DETERMINATION OF THE HAZARD INDEX FROM THE MAPPING OF SUSCEPTIBLE AREAS TO FLOOD WITH THE HAND MODEL

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ABSTRACT– One of the most efficient and simplest flood disaster prevention measures is the identification and mapping of areas of flood susceptibility. Thus, the objective of the present work was to map flood hazard areas of the municipality of Igrejinha-RS, based on the results of the Height Above the Nearest Drainage (HAND) model. A 2.5-m resolution DEM was used. From the reclassification of the HAND topology, three flood susceptibility thresholds were generated: low, medium and high. The result of the HAND topology was used to calculate the flow depths. The flow velocity was obtained using the Manning equation along the slope raster obtained from the DEM. With the velocity and the depth, the hazard index (HI) was calculated for the three susceptibility thresholds. The results evidenced both the usefulness of this new methodology and its limitations. Due to the low velocity, the flow depth affected the HI variation more.

Keywords – Hazard Index, HAND, Flood

1 - INTRODUCTION

A data analysis of the Emergency Disasters Data Base (EM-DAT, 2018) allows observing that the most relevant natural disasters in Brazil are the floods, responsible for more than 60% of deaths and economic losses during the period 1982 to 2010. According to the Brazilian National Civil Protection and Defense System (SINPDEC), in Rio Grande do Sul state, during the period 1991 and 2012, 413 occurrences of exceptional floods were recorded, and 42% of the municipalities were affected by this type of episode at least once.

Brazil has still lacked an official flood control system that encompasses all the agents and aspects involving its occurrences. Currently-existing agents are individual and isolated among themselves. The Brazilian Law No. 12,608 of April 2012 (Brazil, 2012) defines prevention actions in order to reduce the occurrence and intensity of disasters by identifying, mapping and monitoring local risks, hazards and vulnerabilities. These actions above-mentioned are considered as non-structural measures, while structural measures are those involving engineering works. According to Kobiyama *et al*. (2006) the non-structural ones stand out due to their low cost and more ease and simplicity in implementation.

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Without consideration on return period, Stephenson (2002) proposed the Hazard Index (HI) which is expressed with the product of water height and its speed. Monteiro and Kobiyama (2013 and 2014) and Neto *et al*. (2016) developed a methodology for mapping the HI with hydrological and hydrodynamic models based on local precipitation measurement.

The integration of the Digital Elevation Model (DEM) into Geographic Information Systems (GIS) permits to estimate several hydrologic parameters, such as flow direction, flow contribution area and drainage network (Moore *et al*., 1991). Furthermore, hydrological and hydrodynamic models, which are used in flood hazard mapping, also use DEM as one of the input data.

The Height Above the Nearest Drainage (HAND) model developed by Rennó *et al*. (2008) was used to landscape classification (waterlogged, ecotone, slope and plateau) by the Negro River in the Amazon. Beside some works using the HAND model to flood mapping (Mengue *et al*., 2016; Momo *et al*., 2016), there is still no work calculating the HI with the HAND application. Therefore, the objective of the present study was to elaborate the HI map of the municipality of Igrejinha-RS by using the HAND but without consideration of return period. The HAND had been applied to this municipality by Goerl *et al* (2017) whose data were partially utilized in the present study.

2 - METHODS AND MATERIALS

2.1 - HAND Model

The HAND model generates a grid of vertical distances from a normalized DEM and determines the difference between the height of a given pixel and the height of the nearest drainage network. According to Mengue *et al.* (2016) the model results can be used to simulate the flood height and to map areas with larger susceptibility to flood.

The HAND implemented in the TerraHidro software (INPE, 2018) can be preceded with three steps. The first is the DEM's hydrological correction and the calculation of the flow direction (D-8 method), which uses the slope between two points to obtain the direction of flow (Momo *et al*., 2016). The second step consists of the drainage network calculation, based on the hydrologically corrected DEM and the flow accumulation area. In the third step, the HAND topology is generated, by reclassifying the DEM with the results of the unevenness between the altimetric height and the height of the nearest drainage channel. A 2.5-m resolution DEM (scale of 1:25,000) available by the Brazilian Geological Service (CPRM) was used.

2.2 - Hazard Index Mapping

2.2.1 - Hazard Index

Stephenson (2002) defined the HI as follows:

$$HI = h \cdot v \tag{1}$$

where *v* is the flow velocity (m/s); and *h* is the flow depth (m). The HI is linked directly to the flow energy, i.e., to its destructive potential (Monteiro and Kobiyama, 2013 and 2014).

The HI mapping requires its quantification, because different magnitudes of a flood event may cause different damages. Several authors have proposed different HI classes which normally range from 3 to 6 classes and are based on the damage occurred to people, vehicles and buildings (Prevene, 2001; Stephenson, 2002; Ramsbottom *et al*., 2003; and Smith *et al*., 2014). Based on the classes proposed by Ramsbottom *et al*. (2003) and Smith *et al*. (2014), the present study elaborated 5 classes of flood hazard levels (Table 1).

Table 1 - Flood Hazard Levels

Definition of Flood Hazard		
Hazard level	**Range of HI**	**Description**
Very high	2.5 <	People are in danger, both inside and outside their homes. The buildings have a high possibility of being damaged
High	1.5 – 2.5	The passage of small vehicles such as cars and trucks is no longer safe.
Medium	0.7 – 1.5	It becomes dangerous the passage of anyone, whether child, senior or adult.
Low	0.25 – 0.7	It becomes dangerous the passage of children and the elderly.
Very low	< 0.25	Virtually zero danger for people, children and adults, as well as vehicles.

2.2.2 - **Depth calculation**

The flow depth is determined using the results of the HAND topology, and is expressed by:

$$h = h_i - h_n \qquad (2)$$

where h_i is the flood level (m) and also the HAND value for the waterlogged threshold, which is obtained by comparing the resulting HAND topology with the points reached by previous floods; and h_n is the nominal value of the pixel (m) that is obtained, for each pixel, in the HAND topology.

2.2.3 - **Velocity calculation**

The flow velocity can be calculated with the Manning equation:

$$v = \frac{1}{n} \cdot R_h^{2/3} \cdot S^{1/2} \qquad (3)$$

where *n* is the roughness coefficient of Manning (s/m$^{1/3}$); R_h is the hydraulic radius (m) and *S* is the slope (m/m). The *n* value for the floodplain was calculated according to Chow (1959) which considered the roughness of a channel as the sum of several factors such as vegetation, soil type, irregularities of the flow and obstructions in the channel. Then the present study adopted 0.2975 for *n*, which is a high value due to the heterogeneity of the study area. The *S* value was obtained through the DEM, using the slope tool in ArcGis, first calculated in percentage, and converted to the value in m/m.

The land surface slope is not equal to that of the flood surface, especially near the river bank zone. However, because of the simplification of the procedure, the present study assumed that both slopes are the same.

2.2.4 - **HI Mapping**

As the flood extension is normally much larger than the h value, the equation (1) becomes:

$$HI = \frac{1}{n} \cdot h^{5/3} \cdot S^{1/2} \qquad (4)$$

With map algebra, using the slope and the HAND topology, the *h* and *S* values can be calculated. Finally, the raster multiplication is performed for obtaining the HI map.

2.3 - Study Area

To verify the proposed methodology, the present study chose the Igrejinha municipality (136 km^2), in the northeast of Rio Grande do Sul state; which lies inside the Paranhana river valley and also in the Southern Plateau geological region (Figure 1). Its population is 31,660 inhabitants (IBGE, 2010). In the Köppen-Geiger classification (Belda *et al*., 2014), the regional climate is Cfa.

The Paranhana valley has been frequently affected by floods as disaster due to the proximity of the urban areas to the river. In 2010, floods affected more than 57,000 people in the four municipalities that make up the valley (Oliveira *et al*. 2013).

Following the methodology of Goerl *et al*. (2017) the reclassification of the model was based on the overlapping of the areas susceptible to flooding with the flood reaching points mapped by Oliveira *et al*. (2013).

Figure 1 - Location of the Municipality of Igrejinha.

3 - RESULTS AND DISCUSSION

Rennó *et al*. (2008) and Nobre *et al*. (2011) presented four categories for the HAND topology segmentation: waterlogged (< 5m); Ecotone (5 to 15m); Slopes (15 to 50m) and Top of hill (> 50m). Similar to the proposal of Goerl *et al*. (2017), the present study considered spots with a HAND value less than 5.5 m as areas susceptible to flood, which covered 91% of the points surveyed by Oliveira *et al*. (2013). These points do not refer to a specific event, but to places that frequently have flood. The adopted area of contribution was 18 km^2 in order to focus the flood areas on the Paranhana River. Note that Goerl *et al*. (2017) used the value of 18.75 km^2.

It was assumed that the closer place (pixel) to the river and the lower altimetric difference between this place and the nearest channel make the larger susceptibility to flood. By adjusting the areas susceptible to the flood and by applying the methodology of Goerl *et al*. (2017), the susceptible areas were classified: high (0 to 1.83 m), medium (1.83 to 3.66 m) and low (3.66 to 5.5 m) (Figure 2). These classes were established by dividing the HAND value (5.5 m) which coincides with 91% of the flood points into three equal intervals. Since there is no gauge station in Igrejinha municipality, this procedure was adopted to establish the flood susceptibility classes. A high susceptibility place is often flooded. Thus, by analogy, susceptibility and frequency could be considered similar and the place with high susceptibility (HAND < 1.83m) is also a place with high frequency. Many cells with the medium susceptibility were isolated, because the DEM was obtained through a Synthetic Aperture Radar (SAR), causing the noise of the urban areas to be passed to the DEM.

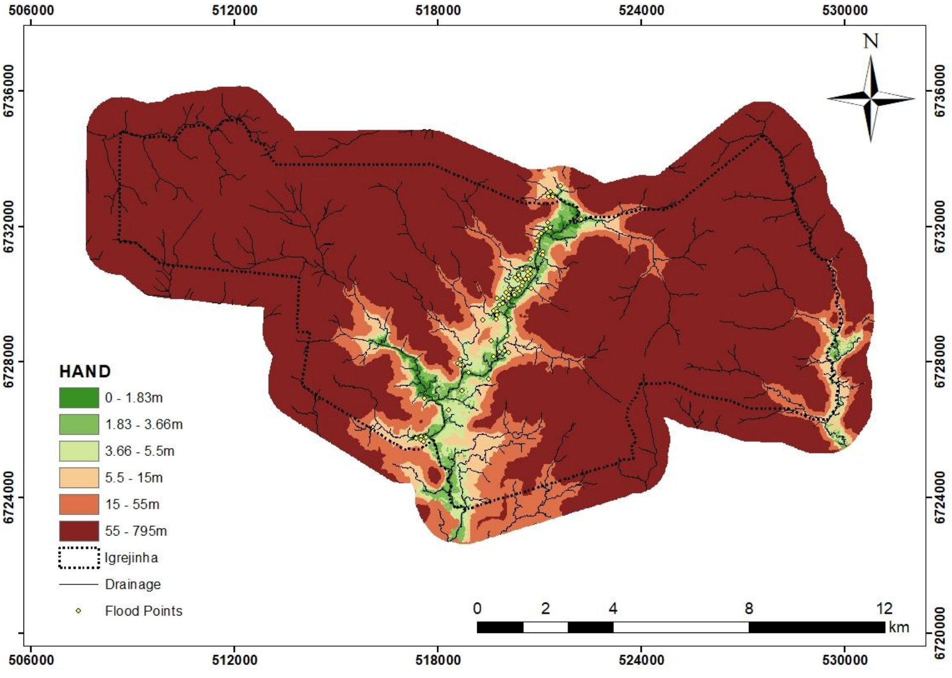

Figure 2 - Classification of the HAND Model

Next, the *v* and *h* values were calculated (Figure 3 and 4) using map algebra in ArcGis. It was decided to make the calculations for three different hypothetical events, based on the previously susceptible flood-prone areas, i.e. a high frequency event (high susceptibility class), a medium frequency event (middle susceptibility class) and a low frequency event (low susceptibility class). The *v* values were mostly lower than 1 m/s. For a high susceptibility flood more than 99% of the cells fell in that zone, meanwhile for a flood of low susceptibility 78% of the pixels were at that threshold. High velocities, over 5 m/s, were found only in the largest flood scenario, but they were encountered in less than 0.05% of the area. It occurred due to the simple assumption where the flood surface slope is equal to that of the land surface slope. There is a notable error in the calculation, because the slope is practically null along the river and very high in its banks, which resulted in high values located at the river's banks, probably because the uncorrected altimetry of the DEM, in which the riparian forest was represented as topographic data.

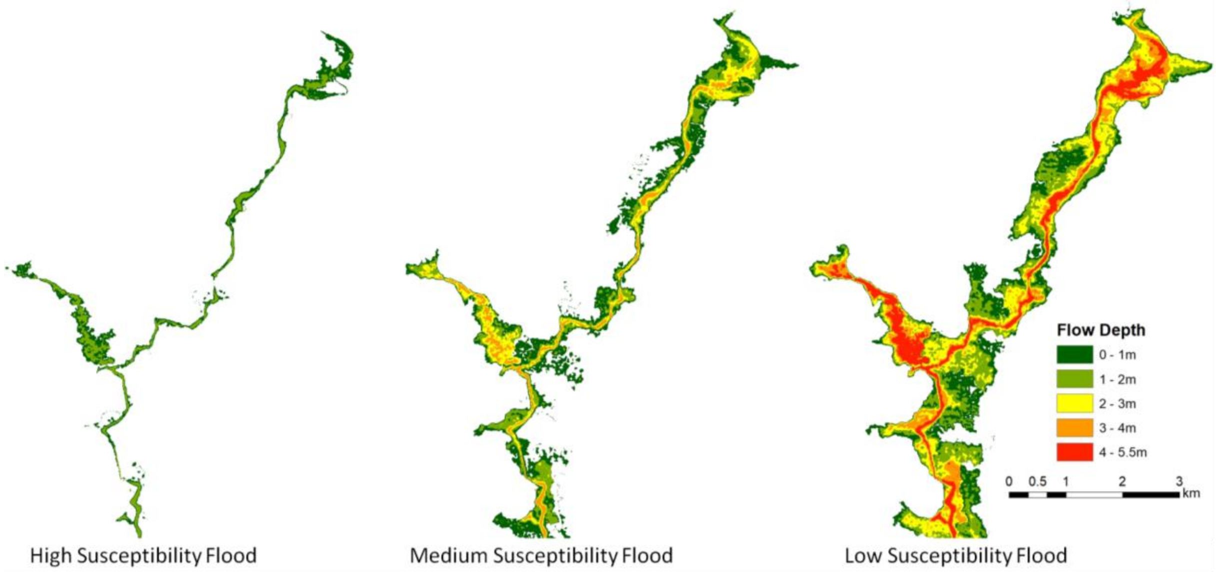

Figure 3 –Flow depth distribution with three different susceptibility flood levels.

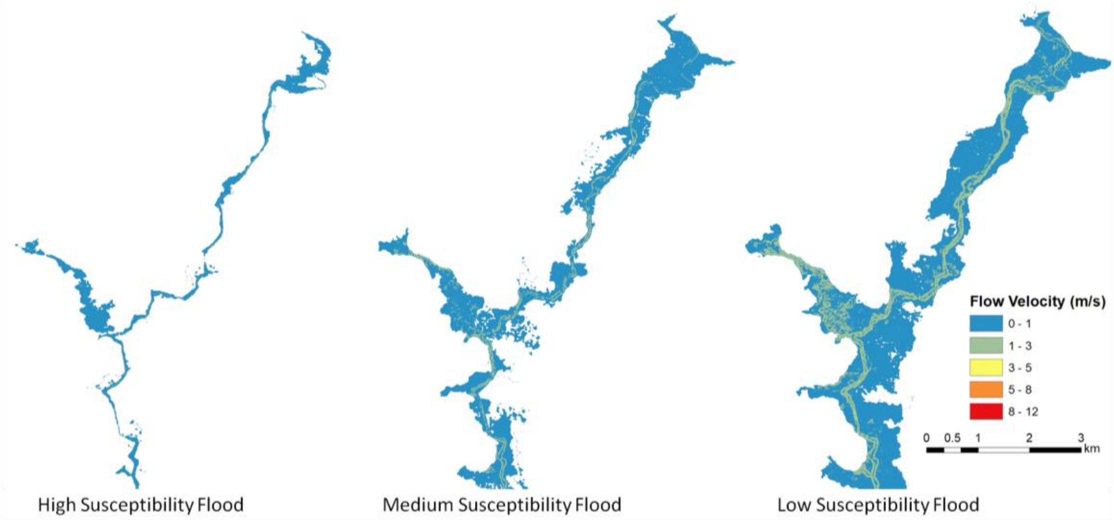

Figure 4 – Flow velocity distribution with three different susceptibility flood levels.

For a flood of high frequency, almost 50% of the susceptible area was at Very Low HI level, 33% was classified as Low HI and 14% as Medium HI. The High and Very High HI thresholds account for less than 4% of the total area, concentrating on the riverbanks. For a flood of medium susceptibility, the results were similar, but with a substantial increase of the highest thresholds, with their sum reaching 22% (Figure 5).

The low frequency flood, the most hazardous, was the one with the most homogeneous results, with almost all levels of hazard reaching 20% of the flood area. The most representative threshold was, with 26% of the pixels, the Very High HI, which was mainly due to the flow depth, which in the areas closest to the river were larger than 4 m.

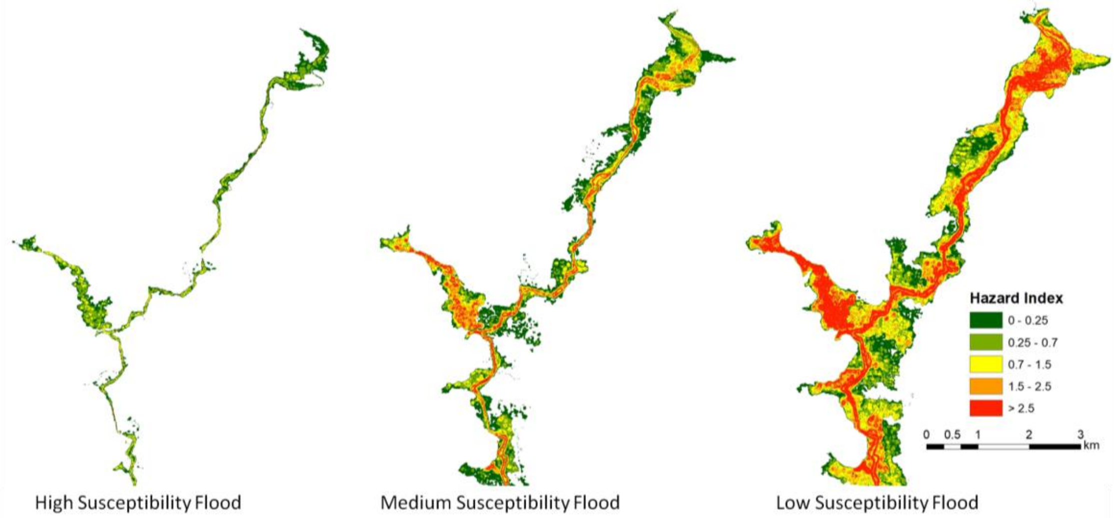

Figure 5 – Hazard index maps with three different susceptibility flood levels.

As Figures 3 and 5 are very similar and the *v* values were very low, it can be said that the main variable to determin the HI values in the present study is the flow depth. Another factor that influenced the result was the low slope found along the floodplain, with the exception of the river bank.

4 - CONCLUSION

The present study proposed a new methodology for mapping of the hazard index for floods and applied it to the municipality of Igrejinha-RS, as study case. The results obtained can be used both in urban planning and in Civil Defense logistics in case of future disasters.

The procedures to obtain the final results are, firstly, the acquisition of a high-quality DEM, followed by its processing by the HAND model. With the HAND topology, flow depth is calculated. Then the flow velocity is calculated by using the Manning equation and by considering that the flow depth is equal to the hydraulic radius. Finally, the velocity and depth values are multiplied to obtain the hazard index.

In the present study, the spatial variability of the velocity was low. Probably, the values of the roughness coefficient should be changed due to the local characteristics and the variation of land use. Thus, in order to obtain more reliable results, it is necessary to adapt the formula or even to develop a new formula that reproduces the diversity of a vast flood plain.

The present methodology's effectiveness should be verified with field observation of real height and velocity during the flood occurrence. Furthermore, the methodology should be applied to other floods areas.

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