Rainfall analysis in mountain streams affected by torrential floods on Madeira Island, Portugal

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Abstract.

Torrential flows are powerful and destructive events that result from a mix of debris and water moving rapidly down steep channels in mountainous areas. They are normally triggered by heavy rainfall. This combination creates a high-density mass that is displaced by gravitational force, often through successive impulses. Predicting torrential flows is crucial because this natural hazard can pose a significant threat to both humans and infrastructure. Critical rainfall analyses is a fundamental research task with practical applications in civil protection early warning systems.

Empirical rainfall thresholds are calculated based on historical local-scale torrential flow events and past rainfall measurements that occurred on Madeira Island between 2009 and 2021. This analysis differentiates between rainfall from previous days and weeks and event rainfall. The first parameter uses a calibrated antecedent precipitation technique based on a power law that accounts for the drainage process over time in the catchments. The second corresponds to the maximum 24-hour precipitation, calculated as a sliding sum over the day(s) of heavy rainfall. The results from the combinations between these two parameters are considered to establish empirical rainfall thresholds related to torrential flows.

Our results statistically demonstrate that calibrated antecedent precipitation was significantly different between triggering and non-triggering rainfalls. Therefore, antecedent rainfall influences the occurrence of torrential floods on Madeira Island.

By applying this methodology, we were able to determine predefined rainfall thresholds for the occurrence of torrential floods. Calibrated antecedent precipitation over 15 days (110 mm) and 30 days (130 mm), combined with a maximum rainfall of 250 mm in 24 hours, exemplify critical conditions. Nevertheless, in some cases, the rainfall from the event can be high enough to cause torrential floods, regardless of the preceding rainfall. Interestingly, there exists a strong correlation between maximum precipitation in 24 hours and 12 hours. This correlation can be mathematically described by a linear regression model, which serves as a rule for predicting probable critical maximums within a 12-hour period. The estimation of streamflow peaks through rainfall-runoff modelling has also been conducted, revealing preliminary results regarding the relationship between the catchment area, sub-daily precipitation peaks, and consequent peak discharge.

As far as we know, this is the first study to introduce combined rainfall thresholds for the occurrence of torrential floods in Madeira Island catchments. In this context, the rainfall thresholds, particularly the results we have obtained, serve as a crucial input parameter for establishing a robust torrential flood warning system.

1 Introduction

Torrential flows, such as debris flows and debris floods, constitute mixed masses of debris and water that move at high velocities within steep channels in mountainous regions. In areas where these channels are formed by deep and narrow-bottomed valleys, there tends to be a higher occurrence of interactions between slope movements (such as landslides and debris flows) and fluvial dynamics (such as flash floods). Often, these flows are amplified by shallow translational slides that occur in the upper sectors of slopes and headwaters of catchments (SRES, 2010; Fragoso et al., 2012; Lopes et al., 2020). As these materials descend toward valley bottoms and streamlines, the initially stationary soils are rapidly transformed into a mixture of fine particles (sand, silt, clay) and coarse materials (cobble, boulder). This mixture also includes woody debris and water, resulting in a high-density mass where the solid load often exceeds 50% of the total mass. These materials are displaced by gravitational force, typically through successive impulses (Costa, 1988; Scott, 1988; Zêzere et al., 2005; Fragoso et al., 2012). Ultimately, this material is deposited only in areas with low ground gradient (MLIT, 2004), where flooding can occur.

Monitoring-based analysis is crucial for improving our understanding of the mechanisms that trigger torrential flows and their propagation. Rainfall is the most common triggering factor for these events (e.g., Zêzere et al., 2005). Understanding the specific rainfall conditions that lead to torrential flows is critical for providing timely early warnings related to such phenomena. The antecedent rainfall and the soil moisture conditions, may influence the triggering of torrential flows (Oorthuis et al., 2021; Oorthuis et al., 2023). In this sense, when analysing critical rainfall conditions for the initiation of torrential flows, it is important to differentiate between event rainfall and antecedent rainfall (Schröter et al., 2015). However, previous research have primarily focused on establishing specific rainfall thresholds for the initiation of torrential flows, emphasizing the impact of rainfall duration and intensity (Abancó et al., 2016).

Indeed, the temporal variation of rainfall, including antecedent rainfall (over days and weeks), as well as the duration and intensity of heavy rainfall, significantly influences the occurrence of torrential flows and other related disasters. The impact of antecedent rainfall on terrain is a complex process which can lead to soil saturation. Normally, the rain that is retained on the ground in a given area on any given day decreases over time due to the drainage process. This effect can be quantified applying a power law, which accounts for the draining of early precipitation and accumulation of late rainfall (Crozier, 1986; Glade et al., 2000). However, few studies have focused on analysing the combinations between antecedent rainfall and maximum values of heavy rain events for empirical rainfall thresholds related to torrential floods. It is true that several studies have focused on the study of intense rainfall on Madeira Island, especially after the great flood of 20 February 2010 (Luna et al., 2011; Fragoso et al., 2012; Gorricha et al., 2012; Couto et al., 2012; Levizzani et al., 2013). However, there is still limited concrete information regarding critical rainfall thresholds.

Having a dense network of rain gauges in catchment areas is important for accurately measuring rainfall and understanding its impact on torrential flow occurrence. The recommended average density of rain gauges for analyzing the spatial variation of rainfall in mountainous areas is 1 per 15 km² (Linacre, 1992), a standard that is met on Madeira Island. However, obtaining direct rainfall data near torrential flow source areas can be challenging due to technical limitations of covering the entire territory, especially in complex terrains. Nikolopoulos (2014) emphasizes the significance of uncertainty in spatial rainfall estimation when identifying rainfall thresholds for debris flow occurrence. For example, Segoni et al. (2014) argue that a regional-scale warning system can be significantly enhanced by using a mosaic of site-specific thresholds instead of relying solely on a single regional threshold. Additionally, ensuring an appropriate spatial distribution of rain gauges is essential for improving the reliability of rainfall thresholds for early warning systems, especially in mountainous regions, as is the case here. Conversely, when estimating rainfall thresholds, it is crucial to underscore the need for accurate and reliable climatological data (Montesarchio, 2015); this means regularly reviewing the data recorded by the devices and avoiding gaps.

The primary objective of this study is to determine critical precipitation threshold values that can lead to torrential floods. To achieve this, we will base our analysis on historical torrential flow events and past rainfall measurements. Specifically, we will compare data from rainfall events that triggered torrential events with data from those that did not. A secondary objective is to obtain complementary hydrological information regarding the relationship between heavy rainfall amounts and flow discharges in small catchments, achieved through a hydrological modelling exercise. The third goal is to discuss aspects related to the uncertainty surrounding the definition of rainfall thresholds and consequent flow discharges.

Establishing accurate rainfall thresholds for torrential flow early warning systems is essential, but the lack of standardized procedures poses a challenge. The proposed criteria consider antecedent rainfall conditions along with maximum daily and sub-daily rainfall amounts.

1 Data and methods

The methodology employed in this research is depicted in Fig. 1. The amount of precipitation occurring in a given event and its duration can be determined based on various criteria. For instance, according to the rule of thumb used by the Portuguese Meteorological Institute (IPMA)—which considers total precipitation in a 6-hour moving interval greater than 30 mm—an average of 18 days of heavy precipitation occurs annually in the mountains (such as Areeiro, as shown in Fig. 2). Another criterion specifies that an event begins when hourly precipitation equals or exceeds 4 mm and ends when hourly precipitation falls below this threshold for a consecutive 6-hour period. Normally, most heavy rainfall events are concentrated within a 24-hour timeframe (Lopes, 2015). Thus, in this analysis, event precipitation corresponds to the maximum 24-hour precipitation, calculated as a sliding sum over the day(s) of heavy rainfall. This calculation is based on 10-minute readings (in millimetres), which are available for most events through the regional network of rain gauge stations. Maximums for

different sub-daily durations were also calculated (1 hour, 3 hours, 6 hours, and 12 hours). These values were relative to the rain gauges localized in the area of influence of the localities most affected by torrential floods (Fig. 2).
However, the precipitation thresholds were determined using a mosaic of site-specific local rainfall data. A similar procedure was adopted by Segoni et al. (2014). Given the general characteristics of the Madeira territory, this approach appears to be more effective than using a single regional threshold derived from just one rain gauge. In years without records of torrential floods, the precipitation values needed to analyse the relationship between daily precipitation and antecedent precipitation were obtained using the maximum annual precipitation technique for various durations. However, when constructing these extreme value series, multiple values per year can be utilized. This becomes particularly relevant when two heavy rainfall events followed by floods occur within the same hydrological year. On the other hand, when analysing the influence of precipitation that occurs in the days preceding a specific rainfall event, it is logical to follow the rule of separating event precipitation from antecedent precipitation (Schröter et al., 2015). This criterion is also applied here.

Madeira, a relatively small mountainous island covering 741 km², contains approximately 126 catchments, of which 94% have an area less than 25 km². The island experiences a diverse spatial distribution of heavy rainfall events, and notably, all the events analysed here have resulted in small local torrential floods. The inventory of torrential floods was compiled by applying one of the following selection criteria based on the occurrence of: a) interactions between slope instability and stream flow; b) people affected (evacuated, displaced, or injured); c) at least one victim (deceased or missing) d) damage to at least one public or private infrastructure.

Precipitation from previous days can significantly or partially influence the triggering of slope movements and flash floods. A paradigmatic example of this influence occurred during the intense rainfall event on February 20, 2010, which caused torrential floods in Madeira during a particularly anomalous wet winter (Fragoso et al., 2012). However, the overland flow following the rain, diminishes over time due to surface drainage (Zêzere et al., 2005). To assess the impact of rainfall in the days and weeks preceding slope instability, Crozier (1986) proposes introducing an exponential function to express the diminishing significance of rainfall with increasing temporal distance from the date of interest.

The mathematical expression used to calculate calibrated antecedent precipitation (Zêzere et al., 2005, in Crozier, 1986) is as follows:

$$CAPx = K\ P1 + K2\ P2 + ...Kn\ Pn$$

where CAPx is the calibrated antecedent precipitation 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 typically considered between 0.8 and 0.9, depending on the draining capacity of the material and the hydrological characteristics of the area. In this study, we adopt the value K = 0.9, based on references from existing literature (Zêzere et al., 2005; Marques et al., 2008). This equation makes negligible precipitation occurred more than 30 days before a torrential flood event. Consequently, the reconstitution of the calibrated antecedent precipitation was only calculated for durations of 5, 10, 15, and 30 days.

In theory, with the empirical parameter K = 0.9, we assume that 90% of the rainwater that occurred in a certain period prior to the day of interest (even before applying the exponent) remains accumulated in the soils of the catchment-stream system.

This evaluation considers rainwater from previous days and weeks, which can contribute to soil saturation and slope instability. The remaining 10% of that water has already been drained into the water network, percolated, or evaporated.

In the specific analysis of the December 2020 and January 2021 torrential floods, rainfall data were processed, and the monthly totals and accumulated rainfall for the previous days and weeks were determined. This calculation was based on the records available at the rain gauges located in the vicinity of the affected areas (specifically, *Fanal*, *Fajã do Penedo*, and *Fajã da Nogueira*, as shown in Fig. 2). The respective hyetographs were prepared using the hourly right time precipitation values.

The estimation of peak discharges was conducted for five catchments situated on the northern side of Madeira Island: Faial, São Jorge, Porco, Seixal, and Moinhos streams (Fig. 2). This analysis considered the rainfall data from the January 7, 2021 event. The flood hydrographs and peak flows were calculated under the assumption that the amount of rainfall recorded at each rain-gauge station uniformly affected the catchments where they are located. The estimated values pertain to the outflow at the mouth of the catchments.

Flood hydrographs are determined based on the hyetograph data mentioned earlier and the synthetic unit hydrograph from the Soil Conservation Service (S. C. S.). This calculation is performed using the HEC-HMS model (Hydrologic Engineering Center - Hydrologic Modeling 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's response time to peak precipitation, as 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. To estimate the volume of precipitation water transformed into flow, the lag time method was employed.

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 in Madeira's catchments is primarily due to natural conditions, which are largely influenced by the characteristics of volcanic rocks and soils (Leal et al., 2020). Considering the prevalence of agricultural and forestry areas, and referring to the S. C. S. tables, it was decided to adopt a common CN of 81 for all catchments in this hydrological modelling exercise. This choice corresponds to AMCIII conditions (completely saturated soil).

Rainfall data from three rain gauges (Fajã da Nogueira, Fajã do Penedo, and Fanal, numbered 7, 6, and 1 in Fig. 2, respectively), with 10-minute recording intervals, were used as input parameters for the hydrological model. The modeling exercise was conducted for five catchments located on the northern side of Madeira Island (as discussed in topic 4). This area was specifically chosen because it was the most affected by the heavy rain event on January 7, 2021.

Table 1: Physical parameters of the catchments under study.

	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

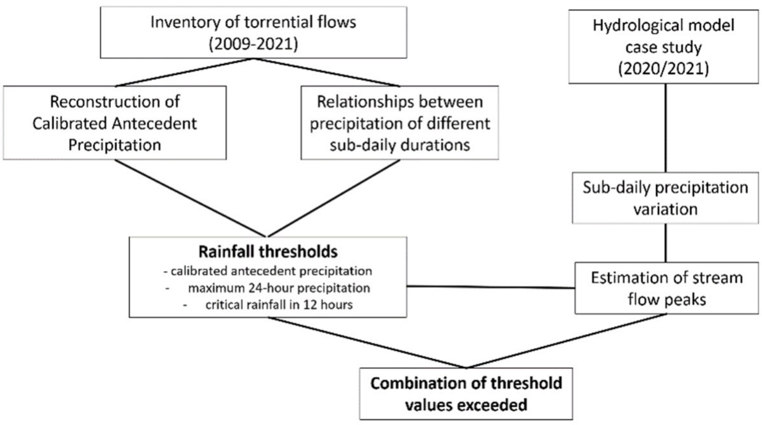


Fig. 1 Methodology for determining probable rainfall thresholds related to torrential flows and consequent peak discharges.

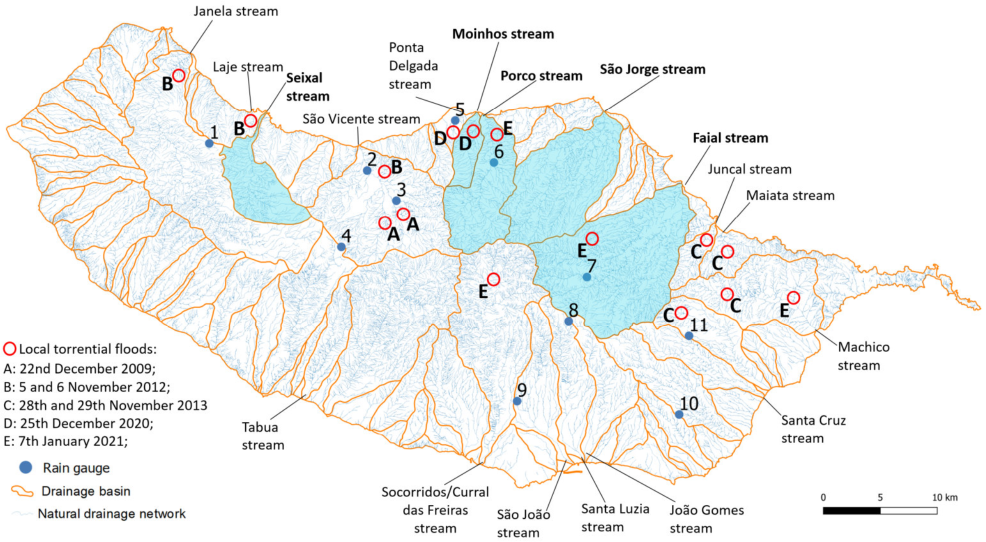


Fig. 2 Madeira Island hydrographic system. The catchments that will be the subject of the hydrological study are highlighted in blue. The red circles indicate the localities affected by torrential floods from 2009 to 2021.
Rain-gauges used in this research: 1 Fanal; 2 Posto Florestal São Vicente; 3 Achada 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.

3 Rainfall thresholds

This study identified heavy rainfall events that triggered torrential floods ~~ws~~ between 2009 and 2021. The five events inventoried in Table 2, along with their respective occurrences mapped in Fig. 2, illustrate that during certain rainfall storms, subsequent floods tend to have a localized spatial impact. These events primarily occurred on the northern side of the island, characterized by rocky and mountainous terrain. Vertical erosion has shaped ravines and exceptionally deep valleys within the island's interior. Field surveys conducted immediately after the torrential flood disasters allowed for the georeferencing of 10 streams affected between 2009 and 2021. These areas experienced the displacement of people and material damage, impacting both private property and public infrastructure. As an example, the photographic record illustrates the destructive effects that occur in local settlements affected by torrential floods (Fig. 3).

3.1 Calibrated antecedent precipitation

The characteristic combinations between precipitation from preceding days and that of heavy rain events were the subject of investigation. This was done by examining the relationship between the maximum precipitation in 24 hours (Pmax24h) and the corresponding antecedent precipitation calibrated for different periods (5, 10, 15, and 30 days). A set of known episodes of heavy rainfall from 2009 to 2021 was considered, including the five events referenced in Table 2, as well as the events from 2 and 20 February 2010 and 25 January 2011. For this purpose, a data sample was collected from rain gauges located near the areas most affected by torrential flows. One of the conditions followed in setting up this sample was to ensure that there were no data gaps in the previous weeks, allowing for a more rigorous calculation of the calibrated antecedent precipitation. Furthermore, we incorporated the heavy rainfall event that took place on 5 and 6 June 2023, as it established a new record for 24-hour rainfall in Portugal (609.8 mm).

In the compilation of these climate series, rainfall data from a set of years without records of torrential flood events were also included (Fig. 4). 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).

In all graphs in Figure 4, it is evident that maximum rainfall pairs for years without recorded torrential floods (represented by the blue and black dots) consistently fall below the horizontal line corresponding to the maximum 24-hour rainfall of 250 mm. Conversely, most of the points in pairs related to known heavy rainfall events are located close to or above the line (indicated by orange points). This observation confirms that the value of maximum rainfall in 24 hours can be used as a probable threshold for the occurrence of torrential floods on Madeira Island. This threshold can be combined with the corresponding values of antecedent rainfall calibrated for different durations in days, as shown below.

The graphical information that relates the maximum precipitation in 24 hours (Pmax24h) to the antecedent precipitation calibrated for different durations (5, 10, 15, and 30 days) indicates a pattern of data grouping. This pattern can be used to identify critical precipitation thresholds, beyond which torrential flood events may occur (Fig. 4). Additionally, Table 2 presents the calibrated antecedent precipitation values for different durations and for the five case studies.

In order to define the number of days that are most relevant to antecedent precipitation, the best results obtained correspond to the CAP at 15 and 30 days, where the graphs show only three critical precipitation pairs positioned to the left of the respective vertical lines of calibrated antecedent precipitation (Figs. 4c and 4d). However, even for the other durations (5 and 10 days), there is a tendency for points to be more concentrated to the right of the respective vertical lines (Figs. 4a and 4b), so all the combinations obtained can be used as probable thresholds for torrential floods on Madeira Island.

The calibrated antecedent precipitation show that the rainfall of previous days and weeks does not always play a major role in triggering torrential floods. For example, in the case of the torrential floods of 25 December 2020 on the north coast of the island, as seen above, the daily and sub-daily maximum values were high enough to cause catastrophic flooding.

The information summarized in Fig. 5 pertains to a specific case involving two events of heavy rainfall-to-runoff torrential floods. These events occurred within the same hydrological year (2020/2021). In this particular scenario, the calibrated antecedent precipitation (CAP) at 5 and 15 days on the date of the first event (December 25, 2020) was relatively low. However, during the second event (January 7, 2021), the precipitation from the first event significantly influenced the high value of the CAP at 15 days (158 mm). This case study demonstrates that the precipitation in the preceding days and weeks does not always play a decisive role in triggering torrential floods. For instance, during the floods on December 25, 2020, the daily and sub-daily maximum precipitation values (Table 3) were sufficiently high to cause catastrophic floods.

a) b)

Fig. 3 Destructive effects caused by torrential floods–on the north side of Madeira Island: a) 5 and 6 November 2012; b) 25 December 2020.

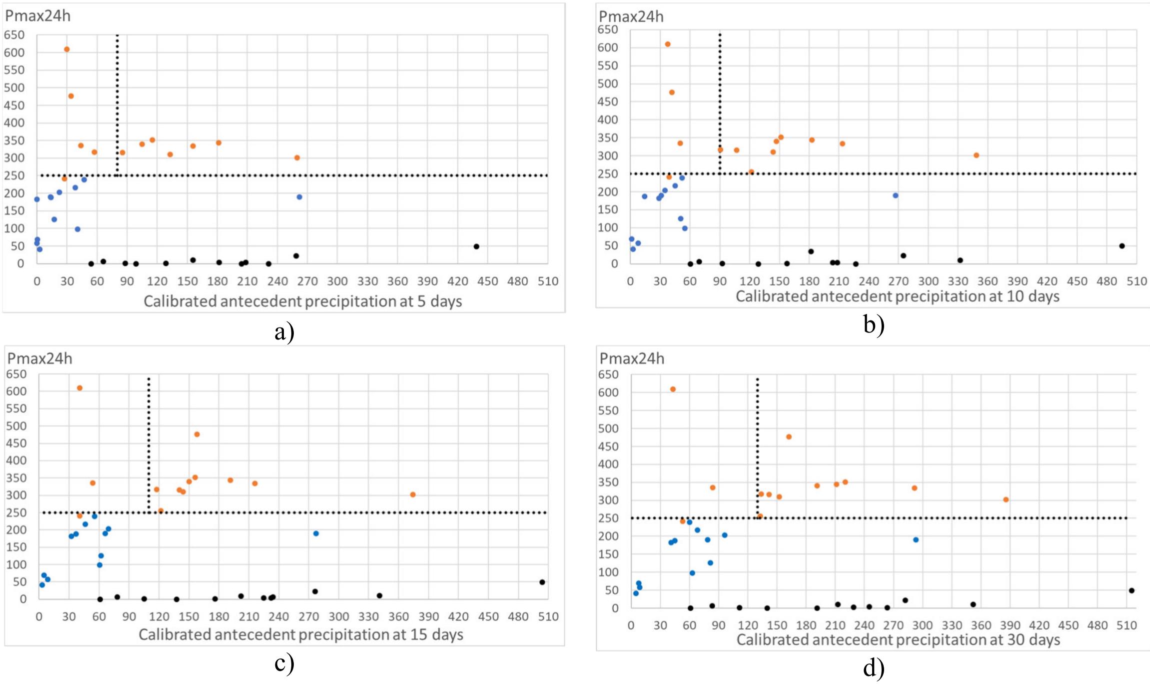


Fig. 4 Relation between maximum 24-hour precipitation and calibrated antecedent precipitation at 5 days (a), 10 days (b), 15 days (c) and 30 days (d). The orange dots refer to the values associated with heavy rainfall events between 2009 and 2023. The blue dots correspond to values obtained from the yearly maximum 24-hour rainfall, while the black dots represent the yearly maximum calibrated antecedent precipitation, computed for years without torrential floods.

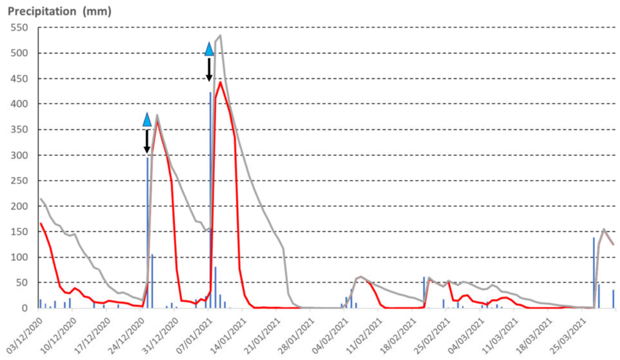


Fig. 5 Daily precipitation and calibrated antecedent precipitation (CAP) at 5 and 15 days, between December 2020 and March 2021, in *Fajã do Penedo*. Blue bars: daily precipitation; red line: 5-day CAP; grey line: 15-day CAP; blue triangles: date of occurrence for torrential flood events.

Table 2 Precipitation- torrential floods events and their calibrated antecedent precipitation (CAP).

			Calibrated antecedent precipitation				
Date	Rain-gauges	Maximum precipitation in 24 hours	**3 days**	**5 days**	**10 days**	**15 days**	**30 days**
22 December 2009	Achada do Til	290.8	131.9	259.7	348.6	374.5	385.6
5 and 6 November 2012	Posto Florestal São Vicente	317	57.2	57.3	90.5	117.8	134
28 and 29 November 2013	Santo da Serra	241	20.3	27.3	38.9	40.6	53.1
25 December 2020	Fajã do Penedo	335.5	43.7	43.7	49.9	53.7	83.7
7 January 2021	Fajã do Penedo	475	33.9	33.9	41.9	158.1	162.1

3.2 Relationships between precipitation of different sub-daily durations

Based on a sample of five heavy precipitation events followed by torrential floods, we accessed higher temporal resolution data. From this data, we computed the maximum characteristic values for various sub-daily durations, as shown in Table 3. Through comparative analysis, we examined the relationship between two sets of precipitation values: the maximum precipitation over 24 hours (Pmax24h) and the maximum precipitation over shorter durations (Pmax12h, Pmax6h, Pmax3h, and Pmax1h). This was done to evaluate the statistical significance of the dependencies existing between these variables.

To conduct this study, we formed a larger dataset using nine rain gauges located in the mountains and on the north side of the island (rain gauges 1, 2, 3, 6, 7, 8, 9, 10, and 11, as shown in Fig. 2). This dataset covered a total of eleven heavy rainfall events that occurred between 2009 and 2021. In addition to the five previously analysed events (Table 2), we decided to include an additional set of six other heavy precipitation events, which had been previously studied by Lopes in 2015. By incorporating additional events and data from different rain gauges in the same sample, we aimed to emphasize the importance of identifying characteristic values that represent the climatology of intense rainfalls at higher altitudes (mountain top) and on the north side of the island. These values play a crucial role in understanding the occurrence of floods. Notably, while three heavy rainfall events in the last quarter of 2010 and the one on January 25, 2011 did not trigger torrential floods, they did lead to increased flow discharges in various streams across the island.

The results reveal a strong correlation ($R^2 = 0.83$) that can be mathematically described by a linear regression model between Pmax24h (maximum precipitation over 24 hours) and Pmax12h (maximum precipitation over 12 hours), following the equation: $Pmax12h = 0.7553*Pmax24h + 16.257$ (Fig. 6). These indicated relationships allow us to estimate the probable critical maximums within a 12-hour period, based on the predicted precipitable water values over 24 hours. Based on the database of heavy rainfall events, it can be seen that the weight of maximum rainfall in 12 hours compared to *Pmax24h* is significantly high (83%). Interestingly, there is no significant correlation between Pmax24h and the maximum precipitation for shorter durations: 6 hours ($R^2 = 0.57$), 3 hours ($R^2 = 0.40$), and 1 hour ($R^2 = 0.12$). However, for mountainous areas on the northern side of Madeira Island, certain average values of heavy rainfall can be inferred (Table 3).

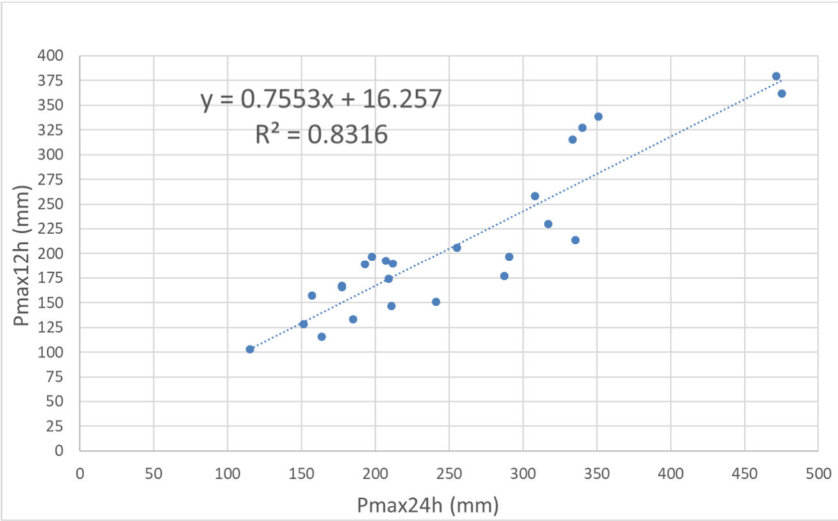


Fig. 6 Relation between precipitation in 12 h (Pmax12h) and 24 h (Pmax24h), using data from events from 2009 to 2021.

Table 3 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	211	146.6	93	54	26.2
	Posto Florestal São Vicente	317	229.8	121.4	78.4	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	**475**	362	**212.5**	116	43
	Fajã da Nogueira	287.4	177	115.8	81.6	39.4
	Fanal	**471.6**	**379.4**	195.4	117.8	45.4
	Average	**328.7**	**232.0**	**147.7**	**100.8**	**48.1**

4 Estimation of peak discharges

The objective of this section is to enhance our understanding of the relationships that exist between sub-daily precipitation peaks and the subsequent stream flow peaks generated in the terminal sections of catchments affected by heavy rainfall events. We will examine in detail two specific heavy rain events that occurred within a 15-day time frame—specifically, on December 25, 2020, and January 7, 2021. For this purpose, we processed data collected from the *Fajã da Nogueira*, *Fajã do Penedo*, *São Vicente*, and *Fanal* rain gauges (Fig. 2)

The hydrological year 2020/2021 brought abundant rainfall to the northern side of Madeira Island. In December 2020, *Fajã da Nogueira* received a cumulative total of 454.6 mm, while *Fajã do Penedo* experienced even higher precipitation at 616.5 mm. The trend continued into January 2021, with rainfall in these localities reaching approximately 590 mm. According to the climatological normal (from 1951 to 1980), it becomes evident that January consistently stands out as the wettest month. At the mountain's peak (*Bica da Cana*, situated at an altitude of 1560 meters, as depicted in Fig. 2), the average total for January precipitation is 480 mm.

In general, precipitation on Madeira Island exhibits an irregular temporal distribution, with a tendency to concentrate more than 50% of monthly rainfall within a reduced number of days (Lopes, 2015). This trend becomes particularly pronounced during hydrological years marked by heavy rainfall events. For instance, on January 7, 2021, the maximum 24-hour totals in *Fajã do Penedo* (475 mm) and *Fanal* (471.6 mm) corresponded to 80% and 72% of the respective monthly rainfall. Similarly, in *Fajã da Nogueira*, the maximum 24-hour rainfall (287.4 mm) represented 49% of the monthly total. A previous study by Ferreira (2005) highlighted that in years lacking strong daily rainfall events from November to January, the overall amount of rainfall received on the island of Madeira becomes exceptionally low.

On December 25, 2020, there was particularly intense rainfall on the northern coast of the island, specifically in the streams of Ponta Delgada and Moinhos (Fig. 2). The records from the *Fajã do Penedo* rain gauge clearly indicate the exceptional precipitation during this event, with 24-hour maximums exceeding 300 mm (Table 3). The hyetograph of *Fajã do Penedo* (Fig. 7a) reveals abundant rainfall during the first 15 hours of the day, totalling 136.5 mm. Subsequently, a critical period of heavy rainfall occurs in the afternoon, with 124 mm recorded over 4 hours (Fig. 7a). During this time, several slope movements occurred in the Ponta Delgada catchment (Fig. 2). For the heavy rain event of January 7 to 8, 2021, we highlight the occurrence of 7 non-consecutive hours with hourly precipitation exceeding 30 mm (Fig. 7b).

The studied catchments vary in size, ranging from 5.2 km² (Moinhos) to 50 km² (Faial), and exhibit a generally elongated shape (Fig. 2). Their physical parameters are detailed in Table 1. The lengths of the respective main streams are relatively short, with the longest being 14.3 km (Faial) and the shortest measuring 5.5 km (Moinhos). All catchments share a common feature: the predominance of steep slopes and a short time of concentration, typically about 3 hours or less (as shown in Table 1). The topographic conditions of these catchments, along with their land use characteristics, play a crucial role in the occurrence of torrential floods (Lopes et al., 2020).

The case study selected for estimating peak discharges was the heavy rainfall event of January 7, 2021. During this event, a longer sequence of records was available at a 10-minute interval, without any data gaps. The HEC-HMS model estimated peak flows for the mouth of the Faial catchment (50 km²) and the São Jorge catchment (32 km²), reaching 297 m³/s and 215.6 m³/s, respectively. In the Porco catchment (20 km²), the peak flow at the mouth was 204 m³/s, while at Seixal (14 km²), it reached 137 m³/s. Notably, the differences in peak flows were 81.4 m³/s (Faial vs. São Jorge) and 148 m³/s (Porco vs. Moinhos). Additionally, the time intervals between flood peaks varied: 35 minutes (São Jorge vs. Faial) and 29 minutes (Moinhos vs. Porco).

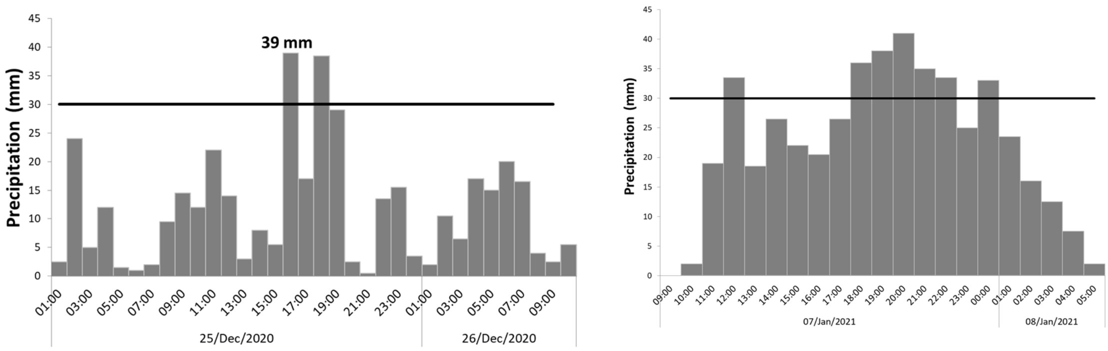
The hydrograms of the Faial and São Jorge streams (Fig. 8a) stand out due to the occurrence of several peak discharges, often associated with secondary peaks of intense rainfall. This flow pattern, which varies over time, is indicative of a complex flood event whose duration exceeds that of a simple flood. These secondary peaks of intense rainfall tend to increase the instability of the terrain in the upper sectors of the catchments.

The results obtained contribute to the creation and maintenance of a hydrological database for Madeira Island’s streams, specifically focusing on the relationship between sub-daily precipitation maxima and the corresponding peak flows expected at the stream mouth. This relationship is primarily influenced by the area of the respective catchments. For instance, during the January 7, 2021 event, hourly peaks of 40 mm within the Faial catchment resulted in a maximum discharge of 297 m³/s in the terminal stream section (Table 4).

Table 4 Peak precipitation and subsequent peak flows occurred at the catchment outlet during the heavy rainfall event on January 7, 2021.

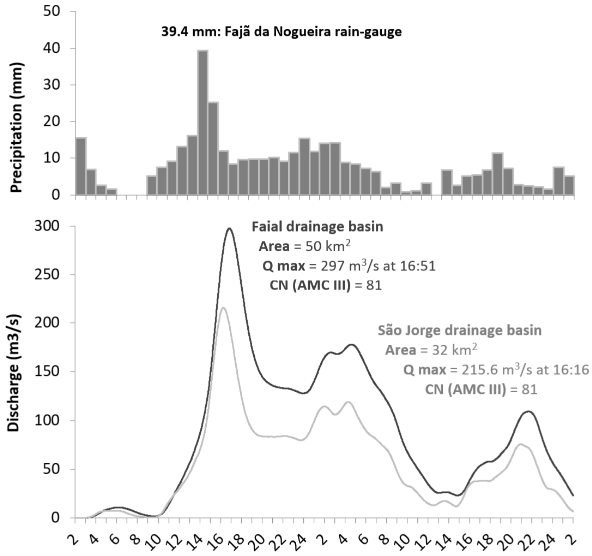
Maximum Precipitation (mm)	Fajã Nogueira gauge	Fajã do Penedo gauge	Fanal gauge
1 hour	39.4	43	45.4
6 hours	115.8	212.5	195.4
12 hours	177	362	379.4

Catchments	Faial	São Jorge	Seixal
Area (km^2)	50 km^2	32 km^2	14.1 km^2
Peak flow at the catchment outlet (m^3/s). HEC-HMS estimations.	297 m^3/s	216 m^3/s	137 m^3/s

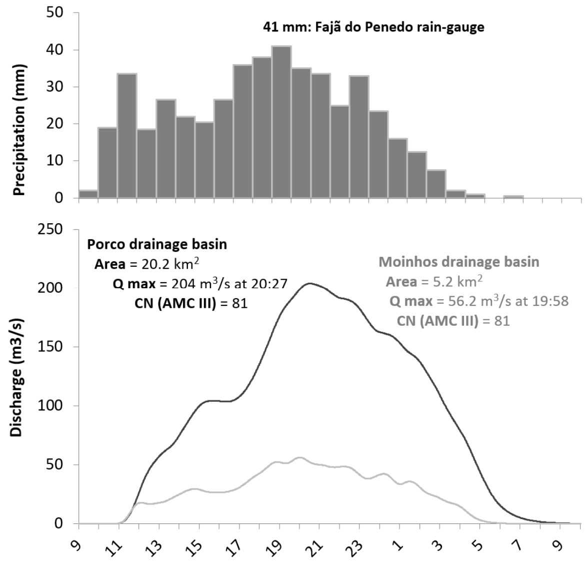


a) b)

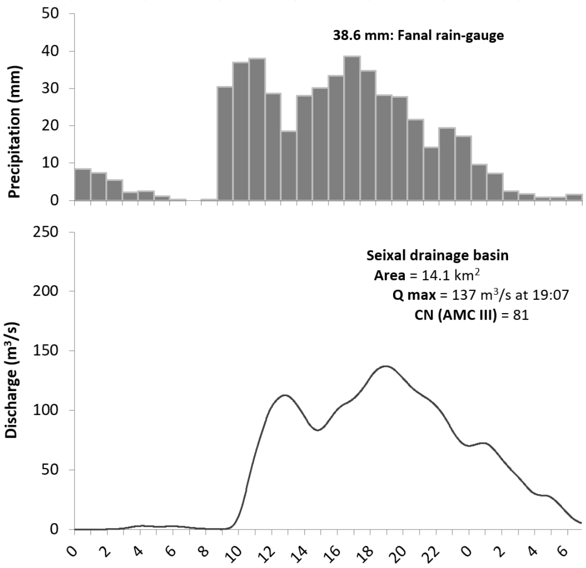
Fig. 7 Hyetograph of *Fajã do Penedo* during the heavy rainfall events of:
(a) December 25, 2020; (b) January 7 and 8, 2021.



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 catchment in the areas of influence of these rain-gauges.

5 Discussion

Heavy rain events can occur anywhere on the island, but they are more frequent at higher altitudes. In this methodology, critical thresholds for heavy rainfall were determined by considering a sample of rainfall data from different rain gauges. These gauges are located on the mountain (south side of the island above 500 meters) and on the north side, regardless of altitude. By doing so, the critical thresholds obtained for different durations reflect the behaviour of heavy rainfall in these specific areas, corresponding to the upper sectors of the catchments where torrential flows generally begin. This deliberate approach allows for the determination of a combined regional threshold, rather than relying solely on a single threshold from just one rain gauge. In terms of climate, rainfall behaviour at higher altitudes may differ significantly from coastal regions. Additionally, it is well-known that the north and south sides of the island experience distinct weather patterns. However, when it comes to heavy rain events, their spatial incidence does not follow strict patterns. In fact, meteorological events of this nature could happen anywhere on the island. However, only events occurring in mountainous areas will trigger torrential floods. The key difference lies in the distribution of catchments: the north coast of the island has more catchments in mountainous environments than the south coast. Consequently, intense precipitation on the north coast is associated with a greater probability of local torrential floods compared to the same altitude on the south coast.

The peaks recorded at different rain gauges associated with recent flood events studied here correspond to truly impressive amounts of localized water discharge in 24 hours. For instance, on January 7, 2021, *Fajã do Penedo* (north coast of the island) experienced 475 mm of rainfall, while *Fanal* (mountain top) received 471 mm. These amounts even surpass the maxima observed 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), has published in Fragoso et al. (2012). The exceptional character of these extreme values finds parallels with other historical daily extremes. For example, in March 1943, the northern slope (Queimadas) received 455 mm of rainfall, and in November 1952, the northern coast (Ponta Delgada) experienced 300.1 mm. Additionally, *Areeiro* saw 522.3 mm in November 1963, and both June 1964 and January 1965 witnessed heavy rainfall (441 mm and 434.2 mm, respectively) in *Areeiro*. In March 2001, *Encumeada/São Vicente* received 400 mm of rainfall (Ferreira, 2005).

It's worth noting that, in some cases, the rainfall of the event may be sufficient to trigger torrential flows, while in other cases, the rainfall during the days and weeks preceding a rain event may play a determining role in the occurrence of these disasters. In other words, torrential floods can be triggered either exclusively by the precipitation during the event or by a combination of both the preceding precipitation and the event-specific rainfall. However, even when dealing with relatively high 24-hour rainfall maximums (for instance, exceeding 300 mm), the potential occurrence of floods depends mainly on the hourly variation of that maximum daily quantity. The higher the hourly concentration, the greater the likelihood of torrential flooding.

Heavy rainfall occurring over several hours can indeed 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. Normally, more than 80% of this rain is concentrated in less than 12 hours. On average, about 45% of this precipitation—corresponding to an average accumulation of 150 mm—occurs concentrated in less than 6 hours. At the hourly interval, it is worth highlighting some maximum values that occurred on the northern side of the island. Specifically, there was an extreme amount of 108 mm in *Achada do Til* in São Vicente on December 22, 2009. Additionally, *Fajã do Penedo* experienced a maximum of 47 mm on January 7, 2022. In comparison, equally extreme values occurred on the southern side of the island: 114 mm in *Camacha*, 99 mm in *Trapiche*, and 65 mm in *Areeiro*, all on February 20, 2010.

In catchments where rocks and soils are highly permeable (such as sandy glacial soil), the preceding rainfall is not relevant for triggering floods. Consequently, there are no significant differences between triggering and non-triggering rainfalls (Abancó, 2016). However, this is not the case on Madeira Island, where the characteristics of volcanic rocks and soils favor soil surface water retention over days and weeks, leading to increased slope instability. This hydrological behaviour makes preceding rainfall conditions a crucial variable in determining whether torrential flood events are triggered or not.

The calibrated antecedent precipitation was applied in an attempt to evaluate the critical combinations between precipitation from preceding days and the event-specific precipitation on Madeira Island. Based on the available data, it was possible to determine, with some degree of confidence, a strong relationship between rainfall patterns and the occurrence of local torrential floods. In some cases, the precipitation of a given event, combined with the calibrated antecedent precipitation from the preceding 15 days, can easily exceed the critical threshold of 400 mm. Consequently, some torrential flood events on Madeira Island appear to be linked to the combination of precipitation during a preparatory period of soil instability (up to 15 days prior) and the intense, short-duration rainfall during the event (typically concentrated in less than 24 hours). Similar results were obtained in a study of rainfall patterns and critical values associated with landslides in Povoação County, São Miguel Island, Azores (Marques et al., 2008).

Therefore, the results are sufficiently consistent to propose criteria for predefined rainfall thresholds (Table 5). The thresholds obtained can be enhanced by incorporating rainfall measurement data from future heavy rainfall events. However, it is crucial to acknowledge the uncertainties and limitations of the results obtained, especially considering the constraints of rainfall point measurement methods. Rainfall often occurs in a dispersed manner, making it challenging to obtain a sample that accurately represents the physical conditions. Nevertheless, this research was feasible due to the availability of high-quality observational data. The data includes temporal resolution readings at 10-minute intervals from a network of approximately 40 rain gauges distributed across different locations. This comprehensive spatial coverage enables effective rainfall monitoring in the catchments of Madeira Island and the establishment of an outstanding data collection platform.

According to the HEC-HMS model results, under streamflow conditions generated on January 7, 2021, the corresponding peak flows at the mouth of the 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, characterized by several flood peaks synchronized with secondary peaks of precipitation occurring in the preceding two or three hours. Generally, the occurrence of secondary peaks of intense precipitation prolongs flood discharges for extended periods (hours), thereby increasing the risk of catastrophic floods.

However, the peak flood flow estimations obtained from the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model may differ from the values obtained with direct measurements in cross sections using channel geometry methods. This discrepancy arises because the model is specifically used for calculating fluvial liquid discharge. But, in reality, torrential floods consist of a mixed flow of solid material and water. Unfortunately, the current torrential flood risk assessment system lacks an important factor: sediment supply (Lane et al., 2008; Wang et al., 2019). While constant sediment inflow from upstream has little effect on the water level during stream flow discharge, sudden sediment inflows from valley slopes, such as debris flows, significantly increase flood risk in a given stream reach, especially near stream junctions (Liu et al., 2022). Sediment transport can indeed lead to higher flood discharge. In reality, there is a complex relationship between sediment transport and flood discharge, with both processes influencing and being influenced by each other. However, for the purposes of comparative analysis between catchments, we considered that the values obtained reflect an order of magnitude sufficient to perceive the spatial variations of floods. Nevertheless, comparing the values estimated by modeling with those obtained by applying the Manning-Strickler Formula, based on direct measurements in cross sections using channel geometry methods (only available in one of the catchments studied), reveals that the former are underestimated compared to the latter. This flood factor is not the central theme of this research and should be the subject of in-depth investigation in future work.

The torrential floods studied here were intensified by the rapid mobilization of substantial amounts of solid material resulting from slope movements. The debris flow led to a significant alteration in the morphology of streambeds and banks, obstructing several hydraulic passages that were notably undersized to accommodate the passage of solid material. Consequently, it can be inferred that these floods were also influenced by artificial obstacles. Field observations and markings highlight the necessity for interventions aimed at resizing the cross-sectional area of these hydraulic structures, thereby mitigating hydrological risks in the affected localities.

Table 5 Proposed criteria for classifying probability of occurrence of torrential floods in Madeira Island's catchments.

Relationships between rainfall for different durations	**Probable thresholds of maximum rainfall pairs (*)**	**Probability of torrential floods**
PAC5 days – Pmax24h **(a)**	- Pmax24h > 250 mm e - PAC 5 days > 80 mm;	**High probability: Pmax24h > 250 mm**
PAC10 days – Pmax24h **(b)**	- Pmax24h > 250 mm e - PAC 10 days > 90 mm;	
PAC15 days – Pmax24h **(c)**	- Pmax24h > 250 mm e - PAC 15 days > 110 mm;	**Very high probability:** **(a)** or **(b)** or **(c) or (d)**
PAC30 days – Pmax24h **(d)**	- Pmax24h > 250 mm e - PAC 30 days > 130 mm;	

(*) Condition that critical thresholds occur in at least one rain gauge located either in the mountains (including the south side of the island above 500 meters above sea level) or on the north coast of Madeira Island (regardless of altitude).

Conclusions

According to historical records, heavy rain events can occur anywhere on the island, although they are more frequent in the mountains. Rainfall behavior at higher altitudes may differ significantly from that in coastal regions. Additionally, the north and south sides of the island experience distinct weather patterns. However, in the case of heavy rainfall events, there is a certain randomness in the spatial distribution of maximum rainfall values recorded by the rain gauge network, which is independent of altitude and geographical exposure. Therefore, we decided to use data from a mosaic of site-specific rain gauges across the island. The goal was to extract a combined regional threshold that depicts the behavior of heavy rainfall events, which are responsible for triggering torrential floods on a relatively small mountainous island (741 km²) with short distances between the mountain tops and the coast (less than 15 km).

The research has identified predefined rainfall thresholds for torrential floods based on antecedent and event rainfall and maximum rainfall in 24 hours. Furthermore, it was also possible to conclude that, in most cases, antecedent rainfall significantly influences the occurrence of torrential floods on Madeira Island, thus validating the selected method, has appropriate, given the hydrogeological characteristics of the region. However, in other cases, the rainfall from the event can be high enough to cause torrential floods, regardless of the preceding rainfall. On a sub-daily scale, it is interesting to observe a strong correlation between maximum precipitation over 24 hours and that over 12 hours. Consequently, with access to 24-hour numerical precipitation forecast data, it becomes feasible to estimate the maximum precipitation concentrated in less than 12 hours, which has the potential to trigger torrential floods.

In fact, this methodology can be applied in other places if there is access to historical data on heavy rainfall episodes. However, the influence of rainfall from preceding days and weeks on triggering floods depends primarily on the type of soils and rocks prevailing in a given area, as well as their retention capacity in the superficial soil layer. Understanding heavy rainfall and its impact on flooding is crucial for disaster preparedness and risk management.

Further refinement of the results is possible with additional data, so maintaining an inventory of heavy rainfall-torrential flow events, by incorporating data from future occurrences, is essential to keep the critical thresholds for the system up to date. In our opinion, this study has significantly reduced uncertainty regarding precipitation thresholds in Madeira Island. In this way, we are contributing to the common objective of any early warning system: the timely detection of heavy rainfall events that exceed specific thresholds. This allows for issuing warnings to the population and preparing a response to minimize the negative effects of torrential floods.

The HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) software was used to estimate flow hydrographs and peak discharges, but without supplemental analysis tools addressing erosion and sediment transport. In this sense, the results obtained have some limitations. In reality, torrential flows are a mixture of water and debris. Further investigation should be done to better understand the temporal and spatial patterns of rainfall-runoff events in these catchments. Since the results related to peak discharge are still incipient, future research should focus on the systematization of information resulting from real-time monitoring of fluvial flow conditions during flood episodes.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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