 and characterized according to Prevene (2001), it was observed that, in the community of São Bento Alto, the danger is low in the largest area (Figure 6c), but some places present intermediary and high hazard levels, that is, since the arrival of the wave, people are already in danger, inside or outside their homes and with a high possibility of buildings being destroyed. In turn, in the community of São Bento Baixo (Figure 7c) and the central region of Forquilhinha (Figure 8c), the hazard is high only in the river channel, with the hazard being low for the community, so people have a low or non-existent possibility of fatalities, but the buildings may suffer some damage.

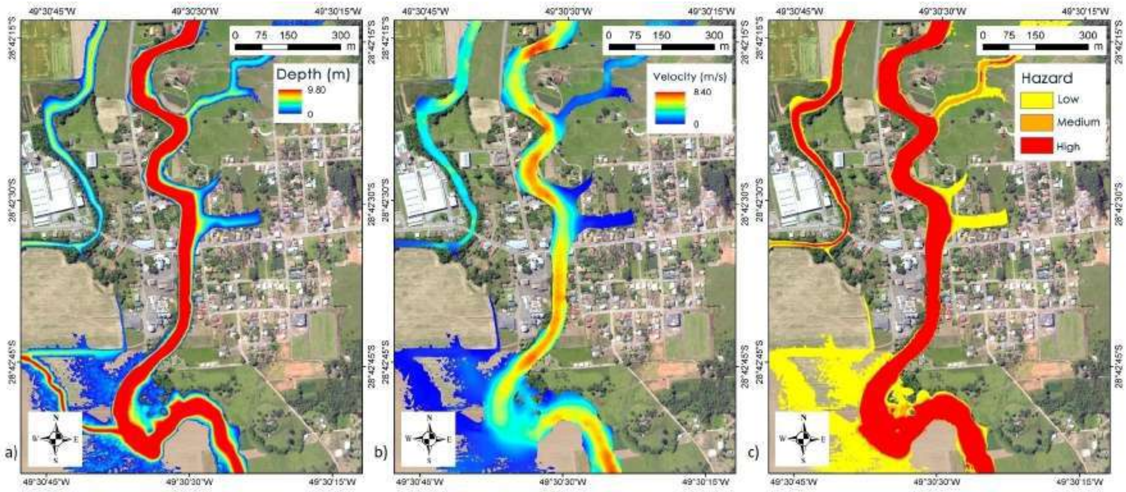

Figure 7 - São Bento Baixo’s community situation at the wave time arrival (a) depth; (b) velocity; (c) hazard index.

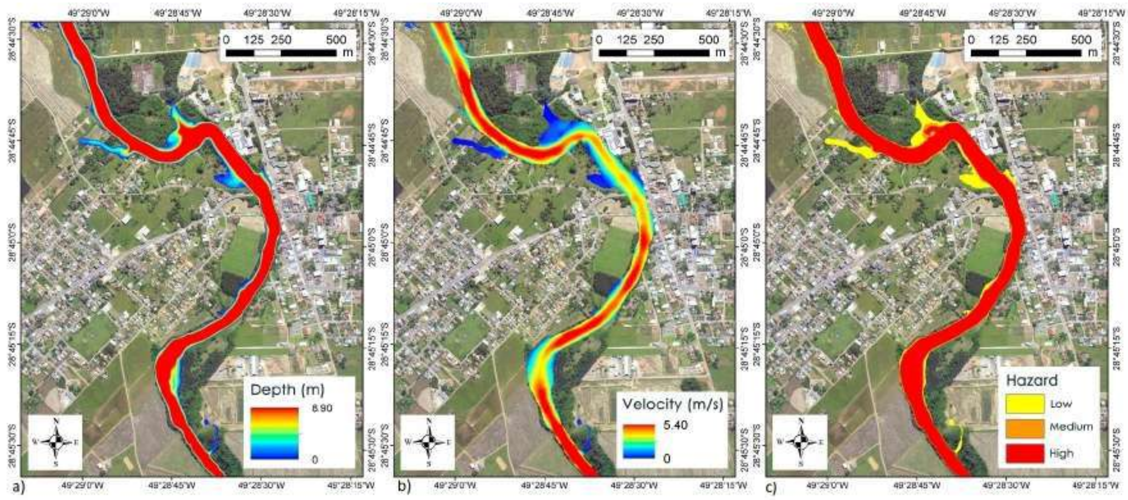

Figure 8 - Forquilinha's community situation at the wave time arrival: (a) depth; (b) velocity; (c) hazard index.

HAZARD INDEX MAP

The flood HI map represents the spatial distribution of the potential damage that the flood wave may cause. Thus, to map the areas with a given flood hazard potential for the area downstream of the São Bento Dam, the HI value was calculated considering the depth and velocity of the flow resulting from the hypothetical dam break, simulated with the HEC-RAS 2D model.

Figure 9 shows the maximum depth and velocity and hazard index maps of the entire flooded area downstream of the dam. It should be noted that, in most of the area, the depth of the water line did not exceed 2 m, and the water velocity was below 2 $m \cdot s^{-1}$, especially in the flatter areas, where irrigated rice plantations predominate. However, in the places closest to the dam (up to 6 km away), the depth reached 12 m, and the velocity was approximately 20 $m \cdot s^{-1}$, just as river channels, especially those stretches with more significant slopes or with the presence of bends, in which the velocities reached 6 $m \cdot s^{-1}$ to 8 $m \cdot s^{-1}$ and the depth from 10 m to 12 m.

As a result of multiplying the depth map by the velocity map, a map was obtained where each pixel represents a HI (Figure 9c). This map was classified into three hazard classes (Table 3). One may observe that the largest flooded area (36.68 m²) was classified as low hazard, representing 56.60% of the total area (Table 4), i.e., the flood wave presented HI values under 0.5 $m^2 \cdot s^{-1}$. According to the classification by Prevene (2001), people in these regions have a low or non-existent possibility of fatalities, but buildings may suffer some damage.

Hazard Level	Area (km²)	Percentage
Low	36.68	56.60
Medium	9.96	15.37
High	18.16	28.02
Total	64.80	100.00

Table 4 - Classification of flood areas in km² for each hazard degree

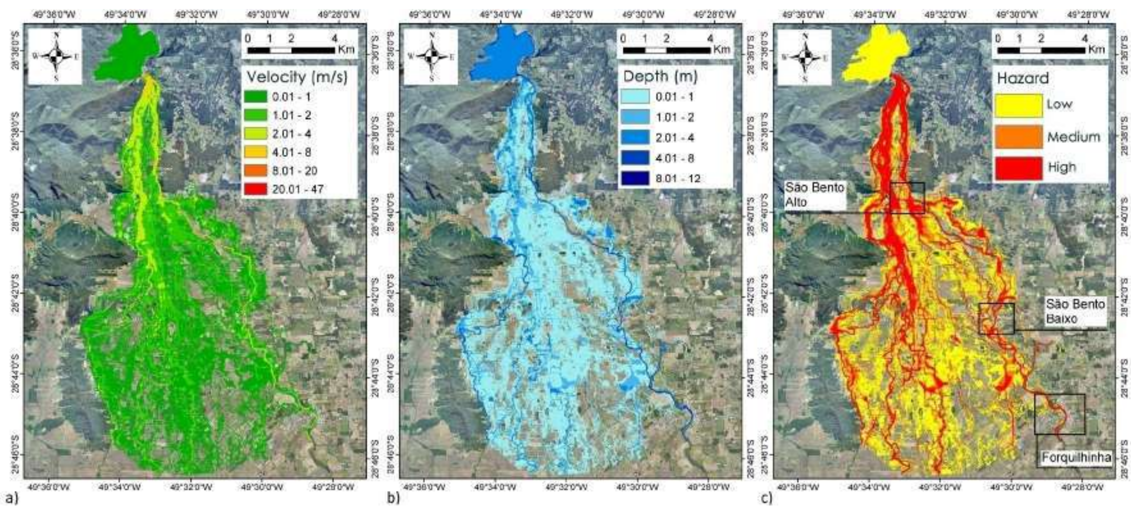

Figure 9 - Entire flooded area maps after São Bento's Dam break: (a) depth; (b) velocity; (c) hazard index.

Figures 10, 11, and 12 show the maps of maximum depth (a), maximum velocity (b), and hazard index (c) of the three affected communities. In the community of São Bento Alto (Figure 10), the maximum depth was 2.90 m, and the maximum velocity was 5.70 $m \cdot s^{-1}$, so the high hazard level predominates in the region; thus, people are in danger inside or outside their homes, with a high possibility of buildings being destroyed. In turn, in the community of São Bento Baixo (Figure 11), the flood wave partially reached the homes, with a maximum depth of 2.60 m and a maximum velocity of 2.00 m·s-1, with a high hazard level prevailing in the São Bento River channel and in the areas with little or no human occupation. The HI predominates as low in the most inhabited areas, with intermediary levels in some points. The central region of the municipality of Forquilhinha (Figure 12), which is further from the dam, suffers little from the impacts of the hypothetical break of the dam: in the few areas reached, the maximum depth was 0.60 m, and the maximum velocity was 0.70 $m \cdot s^{-1}$, with a high hazard level mainly in the river channel and near its banks (20 m), providing more significant concern to buildings and people who live near the banks of the river, as they have a high possibility of suffering damage.

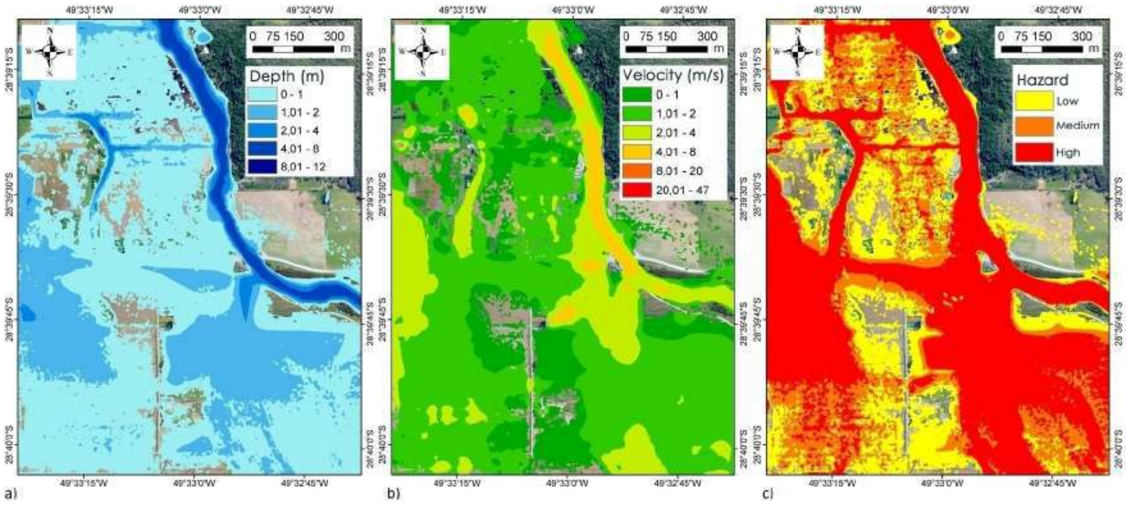

Figure 10 - São Bento Alto's community flood maps: (a) maximum depth; (b) maximum velocity; (c) hazard index.

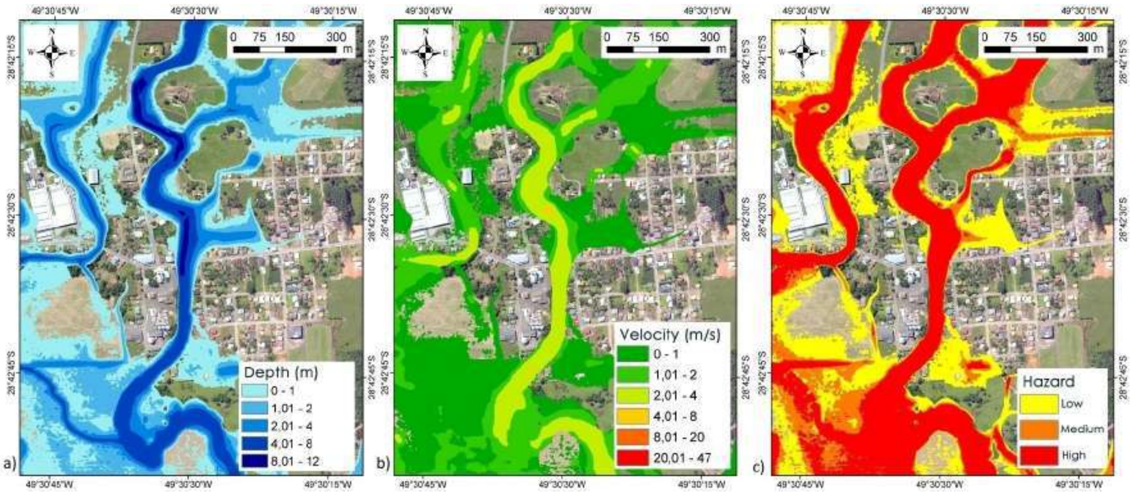

Figure 11 - São Bento Baixo's community flood maps: (a) maximum depth; (b) maximum velocity; (c) hazard index.

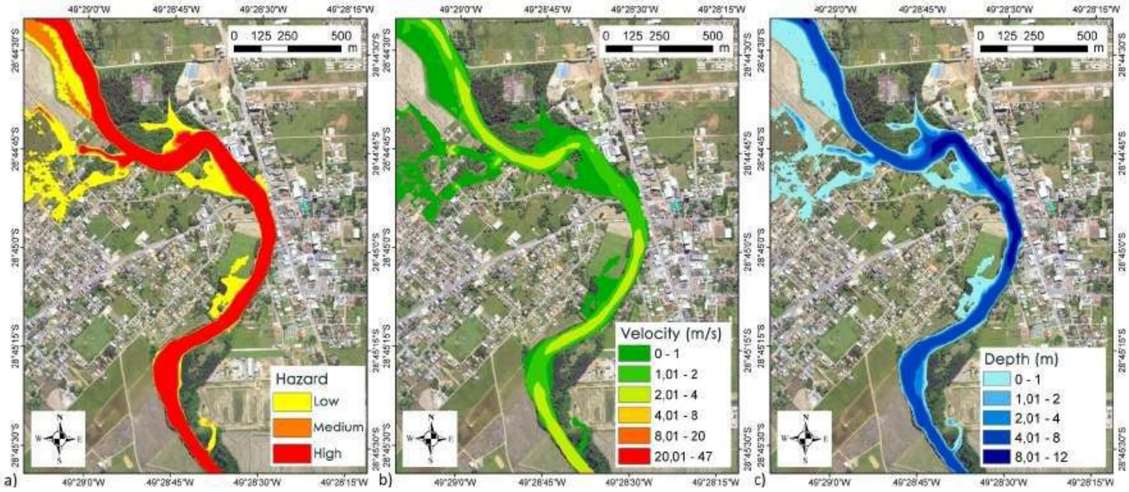

Figure 12 - Forquilhinha's community flood maps: (a) maximum depth; (b) maximum velocity; (c) hazard index.

VULNERABILITY INDEX MAP

Figure 13 presents the six census variables used to estimate the vulnerability index. In the stretch downstream of the dam, the most populous tracts (Figure 13a) have a more extensive territory but with a low population density (Figure 13b), from 6.84 to 166.4 inhabitants·km-2, and the average number of residents per household (Figure 13c) is 2.87 to 3.43. The tracts with the highest population density have 1474.78 to 4075.56 inhabitants·km^{-2}, with the communities of São Bento Alto, São Bento Baixo, and the central region of the municipality of Forquilhinha being among them. Despite the low population density in the rural area, this is an area where most residents are over the age of 60 (Figure 13d). This increases the vulnerability of the people to the flood hazard in the event of a dam break.

Reis et al. (2016), who used the same methodology proposed by Goerl et al. (2012) to define the census variables of the vulnerability index, also found a lower population density and a higher rate of dependents in the analyzed rural tracts corresponding to the municipalities of Alto Feliz and São Vendelino, in Rio Grande do Sul. Figure 13f shows that the low-income population is concentrated closer to the dam (up to 9 km). The tracts with the highest per capita income are located farther from the dam (20 km), mainly in the urban area of the municipality of Forquilhinha. Reis et al. (2016) also found that urban tracts have higher incomes than rural tracts.

With regard to the illiteracy rate of people over 12 years old per census tract, the map shows that the region does not have a homogeneous distribution (Figure 13e) but presents a relationship with the low-income population, demonstrating that tracts in which income is higher tend to have a lower illiteracy rate.

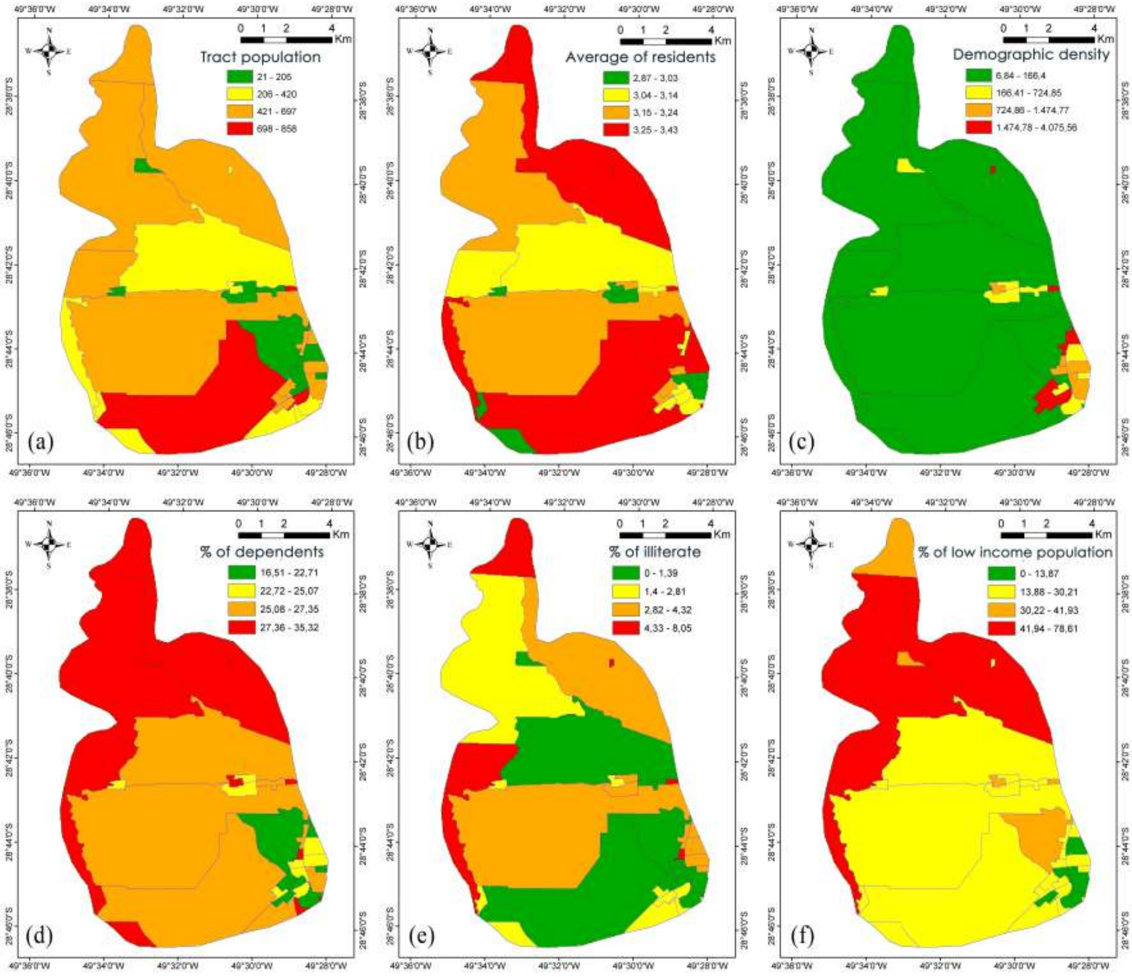

Figure 13 - Census variables maps: (a) tract total population; (b) average number of residents per household; (c) population density; (d) % of dependent population; (e) % of illiterate; (f) % of the population with low income.

Figure 14 shows the vulnerability index map, with the index varying from 0.85 to 5.92 and classified into four categories using the Natural Breaks method: Low (< 1.53); Medium (1.53 to 2.70); High (2.70 to 3.80); Very high (> 3.80).

Among the 35 census tracts analyzed, within the flooded area simulated by the HEC-RAS 2D, only two presented low vulnerability: tracts F509 and F510, which showed low values for all variables analyzed (Figure 12). It was also observed that the tracts closest to the dam presented high and very high vulnerability. This aspect draws attention to the flood caused by a possible break of the São Bento River Dam due to a failure in its structure. Other tracts further away from the dam also showed very high vulnerability, such as sectors N1002, F505, F507, F513, and F514. However, tract N1002 presented the highest vulnerability index value due to the most considerable number of residents (858), high average number of residents per household (3.34), high demographic density (3844.65 inhabitants·km-2), and a high rate of dependents (29.72 %).

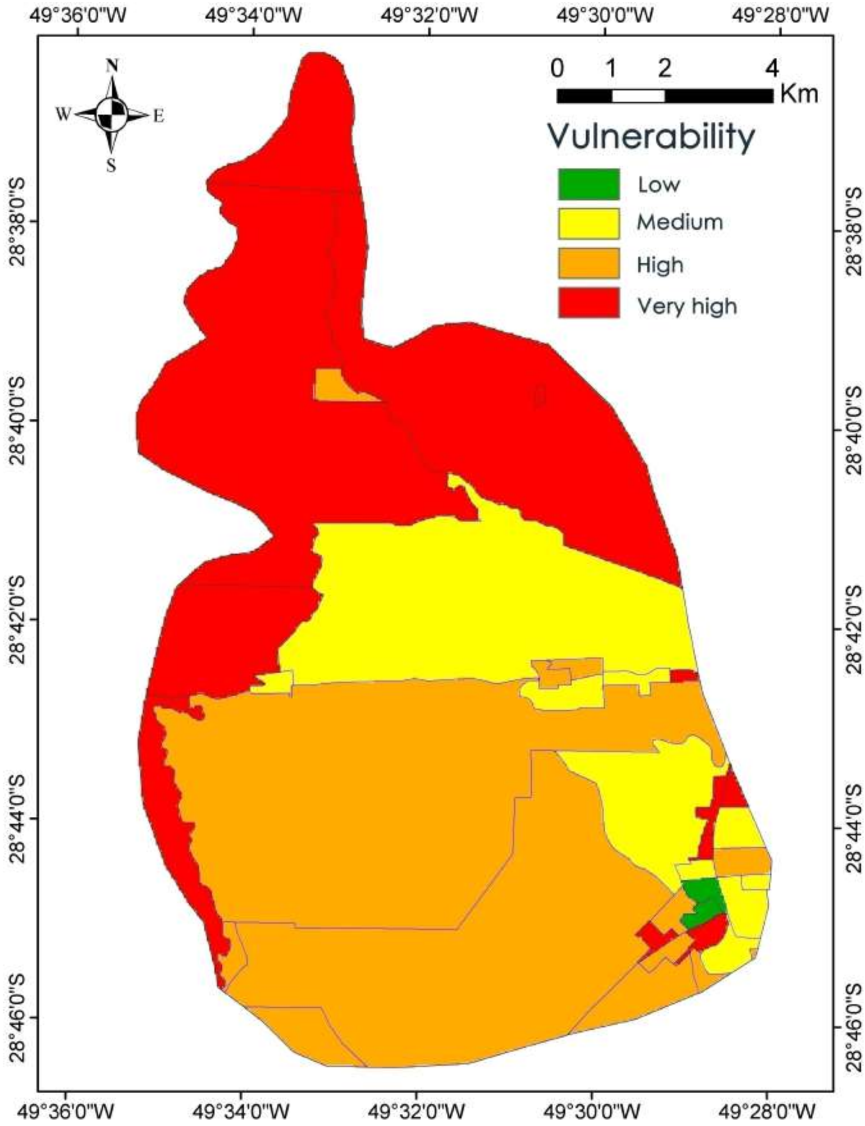

Figure 14 - Vulnerability map by census tract.

RISK INDEX MAP

The risk index map is shown in Figure 15. In this map, the risk levels were characterized into three classes: low, intermediary, and high, following the same criteria adopted for the HI (Table 3) since it is through the flood wave, with a certain velocity and depth, that it is possible to assess the potential damage to the population and the buildings downstream of the São Bento Dam.

One may observe that the risk map is similar to the hazard map (Figure 9c); however, the high-risk area was larger (36.53 km²) and represented 56.37% of the total simulated area (Table 5). This result was because the VI is calculated based on socioeconomic variables, which increased the risk stemming from a possible dam break. The 6 km after the dam presented the high-risk index, even though the region had a low demographic density. Because it is a rural area, people are more vulnerable to danger, as they are over 60 and have a low income. It was observed that, although some regions presented a very high vulnerability index, the risk is zero because the area has no hazard of being flooded. This shows that the risk is directly related to the danger of flooding with the dam break.

The risk map (Figure 15) also shows that the community of São Bento Alto was entirely affected by the flood wave, being classified as high risk. On the other hand, the community of São Bento Baixo, which was also classified as high-risk, was partially affected by the flood wave. In turn, the central region of Forquilhinha presented a high-risk index only in the areas near the banks of the São Bento River (about 20 m).

It should be noted that, in the areas that presented high and intermediary risk levels, there are many homes, schools, primary health units, businesses, fuel stations, factories, and restaurants, among other infrastructures. In such sites, people are not safe inside or outside buildings because there is a probability of them being destroyed due to the depth and average velocity of the water.

Risk Level	Area (km²)	Percentage
Low	18.68	28.83
Medium	9.59	14.80
High	36.53	56.37
Total	64.80	100.00

Table 5 - Classification of flood areas in km² for each risk degree.

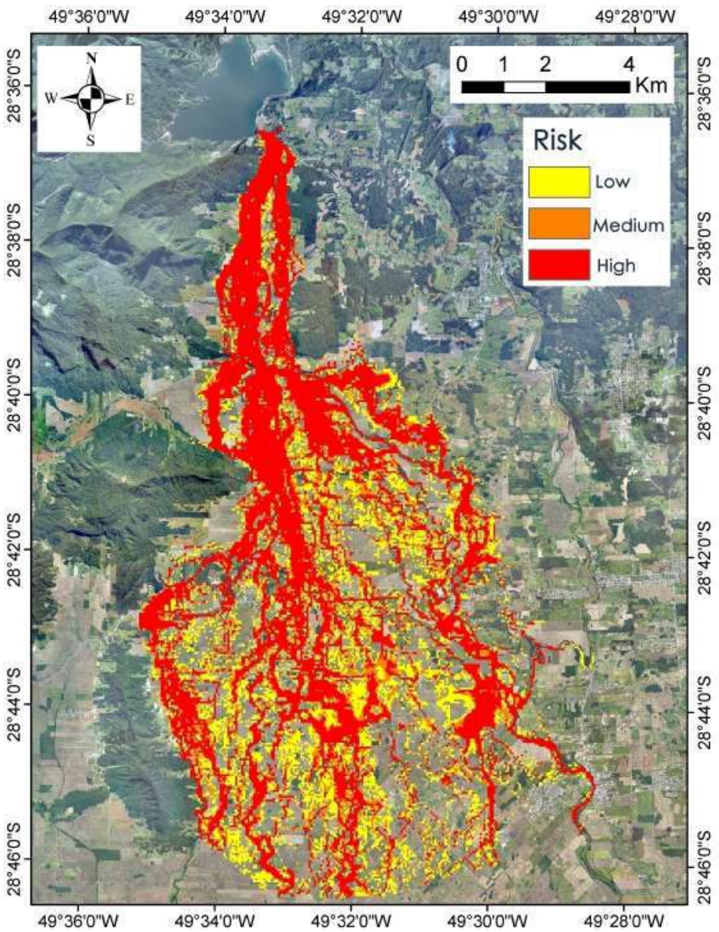

Figure 15 - Risk map.

CONCLUSION

The present study evaluated the flood risk index due to the break of the São Bento River Dam in southern Santa Catarina, calculated according to the flood hazard and vulnerability of the downstream area.

The hazard index was calculated by the equation proposed by Stephenson (2002), multiplying the velocity and depth of the water line, simulated by HEC-RAS 2D. The vulnerability was calculated considering six variables from the 2010 IBGE demographic census and the census tract as the unit of analysis.

The result obtained in the form of a risk index map allows us to infer that the risk level is high in the areas closest to the dam (up to 6 km away). Also, in the area that may be hit by the flood wave, there are homes, schools, businesses, and factories. In these places, people are not safe inside buildings because they have a high possibility of being destroyed due to the velocity and depth of the flood wave.

The Brazilian National Dam Safety Policy (Law No. 12334/2010) requires an emergency action plan (EAP) for the construction of some dams that does not address the mapping of the vulnerability of the downstream region. However, the study showed that the vulnerability index influences the calculation of the flood risk index due to a dam break since it considers the socioeconomic factors of the affected region in its determination. Therefore, vulnerability index mapping is an important tool for identifying priority sites for implementing public policies and prevention and mitigation actions in emergency situations in the event of a dam break.

Risk mapping is extremely important to identify in a spatialized way the propagation of the flood wave due to the possible break of the São Bento River Dam, given that it takes into account the depth and velocity of the water, as well as the vulnerability of people living downstream of the dam.

Dam break-related disasters happen almost every year in Brazil. Thus, low-cost methodologies such as risk mapping may be adopted as a prevention measure. Moreover, this map may help in the elaboration of an emergency action plan, in addition to being an instrument for the education of communities, territorial planning, and future urban buildings and infrastructures.

For future work, it is recommended to evaluate the variables used to calculate the vulnerability index, analyzing their relationships with the risk and hazard indices to verify which ones significantly influence these calculations. It is also recommended to perform the simulation of the hypothetical break of the primary and secondary dikes of the reservoir of the São Bento River Dam and evaluate the behavior of the flood wave if they present failure in their structures.

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Kobiyama, M. - The author reviewed the analyzes and assisted in writing and revising the results.
Corseuil, C.W - The author proposed the research, analyzed the data, reviewed the analyzes and assisted in writing and reviewing the results.

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