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# Using relief patterns and quartile deviation for modeling of flood susceptibility maps: examples from Presidente Kennedy and Conceição do Castelo, Espírito Santo, Brazil

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## Abstract

Flood modeling is one of the layers that compose the preliminary susceptibility map, which after the field investigation step is part of the Mass Movement and Flood Susceptibility Map. These maps are produced by the Geological Survey of Brazil, through the National Plan for Risk Management and Response to Natural Disasters (Programa Nacional de Gestão de Riscos e Respostas a Desastres Naturais, PNGRRDN). Initially, the flood modeling methodology consisted of applying the HAND model based on the following variables, hydrographic basin, and soil susceptibility. However, several inconsistencies were observed during fieldwork, especially regarding the model capacity to describe regions with specific hydrological regimes. A methodological improvement using other variables became necessary. Among the proposed variables, the relief susceptibility to floods yielded the most satisfactory results, especially since it could be applied to the entire national territory and was, therefore, introduced to replace the hydrographic basin susceptibility. Furthermore, the methodology used for defining the thresholds of the three flooding susceptibility classes (high, average and low) has also been modified by using the quartile deviation, which provides a less subjective class distribution. Using relief susceptibility and quartile deviation in flood modeling was tested in the Conceição do Castelo and Presidente Kennedy municipalities (Espírito Santo, Brazil), where the morphological configuration covers a wide variety of environments, which is fundamental for the validation of the new variable. The results of the new model were satisfactory. The various types of plains continue to be well represented while a substantial improvement has been observed in the representation of flood-susceptible areas such as marine terraces and colluvium ramps.

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## 1. Introduction

Floods are hydrological processes that cause damages and disruptions every year, especially when occurring in urban centers that have been occupied or expanded in a disorganized way toward the seasonally flooded river plains (Goerl and Kobiyama 2013; Stevaux and Latrubesse 2017). The occupation or not of such areas requires planning based on the technical knowledge of the flooding process while identifying the areas prone to flooding in the municipal territories.

The aforementioned issues and the objective of minimizing the damage caused by natural disasters led to the formation of the National Policy for Civil Protection and Defense (Politíca Nacional de Proteção e Defesa Civil) according to Federal Law No. 12.608/2012 (Brasil 2012), which provides for the identification and evaluation of areas susceptible to geological and hydrological processes. To this end, the Plano Nacional de Gestão de Riscos e Resposta a Desastres Naturais (Brasil 2013) instructed the Geological Survey of Brazil (SGB/CPRM) to draw up susceptibility maps indicating areas prone to mass and flood gravitational movements. These maps covering the entire national territory should be employed in the planning and management of municipal territories.

The flooded areas are mapped and elaborated in a GIS environment, based on operations involving map algebra, which assigns a quantitative or qualitative value to each site in an area (Tomlin 1990). These values are attributed to certain characteristics of the variables used. The variables, initially, flood susceptibilities of both the local sub-basins (defined by the morphometric parameters) and the terrain itself, were calculated by the heights relative to the local base level defined by the thalwegs of the channel networks using the Height Above Nearest Drainage (HAND) model, according to Rennó et al. (2008) and Nobre et al. (2016).

The HAND model was based on the thresholds of class susceptibility (high, moderate, low), the evaluation of topographic profiles extracted from Digital Elevation



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Models (MDE-SRTM and Topodata), analysis of historical measurement series of the quotas of the main river in the municipality (data from the hydrometeorological stations) and reports of the residents.

At first, this methodology was satisfactory for the proposed objective, especially for municipalities in the South and Southeastern Brazil, however, improvements became necessary since some inconsistencies were observed and reported by Silva and Bitar (2014), especially regarding the susceptibility of hydrographic basins in regions with a specific hydrological regime, such as the Amazon. These questions fostered the need for methodological improvement, especially regarding the low accuracy of the sub-basin susceptibility that was obtained only through the morphometric parameters of the basins, class spatialization conflicts when crossed with the classified HAND model, and the high subjectivity of the criteria for establishing the lower and upper thresholds of the susceptibility classes in the HAND model.

To this end, this study aims at presenting the results of tests using relief patterns to replace morphometry of the sub-basins and applying the quartile deviation for determining the HAND susceptibility thresholds, in order to redefine some methodological criteria related to the terrain morphological characteristics and their respective susceptibility to flooding. Comparisons will also be made between the two models.

## 2. Considerations about the previous model

The flood modeling methodology adopted previously to define flood susceptibility used as one of the parameters, the data on the morphological and hydrological characteristics of the sub-basins in the studied municipality, provided by the following indices and morphometric parameters: basin contribution area; relief relationship (relationship between topographic amplitude and main river length); drainage density; circularity index; and sinuosity index (Bitar 2014).

This information was combined to generate the flooding susceptibility of the sub-basins covering the area of each municipality mapped. This susceptibility was satisfactory for the project objectives; however, some inconsistencies were identified in the mappings during validating fieldwork, especially the low adequacy of this information in the municipalities of northern Brazil. Also, in some cases, regardless of the region in Brazil where the municipality was located, sometimes a sudden rupture of the class susceptibility to flooding (high, moderate or low) was observed along the plain of the same drainage due to the changing hydrographic sub-basin and its own susceptibility.

In view of the inadequacies between the susceptibility information provided by the method that uses as source the morphometric parameters of the sub-basins and the reality of the areas susceptible to the flood observed in the fieldwork, the method was improved by replacing these data with the flood susceptibility of relief patterns.

This replacement is justified by the fact that CPRM/SGB already has a library of Relief Patterns and expertise in relief mapping. Additionally, it is also part of the project methodology to map the relief of the municipality on the same scale (1: 25,000) of the susceptibility map (Bitar 2014). Thus, this replacement is not something new and little experienced for the project and the team.

## 3. Study area

To test the methodological changes in environments with extensive geomorphological and hydrological characteristics, the Presidente Kennedy and Conceição do Castelo municipalities in Espírito Santo, Brazil (Figure 1) were selected, since their highly variable reliefs are represented by the typical morphologies of both mountainous and coastal regions, as in the case of Presidente Kennedy.

During the period from 2000 to 2012, the municipalities of Presidente Kennedy and Conceição do Castelo recorded between 2 and 3, and 8 to 9 water disasters (flood, flash flood, and urban flooding), respectively (Espírito Santo 2013). According to Instituto Estadual de Meio Ambiente e Recursos Hídricos (2013), Presidente Kennedy is classified as having a moderate flooding susceptibility, while the Conceição do Castelo is classified as moderate to high flooding susceptibility.

## 4. Materials and methods

The mapping of flooding susceptible areas involves a complex thematic, without definitive formulas. One of the adopted approaches is based on permanent factors, that is, on the terrain predisposing conditions, especially regarding the geological, topographical and morphological characteristics of the basins, which tend to favor the overflow of the water level during heavy rains (Bitar 2014).

The terrain characteristics are translated into this methodological proposal as two variables: the relief patterns and terrain height in relation to the nearest drainage (HAND model). These two parameters were selected because they are easily obtained, applicable to the national territory and to the execution scale of the susceptibility charts (1: 25,000 to 1: 50,000).

The standard relief variable results from the photo-interpretative analysis on a 1: 25,000 scale, using high-resolution images and products derived from the Digital Elevation Model (DEM), such as slope, hydrography, contours, and shaded relief, aiming at a physiographic characterization of the study site, and from there, we propose to compartmentalize the terrain into land units to evaluate the geological-geotechnical behavior of the materials and their spatial variability (Dantas et al. 2014). The behavior of relief patterns against flood susceptibility was classified (Table 1) following the definitions of Dantas (2013), together with information from other studies reporting on the behavior of these relief patterns when faced with the hydrological processes (Dantas and Maia 2010; Dantas and Teixeira 2013; Dantas et al. 2014). After classifying the susceptibility, the relief layer is transformed into raster to perform the sum (Boolean analysis) with the raster resulting from applying the HAND model to the DEM of the study area.

The terrain height in relation to the nearest drainage is obtained by the HAND (Height Above the Nearest Drainage) model, which uses the difference between the extracted DEM altitude and the reference drainage network to calculate the relative heights that are correlated with the water table depth and the terrain topography (Rennó et al. 2008), so that areas with low relative heights may indicate regions more susceptible to flooding (Silva et al. 2013).

To elaborate the HAND raster of the selected municipalities, the DEM-ALOS/PALSAR with 12.5 m spatial resolution, obtained at the site of the Alaska Satellite Facility (https://vertex.

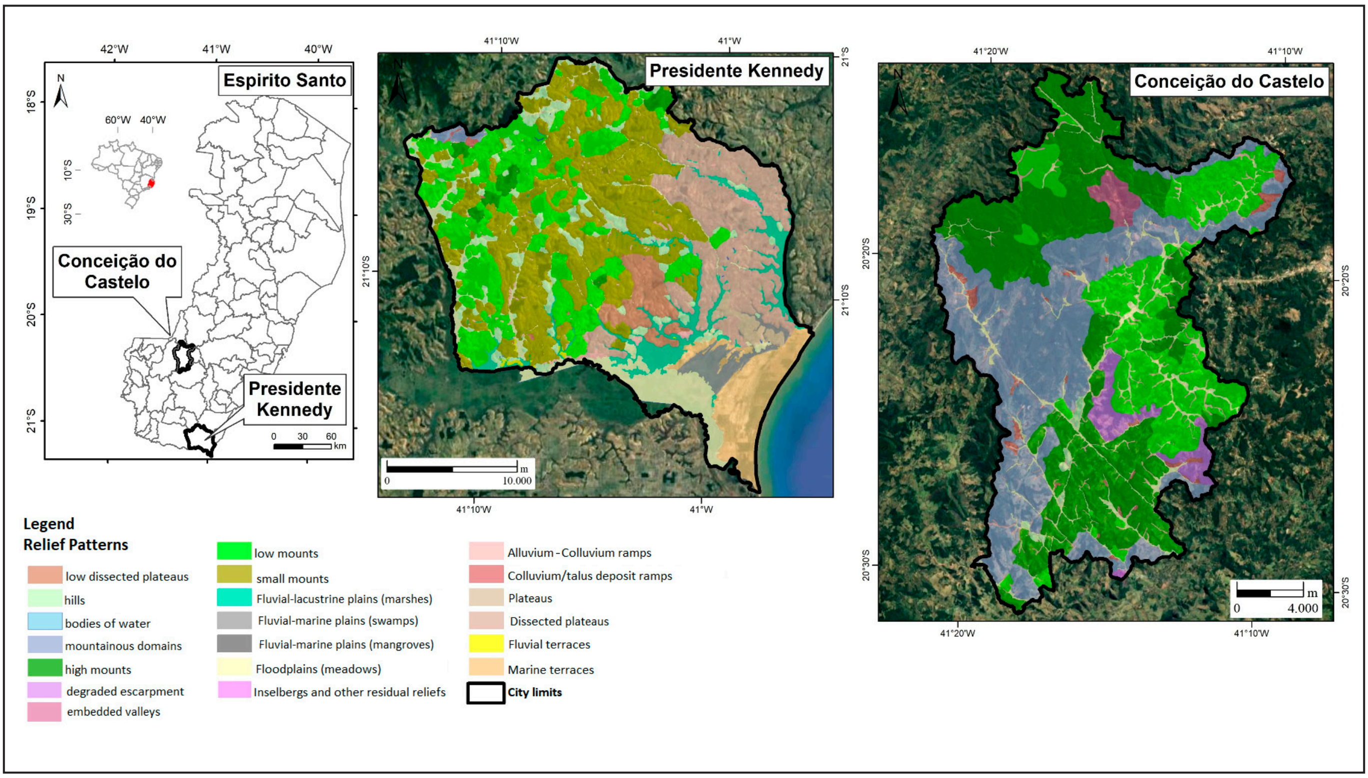


**FIGURE 1** – Maps showing the local and relief patterns of the study area: the Presidente Kennedy and Conceição do Castelo municipalities, Espírito Santo state, Brazil.

**TABLE 1** – Flood susceptibility classes of the Relief patterns adapted from Dantas (2013).

| Relief patterns | Susceptibility | Attribute |
|---|---|---|
| Floodplains (meadow) | High | 3 |
| River/fluvial Terraces | Low | 1 |
| Lagoon terraces | Low | 1 |
| Marine Terraces | Low | 1 |
| Alluvial-Colluvial lows | Moderate | 2 |
| Alluvium-colluvium ramps | Low | 1 |
| Alluvial fans | Moderate | 2 |
| Fluvial-marine plains (mangroves) | High | 3 |
| Fluvial-marine plains (marshes) | High | 3 |
| Fluvial-lacustrine plains (marshes) | High | 3 |
| Fluvial-deltaic plains (marshes) | High | 3 |
| Lagoon plains (marshes) | High | 3 |
| Coastal plains (restingas) | Low | 1 |
| Reefs | High | 3 |
| Technogenic deposits (landfills over bodies of water) | Low | 1 |
| Karstic features (dolines, uvalas, poliés, sinkholes) | Moderate | 2 |

daac.asf.alaska.edu) was used. The DEM was preprocessed for removing depressions (spurious pixels), followed by the extraction of flow directions. Drainage was generated considering a given contribution threshold, which is the minimum amount of accumulated flow cells needed to establish a channel from which drainage lines are initiated (Fernández et al. 2012). This threshold depends on the morphological conditions of the relief of each study area. The HAND result is a matrix image where all pixel values are the vertical distance (hence a possible flood quota) to the nearest drainage.

Subsequently, the HAND is classified as high, moderate and low susceptibility by the quartile deviation statistical method (Quartile). In this method, the data series is divided into four quartiles with the same occurrence, each with 25% of the total data on frequency values (Ramos and Sanchez 2000). This classification to attend the different geomorphological environments of the Brazilian territory according to flood susceptibility was defined by three classes that are addressed in the discussion section.

The final flood susceptibility model consists of the summation of the classifications obtained (map algebra) plus the susceptibility of the relief patterns and the resulting susceptibility of the HAND model, according to the correlation matrix shown in Figure 3. Subsequently, the information modeled on the pre-map of flood susceptibility is validated in the fieldwork. The methodological steps are summarized in Figure 4.

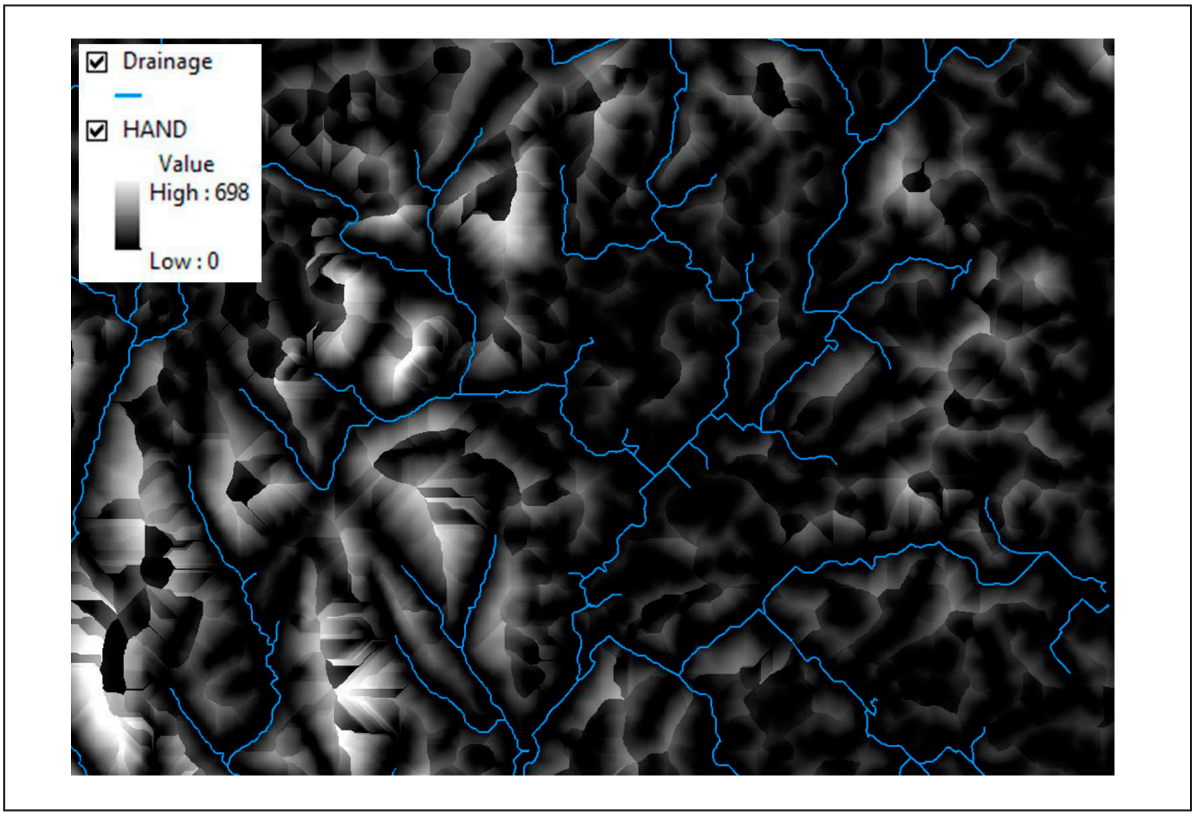


**FIGURE 2** – Result of the HAND raster of Conceição do Castelo

| HAND Model | High | Medium | Low |
|---|---|---|---|
| Relief Patterns | | | |
| High | High | High | Medium |
| Medium | High | Medium | Low |
| Low | Medium | Low | Low |

**FIGURE 3** – Correlation matrix between the two susceptibility classifications obtained, according to the relief patterns and the HAND model.

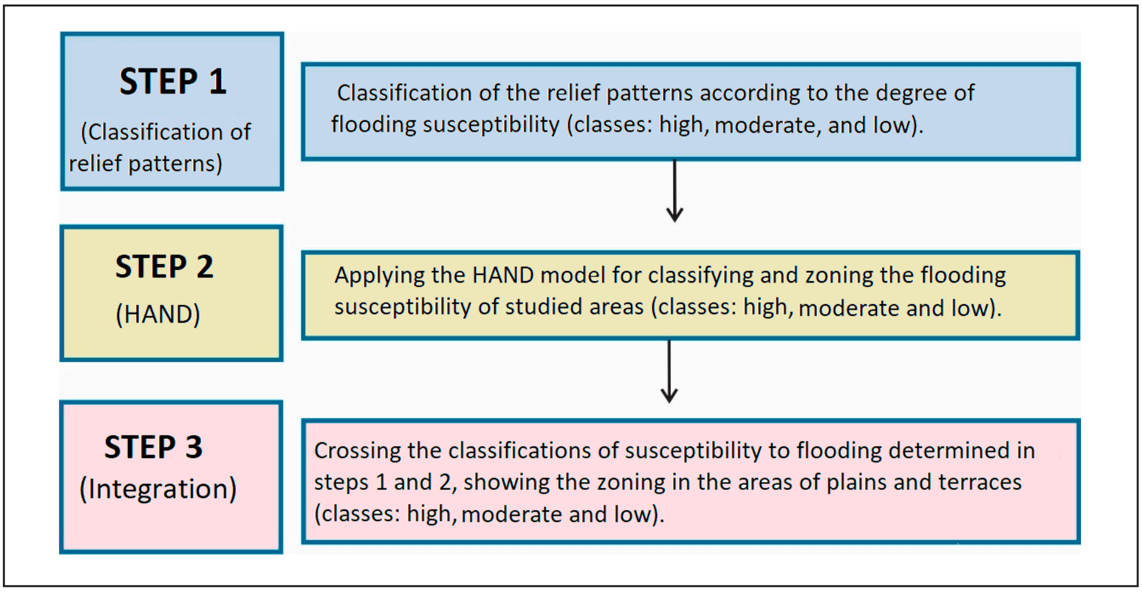


**FIGURE 4** – Flowchart of the three basic steps performed for the analysis, classification, and zoning of flood susceptibility.

## 5. Results

The susceptibility classes of relief pattern were given by the natural characteristics of each relief and to its greater or lesser propensity to flooding. Table 01 shows the proposed classification based on previous mappings of susceptibility and feature behavior in relation to the flooding process, verified in other studies (Dantas and Maia 2010; Dantas 2013; Dantas and Teixeira 2013; Dantas et al. 2014).

In order to classify the susceptibility of relief patterns such as river terraces, coastal plains, alluvium-colluvium ramps, technogenic deposits (embankments on water bodies), and alluvial-colluvial lows according to the regional specificities, the flood classes (high, moderate and low) may vary so that the field team must pay special attention to the relief patterns, adjusting the susceptibility class according to local and regional specificities.

The studied municipalities did not present relief patterns with moderate susceptibility. In both, floodplains (meadows) were classified as highly susceptible to flooding, while the alluvium-colluvium/talus deposition ramps were classified as low susceptibility. In Presidente Kennedy, due to its morphological diversity, the fluvial-lacustrine plains (swamps), fluvial plains (swamps), and fluvial-marine plains (mangroves), as highly susceptible to floods and the fluvial and marine terraces in the low susceptibility class (Figure 5).

The HAND model, which in turn, defines the terrain height thresholds that fall into the susceptibility classes, was cut from the susceptible relief vectors, i.e., areas of the model that were considered not susceptible according to the relief standards, were discarded (mountainous, mounts, and hill domains among others), keeping in mind that these areas would influence the quartile deviation definition and the degree of susceptibility is practically nil.

The quartile deviation analysis of the HAND of Presidente Kennedy and Conceição do Castelo is shown in Table 2.

In Presidente Kennedy, it is observed that 50% of the HAND area was defined as less than 0.55 m, that is, about half of the susceptible land is very close to the drainage level, which already indicates an area highly susceptible to flooding.

Considering the inherent and inevitable geometric errors of any DEM used since they are simplified visions of reality, submitted to a generalization process (Felicísimo 1994), class thresholds below 1 m in height were discarded. Therefore, in Presidente Kennedy the high-class thresholds are between 0 and 1 m.

On the other hand, Conceição do Castelo has the first two quartiles with zero values in their group, so the first two quartiles are used as the high-class threshold (0 to 2.5 m). High terrain values are also observed in the fourth quartile, resulting from the manual photointerpretation of susceptible relief patterns, which in some cases, unintentionally cover areas (pixels) with high altimetric value. Even so, the pixels with a high altimetric value are negligible when compared to the total quantity analyzed.

The algebra results of map involving the resulting rasters (relief susceptibility and terrain susceptibility - HAND) for Presidente Kennedy and Conceição do Castelo can be observed, respectively, in Figures 7 and 8, which compares the old and current/new methodologies. There is considerable improvement in flood modeling using relief patterns, especially in the first municipality.

In general, the Presidente Kennedy municipality is marked by an extensive area classified as highly susceptible to flooding according to model A (Figure 7A), especially in the southeast portion of the municipality. The results of model B (Figure 7B) using the relief information, shows an increase in the area with moderate and low susceptibility, in areas where the relief patterns consist of sea terraces, which present a low susceptibility to flooding, according to relief characteristics.

The areas of the southeastern portion corresponding to the flood plains, fluvial-marine plains (swamps), fluvial-lacustrine plains (marshes) classified as high according to the relief, remain so in model B, composing portions of high flood susceptibility.

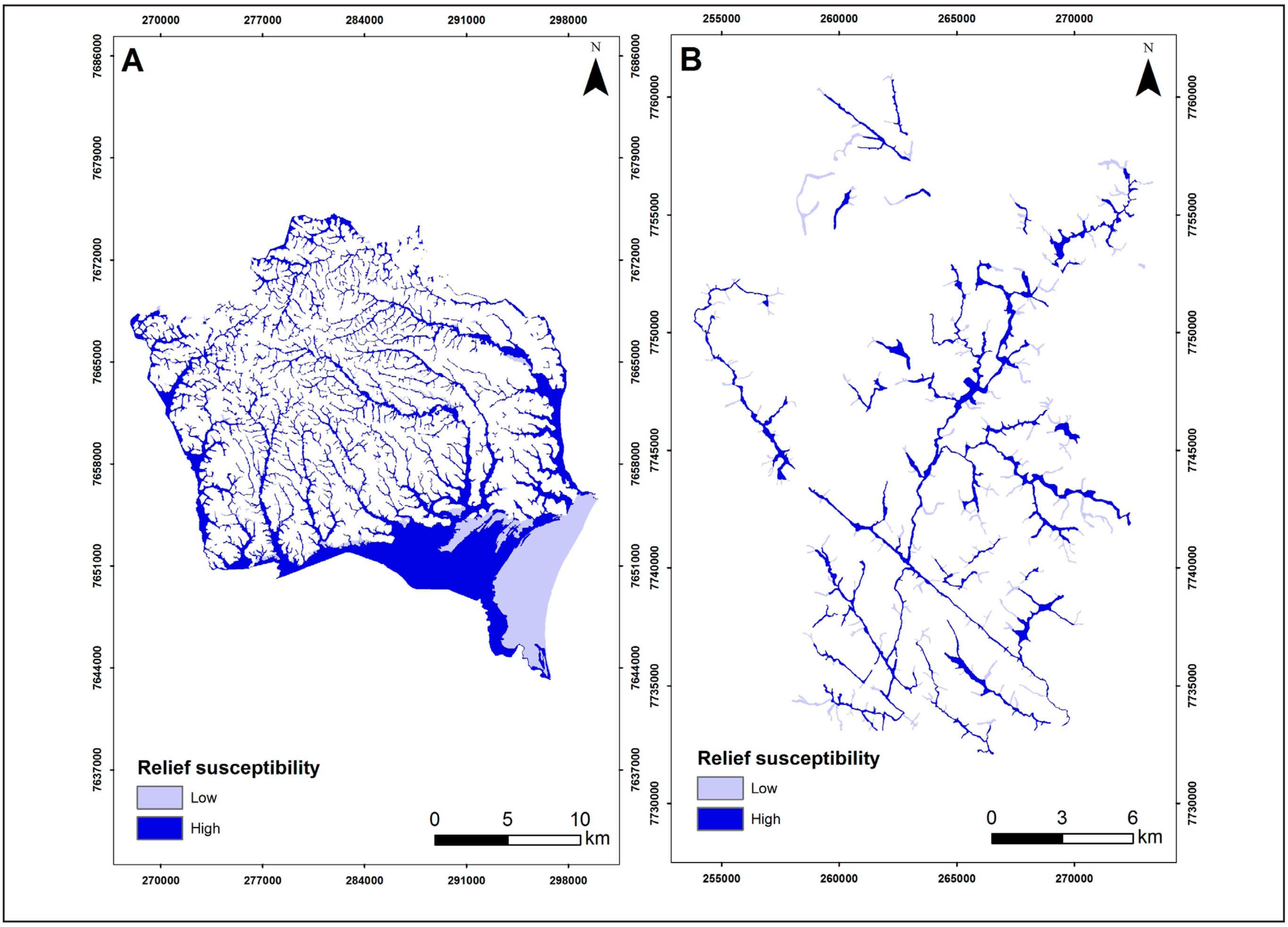


**FIGURE 5** – Raster susceptibility classification of relief patterns regarding the flooding process.

**TABLE 2** – Results of the HART quartile deviation of the studied municipalities.

| **Data frequency (Quartile deviation)** | **Elevation intervals (m)** | |
|---|---|---|
| | **Presidente Kennedy** | **Conceição do Castelo** |
| 0 to 25% | 0 - 0 | 0 – 0 |
| 25 to 50% | 0 – 0.55 | 0 – 2.50 |
| 50 to 75% | 0.55 – 1,93 | 2.50 – 9.10 |
| 75 to 100% | 1.93 a 70,0 | 9.10 – 211.00 |

Conceicao do Castelo, in turn, has more restricted flood plains in all its extension, with some areas where they are more extensive and spread out. Even in these areas, model A assigns low to moderate susceptibility. The model B, however, prioritizes the plains as high to moderate susceptibility, extending to low susceptibility in the alluvium-colluvium ramps.

## 6. Discussions

The analysis of the results given by the two flood modeling methodologies used in Presidente Kennedy and Conceição do Castelo, shows that some significant advances have been achieved, although other obstacles still need further studies.

Table 3 shows the stark difference between the two flood modeling methodologies regarding the area distribution by susceptibility class. In President Kennedy, the area classified as of high susceptibility (96.15%) in model A is much more extensive compared to the area of model B. According to field data collected by the field team using the susceptibility map of model A, the areas of high susceptibility are overestimated, especially in the places with relief patterns such as the marine terraces and alluvium-colluvium ramps.

Furthermore, the reverse process was observed in Conceição do Castelo. Model A underestimated the size of the high susceptibility areas since several flood plains, even the most extensive and distant from the headwaters, were classified as low or moderate susceptibility, when generally in this relief, the water table is usually located near the surface or outcropping in the wet season, defining a high susceptibility to flooding (Dantas et al. 2014).

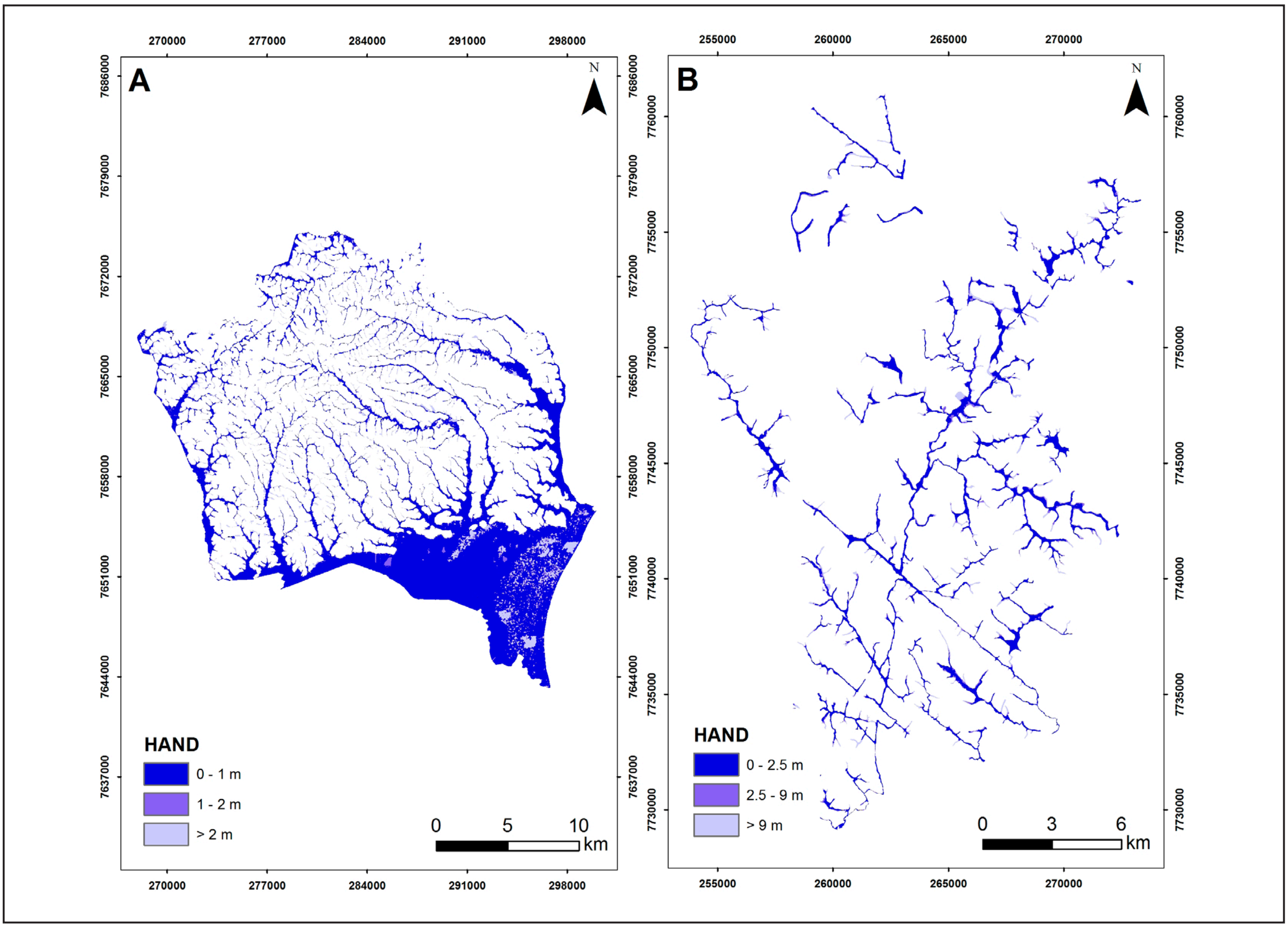


**FIGURE 6** – Raster classification of terrain susceptibility to flooding, based on the HAND model.

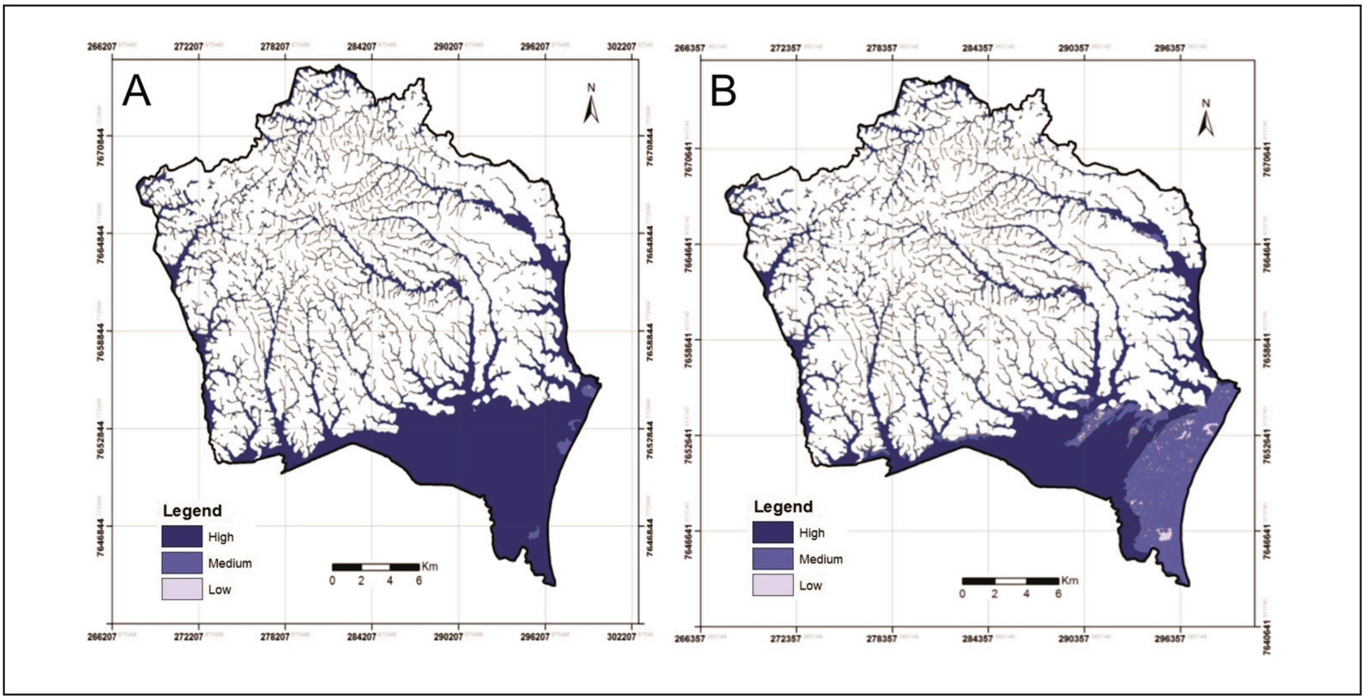


**FIGURE 7** – Flood modeling of Presidente Kennedy, ES. (A) Modeling following the old methodology. (B) Flood modeling using the new methodology that replaces basin information with flood susceptibility of relief patterns.

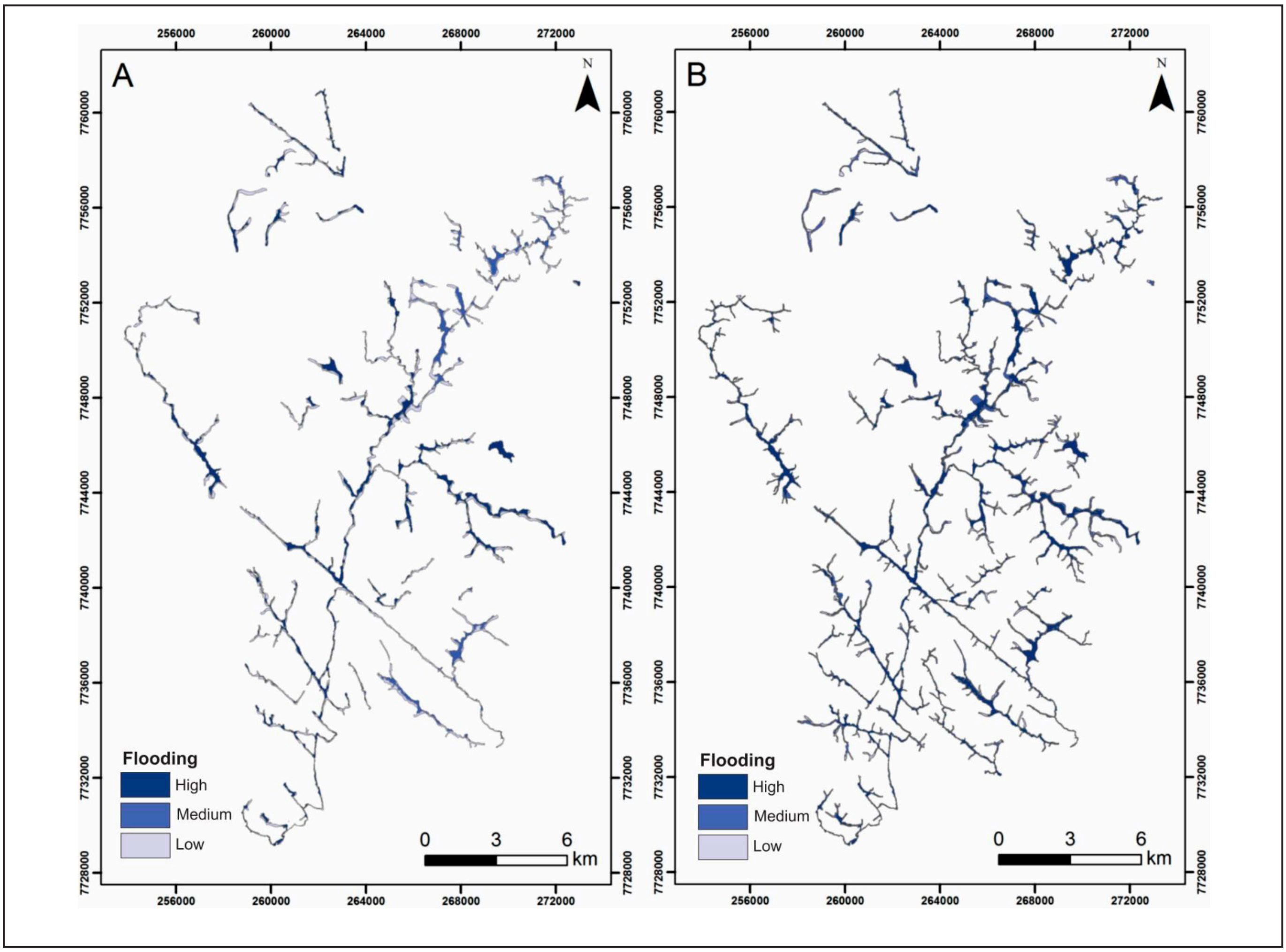


**FIGURE 8** – Flood modeling of Conceição do Castelo, ES. (A) Modeling following the old methodology. (B) Flood modeling using the new methodology that replaces basin information by flood susceptibility of relief patterns.

**TABLE 3** – Quantification of areas in the low, moderate and high susceptibility classes according to flooding Models A (based on the susceptibility of sub-basins), and B (based on the relief patterns susceptibility).

| Class | Presidente Kennedy | | | | Conceição do Castelo | | | |
|---|---|---|---|---|---|---|---|---|
| | Modeling A | | Modeling B | | Modeling A | | Modeling B | |
| | Area (m) | % | Area (m) | % | Area (m) | % | Area (m) | % |
| Low | 1.45 | 0.86 | 5.62 | 3.40 | 7.44 | 38.02 | 4.3 | 16.98 |
| Medium | 4.93 | 2.99 | 43.56 | 26.33 | 4.47 | 22.84 | 7.4 | 29.40 |
| High | 159.39 | 96.15 | 116.24 | 70.27 | 7.66 | 39.14 | 13.62 | 53.62 |

Figures 9 and 10 show in detail how the susceptibility of the relief patterns such as marine terrace and alluvium-colluvium ramps present different results for the models A and B. The field team concluded that the flood areas of these relief patterns are not highly susceptible to flooding, thus indicating that model B describes better the real flooding process in President Kennedy.

Figure 10 also shows that some headwater drainage areas or close to them are classified as highly susceptible to flooding; however, with restricted floodplains, these are usually drainage areas, with a high slope that produce a high-velocity flow (Tucci 2003), more characteristic of flash floods. Therefore, a better representation of the susceptibility in these locations is still necessary.

Regarding the HAND class thresholds, the different experiences with the flood modeling of several Brazilian municipalities and data validation in the field conducted by field teams, indicated that the thresholds obtained from the profiles on the DEM, data from previous floods (which were rarely easily adapted to the methodology), data from

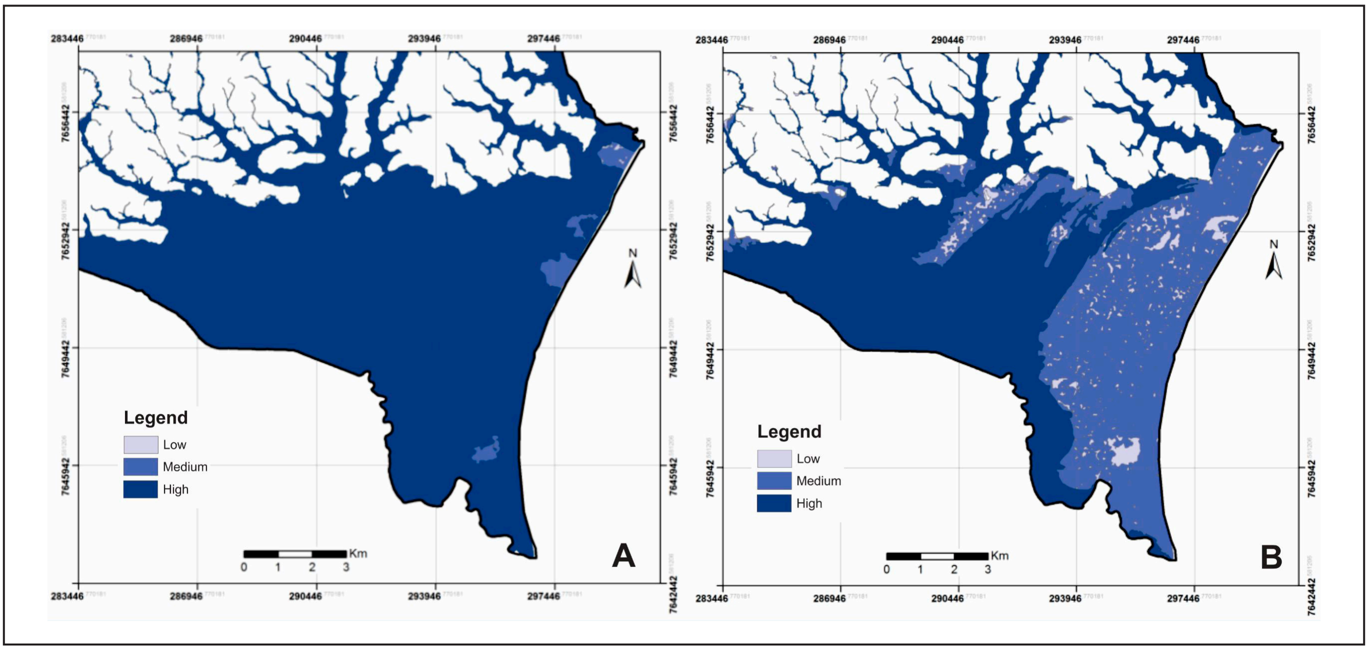


**FIGURE 9** – Modeling detail of the southeast region of Presidente Kennedy/ES. (A) Modeling using the previous methodology (Hand + morphometric information of the hydrographic basins); (B) Flood modeling using the methodology that replaces hydrographic basin information with the flood susceptibility of relief patterns.

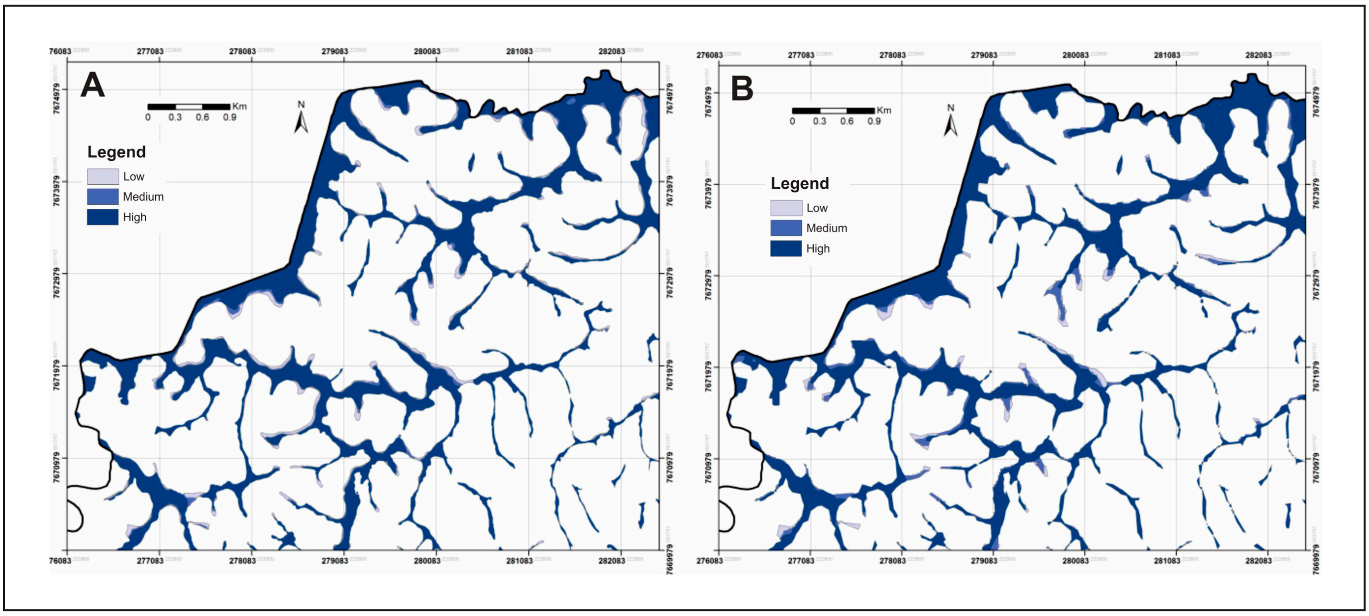


**FIGURE 10** – Modeling detail of the southeast region of Presidente Kennedy/ES. (A) Modeling using the new methodology (Hand + morphometric information of the hydrographic basins); (B) Flood modeling using the methodology that replaces hydrographic basin information with the flood susceptibility of relief patterns.

hydrometeorological stations, and reports from the region residents (difficult to apply to the model) could not meet the classification satisfactorily. This whole process was highly subjective or had widely different thresholds (in the case of hydrometeorological stations) even in municipalities with similar climatic and geomorphological regimes, making it very difficult to reach data compatibility when grouped. A new approach consisting of adopting statistical parameters to remove the subjectivity of the process was then used for this classification.

Several statistical techniques are used for classifying data in cartography, among them: Dispersion Diagram, Column Diagram Analysis, Lorenz Curve, Sturges, Reciprocal Peer Hierarchical Classification, and Quartile Deviation. This last technique is simple to apply and already used in several Geographic Information System software, where the data are automatically calculated and classified (Ramos and Sanchez 2000).

After evaluating each technique, the Quartile Deviation method was chosen because it is a simple and objective method that excludes the subjectivity of the process of defining the cut-off threshold of the classes (Pinto et al. 2015). Basically, it divides the data series into groups with an equal number of occurrences, each comprising approximately 25% of the total frequency of the values presented in the series.

However, as part of this flood modeling methodology, the quartile classification approach should be adapted to the susceptibility classes and the geomorphological conditions presented by the relief patterns. In the mountainous regions with embedded valleys, narrow and restricted plains, with the presence of many alluvium-colluvium ramps, the classification of HAND values should be differentiated from regions characterized by a flatter relief dominated by flood plains or fluvial-marine, lacustrine and deltaic plains, and lagoons. Based on this perspective and on the field validations of modeling data, it was possible to establish three classification hypotheses for the HAND model:

Hypothesis 1: frequency values are divided into 3 groups with approximately 33% each, where the susceptibility of the 1st group (≤ 33.3%) is classified as high; the second group (> 33.3% and ≤ 66.6%) as moderate, and the 3rd group (> 66.6%) as low. This classification is generally applied to environments with high altimetric variation and flattened areas, which are more restricted or confined in embedded valleys.

Hypothesis 2: frequency values are divided into 4 groups with 25% each, where the susceptibility of 1st and 2nd groups (≤ 50%) is classified as high; the 3rd group (> 50% and ≤ 75%) as moderate, and the 4th group (> 75%) as low. This classification is generally applied to environments with relatively high altimetric variation, with the occurrence of embedded valleys, but with more representative flattened areas.

Hypothesis 3: frequency values are divided into 3 groups, the susceptibility of first group is considered high and automatically represented by pixels with a relative height between 0 and 1 m. In this situation the lower threshold of the 2nd group is undefined in terms of percentage; however, the upper threshold should be maintained at the value that represents half of the data frequency, indicating the moderate susceptibility class. From this half, the 3rd group is represented and classified as low susceptibility. This condition is generally applied to environments with low altimetric variation and predominant flattened areas, with the presence of vast plains (of flooding, fluvial-marine, fluvial-lacustrine, etc.) that have extensive flat depositional surfaces drained by a meandering drainage network and the water table is very close to the surface.

Figure 11 shows the heights relative to the nearest thalweg, distributed by the flood-susceptible area in Conceição do Castelo. The 1st and 2nd quartiles (high susceptibility) refer to the 0-3 m interval; the third quartile (moderate susceptibility) corresponds to the 3-10 m interval, and the fourth quartile (low susceptibility) corresponds to the 17-250 m interval, fitting the hypothesis 2 of HAND classification.

Figure 12 shows the heights related to the nearest thalweg, distributed according to the flood-susceptible area in Presidente Kennedy, ES. Unlike the previous case, relative heights with values close to or equal to zero (about 70% of the area) dominate this area. Therefore, hypothesis 3 with the following class thresholds were adopted, 0 -1 m for high, 1-2 m for moderate, and 2-54 m for low susceptibility.

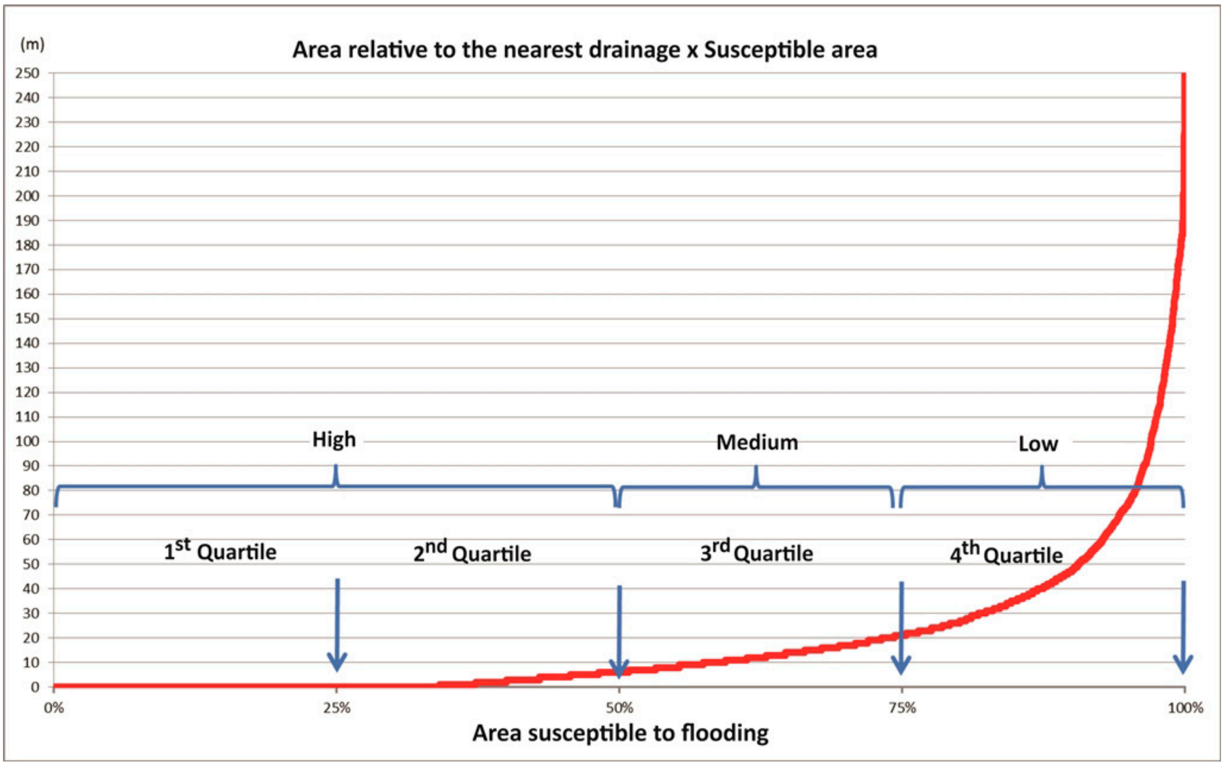


**FIGURE 11** – Graph correlating the height relative to the nearest thalweg (HAND) with the flooding susceptible area in Conceição do Castelo, ES. The 1st and 2nd quartile data are classified as high susceptibility, 3rd quartile, as moderate susceptibility, and 4th quartile, as low susceptibility.

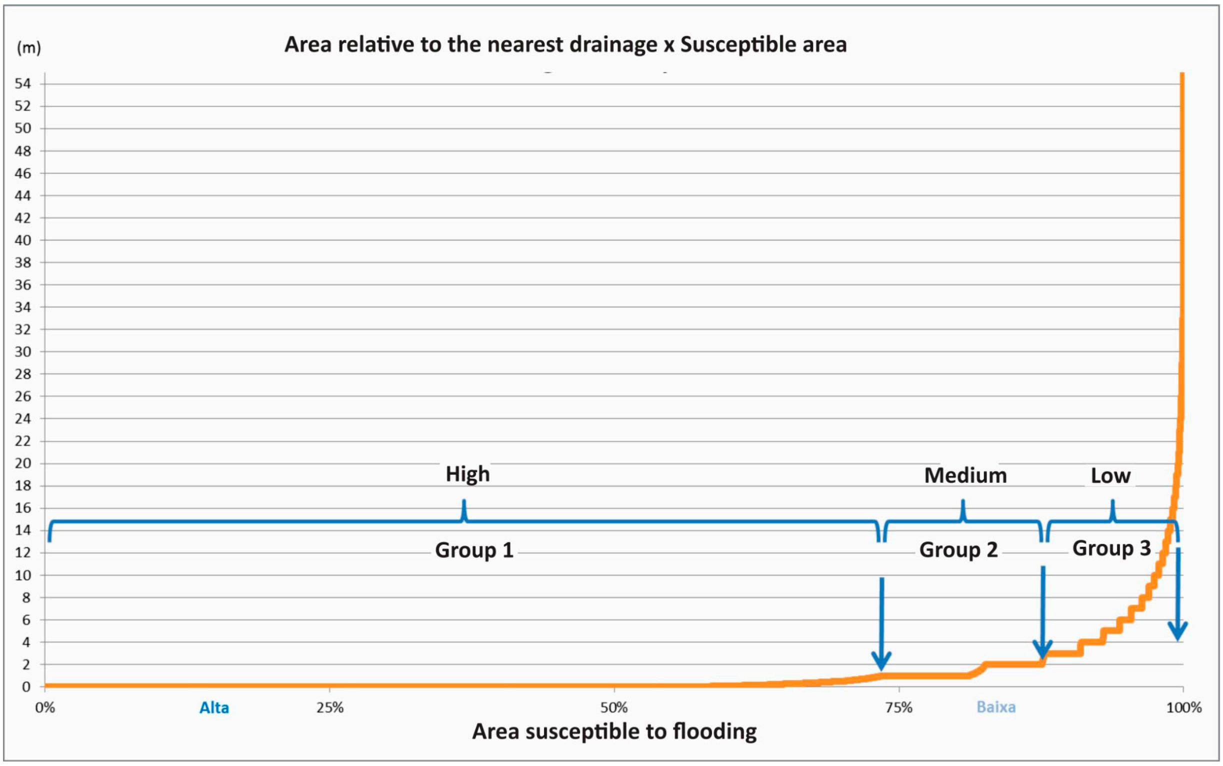


**FIGURE 12** – Graph correlating the height relative to the nearest thalweg (HAND) with the flooding susceptible area in Presidente Kennedy, ES. The high susceptibility class had a threshold close to 70%. The moderate class had an upper threshold value close to 85% and the low class, above 85%.

## 7. Conclusion

The results of this work indicate that the relief patterns associated with the HAND model are efficient methodologies for determining the flood susceptibility of an area, considering the challenge posed by the highly diverse hydrological and geomorphological characteristics of the Brazilian territory.

The flood susceptibility information of the relief patterns generated a final product more consistent with the evaluations carried out in the field, both in Presidente Kennedy and in Conceição do Castelo, even considering the specificities of each municipality.

The flooding susceptibility of areas corresponding to the marine terrace and colluvium-alluvium ramp reliefs are consistently represented in the new modeling methodology.

Using the frequency statistical data of terrain relative height in the classification of the HAND model substantially diminishes the subjectivity in the interpretation of the lower and upper thresholds of each class. The model classification data given by adapting the quartile deviation method is based on the altimetric value of the model pixels corresponding to the whole extension of the terrain susceptible to flood, abandoning the punctual information (in the case of the station data), the subjectivity of the conversations with the region residents, and the estimates made using DEM sections.

It is important to emphasize that these results fulfill the main objective of the study by improving flood modeling methodology but does not end the search for further improvements as the susceptibility mappings advance to different regions of Brazil. Several tests can still be performed using other data sources such as altimetry and slope to improve the models in drainage headwater regions.

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