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Advances in Environmental and Engineering Research

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Research Article

Risk Matrix of Hydrological Disasters Combining Rainfall Thresholds and Social-Environmental Criteria

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Academic Editor: Leonel J. R. Nunes

Special Issue: Environmental Risk Assessment and Risk Management

Adv Environ Eng Res
2023, volume 4, issue 1
doi:10.21926/aeer.2301019

Received: September 30, 2022
Accepted: January 18, 2023
Published: February 07, 2023

Abstract

This paper presents a procedure for risk assessment for hydrological disasters considering the threshold rainfall and environmental and social criteria. A case study was carried out to test its feasibility in the northern region of the State of São Paulo, Brazil. The advantage of this procedure is that it only uses data available on government institutions and websites. For this reason, other regions and countries can easily adapt the procedure to their reality. Initially, the hydrological disasters were obtained including date, type of disaster, geographical coordinates and the number of victims. Next, for each disaster, the daily rains corresponding to the dates of the events were obtained from government websites, to establish the rainfall thresholds. Social criteria weighted the poverty index, population density, and the elderly population. The Environmental criteria weighted hydrology, geomorphology and geology factors. An open-source Geographic Information System (GIS) enabled the spatial distribution of disasters through the characterization of the physical environment in hydrology, geomorphology and geology features. The risk assessment was then obtained by combining the rainfall-triggering event with the environmental Susceptibility with social vulnerability. As a result, 31 of the 138 studied municipalities suffered from hydrological disasters, accounting for 99 occurrences between 2002 and 2017.

Keywords

Hydrological disasters; social criteria; environmental criteria; triggering event; rainfall

1. Introduction

Currently, governments and society are searching for ways to achieve a more rational and adequate use of urban and rural areas, for their protection and preservation for future generations and to mitigate socioeconomic losses related to natural disasters.

Furthermore, Intergovernmental Panel on Climate Change [1] reported that global warming is linked to increased precipitation in some parts of the world. Storms and floods can cause hydrological disasters, and are one of the main causes of climate-related socio-economic losses on a global scale. In addition, anthropic activities can influence the recurrence and magnitude of floods and aggravate the consequences of severe events [2].

Hence, studies of hydrological disasters triggered by meteorological events should consider their probability of occurrence and social and environmental components. Hence, the analyses of risk need to consider both the data of historical occurrences, such as location, intensity, frequency and probability, and environmental, social and economic factors [3].

A considerable amount of literature addresses floods considering climate change and human factors. However, these studies point to the difficulty of quantifying how much each one of these factors interferes with the magnitude of the event. Another problem is the lack of historical data on triggering factors for hydrological disasters [4]. Likewise, Hartmann [5] highlighted the difficulty of working with precipitation and temperature data in tropical regions such as South America. Although Greve [6] also agreed about the uncertainty of the sensitivity of precipitation to global temperature change, their findings revealed a tendency to increase both the precipitation and the precipitation minus evapotranspiration.

As Kundzewicz [7] argues, deforestation and urbanization contribute to the increase in the flood risk, since with the reduced storage capacity of the soil, there is a propensity for greater surface runoff to intensify the number and dimension of the floods. In addition, urban occupation in risk areas increases the potential for damage, as it exposes part of the population to hazards.

Kinoshita [8] points to a worldwide trend of reducing deaths and increasing socioeconomic losses, when analyzing the damage caused by floods. Thus, socioeconomic changes significantly contribute to the potentially greater consequences of future floods. On the other hand, social and economic development reduces vulnerability when directed towards preventive efforts to mitigate damage rather than increasing it. Therefore, socioeconomic changes significantly influence the potential consequences of future floods.

The paper's main goal is to suggest a risk assessment procedure considering the triggering factor of rain against social and environmental factors. The advantage of this framework is the use of available data at the governmental websites making replication in other communities possible.

2. Materials and Methods

2.1 Terminologies

Firstly, the terminologies of risk, hazard and vulnerability concepts used in this paper are described as follows.

Disaster is a serious derangement of a society involving human, material, economic or environmental losses that the community cannot manage with its means Kinoshita [8].

Risk quantifies the potential losses involved in a disaster. It involves the quantification through the mapping or development of models to evaluate socio-economic and environmental aspects or the association of both techniques. It can also be set as a probability of losses from combining technical and environmental disasters with vulnerable circumstances.

In this way, the hazard is a potential physical event capable of generating social, environmental, and economic losses [3].

Hence, the analyses of risk need to consider both the data of historical occurrences as location, intensity, frequency and probability, and environmental, social and economic aspects [9].

Resilience is the ability of society to resist and recover from the consequences of a hazard, preserving or recovering the essential basic functions of that system, with its resources or efforts, before and during the events [10].

Vulnerability encompasses both lack of resilience and susceptibility to damage. Accordingly, it can also be defined as conditions of a society or community that magnify the impact of a hazard [9].

According to UNISDR (United Nations International Strategy for Disaster Reduction) [10] the socio-natural hazard must be based on an analysis of environmental susceptibility added to social vulnerability combined with the triggering rainfall.

Environmental susceptibility involves the characteristics of the place that make it more likely to be affected by a given disaster, such as geology, geomorphology and geotechnics. Social vulnerability uses the concepts of [11] and [12] that combine demographic density, poverty index and elderly population.

This article considers the definition of UNISDR [10] for risk using a matrix in which environmental susceptibility and social vulnerability are added to create the index (S) and crossed with the triggering rainfall (R).

2.2 Description of the Area to be Analyzed

To test the feasibility of the procedure a region of the state of São Paulo that has predominantly small and medium-sized cities was chosen. The region of interest involves three administrative regions of the north of São Paulo state, comprising 138 cities (see Figure 1), and focused on urban areas. In this research stage, we focus only on urban areas, since rural areas present divergences of environmental, economic and social contexts regarding disasters that occur in urbanized areas. Such divergences could make it difficult to analyze the importance of factors in the analysis.

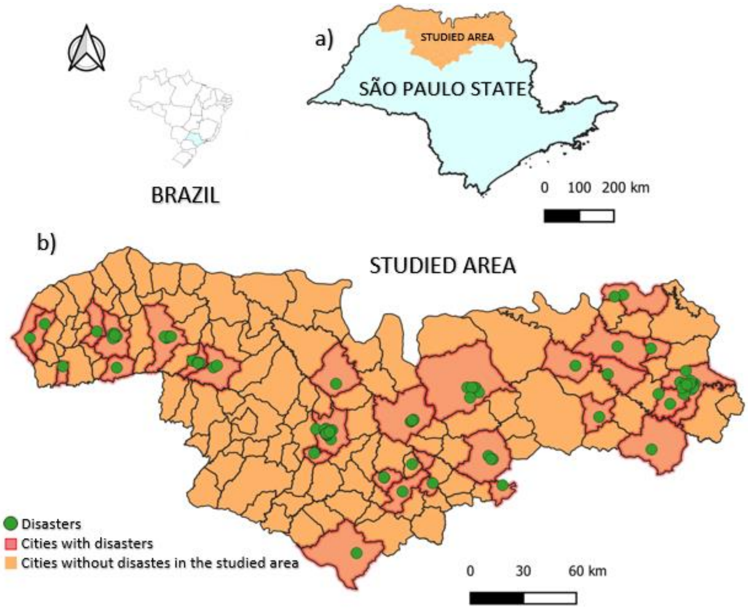

Figure 1 (a) North of São Paulo State, Brazil. (b) The Study area, 31 cities with flood data.

The study period was between 2000/09/01 and 2017/08/31, since in South America the hydrological year starts in September and ends in August of the subsequent year, to obtain consistent results of the rainfall that is a preponderant triggering agent of floods.

From 2017 until now few investments were made in the study region so the study period still represents the current reality. For example, Martello [11] reports that even after the conclusion of the urban drainage works, flooding still occurs in São José do Rio Preto due to the insufficiency of the works carried out. Previous studies by Pereira [12] and PDU [13] proposed and budgeted drainage works for the city of Franca to solve the recurrent floods, mainly in January. However, to date, no work has been carried out. The city of Barretos started the project to restructure the urban drainage infrastructure in February 2022 and started the works in August 2022. The lack of planning in Brazilian cities is related to the increased records of floods, inundations and floods Silva Ferentz [14]. This scenario can be explained by the fact that the necessary importance of investments in drainage and storm sewers is not given in emerging Latin American countries [15].

Then, the occurrences were obtained from the database of Pellegrina [16] and the Meteorological Research Institute of the São Paulo State University (IPMET-UNESP) [17], including date, type of damage and triggering rain, geographic coordinates and the number of victims. 31 cities presented hydrological disasters resulting in 99 disasters (see Figure 1).

2.3 Rainfall Triggering Data

For each hydrological disaster the rainfall on the day of the occurrence was obtained from open data at the websites of government agencies, such as: ANA (National Water Agency) [18]; DAEE (Department of Water and Electric Power) [19]; CEMADEN (National Center for Monitoring and Alerting Natural Disasters) [20].

The probability of a certain interval of rainfall triggering a hydrological disaster is considered daily rains. Not all cities had consistent rainfall data. As a result, the triggering rainfall was studied with the data of the only two cities with sufficient data for statistical analysis: Franca and São José do Rio Preto.

Franca with 23 disasters and São José do Rio Preto with 18 disasters. Therefore, the daily rainfall data for the day of the occurrences were grouped into two regions, cities geographically closer to Franca and São José do Rio Preto, respectively, obtaining a different number of precipitation intervals (equation 1) and also the rainfalls amplitudes (equation 1). Such a procedure provides the triggering factors for the hazard calculation, but will only provide a benchmark for interpreting the rainfall data. In this way, the rainfall historic of Franca was applied to the cities close to it, and similarly to cities close to São José do Rio Preto, since the ratio between the number of disasters within a given range of millimeters of rainfall history within the period under analysis under analysis obtains the calculation of the weight of the triggering factor.

Thus, the precipitation intervals resulted from histograms constructed following the Sturge's rule as equation 1.

$$K \cong 1 + 3{,}33 \log N \tag{1}$$

K: number of classes; N: size of the data (number of disasters).

$$A = \frac{(Max. - Min.)}{K} \tag{2}$$

A: Amplitude; Max: Maximum value of rainfall; Min: Minimum value of rainfall.

The amplitude of each class considered the difference between the maximum and minimum rainfall triggering disaster for the studied city. Equation 3 made it possible to normalize, besides the rainfall data, all the data from the environmental and social criteria used in the present study, so that the quantification of the influence of rain on the occurrence of disasters was restricted to the interval between 0 to 1, to which 0 represents the minimum influence of rainfall as the occurrence of that specific disaster and 1 represents the maximum influence compared with other locations.

$$I_i = \frac{(V_{observed} - V_{minimun})}{(V_{maximum} - V_{minimun})} \tag{3}$$

where:

I: the data to be normalized

$V_{observed}$ = value observed

$V_{minimum}$: minimum value of the sample

$V_{maximum}$: maximum value of the sample

2.4 Environmental Susceptibility

The environmental assessment of the place of occurrence considered the geological, geomorphologic and geotechnical characterization by the respective maps: Geological Map of the State of São Paulo [21]; Geomorphologic Map of the State of São Paulo [22] and Geotechnical Chart of the State of São Paulo [23]. From the maps and geographic coordinates of each disaster, it was possible to know the environmental characterizations of each local disaster. In this way, each type of characterization, whether geological, geomorphologic or geotechnical, is weighted directly proportional to the number of disaster occurrences on the respective characterization. For example, 66 disasters out of 99 occurred in the Adamantina geological formation. Thus we divided 66 by 99 and obtained the $V_{maximum}$ of 0.68 which was adopted to normalize Geology according to equation 3. The $V_{minimum}$ adopted was 0, as geological formations did not occur in the study area. The same was adopted for the weighting of the geomorphology and the geotechnical.

After obtaining the normalized values for each of the three environmental criteria using equation 3, equation 4 was used, adding the normalized values of each environmental criteria. Subsequently, the environmental criterion was also normalized between 0 and 1 using equation 3. For example, the city of Batatais presented 0.22 for geology, 0.80 for geomorphology, and 0.73 for geotechnical, adding up to 1.75, which normalized became 0.51

$$Environmental\ Criteria = Geology\ criteria + Geomorphology\ criteria + Geotechnic\ criteria \quad (4)$$

2.5 Social Vulnerability

The Poverty Factor, Elderly Population and Demographic Density were the three indices considered for the social criterion, as shown in equation (5), according to the methodology proposed by Palmeira [24] and by Hadder [25]

$$Social\ Criteria = Poverty\ index + Density\ criteria + Eldery\ population\ criteria \quad (5)$$

2.5.1 Poverty Index

The poverty index was obtained by the deviation of the monthly income of the poor population of each location under study about the poverty line, defined in 1990 by the Central Bank as US $1.90 per day. As the Brazilian Real (BRL, current currency) about USD (North American Dollars) undergoes a daily variation, to obtain the value in USD, the average value of the exchange rate for the months of 2010 was taken as a reference, resulting in BRL 52.00 monthly, obtained by the Commercial Association of São Paulo [26], so that the fluctuation of the North American currency would not influence the data. The per capita income of the poor in the urban region of the analyzed municipalities was based on the Atlas of Human Development in Brazil [27]. For comparative purposes, the index was adopted as the ratio between the monthly income, BRL 52.00 of the poverty line, by the monthly income of the poor in the municipality of the accident.

2.5.2 Demographic Density

Based on EMBRAPA [28], urban population data for 2010 were obtained, divided by the urban area provided by IBGE [29], which made it possible to generate the population density only for the urbanized area of the municipalities studied. Subsequently, equation (6) was applied to normalize the values.

2.5.3 Elderly Population

The representative index of the elderly population was constituted as the percentage of the population over 60 years old about the total population of the municipality, both demographic data were obtained from Segoni [30]. As with the other indices, equation (6) was also applied to the final data.

2.6 Risk Assessment Procedure

Segoni [30] proposes a methodology for the construction of a disaster susceptibility map in which it presents three levels of Rain and three levels of Susceptibility, resulting in four levels of Hazards to form a square matrix that combines these data. The present work applies the same methodology to floods. However, dividing five Rain classes and five Susceptibility (Social + Environmental Criteria) classes, which results in eight Risk classes, guarantees the interpretation of the results in a more detailed and accurate way (see Figure 2). According to the methodology proposed by the author, each Rain Threshold and each Susceptibility index has a lower and upper limit so that the gradual risks are obtained by combining each class T with the entire S and each class S with all the T. In this study, the term socio-natural Criteria was used instead of the term Susceptibility. The limit S1/T1, as well as the R1/T1, both result in R0, represents the hazard class that comprises the disasters with the lowest probability of occurrence since there is a low history of disasters with the rainfall in question and low influence of the socio-environmental conditions. On the other hand, the S5/R5 limit, which results in R8, comprises the locations where there is a greater probability of disasters, since the registered rainfall and the environmental and social criteria were the ones that most influenced the claims of the period and area studied. Thus, between R0 and R8, the Hazard classes combine the intermediate weights of the analyzed criteria to generate the necessary categorization used in the risk/risk spatial distribution. To optimize the spatial analysis of the data, it was necessary to adopt the color pattern representing the parameters T, S and R.

Susceptibility (Social +Environmental Criteria)

Rainfall Thresholds	S1	S2	S3	S4	S5
T1	R0	R1	R2	R3	R4
T2	R1	R2	R3	R4	R5
T3	R2	R3	R4	R5	R6
T4	R3	R4	R5	R6	R7
T5	R4	R5	R6	R7	R8

Figure 2 Risk Matrix adapted of [25]. S1: very low susceptibility; S2: low susceptibility; S3: medium susceptibility; S4: high susceptibility; S5: very high susceptibility; T1: very low rainfall; T2: low rainfall; T3: medium rainfall; T4: high rainfall; T5: very high rainfall; R0: null risk; R1: extremely low risk; R2: very low risk; R3: low risk; R4: medium risk. R5: high risk; R6: very high risk; R7: extremely risk. R8: very extremely risk.

Hader [25] uses a similar matrix as the one presented in Figure 2 for landslide analyses in the São Paulo State coastline. The adopted methodology used spatial information on socio-natural susceptibility and rainfall thresholds to produce a risk map.

3. Results

3.1 Triggering Results

As shown in Table 1, the rainfall in the Franca analysis group had shorter rainfall intervals. However, a higher proportion of the number of disasters per city, shows that the municipalities in the Franca group have a greater susceptibility to hydrological disasters when considering only the triggering agent. The São José do Rio Preto group, however, with a smaller number of events in the historical period, a higher proportion between disasters and rainy days, a fact the greater recurrence of heavier daily rains in relation to Franca can explain that. In general, high rainfall causes more hydrological disasters; nevertheless, as such rainfall is less recurrent than lower rainfall, when divided by the number of rainfall belonging to the interval in which it is found, it is possible to know the real influence of each rainfall as shown in Table 1.

The choice of grouping the two areas for analysis, the Franca group and the São José do Rio Preto group, offers benchmarks for comparison that measure the influence of the volume of rainfall on the occurrence of hydrological disasters. If the unified data were treated in a single history and amplitude and a fixed number of intervals, the perception of the quantitative and qualitative differences between the two groups shown respectively in Table 1 and Table 2, respectively could not be analyzed because there would be no statistical consistency due to the small number of disasters per group. On the other hand, the joint analysis of all data would be impaired due to distances.

Table 1 Two groups of qualitative analysis of daily rainfall.

São José do Rio Preto			Franca		
Ranges	Probability	Normalized Probability	Ranges	Probability	Normalized Probability
0-22	0.036	0.036	0-11	0.008	0
22-44	0.028	0.028	11-22	0.021	0.070
44-66	0.084	0.084	22-33	0.028	0.103
66-88	0.04	0.040	33-44	0.026	0.092
88-110	0.143	0.143	44-55	0.071	0.333
110-132	0	0	55-66	0.2	1
132-154	1	1	-	-	-

Table 2 Quantitative with comparison São José do Rio Preto and Franca.

	São José do Rio Preto	Franca
Number of disasters	67	32
Number of cities with disaster	22	9
N° Disasters/N° Cities	3.05	3.44
Days with rain in the analysis period	1671	3008
Total days in the analysis period	6205	6205
N° Disasters/N° Days with rain	0.0401	0.0103

According to Figure 3 the rains present a uniformity of relevance classification. However, such uniformity is apparent because as already discussed and shown in Table 1 the intervals and frequencies of rain that causes more disasters are different for the two groups. In general, the locations had a low influence on the occurrence of disasters due to the discrepancy between the most recurrent rainfall intervals.

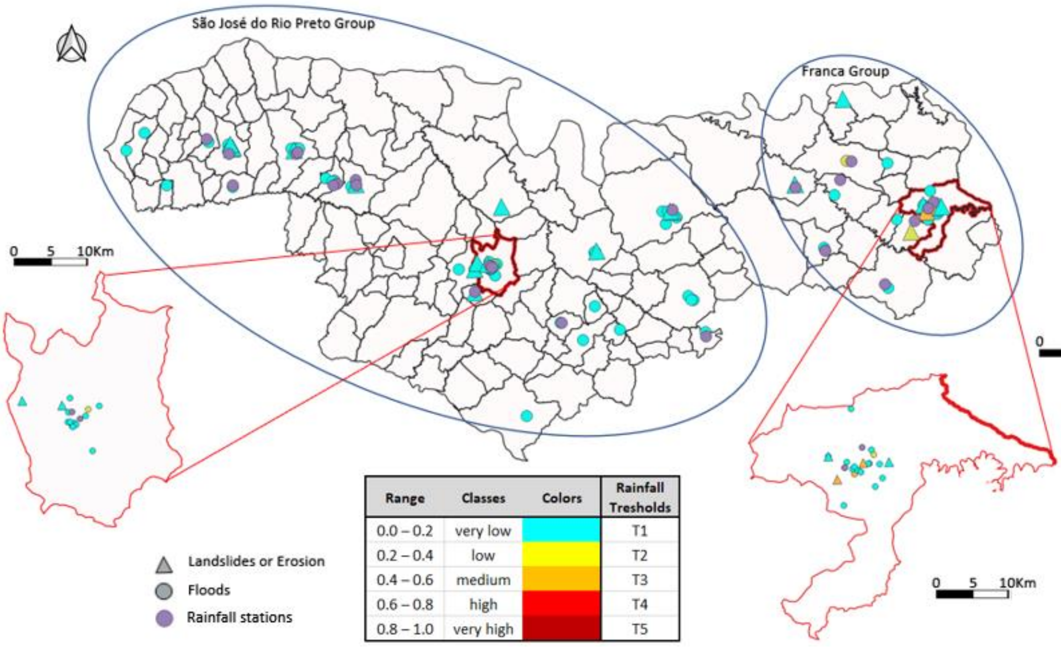

Figure 3 Rainfall thresholds, stations and events.

Figure 3 also shows the location of rainfall stations. Four cities in the study region have two rainfall stations. Among them Franca and São José do Rio Preto, which are shown in detail in Figure 3. The disasters, in general, are concentrated in urban areas and the location of rainfall stations. For cities that did not have rainfall stations, data from the nearest one was used.

3.2 Environmental Results

The Adamantina Formation (Bauru Basin) presented the area with more disasters, as shown in Table 3, since most of the northern territory of the state of São Paulo is also composed of this Geological Formation. The such formation had the predominance of fine and very fine sandstones with carbonate cement. This explains the geotechnical predominance of regions with disasters, which have great susceptibility to erosion, since the sandstones have low cohesion between the quartz particles.

Table 3 Geological influence on floods.

Geology	N° disasters	N° disasters/Total of disasters	Normalized
Itaqueri Formation (Bauru Basin)	14	0.14	0.22
Adamantina Formation (Bauru Basin)	68	0.68	1.00
Santo Anastácio formation (Bauru Basin)	1	0.01	0.01

Serra Geral formation	9	0.09	0.10
Continentals Sediments	7	0.07	0.13

The greater recurrence of disasters had Medium hills and Wide hills as geomorphologic characteristics, as shown in Table 4, since such a geomorphologic characteristic occurs on the Adamantine formation, which provides greater probabilities of disasters. Although such geomorphology is characterized by low and medium drainage density, many valleys and plains provide urban flooding because the lower gradients make the flow difficult and favor the accumulation of rainwater.

Table 4 Geomorphologic influence on floods.

Geomorphology	N° disasters	N° disasters/Total of disasters	Normalized
Wide hills	42	0.42	0.80
Medium hills	52	0.52	1.00
Wide elevations	2	0.02	0.04
Rounded elevations	2	0.02	0.04

When analyzing Table 5, it is noted that there is a predominance of soils that are more susceptible to erosion, having as a predominant factor the large number of disasters in the Adamantina Formation (Bauru Basin) and Itaqueri Formation, composed of sandstones with clay cement that also have great credibility. It is important to analyze erodibility because the soil properties that influence its credibility also affect the infiltration rate, permeability and total water storage capacity, resistance to dispersion forces and transport by rain. Another possible explanation is the greater probability of clogging of rainwater networks by particles carried by water that also contribute to the silting up of rivers and streams.

Table 5 Geotechnical influence on floods.

Geotechnical	N° disasters	N° disasters/Total of disasters	Normalized
Low susceptibility to the various processes of the physical environment	19	0.19	0.40
High susceptibility to erosion	34	0.34	0.73
Very high susceptibility to erosion	46	0.46	1.00

In Figure 3, disasters with erosion and landslides add up to 20, and floods add up to 79. In the study area, 46 localities presented very high susceptibility to erosion and medium hills, not wide hills. That points to the main influence of the hydrological factor, which is characteristic of hydrological disasters.

3.3 Social Results

When analyzing individually the two cities most evidenced by the study, São José do Rio Preto is highlighted in the poverty index. However, its total social vulnerability is lower than Franca's. Demographic density had more influence in the region of Franca, since the municipalities located more to the northeast of the studied region have smaller urban areas and are more populous than the rest of the municipalities. Thus, it can be concluded that more concentrated urbanization is directly related to social vulnerability, since cities with denser populations (besides Franca, Taiúva and Restinga) presented higher values of social vulnerability. When analyzing all cities, the Poverty Index weighs more significantly the cities with greater social vulnerability (Igarapava, Rubnéia and Restinga), placing the elderly population as the least influential factor in the social vulnerability except in the city of Jales. Figure 4a shows the medium classification's predominance in the social criterion representation.

Figure 4b shows the predominance of the very high classification in the entire region close to São José do Rio Preto, Jales and Barretos, a region where the Adamantine formation predominates, as already explained, which allows us to conclude that this geological formation prevails over the Environmental susceptibility.

Figure 4c shows that the Franca region has a vulnerability predominantly classified as medium, low and very low. In contrast, Barretos and its surroundings, as well as Jales and its surroundings, are classified as high. São José do Rio Preto is not classified as high but as medium as it has a low weight in the social criterion. Franca in particular has a high and medium rating as it is less weighted by the Environmental criterion (belonging to Itaqueri Formation) and more by the social one.

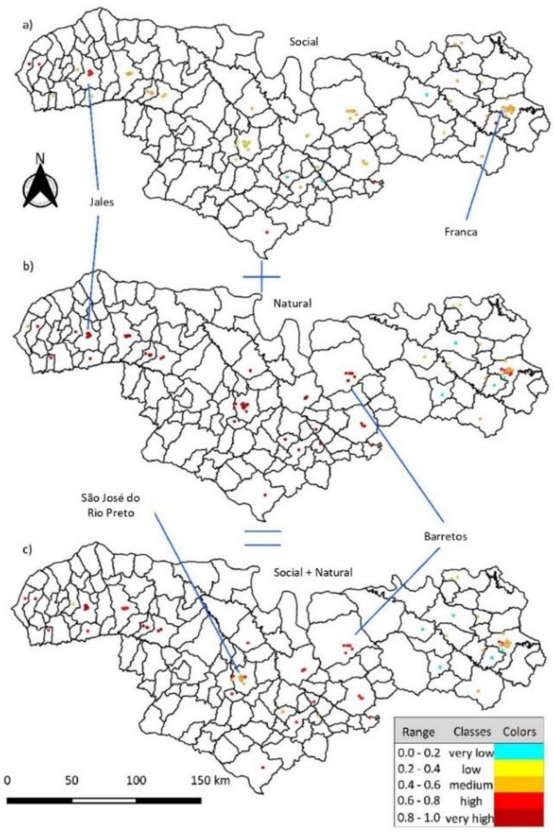

Figure 4 S-Social and Environmental Criteria's combination.

This analysis allows us to conclude that the two largest cities are less vulnerable than the smallest cities analyzed. Thus, to conclude that for the same given rainfall, disasters are more likely to occur in the smaller cities than in Franca and São José do Rio Preto. Furthermore, disasters are less likely to occur in the Franca region for the same rainfall than in other regions, so the preponderant factor of disasters in this region is rainfall.

4. Discussion

Figure 5 shows the final risk map for daily and three days of rain. The predominant classifications for those two risk maps were R3, R4 and R5. Comparing daily rain and three days rain maps, we can notice a 40% increase in the number of disasters classified as R3, a 200% increase in the R4 and a 30% increase in the R5 classification. On the other hand, there were decreases for the classification of R6 at 25%, R7 at 80% and R8 at 40%. Therefore, it can be concluded that continuous rains over a long period cause fewer disasters than short rains.

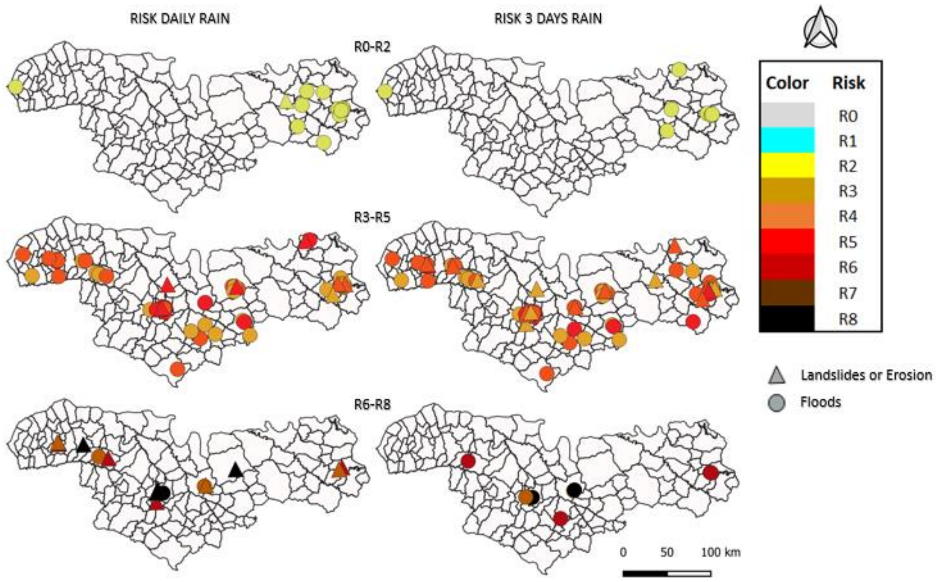

Figure 5 Risk Map based on the risk matrix for daily rain and 3 days rain.

The common point between the events classified by H8 is: they are founded in the Adamantine formation, Medium hills, High susceptibility to erosion and high weight to social criteria and daily rainfall well above the disaster average. For three days of rain, we had two disasters with H8, the occurrences are more related to high rainfall and such physical characteristics. There are some dots that we cannot see in R6-8 for daily rain but we can see in R6-8 three days of rain. This points to the vulnerability of the urban drainage over a long period, or the volume of rain that triggered this disaster is more common in this localization; therefore, the probability of disaster increases.

On the other hand, the administrative region of Franca is well represented by occurrences in locations with higher demographic densities and lower rainfall, which present risks below class 5.As shown in Table 2, the region of Franca presents less intense rainfall, but more rainy days, so when the accumulated three days of rain are analyzed, such a region turns from class T2 to classes T3, T4 and T5. The 3 days accumulated rain in São José do Rio Preto region showed that some disaster locations classified as T6, T7 or T8 changed to classes T3, T4 or T5 due to the predominance of more punctual rains than long duration.

5. Conclusions

The georeferenced representations of the area in the northwest of the state of São Paulo allow us to conclude that the drainage networks are overloaded in these cities, since urban planning did not adapt to the sudden population growth. In addition, the physical characteristics are less influential in disasters in this region, a fact that is explained by the current drainage conduit that prevents water from coming into contact with the soil. In this sense, the social criterion of urban population density mainly represents the sudden urban occupation in disagreement with the drainage dimensions.

It can be concluded from Table 1 and Table 2 that it is not the highest volumes of daily rainfall that are more likely to trigger disasters, but smaller and more frequent ones. The group from São José do Rio Preto covers the two most dangerous occurrences but is mainly due to the socio-natural criteria being the rain contributor, so it is possible effective state interventions that mitigate the consequences of disasters in order to establish more resilient cities to the climate conditions.

It was impossible to find all the rainfall data for all municipalities with disasters, so the daily rainfall data from the nearest rain gauge was adopted to compose the data. The final result was fewer disasters than expected due to insufficient data essential to the composition of all analyzed parameters; disasters with other divergent damages from floods, inundations, and runoff were also disregarded since the focus of this article is only hydrological disasters. Corroborating with Kundzewicz [4], it was impossible to detect the influence of climate change on the occurrences due to the brief period studied. However, knowing the danger can serve as a starting point for other studies focused on climate change, once the social, economic and environmental influences are known. Thus, with the physical factors, the influence of climate change can be better analyzed separately.

Acknowledgments

The author would like to thanks the retired Professor Dr. Ilza Kaiser for her insights for the development of this research.

Author Contributions

Leonardo Vaz Moreira Magalhães: data management and GIS modelling; Anna Silvia P. Peixoto: conceptualization, methodology and paper revision, Gustavo Garcia Manzato: GIS modelling and conceptualization, paper revision; Barbara Stolte Bezerra: methodology, paper revision and edition.

Funding

CNPq-National Council for Scientific and Technological Development.

Competing Interests

The authors have declared that no competing interests exist.

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