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The deadliest storm of the 20th century striking Portugal: Flood impacts and atmospheric circulation

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SUMMARY

The deadliest storm affecting Portugal since, at least, the early 19th century, took place on the 25 and 26 November 1967 causing more than 500 fatalities. This work aims to assess the most relevant aspects of this episode. This includes describing the associated meteorological conditions and key hydrological characterisation such as the level of exceptionality of the observed precipitation at different temporal scales, or the estimation of peak discharge values in 20 small river catchments affected. Additionally, from a human impact perspective we provide a full account of all the main socio-economic impacts, particularly the numbers and location of victims (dead, injured, homeless and evacuated).

Based on the sub-daily time series of a representative station, and its Intensity–Duration–Frequency curves, we have found that the exceptionality of this rainfall event is particularly linked to rainfall intensities ranging in duration from 4 to 9 h compatible with return periods of 100-years or more. This range of time scale which are similar to the estimated concentration time values of the hydrographic basins affected by the flash flood event. From a meteorological perspective, this episode was characterised by strong convection at the regional scale, fuelled by high availability of moisture over the Lisbon region associated with a low pressure system centered near Lisbon that favoured the convective instability.

Most victims were sleeping or were caught by surprise at home in the small river catchments around the main Lisbon metropolitan area. The majority of people who died or who were severely affected by the flood lived in degraded housing conditions often raised in a clandestine way, occupying flood plains near the stream beds. This level of destruction observed at the time is in stark contrast to what was observed in subsequent episodes of similar amplitude. In particular, since 1967 the Lisbon area, was struck by two comparable intense precipitation events in 1983 and 2008 but generating considerably fewer deaths and evacuated people.

1. Introduction

Flash floods induced by extreme precipitation events are one of the most life-threatening hazards in western Iberia (Fragoso et al., 2010; Liberato et al., 2012; Trigo et al., 2014). This fact is in line with many other regions of the world, where flooding events represent one the most frequent and costly natural hazards. Moreover, while most floods are originally triggered by favouring meteorological conditions, such as extreme precipitation or early snow melt associated with a heatwave, they are often amplified by undesirable human interference such as urban development and/or vegetation clearing (Smith and Ward, 1998). In particular, humans can alter river catchments in such a way that influences the magnitude and behaviour of floods (Nott, 2006).

Recently, some of us have developed a long-term database of hydrological events for Portugal, since 1865, within the scope of project DISASTER. The DISASTER database comprises 1621 flood cases for the period 1865–2010 that were responsible for a combined death toll of 1012 people and more than 40,000 homeless people (Zêzere et al., 2014). More than half of these fatalities took place in a single event in November 1967.

On 25–26 November 1967 heavy precipitation occurred with unprecedented intensity around the Lisbon metropolitan area,

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soon followed by flash flooding and a burst of landslides in the peripheries of Lisbon (Zêzere et al., 2005) causing significant socio-economic impacts. Without a proper warning system installed, according to Ramos and Reis (2002) 700 people died as a consequence of the floods on the heavily populated metropolitan area of Lisbon. Additionally, almost 900 people lost their homes and several road and train communications were disrupted. The official number of dead people was 495, but at that time the media were strictly controlled by the government and the catastrophe numbers could have been kept lower for political reasons. According to the DISASTER database the death toll reached 522 casualties (Zêzere et al., 2014), while unofficial assessments indicate more than 700 deaths.

It should be noted that most flood occurrences in Portuguese territory fall into two main distinct types, namely: (a) flash floods, usually affecting small river catchments, especially in urban areas (e.g., Ramos and Reis, 2002; Fragoso et al., 2010; Liberato et al., 2012) resulting from short bursts of precipitation and (b) floods in the major river basins, including the international rivers (Tagus, Douro, Guadiana) that are caused by several days (even weeks) of continuous precipitation (e.g., Ramos and Reis, 2002; Trigo et al., 2014).

Overall, this was the deadliest storm in Portugal during the 20th century and the deadliest natural hazard since the 1755 Lisbon earthquake, not accounting heat waves. Nevertheless, to the best of our knowledge this extreme hydro-meteorological episode was never studied in detail. Part of this apparent negligence to assess such an extreme event may be due to the unfavourable political context of the time. However, we should recognize three additional factors that have contributed for the inexistence of an in-depth analysis of such extreme event both in the Portuguese and international literature until now: (1) the absence of a dynamic meteorological and hydrological research community, (2) the unavailability of a high resolution precipitation dataset covering the entire territory and (3) the inexistence of a list of places with the affected people and socio-economic impacts. These last two limitations were overcome to a large extent in recent years. Firstly, a comprehensive list of people affected (fatalities, injured, displaced, evacuated and disappeared) has been obtained through the DISASTER database (Zêzere et al., 2014). Secondly, a new high density daily precipitation gridded dataset developed by the Portuguese and Spanish meteorological offices is particularly appropriate for this study and was already used to rank extreme precipitation events in Iberia (Ramos et al., 2014).

The aim of this work is to evaluate and characterise the impacts of the November 1967 floods, but equally to probe the atmospheric circulation conditions associated to such an extreme event. To achieve these goals, the following objectives must be addressed:

(1) To determine the spatial distribution of precipitation anomalies using a recent high resolution dataset for Portugal.
(2) To characterise the impacts and spatial distribution of flash floods in Lisbon and 14 surrounding municipalities around the Lisbon area.
(3) To assess the role played by the large-scale atmospheric circulation.

2. Datasets and methodology

2.1. Historical sources

The main historical data source used here corresponds to the recent dataset of flooding and landslide events that took place in Portugal since 1865 (Quaresma, 2009) and aggregated within the scope of DISASTER project (Zêzere et al., 2014). The main objective of the DISASTER project was precisely to construct a database on hydro-geomorphologic disasters that have occurred in Portugal in the last 150 years, based on information available within several daily Portuguese newspapers. The DISASTER database provides detailed information on each individual hydro-meteorological case including; (1) its location, (2) type (flood or landslide), (3) occurrences date, (4) date of the corresponding newspaper publication and (5) involved rescue entities. Additionally, this database often makes available further contextual information for each event and the nearby affected town/region, including the number of (i) human fatalities, (ii) people injured, (iii) people disappeared, (iv) homeless people, (v) people evacuated as well as the overall socio-economic costs.

The DISASTER database was used to extract the DISASTER cases of the November 1967 event. A DISASTER case is a unique hydro-geomorphologic occurrence – flood or landslide –, which independently of the number of affected people, caused casualties, injured or missing, evacuated or homeless people, and is related to a unique space location (Zêzere et al., 2014). A DISASTER flood event in the database is a set of DISASTER cases sharing the same trigger which can have a widespread spatial extension, thus including floods of different rivers (Zêzere et al., 2014). In addition, the flood of a unique river can affect different places and be considered as different flood cases.

Usually, press data does not provide complete and specific information about the space location of DISASTER cases, but this was not the case of the November 1967 event. This event was reported in three different editions of the 'Diário de Notícias' that were published on the 26 November 1967 giving very detailed descriptions and photos of damages, which were useful for the georeferencing process. Therefore we were able to georeference with a point shapefile all the reported DISASTER cases that caused casualties, injured or missing, evacuated or homeless people during the November 1967 event. The precision of DISASTER cases location of this event has two classes depending on the quality of the case description in the newspapers: (i) location based on local toponymy/name of the street (accuracy associated to 1:10,000 scale); (ii) location based on local geomorphology and river path, as they were at the time of the flash flood (accuracy associated to 1:25,000 scale).

2.2. ECMWF reanalysis

We have used the ERA-40 European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalyses (Uppala et al., 2005), namely the geopotential height fields, temperature, wind, divergence data and the specific humidity at all pressure levels. In addition, mean sea level pressure (SLP) and total column water vapour (TCWV) for the Euro-Atlantic sector (100°W-50°E, 0°N-70°N) were also utilized. These fields were extracted for November 1967, at full temporal (six-hourly) and spatial (T159; 1.125° regular horizontal grid) resolutions available, to analyse large-scale meteorological conditions associated with the extreme event.

2.3. Precipitation datasets

To characterise the distribution and spatial extent of this extreme event we have used 'IB02' the most comprehensive database of daily precipitation available for mainland Portugal (PT02, Belo-Pereira et al., 2011) and Spain (SPAIN02, Herrera et al., 2012). The 'IB02' database spans from 1950 to 2008, with a spatial resolution of 0.2° latitude/longitude grid. This database is based on a dense network of rain gauges, combining with a total of more than eight hundred stations over Portugal, and two thousand over Spain all quality-controlled and homogenized. This large number of stations is crucial to allow meaningful regional assessments of extreme precipitation over a relatively small area such as the Lisbon area. The most important difference between SPAIN02 and PT02 is in the start of the daily accumulation period: daily precipitation records obtained in Portugal for any given day n correspond to the precipitation registered between 0900UTC of day $n-1$ and 0900UTC of day n. Nevertheless, Spanish rainfall records for the same day n correspond to the precipitation registered between 0700UTC of day n and 0700UTC of day $n+1$ (notice the difference in both the hours and the days). Thus, in order to derive the most consistent common data set, the Portuguese daily precipitation database was shifted by 1 day, reducing the temporal difference between the two databases from 22 h to only 2 h. Therefore, for this particular case, the 25 of November, corresponds to accumulated precipitation between 0900UTC (0700UTC) of the 25 of November and 0900UTC (0700UTC) of the 26 of November in Portugal (Spain).

This dataset has been used to rank extreme precipitation events in Portugal, the entire Iberia but also on several major river basins in the Iberian Peninsula (Ramos et al., 2014), as well as, to characterise specific events such as the floods in November 1983 (Liberato et al., 2012).

Additionally we used daily and hourly precipitation data registered in four rain gauges: S. Julião do Tojal, Monte Estoril, Lisbon/Airport and Lisbon/Geophysical Institute from the National Weather Service (see location in Fig. 1).

2.4. Hydrological data

The S. Julião do Tojal station was selected for a deeper analysis of the hourly precipitation distribution, for three reasons: (i) the duration and reliability of the precipitation series (Fragoso et al., 2011); (ii) the geographic location of the rain gauge in the central part of the affected area by the event and equidistant to the complete set of affected hydrographic basins (Fig. 1); and (iii) the availability of Intensity–Duration–Frequency (IDF) curves, that are crucial for the indirect determination of flood discharges in small basins without flow measurements, as is the case. The IDF curves were defined for the period of 1957–1993 by the Portuguese Water Institute (Brandão et al., 2001). These IDF curves are potential curves ($I = a \times D^b$) that best fit the relationship between the rainfall intensity (I) and duration (D) for a given return period. Parameters a and b result from the adjustment between the rainfall intensities and durations (associated to a return period) through the least square method (Brandão et al., 2001).

Unfortunately, there is no measured flood discharge data during 25–26 November 1967 for the study area. Furthermore, there is a lack of discharge data in the small drainage basins of the Lisbon area till the present-day. This fact prevents the use of regional correlation methods, available to other regions of Portugal. Another drawback is the lack of digital information of land use for the event's date. Therefore, in order to estimate the peak discharges associated to this event, the Rational method was chosen due to the small size of the drainage basins affected by the flash flood (<300 km^2; Table 1) and the short duration of the rainfall event that caused the flash flood. The Rational method relates runoff peak discharge with rainfall-intensity and despite its simplicity, it is still strongly favoured by engineers and recent developments have improved its application (Crobeddu et al., 2007).

The Rational method is given by:

$$Qp = C \times i \times A \tag{1}$$

where Qp is the peak discharge (m^3/s), i is the mean rainfall intensity (m/s) corresponding to the maximum rainfall for the time period equal to the concentration time of the hydrographic basin and for the return period t (years); A is the area of the hydrographic basin (m^2); and C is a dimensionless runoff coefficient dependent on the land use and the permeability of vadose zone. The hydrographic basins of Lisbon region develop on carbonate, detrital, marl and clay geological formations, in general, with low to very low permeability, enhancing stormflow and justifying high values of C (Lencastre and Franco, 2010). Due to the lack of the already mentioned digital information of land use, we use the runoff coefficient $C = 0.81$ as suggested by Quintela (1984) which has been often adopted as project criterion in Portugal (e.g., Portela and Hora, 2002; Lencastre and Franco, 2010; Hipólito and Vaz, 2011).

The concentration time of the hydrographic basins was calculated using the method of Temez, (1978), which is a modification of the US Army Corps of Engineers formula for the Iberian Peninsula.

The expression of the Temez formula is:

$$Ct = 0.3 \times (Ch/I^{0.25})^{0.76} \tag{2}$$

where Ct is the basin concentration time (hours); Ch is the length of the main river of the basin (km); and I is the average slope of the main river of the basin (km/km). The response time of hydrographic basins is given by Correia (1984):

$$Rt = Ct \times 0.6 \tag{3}$$

A Digital Elevation Model (DEM) of the Lisbon area with resolution 20 × 20 m was drawing using contour lines 10 m equidistance, extracted from topographic maps at 1:25,000 scale dated from 2009 and was used to define the hydrographic basin boundaries (Fig. 1). Next, hydrographic network and hydrographic basin boundaries were adjusted in some spots to eliminate recent hydrographic deviations and river channels that were artificially constructed after the 1967 flash flood event. This work was supported by topographic maps at 1:25,000 scale dated from 1965.

3. Flood analysis and human impacts

3.1. Rainfall event and hydrologic context

Although previous brief descriptions of the 1967 flash flood have been made (e.g., Amaral, 1968; Costa, 1986), the availability of the DISASTER database has made possible, for the first time, the comprehensive analysis of the affected area and the evaluation of social consequences of this natural disaster.

The sudden floods that occurred during the night of 25 November and early morning of 26 November took everybody by surprise as most of the victims were at home sleeping and did not notice the rapid accumulation of water in small streams. The main cause for these catastrophic floods is related to the large amount of precipitation concentrated during a few hours on the night of 25–26 November. According to the IB02 database the pattern of intense precipitation (above 75 mm) is oriented with a SW–NE axis and crosses roughly the central region of Portugal (Fig. 2). Moreover, it is possible to observe an area where the daily precipitation surpassed the 120 mm threshold located over the metropolitan region of Lisbon. In addition, this extreme value corresponds to an anomaly above 8 standard deviation from the long term climatology (1950–2008).

In order to put into context the November 1967 event, we have selected an area over the Lisbon metropolitan region (red square Fig. 2) and for each day, the mean precipitation over that area was computed. Results show that the November 1967 event corresponds to the second most intense 24 h average precipitation for that area between 1950 and 2008, with a mean precipitation of about 86 mm. The most intense precipitation event within this period, over that same Lisbon region, corresponds to the case of November 1983 (mean precipitation of around 95 mm) which

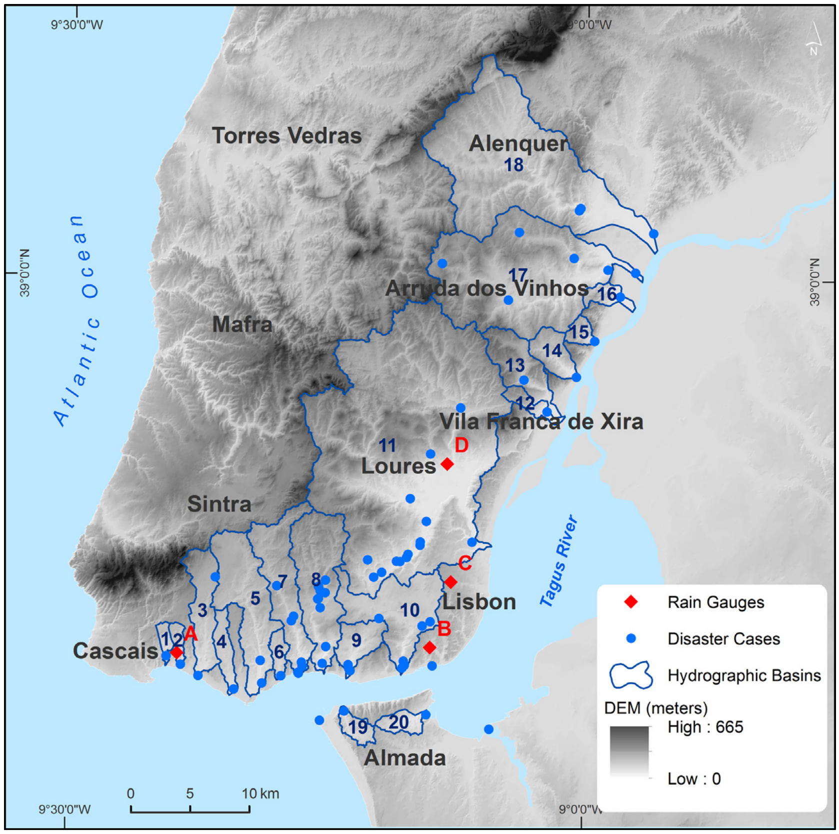

Fig. 1. Location of the drainage basins affected by the November 1967 flood (blue numbers), the DISASTER cases (blue dots) and the rain gauges (red). *Hydrographic Basins* (*blue*): 1 – Monte Estoril; 2 – São João do Estoril; 3 – Caparide; 4 – Marianas; 5 – Laje; 6 – Porto Salvo; 7 – Barcarena; 8 – Jamor; 9 – Algés; 10 – Alcântara; 11 – Trancão; 12 – Crós Cós; 13 – Silveira; 14 – Santo António; 15 – Santa Sofia; 16 – Castanheira; 17 – Grande da Pipa; 18 – Alenquer; 19 – Caneira; 20 – Caramujo. *Rain gauges* (*red*): A – Monte Estoril; B – Lisbon, Geophysical Institute; C – Lisbon, Airport; D – São Julião do Tojal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Main characteristics of the hydrographic basins of the Lisbon area affected by the November 1967 flash flood.

Hydrographic Basin		Area (km^2)	Main river length (km)	Main stream gradient (m/km)	Concentration time (Temez)	Response time (Temez)	*Qp* (m^3/s) (Rational method)
1	Monte Estoril	2.8	3.8	31.7	1 h 36 m	57 m	18.0
2	S. João Estoril	3.0	4.1	28.6	1 h 44 m	1 h 02 m	19.3
3	Caparide	20.5	12.6	19.9	4 h 20 m	2 h 36 m	108.9
4	Marianas	8.0	8.6	15.0	3 h 25 m	2 h 03 m	46.2
5	Laje	41.5	17.1	11.7	6 h 03 m	3 h 37 m	182.0
6	Porto Salvo	4.5	4.2	27.0	1 h 46 m	1 h 03 m	29.0
7	Barcarena	34.2	18.4	15.8	6 h 02 m	3 h 37 m	150.3
8	Jamor	44.0	16.3	19.0	5 h 19 m	3 h 11 m	210.1
9	Algés	12.1	5.9	18.7	2 h 27 m	1 h 28 m	74.3
10	Alcântara	39.2	14.0	15.0	4 h 57 m	2 h 58 m	196.0
11	Trancão	293.2	26.6	12.0	8 h 24 m	5 h 03 m	996.2
12	Crós Cós	5.6	6.9	39.1	2 h 24 m	1 h 27 m	34.1
13	Silveira	20.9	11.9	29.7	3 h 50 m	2 h 18 m	116.4
14	Santo António	11.0	5.7	35.4	2 h 07 m	1 h 16 m	68.6
15	Santa Sofia	4.3	3.2	55.9	1 h 15 m	45 m	28.6
16	Castanheira	5.7	6.9	27.5	2 h 34 m	1 h 33 m	35.0
17	Grande da Pipa	117.1	26.4	11.9	8 h 22 m	5 h 01 m	400.4
18	Alenquer	138.2	30.5	11.8	9 h 21 m	5 h 37 m	429.1
19	Caneira	5.6	4.9	18.4	2 h 08 m	1 h 17 m	35.0
20	Caramujo	5.9	4.3	22.6	1 h 52 m	1 h 07 m	37.5

Note: Concentration time, response time and *Qp* estimated at river mouth.

was already mentioned in the introduction section and evaluated in detail in Liberato et al. (2012).

The 25–26 November 1967 flash flood event was triggered by an extreme rainfall event that reached 137 mm in 24 h, almost 1/5 of the mean annual rainfall at S. Julião do Tojal. Fig. 3 shows the hourly rainfall registered at four rain gauges in the Lisbon region, starting at 1000UTC on the 25 November and finishing at 0300UTC on the 26 November. The hourly data shows that most

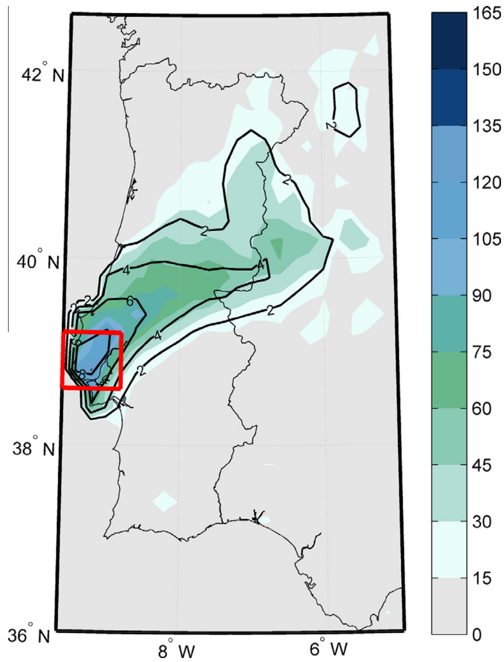

Fig. 2. Daily accumulated precipitation (mm, shaded) and corresponding standard deviation anomalies (black contour) for the 25 November 1967. The standard deviation anomalies were smoothed with the neighbour grid points. The red box highlights the selected area over the Lisbon metropolitan where the mean precipitation over that area was computed (see Section 3.1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the rainfall was concentrated in just five hours (between 1900UTC and midnight). Moreover, during these five hours 110.6 mm were registered in S. Julião Tojal, which is equivalent to the monthly average rainfall of November (112.5 mm). In this station, a peak of precipitation 30 mm/h was recorded between 2200UTC and 2300UTC, corresponding to a 10-year return period. However, the maximum hourly rainfall (60 mm/h) was registered in a different station, namely Monte Estoril between 2100UTC and 2200UTC (Fig. 3). Monte Estoril is located in the western part of the study area and was firstly affected by the precipitation. In fact, the meteorological system associated with this intense rainfall event was originated from the Atlantic Ocean, crossed the Portuguese territory from SW to NE (Fig. 2), where particularly high values of precipitation along 60 km between Estoril and Alenquer occurred (Figs. 1 and 2). The DISASTER database shows that the assistance was provided to the affected population mainly between 2000UTC of the 25 November and the 0200UTC the 26 November, except for the Alenquer basin, located in the extreme NE of the affected area, where the flood occurred on the dawn and morning of 26 November between 0200UTC and 0800UTC. These observations are compatible with the response times (Table 1) and the period hours of rainfall intensity (Fig. 3).

The exceptionality of this rainfall event is not well defined by short duration rainfall intensities (1–2 h), but by rainfall intensities ranging in duration from 4 to 5 h, associated with return periods ranging from 120 to 130 years as shown in the example for S. Julião do Tojal (Fig. 4). For durations between 6 and 9 h, the rainfall intensity (mm/h) remains close to the 100-year IDF curve. Peak discharges and concentration time of the hydrographic basins affected by the flash flood event are summarized in Table 1. The concentration time is less than 6 h in 70% of the hydrographic basins and the remaining basins have corresponding concentration time ranging from 6 h to 9 h 30 m (Table 1). These results are important because the concentration time of the hydrographic basins are less or equal than the event rainfall duration, which increased the peak discharges of the 1967 flash flood.

Twenty small and medium size hydrographic basins were affected, covering 14 municipalities (Fig. 1). The maximum altitude within the hydrographic basins is 360 m asl. Landscape is dominated by hills and includes structural landforms (e.g., cuestas) and large erosional depressions such as the Loures depression (Zêzere et al., 2008). The main rivers have a slope comprised in the range 10–60 m/km and most of them (80%) are contained in the range 10–30 m/km. The prevalent low to very low permeable geological formations hinders the infiltration of water and increases the stormflow. As a consequence, the hydrographic network is well developed and the average drainage density is 3 km/km^2. The 20 hydrographic basins were divided into two groups regarding the basin area (A): the first group is composed of 17 small basins, with A <40 km^2; the second group is composed of three slightly larger basins (Trancão, Alenquer and Grande da Pipa), with basin area ranging from 100 to 300 km^2 (Table 1 and Fig. 1).

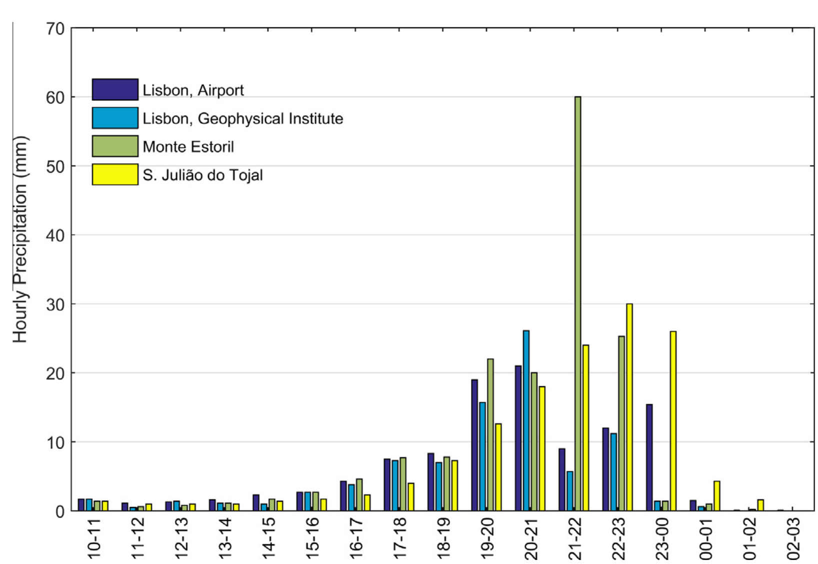

Fig. 3. Hourly precipitation registered at four rain gauges located over the Lisbon region (see Fig. 1 for location) starting at 1000UTC of 25 November and ending at 0300UTC of 26 November 1967. Source: Portuguese National Weather Service (Instituto Português do Mar e da Atmosfera).

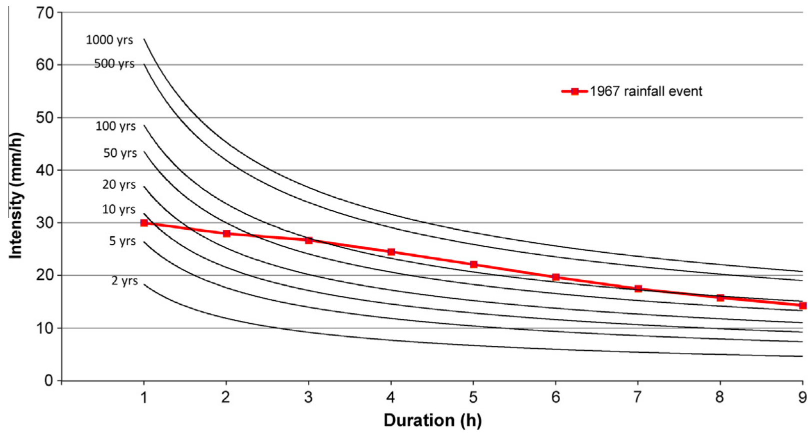

Fig. 4. Intensity vs Duration curves for different return period computed using the S. Julião do Tojal precipitation dataset (black curves) and for the 25–26 November 1967 precipitation event (red curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

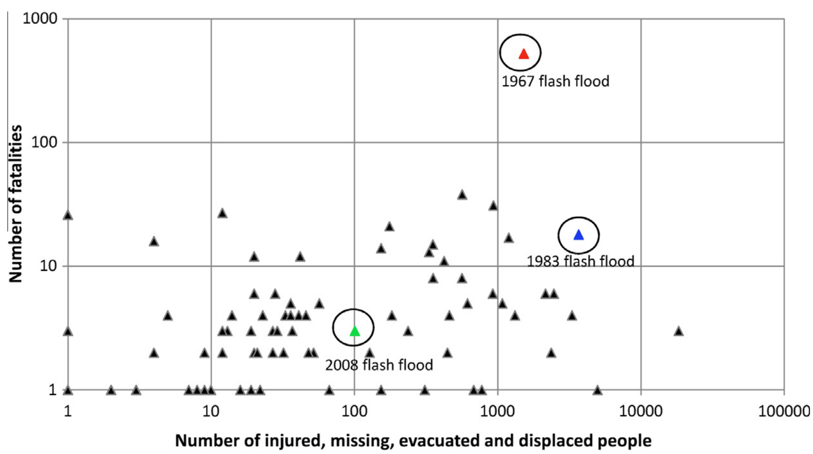

Fig. 5. Number of fatalities vs the number of injured, missing and evacuated people caused by the different disastrous floods in Portugal (1865–2010). Source: DISASTER database (Zêzere et al., 2014). The 1967, 1983 and 2008 events are highlighted. Notice the logarithmic scale.

The main rivers of the last group have a length >20 km. The main rivers of the remaining basins are small in length; 11 have a length <10 km and 6 (Caparide, Laje, Barcarena, Jamor, Alcântara and Silveira) have a length between 10 and 20 km (Table 1).

The abovementioned geomorphologic and hydrographic characteristics determine response times (for the terminal section of the hydrographic basins) below 4 h for the 17 small basins and ranging from 5 h to 5 h 40 m for the 3 medium-size basins (Table 1). Therefore, the natural conditions of these hydrographic basins are able to generate flash floods. According to the Rational method, the specific peak discharges during the 1967 flash flood reached between 3.1 and 6.6 $m^3/s/km^2$. In the nine largest hydrographic basins (Trancão, Alenquer, Grande da Pipa, Caparide, Laje, Barcarena, Jamor, Alcântara and Silveira) the flood peak was estimated between 108.86 m^3/s and 996.15 m^3/s (Table 1), which corresponds to the 100-year flood.

Another factor that increased the magnitude of the November 1967 flash flood was the tide that influenced the terminal sections of the hydrographic basins. According to the Portuguese Hydrographic Institute (Instituto Hidrográfico, 1967), the high tide was registered at 2150UTC on the 25 November and the highest levels of the tide occurred between 1835UTC and 0046UTC, thus matching the occurrence time of the flash flood.

3.2. Exposure and socio-economic impacts

According to the DISASTER database, 2045 people were directly affected by the November 1967 flash floods. The number of confirmed fatalities is 522, but this is certainly underestimated, because of censorship on newspapers imposed at that time by the Portuguese dictatorial political regime. In addition, 330 injured, 885 homeless, 307 evacuated and one missing people were reported. Of the 121 years with flood events with human damage, registered in Portugal between 1865 and 2010, the November 1967 flash flood was the deadliest and the one that generated more fatalities (Fig. 5). The numbers are impressive: the November 1967 flash flood was responsible for 52% of total casualties and 69% of the total number of injured caused by floods in Portugal from 1865 to 2010. For comparison purposes, we have marked the most intense precipitation events in the Lisbon area, with comparable amounts of rainfall, namely in 1983 (Liberato et al., 2012) and 2008 (Fragoso et al., 2010) but having a considerable minor impact according to the DISASTER database (Fig. 5).

Reports of survivors and firemen on newspapers indicate that the majority of deaths have occurred during the peak of the flood between 2230UTC and 0230UTC, depending on the river basins. Therefore, many of the victims were sleeping or were caught by surprise at home. The people who died or who were severely affected by the flood (injured, homeless or evacuated) lived in flood prone zones, often in degraded housing conditions (slums or prefabricated storey houses). At that time, a huge exodus from the rural areas towards the coastal cities was registered (in particular to the Lisbon metropolitan area), due to socio-economic conditions of extreme poverty and high birth rates in the inner country. These people built many of their houses or shacks in a clandestine way, occupying flood plains and stream banks. The names and

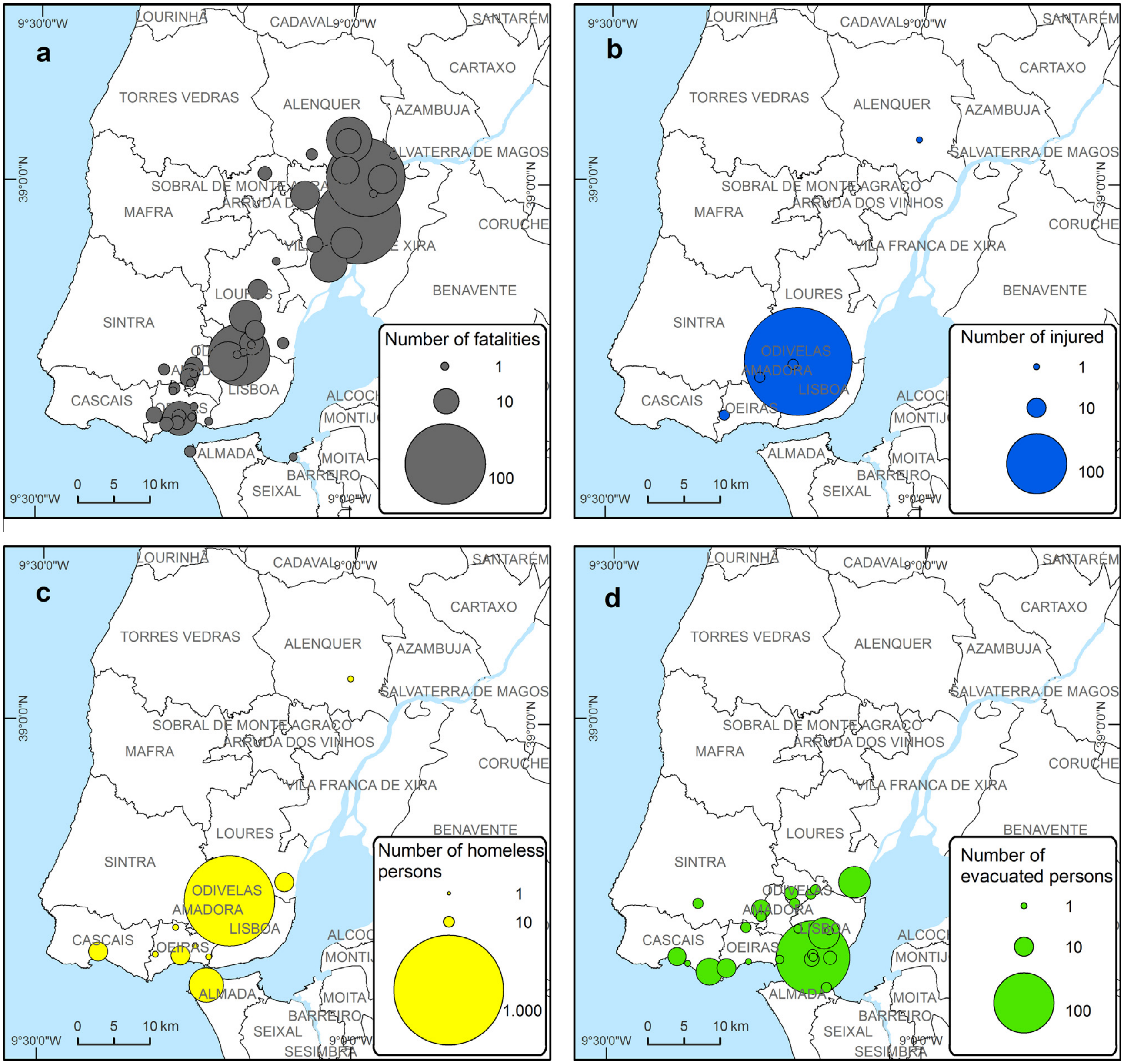

Fig. 6. Location and number of (a) fatalities, (b) injured, (c) homeless persons and (d) evacuated persons caused by the November 1967 flash flood. Results were aggregated per municipalities. Source: DISASTER database (Zêzere et al., 2014).

birthplaces of dead victims that were published by the newspapers the days after the event indicate that most of the victims were coming from the rural areas of the country (mostly North and Alentejo).

Flash floods also dragged a large amount of debris (wood, tiles, and metallic structures from the shacks destruction, vehicles, stones and mud) that raised the destruction capacity of the flood. According to newspapers, two important bridges were destroyed. One located in Odivelas municipality over the Costa stream that cut the road connection between Lisbon and Odivelas to Loures. Another bridge was destroyed over the Trancão River cutting the road connection between Loures and Odivelas. In these cases, flood effects were more devastating and emergency operations were even more difficult due to the increasing of the travel times.

The distribution of fatalities, injured, homeless and evacuated persons, by municipalities and hydrographic basins is shown in Figs. 6 and 7, respectively. The spatial distribution of fatalities is the one that best shows the "trail of the storm" (SW–NE; Fig. 6a), emphasizing three municipalities drained by three major hydrographic basins (Fig. 7): Vila Franca de Xira (Grande da Pipa river basin), Odivelas (Trancão river basin and its sub-basin of Póvoa stream) and Alenquer (Alenquer river basin). The homeless (80%) and injured (98%) people (Fig. 6b and c) concentrated in the municipality of Odivelas, in the hydrographic basin of the Trancão River (Póvoa sub-basin), north of Lisbon, where several residential areas of illegal origin (slums) were present. Evacuated people (Fig. 6d) that were rescued by firemen were mainly located in the city of Lisbon (64%) in the hydrographic basin of Alcântara (Fig. 7), which had already an underground waterway at the time.

Although most of the fatalities have occurred in three major stream basins, the relationship between drainage area (km^2) and stream discharge with number of deaths is not straightforward. In fact, few particular places concentrate a large fraction of people that perished (Fig. 6a) and present peculiar characteristics that are important to analyse. In particular, two places registered over 220 deaths: (i) the valley drained by Póvoa stream (tributary of the Trancão river) and (ii) the small village of Quintas (in the Grande da Pipa river basin).

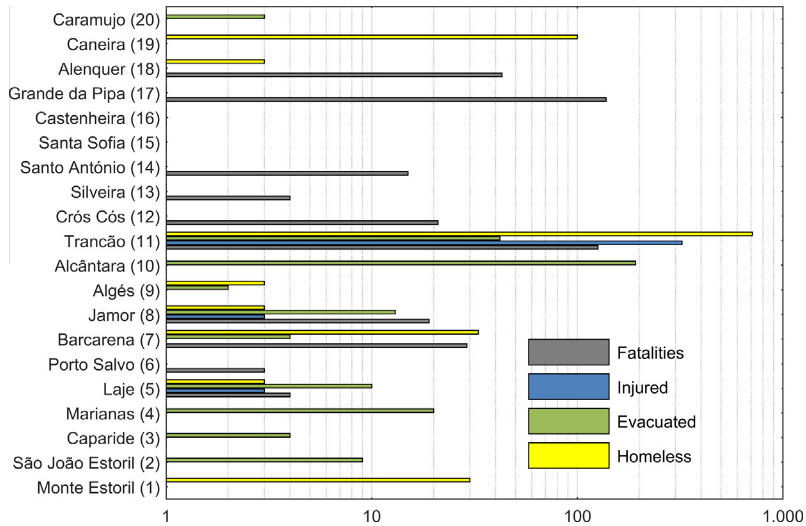

Fig. 7. Human damages caused by the November 1967 flash flood, per hydrographic basin. In addition, 115 fatalities that occurred in the Vila Franca de Xira municipality were not included in any hydrographic basin since there is no specific information regarding its exact location. The same occur for the 3 fatalities that were found in the Tagus River. Source: DISASTER database (Zêzere et al., 2014). Notice the logarithmic scale.

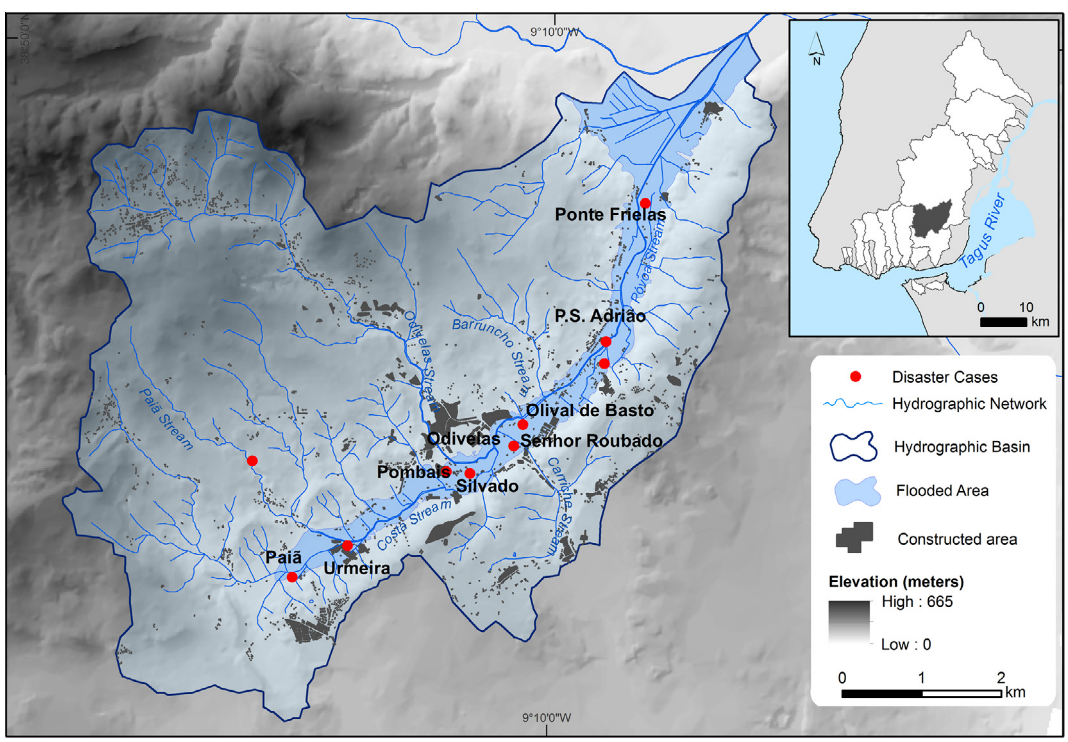

Fig. 8. The "valley of death" in Póvoa sub-basin, flooded area in the November 1967 flash flood (dark blue shaded area) and the location of the human damages highlighted with a blue dot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) Source: DISASTER database (Zêzere et al., 2014).

4. Case studies: Póvoa Stream Valley and Quintas village

The sub-basin of Póvoa stream is part of the Trancão River basin and is located in the municipality of Odivelas, north of Lisbon. The sub-basin has an area of 45.2 km^2, 70.2% of which correspond to low to very low permeable geologic formations (Leal and Ramos, 2013). The Póvoa stream (14.4 km in length) is the main river of the sub-basin (Fig. 8) reaching the stream order 4 according to Strahler classification. This sub-basin experienced an intense urban pressure during the second half of the 20th century and many houses (some illegal) were built in the floodplain.

The application of the Rational method to Póvoa sub-basin shows that peak discharge of the 1967 flash flood had reached 226.8 m^3/s near river mouth, which is slightly higher than the 100-year flood. The flooded area (provided by the City Hall of Odivelas and further adjusted with the georeferentiation of the DISASTER cases) reached 10.5% of the basin area (Fig. 8). Critical points with human damages in the Póvoa sub-basin are shown in Fig. 8 and include from upstream to downstream the following villages: Paiã, Urmeira, Pombais, Silvado, Odivelas, Senhor Roubado, Olival de Basto, Póvoa de Sto. Adrião, and Ponte de Frielas.

Flood discharges were estimated for the critical river sections of Póvoa sub-basin and considering different return periods (Fig. 9),

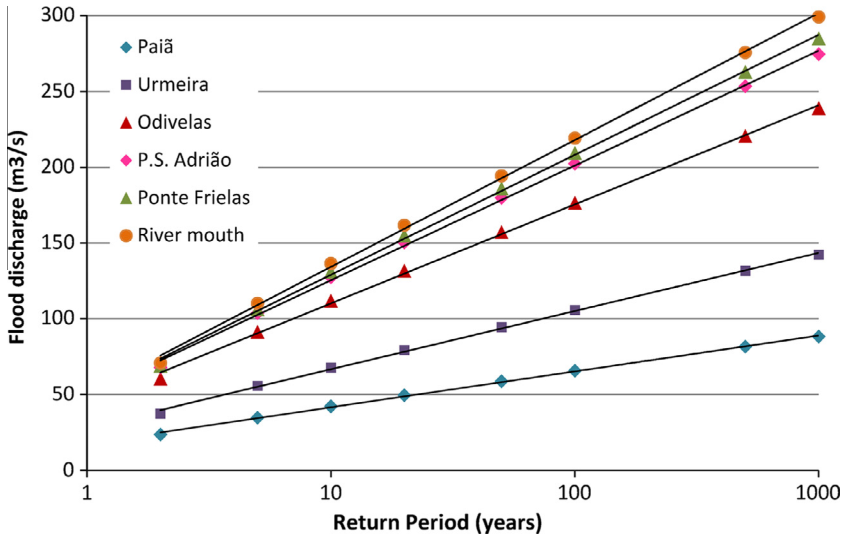

Fig. 9. Estimated flood discharges for different return periods in several critical river sections of Póvoa sub-basin (see Fig. 8).

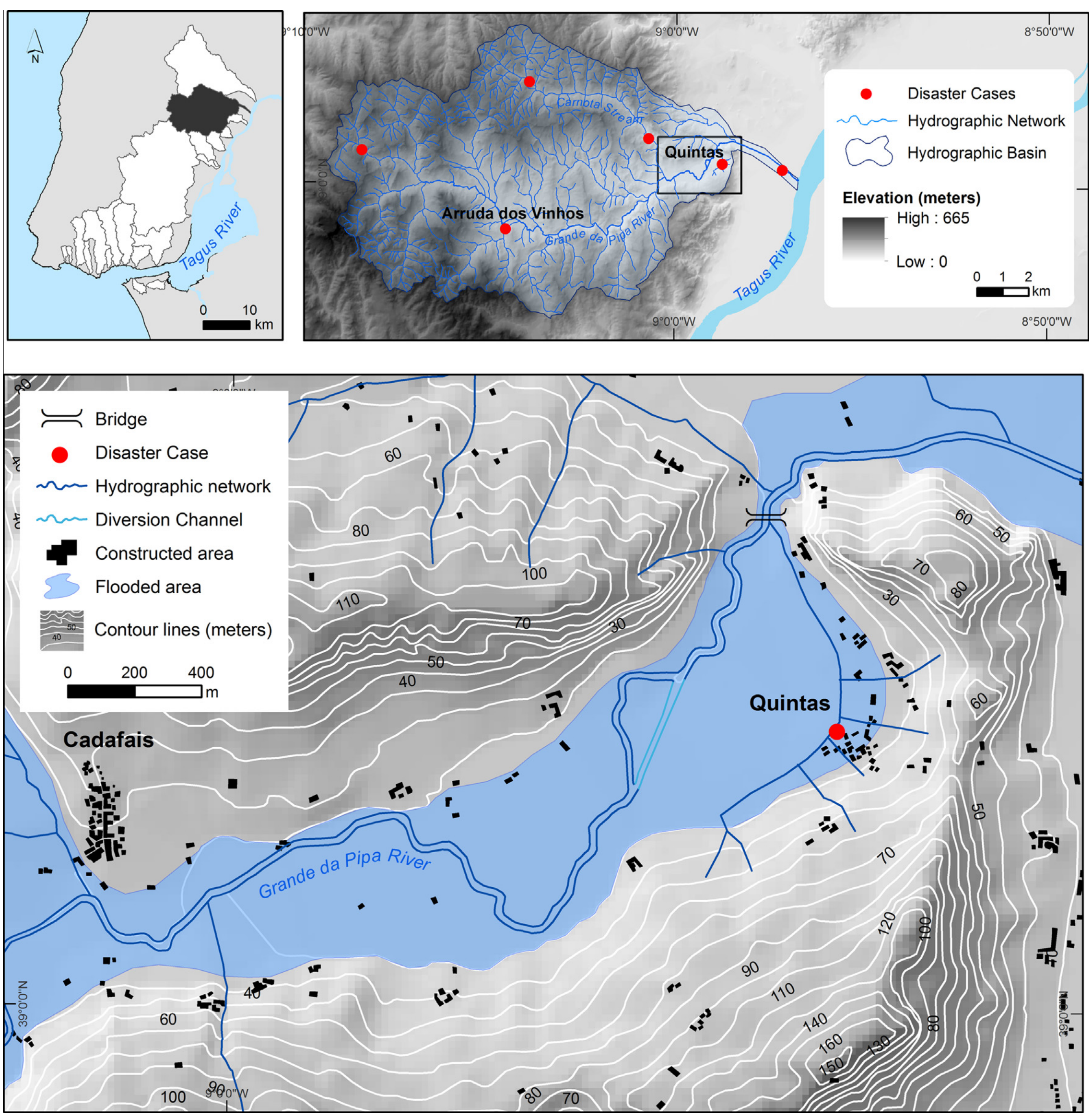

Fig. 10. Details of Grande da Pipa basin (upper right panel) and Quintas village morphologic context and flooded area (lower panel) during the November 1967 flash flood along with the location of the human damages highlighted with a blue dot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) Source: DISASTER database (Zêzere et al., 2014).

which allows understanding the succession of human damages, in particular the casualties, from upstream to downstream. In Paiã, the 1967 flash flood caused only three injured and three people were evacuated. However in Urmeira, located less than 1 km downstream, the human damage increased considerably (24 fatalities, 320 injured and 680 homeless people), not only due to the increase of the stream discharge, by receiving its first large tributary (Paiã stream; Fig. 8), but essentially because the major part of the village was located within the flood prone area. In the neighbourhoods of Silvado and Pombais the fatal consequences were worst (59 fatalities). This is the basin's critical point (confluence of Costa stream with the Odivelas stream, from which results the Póvoa stream; Fig. 8), where the greatest increase in estimated discharge occurred (Fig. 9). The village of Silvado was destroyed to a large extent, and its inhabitants were trapped between the two streams. Downstream along the valley several houses were located in the floodplain in the villages of Olival de Basto, Póvoa de Sto. Adrião and Ponte de Frielas (Fig. 8), and over three dozen of fatalities were accounted. In total, more than 121 people perished in the Póvoa valley, that is, more than 25 deaths/km^2 of flooded area.

However, it should be stressed that during the 1967 flash flood not all the people have died in urban areas subjected to a chaotic urbanization process. In fact, the most deadly place of the 1967 flash flood occurred on a rural area, in the small village of Quintas (Fig. 10) where local conditions constituted a "trap" for the population. Quintas village is located in the terminal sector of the Grande da Pipa river basin, on the right bank of the river, between the floodplain and the slope bottom (Fig. 10). The hydrographic basin upstream Quintas village has an area of 108.7 km^2 (93% of the total basin), the river has a stream order 5 according to Strahler classification and 403 tributaries. The most important tributary is the Carnota stream that converges only 2240 m upstream of Quintas village.

Using the Rational method, the estimated peak discharge reached 441.48 m^3/s, corresponding to the 100-year flood. However, the disaster of Quintas is mostly explained by adverse local geomorphologic and hydrographic conditions, which have raised the height of water column at the bottom of the valley (Fig. 10). In this sector, the floodplain is approximately 580 m width, with a slight slope towards the southeast. The most depressed area of the floodplain had a small yazoo stream, very close to the village, located near the concave sector of the meander (Fig. 10). During the flood, this was, therefore, a preferred corridor for the floodwaters circulation that swept through the central part of the village. Nevertheless, what exacerbated the flood height and affected area was the narrowing of the valley, 720 m downstream of the village (Fig. 10). This bottleneck is caused by interbedded limestone layers within the sandy-clay complexes that make up the geological substratum of the region. In the narrow place the bottom of the valley is only 130 m wide and had a small bridge over the river, which was a barrier to the flood water circulation, loaded with debris and mud. The elevation of the water column was inevitable and the flood covered the ground floors of the houses, many of which had only one floor.

According to the DISASTER database, in this village about 103 people died (70% of the total inhabitants). The resultant trauma led to the non-construction of houses where whole families died, extending the village, today, along the slope overhanging the valley. After the 1967 flash flood, a diversion channel was built to protect the village (Fig. 10).

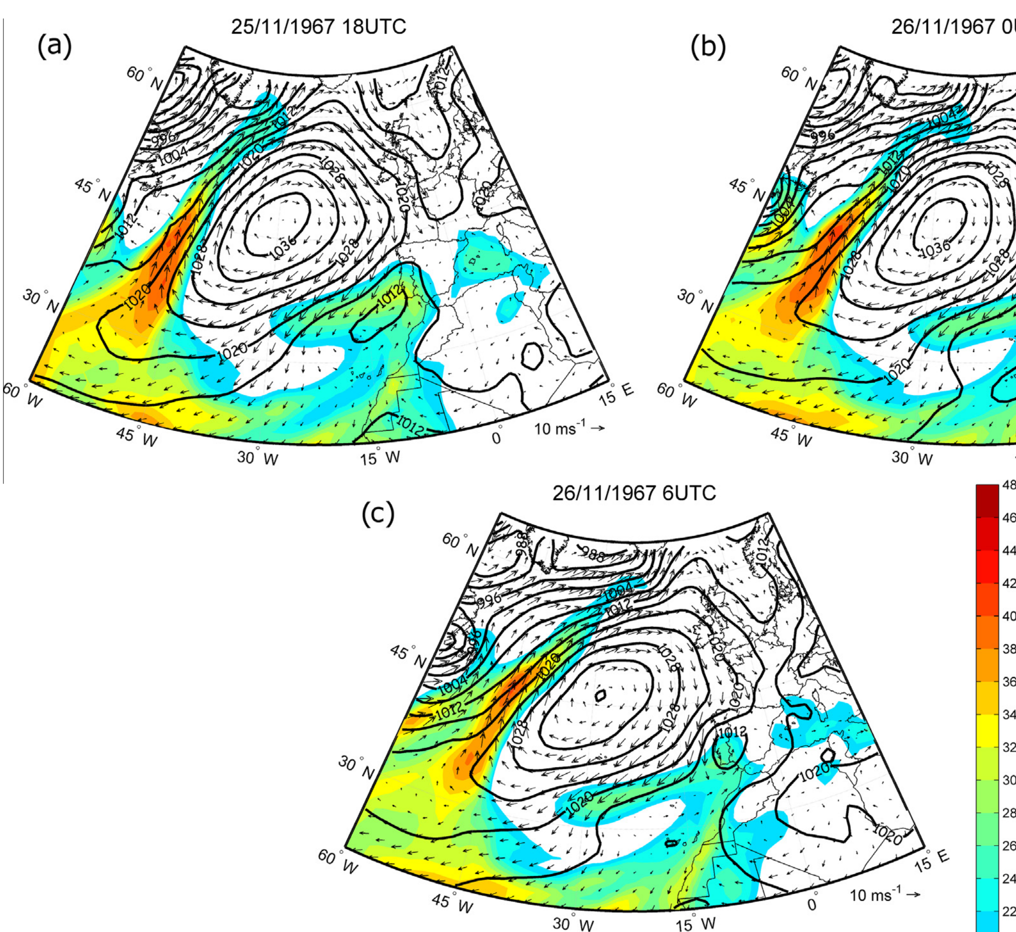

Fig. 11. The mean sea level pressure (contour interval 4 hPa), total column water vapour (shaded; mm) along with the vector wind (m/s) at 10 m for: (a) 1800UTC on 25 November, (b) 0000UTC on 26 November, (c) 0600UTC on 26 November.

5. Assessing the atmospheric circulation

The atmospheric circulation conditions associated with the November 1967 extreme event in the Lisbon region will be analysed in detail in this section. Different meteorological fields' sequences were obtained relative to the days prior to the peak of precipitation but results only will be shown between 1800UTC of the 25 November and 0600UTC of the 26 November. Regarding the sea level pressure (SLP) field, the extreme event is characterised by a low pressure system that remained stationary over southwest of the Iberian Peninsula (near Madeira Island) since 20 November 1967 due to the presence of a high pressure system located over the British Isles (not shown) and similar to a winter like blocking configuration (Trigo et al., 2004). At higher levels, the jet stream crossed the North Atlantic Ocean at very high latitudes, passing through Iceland and north of the British Isles. On 23 November, the high pressure system started to weaken and the low pressure system started to move towards the Iberian Peninsula in a SW–NE direction. In the afternoon of the day of the event, 1800UTC of 25 November (Fig. 11a), the weak low pressure system was characterised by an elongated form with a central pressure of 1012 hPa being located SW Portugal nearly making landfall. In addition, the moisture availability in the region was high as shown by the values of total column water vapour (TCWV) that surpassed 30 mm over the Portuguese Atlantic coast and Lisbon region. On 25 November at 0000UTC (Fig. 11b), the low pressure system already makes landfall and it is stationary till 0600UTC (Fig. 11c) over the Lisbon area while the moisture availability remained high.

The upper level fields show a very disturbed jet stream, which meanders through Iceland and turns south passing over the Azores. The geopotential height at 500 hPa (Fig. 12) is characterised, from 1800UTC to 25 November to 0000UTC 26 November, by a very deep trough passing over British Isles and western Iberian Peninsula towards the Azores Isles. This configuration led to a strong advection of cold (temperature at 500 hPa level in Fig. 12, colour[1] shading) from higher latitudes towards the Azores isles, although it does not affect directly the Lisbon region.

From the analysis of the SLP and surface winds along with the TCWV (Fig. 11), it seems apparent the existence of lower level convergence located near the Lisbon region, mainly due to the position of the Anticyclone located in the middle of the Atlantic and northern of the Azores Isles along with the position of the low pressure systems is responsible for the advection of moisture from southwest towards the Iberian Peninsula favouring atmospheric instability.

In order to confirm the existence of atmospheric instability due to convergence at low levels, the divergence field at both the 925 hPa and the 250 hPa are analysed in detail in Fig. 13. At lower levels, the values of divergence close to the surface are negative; therefore, there is lower level convergence around the Lisbon region as suspected when analysing the surface wind field. Divergence values around $-5 \times 10^{-5}\ s^{-1}$ are located near Lisbon region at 1800UTC of the 25 November (Fig. 13a) while for 0000UTC of 26 November this value is even more intense (around $-9 \times 10^{-5}\ s^{-1}$) and still located around the Lisbon region (Fig. 13b). The upper level (250 hPa) divergence over Portugal is positive on the two time steps (Fig. 13c and d), proving that this event was mainly of convective nature with strong convergence of moisty air at low levels along with divergence at upper levels.

Attending the different impacts in hourly precipitation at different locations in the Lisbon region (Fig. 3), where the recorded max-

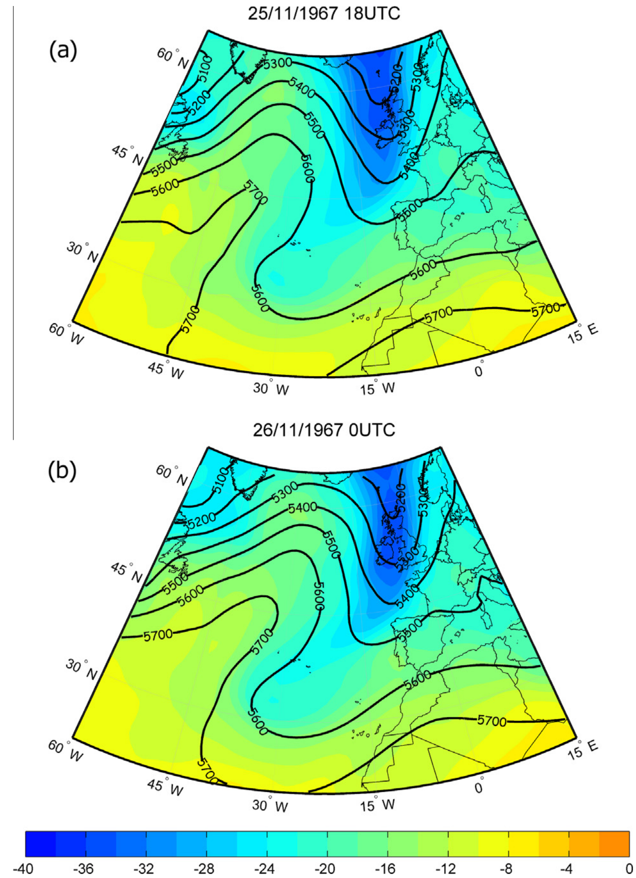

Fig. 12. The geopotential height (contour interval 1000 m) and air temperature (shaded; °C) at 500 hPa level for: (a) 1800UTC on 25 November, (b) 0000UTC on 26 November.

imum was above 60 mm/h, probably a mesoscale convective system with different cells was the responsible for this event. The occurrence of Mesoscale Convective Systems is relatively frequent in the Iberian Peninsula as observed for the year 2001 (García-Herrera et al., 2005). Unfortunately, the event took place prior to meteorological satellite era and therefore no meteorological satellite image is available for that time. Considering the daily precipitation values observed, the fairly small area affected by precipitation, and also the SW–NE footprint of precipitation we believe that this 1967 event has similar characteristics with the February 2008 episode (Fragoso et al., 2010), where deep convention was the main responsible for the intense precipitation.

In addition, most of these convective events are usually associated with mesoscale factors which are impossible to depict from a 1.125° horizontal resolution reanalysis like ERA-40. The authors are currently planning to use Non-hydrostatic Mesoscale models in order to improve the knowledge of the possible mesoscale factors behind this event.

6. Discussion and conclusions

On the night of 25 November 1967 and early morning hours of the following day, the Lisbon area suffered the deadliest natural hazard since the ill-famed 1755 earthquake. Nevertheless, several factors, including lack of appropriate datasets (meteorological, hydrological and human impacts), have hampered an in depth analysis of this extreme event. This study provides the first comprehensive assessment of key aspects of this episode, including; (1) the spatial and temporal characteristics of the precipitation, (2) the large-scale meteorological conditions that favoured the

[1] For interpretation of colour in Fig. 12, the reader is referred to the web version of this article.

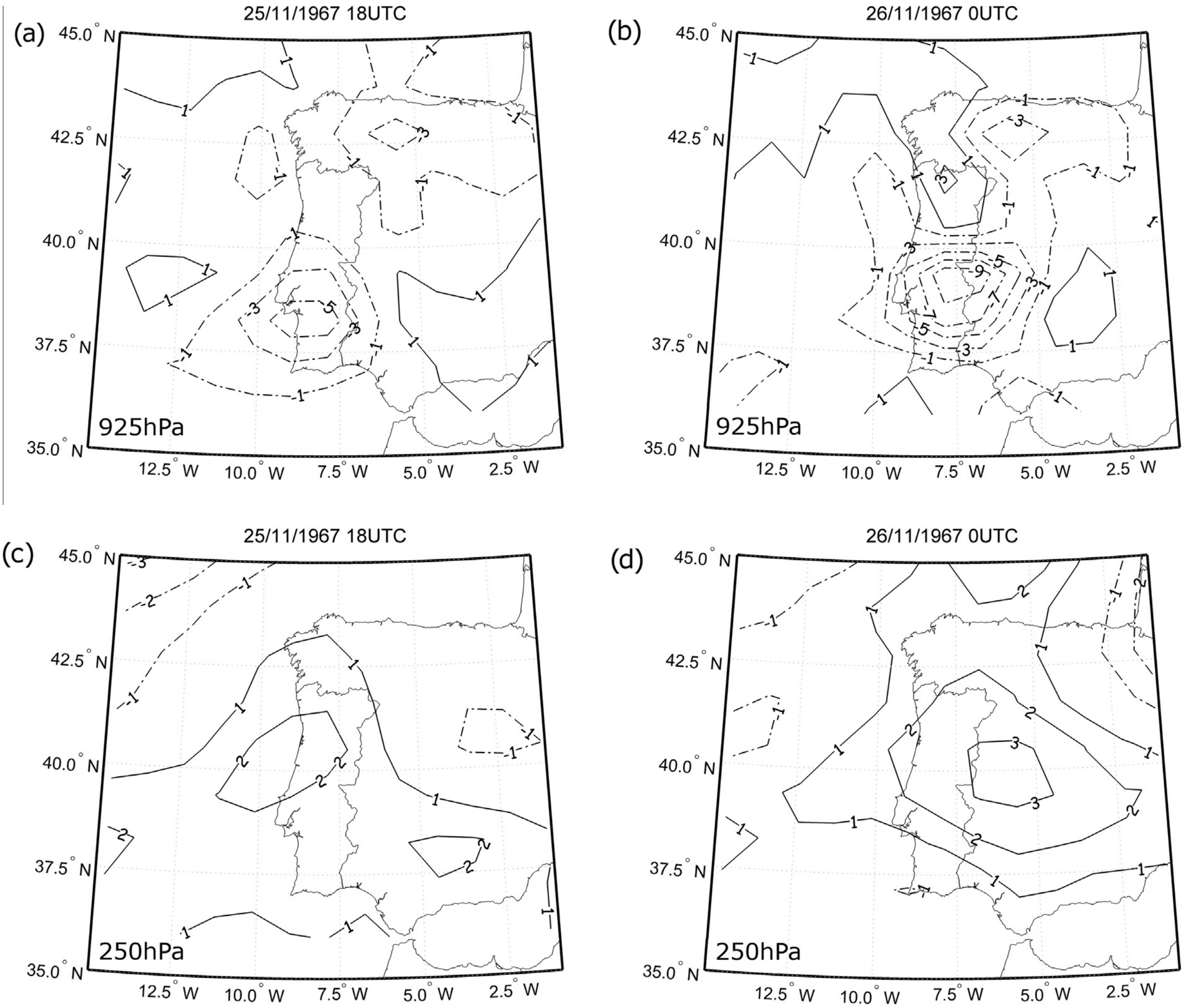

Fig. 13. Divergence (contours; 10-5s-1) at 1800UTC on 25 November and 0000UTC on 26 November for (a and b) the 925 hPa level, and (c and d) at the 250 hPa level.

extreme event, (3) the location of all the victims of the event on a municipality and river catchment basis and (4) the definition of flash flood hazard context, population exposure to flash flood damages and some vulnerability characteristics of the affected people.

Based on the sub-daily time series of a representative station, and its IDF curves, we have found that the exceptionality of this rainfall event is particularly linked to rainfall intensities ranging in duration from 4 to 9 h. For this range of temporal scales, the rainfall intensity (mm/h) is characterised by return period values close or clearly above to the 100-year IDF curve. This conclusion is particularly important because the estimated concentration time values of the hydrographic basins affected by the flash flood event are of a similar duration, less than 6 h in 70% of the hydrographic basins and the remaining 30% present concentration times ranging from 6 h to 9 h 30 m. From a meteorological perspective this episode was characterised by strong convection at the regional scale, fuelled by high availability of moisture over the Lisbon associated with a low pressure system near Lisbon that also favour the convective instability.

Most victims were registered in the small river catchments around the main Lisbon metropolitan area, including more than 500 fatalities, and many more injured, displaced, evacuated and disappeared. Considering the time of the flash floods in the different stream catchments most victims were sleeping and were caught at home. The majority of people who died or who were severely affected by the flood lived in degraded illegal houses, often occupying flood plains and stream banks. This socio-economic context is important to appreciate the level of destruction observed at the time, in contrast to comparable episodes that took place afterwards. Interestingly, since 1967 the larger metropolitan region of Lisbon was hit by other intense precipitation events with comparable amounts of rainfall, namely in 1983 (Liberato et al., 2012) and 2008 (Fragoso et al., 2010) but generating considerably fewer deaths and evacuated people as quantified in the DISASTER database (Zêzere et al., 2014). This significant change in the amplitude of the human havoc might reflect the improvement of construction codes in flood prone areas after 1967. In fact from the total 522 casualties, near 100 deaths occurred in a very small locality called "Quintas" village located northern of Lisbon, where a flash flood event along with the topographic location of the village led to a terrific constrain to the water flow in the village's bridge. This type of water bottleneck, with dramatic impact in human lives, would be avoided (to a large extent) in future similar extreme precipitation events.

Flood **risk** is generally defined as the function of (1) **hazard** – the probability of a flood event that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental

Table 2
A comprehensive list of causes associated to the Hazard, Exposure and Vulnerability components of the 1967 flash flood event.

Hazard	Exposure	Vulnerability
100-year extreme rainfall event, between 4 and 9 h	Little farms with cattle located in flood prone areas	Population with high levels of poverty and illiteracy
Concentration time of the basins $\leqslant$ to the duration of the extreme rainfall event	Residential neighbourhoods located in flood prone areas	Allochthonous population (migrants from other parts of the country)
Vadose zone of the basins with low permeability enhancing peak discharges	Residential areas located next and along stream banks	Slums and houses little resistant to floods
Drainage system well developed leading to rapid concentration of surface runoff in the streams	Residential areas in critical points where main streams converge	Lack of urban planning (illegal establishment of several neighbourhoods)
Wide flood prone areas	Submersible communication routes (main roads)	Absence of any early warning system for floods
Natural and artificial valley bottlenecks leading to rising of the upstream water column		
High tide during the first half of the flood		

damage; (2) **exposure** – people, property, systems, or other elements present in hazardous zones that are thereby subject to potential losses; and (3) **vulnerability** – the capacity of a society to deal with the event, i.e, the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNISDR, 2009; Koks et al., 2015). Within these concepts, we defined 17 causes for the 1967 flash flood disaster (Table 2). From these causes, we highlight the following: (i) the rainfall intensity with a 100-year return period had a duration higher or equal than the concentration time of the hydrographic basins; (ii) the construction in critical points located in the convergence of the main streams; (iii) the existence of shacks or one storey houses not very resistant to flooding; (iv) the absence of information of the resident population (migrants) on the local flood danger; (v) the lack of spatial planning in urban areas, (vi); the absence of an early warning system for floods.

Appropriate policy measures associated to large infra-structure investments have changed the level of vulnerability to floods in the Lisbon Metropolitan area since 1967 flood. In fact, in recent decades, millions of euros have been invested by the State and Municipal Councils, in flood mitigation, mainly through structural measures. Also, the increasing quality of the buildings, the disappearance of the shack boroughs and the adjustment of residential buildings with several floors on pillars on the floodplain, prevented that, in the two subsequent major flash floods (1983 and 2008) that affected the Lisbon region, the human damage was not as serious as the 1967 flash flood. However, the sensation of "false protection" in use continues to encourage risk-taking behaviours, such as the growing construction in floodplains, which continues to cause essentially material damages.

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