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Numerical simulation of the deadliest flood event of Portugal: Unravelling the causes of the disaster

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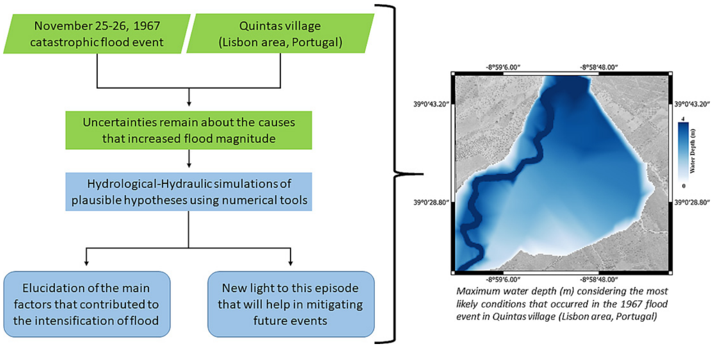
HIGHLIGHTS

- Hydrological modelling of the deadliest flood in Portugal: November 25 and 26, 1967
- Simulations of the most plausible contributing physical mechanisms to the flood
- Interpretation of the main factors that contributed to the intensification of flood
- Unusual debris around a bridge bottleneck played a key role to intensify flood.
- A rapid rise in water depth during the night contributed to increase the fatalities.

GRAPHICAL ABSTRACT



Maximum water depth (m) considering the most likely conditions that occurred in the 1967 flood event in Quintas village (Lisbon area, Portugal)

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ABSTRACT

The flood event of November 25 and 26, 1967 corresponds to the deadliest storm affecting Portugal in recent centuries being responsible for >500 fatalities. The main trigger was the heavy rain that fell in just a few hours, provoking a rapid increase in river flows, although other concurrent circumstances had to occur to reach the dramatic water levels estimated in some affected places. However, even today, several important uncertainties related to water levels achieved and timing of floods remain. Here we aim to clarify some of the pending issues by applying suitable high performance numerical tools to elucidate the main conditioning factors that played a key role in the intensification of this dramatic flood. In particular, the analysis has been focused on Quintas village, the location most affected, where >100 fatalities were recorded, close to 2/3 of its total population at the time. The main conclusion provided by the numerical simulations was that a plugging of water flow downstream of Quintas village, favoured by a poor terrain maintenance coupled with the bottleneck created by topographic features, caused the critical over-elevation of water levels. Simulations also corroborate the rapid increase in water levels in Quintas village, with an estimated rise of >2 m in just two hours, as well as the occurrence of the flood during the night, preventing many people to be aware of the extreme danger they were facing and safeguarding themselves.

1. Introduction

Floods are widely considered as one of the most dramatic extreme events occurring in the planet (Noji, 2000; Paprotny et al., 2018). The destructive capacity of floods can cause important damages in infrastructures

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and put at risk the integrity of the population (Jonkman, 2005; Fekete et al., 2017; Wallemacq et al., 2018). In addition, the current temperature trends, fuelled by global warming, have already raised impacts in the hydrological cycle (Held and Soden, 2006; Davis et al., 2015), including flooding development (Allan et al., 2020). In particular, it is now well established that rising temperatures increase the water holding capacity of the atmosphere which can provoke an intensification of extreme precipitation events, as well as, of the associated floods (IPCC, 2021; Zhang et al., 2021). In fact, some regions of the world have already suffered an intensification of floods in recent decades as a result of such mechanism (Alfieri et al., 2017; Tabari, 2020). Likewise, climate change scenarios also project an increment in the frequency and intensity of extreme flood events in some regions of the world in the coming decades (Dankers and Feyen, 2008; Alfieri et al., 2017; Jongman, 2018; Fernández-Nóvoa et al., 2022). However, while these increasing trends have been observed for some particular regions, it should be noted that several comprehensive pan-European studies also highlight that changes in flooding are still regional dependent (Hall et al., 2014; Hall et al., 2015; Blöschl et al., 2019). In fact, Blöschl et al. (2019) detected both decreasing and increasing trends in flood discharges, in past decades for different regions of Europe. These authors concluded that despite changes in precipitation patterns, climate change also affects other important factors influencing flooding, such as soil moisture, evaporation, snow cover or snow melt, among others, leading to different flood trends depending on the region and the relative importance of these factors (Blöschl et al., 2019). However, these authors also stated that, even in regions where a decreasing trend in flood discharges was detected in medium-large catchments, there could be an intensification of floods in small basins, those more dependent on local storms that are expected to intensify in a warmer climate as commented above (Blöschl et al., 2019; IPCC, 2021). In any case, it seems clear that climatic change has already affected flooding events in Europe (Blöschl et al., 2017; Blöschl et al., 2019) and will affect further in the near future (IPCC, 2021). Thus, an important scientific goal in hydrological sciences in the coming decades is focused on improving the flood understanding and the mitigation measures that are necessary to implement, considering different possible climate change scenarios (IPCC, 2012, 2021). For that, and as established by the European directive (E.D.2007/60/C, n.d.), it is essential to improve the understanding of historical floods with significant adverse impacts given the increased likelihood of similar, or even more serious, events in the future. To address these challenges, the development and improving of available numerical tools is particularly welcomed, as it allows the analysis of floods from a point of view of numerical simulations (González-Cao et al., 2021, 2022). In particular, numerical simulation tools allow the detailed analysis of past floods where data is often sparse, as well as the evaluation of different scenarios (Macchione et al., 2019; González-Cao et al., 2022). This approach allows filling many gaps in terms of the spatial and temporal characterization of such phenomena, providing relevant information that contribute to better understand these events and mitigate their negative impacts (Bárdossy et al., 2020; Benito et al., 2021; González-Cao et al., 2021).

Among the different types of floods, flash floods are especially dangerous given their speed and fast increase in associated water levels, hampering the ability of people to take shelter due to the characteristic short warning time of these events (Bronstert, 2003). This need prompted several countries to invest in projects to better understand this type of events and mitigate their impacts, including the HYDRATE project in Europe (Borga et al., 2011), the FLASH project in United States (Gourley et al., 2017) or the CFFSE project in China (Yuan et al., 2017). The two Iberian Peninsula countries (Spain and Portugal), and their main archipelagos, present synoptic conditions especially favourable to this type of events (e.g. Alcoverro et al., 1999; Lavers et al., 2011; Trigo et al., 2014). Some particular examples of the consequences of these sudden events in both continental and insular Iberian areas, were the >800 fatalities estimated in the flash flood that occurred in Rubí (Barcelona, Spain) in 1962 (López Bustos et al., 1964; Lumbroso and Gaume, 2012; Martín-Vide and Llasat, 2018), the 86 fatalities occurred in a camping site in the Spanish Pyrenees in 1996 (IPCC, 2012), the 45 fatalities that took place in February 2010, in the Madeira Island of Portugal (Fragoso et al., 2012) or the 21 deceases occurred in the city of Badajoz, Spain, in November 1997 (González-Cao et al., 2022). In this context, it is also especially remarkable the dramatic event of late November 1967 in Portugal, the deadliest storm affecting this country in, at least, the last 200 years, causing >500 fatalities associated to flash flood processes in the Lisbon area (Trigo et al., 2016). The storm, which occurred between the evening of 25 November and the first hours of 26 November, triggered flash floods and landslides which, together with adverse geomorphologic features and other concurrent circumstances, caused significant structural damages in the Lisbon region, and also a high number of fatalities in several peripheral locations (Trigo et al., 2016). However, even today, the exact role played by these other constraining mechanisms, as amplifications factors, for the extreme water levels achieved, has not been well established. Especially remarkable is the case of the Quintas village, the location most affected by this storm, where >100 fatalities were recorded, close to two thirds of its total population at the time (Floods of 67, 2020; Trigo et al., 2016).

Thus, the main aim of this work is to apply the high capabilities of numerical tools to this particular event in order to elucidate the main conditioning factors that played a key role in the dramatic flood that occurred in Quintas village in November 1967. Firstly, several documentary information related to this event, including newspapers, books, scientific reports, historical archives and witness testimonies, was consulted and analysed to determine the most likely physical mechanisms that conditioned this event. Then, the effective influence of each of these possible conditions on the Quintas flood was tested taking advantage of the ability of Iber+ model to simulate different plausible scenarios and conditions. The assessment starts by considering only the natural conditions, in order to obtain the response of the system in the absence of other factors. Only afterwards, when simulating more realistically the event, some possible conditioning factors of flood development are added (according to the documentary information consulted) allowing to analyse their potential impact. This approach allows assessing, in a controlled environment, what were the most probable causes that amplified this specific event.

We are confident that the use of multiple simulations of this event, under different conditions, will bring new light to this catastrophic episode and, additionally that this analysis will allow a better understanding of the flood dynamics in this area, and therefore, will help in mitigating similar (or even worse) events under future climate change scenarios.

This document is organized as follows: in Section 2 the area under scope and a brief description of the event are presented. Section 3 is devoted to describing the data and the methodology. In Section 4, the main hypotheses about the causes that could have intensified the 26 November 1967 flood event in Quintas village are tested by means of numerical simulations. Then, based on documentary sources that describe the water levels observed in the event, we provide an in-depth analysis of the most probable situation that occurred, according to the simulation results. Finally, this flood is contextualized in a wider general framework by comparing with other well-known extreme flood events. The main conclusions obtained are summarized in Section 5.

2. Area under scope and case of study

Quintas village belongs to the Vila Franca da Xira municipality, about 20 km north to Lisbon (Fig. 1a). It is located in the lower sector of the ephemeral Grande da Pipa river, with an upstream hydrographic basin of about 110 km^2 (≈ 93 % of total Grande da Pipa basin). In particular, Quintas village is located on the right bank of the river, between the floodplain of the Quintas valley and the beginning of the hill (Fig. 1b and c). Quintas valley floodplain is rather small, presenting a width of approximately 600 m narrowing at the bottom, approximately 700 m downstream of Quintas village, where the width is reduced to just 130 m (Fig. 1c). This kind of bottleneck is caused by interbedded limestone layers within sandy clay complexes which forms the geological substratum of the region, as described in Trigo et al. (2016). In the central spot of this narrow part of the valley it is also necessary to highlight the existence of a small bridge

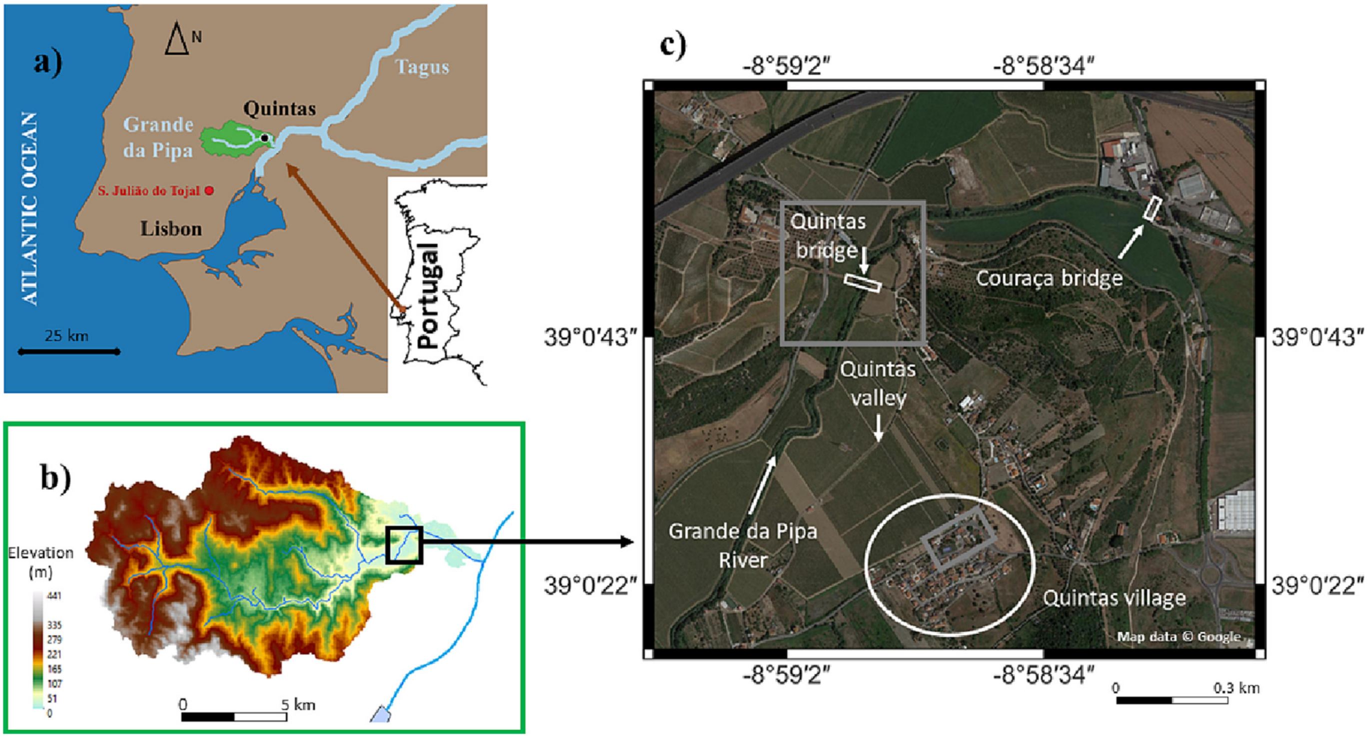

Fig. 1. Location and main features of the area under study. a) Location of the Quintas village (black circle), the Grande da Pipa river basin (green colour) and the main rain gauge station considered (red circle). b) Digital elevation model of the Grande da Pipa river basin. c) Aerial image of Quintas village including the main locations considered in this study. The grey rectangles locate important areas where there is relevant map information on dates close to the event under scope, and used at a later stage. Map data © Google Satellite (accessed: December 2022). Photographs taken by the authors that show a general view of Quintas valley, including the village of Quintas, the bottleneck formed by the terrain topography at the bottom of the valley, and the Quintas bridge, are provided in the Supplementary Material (Fig. S1). An old map with the detailed Quintas bridge structure obtained from Grupo Águas de Portugal (EPAL, https://www.epal.pt/epal) is shown in Fig. S2 of Supplementary Material. The elevation of the bridge and surroundings detailed in this old map are highly coincident with the current values measured by the authors.

(from now on Quintas bridge) built over the river (Fig. 1c), that partially occupies the width of the valley.

Quintas village was dramatically impacted by the floods resulting from the storm event that took place on November 1967. This storm was caused by a strong convective cell fuelled by the large amount of moisture in the atmosphere associated to a low pressure system centred close to Lisbon, as described in detail Trigo et al. (2016). Several hypotheses were made about the main causes that, besides the intense rain, contributed most to the extraordinary floods that occurred in this village during this catastrophic event. It is worth remembering that in the small village of Quintas >100 fatalities were registered out of the approximately 700 total estimated in the entire Lisbon region, which seems to indicate that special hazardous conditions must have occurred, which contributed to the dramatic levels reached by water during the event (Ramos and Reis, 2002; Trigo et al., 2016). Of course, the high amount of precipitation that fell during the last hours of November 25 and the first hours of November 26 can be considered as the main trigger for this event, causing a rapid increase in river flow through the Quintas valley. In fact, some stations registered daily accumulated rainfall surpassing 130 mm, and previous reports confirmed that this value corresponds approximately to a 100-year extreme rainfall event, which underlines its extraordinary extreme nature (Trigo et al., 2016). In addition, the precipitation event occurred in a short period of time, beginning at 1000 UTC on 25 November and ending at 0300 UTC on 26 November, with most of the precipitation accumulated in just five hours, between 1900 UTC and 0000 UTC. This concentrated nature of the precipitation, and the small drainage area of the Grande Pipa river, caused important peaks in river flow to occur at night, which took people by surprise in their homes with most of them probably sleeping. In this context, it is of little surprise that most inhabitants of Quintas did not notice the rapid rise in water levels on time (Floods of 67, 2020) and most people could no longer save themselves (Trigo et al., 2016). However, a question remains uncertain: could this amount of precipitated water alone be the unique cause for the high water levels reached at Quintas location? Or were other natural and/or human enhancers necessary to reach the true magnitude of the flood? Previous reports hypothesized that the special topographic features of the area, could also play an important role in this flood (Trigo et al., 2016; Floods of 67, 2020). In addition, the documentary information consulted also confirmed a large amount of material dragged by the rivers, including entire trees, tree branches, crops, stones or mud to different types of manmade debris (tiles, cars, parts of structures…), which could also affect flood development (Trigo et al., 2016; Floods of 67, 2020). However, these hypotheses, and others (e.g. bridges blocked downstream, high tide…) raised in documentary data such as books and newspapers, must be adequately weighted and evaluated. For that, different conditions will be simulated with a hydrodynamic model in order to detect those that are most likely to have influenced this event. Fortunately, there is some documentary information related to this flood event that can be used as benchmark for the flood analysis. In particular, we obtained at the historical archive of the municipality of Vila Franca da Xira maps of the village of Quintas at the time of the event, including relative precise indications of the water extension and levels reached by the flood (Fig. 2). For the analysis of the flood event under consideration, two specific references were taken into account based on this information: i) the maximum water level in the Quintas valley (≈ 14 m), and the water depth reached at the centre of the main square of Quintas village (≈ 2.75 m). In addition, there is a map sketch that was prepared by a resident of the area at the time of the event, named Jose Ferreira Fonte, where he identifies and locates all the houses affected by the flood, including the number of victims that occurred in each one (Floods of 67, 2020). These houses were georeferenced in this work and were incorporated on the flood maps obtained for the different simulations, in order to analyse how the flood affected them.

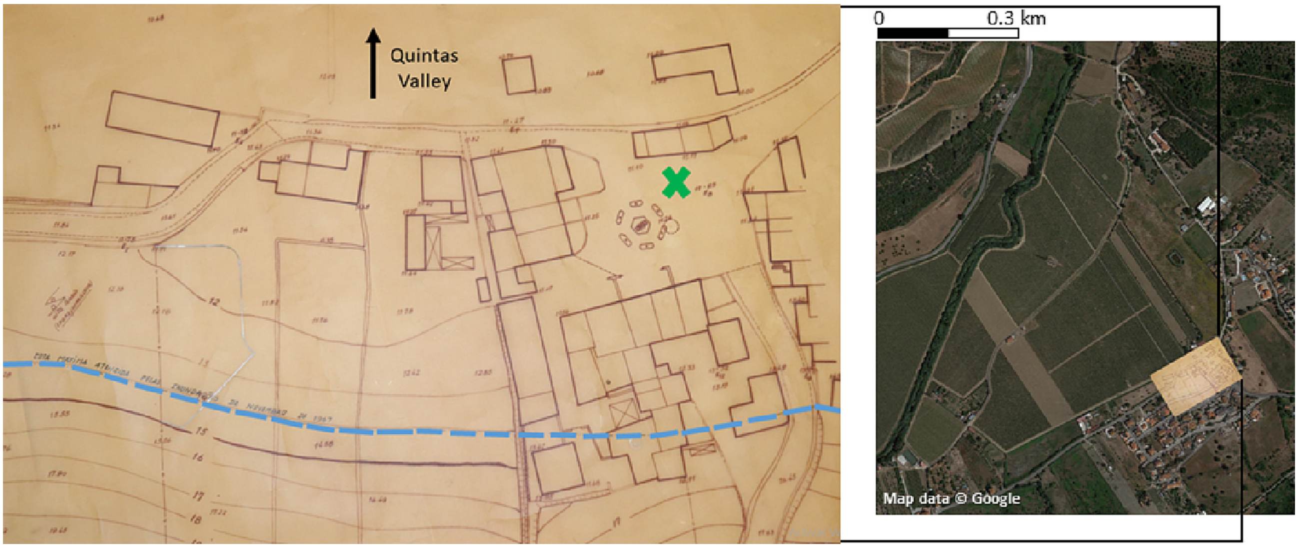

Fig. 2. The left panel shows a topographic map of the centre of Quintas village in 1967 (see the lower grey rectangle in Fig. 1c to visualize its location within the context of Quintas valley), including a line indicating the maximum water level reached in the November 1967 flood (approximately coincident with the 14-m topographic isoline). The original flood line was highlighted in dashed blue to facilitate the visualization. The main square of Quintas, located in the upper right part of the figure (marked with a green cross), was considered as a benchmark for the flood in Quintas village. This point presents an approximate level of 11.25 m, which means that water depth reached approximately 2.75 m in this point. The direction where Quintas valley is located is also indicated. The photograph was taken by the authors within the framework of the official consultation to the historical archive of the municipality of Vila Franca da Xira. The right panel shows the area of Quintas village represented on the map. Map data © Google Satellite (accessed: December 2022).

3. Data and methods

3.1. Precipitation data

The hourly precipitation data recorded at the S. Julião do Tojal meteorological station (Fig. 1a) for November 25 and 26, 1967 were obtained from the SNIRH (Sistema Nacional de Informação de Recursos Hídricos, https://snirh.apambiente.pt/). This station was selected because it is the closest to the village of Quintas with hourly records. Previous works dealing with this extreme event also took as a reference the precipitation registered in this station (Trigo et al., 2016).

3.2. Digital elevation model

Since there are no high-resolution local Digital Elevation Models (DEM) for the area under scope, such as those based on LiDAR technology, a DEM for the Grande da Pipa basin, with a resolution of 5 m, was created using level curves of 10 m equidistance, extracted from topographic maps at 1:25,000 scale obtained from Centro de Informação Geoespacial do Exército (CIGeoE, https://www.igeoe.pt/index.php?id=1), together with in situ measurements in the Quintas valley taken by the authors (see Fig. S3 of Supplementary Material). The in situ measurements were made using a Global Navigation Satellite System (GNSS). The topographic survey was carried out with a GNSS Topcon GR-5 equipment, with real-time measurement (Real Time Kinematic, RTK), through Ntrip (Networked Transport of RTCM via Internet Protocol) link to the reference station located in Arruda dos Vinhos (see Fig. S3 of Supplementary Material), belonging to the Rede Nacional de Estações Permanentantes GNSS (ReNEP) of the Direção-Geral do Território (DGT, https://www.dgterritorio.gov.pt/), obtaining precisions of 20 mm ± 2 ppm, in the determination of the points. Recent hydrographic channels and deviations built after the 1967 flood event were not considered when reproducing the real conditions of this flood event. For that, authors consulted aerial maps dated from 1965.

3.3. Numerical model: Iber+

Iber+ is a state-of-the-art numerical model, whose executable version can be freely downloaded from http://iberaula.es, that solves the 2D depth-averaged shallow water equations applying an unstructured finite volume solver (García-Feal et al., 2018). Iber+ is a new implementation of Iber model (Bladé et al., 2014) based on the parallelization of its hydraulic module. In particular, Iber+ is implemented in C++ and CUDA, which improves the efficiency of the model by achieving a speed-up of two-order of magnitude maintaining the same precision by using GPU (graphical processing unit) computing and HPC (high performance computing) techniques (García-Feal et al., 2018). These improvements allow analysing the entire hydrological-hydraulic procedures in large spatial domains and for long-term events (Fernández-Nóvoa et al., 2020; Bonasia and Ceragene, 2021; González-Cao et al., 2022). In fact, Iber+ hydrodynamic model has been successfully applied to analyse other flood events in western Iberia (Fernández-Nóvoa et al., 2020; Fraga et al., 2020; Benito et al., 2021; González-Cao et al., 2021, 2022). For that, in the present study, Iber+ model was used to simulate the hydrologic-hydraulic evolution of the flood that took place on November 25–26, 1967, in the entire catchment of Grande da Pipa river, and with special attention to the evolution of the flood in the village of Quintas.

The inlet condition is defined by the hyetograph corresponding to the hourly precipitation data recorded in S. Julião do Tojal, which is applied over the entire Grande da Pipa river basin, while the outlet is defined by a Supercritical/Critical condition at the end of the domain. Initial water level and discharge conditions were considered zero because Grande da Pipa is an ephemeral network. The domain was discretized through a mesh of unstructured triangles with a size that varies from 5 m in the surroundings of the Quintas village to 25 m in the rest of the domain. The numerical domain was adapted to the topography extracted from the reconstructed DEM. The infiltration procedure was performed by means of the curve number (CN) methodology. In this sense, data provided by GCN250 (Jaafar et al., 2019) were used and intermediate soil moisture conditions (normal CN) were considered attending to the precipitation of the previous days (111.5 mm in the previous 30 days) (Schulze, 1982; Cea and Fraga, 2018), resulting in a mean value of 75.446 for the area under scope. The land uses applied were those defined by the Corine Land Cover (CLC, 2000) for the area under scope, with an average Manning coefficient of 0.047.

Unfortunately, there are no similar events registered in this small basin with enough data available to calibrate the model parameters beyond these reference values. However, flood development will be validated, as far as possible, by comparison with some information on the evolution of the flood, as well as with some quantitative data available from previous works. However, we acknowledge that some uncertainties remain. In this sense, it is important to take into account that the characterization of the terrain conditions at a particular event is one of the parameters with a greater associated uncertainty, especially when dealing with historical events (Lastra et al., 2008; González-Cao et al., 2022). We acknowledge that these caveats can weaken the hydrological procedure and the associated river flows. Therefore, following previous works, the uncertainty in the curve number and land use parameters will be considered by applying a range of variation ±10 % in these coefficients in the simulations considered (González-Cao et al., 2021). Thus, minimum and maximum CN and Manning coefficients of 67.901–82.991 and 0.042–0.052, respectively, will be also considered. In addition, some uncertainty also remains regarding the precipitation that fell in the area under scope, as the available precipitation was registered in a single meteorological station close to the area under scope. Therefore, a range of variation of ±10 % was also applied to this variable. Thus, for each case under consideration, in addition to the simulation performed considering the reference values of the parameters involved, additional simulations will also be performed, considering the different possible combinations of the range values applied to the mentioned parameters. In this sense, only the minimum and maximum water level values reached in Quintas valley, considering all these extra simulations, will be taken into account to establish the range of variability, regardless of the combination that produces them. Thus, in addition to the core values associated with Quintas flood obtained using the reference values of model parameters and precipitation, a certain range of variability can be provided, which allows addressing the uncertainty of the event.

4. Results and discussion

4.1. Testing the different factors that could have influenced the 1967 flood in Quintas village

This section shows the results obtained for different test cases simulated where the main hypotheses about the causes that enhanced the flood in Quintas village are analysed. Those hypotheses, are sum up in Table 1, that also summarizes the main results of the analysed cases.

- In the first test (*Natural Conditions*), the natural conditions of the study area were reproduced to check if the observed precipitation, together with the topographic characteristics, could have caused the water levels registered in the 1967 flood event. In this case, no other conditions will be applied (e.g. bridges are not blocked). The simulated peak flow of Grande da Pipa river reached in Quintas valley was about 480 m^3s^{-1}, and it occurs at around 0200 UTC (Fig. 3). The time of the peak and the velocity of river flow increase, are in agreement with the testimonies (registered in the books and newspapers), with information of the event that confirm the rapid increase in river flow levels and also indicate that the clock of some of the victims stopped at 0150 UTC (Floods of 67, 2020), confirming that the most extreme part of the event occurred roughly around this time. Unfortunately, there are no measured river flow data to validate the peak flow obtained in the simulation, however, previous studies obtained a similar (although slightly lower) peak flow about of 450 m^3s^{-1} using the Rational method (Trigo et al., 2016). This allows reducing the uncertainty of the value adding more reliability that the peak value must have been of that order (Lumbroso and Gaume, 2012). However, due to the uncertainty that remains of this value, the influence of the possible variability of estimated river flow on the water depths reached in Quintas was also considered in the cases under analysis, as was commented in previous section. Regarding the flood magnitude considering the natural conditions, the water level in the Quintas valley reaches 12.26 m in the simulation, with a water depth of 0.91 m in the main Quintas square (Table 1). These levels are lower than those effectively reached in this flooding (approximately 14.00 m of water level in Quintas valley and 2.75 m of water depth in Quintas square), which means that the high discharge alone cannot explain the water depth reached in the 1967 event. Even if the worst condition framed within the uncertainty considered is taken into account, which implies the consideration of a peak flow above 700 m^3s^{-1}, (a clearly overestimated value), the increase in water depth in Quintas village is only 0.58 m, reaching a maximum depth value of 1.49 m in Quintas main square, well below the levels reached in 1967 (Table 1). This analysis also confirms that, in this particular case, the exact figure of the river flow evolution, within the associated uncertainty of the event, is not the most relevant factor, since even the highest values of peak flow are not sufficient to explain the observed levels reached by the water in Quintas, and therefore, other constraining factors must have occurred for the flood to reach the dramatic water levels registered.

- The second test case (*Couraça bridge blocked*) was developed since some testimonies affirm that the Couraça bridge, downstream of Quintas valley (Fig. 1), was blocked by the numerous materials dragged by the river (Floods of 67, 2020). This fact could increase the water levels downstream of Quintas valley and condition, to a certain extent, the outflow of water from the Quintas valley. Thus, this circumstance was tested by adding a wall along the location of the Couraça bridge in the numerical model, to simulate its total blockage. In spite that the water levels downstream of Quintas valley increase when the blockage of Couraça bridge is considered, this fact does not seem to affect flood levels reached at Quintas village (Table 1). Thus, the simulation indicates that the conditions downstream of Quintas valley alone had little influence on the flood in the village of Quintas. In this sense, the in situ measurements carried out by the authors reveal that the upper part of the Couraça bridge has an elevation of approximately 10 m.a.s.l., rising >3 m above the river surroundings, which are below of 7 m.a.s.l. This implies

Table 1

Different simulated conditions and water levels reached. Numbers in brackets indicate the associated uncertainty. S indicates the different simulations performed. E refers to the actual values reached in the 1967 flood event. N D indicates that no data are available.

	Different simulated conditions			Flood results		
S	Couraça bridge	Quintas bridge	Material accumulation in Quintas bridge surroundings	Maximum water depth (Quintas square)	Maximum water level (Quintas valley)	Peak flow
1	Not Blocked	Not Blocked	–	**0.91 m** (0.17–1.49 m)	**12.26 m** (11.52–12.84 m)	478 m^3s^{-1} (208–728 m^3s^{-1})
2	Blocked	Not Blocked	–	**0.93 m** (0.19–1.52 m)	**12.28 m** (11.54–12.87 m)	
3	Not Blocked	Blocked	–	**1.28 m** (0.47–1.97 m)	**12.63 m** (11.82–13.32 m)	
4	Not Blocked	Blocked	Peak flow partially blocked (70 %)	**2.74 m** (1.80–3.48 m)	**14.09 m** (13.15–14.83 m)	
E	November 1967 flood event			**2.75 m**	**14.00 m**	N D

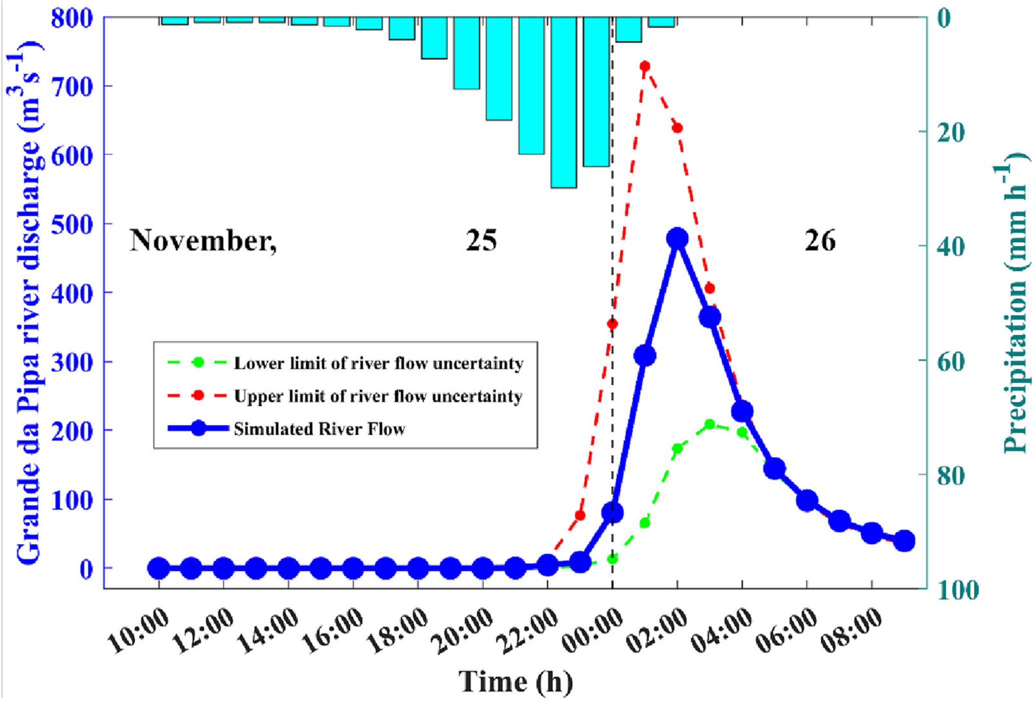

Fig. 3. Hourly evolution of Grande da Pipa river flow (m^3s^{-1}) simulation in Quintas valley for the flood event of November 25–26, 1967, obtained from Iber+ model (blue line) considering the precipitation registered in S. Julião do Tojal meteorological station (cyan bars). The thinner dotted lines represent the uncertainty considered in river flow. The black dashed vertical line indicates the transition between November 25 and 26.

that even if this bridge was blocked, the water elevation between Quintas and Couraça bridges (see Fig. 1) would not exceed 10 m.a.s.l. In situ measurements also reveals that the bottom of Quintas valley, in the vicinity of Quintas bridge, presents an elevation of about 10 m.a.s.l. This implies that even if the Couraça bridge had been totally blocked, the water levels reached between both bridges are not sufficient to significantly affect the outflow of water from Quintas valley, and therefore do not influence what occurred in the centre of Quintas village. In fact, in the following simulations, where other conditioning factors are analysed, it was also verified that Couraça bridge did not affect the water levels in Quintas village. Therefore, for the sake of clarity, and due to its negligible influence, the results considering this bridge in the simulations were no longer presented.

Additionally, some previous documents and studies also stated that the peak of the flood coincided with high tide, and that this could have had some influence in some areas of the Lisbon region (Floods of 67, 2020). However, taking into account the location of Quintas valley, as well as the scarce influence of the downstream conditions commented above, it can be also discarded that the high tide had influenced significantly the flood levels observed in Quintas.

- In the third test (*Quintas bridge blocked*) the influence of the blocking of the Quintas bridge (located in the central part at the bottom of Quintas valley) was analysed in further detail, since in view of the results described above, other circumstances must have contributed decisively to the increase in water level observed. In this sense, as previously mentioned, some testimonies described that the bridge located at the bottom of the valley was blocked by debris, trees and mud (Trigo et al., 2016; Floods of 67, 2020). Therefore, in this third simulation, the blockage of this bridge will be added to the numerical model, that is, when the peak flows reach this location, the bridge will be obstructed in the model in order to analyse the impact on the water levels reached in Quintas village. The results of the simulation indicate that the blockage of this bridge causes an additional increase in water depth upstream of 0.37 m, reaching a water depth of 1.28 m in Quintas main square with a water elevation about of 12.63 m in Quintas valley (Table 1). Nevertheless, despite the additional increase in water depths simulated when considering the blockage of this bridge, this is still not enough to explain the water levels reached in the 1967 event. Therefore, other conditions will be necessary to take into account. In this regard, as the blocking of this bridge is well documented in previous works and documents, and taking into account that its obstruction presents a certain influence on flood development at Quintas village, it will remain blocked in the following simulation.
- Finally, in the fourth test (*Material accumulation in Quintas bridge surroundings*), the influence of the accumulation of the material dragged by the river on both lateral sides of the Quintas bridge, that is, in the two small lateral sections on the both the left and right banks that remains between the ends of the bridge and the beginning of the hills, was evaluated. This simulation was carried out considering that at the bottom of Quintas valley, not only Quintas bridge, which covers the central part, was blocked by debris, mud and trees, but also this material was accumulated on both sides of the bridge, between the end of the bridge and the beginning of the hill, hindering water flow at this bottleneck point. In fact, some descriptions of the rescue team that arrived at Quintas village the morning after the flood, documented this fact. They went to Quintas by boat and found a wall of weeds and mud on both sides of the bridge, blocking their way (Floods of 67, 2020; https://www.museumunicipalvfxira.pt/pages/3876?event_id=11205). In order to simulate this scenario, an approximation was implemented in the numerical model through a specific internal condition to effectively limit river flow. This model condition, situated along both lateral sides of the bridge, between the end of the bridge and the beginning of the hill, tries to reproduce the effects of the partial blockage considered in this scenario. For this, the internal condition partially blocks the water circulation, allowing the flow only in specific points spanned along the line where the internal condition is applied, trying to simulate the uneven accumulation of material and the effects on the flow. In this sense, different distributions and levels of plugging were taken into account and their impact on Quintas village was analysed (Fig. 4). This set of simulations confirms that the material accumulation on both lateral

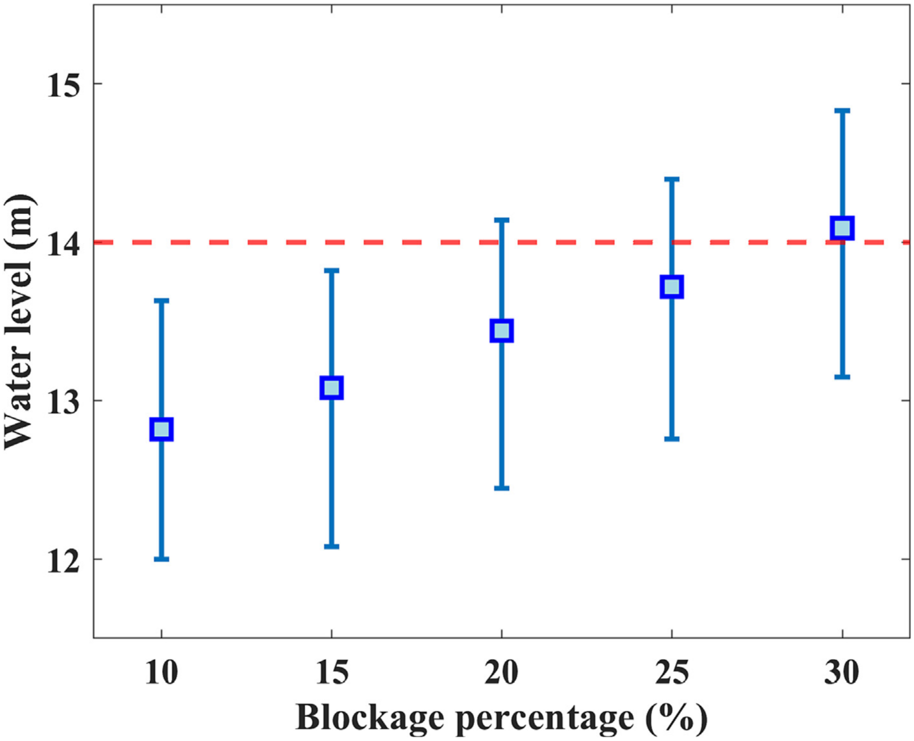

Fig. 4. Evolution of the water level (m) in Quintas valley considering different magnitudes of the river flow plugging at the bottom of the valley. Thus, a blockage of 30 % means that, when the peak arrives, only a 70 % of the water flow reaching this location is able to pass at that time. Bars correspond to the minimum and maximum water levels reached within the considered uncertainty range.

sides of the bridge, substantially limiting the effective outflow of water from the valley, implies an important increase in water levels upstream. In particular, when considering that this plugging limits water outflow by approximately 30 % when the peak arrives, that is, only 70 % of the flow is capable of passing at that time, the water level in Quintas valley reaches 14.09 m, implying a water depth of 2.74 m in Quintas square (Table 1), highly coincident with peak levels effectively observed on the early hours of 26 November 1967. These simulations also confirm that although the most extreme conditions, within the uncertainty considered, were taken into account, a certain level of plugging would be necessary to reach water levels recorded in this flood (Fig. 4), confirming this as the most probable cause that exacerbated the flood at Quintas village. In particular, according to Fig. 4, under the most extreme conditions explained by the uncertainty considered, a limitation of 20 % of the flow is still needed to reach the observed water level of 14 m (as shown by the upper whisker).

In this sense, the special characteristics of the valley, creating a bottleneck in this area due to its narrowing, favour that the material transported by the river accumulates at this location, a fact that is supported by previous works that documented not only the high amount of material dragged by the river, but also the blocking of the Quintas bridge due to their accumulation in that area (Trigo et al., 2016; Floods of 67, 2020; https://www.publico.pt/2017/11/12/sociedade/noticia/a-noite-do-fim-do-mundo-1791985). Although the bottleneck formed by the terrain topography makes this area prone to material retention, thus explaining the accumulation of material, other factors could also have favoured this fact. In this sense, an available aerial picture of the bridge area dated from 1965 was examined in order to analyse the spatial characteristics on a date close to the event under analysis (see Fig. S4 of Supplementary Material). Despite the low quality of the photograph, it can be detected the existence of vegetation on both sides of the bridge, especially in the left side of the bridge (in downstream direction). This vegetation alone could have limited the water flow when overflows the main channel, as well as it could have facilitated the accumulation of material dragged by the river, similar to what occurred in the bridge piers. Finally, it is important to stress that this bridge included a fairly wide water pipe associated that also crossed the Quintas valley (see Fig. S2 in Supplementary Material). Although this infrastructure was buried underground in most of the route, except for the bridge where it stayed above, it is reasonable to consider that it also contributed to the dragging and accumulation of material between the bridge and the hilly sides since it is covered by loose soil and materials that can be dragged more easily by rainwater down the slope of the mountains. The aforementioned features support the probable accumulation of an important part of the material carried out by the river at this narrow location, limiting the flow of water, which increased dramatically water levels upstream.

4.2. Reproduction and analysis of the 1967 flood event in Quintas village

Once the main hypotheses and conditions that could affect the case under study have been simulated and analysed, an important conclusion emerges; natural conditions alone are not sufficient to explain the full magnitude of the flood in Quintas village. It is clear that the trigger of the flood was the extraordinary precipitation rates that generate an important river flow capable of dragging material. However, even assuming an important range of variability in terrain conditions and associated peak flows, the simulated flood magnitude in the most unfavourable conditions falls short of water levels reached in early hours of 26 November 1967, suggesting that other factors should exert some influence on the flood. In particular, our simulations seem to confirm that the plugging of water flow in the valley, caused by the blockage of Quintas bridge together with the material accumulation on its both sides, is necessary to be considered explicitly so to reach the water levels registered in the 1967 flood in Quintas village. This fact was considered the most likely enhancer that can explain the dramatic flood levels reached upstream.

Taking all the above considerations into account the event was fully reproduced using simulation 4 (for the sake of clarity and better analysis of flood development, only those water depths that exceed 0.1 m will be considered for the flood analysis). As can be observed in Fig. 5, even at

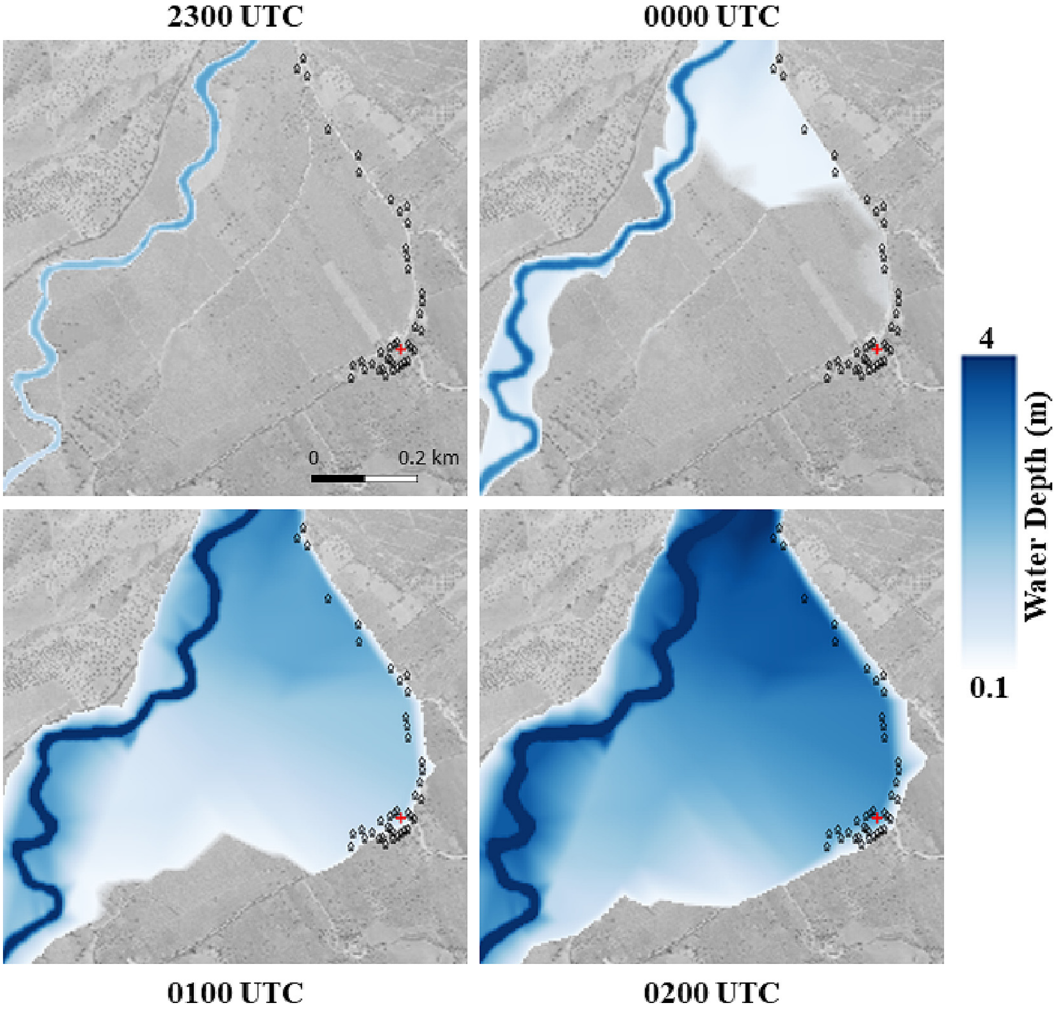

Fig. 5. Evolution of water depth maps in the most critical part of the 1967 flood event in the Quintas valley. The background aerial map corresponds to an aerial picture taken in 1965 obtained from Direção-Geral do Território (DGT, https://www.dgterritorio.gov.pt/cartografia/fotografia-aerea). Black house symbols indicate the location of the houses with fatalities extracted from the map drawn by Jose Ferreira Fonte (Floods of 67, 2020). Red cross indicates the location of Quintas main square.

2300 UTC, a time when dark night had already settled in for several hours, the situation was not dangerous in Quintas valley. As mentioned previously, despite the relentless precipitation, the lack of any early warning signals of a possible flood led many people to get to bed relatively quietly, preventing them from noticing when the fast flood was eminent. At 0000 UTC some water already flows over the valley, but between 0000 UTC and 0100 UTC, the increase in water depth is incredibly fast, covering the entire valley in few minutes and affecting a great number of houses. Between 0100 UTC and 0200 UTC the water level continues to rise, reaching its maximum values around this hour (Fig. 5).

A graph with water depth evolution was also analysed considering the Quintas square as a control point in order to check the time evolution of the increase in water depths in the area where most of the houses were located (Fig. 6). The graph confirms the exceptionally rapid increase in water depth that occurred at night. Between 0000 UTC and 0100 UTC water level at Quintas square passed from a few centimetres to approximately 1.30 m, which means a very fast rise up to 2 cm per minute, reaching a water depth of 2.71 m at 0200 UTC. The velocity of the water depth increase, together with the fact that it occurred in the early hours of the 26th November, during the night, hampered the capacity of many people from realizing the extreme dangerous situation, contributing decisively to the high number of fatalities that took place in this village. The temporal evolution of the water elevation agrees with the testimonies available, but also since some clocks of the victims stopped at 0150 UTC, which corroborates the timing evolution described by this simulation. According to our simulation results, the water depth remains very high until 0300 UTC, even increasing by a few centimetres, and then the level begins to drop at a much slower rate than during the raising.

Different levels of flood intensity, based on the maximum water depths reached, were also considered in the area where the affected houses were located, in order to analyse more in detail how the flood affected them. The first important conclusion to be drawn from the water levels reached in this simulation is that all houses included in this map were reached by the flood confirming the adequate performance of the hydraulic model (Fig. 7). Analysing more in detail, it can be observed that some houses were impacted by extraordinary water depths higher than 3 m (red colour), and also a significant number of them were affected by water depths between 2 and 3 m (orange colour). Thus, according to this simulation 4 (Table 1), maximum water depths attained indicate that these houses were totally covered by water. This result is consistent with the historical reports and testimonies, which state additionally that most of the houses were low-storey and waterlogged by the flood (Floods of 67, 2020; https://www.museumunicipalvfxira.pt/evento-51/exposicao-cheias-de-67). The rest of the houses were affected by water depths ranging between 1 and 2 m (yellow colour) or 0.5–1 m (green colour). Even in this last case, it is important to stress that the vast majority of constructions affected were humble and not very robust, hampering their capacity to resist the force of the water (Floods of 67, 2020). This fact contributed to the dramatic consequences in terms of lost lives (as well as loss of many households) even in these locations apparently less affected by the flood impact.

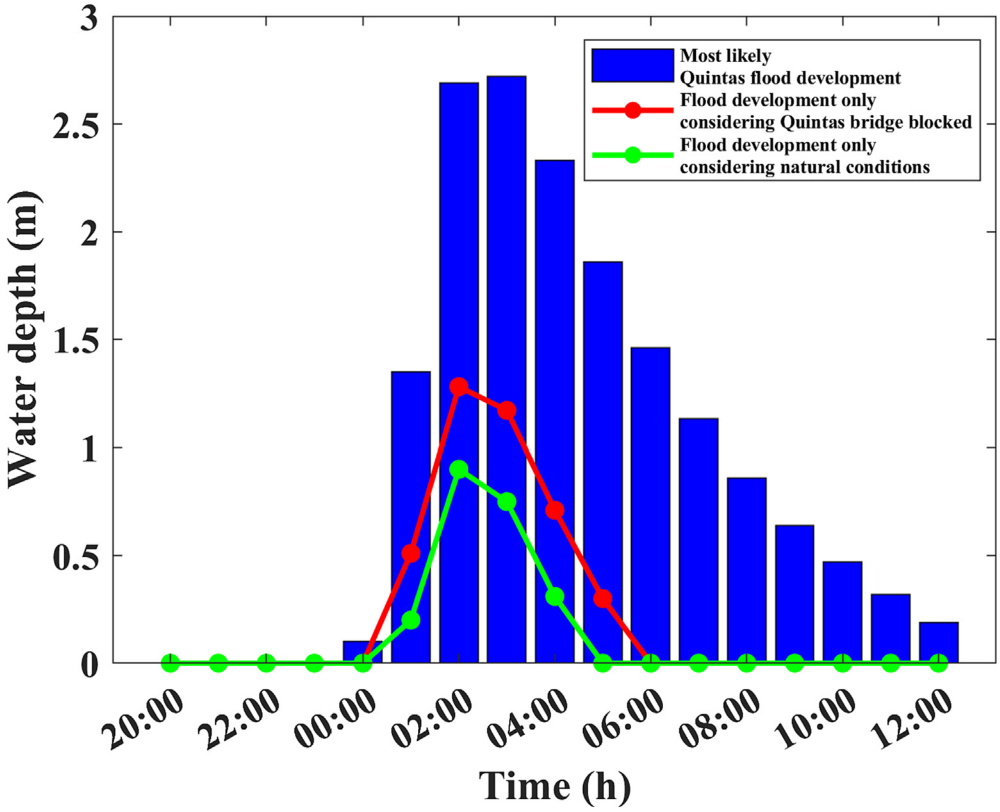

Fig. 6. Water depth (m) evolution in Quintas square is shown: i) considering the most likely conditions that occurred in the 1967 flood event, that is, the plugging at the bottom of Quintas valley caused by the blockage of Quintas bridge together with the material accumulation on its sides (blue bars); ii) considering only the blockage of Quintas bridge (red line); iii) considering only the natural conditions without obstructions (green line). In particular, i), ii) and iii) correspond to simulations 4, 3 and 1 respectively (Table 1). The last two lines were added for comparison purposes.

4.3. Wider contextualization of Quintas flood

Now that the analysis of the flood that occurred in Quintas village in 1967 was carried out, including the evaluation and unravel of the main probable causes that exacerbated this event, it is important to put this flood into a wider context framework. In this sense, the magnitude of the Quintas flood was assessed by means of the unit peak discharge, that is, peak discharge normalised by the upstream drainage area, for comparison purposes. A unit peak discharge of 4.4 m^3s^{-1} km^{-2} was reached, confirming this event as an important flash flood, since it far exceeds the limit of 0.5 m^3s^{-1} km^{-2} established as the lowest value for defining flash flood events in previous works (Gaume et al., 2009; Marchi et al., 2010; Taroli et al., 2012; Braud et al., 2014). However, despite the dramatic consequences of this flood, it cannot be considered an outlier when compared to similar type of events. To make this consideration, the magnitude of Quintas flood was compared with several flash floods occurred in the European continent and summarized in the work of Amponsah et al. (2018). In this context, it is important to take into account that the unit peak discharge for flash flood events presents a marked dependence on basin area, generally increasing with the decrease in the drained area (Lumbroso and Gaume, 2012; Amponsah et al., 2018). Therefore, Quintas flood was compared with floods that occurred in locations with upstream areas of similar size, between 90 and 130 km^2. It can be concluded that although the unit peak discharge in Quintas flood is above the average, it is far for the unit peak discharges of the most extreme flood events. In fact, if the general envelope curve (observed upper limit of the relationship between unit peak discharge and catchment area) extracted by Amponsah et al. (2018) is taken into account, Quintas flood is far from this upper limit. In particular, Amponsah et al. (2018) proposed the following envelope curve relationship: $Q = 120{*}A^{-0.4}$, where Q is the unit discharge (m^3s^{-1} km^{-2}), 120 corresponds to an independent coefficient, and A is the basin area (km^2).

The maximum unit peak discharge expected for Quintas basin, according to this proposed envelope curve, is of the order of 18 m^3s^{-1} km^{-2}. However, the unit peak discharge reached in Quintas in 1967, even including the worst possible conditions within the uncertainty considered, is far from this value (6.7 m^3s^{-1} km^2). However, we should also keep in mind that this flood caused a higher number of fatalities compared to other more intense floods in terms of unit peak discharges (Gaume et al., 2004; Delrieu et al., 2005), which reinforces the idea that other constrain factors play a key role in flood development, and hence, the need to better understand the development and main conditioning factors of this flood. In fact, if the analysis of the present study, including the modelling of the entire catchment and the consideration of the different constraining factors, were not carried out, some misinterpretations could result. In particular, if the river flow required to reach water marks was simply estimated without taking into account other factors, unrealistic values of river flow, above the envelope curves and even surpassing the total rainfall of the event, could be achieved. This would take this flood out of context and would lead to misleading interpretations when compared with other floods, as previously occurred in other cases. In this sense, a case with some similarities was the flood event that took place in 1962 in Rubí (Barcelona, Spain), the most dramatic flash-flood event in this neighbouring country. Previous analysis of this event using the slope–area method in cross sections and which did not consider conditioning factors, obtained unrealistic peak flows (and unit peak discharges), that even exceed the envelope curves and above the total rainfall volume. Subsequent works were necessary to correct these values (Lumbroso and Gaume, 2012; Martín-Vide and Llasat, 2018), which were useful to put into context the real values reached in this flood, and allowed a more adequate comparison with other extreme events. These latter works estimated unit peak discharge values ranged between 16.5 and 8 m^3s^{-1} km^{-2} for basin contributions of 22–82 km^2. Even in that case, more extreme in terms of unit peak discharge that Quintas

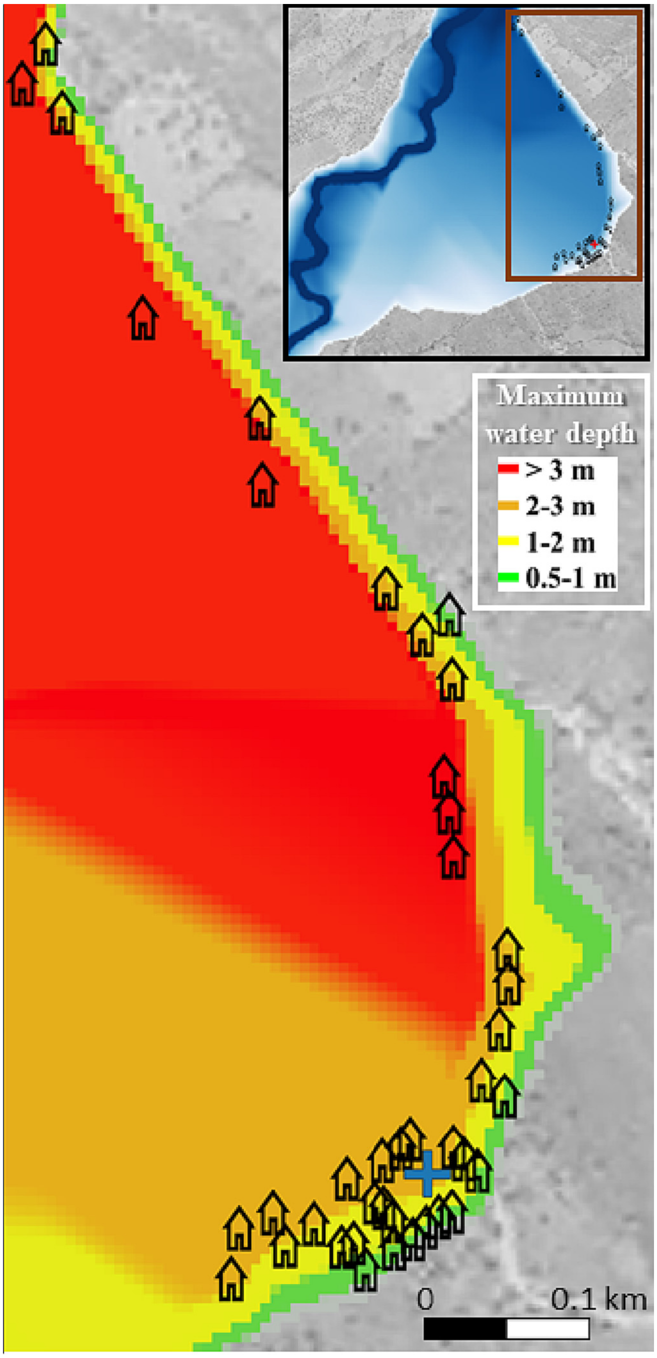

Fig. 7. Different levels of maximum water depth in Quintas village when simulating the 1967 event. Green colour indicates maximum water depth in the range 0.5–1 m, yellow colour indicates maximum water depth between 1 and 2 m, orange colour indicates maximum water depth between 2 and 3 m, and red colour indicate water depths >3 m. The background aerial map corresponds to a photograph taken in 1965 obtained from Direção-Geral do Território (DGT, https://www.dgterritorio.gov.pt/cartografia/fotografia-aerea). The house symbols indicate the location of all the houses that registered fatalities extracted from the map drawn by Jose Ferreira Fonte (Floods of 67, 2020). The blue cross indicates the location of Quintas square. The brown rectangle on the inset map represents the Quintas village area zoomed in the main figure.

flood, other additional factors, as the sediment drag and the blocking of some bridges, were necessary to be considered to reach the real water levels measured and that provoked the dramatic consequences registered. This highlights that the development of this type of studies, such as the presented here, are fundamental to put such historical floods into a general and wider framework, contributing to an accurate international database of flash floods and helping to better understand and mitigate these events.

Finally, it is important to comment that, in addition to unravelling the most probable causes of the Quintas flood, and framing this flood event in a wider framework, the line of development followed in the present work can also serve to be applied in further analysis of other flood events under different triggering mechanisms. In this sense, the present work demonstrated that the recompilation and analysis of historical documentary data is fundamental to evaluate historical floods due to the usual lack of field measurements in these events. This information, although much of it may be qualitative, can be quite useful to constrain robustly the flood extension and water depth reached, as well as the timing of the flood and some of the main facts that could have affected its development. Thus, this recompilation of information is essential to contrast the numerical results of the simulations and limit misleading interpretations. In turn, the multiple numerical simulation of different plausible flood scenarios proposed is critical to contextualize flood magnitude and its probable evolution and, if any, the conditioning factors that intensify flood impact. This procedure could be applied to assess flood events that still remain uncertain, as well as to verify peak flow values estimated in other historical floods.

5. Conclusions

In the present study, the analysis of the flood event that took place in November, 25 and 26, 1967, in the metropolitan area of Lisbon in Portugal, was approached from the numerical modelling perspective. In particular, the simulations were focused in the small village of Quintas (north to Lisbon), the location most affected by the flood, where >100 fatalities were recorded, i.e. about 70 % of its total population at the time. The recompilation and analysis of previous historical documentary information and related works stated that, in spite that the main trigger was the intense precipitation that fell in just a few hours, causing a rapid increase in river flow, additional hazardous conditions must have occurred to reach the dramatic water levels occurred in this village. However, the exact role played by these constraining factors has not been yet well established. In this sense, the multi-modelling approach undertaken in this work, through which the different possible hypotheses that could explain the intensification of this flood event were tested, contributed to better frame the causes of the disaster.

First, an analysis of the event was carried out considering only the natural conditions in order to obtain the response of the system in the absence of other factors. The numerical results confirm that the water levels obtained in this case were well below the levels reached in 1967 at the main square of Quintas. Therefore, other constraining conditions were explored, attending to documentary information previously consulted, including newspapers, books, scientific reports, historical archives and witness testimonies, and taking advantage of the numerical model to simulate different scenarios. Thus, the most likely mechanisms that could intensify the flood were tested. The main conclusion extracted for the different simulations carried out is that the blockage of a bridge that partially occupies the bottom of the Quintas valley, downstream of Quintas village, by the material dragged by the river, together with the accumulation of part of this material on both sides of this bridge, between bridge and the hill, was the most probable additional factor explaining the water levels reached in Quintas village. This caused a plugging of likely 30 % of the water flow at this location which increased water levels upstream. This fact is explained by the well-documented large amount of material dragged by the river and because this area is prone to the retention of materials due to the terrain features, that form a bottleneck by narrowing the valley in this final part. In fact, some testimonies documented the bridge blockage by debris, trees and mud. We must stress that the results are robust because we have applied a sensitivity analysis to take into account the uncertainty of both the precipitation and also to the model parameters that characterise the terrain conditions. Even in the most extreme conditions explained within the associated uncertainty, a certain level of plugging is necessary to reach water levels recorded in this flood.

Taking this scenario as the most probable, the event was reproduced and analysed in depth. The simulation results indicate that the most critical part of the event occurred during the night, with an estimated very rapid rise of >2 m in water levels in Quintas village between midnight and 0200 UTC. Both the levels attained in the peak time and the hourly time evolution agree quite well with the available water marks and testimonies. The velocity of the water depth increase, together with the fact that it occurred during the early hours of the 26th November hampered the capacity of many people from realizing the extreme dangerous situation in time, contributing decisively to the high number of fatalities that took place in this village.

The simulations performed also allowed estimating the river flow evolution that reached the Quintas valley during the event, suggesting an estimated peak flow near to 500 m^3s^{-1} occurring around 0200 UTC, a magnitude and timing in accordance with previous works and documentary information. This also served to put into a wider context the magnitude of the flood by means of the unit peak discharge, yielding a value above 4 m^3s^{-1} km^2. In this sense, the magnitude of the Quintas flood, compared to unit peak discharges of other international flood events, can be considered above the average, but not an outlier at all, being far for the most extreme flash flood events recorded. This reinforces the idea of the important role played by additional constrain factors, as described above, and therefore the need to unravel the development and main conditioning factors of this flood, which also allowed the flood to be contextualized in a wider general framework.

The methodology followed here, starting from the analysis of documentary information of the historical event to contextualize it, and the subsequent multi-modelling and analysis of the plausible scenarios that can explain flood development, could serve as example to be applied to other flood events where uncertainties still remain, contributing to advance in the knowledge and understanding of floods. This is particularly relevant in a warming world where extreme precipitation and flash floods might increase as a consequence of global warming and additional availability of water vapour.

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CRediT authorship contribution statement

Diego Fernández-Nóvoa: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **José González-Cao:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Jose R. Figueira:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Cristina Catita:** Investigation, Writing – review & editing. **Orlando García-Feal:** Methodology, Writing – review & editing. **Moncho Gómez-Gesteira:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision. **Ricardo M. Trigo:** Conceptualization, Investigation, Writing – review & editing, Supervision.

Data availability

Freely available data and software were used for this work

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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