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Local floods in Madeira Island between 2009 and 2021. Rainfall analysis and risk assessment in mountain streams.

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Abstract. The torrential floods that occurred in December 2020 and January 2021 in villages located mainly on the northern side of Madeira Island, are analysed in comparison with other local scale events that occurred in 2009, 2012 and 2013. The term torrential flood is adopted in this work to designate the hydrogeomorphologic events, characterized by the occurrence of interactions between slope movements (landslides, debris flows) and fluvial dynamics (flash floods), typical in mountainous regions, formed by deep and narrow-bottomed valleys, as is the case in Madeira Island.

The heavy rainfall episodes of 25 December 2020 and 7 January 2021 were particularly surprising for the localised incidence of numerous occurrences of landslides, debris flows, and flash floods triggered by them.

Intense precipitation episodes, with hourly maximums of more than 40 mm and accumulated amounts in 24 hours exceeding, in some rain-gauges, the critical threshold of 300 mm, triggered peak discharges in several catchments, the largest with an area of up to 50 km^2 and the smallest with less than 20 km^2. The flow hydrographs of some streams show several flood peaks, associated with secondary maximums of heavy rainfall.

Daily and sub-daily rainfall peaks over catchments are crucial conditions for triggering floods. It was found that there is a very strong correlation between maximum precipitation in 24 hours and 12 hours, which can be mathematically described by a linear regression law. On the other hand, antecedent daily rainfall may also influence the occurrence of torrential floods in Madeira Island: the analysis of the combinations of critical pairs, consisting of the maximum rainfall in 24 hours and the antecedent rainfall calibrated for different durations (in days), allowing the identification of polynomial regression rules, which can be used to detect, in time and space, critical scenarios of torrential floods. The constitution and maintenance of an inventory of critical precipitation values, represents a relevant source of information to ensure the quality of the results issued by any flood early warning system.

Finally, hydrogeomorphological susceptibility mapping, which was produced through the collection of field information in the aftermath of catastrophic floods, embodies a complementary approach that provides a distinct spatial perspective of the areas of sediment production, flooding and deposition.

Introduction

On 25 December 2020, a heavy rainstorm hit with violence in two small villages on the northern coast of Madeira Island. The material damage was significant, especially on roads, agricultural land and in the houses located at the base and middle of the slope, which were affected by landslides and by the passage of debris flows. In the bibliography that summarises the historic main floods on the island of Madeira, we can find no record of this type of occurrence in the catchments now affected (Ribeiro, 1985; Quintal, 1999; SRES, 2010).

Local people were still recovering from the damage caused by this flood, when another heavy rainfall event (7 January 2021), triggered small floods in several other streams. Previous small floods occurred in 2009, 2012 and 2013 at other locations on the north side of the island. The last big flood took place on 20 February 2010, affecting mainly the southern side of the island, with an impressive trace of destruction and around fifty deaths (Fragoso et al., 2012).

In Madeira Island, torrential floods are related to the formation of debris flows, which in turn are usually enhanced by the occurrence of shallow translational slides in the upper sector of the slopes and the headwaters of catchments (SRES, 2010; Fragoso et al., 2012; Lopes et al., 2020). In their downward trajectory towards valley bottoms and streamlines, the soils, which are initially moved by slide, tend to evolve rapidly into a mixture of fine (sand, silt, clay) and coarse (cobble, boulder) material, with woody debris and water, forming a mass of high density, in which the solid load often exceeds 50 % of the total mass, which is displaced by gravitational force, usually by successive impulses (WL/WLI, 1993; Zêzere et al., 2005; Fragoso et al., 2012). The accumulation of discharged material only occurs in areas of low ground gradient (MLIT, 2004).

In general, the physical characteristics of catchments in morphometric terms (geometry, drainage network and relief), are determinant to explain their hydrological regime (Ramos, 2009). With an approximate area of 741 km2, there are around 126 catchments in Madeira Island, 94% of which with an area of less than 25 km2. In the European continent, more than 80% of flash floods occur precisely in catchments with an area of less than 100 km2 (Marchi et al, 2010).

The catchments have an elongated shape. According to the hydrographic network map, the length of the main streams is short (< 21 km) and, therefore, the time of concentration of runoff in the catchment outlet is always less than 5 hours. The vulnerable location of entire settlements in the terminal sectors of these catchments contributes to increased flood risk.

Madeira Island has a Mediterranean climate: the summer is dry and rainfall is concentrated mainly in winter and then in autumn. In almost every hydrological year there are heavy rainfall events, but not all of them give rise to floods. The very concept of heavy rainfall event depends on the classification criterion adopted. For example, according to the rule of thumb of total precipitation in a 6-hour moving interval greater than 30 mm (used by the Portuguese Meteorological Institute, IPMA), in the mountains (Areeiro, Fig. 1), an average of 18 days of heavy precipitation occur per year (Lopes, 2015).

The general objective of this study is to deepen the knowledge of the characteristics and causes of torrential floods in catchments, expecting to bring new scientific contributions to improve risk management. The specific objectives are: (i) analyse the precipitation and hydrology data regarding a set of torrential floods that occurred mostly in the northern part of Madeira Island, between 2009 and 2021; (ii) characterise the events in terms of critical rainfall conditions, taking into consideration, on the one hand, the combinatory relations between the precipitation of the event and the precipitation of the preceding days and, on the other hand, the relations between the maximum precipitation in 24 hours and the maximum precipitation of shorter duration (1h, 3h, 6h, 12h) and relate them to the peak flows in the terminal flow sections of the respective catchments. (iii) demonstrate the relevance of high-resolution susceptibility mapping for risk analysis and management and its implications for land use planning.

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1 Data and methods

The inventory of torrential flood damage events was obtained by checking one of the following selection criteria, based on the occurrence of: a) interactions between slope instability and stream flow; b) people affected (evacuated or displaced, injured); c) at least one victim (dead, missing); d) damage to at least one public/private infrastructure.

Regarding the precipitation analysis, maximum values were determined for different durations (1h, 3h, 6h, 12h and 24h), relative to the rain gauges in the area of influence of the localities most affected by torrential floods, namely: Posto Florestal São Vicente; Achada do Til; Santo da Serra, Fajã do Penedo, Fajã da Nogueira and Fanal (Fig.1).

The precipitation data necessary for the analysis of the relationships between daily rainfall and antecedent rainfall was obtained based on the technique of annual maximums for different durations. However, in the constitution of these extreme values series, more than one value per year can be used, namely when two intense precipitation events followed by floods occur in the same hydrological year.

The amount of precipitation that occurs in a given event and its duration can be determined based on different criteria. One of them, for example, determines that the beginning of an event occurs whenever there is an hourly precipitation equal to or greater than 4 mm and ends whenever the hourly precipitation is less than this value in a consecutive period of 6 hours (NORVIA & CENOR, 2012). In Madeira Island, most heavy rainfall events occur concentrated in less than 24 hours (Lopes, 2015). Thus, to analyse the critical combination between event precipitation and antecedent precipitation, the maximum precipitation variable in 24 hours was chosen, calculated from the series of 10-minute records, available for most events and rain gauge station.

In this sense, the precipitation of the event corresponds to the maximum precipitation in 24 h, calculated as a sliding sum on the day(s) of heavy rainfall. In analysing the influence of precipitation that may occur in the days preceding the date of occurrence of a specific rainfall event, it is logical to follow the rule of separation between event precipitation and antecedent precipitation (Schröter et al., 2015).

Precipitation from previous days may have a decisive or partial influence on the triggering of slope movements and flash floods. The paradigmatic example of this influence was the intense rainfall event responsible for the 20 February 2010 flash-floods in Madeira that occurred during a particularly anomalous wet winter (Fragoso et al., 2012). However, the overland flow resulting from the rainfall is no longer felt after a certain period, due to the surface drainage (Zêzere et al., 2005). Thus, to know the influence of rainfall in the days and weeks before the occurrence of slope instability and flood events, Crozier (1986) proposes the introduction of an exponential function to express the decrease in the importance of rainfall with temporal distance from the date of interest.

The mathematical expression used to calculate the calibrated antecedent rainfall (Zêzere et al., 2005) is the following:

$$CARx = K\ P1 + K2\ P2 + \ldots Kn\ Pn$$

where CARx is the calibrated antecedent rainfall for day x; P1 is the daily rainfall for the day before day x; Pn is the daily rainfall for the n-th day before day x. K is an empirical parameter usually considered between 0.8 and 0.9, depending on the draining capacity of the material and the hydrological characteristics of the area. In line with values referenced in existing literature (Capecchi and Focardi, 1988; Zêzere et al. 2005; Marques et al., 2008), we decided to assume in this study that K = 0,9. This equation makes negligible precipitation occurred more than 30 days before a torrential flood event. Therefore, the reconstitution of the calibrated antecedent precipitation was only calculated for the durations of 5, 10, 15 and 30 days.

Based on the rainfall data of December 2020 and January 2021, the monthly totals and accumulated precipitation in the previous days and weeks were calculated, according to the records available at the rain gauges located in the vicinity of the affected areas (Fanal, Fajã do Penedo and Fajã da Nogueira, Fig. 1). The hyetographs of rainfall events were prepared based on fixed hourly precipitation values.

The estimation of peak discharges is carried out for five catchments located on the northern side of Madeira Island: Faial, São Jorge, Porco, Seixal and Moinhos streams (Fig. 1), considering the precipitation data from the January 7, 2021 event. The flood hydrographs and peak flows were calculated on the condition that the amount of rainfall recorded at each rain-gauge station has uniformly affected the catchments where they are located. The estimated values were obtained for the mouth of the catchments.

Flood hydrographs are determined based on the above-mentioned hyetograph data and the synthetic unit hydrograph of the Soil Conservation Service (S. C. S.), through an operation performed using the HEC-HMS model (Hydrologic Engineering Center - Hydrologic Modelling System) developed by the U.S. Army Corps of Engineers (version HEC-HMS 4.8).

The S. C. S. unit hydrograph is characterized by the catchment response time to peak precipitation, given by the expression: $tP = 0,6 \times tC$, where tP is the lag time and tC is the time of concentration of the catchment. The concentration and lag times for the studied catchments are shown in Table 1. The transformation method used to estimate the volume of precipitation water transformed into flow was the lag time.

The curve number (CN), an empirical parameter developed by the Soil Conservation Service (SCS), was used to classify permeability in the catchments studied (McCuen, 1982; Leal, 2012; Lopes, 2020). The low degree of permeability of Madeira's catchments is due to natural conditions, being mainly imposed by the characteristics of volcanic rocks and soils. Based on this, and the prevalence of agricultural and forestry areas, and according to the S. C. S. tables, it was decided to adopt, in the present hydrological modelling exercise, a common CN of 81 for all catchments, considering AMCIII conditions (completely saturated soil).

Rainfall data from three rain gauges (Fajã da Nogueira, Fajã do Penedo and Fanal, respectively 7, 6 and 1 in Fig. 1), with 10-minute records, were used as input parameters of the hydrological model. As a result of the model application, the reference hydrographs and respective peak flows for extreme events in a set of five catchments located in the northern flanks of Madeira Island were obtained (see topic 4).

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Table 1: Physical parameters of the drainage catchments considered in the hydrological modelling exercise for the heavy rainfall event of 7 January 2021.

	Faial	*São Jorge*	*Porco*	*Seixal*	*Moinhos*
Catchment area (km^2)	50	32	20.2	14.1	5.2
Length of main stream (km)	14.3	10.4	10.2	10.3	5.5
Average gradient of main stream (km/km)	0.154	0.145	0.154	0.153	0.249
Time of concentration (hours)	3h27	2h34	2h30	2h31	1h26
Lag time (hours)	2h04	1h32	1h30	1h31	0h51

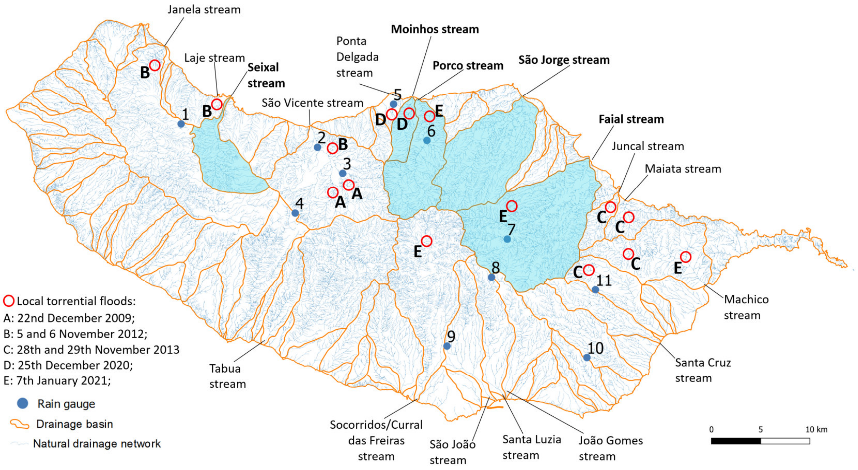

Fig. 1 Madeira Island hydrographic system. The catchments that will be the subject of the hydrological study are highlighted in blue. The red circles indicate the localities affected by torrential floods from 2009 to 2021. The blue points correspond to the rain-gauges used in this work: 1 Fanal; 2 Posto Florestal São Vicente; 3 Achada do Til; 4 Bica da Cana; 5 Ponta Delgada; 6 Fajã do Penedo; 7 Fajã da Nogueira; 8 Areeiro; 9 Trapiche; 10 Camacha; 11 Santo da Serra.

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2 Inventory of torrential flood disasters (2009-2021)

The five flood events inventoried (Table 2) and the respective occurrences mapped in Figure 1, are illustrative that in some heavy rainfall storm events, the subsequent floods tend to have a localized spatial incidence. These events occurred mainly on the northern side of the island, marked by rocky and mountainous terrain, dissected by vertical erosion that formed ravines and very deep valleys in the interior of the island.

The field survey conducted immediately after the floods allowed georeferencing a total of 10 mountain streams (some of which are represented in Figure 2), whose respective territory was affected by the occurrence of displaced people and material damage, both in private property and in public infrastructure (Table 2). The summary photo report (Fig. 3) illustrates the damage caused in different localities affected by the storms.

The floods of 22 December 2009 affected mainly the upper and middle sectors of the São Vicente catchment (Figs. 1, 2a and 3a). The floods of 5 and 6 January 2012 affected the right flank streams of the São Vicente catchment, Laje stream and the mountain streams of the right flank of Ribeira da Janela (Figs. 1, 2a and 3b). The floods of 28 and 29 November 2013 affected mainly the east-northeast sector of Madeira Island, in the catchments of Juncal, Maiata, Machico and Santa Cruz (Figs. 1, 2c and 3c). In these localities, marked by the dominance of very intense weathering processes, numerous superficial landslides were recorded (Fig. 2c). Floods of 25 December 2020 were confined to a restricted band on the northern coast of the island, in Ponta Delgada and Moinhos streams (Fig. 1), severely affected by the occurrence of numerous slope movements (Figs. 2d and 3d). The floods that occurred on 7 January 2021 only affected small tributaries (in the streams of Porco, Machico and Curral das Freiras, Figs. 1, 2e and 3e).

Regarding cases of the heavy rain events of 5 and 6 January 2012 and 25 December 2020 a common characteristic stood out, which lies in the fact that both affected mainly restricted bands of the northern coast of the island, but still gave rise to torrential floods in catchments nestled between vigorous cliffs.

Table 2: Summary of the consequences of torrential flood events occurring between 2009 and 2021 on mountain streams. See affected areas in figure 1.

Date	No. of victims (1)	Affected people (2)	Damage to Infrastructure and economic costs (3)
22 December 2009 (A)	No casualties	People evacuated	- Destruction of communication routes, houses, warehouses, commercial shops and vehicles - Destruction of several land parcels
5 and 6 November 2012 (B)	6 injured	70 displaced persons	- 11 houses
28 and 29 November 2013 (C)	5 injured	6 families displaced	- 6 houses; - Regional and municipal roads - Destruction of private property - Costs of clean-up and immediate response operations: 2 million euros
25 December 2020 (D)	No casualties	27 displaced persons	- Cost of damage: EUR 40.6 million (4) - Road network and fluvial infrastructures - 16 houses; field irrigation water system - Electric power-line; Municipal property
7 January 2021 (E)	No casualties		- Destruction of communication routes and several parcels of land.

(1) Dead, missing or injured;
(2) No. of people evacuated or displaced;
(3) Public or private commercial, transport and communication infrastructures;
(4) Source: Diário Notícias da Madeira, January 18, 2021. The total amount includes damages to the regional road network, fluvial infrastructures, houses and resettlement, irrigation water network, electricity supply and replacement and reconstruction of municipal property.

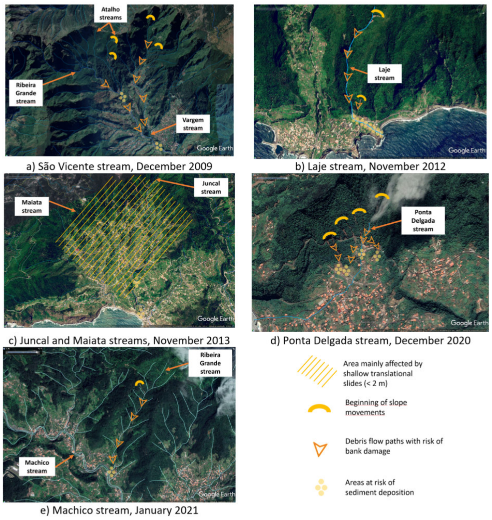


Fig. 2 Preliminary analysis of torrential floods in different streams between 2009 and 2021. © Google Earth.

Fig. 3 Photographic record of floods destructive effects: (a) 22 December 2009; (b) 5 and 6 November 2012; (c) 28 and 29 November 2013; (d) 25 December 2020; (e) 7 January 2021.

3 Rainfall analysis and critical thresholds

Concerning the five heavy precipitation events followed by torrential floods, it was possible to access higher temporal resolution data, from which the maximum characteristic values for different sub-daily durations were computed (Table 3). In the results presented below, it is important to bear in mind the limitations of rainfall point measurement methods, since the phenomenon of precipitation often occurs in a dispersed way, which makes it difficult to obtain a sample with real physical meaning.

3.1 Relationships between precipitation of different sub-daily durations

Through comparative analysis between the series of maximum precipitation values in 24 h (Pmax24h) and the maximum precipitation of shorter duration (Pmax12h, Pmax6h, Pmax3h and Pmax1h), it was possible to evaluate the statistical significance of the existing dependencies between these variables. In this exercise, a larger set of precipitation data was used, namely from 9 rain-gauges, concerning a total of 11 heavy rainfall events that occurred between 2009 and 2021. This means that, to the five previous ones (Table 2), it was decided to add a set of six other heavy precipitation events (Table 4 and Fig. 1), previously analysed in Lopes (2015). By adding these events we are giving greater importance to finding characteristic values (which are obtained with a greater number of cases in the sample), that are representative of the climatology of intense rainfalls at the regional scale, with influence on the occurrence of floods. The three heavy rainfall events that occurred in the last quarter of 2010 and the one on 25 January 2011 did not trigger torrential floods, however, they caused increases in the flow discharges of various streams of the island.

The results show a very strong correlation ($R^2=0.83$), which can be mathematically described by a linear regression law between Pmax24h and Pmax12h, following the equation $Pmax12h = 0.7553*Pmax24h + 16.257$ (Fig. 4). The indicated relations can be used to estimate the probable critical maximums in 12 hours, according to the predicted precipitable water values in 24 hours. The same extremely strong relationship between these two variables was also identified when analysing the hydrological behaviour of two streams located in southern Portugal (Reis, 2019). Statistical information showing the more or less concentrated nature of sub-daily rainfall is shown in Table 4. There is no significant correlation between Pmax24h and maximum precipitation for shorter durations: 6h ($R^2=0.57$), 3h (0,40) and 1h (0,12). Nevertheless, for mountainous areas on the northern side of Madeira Island, some average values of heavy rainfall can be advanced (Table 3).

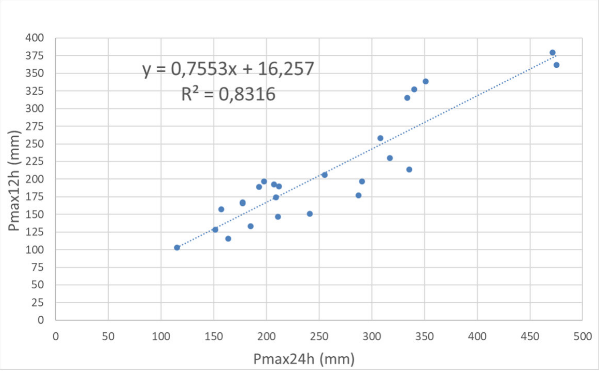


Fig. 4 Relation between precipitation in 12 h (Pmax12h) and 24 h (Pmax24h), based on a sample of 25 pairs of rainfall values from 8 rain-gauge stations, for a set of 11 heavy rainfall events that occurred from 2009 to 2021, in the north side, in the mountain and above 500 m altitude in the south slope of Madeira Island.

Table 3 Records of maximum rainfall for different sub-daily intervals, in moving time window.

Flood events	Rain-gauges	Pmax24h	Pmax12h	Pmax6h	Pmax3h	Pmax1h
22 December 2009	Achada do Til	290.8	197	179.6	**150.4**	**107.8**
5 and 6 November 2012	Achada do Til Posto Florestal São Vicente	211 317	146.6 229.8	93 121.4	54 78.4	26.2 32.8
28 and 29 November 2013	Santo da Serra	241	150.8	126.6	101.4	43.2
25 December 2020	Fajã do Penedo	335.5	213.5	137	106.5	47
7 January 2021	Fajã do Penedo Fajã da Nogueira Fanal	**475** 287.4 **471.6**	362 177 **379.4**	**212.5** 115.8 195.4	116 81.6 117.8	43 39.4 45.4
	Average	328.7	232.0	147.7	100.8	48.1

Table 4 Statistical relationships between maximum precipitation in 24 hours and of shorter duration.

			Relative weight (%)			
Rain-gauges	**Heavy rainfall events**	**Pmax24h**	**A**	**B**	**C**	**D**
Achada Til	22/Dec/2009	290.8	67.7	61.8	51.7	37.1
Areeiro	02/Feb/2010	209.2	83.2	52.9	27.1	11.8
Trapiche	02/Feb/2010	163.8	70.7	44.2	28.4	16.8
Camacha	02/Feb/2010	255.4	80.5	50.5	31.6	13.2
Areeiro	20/Feb/2010	333.8	94.4	67.2	41.8	19.4
Trapiche	20/Feb/2010	340.2	96.2	78.4	57.1	29.0
Camacha	20/Feb/2010	351.0	96.5	55.3	55.3	32.6
Areeiro	21/Oct/2010	157.2	99.8	77.5	46.6	20.7
Trapiche	21/Oct/2010	197.6	99.6	81.4	62.9	35.3
Camacha	21/Oct/2010	177.6	93.5	72.2	55.9	35.5
Areeiro	25/Nov/2010	185.0	72.1	51.5	37.7	15.7
Trapiche	25/Nov/2010	177.4	94.4	52.0	45.7	21.6
Camacha	25/Nov/2010	193.2	97.8	54.1	46.2	29.6
Areeiro	20/Dec/2010	151.6	84.6	66.3	37.1	23.9
Trapiche	20/Dec/2010	115.4	89.3	86.8	54.1	29.1
Areeiro	25/Jan/2011	308.0	83.8	47.7	28.1	12.1
Trapiche	25/Jan/2011	211.8	89.5	53.0	27.2	11.3
Camacha	25/Jan/2011	207.4	92.9	54.6	32.4	12.3
Achada do Til	5 and 6 Nov/2012	211.0	69.5	44.1	25.6	12.4
P. F. São Vicente	5 and 6 Nov/2012	317.0	72.5	38.3	24.7	10.3
Santo da Serra	28 and 29 Nov/2013	241.0	62.6	52.5	42.1	17.9
Fajã do Penedo	25/Dec/2020	335.5	63.6	40.8	31.7	14.0
Fajã do Penedo	07/Jan/2021	475.0	76.2	44.7	24.4	9.1
Fajã da Nogueira	07/Jan/2021	287.4	61.6	40.3	28.4	13.7
Fanal	07/Jan/2021	471.6	80.4	41.4	25.0	9.6
		Average	**82.9**	**56.4**	**38.7**	**19.8**

A – Pmax12h-Pmax24h; **B** – Pmax6h-Pmax24h;
C – Pmax3h-Pmax24h; **D** – Pmax1h-Pmax24h

3.2 Heavy rainfall events in 2020/2021

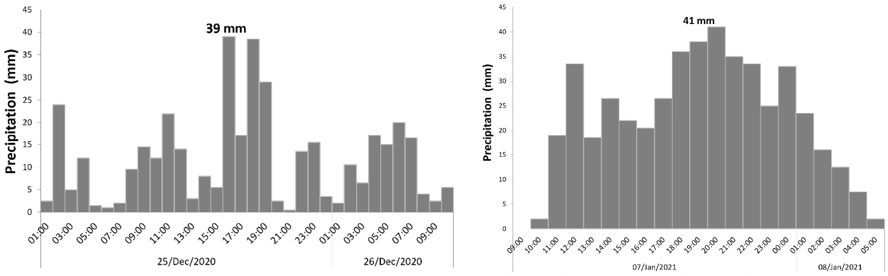
The two heavy rain events that occurred in less than a 15 day time lapse (25 December 2020 and 7 January 2021), are analysed in more detail below. For this purpose, data from *Fajã da Nogueira*, *Fajã do Penedo*, *São Vicente* and *Fanal* rain-gauges are used (Fig. 1).

The hydrological year 2020/2021 was rainy on the northern side of the Madeira island. December 2020 recorded a cumulation of 454.6 mm in *Fajã da Nogueira* and 616.5 mm in *Fajã do Penedo*. The January 2021 rainfall in these localities was also high (around 590 mm). According to the available climatological normal (1951 - 1980), January tends to be the wettest month, with average totals of 190 mm at *Ponta Delgada* (136 m altitude) and 480 mm at *Bica da Cana* (1560 m altitude, Fig.1). At *Ponta Delgada* the average annual rainfall varies from 1000 to 2000 mm (Machado, 1984).

In general, precipitation is characterized by an irregular temporal distribution in Madeira Island, with a tendency to concentrate more than 50% of monthly precipitation in a short set of days (Lopes, 2015). This trend is particularly evident in hydrological years with the occurrence of heavy rainfall events. For example, on January 7, 2021, the maximum totals in 24 hours in *Fajã do Penedo* (475 mm) and *Fanal* (471.6 mm) correspond respectively to 80 % and 72 % of the corresponding monthly rain. In *Fajã da Nogueira* the maximum in 24 hours (287.4 mm) represents 49 % of the monthly rain. In a previous study, Ferreira (2005), argued that the amount of rainfall received on the island of Madeira becomes extremely low in years when there are not strong daily rainfall intensities in November to January.

On December 25, 2020, the rainfall was particularly strong on the northern coast of the island, namely in the streams of *Ponta Delgada* and *Moinhos* (Fig. 1). The records from *Fajã do Penedo* (Fig. 1), are sufficient to infer the exceptional character of the precipitation occurred in any of the events, with maximums in 24 h exceeding 300 mm (Table 3).

The *Fajã do Penedo* hyetogram on 25 December 2020 reveals the occurrence of abundant rainfall during the first 15 hours of the day (136.5 mm). Then, a critical period of heavy rainfall occurs during the afternoon, with 124 mm in 4 hours (Fig. 5a). At this time of the day, several occurrences of slope movements took place in the *Ponta Delgada* catchment (see section 5). In the heavy rain event of January 7 to 8, 2021, we highlight the occurrence of 7 non-consecutive hours, with hourly precipitation greater than 30 mm (Fig. 5b).



a) b)

**Fig. 5 Hyetograph of *Fajã do Penedo* during the heavy rainfall events of:
(a) December 25, 2020; (b) January 7 and 8, 2021.**

3.3 Calibrated antecedent precipitation

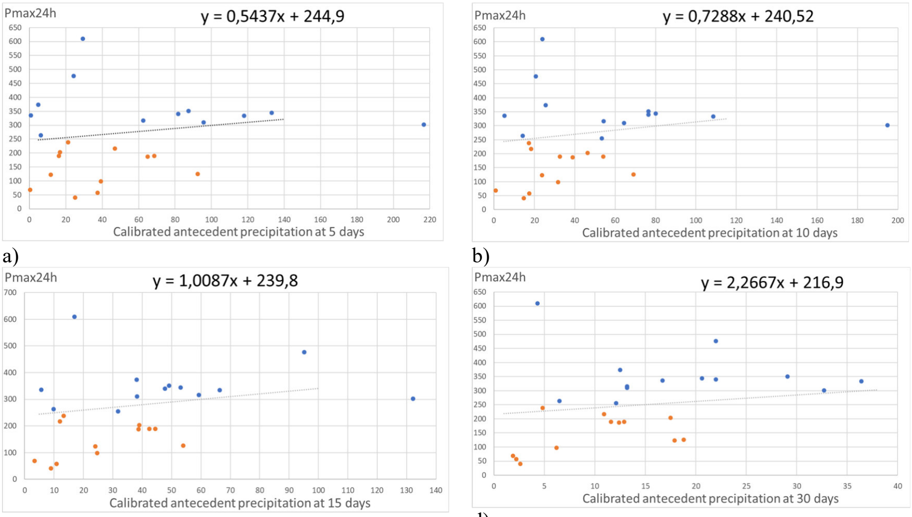
Table 5 shows the calibrated antecedent precipitation (CAP) values for the five case studies. The event of 25 December 2020 is the only one that presents practically irrelevant accumulated totals at 3, 5, 10 and 15 days (less than 6 mm). For the other four events in the sample, the reference thresholds are as follows: 100 mm of calibrated antecedent precipitation at 5 days, and approximately 80 mm for the 10-day and 15-day durations.

The characteristic combinations between precipitation of preceding days and that of heavy rain events were analysed through the relationship between the maximum precipitation in 24 hours (Pmax24h), with the corresponding antecedent precipitation calibrated for different periods (5, 10, 15 and 30 days). In this exercise, a set of known episodes of heavy rainfall (from 2009 to 2021) was considered, selecting for this purpose, rainfall data from rain gauges representative of the areas most affected by them (Table 4), without records of data gaps in the previous weeks, to allow a more rigorous calculation of the calibrated antecedent rainfall. To this data sample was also added the heavy rainfall event of 5 and 6 June 2023. This storm resulted in a new record for rainfall in 24 hours in Portugal (609,8 mm).

For the composition of these climate series, data of maximum annual daily precipitation and maximum annual calibrated antecedent precipitation were also used, from a set of years without records of torrential flood events (Fig. 6). The identification of critical thresholds requires a statistical analysis of precipitation data from years with and without torrential flood records, to detect the existence of a clear separation in precipitation behaviour between both samples (Zêzere et al., 2005).

The information provided by the graphs relating the maximum precipitation in 24 (Pmax24h) with the antecedent precipitation calibrated for different durations in days (5, 10, 15 and 30 days), allowed the determination of different linear regression rules, which can be used to identify critical precipitation thresholds, from which torrential flood events can occur (Fig. 6). The four graphs shows that the maximum rainfall pairs for years with no recorded torrential floods (orange points) are always below the regression line, except just one point (Fig 6d). On the other hand, most of the pairs of points related to known heavy rainfall events are located near or above the line, confirming that the respective equations can be used as probable thresholds of torrential flood occurrence in Madeira Island. The best fit of points can be observed on the graph corresponding to the 30-day CAP, where there are no critical precipitation pairs (blue points) below the line (Fig. 6d).

The information summarized in Figure 7 represents a specific case of two events of heavy rainfall-to-runoff torrential floods, occurring in the same hydrological year (2020/2021), and their respective relationships with the antecedent calibrated precipitation at 5 and 15 days. In this specific case, the CAP at 5 and 15 days at the date of the first event (25 December 2020), is relatively low. Naturally, at the time of the second event (7 January 2021), the precipitation from the first event has a significant influence on the high value of the CAP at 15 days (95 mm). This case study demonstrates that the precipitation of the preceding days and weeks does not always have a decisive role in triggering torrential floods. In the case of the 25 December 2020 floods, the daily and sub-daily maximum values were high enough to cause catastrophic floods.



a) b) c) d)

Fig. 6 Relation between maximum 24-hour precipitation and calibrated antecedent precipitation at 5 days (a), 10 days (b), 15 days (c) and 30 days (d). The blue points refer to values associated with heavy rainfall events between 2009 and 2021 and the orange points to pairs of values obtained by calculating the maximum annual 24 hours precipitation and calibrated antecedent precipitation in years without torrential floods (between 2011 and 2020).

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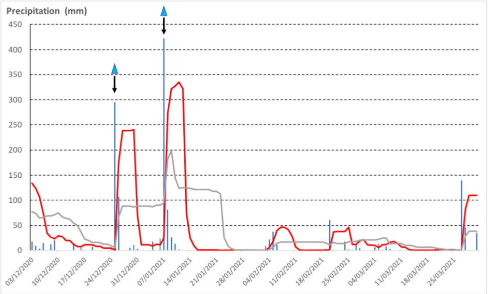

Fig. 7 Daily precipitation and calibrated antecedent precipitation (CAP) at 5 and 15 days, between December 2020 and March 2021, at Fajã do Penedo. Blue bars: daily precipitation; red line: 5-day CAP; grey line: 15-day CAP; blue triangles: date of occurrence of the torrential flood events.

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Table 5 Precipitation events that triggered torrential floods and their calibrated antecedent precipitation (CAP) to different durations.

			Calibrated antecedent precipitation				
Date	Rain-gauges	Precipitation on the day of the event (00h00-24h00)	3 dias	5 dias	10 dias	15 dias	30 dias
22 December 2009	Achada do Til	199.6	113.7	216.6	194.8	132.2	32.7
5 and 6 November 2012	Posto Florestal São Vicente	235.6 (day 6)	111.5	90.3	75.3	67.7	18.9
28 and 29 November 2013	Santo da Serra	172.5 (day 29)	68.3	61.5	44.3	28.4	10.2
25 December 2020	Fajã do Penedo	295.5	1.1	0.9	5.2	5.7	16.7
7 January 2021	Fajã do Penedo	422.5	29.9	24.2	20.7	95.2	22.0

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4 Estimation of peak discharges

The objective of this section is to deepen the knowledge about the relations that occur between sub-daily precipitation peaks and the consequent stream flow peaks generated in the terminal sections of the catchments affected by heavy rainfall events.

The studied catchments vary in size between 5.2 km^2 (Moinhos) and 50 km^2 (Faial) and have a generally elongated shape (Fig. 1). Their physical parameters are shown in Table 1. The lengths of the respective main streams are relatively short, being the longest 14.3 km (Faial) and the shortest 5.5 km (Moinhos). All of them have in common the predominance of steep slopes and short time of concentration, less than 3 hours, except for the Faial stream (3h27). In general, the topographic conditions of the catchments and their characteristics in terms of land use are the main conditioning factors for the occurrence of torrential floods (Lopes et al., 2020).

The case study selected was the heavy rainfall event of January 7, 2021, for which there is a longer sequence of records in the 10-minute interval, without data gaps. The peak flood flows estimated by the HEC-HMS model for the mouth of Faial (50 km^2) and São Jorge (32 km^2) catchments reached 297 m^3/s and 215.6 m^3/s respectively. In the Porco catchment (20 km^2), the peak flood flow at the mouth was 204 m^3/s. At Seixal (14 km^2) it was 137 m^3/s. The differences between peak flows were 81.4 m^3/s (Faial vs. São Jorge) and 148 m^3/s (Porco vs. Moinhos). The differences in time between flood peaks were 35 minutes (São Jorge vs. Faial) and 29 minutes (Moinhos vs. Porco).

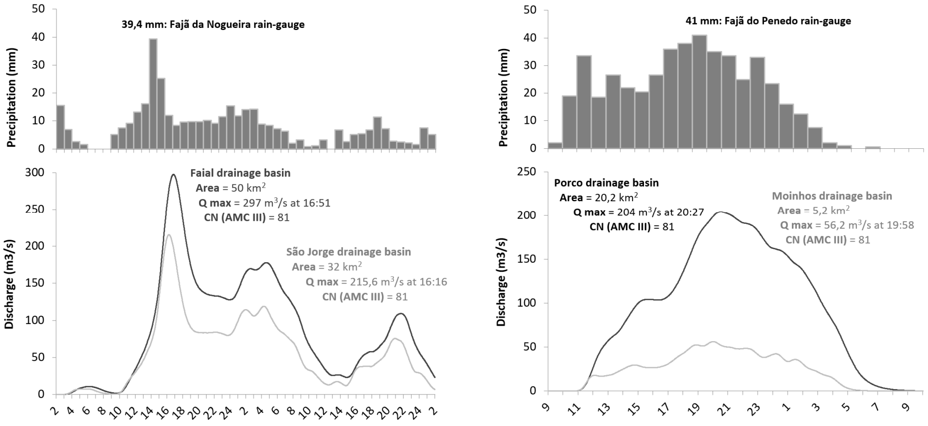
The hydrograms of *Faial* and *São Jorge* streams (Fig. 8a) stand out in the occurrence of several peak discharges, associated with secondary peaks of intense rainfall. This pattern of flow variation with time is indicative of a complex flood, whose duration is longer than that of a simple flood.

The results obtained constitute a contribution to the systematization of information on the relationships between sub-daily precipitation maxima and the corresponding peak flows expected in the stream mouth, as a function of the area of the respective catchments. In the January 7, 2021 event, the occurrence of hourly peaks of 40 mm within the *Faial* catchment, generated a maximum discharge of 297 m^3/s in the terminal stream section (Table 6).

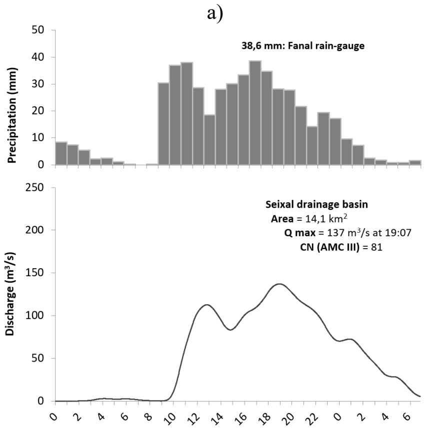
Table 6 Relationships between sub-daily precipitation peaks and the consequent floods generated in the terminal sections of the affected catchments.

Heavy rainfall event on 7 January 2021			
Maximum Precipitation (mm)	Fajã Nogueira gauge	Fajã do Penedo gauge	Fanal gauge
1 hour	39.4	41	38.6
6 hours	115.8	212.5	195.4

Drainage basins	Faial	São Jorge	Seixal
Area (km^2)	50 km^2	32 km^2	14,1 km^2
Peak flows at the basin outlet (m^3/s)	297 m^3/s	216 m^3/s	137 m^3/s



a) b)



c)

Fig. 8 Hyetographs of Fajã da Nogueira, Fajã do Penedo and Fanal rain-gauges, during the heavy rainfall event on January 7 and 8, 2021 and flow hydrographs of the basins in the areas of influence of these rain-gauges: a) São Jorge and Faial drainge basins; b) Moinhos and Porco drainage basins; c) Seixal drainage basin.

5 Assessment of flood risk in mountain streams

Different methodologies can be used for cartographic representation of regional and local susceptibility to the occurrence of torrential floods (MLIT, 2004; Lopes, 2020). But, in a complex territory of mountain streams, the option for higher spatial resolution cartography, supported by field survey work, has the advantage of producing more concrete results for land use planning.

A mountain stream should be assessed for the hazard of torrential flooding considering its topographical and geological characteristics. The areas of greatest susceptibility depend strongly on local topographic conditions. In general, the deposition of solid load carried by torrential floods occurs in the areas of weaker gradient, at the base of the mountain front (MLIT, 2004). Based on field survey work, we seek to identify and map the areas of greatest susceptibility to the occurrence of torrential floods.

The cartographic sketch of hydrogeomorphological susceptibility (Figure 9) illustrates the general characteristics of the streamline, whose respective catchment, with only 1 km^2 of area, falls into the class of very small (< 5 km^2). During the historic occupation of the territory, the streamline trajectory has changed significantly, resulting in the confinement of the streambed to a width that never exceeds 2 metres along its course. Being a very small stream, with an upper reach formed by sub-vertical slopes, puts it in a situation of sediment-related hazards due to the formation of debris flows. In the headwater stream, there is the hazard of the passage of debris flows, while the areas at the base of the slope, where the main road is located, are exposed to material deposition. The dynamics previously described occurred in the flood of 25 December 2020, which caused the total destruction of a house (Fig. 9) and the partial destruction of two others, in which functional damage occurred, but without jeopardizing their structural integrity. The destroyed house was implanted in the fluvial bank, corresponding to the band of 10 meters wide from the bed limit, classified as a fluvial domain by Portuguese law.

In this particular case, assuming a scenario of moderate to high probability of torrential flood events in the upper reach of the *Ponta Delgada* stream and a high degree of vulnerability of the populations living in the catchment, the conclusion is that the respective risk is maximum. Thus, any intention to (re)construct residential and other buildings in the 10 m wide band of streambank and in the mapped areas of runoff propagation and sediment deposition path (Fig. 9) should be carefully considered in the context of a specific technical assessment.

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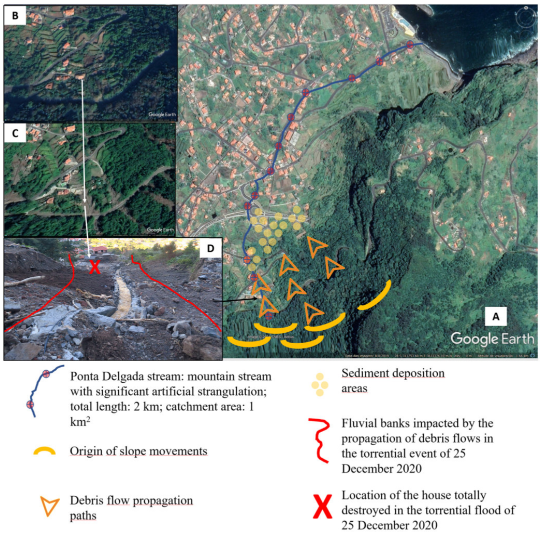

Fig. 9 Cartographic scheme of hydrogeomorphological susceptibility in Ponta Delgada village (north of Madeira Island), with indication of the house totally destroyed in the flood of December 25, 2020. Images source: (A) © Google Earth (August 8, 2019); (B) © Google Earth (March 11, 2020); (C) © Google Earth (May 14, 2021); (D) Photograph by the first author taken in the days following the flood of 25 December 2020.

Discussion and conclusions

The spatial distribution of heavy rainfall events studied in this paper, followed by local torrential floods, especially in mountainous areas of the interior and north flank of Madeira Island, suggests, to some extent, the influence of the orographic lifting effect of oceanic air masses in the genesis and evolution of these extreme events, as argued in other publications (Luna et al, 2011; Fragoso et al., 2012; Gorricha et al., 2012; Couto et al., 2012; Levizzani et al., 2013).

The maximum values of precipitation in 24 hours can occur anywhere on the island but are more frequent at higher altitudes. The peaks recorded at different rain-gauges associated with the recent flood events studied here, correspond to truly impressive amounts of localized water discharges (475 mm in Fajã do Penedo and 471 mm in Fanal on January 7, 2021), which even surpass the maxima that occurred on the southern side of the island during the great flood of February 20, 2010 (340 mm in Trapiche, mid-slope and 334 mm in Areeiro, at the top of the island); (Fragoso et al, 2012), whose exceptional character finds parallel with other known historical daily extremes (455 mm in March 1943 in the northern slope (Queimadas); 300.1 mm in November 1952 in the northern coast (Ponta Delgada); 522.3 mm in November 1963 in *Areeiro*; 434.2 mm in June 1964 and 441 mm in January 1965, also in *Areeiro*; 400 mm in March 2001 in *Encumeada/ São Vicente* (Ferreira, 2005).

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At the hourly interval, we point out the maximum values that occurred on the northern side of the island, namely the extreme amount of 108 mm in *Achada do Til* in *São Vicente* (22 December 2009), and the maximum of 47 mm in *Fajã do Penedo* (7 January 2022), in comparison with the equally extreme values that occurred in the southern side of the island of 114 mm (Camacha), 99 mm (Trapiche) and 65 mm (Areeiro), on 20 February 2010.

Heavy rainfall occurring over several hours can trigger catastrophic floods in mountain streams. Episodes lasting less than 24 hours are usually associated with variable amounts of 200 mm to 400 mm or more. On average, about 45% of this precipitation - corresponding to an average accumulation of 148 mm - occurs concentrated in less than 6 hours.

The calibrated antecedent precipitation was applied as an attempt to evaluate the values of the critical combinations between precipitation of the preceding days and precipitation of the event, in Madeira Island. Based on the available data it was possible to determine, with some degree of confidence, the existence of a strong relationship between rainfall patterns and the occurrence of local torrential floods.

The precipitation of a given event associated with the precipitation of the preceding 15 days can easily exceed the critical threshold of 300 mm. Thus, some torrential flood events, which occur in Madeira Island, seem to be associated with the combination of the precipitation of a previous preparatory period of soil instability (up to 15 days) and the precipitation of the event, intense and of short duration (generally concentrated in less than 24 hours). Relatively similar results to these were obtained in the study of rainfall patterns and critical values associated with landslides in Povoação County (São Miguel Island, Azores) (Marques et al., 2008).

According to the HEC-HMS model results, under streamflow conditions generated on January 7, 2021, the corresponding peak flows at the mouth of Faial (50 km^2) and São Jorge (32 km^2) catchments reached 297 m^3/s and 215.6 m^3/s respectively. The hydrographs of the terminal sections of the catchments provided evidence of the complex nature of these floods, marked by the occurrence of several flood peaks, synchronised with secondary peaks of precipitation in the preceding two or three hours.

The large-scale hydrogeomorphological susceptibility cartography, produced from the collection of field information in the aftermath of the events, represents a useful source of information, of relevant interest in deepening the knowledge on the characteristics of the territory, to avoid the eventual creation of new risk areas.

In mountain streams, the areas of greatest risk of torrential floods are typically located at the base of the mountain fronts, where the sudden decrease of terrain gradient, tends to promote the deposition of material in alluvial fans. The great attraction of these areas for human occupation, precisely because of the weaker gradient, requires special attention to hazards in the spatial planning process.

The studied floods were enhanced by the fast mobilization of large volumes of solid material resulting from slope movements. The debris flow caused a radical change in the morphology of the streambeds and banks and the obstruction of several hydraulic passages, which proved to be notoriously undersized to hold the passage of solid material. It is thus concluded that these were also floods of artificial obstacles. The records and marks observed in the field reveal the need to execute interventions to resize the cross-sectional area of these hydraulic infrastructures, to reduce the hydrological risk in the affected territories.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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