Risk assessment of alluvium in the streams of Madeira island

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Abstract: In Madeira, the risks considered more serious are mainly due to the geomorphological characteristics of the island and there existing weather conditions. It becomes relevant to determine the flood peak discharge in certain sections with interest in Madeira, such as, the river mouth of several watersheds. From the detailed characterization of the watersheds, it was obtained some needed data to introduce in the software HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) such as area, concentration time (t_c) and curve number (CN). Thus, it was possible to make simulations of certain historical events to proceed with the validation of the hydrological model and apply it in the entire extension of the island. Therefore, it was also estimated flood peak discharges for the 39 watersheds in study, according to the defined return periods of 20, 50, 100 and 500 years.

The scarcity of hydrometric data and the spatial variability of the precipitation regime were a constant challenge in this work. However, it was selected and consistently applied a uniform approach to all basins in study. It is recognized that the results are associated with a non-negligible uncertainty that can only be reduced with an ongoing commitment to monitoring.

Areas that are usually affected by events of intense precipitation in Madeira are located at higher heights as, for example, in the central mountains, and mostly on the Northside of the island. The characteristics of the northern watershed, including its largest dimension and the largest slope also contribute to the higher flood peak discharge that is generated comparing to the south side of the island. Nevertheless, watersheds of the North are less populated, so the impact on population and economic activity is potentially smaller.

Keywords: Madeira; watershed; precipitation; alluvium; flood peak discharge; hydrological model.

Introduction

The alluviums are cyclical and natural events that have been occurring with some frequency and different magnitudes in Madeira island. These occurrences are caused by intense rainfall, which cause flash floods of great scale and landslide with huge destructive potential.

The Madeira archipelago is located in the Atlantic Ocean on the Southwest side of the Iberian Peninsula and Madeira, Porto Santo, Desertas and Selvagens constitute it. The present work is based only on Madeira, which has an area of 742 km^2 and an average height of 646 m. The value of the average slope (56%) already shows that this has a very sharp relief and strong shapes that is related with enclosed and deep valleys (SRA & INAG, 2003).

Several episodes of landslides and floods have been occurring in the archipelago since the seventeenth century to the present. Among all the disasters that have occurred, the greater was the alluvium on October 9th, 1803. According to some records must have died between 800 and 1000 people (Quintal, 1999) at the time. Recent events have caused a lower number of victims, however, in the past few years studies has been done concerning these phenomena and presented special measures of control and risk management.

The main objective of this work is the development and application of a methodology that enables the determination of the flood peak discharge in certain areas with interest in Madeira.

Methodology

It was considered convenient to define the hydrographic basins from the digital terrain model in order to control the process of characterization of watersheds and produce a complete and consistent set of data. All the defined watersheds can be seen in Figure 1.

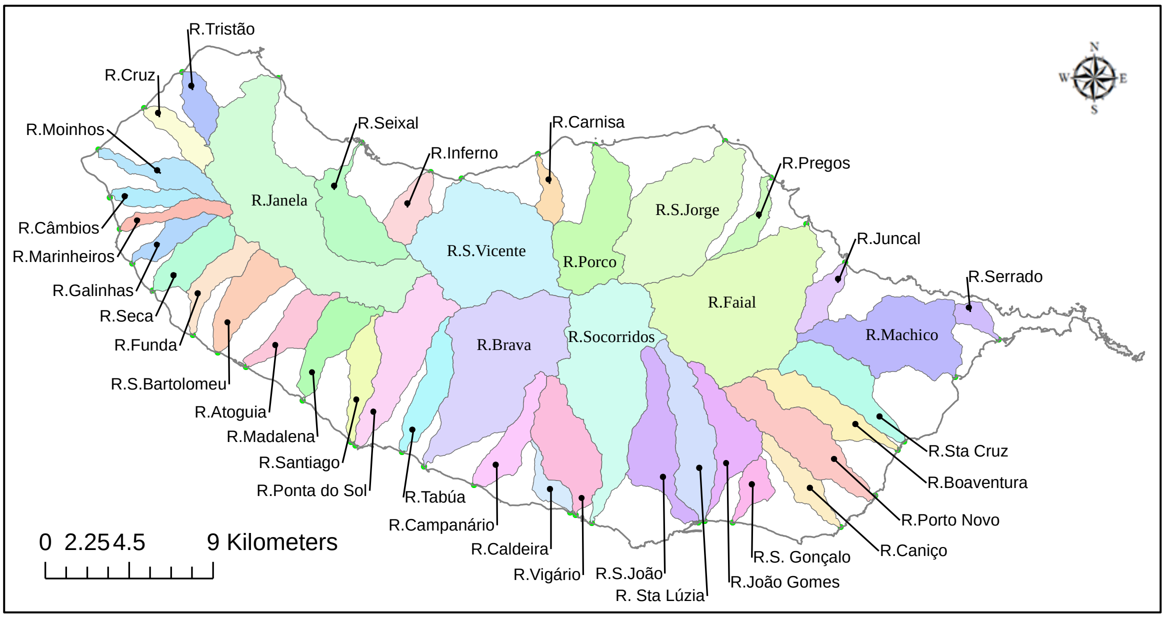

Figure 1: Location of the 39 watersheds of Madeira.

During all the work, the software used was ArcGIS and HEC-HMS. ArcGIS, as a GIS (Geographic Information System) solution allowed, among other functions, manage, edit, create and analyse the available geographic data (Esri, 2013). Concerning the HEC-HMS (Hydrologic Engineering Center's Hydrologic Modelling System), this is a hydrologic modelling system (Scharffenberg, 2013) that was used with the objective of generate hydrograph through hyetographs. Regarding the precipitation records used along this work, they were provided by LREC ("Laboratório Regional de Engenharia Civil"), IGA ("Investimentos e Gestão de Água") and collected from previous studies.

To identify the types of soil, it was used the Madeira Soils Map ("Carta de Solos da Ilha da Madeira") (IICT *et al.*, 1992) that adopts the legend of FAO/UNESCO (1988) for taxonomic systematization of soils. For the study of land use, it was applied the Land Use Map of Madeira

("Carta de Uso do Solo da Madeira") (COSRAM 2007). In both cases, there was an intersection of the respective maps with the Madeira DTM (digital terrain model) where were defined all the watersheds. With these procedures, it was achieved the percentages of the types of soils and land uses for each watershed.

For the calculation of the concentration time for each watershed in Madeira were used four formulas: Giandotti, Kirpich, Temez and the formula of Soil Conservation Service (SCS) (Chow *et al*., 1988; Hipólito & Vaz, 2011). Concerning the value of lag time applied, some studies done by the SCS recognized that the lag time is usually 60% of the concentration time and this was the value applied in this study (Scharffenberg, 2013).

To achieve the value of CN, for the whole area of the island, there was a crossing data of the hydrologic group and the land use. For this, it was used the table that relates the CORINNE LandCover codes, the hydrologic soil type and CN-AMCII (adapted from Lobo-Ferreira, 1995) (APA & MAOTE, 1995).

To conduct simulations is necessary to define methods that are present in the HEC - HMS. For the infiltration losses method it was chosen the SCS curve number while the SCS unit hydrograph was defined as the transformation method. Regarding the hydrologic routing method, it was applied the lag method and for the precipitation methods, the selected were specified hyetograph and gage weights.

For the validation of the hydrological model was first selected four extreme precipitation events that occurred on the island over the last years, which caused significant property damage and fatalities. The events were: October 29th, 1993; 5th and 6th of March, 2001, December 22nd, 2009 and February 20th, 2010. In this step and during the estimation of the flood peak discharge for the all the sections, the watersheds were divided into upstream and downstream (creation of sub-basins), which improved the estimated results.

In relation to the statistical analysis, it was accomplished through two different methods: Annual Maximum Series (AMS) and Partial Duration Series (PDS). For the AMS, the distribution functions defined for performing the statistical analysis of annual maximum daily precipitation selected were: Normal, Log-Normal, Log-Normal3, Gumbel, GEV, and Pearson3 Log-Pearson3. The parameters of these distribution functions were estimated by the method of moments, with the exception of the GEV parameters that were estimated by the linear moments method. In the case of distributions with three parameters, such as GEV, Pearson 3 and Log-Pearson 3, the shape parameter dependent on the 3rd moment was also estimated by regionalization (Stendinger et al., 1993). The identification of the distribution function that fits best to the values of each precipitation sample was performed by visual examination and by using the Filliben test. For the evaluation of the adjustment of each distribution function was used the Gringorten formula to calculate the empirical probability of not exceedance (qi) (Naghettini & Portela, 2011; Stendinger et al., 1993). In the case of the PDS procedure, the analysis of a partial duration series should begin with the selection of the cut-off (x_o) level to ensure the verification of the

Poisson hypothesis. In parallel, it is required to confirm that defined values upper to x_o follow a Generalized Pareto distribution (Oliveira & Simões, 2014).

Concerning the creation of hyetographs with a whole duration of 6 hours and 15 minutes of each block it was essential to obtain spatial average values of annual maximum daily precipitation over each sub-basin considered (for the four return periods) through the maps originated by cokriging. The calculation of the maximum precipitation values for 1h, 3h and 6h durations was based on the values obtained previously and in the precipitation ratios. To define hydrographs, it was used the software HEC - HMS to simulate flood peak discharge values for the 39 watersheds, depending on each return period. It was applied the hydrological models defined, the values of lag time and CN (in AMCIII soil moisture conditions) for each sub-basin and it was introduced the precipitation values obtained by the previously defined hyetographs.

Results and discussion

In general, the soil type that characterizes most of the 39 basins of the island is the "Umbric Andosols", though with smaller quantities, the type of soil “Terreno Dístrico Acidentado” follows it. Concerning the land use, the class with a higher percentage is called as " Florestas e meios naturais e semi-naturais” belonging to the first level of COSRAM 2007. Classes as "Zonas Húmidas” and "Corpos de água” exhibit insignificant percentages.

The high values of CN estimated in both soil conditions (AMCII and AMCIII) demonstrate that the soils have mostly impermeable characteristics. As an example, there are the extreme cases of watersheds “Ribeira da Caldeira” and “Ribeira de S. João” that are exhibiting average CN values of 93.5 and 92.1, in AMCIII soil conditions.

Kirpich and SCS are the equations of concentration time that seem to be more adequate for Madeira’s watersheds. Due to this, it was gathered information about flood peak discharge of previous studies along with the present estimated values on the next sensitivity table (Table 1):

Table 1: Flood peak discharges from previous studies and flow peak discharges estimated from the simulations in HEC - HMS, using the Kirpich and SCS equations of concentration time.

Precipitation Event	Watershed	Previous Studies Q_p (m^3/s)	Flood Peak Discharge, Q_p (m^3/s)			
			Kirpich		SCS	
			AMCII	AMCIII	AMCII	AMCIII
October 29th 1993	Ribeira dos Socorridos[1]	380	345.1	385.0	343.3	386.7
	Ribeira de S. João[2]	250	168.4	205.5	160.8	197.2
5th and 6th of March 2001	Ribeira de São Vicente	-	486.5	516.8	470.3	515.1
December 22nd 2009	Ribeira de São Vicente	-	467.3	501.1	381.4	488.3
February 20th 2010	Ribeira de São João[3]	305	324.6	331.7	322.7	351.5
	Ribeira de Santa Luzia[3]	303	334.3	341.7	310.7	353.5
	Ribeira de João Gomes[3]	234	245.9	256.7	224.6	253.6
	Ribeira Brava[3]	663	601.3	688.5	572.3	685.9

1 Estudo Hidrológico e Hidráulico da Ribeira dos Socorridos na Madeira (LNEC, 1997)”

2 “Auto Zarco, Ribeira de S. João, Funchal (HP, 1993)”

3 “Estudo de avaliação do risco de aluviões na Ilha da Madeira, (IST et al., 2010)”

It can be seen that the estimated values of flood peak discharge in AMCIII soil moisture conditions are higher than the values in AMCII conditions, as expected. Under AMCIII soil moisture conditions, the infiltration rates are lower. The proximity between the values of the studies previously conducted and the flood peak discharge estimated in this thesis suggests that the hydrological model defined is satisfactorily validated which enables its application in the entire length of the Madeira.

Through the application of the Annual Maximum Series method (AMS) and after having examined all the graphical representations along with the Filliben test results, it seems that the best adjustment law is the GEV. This distribution is formed by three parameters which allows a greater flexibility and better fit to the sample.

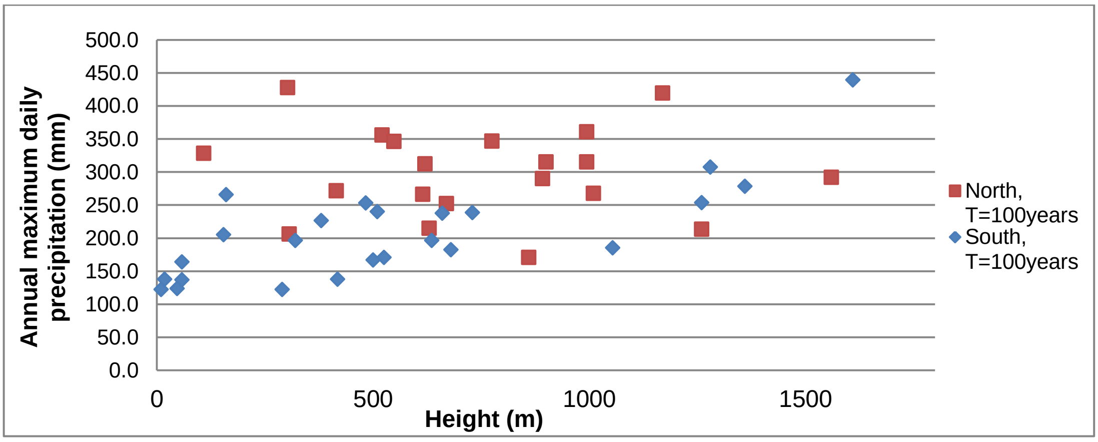

Figure 2: Representation of the annual maximum daily precipitation according to the division of the stations into North and South, for a return period of 100 years (AMS method).

As it can be seen in the previous figure (Figure 2), a huge part of the north stations shows higher values of precipitation, in comparison with the south stations. This is due to some air masses. When these masses are faced with the orographic barrier in the island, they ascend rapidly along the northern slope, cooling and then the condensation process occurs. Likewise, as expected, it is also confirmed that the annual maximum daily precipitation gradually increases with height increasing.

Based on the values of annual maximum daily precipitation originated by the AMS and PDS methods, it was applied the geo-statistical technique of cokriging and kriging which allowed to obtain the maps for each return period (T = 20, 50, 100 and 500 years) using data from 44 stations. After analyse all the obtained maps it was decided to use the cokriging method, which allowed to create the next figures (Figures 3, 4, 5 and 6).

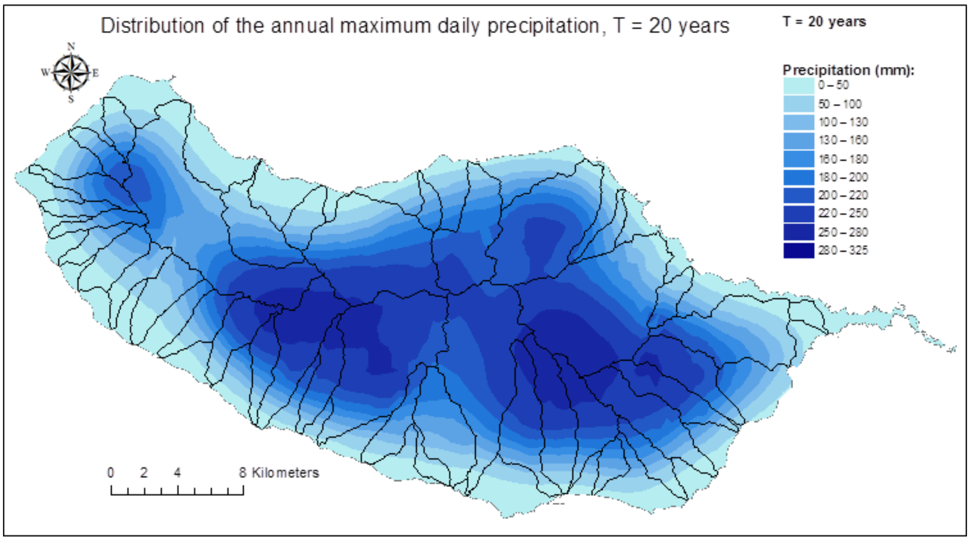

Figure 3: Annual maximum daily precipitation distribution in Madeira for a return period of 20 years.

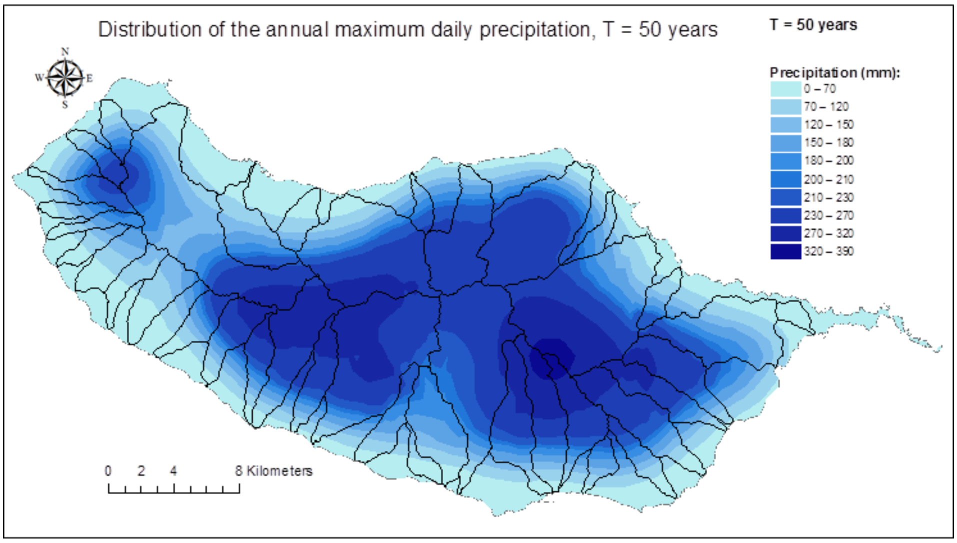

Figure 4: Annual maximum daily precipitation distribution in Madeira for a return period of 50 years.

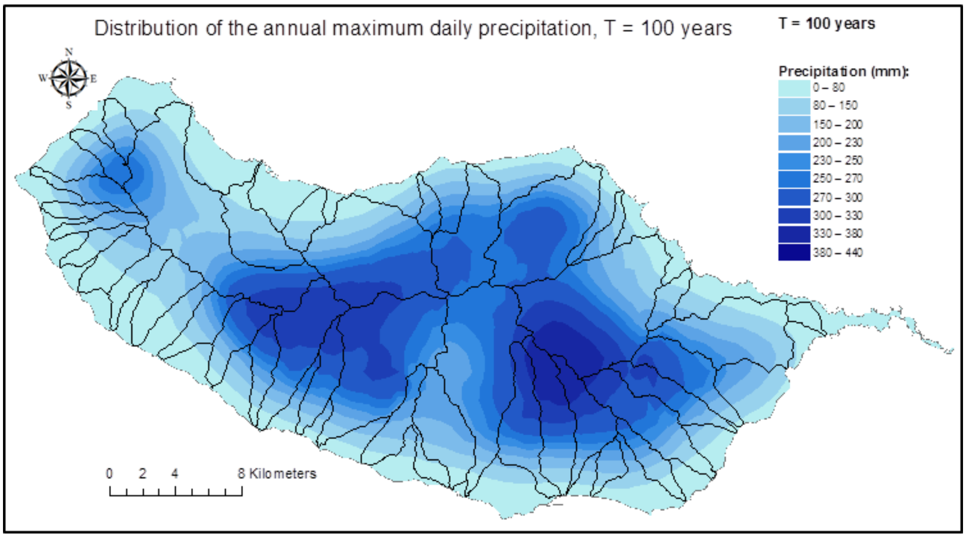

Figure 5: Annual maximum daily precipitation distribution in Madeira for a return period of 100 years.

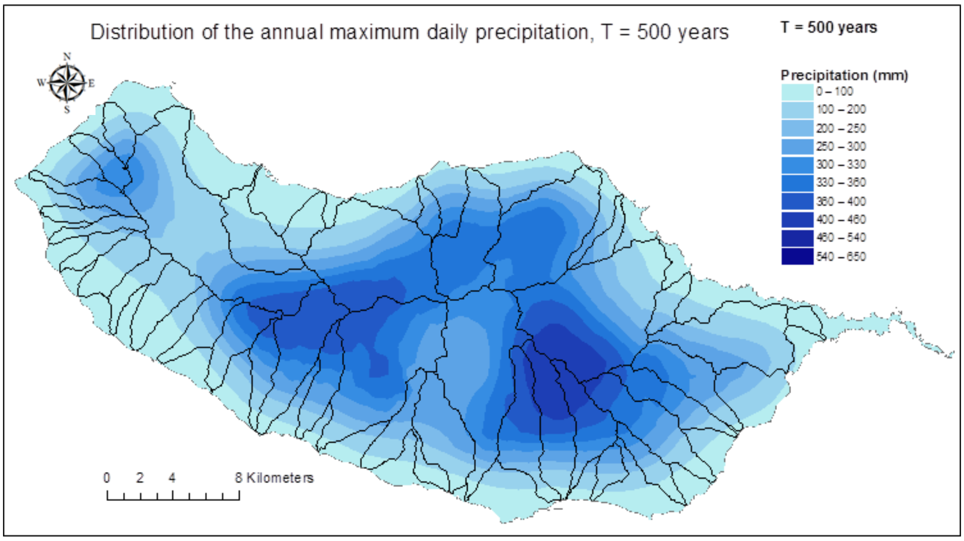

Figure 6: Annual maximum daily precipitation distribution in Madeira for a return period of 500 years.

After analysing the previous figures (Figures 3, 4, 5 and 6), it is possible to identity some areas where higher precipitation occurs because these locations are associated with the higher heights, such as in the central mountains. Although it is not evident, it is also seen in the maps that the northern part of the island has slightly high precipitation. Additionally, certain watersheds, such as "Ribeira Brava", "Ribeira dos Socorridos", "Ribeira de São Vicente" and the three constituent basins of Funchal ("Ribeira de São João", "Ribeira de Santa Luzia" and "Ribeira de João Gomes") have high precipitation values in their upstream zones. This highlights the fact that these areas are strongly affected in situations of extreme precipitation events in Madeira.

The minimum, maximum, average and median ratios of precipitation for 1h, 3h, 6h, 12h and 24h durations are presented in Table 2. It was considered more appropriate to use the median value between the different ratios calculated, because the median has the capacity to attenuate the effect of precipitation outliers.

Table 2: Minimum, maximum, average and median ratios precipitation referring to 1h, 3h, 6h, 12h and 24h durations.

	Minimum	Maximum	Average	Median
1h/1D	0.17	0.51	0.28	0.27
3h/1D	0.36	0.79	0.52	0.52
6h/1D	0.57	0.87	0.70	0.68
12h/1D	0.76	1.11	0.92	0.90
24h/1D	1.05	1.39	1.18	1.18

The simulated flood peak discharge and the specific flood peak discharge values, for all the watersheds studied, are shown in Table 3, disposed in an ascending area order.

Table 3: Specific flood peak discharge and flood peak discharge for watersheds in an ascending order of area (return periods of 20, 50, 100 and 500 years).

Bacia	Área (km^2)	T= 20 anos		T= 50 anos		T= 100 anos		T= 500 anos	
		Q_p (m^3/s)	q_p ($m^3/s/km^2$)	Q_p (m^3/s)	q_p ($m^3/s/km^2$)	Q_p (m^3/s)	q_p ($m^3/s/m^2$)	Q_p (m^3/s)	q_p ($m^3/s/m^2$)
Ribeira do Serrado	2.6	0.8	0.3	1.9	0.7	1.9	0.7	3.2	1.2
Ribeira da Caldeira	3.1	9.2	2.9	12.9	4.1	14.6	4.6	21.7	6.9
Ribeiro da Carnisa	3.3	34.0	10.2	48.5	14.6	53.1	16.0	71.4	21.5
Ribeira dos Câmbios	3.6	24.1	6.8	29.1	8.2	31.2	8.8	38.4	10.8
Ribeira de São Gonçalo	3.9	39.5	10.1	48.7	12.4	53.7	13.7	67.4	17.2
Ribeiro dos Pregos	4.2	30.0	7.2	36.9	8.9	39.1	9.4	47.3	11.4
Ribeira dos Marinheiros	4.3	35.8	8.3	38.8	9.0	41.2	9.6	48.1	11.2
Ribeira das Galinhas	4.5	21.1	4.7	22.9	5.1	23.4	5.3	27.2	6.1
Ribeira do Juncal	4.6	43.8	9.5	47.8	10.4	46.8	10.2	51.7	11.3
Ribeira do Tristão	4.8	30.5	6.4	43.5	9.1	49.0	10.3	66.3	13.9
Ribeira da Cruz	5.0	48.0	9.6	59.1	11.8	66.2	13.2	83.4	16.7
Ribeira do Inferno	5.9	28.1	4.7	29.4	5.0	30.2	5.1	36.7	6.2
Ribeiro do Caniço	6.1	51.8	8.6	61.7	10.2	67.2	11.1	82.7	13.7
Ribeira Funda	6.2	24.5	4.0	26.0	4.2	26.3	4.3	30.6	4.9
Ribeira dos Moinhos	6.8	73.8	10.9	88.8	13.1	98.3	14.5	122.3	18.0
Ribeira de Santiago	6.9	77.0	11.1	89.2	12.9	97.5	14.1	115.9	16.7
Ribeira da Atoguia	7.6	79.9	10.5	92.5	12.1	96.3	12.6	111.2	14.6
Ribeira do Campanário	7.7	59.9	7.8	68.3	8.8	75.9	9.8	95.3	12.3
Ribeira Seca	8.8	40.9	4.7	42.4	4.8	42.5	4.8	48.9	5.6
Ribeira da Tabúa	8.8	121.0	13.8	136.8	15.5	149.0	16.9	175.5	19.9
Ribeira da Madalena	9.6	128.8	13.5	147.3	15.4	160.4	16.8	189.8	19.8
Ribeira de S. Bartolomeu	10.0	47.1	4.7	53.6	5.4	54.2	5.4	63.5	6.3
Ribeira da Boaventura	10.4	136.9	13.1	151.7	14.5	165.1	15.8	195.3	18.7
Ribeira de João Gomes	11.4	159.5	14.0	188.0	16.5	214.4	18.8	275.8	24.2
Ribeira de Santa Cruz	12.9	158.6	12.3	176.1	13.7	188.9	14.7	218.3	17.0
Ribeira do Seixal	13.9	117.4	8.4	125.0	9.0	131.5	9.5	151.7	10.9
Ribeira de São João	15.1	194.2	12.9	229.4	15.2	260.3	17.3	337.4	22.4
Ribeira do Vigário	15.4	116.0	7.5	135.3	8.8	155.5	10.1	218.4	14.2
Ribeira de Santa Lúzia	15.6	213.4	13.7	252.8	16.2	286.1	18.3	366.8	23.5
Ribeira do Porto Novo	17.1	175.7	10.3	199.0	11.6	220.3	12.9	269.2	15.8
Ribeira da Ponta do Sol	19.2	273.3	14.3	308.9	16.1	344.4	18.0	418.5	21.8
Ribeira do Porco	20.1	243.6	12.1	291.3	14.5	325.2	16.2	421.4	20.9
Ribeira de Machico	24.3	183.8	7.6	221.7	9.1	232.7	9.6	280.4	11.6
Ribeira de S. Jorge	32.2	346.7	10.8	410.5	12.7	460.3	14.3	587.7	18.2
Ribeira de São Vicente	38.3	443.4	11.6	530.8	13.9	580.8	15.2	727.6	19.0
Ribeira dos Socorridos	38.7	430.1	11.1	482.9	12.5	522.2	13.5	633.3	16.4
Ribeira Brava	40.9	548.0	13.4	616.0	15.1	674.5	16.5	809.5	19.8
Ribeira do Faial	49.5	650.8	13.2	760.5	15.4	829.2	16.8	1014.4	20.5
Ribeira da Janela	51.7	330.1	6.4	368.2	7.1	400.4	7.8	477.8	9.2

It is not the case for the 39 watershed however, an increase of area is associated to an increase of the estimated flow. Although the flood peak discharge is not exclusively dependent of the precipitation, this parameter could have a predominant role at certain times. For example, when the watersheds have high areas but then they present low values of flood peak discharge (it is the case of the “Ribeira de Machico” and “Ribeira da Janela”). Probably, these values are related with the low precipitation values that can be seen, in those areas, in the previous precipitation distribution maps (Figures 3, 4, 5 and 6).

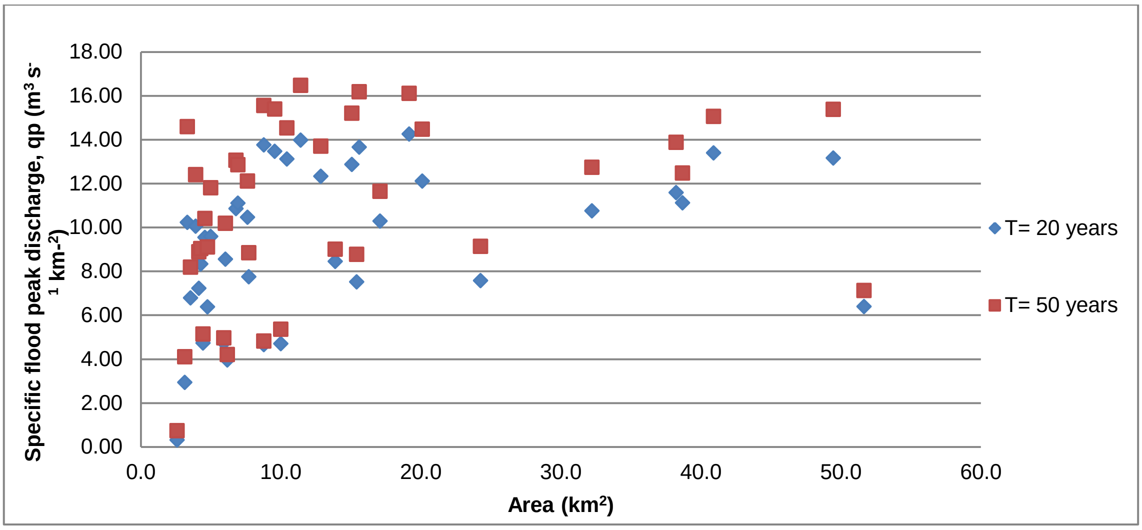

Figure 7: Specific flood peak discharge for T = 20 and 50 years.

In Figure 7 it is possible to observe the specific flood peak discharge for T = 20 and 50 years and for the 39 watersheds. The small specific flood peak discharge in the beginning of the graph can be related with the fact that some watersheds have small areas and are located on the coast of the southern part of Madeira. These conditions are usually associated with lower precipitation and concentration time values.

Conclusions

Since there are records it appears that Madeira has been heavily hit by extreme precipitation events. More important than the property damage, alluviums have been causing several fatalities and injuries all over the territory.

Throughout this study there were found several difficulties while dealing with the Madeira monitoring network. The fact that there are distinct entities responsible for the stations management, with different equipment and methodologies, has generated some problems. One of them is the identification and characterization of the stations that are currently active. In the future, it would be useful to deal with the information in an organized way and, for example, create a common database that would allow an easier access to the precipitation measured values.

It is also important to refer other facts obtained during this dissertation. Kirpich and SCS formulas are those that provide the lowest estimates of concentration time, therefore, they determine higher flood peak discharges. The GEV distribution was defined as the best option to apply in Madeira since there was a good adjustment between the distribution and the precipitation sample. The north of the island appears to have some areas with high precipitation and it is mainly noticed in the zone of the central mountains. Watersheds with high values of areas usually have associated high flood peak discharge, however, precipitation also has a large influence, as it was seen in the estimated values. Regarding the creation of hyetographs, it is necessary to define a peak of rainfall with duration smaller than one hour since there are small watersheds in study and they have low concentration time. Additionally, these are located along the coast in the southern part of the Madeira island.

The Madeira susceptibility to the occurrence of extreme events (such as alluviums) is very high because of their special characteristics. Although it is difficult to completely avoid these events, their effects can be minimized. It is believed as well that is truly important the authorities study and conceive the most effective methods with the implementation of certain measures, as structural and educational ones. These should be applied in order to reduce damage and, especially, to avoid fatalities that usually are associated with alluviums in Madeira.

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