Point-by-point reply to all referee comments (RCs) on "Hydrogeomorphological analysis and modelling for a comprehensive understanding of flash-flood damaging processes: The 9th October 2018 event in North-eastern Mallorca" by Joan Estrany et al.

Joan Estrany[1,2*], Maurici Ruiz-Pérez[1,2,3], Raphael Mutzner[4], Josep Fortesa[1,2], Beatriz Nácher-Rodríguez[5], Miquel Tomàs-Burguera[6], Julián García-Comendador[1,2], Xavier Peña[4], Adolfo Calvo-Cases[7], Francisco J. Vallés-Morán[5]

[1]Mediterranean Ecogeomorphological and Hydrological Connectivity Research Team (http://medhycon.uib.cat), Department of Geography, University of the Balearic Islands, Carretera de Valldemossa Km 7.5, 07122 Palma, Balearic Islands, Spain

[2]Institute of Agro-Environmental and Water Economy Research –INAGEA, University of the Balearic Islands, Carretera de Valldemossa Km 7.5, 07122, Palma, Balearic Islands, Spain

[3]Service of GIS and Remote Sensing, University of the Balearic Islands, 07122 Palma, Balearic Islands, Spain

[4]Hydrique Engineers (http://www.hydrique.ch), Le Mont sur Lausanne, Vaud 1052, Switzerland

[5]Universitat Politècnica de València, Camí de Vera, s/n, València, 46022, Spain

[6]Estación Experimental de Aula Dei (EEAD-CSIC), Avenida Montañana, 1005, 50059 Zaragoza, Spain

[7]Inter-University Institute for Local Development (IIDL) Department of Geography, University of Valencia, Av. Blasco Ibáñez 28, 46010, Valencia, Spain

Correspondence to: Estrany J. (joan.estrany@uib.cat)

The response of the questions and comments provided by both anonymous RC1 and RC2 reviews will be addressed in a point by point format, being the comments from RC1 and RC2 in bold.

RC1 - Anonymous Referee #1 Received and published: 18 December 2019

GENERAL COMMENT. **The paper of Estrany et al. provides an analysis of the devastating flood that hit the North-eastern side of the Mallorca Island in October 2018, considering: 1) the hydrological response of the catchment; 2) damage assessment; and 3) geomorphic changes. The analysis presented is quite detailed, and represents a very good starting point that, linked to a study from a meteorological perspective and to a hydraulic study about the flooding dynamics (two aspects that –I acknowledge- go beyond the scopes of the paper), would provide a rather comprehensive picture of the event from a civil protection perspective. The data provided by the water level station are particularly interesting and valuable.**

We are truly delighted with the comments of Anonymous Referee #1, due to is considering we are providing a valuable insight in improving the comprehension of extreme flash-flood events in Mediterranean environments, highly subject to human pressures.

Regarding meteorological perspective and hydraulic study, we are also aware that they are both out of scope of this first approach carried out within this manuscript. However, the authors we are working to go beyond this first study, precisely (1) addressing a detailed 2D hydraulic modelling in which urban flooding dynamics are being investigated; and (2) evaluating geomorphic changes in two headwaters small catchments through high-resolution digital elevation models built from images captured by a UAV.

My major comment is that the paper has the potential to go beyond the 'simple' description of a case study, where three single pieces (rainfall-runoff modelling, damage assessment and geomorphic changes) are discussed separately. Discussion section could help to bridge this gap. It introduces several topics (e.g., land-use changes, fires, etc.), which, however, are treated in an increasingly qualitative and general way during the discussion itself. What are their actual (and relative) effects on this event? Can they be quantified? Also, the triggering effect of the karstic reservoir(s) should be somehow addressed with more detail (I mean, the authors should try to go beyond the conceptual modelling and provide insights about the physical process, which involves, e.g., specific geological features in specific areas). I wonder about the sudden increase in discharge from 120 to 442 cms (an impressive peak flow rate per unit area) in 15 minutes (very fast response time). The reason for this behaviour is not totally clear. Is it mainly due to the karstic environment or to other reasons (e.g., the failure of a temporary dam)?

It is a very challenging question to assess the effect of land-use change on the event and we believe this is out of scope of the current paper, as it would probably deserve a publication on its own. Our goal in the discussion was to highlight possible further investigation on this aspect.

Concerning the triggering effect of the karstic reservoir, we acknowledge that this is a main part of uncertainty in the model. As modeled, the release of the karstic reservoir is very similar to the failure of a temporary dam, as in the karstic model, the water is stored in a karstic reservoir, which is then suddenly released by syphon effect. There is no evidence that it is solely due to karstic behavior. We mentioned this point through the Discussion section and will be showed in the following comments.

We have deeply modified the Discussion section. Firstly, the two subsections have been unified forming a unique storyline where hydrological response, rainfall-runoff modelling, damage assessment and geomorphic change are integrated. We believe this new version of the MS is bridging the gap between them, because we have introduced several paragraphs especially focused on the predictability of this kind of flash-flood events in order to better join these different issues. In addition, the new Figure 1 is also useful to better understand the integrated approach.

This is the paragraph written to better join the different parts of the Discussion section (see Lines 636-646 of the revised MS):

"*At present, Mallorca does not have any sort of early warning system to assist flood risk management, and nor of course has Sant Llorenç des Cardassar. Similarly, no hydrometeorological early warning was issued by the competent authorities, as the Balearic Islands have no operational hydrological control network releasing real-time information on discharges. In October 2018, Sant Llorenç des Cardassar was one of the four municipalities in Mallorca with a flood risk emergency plan. However, it was not operational at the time the emergency was declared. As a result, the population was completely unaware of how to defend themselves, even during the emergency phase, although Sant Llorenç des Cardassar municipality had significant social vulnerability to floods, as most of the casualties were tourists and the elderly*".

Secondly, we have addressed a qualitative –but also quantitative– discussion about the role played by rainfall intensity and its spatial distribution, complex geology and land cover disturbances, following the suggestion provided by the Anonymous Referee 1#. For this purpose, we have also modified the subsection 2.1. Study area (see Lines 155-165 of the revised MS), where a deeper assessment of permeability in lithology materials as well as a diachronic evaluation of land uses evolution and perturbations (i.e., wildfires) is sustaining the discussion on the role of physical parameters generating the flash flood.

"*The lithology is mainly composed of marls intercalated with limestone (60% of the area) of the Medium-Upper Jurassic (Dogger), dolomites (22% of the area) of the Upper Triassic and Lower Jurassic, and pelagic limestone marls (14% of the area) of the Lower Cretaceous (Fig. 2d). This lithological composition determines the surface water/groundwater interaction. On the one hand, a high degree of fracturing, fissuring and karstification of limestone favours percolation through karstic aquifers. On the other hand, the imperviousness of Dogger and Cretaceous marls (74% of the area) does not allow percolation, enabling runoff generation. The main land use in 2012 was agriculture (58%), mostly located in lowland areas. Forest (26%) and scrubland (17%) were predominant at headwaters. Terraced fields still occupied 10% of the catchment, although most of them were abandoned (Fig. 2e). In 1956, natural vegetation covered 21% of the catchment. This rose to 42% in 2012 due to an afforestation process of former agricultural land in the second half of the twentieth century. In combination with other factors, afforestation triggered a higher fire risk: two wildfires burnt an area of 1.7 km^2: 17% in 1983 and 83% in 2011 (Balearic Forestry and Soil Conservation Service, http://xarxaforestal.caib.es; Fig. 2e)*".

We have also placed special emphasis on the sudden increase in discharge from 120 to 442 $m^3 s^{-1}$, which has resulted from the combination of all these physical parameters. Please, see the Lines 583-607 of the revised MS:

"*This runoff response resulted from the combination of rainfall intensity and its spatial distribution, complex geology and land cover disturbances in generating a high Q_{peak} (i.e., 442 $m^3 s^{-1}$) with high potential for generating geomorphological changes. Thus, the Q_{peak} unit obtained (i.e., 19 $m^3 s^{-1} km^2$) can be classified as the third highest value of all the reported values in Marchi et al. (2010) and the highest of those values obtained from streamflow measurements in a hydrometric station and not by post-event analysis. The hydrologic response analysis in the course of a flash flood shows how storm structure and evolution result in a scale-dependent flood response (Borga et al., 2007). Consequently, spatial rainfall organisation, geology combined with orography and land cover disturbances led to pronounced contrasts in the flood response at the Begura de Salma River. Spatial rainfall on the catchment scale showed that the highest accumulation at the beginning of the storm was located at the* *headwaters of the catchment (at 15:00 h), whilst during the last part of the event the most important rainfall amounts were located in the downstream part. Examination of the flood response illustrated how the extent and the position of the karst terrain (Zanon et al., 2010) and soil conservation practices (Calsamiglia et al., 2018; Tarolli et al., 2014) provided major geological and anthropogenic control of runoff response. Impervious materials cover 74% of the Begura de Salma River catchment, mostly located at the headwaters, which are responsible for the highest values of topographic torrentiality (Estrany and Grimalt, 2014b), facilitating rapid overland flow generation. During the first part of the storm, when the highest rainfall amounts affected the headwaters, runoff response was delayed by the laminar effect of check-dam terraces massively constructed over Cretaceous marls (Calvo-Cases et al., 2020) and by the predominance of percolation in those areas covered by limestone, mostly in the intermediate parts of the catchment. During the last part of the event, when the highest rainfall intensities were in the downstream part, the excess of soil infiltration capacity and the collapse of headwater check-dam structures triggered the sudden increase in discharge from 120 to 442 m^3 s^{-1} in only15 minutes at the hydrometric station. Moreover, the increase of 5 km^2 (21% of the catchment area, see more details in section 2.1) of natural vegetation since the 1960s as a result of afforestation processes, increased fuel loads and the risk of wildfires led to 1.7 km^2 (7% of the catchment) being burnt since 1980. The removal of vegetation by fires has a similar effect (less interception, less soil storage), which has been experimentally documented after major fires. These factors are a major reason why the history of the steady devastation of plant cover in the Mediterranean is likely to enhance flood risk (Wainwright and Thornes, 2004) and increase desertification tendencies*".

Another important point is that authors should take care of the English language and grammar. At the end of the review, I provide some examples, limited to the Abstract and the Introduction, but a thorough review should be carried out throughout the paper.

The authors we are grateful with detailed suggestions on English language and grammar. Following this advice, we have requested an external review on English language by a professional native speaker (see attached the certificate).

Finally, please find below a list of other specific comments. I hope that my comments help to improve the quality of the paper.

We thank to the reviewer for her/his dedication on providing accurate specific comments, which have all been carefully addressed.

Abstract: it could be much more concise, avoiding unnecessary comments (e.g., “comprehensive analyses of catastrophic events are crucial…”). It is of the foremost importance that the abstract is as much straightforward as possible

We think that the abstract is explaining in a concise way the different issues. However, we have deleted these unnecessary comments.

L24: maybe remote sensing is better

It has been changed.

L31: Copernicus EMS: it’s better to avoid acronyms in the abstract without explanation

The acronym has been removed by “Emergency Management Service”. See Line 30 of the modified MS.

L45: also the interaction with the (warming) sea surface is an extremely important and peculiar feature of the Mediterranean area (e.g., Cassola et al., 2016; Avolio et al., 2019)

We have modified this sentence in order to add the “warm of sea surface” as a driven factor, as well one these references. See Lines 42-44 of the modified MS:

“*However, catastrophic flash floods are much more frequent in some parts of the Mediterranean region than in the rest of Europe due to the interaction between geomorphology, climate, vegetation and the warm sea surface (Cassola et al., 2016), all combining to create a flood-prone environment*”.

The new reference:

Cassola, F., Ferrari, F., Mazzino, A. and Miglietta, M. M.: The role of the sea on the flash floods events over Liguria (northwestern Italy), Geophys. Res. Lett., 43(7), 3534–3542, doi:10.1002/2016GL068265, 2016.

L79: ok, but the main uncertainty in predictability is linked not only to hydrological uncertainty but also (mostly, I would say) to the meteorological uncertainty. This aspect should be also introduced.

As the reviewer has also recognized in some comments focused on the Discussion section, it is not the main aim of our study. Despite this, we addressed meteorological uncertainty in the Discussion section. However, following the own recommendations of the reviewer, we have reduced the meteorological uncertainty in the Discussion section and added the issue within the Introduction section with the following sentence in Lines 67-69 of the modified version:

"*The main source of uncertainty is related to the spatio-temporal scales of rainfall pattern. The forecasting of intense thunderstorms by numerical weather prediction systems to provide accurate rainfall information is particularly challenging (Alfieri et al., 2015; Collier, 2007)*".

References used in this comment:

Alfieri, L., Berenguer, M., Knechtl, V., Liechti, K., Sempere-Torres, D. and Zappa, M.: Flash Flood Forecasting Based on Rainfall Thresholds, in Handbook of Hydrometeorological Ensemble Forecasting, edited by Duan Q., F. Pappenberger, A.

Collier, C. G.: Flash flood forecasting: What are the limits of predictability?, Q. J. R. Meteorol. Soc., 133(622), 3–23, doi:10.1002/qj.29, 2007.

L109: since the structure of the paper is complex, a brief introduction to the next Sections could be useful

We believe that the specific objectives deployed in the last part of section 1. Introduction are providing the conceptual structure of the paper that is performed by the typical structure of sections in a scientific paper such as Materials and methods, Results and Discussion. In addition, t the first paragraph of the section 2. Materials and Methods is really useful to provide a comprehension of the paper structure. It is true that the explanation provided in this first paragraph is in terms of methods, but they are completely related with the structure of the paper. However, to provide more consistence to the structure, we have completed this first paragraph of the section 2. Materials and methods, as follows (Lines 125-127 of the new MS version):

"*Finally, high-resolution digital elevation models (HR-DEM) were generated by LiDAR 2014 data from the Spanish National Geographic Institute and by imagery captured through a low-cost UAV just six days after the catastrophe to calculate a sediment connectivity index (IC) and measure geomorphic changes (Fig. 1)*".

In addition, we have designed and performed a new figure with a workflow of the different steps and their relation to the objectives of the manuscript. This is the new Figure 1, captioned as "Methodological workflow of the research study".

L136: please explain what you exactly mean with "torrentiality". This index could be ignored by most of the audience

We have added some words for provide a clear explanation to most of the audience, in Lines 148-149 of the revised MS, as follows:

"*…which is topographically computed as a coefficient between the number of first-order streams and catchment area, multiplied by the drainage density; cf. Strahler, 1964)…*".

L193: a reference is needed to justify the sentence

We added two references to justify the sentence, Lines 208-212 of the revised MS:

"*Two pair of coefficients were tested: (i) the pair a=200 and b=1.6 was tested because AEMET commonly uses these coefficients to obtain near-real time rainfall estimations (http://www.aemet.es/es/eltiempo/observacion/radar/ayuda; last access: 15 May 2020) from the same radar data that we used in this research; (ii) the pair a=300 and b=1.4 was tested because the NWS in the USA uses it at operational level (Fulton et al., 1998) and it is argued that these coefficients perform better in a convective environment than the first ones (e.g. Seo et al., 2020)*".

References used in this comment

Fulton, R.A., Breidenbach, J.P., Seo, D.-J., Miller, D.A., O'Bannon, T.: The WSR-88D rainfall algorithm. Weather Forecast, 13, 377–395, 1998.

Seo, B-C, Krajewski, W.F., Qi, Y.: Utility of Vertically Integrated Liquid Water Content for Radar-Rainfall Estimation: Quality Control and Precipitation Type Classification. Atmospheric Research, 236, 104800, doi:10.1016/j.atmosres.2019.104800, 2020.

L200: Please add in a figure (Fig. 2?) the radar location

The location of the radar has been added in Figure 2b, formerly Figure 1b.

L201: "due to these effects". What effects? Not clear. Please explain and justify with adequate reference(s)

We agree with the reviewer that the sentence was not enough clear. We have restructured the sentence as follows (see Lines 218-223 of the reviewed MS):

"*Mountains may partially or totally block the electromagnetic radar signal and affect radar reflectivity and precipitation estimations(Germann and Joss, 2004). The study area is mountainous, but with low maximum altitudes (~400 m.a.s.l.). This low elevation combined with the regional orography, the distance of the Begura de Salma River from the radar (~50 km), the 0.5º azimuth of the PPI used, and the altitude of the radar location (113 m.a.s.l.) avoided any topographic interference with the radar signal. Thus, no orographic blocking reflectivity correction technique was needed*".

References used in this comment

Germann, U. and Joss, J. (2004) Operational measurements of precipitation in mountainous terrain. In: Weather Radar: Principles and Advanced Applications. Meischner, Peter. (Ed). Springer, Berlin, pp 52-77

LL206-213: this paragraph is not clear. What were the driving data for this analysis? Those provided by the rain gauges surrounding the catchments? If so, the authors should provide some proofs about the reliability of their analysis (e.g., a scatterplot, even in the Supplement). Furthermore, if rainfall data are gridded in 2x2 square cells, why in fig. 6 it looks like they are spatially interpolated? Maybe, because they are related to the GSM-SOCONT scheme (for which the authors refer to inverse distance weighting)?

We have rewrote the paragraph in order to clarify this issue. We have also generated a scatterplot in which the two estimations are compared against the observed rainfall (the new Figure S1).

The new paragraph in Lines 227-234 of the revised MS:

"*With the set of coefficients a=300 and b=1.4, the maximum amount of estimated rainfall using radar data clearly underestimated the observed rainfall, with a PBIAS of –50.6% and an estimation of ca. 149 mm as the maximum rainfall amount, compared with the 257 mm recorded at the Sant Llorenç des Cardassar rain gauging station (see Fig. 2c). Instead of using the recorded rainfall in gauging stations to calibrate the radar-based rainfall, a correction method of the rainfall estimation based on spatial resampling was posited here. Accordingly, the 2*2 km spatial resolution of radar data was resampled by assigning to each grid cell the value of the maximum amount of estimated rainfall at 1*1 km. By this method, the regression coefficient reached* R^2 *= 0.8, a PBIAS of only +2.6% and 258 mm as the maximum estimated rainfall amount, which fitted the rainfall observed at that point (Fig. S1)*".

The estimated rainfall from gridded radar data was directly used in the SOCONT scheme without inverse distance weighting. Only the temperature is interpolated. This has been clarified as follows (see lines 365-367 of the revised MS):

"*Resampled 1 km resolution radar data (see subsection 2.3) were used in the model to obtain precipitation for each elevation band by including all 1 km resolution points falling within each elevation band*".

L218: When introduced, the acronym MEDhyCON (such as any other) should be explained

We have introduced the whole meaning of the acronym MEDhyCON within the Introduction section: MEDiterranean hydrological CONnectivity Research Group.

L251: "a second hydrograph was designed": with what Q values?

A second hydrograph was designed, ranging also between 2 to 512 m^3s^{-1}, with additional flow steps. The first hydrograph consisted of nine different flow values, whereas the second one consisted of nineteen different values or steps, including intermediate values, and some other significant discharge values, such as the maximum channel capacity, and the value at which the presence of the bridges start influencing the hydraulics of the system. All values are represented as points in Figure

5 SDRC (formerly Figure 4). Besides, we have modified the sentence explaining the second hydrograph design. In the former version of the MS (Lines 250-253) was:

"*Under these conditions and with this designed hydrograph, a first approach to the SDRC was obtained. In order to improve the accuracy of the SDRC, a second hydrograph was designed, also containing the Q values of the first hydrograph*".

The new version of the sentence (see Lines 270-273 of the revised MS) is:

"*These conditions and this designed hydrograph gave a first approach to the SDRC. To improve the accuracy of the SDRC, a second hydrograph was designed with nineteen Q values, also containing the previous nine Q values of the first hydrograph, new intermediate values and some other significant Q values such as the maximum channel capacity and the Q value at which bridges influence the hydraulics*".

L262: I would like some more details about the percentages of obstruction detected and how they were calibrated. Do they rely (only) on the three ground control points? Why those points? When/how were the water levels measured on them? Does the simulation consider 0% obstruction up to below the bankfull and 85% immediately after? No transient state?

The percentages of obstruction detected were estimated from post-event photographs and calibrated using maximum water stages observed in situ 10 hours after the event within a period of time in which the high-water marks were still preserved. These marks –fully representatives of the overbank flows– were mapped by using a dGPS Leica 1200 through these three ground control points with high precision. Therefore, intermediate data is not available to compare results in the simulation of the transient state, and maximum water stage must to be compared with maximum obstruction results. Furthermore, the obstruction mechanism was very fast causing that we hydraulically simulated that bridges' obstruction does not occur when water depths are even close to the low chord of the bridge's deck. However, when the firsts floating elements start clogging the bridge opening, the obstruction rapidly increases. In addition, this obstruction was maintained throughout the flash-flood event duration, as it could be checked observing post-event pictures.

Nevertheless, for providing more clarity about the influence on hydraulics of bridges' obstruction, see the answer to the previous comment and its related modification within the MS. In addition, we have added the following sentence (see Lines 283-284 of the revised version of the MS) previous to the sentence "*85% at Bridge 1, 40% at Bridge 2 and with no obstruction for the other ones*":

"*These post-event pictures and maximum water stages observed in situ 10 h after the event was useful to estimate the obstruction percentages of these two bridges*".

In addition, this sentence "*Accordingly, ground control points in three representative locations around the hydrometric station were selected (Fig. 3b), also considering the maximum WS reached in the hydrometric station (4.55 m)*" (Lines 337-341 of the former version of the MS) was also modified to better explain the support of the three selected ground control points (see Lines 290-293 of the new version of the MS):

"*Maximum WS observed in situ 10 hours after the event, within a period of time in which the high-water marks were still preserved, were mapped through ground control points. Three of them were selected as representative locations around the hydrometric station (Fig. 4b), and the maximum WS reached at the hydrometric station (4.55 m) was also included*".

L321: in my opinion, the best tool for this kind of assessment would have been a complete 2D hydraulic study. Please discuss briefly your choice and its advantages (e.g., it's time-saving, etc.)

We agree with this observation, but flow direction here used were useful to firstly assess the role of hydraulics in damages. Furthermore, a detailed and complete 2D hydraulic modelling in which urban flooding dynamics are being investigated. All the buildings and urban elements of Sant Llorenç des Cardassar village will be introduced in the 2D model by using a high-resolution digital elevation model established from LiDAR technology two months after the catastrophe. As we pointed previously out, this complete 2D hydraulic study is out of scope of this first study; although the results of flow direction here developed will be compared to the 2D hydraulic study.

The sentence of Line 321 of the former MS has been modified to reinforce this argument (currently in Lines 344-346 of the revised version of the MS):

"*Second, the flow direction in the urban network was calculated with Arc Hydro Tools (ESRI, 2019). This gave a preliminary assessment of the role of hydraulic processes in physical damage. Due to the flow direction, this is mainly related to the velocity vector component perpendicular to the building element surface (Amirebrahimi et al., 2016)*".

Reference used in this comment:

Amirebrahimi, S., Rajabifard, A., Mendis, P. and Ngo, T.: A framework for a microscale flood damage assessment and visualization for a building using BIM–GIS integration, Int. J. Digit. Earth, 9(4), 363–386, doi:10.1080/17538947.2015.1034201, 2016.

Table 1 needs more explanation. Terms like IPmax should be explained

This comment is rising that NHESS audience is beyond the catchment hydrology expertise. Accordingly, we have added a detailed description of each parameter at the beginning of subsection 3.2 Hydrological response of the flash flood, as follows (Lines 428-439 of the revised version of the MS):

"*The hydrological response of the flash flood was analysed through variables derived from the rainfall (Table 1a, 7 variables) and runoff (Table 1b, 9 variables) of the catchment: Event rainfall duration: duration from the beginning of rainfall until* *stopped it; Time of maximum rainfall: time of the highest rainfall intensity; Centroid storm: central time of the rainfall event; Average radar rainfall: mean rainfall obtained by radar;* IP_{max} *average radar: average of the highest rainfall intensities obtained from radar rainfall points;* IP_{max} *radar: highest rainfall intensity obtained from radar data; IP average radar: average of rainfall intensities obtained from radar rainfall points; Runoff: discharge volume amount divided by the catchment area; Runoff ratio: ratio between runoff and rainfall, also known as runoff coefficient when is expressed in percentage; Event duration: duration of the flood event;* Q_{max}*: peak discharge; Time* Q_{max}*: time of the peak discharge; T centroid storm – T* Q_{max}*: duration between the time of the rainfall centroid and the time of the discharge peak;* $Q_{average}$*: discharge average during the flood event; Unit peak discharge: peak discharge divided by catchment area, allowing the comparison of peak discharge independently from catchment size; Reduced Unit peak discharge: discharge peak divided by catchment area in square kilometres elevated by 0.6. The exponent was obtained from Gaume et al. (2009), who applied this parameter to compare reduced unit peak discharge from different flash-flood events*”.

Figure 7 is not very clear. Maybe it could be divided into more figures. However: in Fig. 7a, are the red dashed polygons all derived from the Copernicus EMS? Also zone 2 and 3? Do the latter perfectly correspond to the Government survey? Figs. 7b and 7c are not very readable/useful, in my opinion.

The Figure 7 is the Figure 8 in the revised MS. Once clarified this structure detail, we must recognize that the legend in Fig. 7a was not comprehensible due to “Affected zones” did not help to observe what are the source for determining the affected zones; i.e., Copernicus EMS or Government survey. As a result, we have modified the sub-figures “a”, “b”, and “c”. With this modification, we believe that sub-figures “b” and “c” are totally useful due to are areas not detected by Copernicus EMS and we explain throughout the main text their damage level supported by these sub-figures.

LL510-511: I guess it is Fig. 8c.

Exactly, many thanks for the accurate detection of this error. It has been changed, in the reviewed version of the MS is Fig. 9c.

LL535-536: “Despite these antecedent…as reported by these authors.” Why?

We have modified this sentence and the following one in order to improve the explanation. The former version (Lines 535-538) was:

“*Despite these antecedent wetness conditions, the runoff coefficient of the event (i.e., 36%) was analogous to the median runoff coefficient under average wetness conditions (37%) than dry ones (20%), as reported by these authors. This response* *illustrated the key role of rainfall intensity in the generation of a high Q_{peak} (i.e., 442 m^3 s^{-1}) with a high potential to generate geomorphological changes*".

The new version (Lines 581-585 of the revised MS) is:

"*Despite these dry prior conditions, the runoff coefficient of the event (i.e., 35%) was analogous to the median runoff coefficient under average wetness conditions (37%) reported by Marchi et al. (2010), rather than dry ones (20%). This runoff response resulted from the combination of rainfall intensity and its spatial distribution, complex geology and land cover disturbances in generating a high Q_{peak} (i.e., 442 m^3 s^{-1}) with high potential for generating geomorphological changes*".

LL547-548: it's not clear why the authors need to adjust the initial conditions manually. Does the model not perform well if used for long periods?

We thank the reviewer for his/her critical reading. Actually, the model is not able to reproduce the event when it is running for a longer period. Therefore, the model was run starting in 2015 until the flash-flood event with meteorological data. When using the initial conditions from the long-term run and the radar data, the model is not able to reproduce the event. The extraordinariness of the flash-flood event and the few flood events recorded since 2015 by the hydrometric station did not allow to calibrate the model for the event. In other words, by using specifically calibrated initial conditions, the model is more an event-based model rather than a classical hydrological model. This issue is thoroughly mentioned in the Discussion section, and we have added a sentence reinforcing it (Lines 614-616 of the revised MS):

"*In this context, the initial condition $H(t_0)$ was manually adjusted, as numerical models applied to simulate catchment runoff response are often unsuccessfully implemented for Mediterranean-climate catchments due to their very heterogeneous responses over time and space (Merheb et al., 2016)*".

References used in this comment

Merheb, M., Moussa, R., Abdallah, C., Colin, F., Perrin, C. and Baghdadi, N.: Hydrological response characteristics of Mediterranean catchments at different time scales: a meta-analysis, Hydrol. Sci. J., 61(14), 2520–2539, doi:10.1080/02626667.2016.1140174, 2016.

LL556-585: the discussion introduces many arguments in a general and qualitative way. I suggest to skip/reduce much of the discussion (especially that about the weather predictability, which is not addressed in this study) and/or try to quantify the different effects (please refer to my main concern).

We are very grateful for this key comment, because it is a great opportunity for going beyond the simple description and join the different issues addressed within this manuscript. Accordingly, we have further and deeply assessed the physical parameters conditioning the hydrological response of the Begura de Salma River catchment; i.e., historical and current land uses / land cover, soil conservation structures, the affection of wildfires and perviousness of lithology throughout the catchment.

English language and grammar review:

L25: at the catchment scale

“the” has been added in the reviewed MS.

L26: peak discharge of 442…

“of” has been added in the reviewed MS.

L28: “i.e.” not needed

We have deleted “i.e.” before the catchment surface area.

L38: For that reason, they usually affect/impact basins…

The beginning of this sentence has been modified following your advice. In the reviewed version of the MS: “For that reason, they usually impact basins…”

L46: very close to the coastline

We have changed “closeness” by “close”.

L48: “scarce soils”. What do the authors exactly mean?

We have deleted the sentence “Another cause is the reduced vegetation cover and scarce soils” to avoiding confusion also considering that this part of the Discussion has been completely rewritten. Besides, the following sentence of the same paragraph was explaining this process in a better way (Lines 604-607 of the revised MS): “*The removal of vegetation by fires has a similar effect (less interception, less soil storage), which has been experimentally documented after major fires. These factors are a major reason why the history of the steady devastation of plant cover in the Mediterranean is likely to enhance flood risk (Wainwright and Thornes, 2004) and increase desertification tendencies*”.

L51: elucidates

The “s” has been added to “elucidate”.

L51: “the hydrological processes from an extreme flood”? Do you mean the hydrological processes activating during an extreme flood or so?

This was the former version of the sentence:

“*Characterising the response of a catchment during flash flood events is important because elucidate the hydrological processes from an extreme flood and their dependency on catchment properties and flood severity (Borga et al., 2007)*.”

And this is the new version of the sentence (Lines 48-50 of the reviewed MS):

“*Characterising the response of a catchment during an extreme flash-flood is important because elucidates the hydrological activating processes and their dependency on catchment properties and flood severity (Borga et al., 2007*”.

L54: small spatial scale usually means low-resolution (e.g., scale 1:50000 is a smaller scale than 1:500). Please rephrase to make the sentence clearer

In order to avoid confusion, we have changed “small” by “limited”: see Line 54 of the revised MS.

LL67-68: in order to reduce the uncertainty of the Q estimate, I suppose

We have added “the uncertainty of”.

L69: “…also adding that…” please rephrase

We have deleted “…also adding that predictability is lowered…”, being changed by “…conditioned by…”. The new version of the sentence is as follows (Lines 73-74 of the revised version of MS):

“*Flash-flood events are also conditioned by high non-linearity in the hydrological response relating to threshold effects (Braud et al., 2014). Therefore, the predictability of such events remains low*”.

L87: regarding vulnerability

We have deleted the beginning of the sentence “Particularly regarding to vulnerability”, because it was also redundant.

L88: “understanding…are developed”. Understanding is not developed. Please rephrase

We have changed “understanding” by “assessment of”.

L92: evaluates

It has been changed.

L97: “with that Copernicus EMS one”. Not clear

We have changed the sentence, being now “*In addition, a comparison of ‘ground-based’ assessment and ‘remote-based’ Copernicus EMS may shed light on the accuracy of this rapid and helpful tool for assessing most catastrophic flash floods*”. Lines 103-105 revised MS.

L112: why “precipitation as well as the Q”? I would write either “Precipitation and discharge” or “P and Q”

We have changed by “Precipitation and discharge”.

Captions: please check also all figure captions (e.g., “left” and “right” pictures in Fig. 3, in Figure 7 there are two references to (f))

In the former Figure 3 (Figure 4 in the revised MS), “left” and “right” was wrongly indicating the dates of the pictures. We have changed by “d” and “e” letters for more internal coherence of the figure and avoiding confusion.

In the former Figure 7 (Figure 8 in the revised MS), we have deleted “(f) Damage level of the buildings and plots by zones”.

Supplement: please check grammar also here (e.g., L’independent; “Schema”). The caption of Figure S2 should declare the meaning of the variables.

The grammar has been reviewed: “L’independant” and “Scheme”.

We have also added the meaning of the variables in the caption of the Figure S2.

RC2 - Anonymous Referee #2 Received and published: 3 February 2020

SUMMARY:

This manuscript analyses a flash flood event in a small catchment in the North-Eastern part of the Spanish Island of Mallorca, that left 13 people dead and caused severe damages to local properties. The analysis looks into four main aspects of the event, namely the meteorological conditions, the hydrological and hydraulic response, the damage assessment and a geomorphological analysis with the aim to improve the understanding of the drivers of this respective event. The authors conducted field measurements on the geomorphology few days after the event and present those findings alongside measurements of the rainfall, discharge and a damage assessment of a severely hit village in the catchment based on ground-based records and remote sensing information. The authors use hydraulic and hydrologic models to model the runoff processes in the catchment. The presented data and results are discussed by topic and summarized in the conclusion.

We are very grateful by the accurate summary provided by the reviewer.

GENERAL COMMENTS:

The paper is very interesting to read and provides important information on frequently underreported local flash flood events. The four aspects of the event are presented in great detail with very detailed information on the technical background of the data collection and modelling.

The authors kindly appreciate the comments from Reviewer#2, which have helped to improve the MS.

However, overall the paper appears very fragmented with little connection between the different analysis. From reading the paper I was not able to fully understand how the presented data sets and models relate to each other and what are the main conclusions from the analysis. While the authors claim that their study uses an "[...] integrated approach with meteorological, hydrological, geomorphological, damage and risk data analysis" (L616f), the different analysis are presented largely isolated and independent including the discussion. Here, it would help if the authors would A) provide an overview figure that shows how the data sets and models are linked and B) A joint discussion that highlights how the individual results are linked and how this contributes to a better understanding of what made the event so devastating.

We agree with the Anonymous Referee #2 comments, which are –at the same time– fitted with some of the concerns highlighted by the Anonymous Referee #1. We are also very pleased to the referee for providing constructive ideas that –we believe– have improved the new version of the MS.

Accordingly, also applying a suggestion provided by the Anonymous Referee #1, we have created an overview figure showing the links between data and models. It is the new Figure 1.

The Discussion section has also been completely restructured without subsections to facilitate the combination of the individual results contributing to an integrated comprehension of the devastation. Firstly, the two subsections have been unified forming a unique storyline where hydrological response, rainfall-runoff modelling, damage assessment and geomorphic change are integrated. We believe this new version of the MS is bridging the gap between them, because we have introduced several paragraphs especially focused on the predictability of this kind of flash-flood events in order to better join these different issues. In addition, the new Figure 1 is also useful to better understand the integrated approach.

Secondly, we have addressed a qualitative –but also quantitative– discussion about the role played by rainfall intensity and its spatial distribution, complex geology and land cover disturbances, following the suggestion provided by the Anonymous Referee 1#. For this purpose, we have also modified the subsection 2.1. Study area, where a deeper assessment of permeability in lithology materials as well as a diachronic evaluation of land uses evolution and perturbations (i.e., wildfires) is sustaining the discussion on the role of physical parameters generating the flash flood (see Lines 155-165 of the revised MS):

"*The lithology is mainly composed of marls intercalated with limestone (60% of the area) of the Medium-Upper Jurassic (Dogger), dolomites (22% of the area) of the Upper Triassic and Lower Jurassic, and pelagic limestone marls (14% of the area) of the Lower Cretaceous (Fig. 2d). This lithological composition determines the surface water/groundwater interaction. On the one hand, a high degree of fracturing, fissuring and karstification of limestone favours percolation through karstic aquifers. On the other hand, the imperviousness of Dogger and Cretaceous marls (74% of the area) does not allow percolation, enabling runoff generation. The main land use in 2012 was agriculture (58%), mostly located in lowland areas. Forest (26%) and scrubland (17%) were predominant at headwaters. Terraced fields still occupied 10% of the catchment, although most of them were abandoned (Fig. 2e). In 1956, natural vegetation covered 21% of the catchment. This rose to 42% in 2012 due to an afforestation process of former agricultural land in the second half of the twentieth century. In combination with other factors, afforestation triggered a higher fire risk: two wildfires burnt an area of 1.7 km^2: 17% in 1983 and 83% in 2011 (Balearic Forestry and Soil Conservation Service, http://xarxaforestal.caib.es; Fig. 2e)*".

We have also placed special emphasis on the sudden increase in discharge from 120 to 442 m^3 s^{-1}, which has resulted from the combination of all these physical parameters. Please, see the Lines 583-607 of the revised MS:

"*This runoff response resulted from the combination of rainfall intensity and its spatial distribution, complex geology and land cover disturbances in generating a high Q_{peak} (i.e., 442 m^3 s^{-1}) with high potential for generating geomorphological changes. Thus, the Q_{peak} unit obtained (i.e., 19 m^3 s^{-1} km^2) can be classified as the third highest value of all the reported values in Marchi et al. (2010) and the highest of those values obtained from streamflow measurements in a hydrometric station and not by post-event analysis. The hydrologic response analysis in the course of a flash flood shows how storm structure and evolution result in a scale-dependent flood response (Borga et al., 2007). Consequently, spatial rainfall organisation, geology combined with orography and land cover disturbances led to pronounced contrasts in the flood response at the Begura de Salma River. Spatial rainfall on the catchment scale showed that the highest accumulation at the beginning of the storm was located at the headwaters of the catchment (at 15:00 h), whilst during the last part of the event the most important rainfall amounts were* *located in the downstream part. Examination of the flood response illustrated how the extent and the position of the karst terrain (Zanon et al., 2010) and soil conservation practices (Calsamiglia et al., 2018; Tarolli et al., 2014) provided major geological and anthropogenic control of runoff response. Impervious materials cover 74% of the Begura de Salma River catchment, mostly located at the headwaters, which are responsible for the highest values of topographic torrentiality (Estrany and Grimalt, 2014b), facilitating rapid overland flow generation. During the first part of the storm, when the highest rainfall amounts affected the headwaters, runoff response was delayed by the laminar effect of check-dam terraces massively constructed over Cretaceous marls (Calvo-Cases et al., 2020) and by the predominance of percolation in those areas covered by limestone, mostly in the intermediate parts of the catchment. During the last part of the event, when the highest rainfall intensities were in the downstream part, the excess of soil infiltration capacity and the collapse of headwater check-dam structures triggered the sudden increase in discharge from 120 to 442 m^3 s^{-1} in only15 minutes at the hydrometric station. Moreover, the increase of 5 km^2 (21% of the catchment area, see more details in section 2.1) of natural vegetation since the 1960s as a result of afforestation processes, increased fuel loads and the risk of wildfires led to 1.7 km^2 (7% of the catchment) being burnt since 1980. The removal of vegetation by fires has a similar effect (less interception, less soil storage), which has been experimentally documented after major fires. These factors are a major reason why the history of the steady devastation of plant cover in the Mediterranean is likely to enhance flood risk (Wainwright and Thornes, 2004) and increase desertification tendencies*".

It also appears that there is quite a disconnect between the results, discussion and conclusion sections, where topics such as driving factors of the damage in urban areas are for the first time explicitly mentioned in the conclusions, while the previous chapters mainly focus on the methodological aspects of the damage assessments. Similarly, language and grammar vary considerably throughout the paper and rigorous copy editing is necessary prior to accepting the manuscript for publication. Given the otherwise interesting and very relevant contribution the paper makes in the field of flash flood post event studies, I recommend considering the manuscript for publication after major revisions.

We have tried to connct the different sections considering the driving factors of the damage. Likewise, we have unified the language and grammar also developing a deep review by a professional (see attached a certificate).

Specific comments

Structure

Introduction

The introduction is very technical and has a very narrow focus on flash flood processes. It also appears to address a lot of specific subjects in no particular order rather then leading to the research questions the authors are aiming to

answer. Restructuring the introduction so it clearly leads to the research questions and highlights the importance of the work would therefore really improve the quality of the paper. As this is not the first study of its kind, I would also recommend including a literature review on previous post event studies (both flash flood related and potentially other natural hazards) and their findings. This would give the reader the opportunity to better evaluate the contribution of the paper to the scientific discourse and what knowledge gaps it addresses.

We have modified the Introduction section amplifying the activating hydrological processes during a flash flood, including extra scientific literature on previous post event studies with a special emphasis on those analysing the role played by physical parameters in runoff generation in these catastrophic events (see Lines 48-61 of the revised MS):

"*Characterising the response of a catchment during an extreme flash-flood event is important because it clarifies flood severity and the activating hydrological processes and their dependency on natural and anthropogenic catchment properties (Borga et al., 2007). Numerous studies have tried to determine these driving factors (Braud et al., 2014), in which geological heterogeneities associated with the presence of karst features are crucial in Mediterranean catchments (Vannier et al., 2016; Wainwright and Thornes, 2004). Likewise, flash floods are closely related to land use: the devastation of plant cover in the Mediterranean may increase the risk of flooding because bare soil leads to larger runoff coefficients (Wainwright and Thornes, 2004). However, the limited spatial and temporal scales of flash floods make these events particularly difficult to monitor and document. In the case of rainfall monitoring, the spatial scales of the events are in general much smaller than the sampling potential offered by apparently dense rain networks (Borga et al., 2008; Amponsah et al., 2016). In the case of streamflow monitoring, there is a lack of flash-flood discharge (Q) data from stream gauge observations (Marchi et al., 2010), although Q data are crucial to obtaining representative hydrometric values and characterizing the runoff response of such extreme flash-flood events (Borga et al., 2008). As a result, further field observations and modelling studies are required in order to assess the interdependencies of flash-flood drivers and, thus, better understand and reproduce the active hydrological processes (Sofia and Nikolopoulos, 2020)*".

Description of the study area

For the sake of readability, I would recommend separating the meteorological conditions that lead to the event from the actual description of the study area.

We have created a new subsection, specifically entitled "2.2 Meteorological context of the 9th October 2018 rain event", being in the revised version of the MS completely separated from the Study area description, as follows:

"*2.2 Meteorological context of the 9th October 2018 rain event*
The 9th October storm affected the two northernmost catchments of the Llevant County; i.e., the Ca n'Amer and Canyamel Rivers (Fig. 2) with 9 and 4 casualties, respectively, and significant damage. The synoptic situation was like the situations generating flash-flood events in the Western Mediterranean (Fig. 3a). A cut-off low at mid-level was located in the eastern

part of the Iberian Peninsula and shallow low-level pressure was affecting the same region, driving warm and wet air from the Mediterranean Sea to the Balearic Islands and the eastern part of the Iberian Peninsula. This occurred in early October, when the sea surface temperature is close to its annual maximum in the Western Mediterranean, providing high quantities of moisture. Moreover, the cut-off low showed a typical divergence at mid-level on its eastern flank, affecting the Balearic Islands and favouring the development of deep convection. Convection started on the sea between the Balearic Islands and the Iberian Peninsula (Figures 3b and 3c) and, due to SW winds at mid-tropospheric levels, the convective cells started to move towards the Balearic Islands, where they triggered the flash-flood event after a heavy rainfall episode (Figures 3d and 3e)”.

Conclusion

The conclusion appears to be quite detached from the rest of the manuscript addressing several points that have not been previously mentioned in the manuscript but are important to fully understand the analysis. For example, how the meteorological, hydrological, geomorphological, damage and risk data analysis are linked. Or what the actual damage driving factor in urban areas are based on the different findings.

We believe that the modifications on the other sections are now helping to better understand those points that in the first version of the MS have not been previously mentioned. In the case of damage driving factors in the Sant Llorenç des Cardassar village, we have added some paragraphs in the Discussion sections, as follows (see Lines 639-646 of the revised MS):

“*At present, Mallorca does not have any sort of early warning system to assist flood risk management, and nor of course has Sant Llorenç des Cardassar. Similarly, no hydrometeorological early warning was issued by the competent authorities, as the Balearic Islands have no operational hydrological control network releasing real-time information on discharges. In October 2018, Sant Llorenç des Cardassar was one of the four municipalities in Mallorca with a flood risk emergency plan. However, it was not operational at the time the emergency was declared. As a result, the population was completely unaware of how to defend themselves, even during the emergency phase, although Sant Llorenç des Cardassar municipality had significant social vulnerability to floods, as most of the casualties were tourists and the elderly*”.

Rainfall

This paper focusses on the hydrological response as a main driver of the flash floods and the authors argue in the introduction that “the uncertainty in hydrological modelling can be large and hydrological models often need to be calibrated […]. Therefore, the predictability of such events remain low also adding that predictability is lowered by a high non-linearity in the hydrological response related to threshold effects”. This implies that the uncertainty in the hydrological models are a key barrier in the predictability of flash floods. However, most other studies on flash floods and flash flood early warning systems find the spatio-temporal uncertainties in the rainfall prediction to be the largest

obstacle in accurately forecasting and modelling flash floods (see for example Alfieri et al. 2017). This issue is also addressed in the description of the rainfall data, but the authors do not report to what extend the results of the subsequent hydrological and hydraulic models are sensitive to the uncertainties of the rainfall input. Therefore, I would recommend adding a short sensitivity analysis in regard to the rainfall input to the discussion section. It would also be interesting to see to what extend the results vary between the radar and gauge data.

We thank the reviewer on this very pertinent and interesting comment. We fully agree that the spatio-temporal uncertainty in the rainfall data is the main source of uncertainty in flash floods, an issue also commented by the Anonymous Referee #1. We recognize that the text in our manuscript was misleading and we have accordingly modified the Introduction section (see Lines 67-69 of the revised MS):

"*The main source of uncertainty is related to the spatio-temporal scales of rainfall pattern. The forecasting of intense thunderstorms by numerical weather prediction systems to provide accurate rainfall information is particularly challenging (Alfieri et al., 2015; Collier, 2007)*".

Otherwise, the scientific issue aroused from this comment is very challenging. We believe that analysing the uncertainty sources of the hydrological model in this particular paper is out of scope, would mislead the reader also considering this topic would deserve a paper on its own. However, we have specifically minimized this uncertainty source by using a spatially interpolated rainfall from gauging stations in order to understand –from a modelling point of view– the processes leading to this event. It is clear that the estimated radar rainfall data used in our piece of work have provided a better spatial interpolation of the rainfall event than using only the radar data (see Fig. S1 and the Lines 232-234 in the subsection *2.3. Rainfall data* of the revised MS). Moreover, the radar data was adjusted with data from San Llorenç des Cardassar station as described in this same supplementary figure (Fig. SF1) so that indirectly the rainfall data is already used in the model. Definitely, it would be interesting to further analyse the results of the uncalibrated radar data in these kind of extreme rain storms but it should be a future scientific work.

Risk management and early warning

Given the high casualties and damage during this event it would be important to also cover the vulnerability of assets and people in the case study area for a comprehensive analysis of the damaging factors. This aspect however is only very briefly mentioned in the discussion and conclusion. Key questions would include: did people in the village receive some sort of early warning? Are their any risk management strategies in place apart from the mentioned flood zones? Discussing these aspects would also help to conclude with more specific recommendations for the improvement of risk management practises.

Nowadays, Mallorca Island does not have implemented any sort of early warning system to flood risk management, nor has the Sant Llorenç des Cardassar village. However, the Spanish Meteorological Agency (AEMET) applying the National Plan for the Observation of Adverse Meteorological Phenomena ("Meteoalerta";

http://www.aemet.es/en/lineas_de_interes/meteoalerta), forecasted storms and intense rains. On 9th October 2018 at 01:58 a.m., AEMET issued a yellow warning for rainfall amounts up to 20 mm in one hour in Balearic Islands, extending the duration of this warning until 12:00 p.m. on 10th October. At 6:53 p.m. on 9th October, the warning was raised to the orange level, 50 mm in one hour, in the east of Mallorca and in the north and northeast of Mallorca, and finally, at 10:07 p.m., reaching the red level, 220 mm in one hour, in the easternmost part of the north of Mallorca, being extended until 02:00 a.m. on 10th October. These different warnings clearly demonstrated that the storm was not well meteorological forecasted, due to both orange and red warnings were delivered when the disaster had already occurred.

Likewise, no hydrometeorological early warning was issued by the competent authorities, also considering that the Balearic Islands do not have both an operational hydrological control network and real-time information on rainfall intensity through automatic weather stations in the headwaters of Begura de Salma River catchment.

The municipality of Sant Llorenç des Cardassar was one of the four municipalities in Mallorca with municipal flood risk emergency plan, implemented previously to the catastrophe. However, it was not operational at the time the emergency was declared. The population was completely unaware of how to defend preventively themselves, even during the emergency phase.

Regarding the social vulnerability, the Sant Llorenç des Cardassar municipality has 8,406 inhabitants, being 23% foreigners (IBESTAT, 2018). In addition, a very high tourist capacity including dispersed rural vacation homes; as well ageing population is > 16%. All these variables increase the social vulnerability, a fact that has been proven due to the most of the casualties were tourists and ageing population during the catastrophe. As a result, any measure to improve social vulnerability should be focused on increasing the knowledge of natural risks by foreign resident population and tourists.

Almost two years after the catastrophe, its consequences have been applied as learnt lessons in preventing the risk. The City Council applying several actions (https://www.santllorenc.es/ca/noticies-ajuntament/lajuntament-de-sant-llorenc-presenta-una-modificacio-puntual-del-seu-planejament-urbanistic-despres-de-la-torrentada-en-vista-a-millorar-la-seguretat-) such as significant modifications within the Urban Planning for reducing the exposed areas to flood risk in urbanized areas, multidisciplinary studies to improve knowledge of the population exposure level, and regulations to reduce the exposure of assets in the case of new flash floods. In addition, works on hydraulic infrastructures focused to restore the previous condition or even lowering the channel roughness, involving a risk increase. Despite population has more information on how to deal with possible new events, the implementation of a hydrometeorological alert system would be more effective, facilitating the monitoring of potential flash floods.

We have refocused the Discussion section with several paragraphs in the Discussion section, as we have previously pointed out.

Damage classes

In Figure 7(e), the distribution of the damage classes for the three different zones and the total of all zones are shown. It seems that the total does not correspond to the sum of the three zones as the by far largest group in total are houses being "Damaged & Non habitable" with 260 houses, while the sum in this group for all three zones is 37 homes. That might be either an error or it should clearly be stated what is meant by "Total".

We must apologize by this mindless error caused by a mixing of cells in the Excel spreadsheet, although the explanation within the main text was correct. Certainly, "Damaged & Non habitable" summed 37 for all three zones, not 260 houses. This 260 houses are "Damaged and habitable". We have pertinently modified in the new Figure 8e.

Sediment connectivity and geomorphic change

While using the sediment connectivity to support search and rescue missions after flash flood events is a very innovative approach, it is not entirely clear what one can learn from the sediment volume calculation. Discussing this number in the context of the other analysis and its implications for a better understanding of the flash flood processes would help to further improve the manuscript. It would also be interesting to learn what is the accuracy of the mentioned approach given the different spatial resolutions and accuracies between the 2014 and 2018 surface models. Can changes in volume attributed to this specific event or does this number also include other changes to the geomorphology (both human and natural) that happened between 2014 and 2018? I would also recommend to clearly separate the sediment connectivity analysis that was used to support the search and rescue efforts and the geomorphic change detection to make clear that the two analysis had different aims.

We must thank again to the referee for these relevant and appropriate questions, allowing an improvement of one of the key issues of our piece of work.

In order to provide the necessary clearness to the readers about what are the real aims from both methods, we have split the methods subsection *2.6 Sediment connectivity and geomorphic change detection*, being currently *2.6 Sediment connectivity* and *2.7 Geomorphic change detection*. In addition, both methods in the new Figure 1 are also clearly separated, although also emphasizing their own relationship.

We have modified the following sentence (see Lines 328-329 of the previous MS version):

"*Firstly, and taking into consideration the emergency situation, the index of (water and sediment) connectivity at the catchment scale was applied to find out the areas with the greatest sediment deposition potential where victims could have been buried by the flash flood*".

This is the new sentence (see Lines 351-353 of the revised MS), in which is better explaining the main aim of the IC implementation in terms of Emergency rescue tasks:

"*Firstly, and taking into account the emergency situation, the index of (water and sediment) connectivity at the catchment scale was applied to find the areas with the greatest sediment deposition potential, which were where victims could have been buried by the flash flood*".

Within the new subsection *2.8 Geomorphic change detection*, we have reinforced its main purpose in the first paragraph, as follows (see Lines 367-372 of the revised MS):

"*HR-DEMs facilitate the improvement of sediment connectivity as a powerful tool to determine preferential flow-paths and those areas with the greatest potential sediment deposition. The evaluation of the flash-flood landform signature by UAVs is the second part of creating a tool for a rapid response of post-catastrophe search and rescue tasks by applying hydrogeomorphological precision techniques. The estimation of overbank sedimentation allowed the calibration of the predicted large sedimentation by IC mapping and its reliability in detecting sites where victims might be buried by flood sediment*".

In order to clarify that no changes in volume occurred between 2014 and 2018, we have added a new sentence in the new subsection 2.8 (see Lines 396-398 of the revised MS):

"*It is worth noting that no geomorphic changes were observed between 2014 and October 2018 by photointerpretation of aerial imagery (PNOA, 2015) and the continuous measurement of water stages since January 2015, with no overbanked flood events*".

Finally, the accuracy of the approach was settled, as mentioned in the first MS version, by an assessment of RMSE in xyz. However, we have reinforced this method adding "*and located on surfaces not modified by the flash flood*".

Additional comments

As mentioned earlier, the manuscript would benefit from English language copy editing. Instead of giving point-by-point corrections I would like to provide a a few examples, which I find difficult to understand:

The authors we are grateful with detailed suggestions on English language and grammar. Following this advice, we have requested an external review on English language by a professional native speaker (see attached the certificate).

L 51f: "Characterising the response of a catchment during flash flood events is important because elucidate the hydrological processes from an extreme flood and their dependency on catchment properties and flood severity (Borga et al., 2007)" should probably be: "Characterising the response of a catchment during flash flood events is important because it helps understanding the hydrological processes of extreme floods and their dependency in regard to the properties of the catchment and the severity of the event."

The Anonymous Referee #1 had also suggested a change in English language style within the sentence.

L 112f: “[…] was developed affording the analysis of the rainfall-runoff processes at small spatial scale during this extreme event.” I did not understand what “affording” means in this context.

We have changed “affording” by “through”.

L125: “high-energy environment” I did not understand what “high-energy” means in this context

We believe that “high-energy environment” is a concept completely accepted in the argot of Earth sciences and is comprehensible in the context developed within this sentence. However, we have modified the beginning of the sentence including the geographical context: “*In such a high-energy environment,…*”.

L156: “under a recurrent affection of wildfires”: does that mean that these areas are regularly affected by wildfires or that these areas are prone to wildfires?

These areas are both prone to wildfires and have been affected by wildfires twice in the last 30 years. In addition, one of the main concerns provided by both referees are related with the physical processes conditioning the hydrological response of the flash flood event. In this way, we have improved the description of the subsection 2.1. Study area in order to better contextualize the influence of lithology, land uses and wildfires in the hydrological response during the extreme flash flood event (see Lines 155-165 of the revised MS):

“*The lithology is mainly composed of marls intercalated with limestone (60% of the area) of the Medium-Upper Jurassic (Dogger), dolomites (22% of the area) of the Upper Triassic and Lower Jurassic, and pelagic limestone marls (14% of the area) of the Lower Cretaceous (Fig. 2d). This lithological composition determines the surface water/groundwater interaction. On the one hand, a high degree of fracturing, fissuring and karstification of limestone favours percolation through karstic aquifers. On the other hand, the imperviousness of Dogger and Cretaceous marls (74% of the area) does not allow percolation, enabling runoff generation. The main land use in 2012 was agriculture (58%), mostly located in lowland areas. Forest (26%) and scrubland (17%) were predominant at headwaters. Terraced fields still occupied 10% of the catchment, although most of them were abandoned (Fig. 2e). In 1956, natural vegetation covered 21% of the catchment. This rose to 42% in 2012 due to an afforestation process of former agricultural land in the second half of the twentieth century. In combination with other factors, afforestation triggered a higher fire risk: two wildfires burnt an area of 1.7 km^2: 17% in 1983 and 83% in 2011 (Balearic Forestry and Soil Conservation Service, http://xarxaforestal.caib.es; Fig. 2e)*”.

To whom it may concern

I certify that I have revised and corrected the grammar, structure and style of the following article:

Title:

Hydrogeomorphological analysis and modelling for a comprehensive understanding of flash-flood damaging processes: the 9th October 2018 event in northeastern Mallorca

Authored by:

Joan Estrany, Maurici Ruiz-Pérez, Raphael Mutzner, Josep Fortesa, Beatriz Nácher-Rodríguez, Miquel Tomàs-Burguera, Julián García-Comendador, Xavier Peña, Adolfo Calvo-Cases, Francisco J. Vallés-Morán

Michael Eaude
Torrent de Can Mariner 7-1
Barcelona 08031
Spain
NIF: X-01117301-F

Signed May 18, 2020:

MS Records

nhess-2019-304 Submitted on 13 Sep 2019 **Hydrogeomorphological analysis and modelling for a comprehensive understanding of flash-flood damaging processes: The 9th October 2018 event in North-eastern Mallorca** Joan Estrany, Maurici Ruiz-Pérez, Raphael Mutzner, Josep Fortesa, Beatriz Nácher-Rodríguez, Miquel Tomàs-Burguera, Julián García-Comendador, Xavier Peña, Adolfo Calvo-Cases, and Francisco J. Vallés-Morán
First Contact: Joan Estrany Bertos
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Handling Editor: Kai Schröter Manuscript Type: Research article
Status: File Upload (NHESS) **Iteration: Major Revision**

Interactive Discussion

Editor Decision: Reconsider after major revisions (further review by editor and referees) (27 May 2020) by Kai Schröter

Comments to the Author:

Response of the Authors to the Editor Comments (in blue):

Comments to the Author:

Dear Joan Estrany and co-authors,

Thank you very much again for submitting your brief communication manuscript 'Hydrogeomorphological analysis and modeling for a comprehensive understanding of flash-flood damaging processes: The 9th October 2018 event in North-eastern Mallorca'. The authors we kindly appreciate the comments from the Associate Editor as well as from the two anonymous referees which have helped to deeply improve the MS.

Two referee reports and a short comment from the scientific community are available which raises important issues with the current version of your manuscript. Major concerns exist regarding the links of individual aspects addressed in the study (meteorological, hydrological, geomorphological, damage, and risk data analysis) which appear to be considered rather separately. In addition, very detailed suggestions are made by the reviewers on how to improve the comprehensibility of your study and achieve a more clear structure. Reading your responses to these comments I am positive that a revised version of your manuscript will address these points appropriately.

We have addressed all the major concerns highlighted by both reviewers and also integrated constructive ideas that –we believe- have improved the comprehensibility of the MS with a clearer structure. We are also very pleased for the positive reaction of the Associate Editor to our responses to the referees' comments.

The main concern based on the lack of continuity in the narrative –taking into account that we had applied an integrated approach with meteorological, hydrological, geomorphological, damage and risk data analysis– of the paper has been addressed creating an overview figure showing the links between data and models, the new Figure 1. This Figure 1 has also been improved following one of the comments of the Associate Editor.

The second idea provided by the Anonymous Referees for addressing a more integrated comprehension has been focused in merging the two subsections of the Discussion section to facilitate the combination of the individual results. As a result, the discussion on hydrological response, rainfall-runoff modelling, damage assessment and geomorphic change are integrated in a unique section.

Also in this same Discussion section, we have also introduced several paragraphs especially focused on the predictability of this kind of flash-flood events and developed a qualitative –but also quantitative– discussion about the role played by rainfall intensity and its spatial distribution, complex geology and land cover disturbances, following the suggestion provided by the Anonymous Referee 1#. For this purpose, we have also modified the subsection 2.1. Study area, where a deeper assessment of permeability in lithology materials as well as a diachronic evaluation of land uses evolution and perturbations (i.e., wildfires) is sustaining the discussion on the role of physical parameters generating the flash flood.

Another main modifications have been performed in the Introduction section, where we have amplified the activating hydrological processes during a flash flood, including extra scientific literature on previous post-event studies with a special emphasis on those analysing the role played by physical parameters in runoff generation.

In addition please make sure that legends and other information given in your Figures are readable (e.g. new Figure 1 with the workflow and Figure 8 (previously Figure 7) are not readable).
We have modified the new Figure 1 slightly changing its structure and also increasing the size of the text to provide more clarity. In addition, the text size of the legend and other information have been also increased in the Figure 8.

Please also note that this decision for major revisions does not necessarily imply acceptance of the manuscript in the journal NHESS, and it still depends on your reply and edits to your manuscript, as well as on the reviewer comments of the revised version. As a next step, I kindly ask you to provide a revised marked up (track changes) version of your manuscript to make clear how you include the changes in response to both referee reports and the short comment. Additionally, you have to upload the new

We have submitted the revised version of our MS and also the supplementary information with tracking changes.

Hydrogeomorphological analysis and modelling for a comprehensive understanding of flash-flood damaging processes: The 9^{th} October 2018 event in North-eastern Mallorca

Joan Estrany[1,2*], Maurici Ruiz-Pérez[1,2,3], Raphael Mutzner[4], Josep Fortesa[1,2], Beatriz Nácher-Rodríguez[5], Miquel Tomàs-Burguera[6], Julián García-Comendador[1,2], Xavier Peña[4], Adolfo Calvo-Cases[7], Francisco J. Vallés-Morán[5]

[1]Mediterranean Ecogeomorphological and Hydrological Connectivity Research Team (http://medhycon.uib.cat), Department of Geography, University of the Balearic Islands, Carretera de Valldemossa Km 7.5, 07122 Palma, Balearic Islands, Spain

[2]Institute of Agro-Environmental and Water Economy Research –INAGEA, University of the Balearic Islands, Carretera de Valldemossa Km 7.5, 07122, Palma, Balearic Islands, Spain

[3]Service of GIS and Remote Sensing, University of the Balearic Islands, 07122 Palma, Balearic Islands, Spain

[4]Hydrique Engineers (http://www.hydrique.ch), Le Mont sur Lausanne, Vaud 1052, Switzerland

[5]Universitat Politècnica de València, Camí de Vera, s/n, València, 46022, Spain

[6]Estación Experimental de Aula Dei (EEAD-CSIC), Avenida Montañana, 1005, 50059 Zaragoza, Spain

[7]Inter-University Institute for Local Development (IIDL) Department of Geography, University of Valencia, Av. Blasco Ibáñez 28, 46010, Valencia, Spain

Correspondence to: Joan Estrany (joan.estrany@uib.cat)

Abstract. A flash-flood event hit ~~in the 9^{th} October 2018~~ the northeastern part of Mallorca Island on 9^{th} October 2018, causing 13 casualties. ~~This island~~Mallorca is prone to catastrophic flash floods acting on a scenario ~~that illustrates the~~of deep landscape transformation ~~of~~ caused by Mediterranean tourist resorts. As global change may exacerbate devastating flash floods, ~~comprehensive~~ analyses of catastrophic events are crucial to support effective prevention and mitigation measures. Field-based, remote-sensing~~e~~ and modelling techniques were used in this study to evaluate rainfall-runoff processes at the catchment scale linked to hydrological modelling. Continuous streamflow monitoring data revealed a peak discharge of 442 $m^3 s^{-1}$ with an unprecedented runoff response ~~(lag time, 15')~~. This ~~very flashy~~exceptional behaviour triggered the natural disaster as a combination of heavy rainfall (249~~6~~ mm in 10 h), karstic features and land cover disturbances in the Begura de ~~Saumà~~Salma River catchment (~~i.e.,~~ 23 km^2). Topography-based connectivity indices~~ex~~ and geomorphic change detection were used as ~~a~~ rapid post-catastrophe decision-making tools, playing a key role during the rescue searchi~~ng tasks~~. These

hydrogeomorphological precision techniques were ~~also applied in~~ combined~~ation~~ with the Copernicus ~~EMS~~ Emergency Management Service and ‘ground-based’ damage assessment, which showed very ~~illustrating with high~~ accuratel~~e~~y the damage driving-~~-~~factors in the village of Sant Llorenç des Cardassar. The main challenges in the future are to readapt hydrological modelling to global change scenarios, implement an early flash-~~-~~flood warning system and ~~apply~~ take adaptive and resilient measures ~~at~~ on the catchment scale.

1 Introduction

Flash floods are related with high-intensity precipitation, mainly of convective origin and with a restricted spatio-temporal occurrence. For this~~at~~ reason, they ~~it~~ usually impact~~ing~~ ~~at~~ basins <1000 km^2 with response times of a few hours or less. These spatial and temporal dimensions of flash-~~-~~flood~~s~~ events are directly linked to (1) geomorphometric characteristics of the catchments and (2) activation mechanisms of runoff as a combination of intense rainfall, soil moisture and soil hydraulic properties (Versini et al., 2013). ~~The l~~Land use modification, urbanization and recurrent wildfires can alter these activation mechanisms and the potential for flash flood casualties and damages. In Europe, 40% of ~~the~~ flood-related casualties in the period 1950–2006 are due to flash floods (Barredo, 2007). However, catastrophic flash-floods are much more frequent in some parts of the Mediterranean region than in the rest of Europe due to the interaction between geomorphology, climate, ~~and~~ vegetation, and the warm sea surface (Cassola et al., 2016) ~~contributing~~ all combining to create a flood-prone environment. The abrupt reliefs surrounding the Mediterranean Sea are very close~~ness~~ to the coastline, shaping small and torrential catchments where the convergence of low-level atmospheric flows and the uplift of warm wet air masses drifting from the Mediterranean Sea to the coasts generate heavy downpours in very short time-spans (Gaume et al., 2009). ~~Another cause is the reduced vegetation cover and scarce soils. Flash-floods are closely related to land use recognizing that the devastation of plant cover in the Mediterranean may increase the risk of flooding because bare soils produce larger runoff coefficients .~~

Characterising the response of a catchment during an extreme flash-~~-~~flood event~~s~~ is important because ~~elucidate~~ it clarifies flood severity and the activating hydrological processes ~~from an extreme flood~~ and their dependency on natural and anthropogenic catchment properties ~~and flood severity~~ (Borga et al., 2007). ~~However, the small spatial and temporal scales of flash-floods make these events particularly difficult to monitor and document. In the case of rainfall monitoring, the spatial scales of the events are in general much smaller than the sampling potential offered by apparently dense rain networks (Borga et al., 2008; Amponsah et al., 2016). In the case of streamflow monitoring, there is a lack of flash flood discharge (*Q*) data from stream gauge observations (Marchi et al., 2010) although *Q* data are crucial to obtain representative hydrometric values and to characterize the runoff response of such extreme flash-flood events (Borga et al., 2008).~~ Numerous studies have tried to determine these driving factors (Braud et al., 2014) in which geological heterogeneities associated with the presence of karst features are crucial in Mediterranean catchments (Vannier et al., 2016; Wainwright and Thornes, 2004). Likewise, flash floods are closely related to land use: the devastation of plant cover in the Mediterranean may increase the risk of flooding because bare soil leads to larger runoff coefficients (Wainwright and Thornes, 2004).In the Mediterranean region, the planning and management of flood hazards are hydro-sociologically crucial (Gaume et al., 2016), especially under the current global change context. Consequently, the hydrometric data reliability of surface water resources requires a temporal continuity and a maintenance system of the gauging stations (Fortesa et al., 2019).

However, the limited spatial and temporal scales of flash-floods make these events particularly difficult to monitor and document. In the case of rainfall monitoring, the spatial scales of the events are in general much smaller than the sampling potential offered by apparently dense rain networks (Borga et al., 2008; Amponsah et al., 2016). In the case of streamflow monitoring, there is a lack of flash flood discharge (*Q*) data from stream gauge observations (Marchi et al., 2010) although *Q* data are crucial to obtaining representative hydrometric values and characterizing the runoff response of such extreme flash-flood events (Borga et al., 2008). As a result, further field observations and modelling studies are required in order to assess the interdependencies of flash-flood drivers and, thus, better understand and reproduce the active hydrological processes (Sofia and Nikolopoulos, 2020).

Earlier flash flood forecasting systems were based on the Flash Flood Guidance (Georgakakos, 1986), consisting in estimatingwhich calculated the a-priori amount of rainfall needed to trigger specific *Q* at the outlet of a catchment, depending on antecedent prior wetness conditions. At the present time, semi-distributed or distributed hydrological models are more widely used for such forecasting purposes (Artinyan et al., 2016; Gourley et al., 2010; Miao et al., 2016; Nguyen et al., 2016), whilst probabilistic and ensemble modelling allow to assess the uncertainty of flash flood forecasting systems (Hardy et al., 2016). However, the uncertainty in hydrological modelling can be large. FirstlyThe main source of uncertainty is related to the spatio-temporal scales of rainfall pattern. The, forecasting of intense thunderstorms by numerical weather prediction systems to provide accurate rainfall information is particularly challenging (Alfieri et al., 2015; Collier, 2007). and Secondly,Another source of uncertainty is related to the hydrological models that often need to be calibrated in order to reduce the uncertainty of the *Q* discharge estimate and to understand the physical processes occurring during flash flood events (Adamovic et al., 2016; Segura-Beltrán et al., 2016; Vannier et al., 2016). -Consequently, the reliability of data measuring surface water resources requires temporal continuity and good maintenance of the gauging stations (Fortesa et al., 2019). Therefore, the predictability of such events remains lowFlash-flood events are also adding that predictability is loweredconditioned by a high non-linearity in the hydrological response relatinged to threshold effects (Braud et al., 2014).

In the Mediterranean region, the planning and management of flood hazards are hydro-sociologically crucial (Gaume et al., 2016), especially in the current global change context. Therefore, the predictability of such events remains low.

It is clearly demonstrated that the understanding of flash floods processes and management further requires an integrated scientific approach (Marchi et al., 2010), encompassing (1) hydrogeomorphological precision techniques with (2) social and territorial aspects of vulnerabilityin which technological advances create opportunities to investigate simultaneously in the areas of Earth and Social Sciences (Wohl et al., 2019). Firstly, geomorphometric techniques applied to topographic surveys can be valuable planning and decision-making tools for producing flood hazard maps that are able to represent flood-prone areas prone to flooding (Kalantari et al., 2017). Another application of gGeomorphometry and digital terrain analysis by using means of a topography-based connectivity index could also be used tothe simulateion of preferential flowpaths for high-magnitude events to determine the main erosion and deposition areas, as a tool for a better and faster responses in front ofto catastrophic flooding events. In addition, post-storm assessments toneed captureing the landforms signature of the event are needed. The use of high-resolution field measurements can beis here critical to understanding the effects of storm effects on fluvial dynamics (Westoby et al., 2012) and also providing input data sets for numerical modelling. Theise data can be difficult to obtain, as traditional post-storm survey techniques are expensive or and time--consuming (Duo et al., 2018). In recent years, unmanned aerial vehicles (UAVs) have been used to improve traditional, expensive, or time-consuming mapping approaches on catchment science research. UAVs permit enabling a rapid deployment and achieve accurate high-resolution topographic data for monitoring geomorphic changes (Estrany et al., 2019; Langhammer and Vacková, 2018).

Secondly, the concept of vulnerability relates to the predisposition of certain stakes to damage or malfunction, implying that a multitude of direct and indirect factors, often interacting in a dynamic and complex way, should be integrated in their assessment. From this point of view, vulnerability particularly relates to the damage to exposed stakes (Defossez and Leone, 2017). Particularly regarding to vulnerability, eEstimations of the elements at risk in flash floods andas well as the damage--driving factors , flash floods are insufficiently understood in the Mediterranean Region, despite even though understanding assessment of specific and subsequent damageing processes from flash floods are developedhave been assessed in from several European and national projects and also publications (cf. Llasat et al., 2013; Gaume et al., 2016). Observed spatial distributions of costs and fatalities are the result of complex interplay between different explanatory factors. Useful information may reveal the economic and social impact of floods on our societies, but its interpretation is questionable (Gaume et al., 2016). In addition, the largest public world databases on disaster events that contain flood events do not include all the catastrophic events occurred in the Mediterranean region (Llasat et al., 2013), emphasizing which underlines the need for further research. Since 2012, the Copernicus Emergency Management Service (Copernicus-EMS) evaluates the intensity and scope of the damage resulting in casescaused by of natural disasters, human-made emergency situations and humanitarian crises throughout the world (Copernicus Emergency Management Service, 2019). To obtain a better understanding of the damage processes of flash floods better, a comprehensive damage assessment linking hydrological process dynamics and intensities with to damage and loss is needed (Laudan et al., 2017). As wellIn addition, a comparison of 'ground-based' assessment with and that 'remote-based' Copernicus EMS one may shed light on the accuracy of this rapid and helpful tool at for assessing most of the catastrophic flash floods.

This paper aims at improving the comprehension of the hydrological and socioeconomic processes comprehension of the devastating flash floods that frequently affects Mallorca Island (Estrany and Grimalt, 2014; Llasat et al., 2013; Lorenzo-Lacruz et al., 2019)(Llasat et al., 2013; (Estrany and Grimalt, 2014), a paradigmatic Mediterranean flood-prone region under intense human occupation and geologically shaped by karstic features. Accordingly, the present work is focusedThe study focuses on the catastrophic flash-flood event that hit the north-eastern part of the island on, in the 9th October 2018, causing 13 casualties. This was, the worst local natural disaster in decades which caused a marked interest among the scientific community, producing early studies of the event. In this way, -Lorenzo-Lacruz et al. (2019) reconstructed this same flash-flood event through the application of hydrological and hydraulic simulations, with a focus on the meteorological input. The specific objectives of this study are ~~to~~ (1) to explain the runoff response ~~for elucidating~~and so clarify the dependency of flood severity on catchment properties and human influence,~~s~~ by using the flash flood *Q* data from a stream gauge installed in 2015 by the Mediterranean Ecogeomorphological and Hydrological Connectivity –MEDhyCON Research Group; (2) to assess the uncertainty of semi-distributed hydrological modelling in such a severe flash flood in a karstic environment; (3) to investigate the socioeconomic and territorial flood damages linked to hydrogeomorphological processes; and (4) to analyse multi-temporally ~~analyse~~ high-~~-~~resolution digital elevation models (HR-DEM) ~~to~~ for detecting and ~~quantify~~ measuring geomorphic changes by using a UAV and a topography-based connectivity index for ~~a~~ rapid response ~~of~~ in post-catastrophe search and rescue tasks.

2 Materials and ~~m~~Methods

To obtain a better understanding of the flash flood as well as of damage processes, a comprehensive and combined analysis of the meteorological synoptic situation, ~~the~~ precipitation ~~as well as the *Q*~~and discharge was developed ~~affording~~ through the analysis of the rainfall-runoff processes at small spatial scale during this extreme event. Likewise, this analysis was linked to hydrological modelling to check the internal consistency of the information gathered by instruments and to flood damage and losses at Sant Llorenç des Cardassar village. Finally, high-resolution digital elevation models (HR-DEM) were generated by LiDAR 2014 data from the Spanish National Geographic Institute and by imagery captured through a low-cost UAV just six days after the catastrophe to calculate a sediment connectivity index (IC) and measure geomorphic changes (Fig. 1).

2.1 Study area ~~and meteorological context of the 9th October 2018 rain event~~

Mallorca is a Mediterranean flood-prone region, historically affected by flash floods. Since the Late Middle Age, devastating flash floods have been systematically ~~well~~ documented, particularly in Palma, the capital of the island. In this town, a catastrophic event caused ca. 5,000 deaths in 1403 (20% of its population), ~~evidencing~~ showing that floods are the main~~jor~~ natural hazard in this type of environment (Petrus et al., 2018). In the rest of the island, the historical distribution patterns of human settlements ~~had been~~were related ~~with~~ to fluvial systems, but ~~always~~ avoided~~ing~~ the occupation of floodplains until the increase of urban areas in the 19th century during the Industrial Revolution. However, in the second part of the 20th century this urban expansion ~~was~~ became exponential, with an increased ~~of~~ urban and tourist settlements (Pons Esteva, 2003) including in flood~~ing~~ hazard areas.

In such a high-energy environment, Mallorca~~, the~~ 's Eastern (~~named~~ 'Llevant' in Catalan ~~language~~) county ~~of Mallorca island~~ constitutes a dramatic combination of physical and human factors ~~to~~ that have created ~~generate~~ a flood-prone environment with a very strong coupling of climate and geomorphology ~~with a~~to constant urban expansion since 1850, wic~~t~~h lead to more than 10 catastrophic flash-flood events ~~occurred~~ during this period (Estrany and Grimalt, 2014). This county ~~is composed~~consists of ~~by~~ two main relief units (Álvaro et al., 1991): (1) The Llevant Ranges occupy the headwater~~ part~~s with altitude ranging~~es~~ from 300 to 500 m a.s.l. They ~~are constituted by~~consist of a series of alpine mountains and hills ~~that are~~

~~primarily constructed~~mainly of Jurassic limestones and dolomites and Cretaceous marls; and (2) The Marinas, a reefal Upper Miocene tabular platform composed of calcarenites, calcisiltites and terra-rossa postreef sediments affected by significant karstic processes ~~endorsed to~~on the eastern slopes of the Llevant Ranges. A morphometric analysis of the catchments ~~carried out~~ by Estrany and Grimalt (2014) showed differences that depend~~ed~~ing on both the width of the platform (i.e., the distance between the coast and the base of the Llevant Ranges through the Miocene platform) and the hypsometry and geological settings at the headwaters. The torrentiality and clinometric variables were th~~ose~~e ones more closely related to the geological settings. Therefore, the catchments with the highest values of torrentiality (i.e.~~,~~ >30; which is topographically computed as a coefficient between the number of first-order streams and catchment area, multiplied by the drainage density; cf. ~~(~~Strahler, 1964)~~)~~ ~~present~~ have impervious materials (i.e., lower Cretaceous and lower Miocene marls) covering approx. > 40% of these catchments. These are ~~being~~ located at headwater~~ part~~s where the clinometry and connectivity between ~~the~~ slopes and channels are the highest.

This study focuses on the Ca n'Amer River catchment (78 km^2), due to the storm that struck several urban areas within it, especially the village of Sant Llorenç des Cardassar. Its main headwater tributary is the Begura de Salma River (23.4 km^2; Fig. 2c) with altitudes ranging from 71 to 485 m.a.s.l. (Fig. 2c). The mean slope of the catchment is 16% and the length of the main channel 9.3 km (average gradient of 3%). The lithology is mainly composed of marls intercalated with limestone (60% of the area) of the Medium-Upper Jurassic (Dogger), dolomites (22% of the area) of the Upper Triassic and Lower Jurassic, and pelagic limestone marls (14% of the area) of the Lower Cretaceous (Fig. 2d). This lithological composition determines the surface water/groundwater interaction. On the one hand, a high degree of fracturing, fissuring and karstification of limestones favours percolation through karstic aquifers. On the other hand, the imperviousness of Dogger and Cretaceous marls (74% of the area) does not allow the percolation, enabling runoff generation. The main land use in 2012 was agriculture (58%), mostly located in lowland areas. Forest (26%) and scrubland (17%) were predominant at headwaters. Terraced fields still occupied 10% of the catchment, although most of them were abandoned (Fig. 2e). In 1956, natural vegetation covered 21% of the catchment. This rose to 42% in 2012 due to an afforestation process of former agricultural land in the second half of the twentieth century. In combination with other factors, afforestation triggered a higher fire risk: two wildfires burned an area of 1.7 km^2: 17% in 1983 and 83% in 2011 (Balearic Forestry and Soil Conservation Service, http://xarxaforestal.caib.es; Fig. 2e). The climate of the area is classified as Mediterranean temperate sub-humid on the Emberger scale (Guijarro, 1986). Mean annual rainfall (1968-2018, B630 AEMET station, see Fig. 2c) is 652 mm y^{-1}. A rainfall amount of 140 mm in 24 hours was estimated to have a recurrence period of 25 years (YACU, 2003).

2.2 Meteorological context of the 9th October 2018 rain event

The 9th October storm affected the two northernmost catchments of the Llevant County; i.e., the Ca n'Amer and Canyamel Rivers (Fig. 2~~1~~) with 9 and 4 casualties respectively and significant damages. The synoptic situation was like the situations generating flash-flood events in the Western Mediterranean (Fig. 3~~2~~a). A cut-off low at mid-level was located in the eastern part of the Iberian Peninsula and a shallow low level pressure was affecting the same region driving warm and wet air from the Mediterranean Sea to Balearic Islands and the eastern part of the Iberian Peninsula. This situation took placeoccurred in early October, when the sea surface temperature is close to its annual maximum in the Western Mediterranean, providing high quantities of moisture. Moreover, the cut-off low showed a typical divergence at mid--levels ion its eastern flank, affecting the Balearic Islands and favouring the development of deep convection. The cConvection initiated started on the sea between the Balearic Islands and the Iberian Peninsula (Figures 32b and 32c) and due to the SW winds at mid tropospheric levels, the convective cells started to move towards the Balearic Islands, where they could triggered the flash-flood event after a heavy rainfall episode (Figures 32d and 32e).

This study will be focused in the Ca n'Amer River catchment (78 km^2), due to the storm struck several urban areas within it, especially the village of Sant Llorenç des Cardassar. Its main headwater tributary is the Begura de Saumà River (23.4 km^2; Fig. 1c) with altitudes ranging from 71 m.a.s.l. to 485 m.a.s.l. (Fig. 1c). The mean slope of the catchment is 16% and the length of the main channel 9.3 km (average gradient of 3%). The lithology is mainly composed by marls intercalated with limestone (60% of the area) of the Medium-Upper Jurassic as well as dolomites (22% of the area) of the Upper Triassic and Lower Jurassic (Fig. 1d). The main land use is agriculture (58%), mostly located in lowland areas. At headwaters parts, forest (26%) and scrubland (17%) are predominant, under a recurrent affection of wildfires. Due to the agricultural activity, 10% of the catchment is occupied by dry-stone terraces, most of them abandoned (Fig. 1e). The climate of the area is classified as Mediterranean temperate sub-humid, applying the Emberger scale (Guijarro, 1986). The mean annual rainfall (1968-2018, B630 AEMET station, see Fig. 1c) is 652 mm y^{-1}. Rainfall amount of 140 mm in 24 hours was estimated to have a recurrence period of 25 years (YACU, 2003).

2.32 Rainfall data

In order to assess the rainfall-runoff processes during the flash flood event in the Begura de SaumàSalma River, the continuous 10-min precipitation record of the event was obtained from radar (see location in Figure 2b) images which that were initially calibrated through rainfall data downloaded at https://opendata.aemet.es/ and http://asomet.balearsmeteo.com/. Both The two webpages contain meteorological data for official stations of the Spanish Meteorological Agency (i.e., AEMET) and the Meteorological Association 'Balearsmeteo', respectively (see Fig. 21c: B526X-Artà-Molí d'en Leu, B496X-Son Servera, B614E-Manacor, B569X-Far de Capdepera and B603X-Colònia de Sant Pere from AEMET; and BM01-Sant Llorenç des Cardassar from Balearsmeteo). After calibration, all radar images were geo-statistically treated to obtain the hourly mean and total precipitation (and its standard deviation) fallen into regular squares of 1x1 km in size (Fig. 21c), thus allowing the analysis of the spatio-temporal distribution of the rainfall event.

The radar, is located in the western part of the island of Mallorca, and it obtains reflectivity data (in dBZ) at 1*1 km of spatial resolution and at a 10-minutes temporal resolution for many altitudes. Thanks to the AEMET Open Data Platform (opendata.aemet.es), data of reflectivity data corresponding to the lower Plan Position Indicator (PPI), which corresponds to an azimuth of 0.5º, can be downloaded in near-real time. Using reflectivity data, rainfall ~~estimation was obtain~~was calculated by using the Marshall-Palmer relation (Marshall and Palmer, 1948).

$$Z = aR^b \qquad (1)$$

where Z is the radar reflectivity (mm^6 m^{-3}), R is the rain rate (mm h^{-1}) and a and b are two coefficients. As the obtained reflectivity data is in dBZ units instead of mm^6 m^{-3} a conversion was necessary using the following relation

$$dBZ = 10 * \log (Z) \qquad (2)$$

The relation between Z and R depends mainly on the drop size distribution (DSD), which is usually unknown, unless disdrometer data are available, which is not the case (Chapon et al., 2008). Hence, coefficients a and b cannot be well established for this event. Multiple pair of values for a and b coefficients can be found in the literature, mostly changing between precipitation types.

We tested two pair of coefficients: (i) the pair a=200 and b=1.6 was tested because AEMET commonly uses these coefficients to obtain near-real time rainfall estimations (http://www.aemet.es/es/eltiempo/observacion/radar/ayuda; Last access: 15 May 2020) from the same radar data that we used in this research; (ii) the pair a=300 and b=1.4 was tested because the NWS in the USA uses~~d~~ it at operational level (Fulton et al., 1998) and it is argued that these coefficients performs better in a convective environment than the first ones (e.g. Seo et al., 2020).

The use of the two pairs of coefficients results in the estimation of high amounts of precipitation (100 mm in the first case and 150 mm in the second case), but an amount much lower than the maximum rainfall observation, which is higher than 250 mm, ~~revealing~~ which shows the complexity of ~~obtaining~~ calculating~~an accurate estimation of~~ the precipitation ~~in~~of this event accurately by~~using~~ radar data. In the scientific literature, many methodologies to enhance precipitation ~~estimation~~ calculation using radar data can be found. While some methods ~~are~~ focus~~ed~~ on the correction of the reflectivity data;~~,~~ others are based on the calibration of the estimation of precipitation using reflectivity data as these are the two main sources of errors (Harrison et al., 2000). ~~In our study case, the combination of the distance to the location of the event (~50 km) with the 0.5º azimuth of the used PPI and the elevation of the surrounding mountains do not justify the application of techniques based on the correction of reflectivity data due to these effects.~~ Mountains may partially or totally block the electromagnetic radar signal and affect radar reflectivity and precipitation estimations (Germann and Joss, 2004). The study area is mountainous, but with low maximum altitudes (~400 m.a.s.l.). This low elevation combined with the regional orography, the distance of the Begura de Salma River from the radar (~50 km), the 0.5º azimuth of the PPI used, and the altitude of the radar location (113 m.a.s.l.), avoided any topographic interference with the radar signal. Thus, no any orographic blocking reflectivity correction technique was needed. To directly correct the estimation of precipitation, geostatistical methods are commonly implemented in combination with the use of rain gauge data (Barbosa et al., 2018), but the ~~number~~ data ~~of~~ available data in the most affected area ~~is~~ are too ~~low~~ few to implement these methods. Available data ~~at~~ from the surrounding area could be used, but due to the sharp differences in rainfall ~~among~~ between the affected and surrounding areas we decided not to use th~~o~~ese data.

With the set of coefficients a=300 and b=1.4, the maximum amount of estimated rainfall using radar data clearly underestimated the observed rainfall, with a PBIAS of –50.6% and an estimation of ca. 149 mm as the maximum rainfall amount, compared with the 257 mm recorded at the Sant Llorenç des Cardassar rain gauging station (see Fig. 2c). Instead of using the recorded rainfall in gauging stations to calibrate the radar-based rainfall, a correction method of the rainfall estimation based on spatial resampling was posited here. Accordingly, the 2*2 km spatial resolution of radar data was resampled by assigning to each grid cell the value of the maximum amount of estimated rainfall at 1*1 km. By this method, the regression coefficient reached R^2= 0.8, a PBIAS of only +2.6% and 258 mm as the maximum estimated rainfall amount, wich fitted to the rainfall at that point (Fig. S1).

~~During convective situations, high spatial and temporal gradients can be detected, both using radar data and dense rain gauge networks. As the time resolution of the radar data is 10-minutes it is difficult to assume that the obtained values of reflectivity affected the same 1*1 km area during all this time. We proposed a correction method of the rainfall estimation based on the spatial resampling, changing the spatial resolution to 2*2 km and assigning to each grid cell the value of the maximum amount of estimated rainfall at 1*1 km using the coefficients a=300 and b=1.4. As pointed out previously, using this set of coefficients leads to a relevant underestimation of the precipitation, which is compensated by the used spatial resampling method, leading to a maximum precipitation estimation > 250 mm and showing a spatial corresponding compared with rain gauge data, but with a poor spatial resolution of 2*2 km.~~

2.4~~3~~ Discharge data

A hydrometric gauging station is located ~~at the entrance~~where ~~of~~ the Begura de ~~Saumà~~Salma River enters ~~into the~~ Sant Llorenç des Cardassar village, ~~located~~ 50 m upstream ~~of~~ from the Ma-3323 road bridge (Fig. 4~~3~~a). The station was built by the water authority in the 1970s ~~decade~~. After years of abandonment, in 2015 the MEDhyCON Research Group installed within the gauge house a Hobo Water Level U20L-04, which measures the water stage by ~~readings of~~ 1-~~-~~minute readings, accumulating 15-minute average values. The station is located at the very beginning of the concrete channelizing that takes the~~ation of the R~~ river through~~that crosses~~ the village, closing a drainage basin of 23 km^2 and located ca. 50 m upstream of the first of the five bridges that cross the r~~R~~iver within the village (see Bridge 1 in Fig. 4~~3~~b). At the cross section where the hydrometric station is located, the channel bed is ~~at~~ 70.25 masl, whilst the top of its bank channels are ~~at~~ 72.00 masl.

The transformation of water stage (hereinafter WS; m) to Q (m^3 s^{-1}) through the stage/discharge rating curves (hereinafter SDRC) into the qualitative range (from low to high Q conditions) are broadly developed by power and also polynomial equations, characterised by physical-based parameters. With the absence of direct flow measurements for the Q estimation, a complete two-dimensional hydraulic model was ~~applied~~ developed with HEC-RAS 5.0.6 software (~~version~~ November 2018 version)~~, developed~~ by the US Army Corps of Engineers, Hydrologic Engineering Center. In this case, a set of differential equations in partial derivatives that govern ~~the~~ flow behaviour, known as Saint Venant's equations, were solved in shallow water equations.

For the generation of the 2D hydraulic model, a HR-DTM derived from a 1 m LiDAR-based DEM dating from 2014 was used; http://pnoa.ign.es/coberturalidar. In addition, the entire concrete channeling~~zation~~ of the Begura de ~~Saumà~~Salma River was topographically surveyed with a dGPS Leica 1200 for its integration to the HR-DTM. Within the model, all the bridges with potential flow effects on the hydrometric station were also introduced (Fig. 3a). This 2D hydraulic model was applied in a longitudinal river section established 150 m upstream~~-~~ and downstream ~~of~~ from the hydrometric station. Previously, the geometry of the gauging section was measured ~~for~~ to characterize~~ing~~ its hydraulic functioning. ~~It~~ This is a regular trapezoidal concrete channeling~~zation~~ of ca. 300 m in length with low sinuosity (Fig. 4~~3~~a), a longitudinal slope of 0.0052 m m^{-1}, 10 m ~~of~~ wide at the bed channel and with~~, being~~ the height of embankments 1.75 m. The slope of the longitudinal section was hydraulically high, ~~causing~~ which meant that the critical depth at the beginning of the channeling~~zation~~ was the constraining factor of its hydraulic capacity (ca. 78 m^3 s^{-1}). This Q value was ~~related~~ related to~~with~~ 1.75 m of WS, coinciding with the height of the embankments.

As boundary conditions, an input hydrograph was arranged at the most upstream part of the section studied~~ section~~, whilst the WS was subsequently arranged in accordance with the slope of the channel bed at the most downstream part. Hydraulic simulations were always started with no flow conditions. ~~Considering~~ Taking into account the hydraulic function~~ing~~ characteristics for obtaining the SDRC, the calculation method used in these simulations was the Diffusion Wave. ~~In order t~~To design an accurate SDRC for the hydrometric station, the hydraulic effects of concrete channelization and bridges were assessed, running iteratively the model by flowing the representative Q values under stable hydraulic functioning conditions.

Accordingly, a first hydrograph was designed step-by-step by using Q values ~~applying~~ for a power equation with 2 as exponent in a range between 2 to 512 m^3 s^{-1}. The duration of each constant Q (step) of this hydrograph was established (from preliminary simulations) ~~in~~ at 4 hours and 15 minutes, significantly longer than the transit of the flood wave through the ~~studied~~ longitudinal section studied. In this way, the flow transit for each step in steady state conditions was guaranteed. ~~Under t~~These conditions and~~ with~~ this designed hydrograph gave~~,~~ a first approach to the SDRC~~ was obtained~~.~~ In order t~~To improve the accuracy of the SDRC, a second hydrograph was designed with nineteen Q values, also containing the previous nine Q values of the first hydrograph, new intermediate values, and some other significant Q values such as the maximum channel capacity and the Q value at which bridges influences the hydraulics. ~~For~~ To optimize~~ing~~ the time consumption of the modelling, this second hydrograph ~~was performed~~employed with a constant Q (step) of shorter temporal duration; i.e., 1 and 2 hours depending on the Q range.

The SDRC was divided into two sections. The first ~~one~~ was related to~~with~~ a scenario where bridges do not impact on the hydraulic functioning at the gauging section, despite flow being bankfull or even overbanking the channeling~~zation~~. The second section~~one~~ was a scenario under the influence of bridges; i.e., the flow ~~functioning~~ below them and also over their decks. It is then clear that the design, dimensions and proximity to the hydrometric station of these bridges ~~caused~~ affected directly~~ influence on the~~ flow behaviour ~~in~~ at the hydrometric station due to ~~they were affected by~~ obstruction (see pictures in

Fig. 43). The obstruction of the Bridge 1 was produceoccurred when the upstream section of the concrete channelizationng reached the bankfull, sucho that the dragging and floating elements began to collide against the baeck of the bridge, triggering the obstruction process. Consequently, it was necessary to integrate in the hydraulic model had to integrate those obstructions observed in at the downstream bridges, at least in the two nearest ones (Fig. 43a). These post-event pictures and maximum water stages observed in situ 10 h after the event were useful for calculating the obstruction percentages of these two bridges:. In detail, 85% of obstruction in theat Bridge 1, 40% in theat Bridge 2 and with noout obstruction for the other ones. The overbank flow coefficients were 2.2 for bridges 1, 4 and 5, and 2.1 for bridges 2 and 3. The obtained SDRC obtained allowed to calculatione of this phenomenon which is activated with Q values ranging 130-160 $m^3 s^{-1}$. Nevertheless, a calibration in the hydraulic model of overbank flow coefficients and the degree of obstruction of these structures was needed and attained by using complete flow equations (Full Momentum) and without changes in boundary conditions. For this purpose, the WS calculated in open channel conditions were compared with those WS observed in the field during and after the event in the hydrometric station and its surrounding floodplain area. Maximum WS observed in situ 10 hours after the event, within a period of time in which the high-water marks were still preserved, were mapped throughAccordingly, ground control points. in tThree of them were selected as representative locations around the hydrometric station were selected (Fig. 43b), andlso considering the maximum WS reached in at the hydrometric station (4.55 m) was also included. The modelling results in open-channel conditions for the ground control points involved an error < 5% error in WS or even <1% in the case of the WS recorded at the hydrometric station.

The SDRC was finally designed (see Fig. 54), showing clearly illustrating the two differentiated sections with a gap between them in WS of ca. 1.5 m because 1.4 m is the edge of the Road Bridge 1 just located just 50 m downstream of from the hydrometric station. The SDRC is fitted to a power equation for both sections, obtaining high values of significance ($R^2 >$ 0.990). Thus, in the case of the first section of the SDRC, the adjustment was R^2 0.999, operating in open channel flows up to 160 $m^3 s^{-1}$ in bankfull or even overbanking the channelizationg, but always without the bridges influence. The second section, with a R^2 0.996, defined for $Q > 160$ $m^3 s^{-1}$, was already influenced by the presence of the bridges. That is in open channel flows but conditioned by the backwater generated in the flowing under pressure inside the span of the Bridge 1 as well as over its concrete decks.

2.54 Hydrological modelling

A semi--distributed hydrological model was used to reproduce the hydrological response of the catchment during the flash-flood event; i.e., the Routing System (RS) model (García-Hernández et al., 2007; Jordan, 2007). Therein, the GSM-SOCONTSOCONT was the used rainfall-runoff model used. This, comprisededing an appraisal of hydrological processes such as snowmelt as well as surface and subsurface infiltration-induced flow and groundwater flow due to percolation (Jordan, 2007; Schaefli et al., 2005). The catchments were divided into elevation bands to incorporate the influence of temperature evolution with altitude and orographic effects within mountainous catchments. In this model, the sub-catchments were divided into 100 meter elevation bands. The ~~GSM-SOCONT~~SOCONT model was applied to each elevation band, which was~~ere~~ added ~~summed~~ at the outlet of each sub-catchment. The input data of the ~~GSM-SOCONT~~SOCONT was the temperature obtained from meteorological stations and the precipitation derived from radar measurements (see previous section).

The ~~scheme of the GSM-SOCONT~~SOCONT model is shown in ~~the~~ Fig. S2~~1~~. First, the ~~precipitation and~~ temperature was~~ere~~ interpolated for each elevation band based on inverse distance weighing using the Shepard method (Shepard, 1968). Resampled 1 km resolution radar data (see subsection 2.3) were used in the model to obtain precipitation for each elevation band by including all 1 km resolution points falling within each elevation band. ~~In this study, all the interpolated precipitation was directly transferred to the soil infiltration model.~~ The soil-infiltration model was based on modified GR3 equations (Schaefli et al., 2005). Infiltration and evaporation were determined by the soil saturation; i.e., infiltration is higher for lower soil saturation whereas evapotranspiration is higher for high soil saturation. Surface runoff was computed with the SWMM model. ~~The s~~Soil-infiltration was modified to simulate karstic hydrological dynamics, as shown in ~~the~~ Fig. S3~~2~~. ~~The p~~Precipitation ~~was~~ infiltrated ~~in~~ the soil, as in Schaefli et al. (2005), as a function of soil saturation (Fig. S3~~2~~a). The resulting outflow from the reservoir (Q_{GR}) is also dependent~~ing~~ on the soil saturation: ~~, with increasing~~ outflow increases with higher soil saturation. In the modified equations, ~~the~~ soil saturation can increase up to a certain level ($H_{GR,threshold}$), with this being a parameter to be adjusted in the model (Fig. S3~~2~~b). When this threshold is reached, the soil reservoir releases all the available volume contained between the $H_{GR,threshold}$ and the minimum water level (k_{karst} in Fig. S3~~2~~c). The released volume of water is then transferred to the SWMM model~~,~~ described in ~~(~~Schaefli et al.~~,~~ (2005). The relevant parameters for the modified version of the soil infiltration model were the maximum soil capacity ($H_{GR,max}$), the threshold for the karstic behaviour ($H_{GR,threshold}$) and the release coefficient (k_{karst}).

2.6~~5~~ Damage assessment

Rapid Mapping is a mature Earth Observation (EO) service with many years of user oriented development since the International Charter `Space and Major Disaster' was established in 1999. ~~This activity of providing~~ EO satellite data-~~-~~derived disaster mapping during emergencies is provided to civil protection and humanitarian user communities ~~occurs~~ at national, continental and worldwide scales. ~~Considering~~ Given the great~~extreme~~ helpfulness of the Copernicus EMS reports ~~performed by using~~ attained by rapid mapping techniques, the damage assessment of the event ~~was~~ focused on the comparison between two information sources. The first one, a 'ground-based' report, was the damage analysis carried out by the Directorate General of Emergencies of the Balearic Islands Government (Pol, 2019a). This 'ground-based' report provided a detailed description of the resources mobilized in the emergency phase and also a damage inventory. The second information source was the 'remote-based' damage assessment ~~carried out~~ by the Copernicus EMS (https://emergency.copernicus.eu/mapping/ems-product-component/EMSR323_01SANTLLORENC_02GRADING_MAP/2), which also included~~ing~~ the flooded areas established by the Copernicus EMS within ~~the~~ Sant Llorenç des Cardassar village.

The damage assessment comparison between the two sources was developed by means of ~~applying~~ a cartographic overlay with GIS tools. ~~In order t~~To provide greater ~~more~~ accuracy, detailed territorial information and ~~also~~ flow direction were also incorporated. First~~ly~~, the type of buildings and land use~~s~~ at the urban plot scale from the General Directorate for the Cadastre (http://www.sedecatastro.gob.es/) were included. Second~~ly~~, ~~an estimation of~~ the flow direction in the urban network was calculated with Arc Hydro Tools (ESRI, 2019). This gave ~~in the urban network were used to~~ a preliminary assessment of the role of ~~hydrological~~ hydraulic processes in physical damage~~ing~~., Due to the flow direction, this is mainly related to the velocity vector component perpendicular to the building element surface (Amirebrahimi et al., 2016). The results are ~~presented~~ given in~~through~~ a set of tables and ~~cartographies~~ maps that summarize the effects of the event and help to reflect on its causes and consequences.

2.7~~6~~ Sediment Connectivity ~~and geomorphic change detection~~

~~Besides~~ As well as the hydrogeomorphological monitoring tasks, the 15th October 2018 MEDhyCON Research Group ~~was incorporated~~collaborated in ~~to~~ the Emergency operation~~al~~ to ~~collaborate in the~~ search ~~o~~for a missing person during the flash flood who had not yet been found ~~yet by then~~. Firstly, and taking into account~~consideration~~ the emergency situation, the index of (water and sediment) connectivity at the catchment scale was applied to find ~~out~~ the areas with the greatest sediment deposition potential, which were where victims could have been buried by the flash flood. The sediment connectivity index (IC) proposed by Borselli et al. (2008) and modified by Cavalli et al. (~~Cavalli et al.,~~ 2013) ~~was applied to~~ determined the preferential flow~~ux~~-paths by exploring the water and sediment transference patterns ~~between~~ in different landscape compartments of the entire ~~study catchment;~~ Ca n'Amer River. Thus~~In this way~~, the IC is a dynamic property of the catchment that indicates the probability of a particle at a certain location ~~to~~ reaching a defined target area, which in this study was established at the catchment outlet (Trevisani and Cavalli, 2016). This morphometric index was mainly derived from a HR-DTM, in this case, a 1 m LiDAR-based DEM dating from 2014; http://pnoa.ign.es/coberturalidar. The IC was calculated as follows:

$$IC = \log 10\left(\frac{D_{up}}{D_{dn}}\right) = \log 10\left(\frac{\bar{W}\,\bar{S}\,\sqrt{A}}{\sum_i \frac{di}{WiSi}}\right) \quad (3)$$

where D_{up} and D_{dn} are ~~an~~ up- and down-slope components respectively, $\bar{S}$ average percentage slope, A the size of the upslope contributing area, $\bar{W}$ an averaged weighting factor representing terrain roughness and a flow length di of the i^{th} cell along the steepest downslope direction. IC was calculated by using the freely available *SedInConnect* (Version 2.3) software developed by Crema and Cavalli (2018).

2.7 Geomorphic change detection

Secondly, in addition to the ability of HR-DEMs in facilitateing the improvement of the sediment connectivity as a powerful tool to determine the preferential fluowx-paths and those areas with the greatest potential sediment deposition. T, the present study evaluation ofed the flash-flood landforms signature of the event by using UAVs is the second part of creatingas a tool for a rapid response of post-catastrophe search and rescue tasks by applying hydrogeomorphological precision techniques. The estimation of overbank sedimentation allowed the calibration of the predicted large sedimentation by IC mapping and its reliability in detecting sites where victims might be buried by flood sediment.

The latest technological advances in remote data acquisition (i.e., UAVs) and topographic modelling (i.e., Structure for Motion –SfM– and Multi-View Stereo –MVS–) led to a huge advance in Earth and environmental sciences. Following the incorporation of MEDhyCON to the emergency operationsve, several UAV flights were carried out all along the Ca n'Amer River, from the headwaters (Begura de SaumàSalma River) to its outlet into the Mediterranean Sea at the village of S'Illot (Fig. 21c). This fieldwork involved the establishment and survey of more than 250 ground control points (GCPs), needed for an appropriate geo-referencing of the aerial photographs taken by the drone. Therefore, on 15th October 2018, just six days after the flash flood, evidence of erosion was recorded by aerial photographs taken with a small unmanned aerial vehicle (UAV *DJI Phantom 4 Pro*, < 2 kg) and its conventional camera. The sensor dimensions are 12.83 x 8.60 mm, 5472 x 3648 px. The camera was calibrated by means of the *Agisoft Lens*, an automatic lens calibration routine included in *Agisoft Metashape* that uses the LCD screen as a calibration target and enables the full camera calibration matrix, including non-linear distortion coefficients (*Manual* Agisoft Lens, 2018), to be calculated. Resolution was set at 20 Mpix, shutter speed at 1/2,000 s and focal length was 8.60 mm. Most of the active zones of the main stream –including the floodplain corridor– with evidence of erosion and deposition were surveyed, which also ensureding the recording of high-water marks.

Imagery acquired during the aerial campaign enabled (1) the creation of mosaics of aerial georeferenced images and (2) the generation of high-resolution digital terrain models (HR-DTM) with a cell size of 0.05 m. These were produced by *Agisoft Metashape Pro® v1.5.3* using automated digital photogrammetry techniques. This software obtains high-quality results easily from algorithms known as 'Structure-from-Motion' (SfM). Further details on the implemented algorithms can be found in Lowe (2004) and Westoby et al. (Westoby et al., 2012). For the proper acquisition of the imagery, flight altitude was set at 70 meters, ensuring ground resolution close to 0.02 m pix^{-1}, and the camera was programmed to shoot every 15 m, flying at an average speed of 5 m s^{-1}.

Once all the drone images were geo-referenced and properly mosaicked, topographic modelling (i.e., Structure from Motion) was applied to generated the post--flash-flood very-high--resolution DEM (i.e. 5 cm pixel size). The comparison of that DEM to that of the catchment prior to the catastrophic event (LiDAR-based DEM dating from 2014) allowed the quantification and assessmenting of the actual magnitude (competence) of the event in terms of, e.g., the volume of sediments eroded and/or deposited and the, alteration of the fluvial morphology. It is worth noting that no geomorphic changes were observed between 2014 and October 2018, by photointerpretation of aerial imagery (PNOA, 2015) and the continuous measurement of water stages since January 2015, with no overbanked flood events. Consequently, geomorphic changes were estimated in a floodplain downstream ~~floodplain of~~ from~~the~~ Sant Llorenç des Cardassar to evaluate the amount of overbank sedimentation in the area of the rescue where IC suggested the search. ~~The m~~Measurements were ~~developed~~ taken with~~using~~ a procedure, similar to DoD, that compar~~ing~~ed the elevation of the ground class points extracted from the LiDAR topography collected in 2014 (http://pnoa.ign.es/coberturalidar) and the points extracted from the 0.05 m-~~-~~resolution DEM obtained by the UAV flight at~~in~~ the same coordinates. Errors (RMSE) in xyz of the UAV DEM w~~as~~ere calculated for 12 precise coordinates~~'~~ points (different from those GCPs used for image geo-reference and located on surfaces not modified by the flash flood) within the floodplain area of volumetric measurements, which were being < 0.175 m.

3 Results

3.1 Catchment hydrological dynamics

The hydrogeological and geomorphological characteristics of the Mallorca river catchments control its surface water/groundwater interactions and thus ~~hence~~ generated~~ing~~ different streamflow regimes (cf. Estrany et al., 2009). The headwaters of all sub-catchments and the tributaries that drain the Llevant Ranges and Marinas are ephemeral due to the high degree of fracturing, fissuring and karstification, which favour~~ing~~ infiltration and percolation through perched karstic aquifers unconnected ~~from~~ to the main stream channels.

The hydrological monitoring period assessed in this paper by using data from ~~in~~ the hydrometric station was from 10th January 2015 to 30th September 2018 (Fig. 6~~5~~). The month of~~, excluding the~~ October 2018 month was reserved to develop a singular and deeper study that could describe better ~~when~~ the catastrophic flash-~~-~~flood event ~~occurred~~ (see results in sub-section 3.2). This gives a series of almost 4 hydrological years under hydrometeorological conditions illustrating ~~an~~ ephemeral behaviour of the Begura de ~~Saumà~~Salma River that was~~, being on~~ average in terms of precipitation (see the inset table of Fig. 6~~5~~). In terms of Q, this inset table also shows the behaviour during the study period of several~~different~~ hydrological parameters. However, these values ~~are~~ cannot ~~possible to~~ be compared ~~at~~ in the long-~~-~~term due to errors of up to two orders of magnitude in Q values measured by the hydrometric network managed by the Balearic Islands Government (cf. Fortesa et al., 2019). Events of different magnitudes occurred during this study period, some of them representative of recurrence ≈ 5 years in terms of rainfall. However, only two events recorded peak Q (here~~in~~after Q_{peak}) values > 1 $m^3\ s^{-1}$, both occurring~~ed~~ in January, when the hydrological pathways were completely active due to saturation processes. In January 2015, ~~with~~ 120 mm of rainfall within 48 h at the AEMET-B630 Ses Pastores rainfall station (see location in Fig. ~~1~~2), cre~~gener~~ated a flow response with a Q_{peak} of 2.8 $m^3\ s^{-1}$. Finally, 153 mm of rain ~~were~~ accumulated in January 2017 ~~with~~in 72 h with a Q_{peak} of 4.8 $m^3\ s^{-1}$, the maximum recorded ~~in~~ at the hydrometric station during the study period before the catastrophic flash flood.

3.2 Hydrological response of the flash flood

The hydrological response of the flash flood was analysed through variables derived from the rainfall (Table 1a, 7 variables) and runoff (Table 1b, 9 variables) of the catchment: Event rainfall duration: duration from the beginning of rainfall until it stopped; Time of maximum rainfall: time of the highest rainfall intensity; Centroid storm: central time of the rainfall event; Average radar rainfall: mean rainfall obtained by radar; IP_{max} average radar: average of the highest rainfall intensities obtained from radar rainfall points; IP_{max} radar: highest rainfall intensity obtained from radar data; IP average radar: average of rainfall intensities obtained from radar rainfall points; Runoff: discharge volume amount divided by the catchment area; Runoff ratio: ratio between runoff and rainfall, also known as runoff coefficient when is expressed as a percentage; Event duration: duration of the flood event; Q_{max}: peak discharge; Time Q_{max}: time the peak discharge lasted; T centroid storm – T Q_{max}: duration between the time of the rainfall centroid and the time of the discharge peak; $Q_{average}$: discharge average during the flood event; Unit peak discharge: peak discharge divided by catchment area, allowing the comparison of peak discharge regardless of catchment size; Reduced Unit peak discharge: discharge peak divided by catchment area in square kilometres elevated by 0.6. The exponent was obtained from Gaume et al. (2009), who applied this last parameter to compare reduced unit peak discharge from different flash-flood events. The duration of the rainfall event was ca. 10 h and the average catchment rainfall amount was 249~~6~~ mm for both the Blanquera and the Begura de ~~Saumà~~Salma catchments. Average and maximum rainfall intensities in 10 minutes were respectively 25~~4~~ mm h^{-1} and 45~~6.4~~ mm h^{-1} (Table 1a). However, spatial differences in rainfall depth within the catchments could be seen~~an be observed~~. Thus~~In this way~~, the total rainfall amount ranged spatially within the catchment from 170 mm (see R1 Fig. 7~~6~~) to 285 mm (See R5 and R6 Fig. 6), ~~being~~ with the highest rainfall amount in 1 h occurring at R12 (~~i.e.,~~ 77.2 mm). These highest rainfall values occurred at the headwater parts of the Begura de ~~Saumà~~Salma River catchment (~~i.e.,~~ R12 Fig. 7~~6~~) at~~during~~ 15:00 h, the beginning of the event~~; i.e., 15:00 h~~. At 17:00 h, the convective train was moving very slowly causing ~~that~~ a new peak of rainfall amounts in 1 h ~~were~~ located in the downstream part of this catchment with values between 60 and 70 mm recorded at R5, R6 and R9 (Fig. 7~~6~~). During the last part of the event, at 19:00 h, rainfall amounts in 1 h of 60 mm h^{-1} were recorded from R2 to R5.

Rain started to fall at 15:00 h (official time; UTC + 2 h). At 18:00 h, its amount was already 104.2 ± 20 mm h^{-1}, but the runoff response was insignificant with Q ~~i.e.~~ 0.089 $m^3 s^{-1}$. However, one hour la~~af~~ter, at 19:00 h, with rainfall reaching an amount of 144.6 ± 36.8 mm h^{-1} Q was already bankfull,~~;~~ i.e., 120 $m^3 s^{-1}$. This was probably ~~-~~because the catchment's soil infiltration capacity ~~of the catchment~~ was ~~likely~~ exceeded, which caused ~~promoting~~ a rapid overland flow ~~generation~~. Consequently, only 15 minutes later, Q_{peak} was recorded (i.e., 442 $m^3 s^{-1}$) ~~and hence~~which triggered~~ing a~~ catastrophic flood. ~~Furthermore~~In addition, Q values continued ~~being~~ to be high (i.e., > 135 $m^3 s^{-1}$) until 20:45 h due to the convective train maintaining~~ed~~ rainfall intensities > 24 mm h^{-1}. At 00:00 h, the rainfall event finished and Q ~~being~~ dropped sharply ~~reduced~~ to 0.016 $m^3 s^{-1}$. T~~he t~~able 1b summarizes the most important runoff parameters, shedding further light on the hydrology of this flash-flood event.

3.3 Reproducing the flashy hydrological response of the catchment~~Hydrological modelling~~

The hydrological model ~~previously~~ described above ~~was us~~helped to ~~better~~ understand the process better during the event. The results of the hydrological model simulation can be seen in Figure ~~6~~7. The input data used in the model were~~as~~ the continuous radar dataset described ~~previously~~ above and the temperature measured at the surrounding meteorological stations; i.e., three stations ~~located~~ within a radius of 12 km. The model was calibrated to reproduce the event and the final parameters were set to:

- $H_{GR,max}$ = 1.4 m
- $H_{GR,threshold}$ = 0.215 m
- K_{karst} = 0.045 m
- Initial conditions of the GR reservoir: $H(t_0)$ 0.08 m, corresponding to a low soil saturation.

The relative volume error was 6% between the simulation and the measurement. The simulated peak ratio was ~~of~~ 437.7 m^3 s^{-1}; with an estimated runoff coefficient of 37.8%. The recession limb was not as sharp as the measured *Q*. It is worth~~y to be~~ noting~~ed~~ that it was not possible to simulate~~ing~~ *Q* ~~under~~with the same magnitude as the *Q* measured ~~*Q*~~ during the episode with a non-modified version of the GR3 model.

The same parameters were ~~applied over~~used for the entire headwater catchment. Accordingly, the Q_{peak} from the other headwater tributary located on the west flank of Sant Llorenç des Cardassar village (Sa Blanquera) was estimated by the model to be 77.2 m^3 s^{-1}, corresponding to an estimated runoff coefficient of 22.7%.

3.4 Socioeconomic and territorial flood damages linked to hydrogeomorphological processes~~Damage assessment~~

The flash ~~-~~flood caused ~~a~~ great~~high~~ social and economic repercussions in ~~the~~ Llevant County and the whole of Mallorca~~ Island~~, as well as ~~an~~ extensive national and international media coverage. The flash-flood event was a catastrophe with 13 deaths and economic damage ~~of~~ with great importact~~nce~~ on the population and infrastructure. The~~is~~ number of casualties ~~impacted the national and international opinion~~ in one of the most important international tourist~~ic~~ resorts, considered traditionally safe, shook national and international opinion. For further assessment of~~n~~ the media impact, see Table S1.

The damage assessment report carried out by the Emergency Services of the Balearic Islands Government ~~illustrated~~ showed an unprecedented mobilization of resources in the Region during the first week after the catastrophe in ~~according~~ line with~~to~~ the high number of victims and amount of damage~~s~~ (Table 2; Pol, 2019). The initial costs of the emergency works exceeded 1.5 million € including the following actions: cleaning and restoring river channels, demolition of walls and structures affected, removal of potential polluting sources (Pol, 2019b). The declaration of disaster area is regulated by ~~the~~ Spanish Law 2/2018, other complementary laws (BOE, 2018, 2019) and ~~-~~Decree 33/2018 (GOIB, 2018). The~~i~~se laws established~~s~~ public support for alleviating the basic needs of families, deaths, housing assistance, ~~and~~ aid~~s~~ for loss of vehicles and~~ also~~ support for the ~~affected~~ economic sectors affected. The laws provided assistance~~additionally aid~~ for the repa~~ration~~r of public infrastructures and environmental damage, also specifying the amount of aid and theits administrative procedures to receive it. These regulations referred to all the affected areas, including the municipalities of Sant Llorenç des Cardassar, but also Artà, Capdepera, Son Servera and Manacor. Recovery was financed jointly by the different public administrations: the Spanish Government, the Balearic Islands Autonomous Government, the Insular Government, and the Sant Llorenç des Cardassar City Council. In April 2019, the expenditure of the Regional Government had reached 30.4 million euros in recovery and mitigation actions (GOIB, 2019). This expenditure included aid to the affected towns and villages of 11.27 million € (2.7 million € for the Sant Llorenç des Cadassar City Council), aid to companies of 3.3 million, for rehabilitation of homes (1.6 million), vehicle recovery (1.5 million), social aid (1.2 million) and 0.264 million euros for deaths.The initial costs of the emergency works exceeded 25.5 million € including the following actions: cleaning and restoring river channels, demolition of walls and structures affected, removal of potential polluting sources (GOIB, 2018). The Sant Llorenç City Council, deployed various funds from the Spanish Government and Autonomous and Insular Governments for an investment plan in Sant Llorenç des Cardassar of 3.51 million € (Ajuntament de Sant Llorenç des Cardassar, 2018). In parallel, the Insurance Compensation Consortium (CCS, 2018), is the Spanish public agency for managingthat handles payments to affected people in cases of damage caused by catastrophic events, . This agency published in December 2018 a list of processed claimdossiers forin theis flash- flood as well as the total amount ofall the payments followconsidering the damage assessment after the disaster in the Sant Llorenç des Cardassar village. A total of 7741,830 dossiers claims were processed, being paid an amount ofwith 6,842,4685,392,540 € paid out (see Table S2).

A territorial and hydrological analysis of the damage assessment is here developed here. The location of the affected buildings and the WS reached in the streets and buildings provided by the DG of Emergencies Department of the Balearic Islands Government and by the Copernicus EMS allowed to mapenabled three different affected zones within the urban area of Sant Llorenç des Cardassar to be mapped (Figure 87a). Zone 1 is producedw as a result of due to the overbank flow of the Begura de SaumàSalma River and correspondeds mostly to the delimitation of affected areas carried outdefined by the Copernicus EMS. In this Zone 1, the highest WS in the streets was reached, exceeding 3.3 m. The Zones 2 and 3 corresponding were to those urban areas affected by the overbank flow of the Sa Muntanyeta Creek, located in the northernmost area of the village. The streets of Sant Llorenç des Cardassar rerouted the overbank flow from both the Begura de SaumàSalma River and the Sa Muntanyeta Creek (Fig. 87b and 7c), causing significant damages to vehicles and public movable goodspublic property. In addition, as most of the buildings of in Sant Llorenç des Cardassar use the ground floor as a home or business, so the event caused a major inundation offlooding by water and mud that made theirdisabling its use impossible and requireding tasks of cleaning and restoringation. In aAccording to the Balearic Islands Government, 392 damaged buildings and plots were inventoried inat the urban area of Sant Llorenç des Cardassar, being located most of them in the Zone 1 (Figures 87cd and 87de). The flow direction illustrated how the N-> S direction, parallel to the Begura de SaumàSalma River, was that caused the most damage in the Zone 1, with 3498 affected buildings and a WS average of ca. 1.03 m. The Zones 2 and 3 showed had lower- -intensity damage, being with 37 and 6 the affected buildings and a maximum WS of 1.80 m and 1.60 m, respectively.

In these Zones 2 and 3, the flow direction ~~did not illustrate~~had no ~~a ~~clear pattern because the Sa Muntanyeta Creek ha~~i~~s a small catchment (~~i.e., ~~2.2 km^2) and the urban street network and ~~parcels ~~plots are not parallel to its natural flow direction.

The ~~cartographies ~~maps included in the Balearic Flood Risk Management Plan (GOIB, 2016) indicate the urban area of Sant Llorenç des Cardassar as a maximum risk area. Accordingly, the Plan developed an analysis of the potentially affected areas by recurrence periods of 10, 100 and 500 years (Figure 8~~7~~e~~f~~). In addition, Table 3 ~~summarizes ~~analyses the damaged buildings ~~analysing ~~to see if they are included in these~~is~~ official flood risk areas in accord with~~ing~~ ~~of ~~the ~~explained ~~recurrence periods. None of the flood risk maps for different return periods encompassed the areas affected as a result of the event. The 10-year recurrence map only included~~s~~ 25% of the affected areas; the 100-year covered~~s~~ 48% of the area~~se~~ damaged~~s~~; while the 500-year map only reached ~~the~~ 60% (Table 3).

On c~~C~~omparing the affected zones where damaged buildings are also depicted ~~with ~~in the Copernicus EMS ~~delimitation~~, some differences between the initial flash-flood ~~delimitation ~~definition carried out by the Copernicus EMS-EU and the distribution of damaged buildings ~~can be observed~~were found (Figure 7f) in Zones 2 and 3. It is worth~~y to be~~ noting~~ed~~ that the post-event definition~~limitation~~ of the Copernicus EMS (Copernicus Emergency Management Service, 2018) covered ca. 90% of the real damage~~s~~.

3.5 Sediment Connectivity and geomorphic change detection as emergency tools

The search ~~of ~~for the only ~~missing ~~person missing during the flash flood who had not yet been found ~~yet ~~6 days after the storm ~~produced ~~caused considerable~~a high~~ social ~~impact ~~consternation in the Balearic Islands and beyond. Subsequently, ~~the application of ~~hydrogeomorphological precision techniques ~~was ~~were crucial. A~~ with a~~ very intense topographical survey ~~carried out to build~~constructed very-high-resolution (i.e. 5 cm pixel size) digital elevation models and orthophotomosaics. First~~ly~~, ~~and taking into consideration~~given the emergency situation, the index of (water and sediment) connectivity at the basin scale was ~~applied to find out~~used to identify those areas with the greatest sediment deposition potential (Fig. 9~~8~~a). The IC allows ~~a better~~good understanding of the sediment transfer processes within drainage catchments. The most connected areas of a basin are those in which their different compartments are more powerfully linked. That favours ~~a ~~the largest water surface ~~fluxes ~~flow generation, and thus erosion and, potentially, larger soil losses. On the c~~C~~ontrar~~il~~y, the zones with low connectivity are those ~~in which their~~whose topographical characteristics disconnect ~~the ~~water and sediment flow~~uxe~~s, acting as ~~like ~~storage or deposition areas. The IC was applied to the whole Ca n'Amer River basin but ~~it ~~was ~~just ~~only analysed from the point where the missing person was last seen (Fig. 9~~8~~b, point 1). That was the exact point where the car in which he was circulating was swept away by the flood-wave. Therefore, the preferential water and sediment paths ~~which were ~~most likely to be followed by the flood ~~fluxes ~~flows were identified, as well as the most important deposition areas downstream from the last point person was~~'s last sight point~~ seen. The~~Such~~ most likely deposition zone was identified~~,~~ and immediately communicated to the Emergency Authorities, upstream from the bridge of the road Ma-15 which crosses ~~over ~~the Ca n'Amer River ~~around ~~about 1 km below ~~the ~~Sant Llorenç des Cardassar~~ village~~. The~~n the~~ search~~ing~~ activities ~~were ~~concentrated ~~at~~on that~~ precise~~ area, which is where the last victim was ~~actually~~ found (Fig. 9~~8~~b, point 2) when the Emergency Authorities had decided to move their~~se~~ search~~ing~~ activities to the mouth~~debouching area~~ of the Ca n'Amer River and beyond into the Mediterranean ~~Sea~~.

In addition to the ability of HR-DEMs ~~in facilitating~~to the improve~~ment of the~~ sediment connectivity as a powerful tool to determine the preferential flow~~ux~~-paths and deposition areas, the present study evaluated the landforms signatures of the event by using UAVs as a tool for a rapid response of post-catastrophe search and rescue tasks along the whole downstream section of the Ca n'Amer River from the village of Sant Llorenç des Cardassar, in order to measure effectively ~~quantify~~ the sediment deposits generated by the flash ~~-~~flood and to locate~~ing~~ and quantify~~ing~~ the most important deposition areas downstream from where the person~~'~~ was last seen ~~sight point~~. As the last missing person was found ~~with the application of~~ by using the connectivity index, in the end the sediment deposition quantification was ~~finally~~ not ~~necessary~~ needed during the Emergency operation~~al~~. However, ~~in~~ this study checked~~,~~ its validity by ~~the~~ assessing~~ment was carried out at~~ the floodplain area where the~~is~~ last person was found ~~in order to check its validity~~. Accordingly, for each of the 7103 LiDAR points ~~included in~~on the right ban~~c~~k of the Ca n'Amer River the elevation was compared~~, and f~~From the differences interpolated (TIN), an elevations raster ~~from which~~for a total volume of 844.28 m^3 was calculated, for an area of 12,254 m^2. The irregular distribution of the sediments in Fig. 9~~8~~c~~d~~ responds to the rescue mobilisation. In the gaps visible in the sedimentation area of ~~the~~ Fig. 9~~8~~c, ~~d~~ vehicles and search machinery w~~h~~ere removed and not included in the volumes.

4 Discussion

~~4.1 Hydrological response and flash flood modelling in small Mediterranean karstic catchments~~

The flash-~~-~~flood event described in this study fits with the monthly distribution of flash floods in Spain carried out by Gaume et al. (2009):~~,~~ ~~being~~ October is the month with the highest number of this type of flood ~~type~~ events. ~~Furthermore~~In addition, the hydrological characteristics of the event were comparable with the flash-~~-~~flood requirements established by Amponsah et al. (2018) ~~to be included~~for inclusion in~~to~~ the EuroMedeFF database, which are a ~~unit~~ Q_{peak} unit higher than 0.5 m^3 s^{-1} km^2, a spatial extent lower than 3,000 km^2 and a storm duration shorter than 48 h. In this case, the ~~unit~~ Q_{peak} unit was 19 m^3 s^{-1} km^2 and the storm duration was 10 h. In addition, the characterization of 60 extreme flash-~~-~~flood events carried out by Marchi et al. (2010) offers a framework for comparing ~~to compare~~ the event on the~~f~~ Begura de ~~Saumà~~Salma River with other flash floods, in terms of ~~regarding the~~ rainfall amount, rainstorm duration, catchment area, lag time, runoff coefficient and ~~unit~~ Q_{peak} unit. With a rainstorm duration of 10 h and a mean rainfall amount of 249~~6~~ mm, the event is located within the flash-~~-~~flood group of events with the highest rainfall intensities, which is a key factor for extreme events due to the question of controlling the magnitude of the runoff response. This group of events ~~is mainly composed~~consists mainly of ~~by~~ Mediterranean and Alpine-Mediterranean catchments. The relationship between catchment area and lag time ~~or response time~~ is located within the lowest flash flood response time ~~exceeded any flash flood~~ reported ~~until nowadays~~still now. The lag time of the event (~~0.25~~2.1 h) was ~~significantly lower than~~the lowest of ~~the lower limit defined through envelope curves~~extreme flash-flood events with streamgauge data reported in Marchi et al. (2010). In addition, the maximum rainfall accumulated in the whole catchment occurred at 19.00 h (45 mm; see Table 1a), just 15 minutes before the Q_{peak}. This short response time was caused by a combination of geographic characteristics of the catchment as well as the occurrence in time and space of maximum rainfall amounts and intensities (Fig. 7~~6~~), as ~~it has been depicted~~is explained in sub-section 3.2. In addition to rainfall characteristics, other factors that play a key role ~~over~~ in flash floods are lithology and ~~antecedent~~ prior wetness conditions. On the one hand, low runoff coefficients have been reported in karst areas with carbonate lithology due to high infiltration rates (Li et al., 2019). On the other hand, ~~Marchi et al. (~~Marchi et al.~~,~~ (2010) reported differences in the median runoff coefficient up to 23%, which were higher on flash floods occurring~~ed under~~ when prior~~ wet antecedent~~ conditions were wet. The flash-flood event of the Begura de ~~Saumà~~Salma River occurred under dry antecedent conditions because the rainfall amount for the 9 preceding days ~~before~~ was only 6.4 mm in a period when evapotranspiration was still high as temperatures were quite warm (i.e.~~,~~ 20ºC). Despite these dry antecedent ~~wetness~~ conditions, the runoff coefficient of the event (i.e., 35~~6~~%) was analogous to the median runoff coefficient under average wetness conditions (37%) reported by Marchi et al. (2010), rather than dry ones (20%)~~, as reported by these authors~~. This runoff response ~~illustrated the key role~~resulted from the combination of rainfall intensity and its spatial distribution, complex geology and land cover disturbances in ~~the~~ generation~~g of~~ a high Q_{peak} (i.e., 442 m^3 s^{-1}) with~~ a~~ high potential for~~to~~ generating~~e~~ geomorphological changes. ~~In this way~~Thus, the ~~unit~~ Q_{peak} unit obtained (i.e., 19 m^3 s^{-1} km^2) can be classified as the third highest value of all the reported values in ~~Marchi et al. (~~Marchi et al.~~,~~ (2010) and the highest of those values obtained from streamflow measurements in a hydrometric station and not by post-event analysis. The hydrologic response analysis in the course of a flash flood shows how storm structure and evolution result in a scale-dependent flood response (Borga et al., 2007). Consequently, spatial rainfall organisation, geology combined with orography and land cover disturbances led to pronounced contrasts in the flood response at the Begura de Salma River. Spatial rainfall on the catchment scale showed that the highest accumulation at the beginning of the storm was located at the headwaters of the catchment (at 15:00 h), whilst during the last part of the event the most important rainfall amounts were located in the downstream part. Examination of the flood response illustrated how the extent and the position of the karst terrain (Zanon et al., 2010) and soil conservation practices (Calsamiglia et al., 2018; Tarolli et al., 2014) provided major geological and anthropogenic control of runoff response. Impervious materials cover 74% of the Begura de Salma River catchment, mostly located at the headwaters, which are responsible for the highest values of topographic torrentiality (Estrany and Grimalt, 2014), facilitating rapid overland flow generation. During the first part of the storm, when the highest rainfall amounts affected the headwaters, runoff response was delayed by the laminar effect of check-dam terraces and field terraces massively constructed over Cretaceous marls and Lias limestones respectively (Calvo-Cases et al., 2020) and by the predominance of percolation in those areas covered by limestone, mostly in the intermediate parts of the catchment. During the last part of the event, when the highest rainfall intensities were in the downstream part, the excess of soil infiltration capacity and the collapse of headwater check-dam structures triggered the sudden increase in discharge from 120 to 442 m^3 s^{-1} in only 15 minutes at the hydrometric station. Moreover, the increase of 5 km^2 (21% of the catchment area, see more details in section 2.1) of natural vegetation since the 1960s as a result of afforestation processes, increased fuel loads and the risk of wildfires led to 1.7 km^2 (7% of the catchment) being burned since 1980. The removal of vegetation by fires has a similar effect (less interception, less soil storage), which has been experimentally documented after major fires. These factors are a major reason why the history of the steady devastation of plant cover in the Mediterranean is likely to enhance flood risk (Wainwright and Thornes, 2004) and increase desertification tendencies.

The hydrological model ~~has been~~was calibrated specifically for the flooding event. The parameters of the modified GR reservoir as well as the initial conditions were adjusted to best represent the flooding event. A very sensitive parameter is the $H_{GR,threshold}$, which regulated the time when additional water reserve in the soil was released. Modelling results were also very sensitive to initial conditions (soil saturation) before the rainfall event. During the calibration process, it was necessary to simulate, on the one hand, smaller flood events observed at the hydrometric station. On the other hand, the model had to reproduce the historical 2018 flood event. However, the flood event could not be reproduced when the model was calculated for a long time period, due to initial conditions that were not adjusted prior to the event. In this context, the initial condition $H(t_0)$ was manually adjusted~~ manually~~, as numerical models applied to simulate catchment runoff response are often unsuccessfully implemented for Mediterranean-climate catchments due to show very heterogeneous responses over time and space (Merheb et al., 2016). The uncertainty for the results regarding the Sa Blanquera River was higher because of the lack of hydrometric data in this catchment. There was no karstic behaviour of the model within this subcatchment, which was the main modelling uncertainty for this ungauged subcatchment. The model analysis clearly showed that, without any massive water storage during the first part of the rainfall event, which was released at the Q_{peak} of the event, it was impossible to reproduce the correct flood magnitude and the very short lag time. This water storage ~~can~~ may be due to underground karstic volumes combined with pipes, or storage / dam break effects. Only future large flood events will ~~allow~~ enable ~~us to~~ validation ofe the chosen parameters, as the 2018 flood event was the only one needing a karstic component in the rainfall model to be correctly represented by the model.

The predictability of flash-flood events is ~~a non-solved issue~~unresolved, especially because forecasting of intense thunderstorms hais also not beenn- solved ~~for~~ by operational meteorology. Even using one of the best state-of-the-art weather forecasting models, Harmonie/AROME, the Spanish National Weather Service (AEMET) only activated a yellow warning for one-hour accumulated precipitation of 20 mm beforehand. In contrast, the synoptic situation was ~~well~~ forecasted well by global forecasting models some days before the event. An experienced~~mented~~ forecaster could anticipate the occurrence of an intense thunderstorm by using these models, but ~~without~~ would lack any quantitative or geographical precision, which are two key factors in flash-flood forecasting. -However, now-casting products, based on radar, satellite and ground- truth may ~~allow a better~~ anticipateion of severe weather situations better. These products are updated ~~at a high frequency~~every often (several minutes to one hour) and compensate the weather forecasting models which are updated ~~with a lower frequency~~less often. The main challenge ~~to apply~~in using the hydrological model ~~in~~ as a~~n early~~ flash--flood early warning system is ~~a good estimate of~~to include correctly initial ~~conditions of the~~ soil saturation conditions as well as accurate rainfall forecasts. For the latter~~ one~~, the scientific community is working on now-casting products that typically deliver short-term (few hours lead time) rainfall forecasts ~~which~~ that are updated ~~on a high frequency~~very often, from a base of 10 minutes to an hour~~ly base~~. These forecasts are based on real-~~-~~time measurements ~~which~~ that combine data from radar~~s~~, satellites and meteorological stations. ~~On the other hand~~However, it is hard to ~~automatically estim~~ calculate initial conditions automatically, as the river is dry most of the time and ~~without~~ there are no soil moisture measurements in the catchment. Data assimilation and automatic adjustment of initial conditions, which are usually applied in operational forecasts, are therefore not relevant here. However, an early warning system can be built using the model proposed in this paper by assessing the uncertainty of the forecast~~, for instance by using different scenarios of initial conditions of soil saturation. Since the proportion of rainfall lost as runoff rises significantly as the percentage of vegetation cover falls below about 30%, bare soils produced a large runoff coefficient~~. ~~Moreover, soils in the Mediterranean often have low infiltration capacities because the soils dry out in the summer, following the winter moisture. Fine surface "seals", ca. 1-2 mm thick, may increase the runoff rates. Sometimes evaporation leads to chemical as well as mechanical seals (often of calcium carbonate) that again reduce infiltration rates vary dramatically. Mediterranean soils with high erosion rates also often have stones exposed at the surface (Schoorl et al., 2004). The stony soils create higher runoff rates and lower infiltration rates when rock fragments are poking out on the surface (Poesen and Lavee, 1994). A hydrology knowledge suggests that flooding is intimately related to land use and that the progressive history of the devastation of plant cover in the Mediterranean is likely to enhance the flood risk (Wainwright and Thornes, 2004). These factors are a major reason for concern about desertification. Moreover, thicker soils can hold more water if they are permeable and as the soil is eroded, this storage is reduced to produce a downward spiral of more runoff, more erosion and more flooding. The removal of vegetation by fires has a similar effect (less interception, less soil storage) and this has been experimentally documented after major fires. In the first few years runoff is usually observably higher because the soils are made hydrophobic (water-resisting) by fire and because there is less vegetation and less soil to store the rainfall.~~

At present, Mallorca does not have any sort of early warning system to assist flood risk management, and nor of course has Sant Llorenç des Cardassar. Similarly, no hydrometeorological early warning was issued by the competent authorities, as the Balearic Islands have no operational hydrological control network releasing real-time information on discharges. In October 2018, Sant Llorenç des Cardassar was one of the four municipalities in Mallorca with a flood risk emergency plan. However, it was not operational at the time the emergency was declared. As a result, the population was completely unaware of how to defend themselves, even during the emergency phase, although Sant Llorenç des Cardassar municipality had significant social vulnerability to floods, as most of the casualties were tourists and the elderly.

~~4.2 Flood damages and hydrogeomorphological techniques as decision-making tools for a rapid response of post-catastrophe operations~~

The ~~incorporation~~ addition of the MEDhyCON research group on~~the~~ 15th October 2018 to the Emergency operational allowed the application and testing of hydrogeomorphological precision techniques. The fundamentals are that flood risk plans and Emergency activities are based on a thorough understanding of linkages between sediment and catchment compartments at all stages of flood events. Integrating topography-based connectivity assessment (Kalantari et al., 2017) and geomorphic change detection ~~can~~ may be a crucial ~~to~~ support to decision-making in flood risk planning and ~~also~~ in Emergency surveys, as ~~it has been demonstrated in~~ this study shows. The combination of hydrological and sediment connectivity (IC in various forms) with other key natural characteristics (i.e., soil type and topography by using LiDAR-based HR-DEM), along with ~~as well as~~ the integration of territorial information such as land cover/uses by using Cadastre data bases (Piaggesi et al., 2011), ~~has~~ results~~ed~~ in a powerful tool ~~as it has been demonstrated validated in this study~~. Accordingly, the easy-to-calculate IC can be an effective tool for rescue tasks after extreme flash-flood events with a huge erosion capacity.

~~Besides~~In addition, the post-event delimitation and damage assessment released by the Copernicus EMS (Copernicus, 2018) ~~allowed the~~ identified~~cation of~~ ca. 90% of the real damage~~s~~ in this traditional Mediterranean village, ~~such as~~ Sant Llorenç des Cardassar, consisting of ~~composed by~~ compact blocks of buildings and plots. The Synthetic Aperture Radar (SAR) technology with very high spatial resolution (1-3 m; Plank, 2014) is fundamental to obtaining ~~a~~ high efficiency and accuracy of this rapid mapping tool at low cost. Consequently, Emergency resources can be directly concentrated on the most damaged areas without ~~the need of~~having to check~~ing~~ the entire affected area on the ground.

The increase in the torrentiality of rainfall as a result of climate change in the Mediterranean region may exacerbate the level of exposure ~~to floods~~ of urban areas and infrastructures to floods. ~~causing an~~Catastrophic events will increase in quantity and ~~also in~~ intensity ~~of catastrophic events~~. ~~Public administrations~~Local government bodies will need to adapt continuously ~~should develop a continuous adaptation of~~ prevention and management of flood risk tools to these new scenarios. The legal framework for flood risk planning and management (GOIB, 2016) ~~evidenced~~ showed that the level of risk exposure was extensively known. In addition, the analysis of current regulations shows that the appropriate preventive measures were being taken to minimize possible damage in a potential event in the Balearic Islands. However, the magnitude of this flash-flood exceeded any type of forecast carried out by the risk and emergency plans. The consequences of the~~is~~ catastrophe revealed~~evidenced~~ deficiencies in prevention ~~tasks~~ by ~~the Public Administration~~Local Government, both at the level of urban planning and infrastructure ~~as well as~~and in ~~the~~ risk management itself. In addition, the population was also ~~not~~ unprepared due to a very low level of risk culture.

5 Conclusions

The hydrogeomorphological analysis and damage assessment developed in this paper has provided a comprehensive understanding of the Sant Llorenç des Cardassar flash-flood event of~~ccurred in the~~ 9th October 2018 by means of an integrated approach with a meteorological, hydrological, geomorphological, damage and risk data analysis. The use of rainfall radar data –corrected with measurements from rainfall stations ~~measurements from~~in the surrounding region– combined with Q data from stream gauge observations ~~elucidated~~ showed how spatio-temporal distribution of rainfall amounts and intensities, karstic features and land use/cover resulted in an unprecedented ~~very flashy~~ runoff response in a Mediterranean environment, triggering this natural disaster. It was shown that the application of different direct estimation approaches may reduce the uncertainty of hydrological modelling and thus increase the credibility and practical value of the whole analysis. ~~Without a~~

~~doubt~~Undoubtedly, the inclusion of streamflow monitoring data for thiskind of flash-flood event proved~~ to be~~ crucial,~~ in this flash-flood type event thorough~~ as~~n~~ did accurate calibration with a two-dimensional hydraulic model also integrating the influence of bridges' obstruction in flow routing.

The flash-flood event was a catastrophe that caused 13 casualties, huge economic damage~~s~~ and an unprecedented mobilization of human resources~~ mobilization~~ in the Balearic Islands~~ Region~~. Rapid mapping from Copernicus EMS and detailed damage~~s~~ reported by regional authorities, linked to territorial information from the Cadastre and hydrogeomorphological processes, showed very accurately~~ illustrated with high accuracy~~ the damage~~-~~-driving factors in the urban area of Sant Llorenç des Cardassar village. ~~Despite~~ Although~~the~~ flood risk planning ~~evidenced~~ showed the high level of risk exposure, the disaster was generated by a very high exposure of buildings and infrastructures to floods, the absence of early warning systems with efficient action protocols~~ in case of flood emergency~~, and the lack of municipal regulations to instruct the population on how to act when ~~occurring~~ struck by an event of this magnitude. The incorporation of hydrogeomorphological precision tools during Emergency post-catastrophe operations~~al~~ ~~h~~was~~ been~~ revealed as a powerful tool. Then, the simple application of a geomorphometric index from easy-access LiDAR-based topographic data resulted in a rapid identification of deposition zones in the different compartments of a catchment, which helped~~ing~~ in the search and rescue of missing persons. In addition, the evaluation of landform~~s~~ signatures by using UAVs measured effectively ~~quantified~~ the sediment deposits generated by the flash~~ ~~-flood and/or mobilised by the Emergency operations~~al~~ during ~~the~~ rescue searches~~ing tasks~~.

This study represents a first step to further improvement of flash-flood risk management in Mediterranean flood-prone regions such as Mallorca, which are likely to recur due to~~ in the future under the~~ global change~~ effects,~~. ~~as they have major consequences in terms of risk management.~~ Mediterranean regions are subject to violent flash floods that ~~could be~~may intensify~~ied~~ –especially in terms of peak discharge– in the future due to forest fire, land uses and/or climate changes. These future consequences of global change should lead to~~be considered in future flood warning systems and flood policy with~~ the modification and adaptation of hydrological and flood risk models, allowing the development of a rule-based system with adaptive and resilient measures to take at the catchment scale.

Author contributions. JE, MR, RM, AC and FV developed the experimental design; whilst JE, JF and JG were responsible for data curation, fieldwork~~ing~~ and figure elaboration and~~.~~ MT carried out the meteorological analysis. BN and FV performed the hydraulic modelling. RM and XP developed the hydrological model code and performed the simulations. MR completed the damage assessment.~~ and~~ AC performed the sediment connectivity and geomorphic change detection. Resources and funding acquisition were supervised by JE and MR. JE prepared the manuscript with contributions from all co-authors.

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Tables and C~~c~~aptions

(a)

Event rainfall duration (h)	Time of maximum rainfall	Centroid storm	Average radar rainfall (mm)	IP_{max} average radar (mm h^{-1})	IP_{max} radar (mm h^{-1})	IP average radar (mm h^{-1})
10	09/10/18 ~~18~~19:00	09/10/2018 17:07~~0~~	249~~6~~	45~~6~~	77	25~~4~~

(b)

Runoff (mm)	Runoff ratio	Event duration (h)	Q_{max} (m^3 s^{-1})	Time Q_{max}	T centroid storm-T Q_{max} (h)	$Q_{average}$ (m^3 s^{-1})	Unit peak discharge (m^3 s^{-1} km^2)	Reduced Unit peak discharge (m^3 s^{-1} km^2)
86	0.35~~6~~	12	442	09/10/18 19:15	~~0.25~~2.1	26	19	67

Table 1 (a) Rainfall and (b) runoff variables of the flash flood at the Begura de ~~Saumà~~Salma River catchment estimated from the continuous water stage monitoring at the MEDhyCON hydrometric station located in the village of Sant Llorenç des Cardassar.

People and goods		**Buildings**	
Death toll	13	Emergency interventions into the structure	52
Slightly injured	4	Demolitions	3
Initial missing persons	74	Affected buildings	> 1000
Infrastructure damages		**Movable properties**	
Cut roads	4 main roads	Motor vehicles	426
Affected roads	22 road sections		
Bridges	8 with structural damages	**Actions undertaken**	
Public hydraulic domain	High ~~affection~~impact	Rubble removal	7,000 tonnes
Drinking and wasting water network	Several points of damage~~s~~	Human Emergency resources mobilized	> 200
Telecom infrastructures	Severe damage~~s~~	Rescue assistance	342 persons
Electricity network	Undetermined severe damage~~s~~ 8355 affected users		

Table 2 Damage summary and emergency actions ~~of~~ after the 9th October 2018 violent flash-flood ~~carried out~~ in ~~the~~ Llevant County, ~~of~~ Mallorca. Source: Pol (2019).

Damage level	Flood risk cartograph~~y~~ies						Copernicus Emergency Management System		Total
	10 years	*%*	*100 years*	*%*	*500 years*	*%*	*Affected area*	*%*	
COLLAPSED	5	50	8	80	9	90	10	100	10
DAMAGED & HABITABLE	52	20	107	41	141	54	225	86	261
DAMAGED & NOT HABITABLE	15	41	26	70	31	84	36	97	37
DAMAGED PLOT	6	35	9	53	9	53	13	76	17
DAMAGED & RESTRI~~N~~CTED~~GE~~ ~~D~~ USE	19	28	39	58	47	70	63	94	67
TOTAL	97	25	189	48	237	60	347	89	392

Table 3 Damaged buildings in the village of Sant Llorenç des Cardassar caused by the violent flash-flood o~~i~~n 9th October 2018 and those encompassed in the official flood risk maps for 10, 100 and 500 years recurrence periods.

Figures and Ceaptions

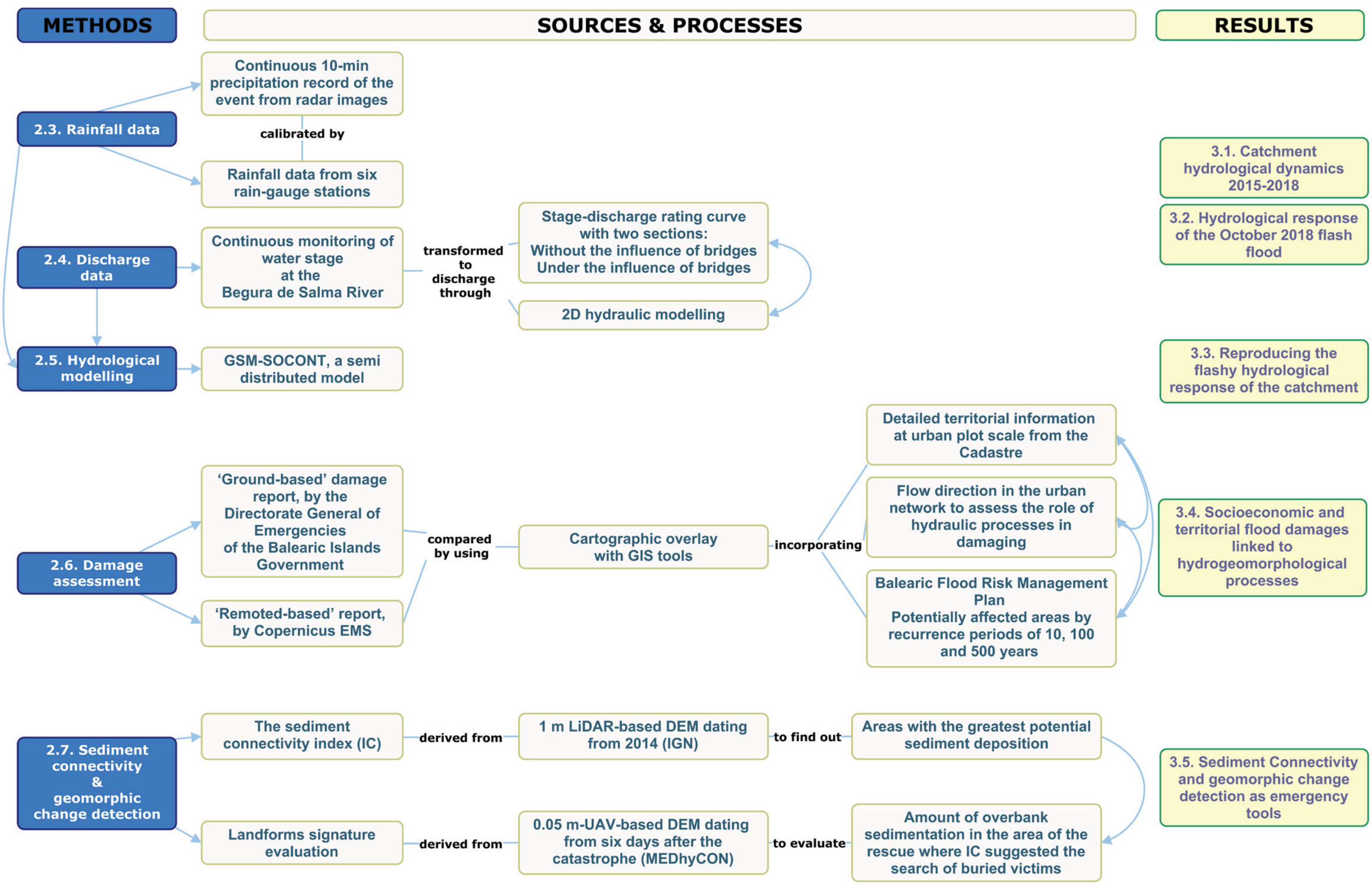


Figure 1 Workflow of the experimental design.

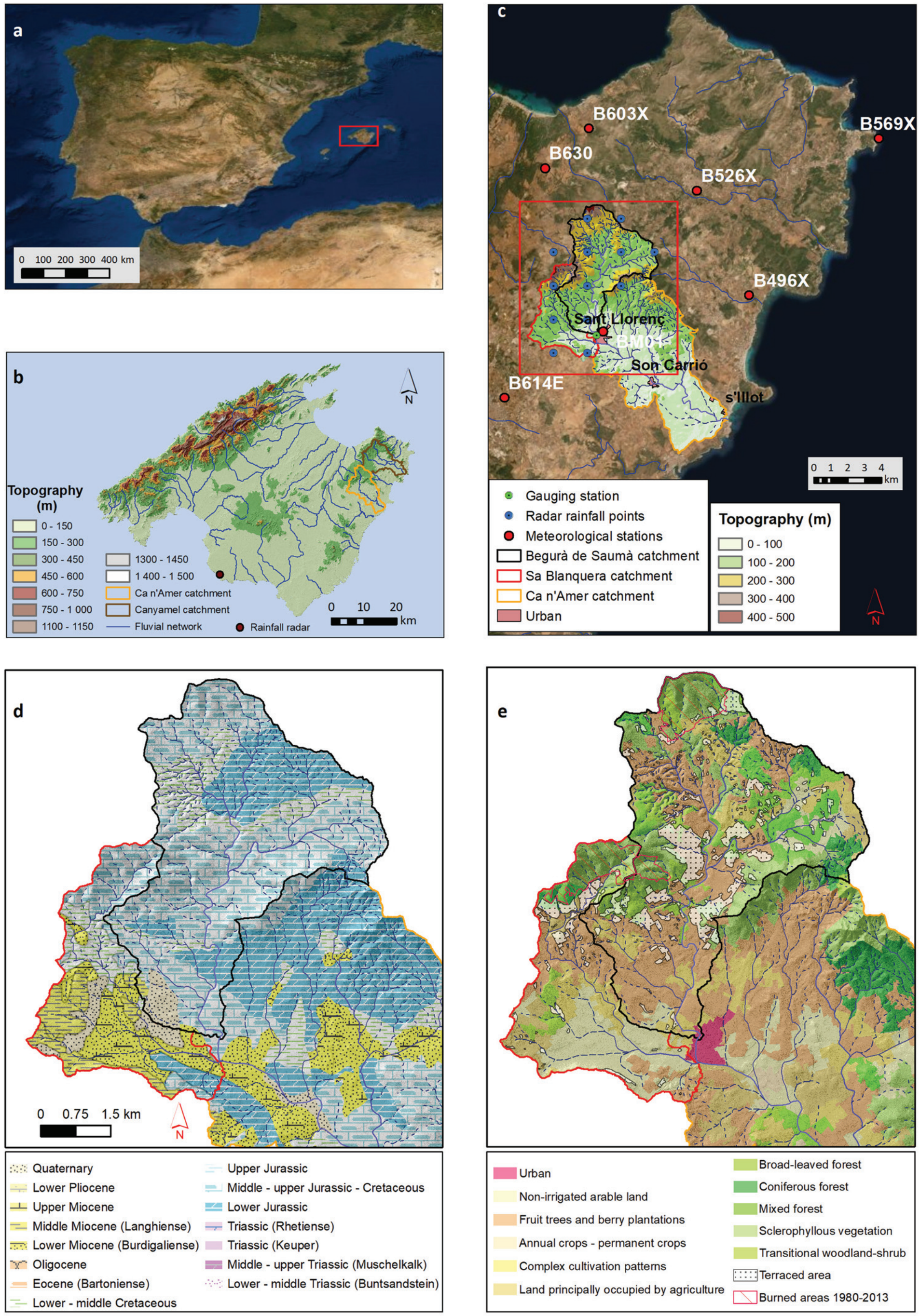


Figure 21 Main characteristics of affected basins during the 9th October 2018 flash-flood. (a) Location of Mallorca in the western Mediterranean. (b) Topography and fluvial network of Mallorca Island with the location of the affected main basins affected: Canyamel and Ca n'Amer rivers. (c) Blanquera and Begura de SaumàSalma headwater river catchments within the Ca n'Amer River, with locationsg of rainfall and hydrometric stations;, and radar rainfall points derived from a regular mesh of 1x1 km. Source: https://opendata.aemet.es. Background: aerial photography and DEM data (PNOA, 2015). (d) Lithology of both Blanquera and Begura de SaumàSalma catchments. (e) Land uses and terraced areas for the same headwater catchments. Source: Corine Land Cover (2018).

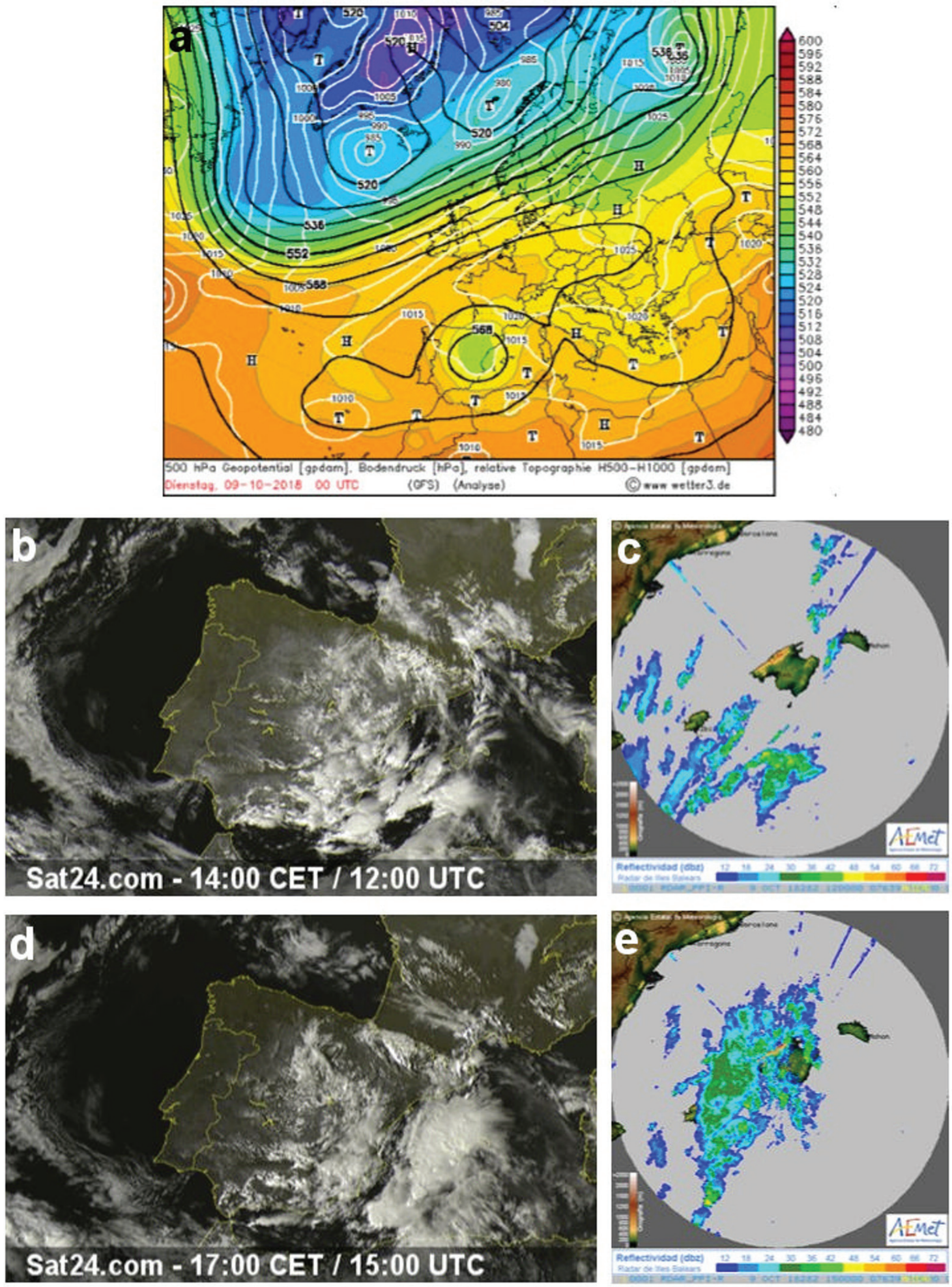


Figure 3~~2~~ (a) Surface pressure and 500-hPa height analyses at 1200 UTC on 9th October 2018 Source: **http://wetter3.de**; i.e. , at the beginning of the precipitation event. Satellite image at (b) 12.00UTC and (d) 15.00UTC Source: http://www.sat24.com. EUMETSAT and radar images at the same hours (c and e) Source: http://www.aemet.es.

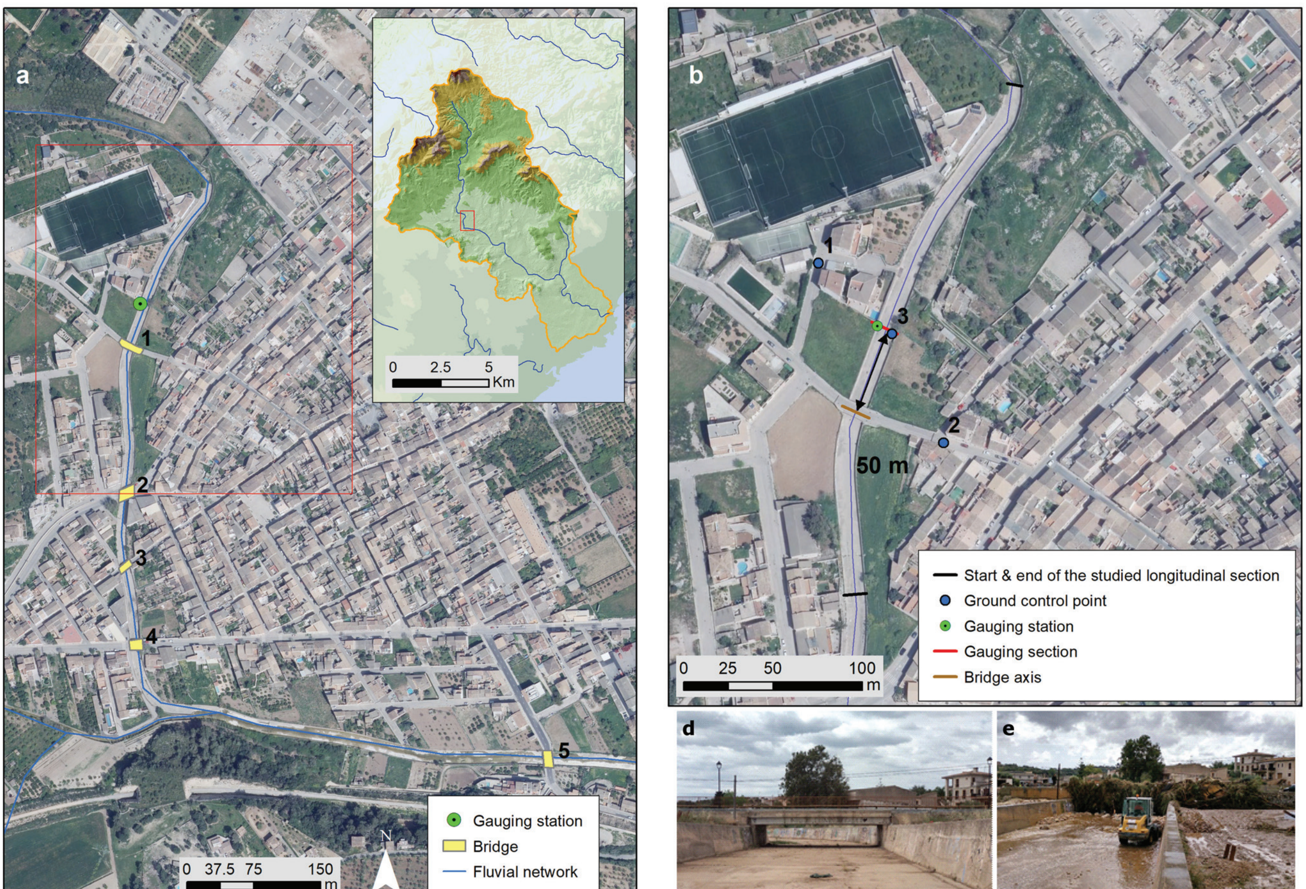


Figure 43 (a) Aerial view of the concrete channeling of the Begura de SaumàSalma River of concrete channelization that crossinges Sant Llorenç des Cardassar village and the location of bridges. (b) Detailed aerial view of the very beginning of this concrete channeling,zation where the hydrometric station is located. The photographs show a view of the Bridge 1 from the hydrometric station when (the right pictured) was installed the digital equipment was installed, on 10th June 2015 and (the left onee) a few hours after the flash flood, on the 10th October 2018. Background: aerial photography and DEM data (PNOA, 2015).

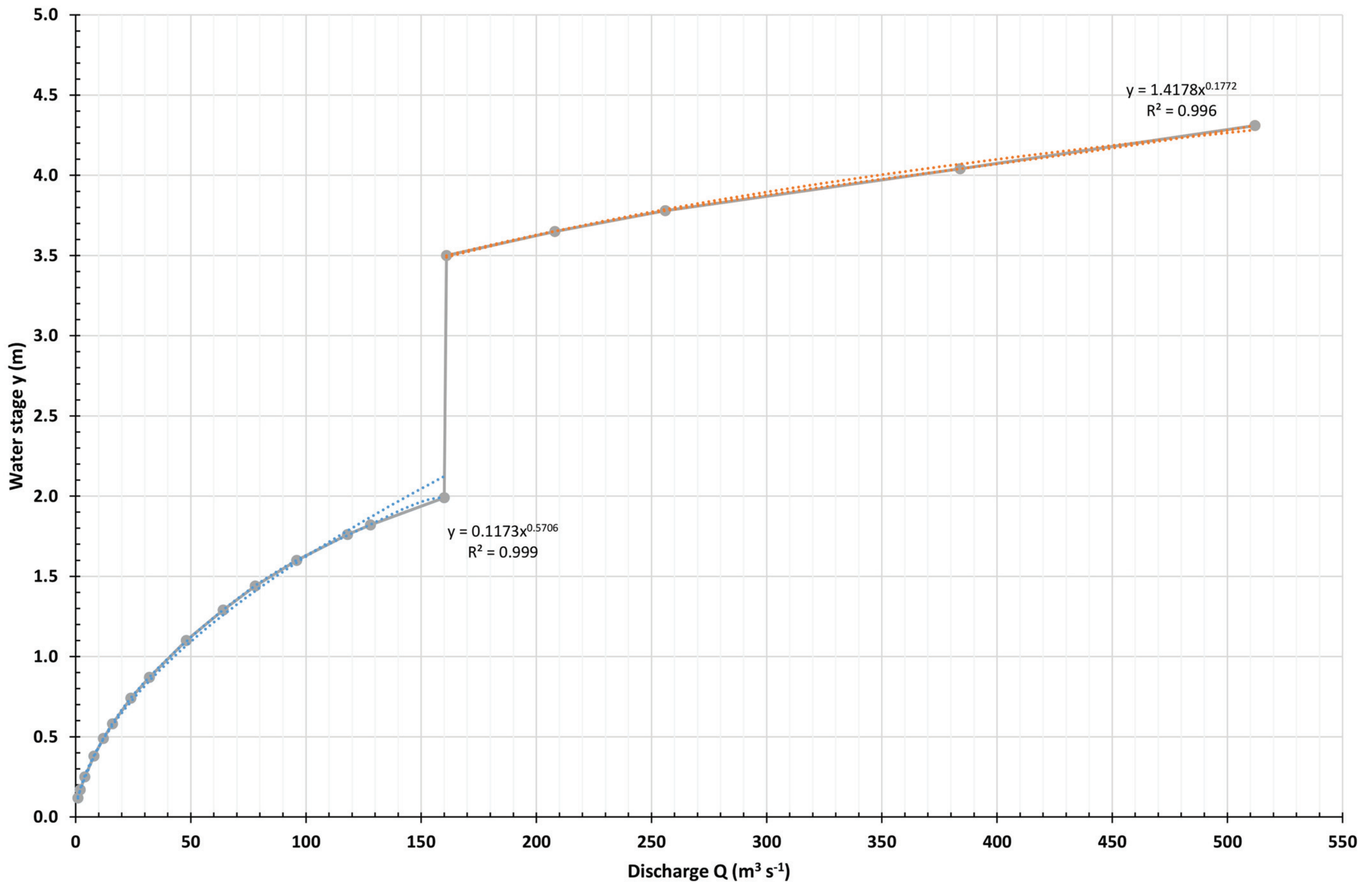
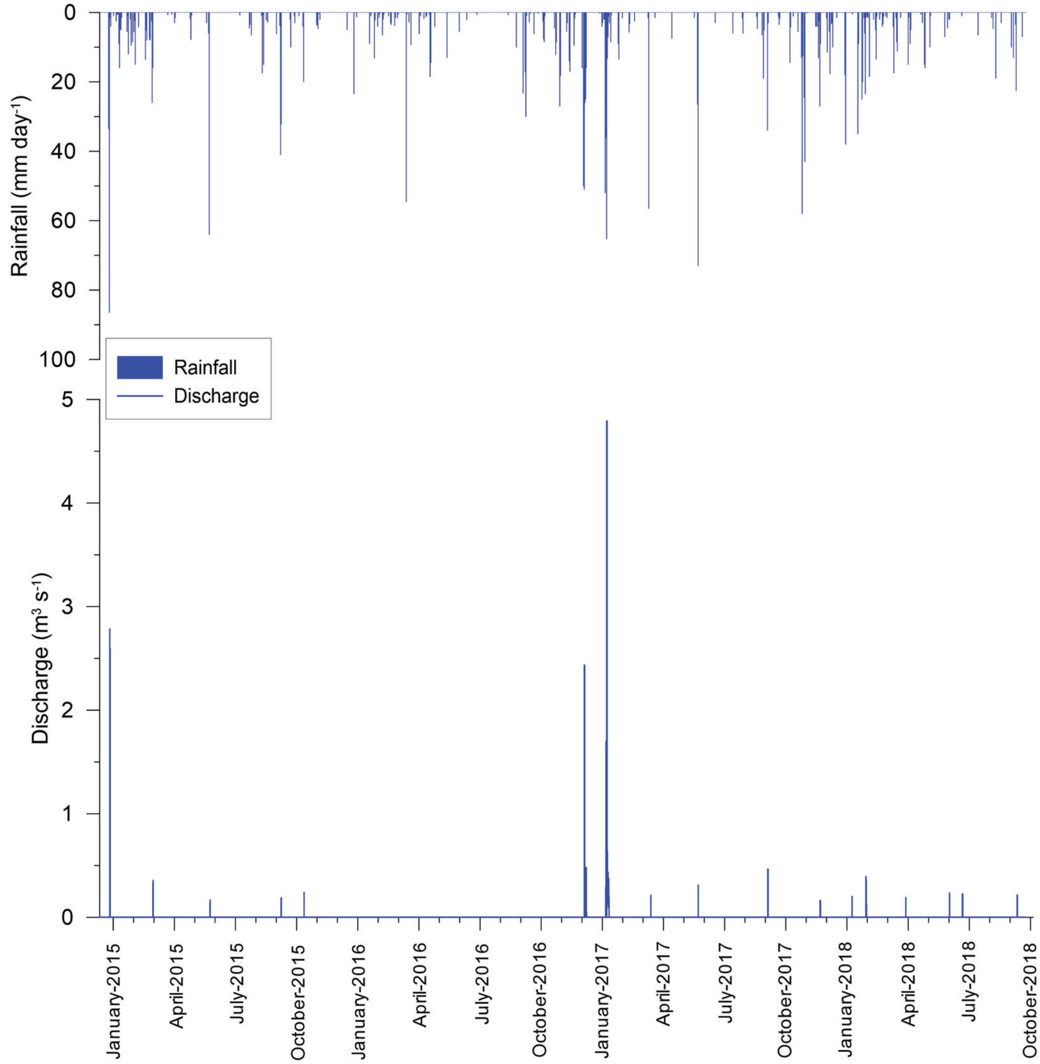


Figure 54 Stage-discharge rating curve performed by means of two-dimensional hydraulic modelling with two differentiated sections in according withto the influence of the Bridge 1 (see Figure 3a) and its potential obstruction.



Hydrological year	Rainfall (mm)	Runoff (mm)	Qmax ($m^3 s^{-1}$)	Qavg ($m^3 s^{-1}$)
2014-15	823	2.0	2.8	0.002
2015-16	363	0.1	0.2	0.000
2016-17	825	12.9	4.8	0.009
2017-18	763	0.8	0.4	0.001
2018-19 (until April)	500	91.8	442.0	0.118
Average study period (2014-2018)	655 ± 211	21.5	---	0.026 ± 0.1
Average long term (1968-2018)	652 ± 176	---	---	---

Figure ~~5~~6 Discharge at 15-min intervals measured at~~in~~ the MEDhyCON hydrometric station located at the beginning of the concrete channeli~~zatio~~ng of the Begura de ~~Saumà~~Salma River in Sant Llorenç des Cardassar. Likewise, the daily rainfall measured at the AEMET-B630 Ses Pastores during the monitored period (10th January 2015-30th September 2018), prior~~evious~~ to the catastrophic flash flood of 9th October 2018. Bottom set table: Rainfall, runoff and peak discharge for hydrological years during study period. Rainfall data ~~is~~ are from AEMET-B630 Ses Pastores, located 10.5 km from the Begura de ~~Saumà~~Salma catchment outlet and representative of the rainfall dynamics of the Llevant Ranges headwater~~ part~~s.

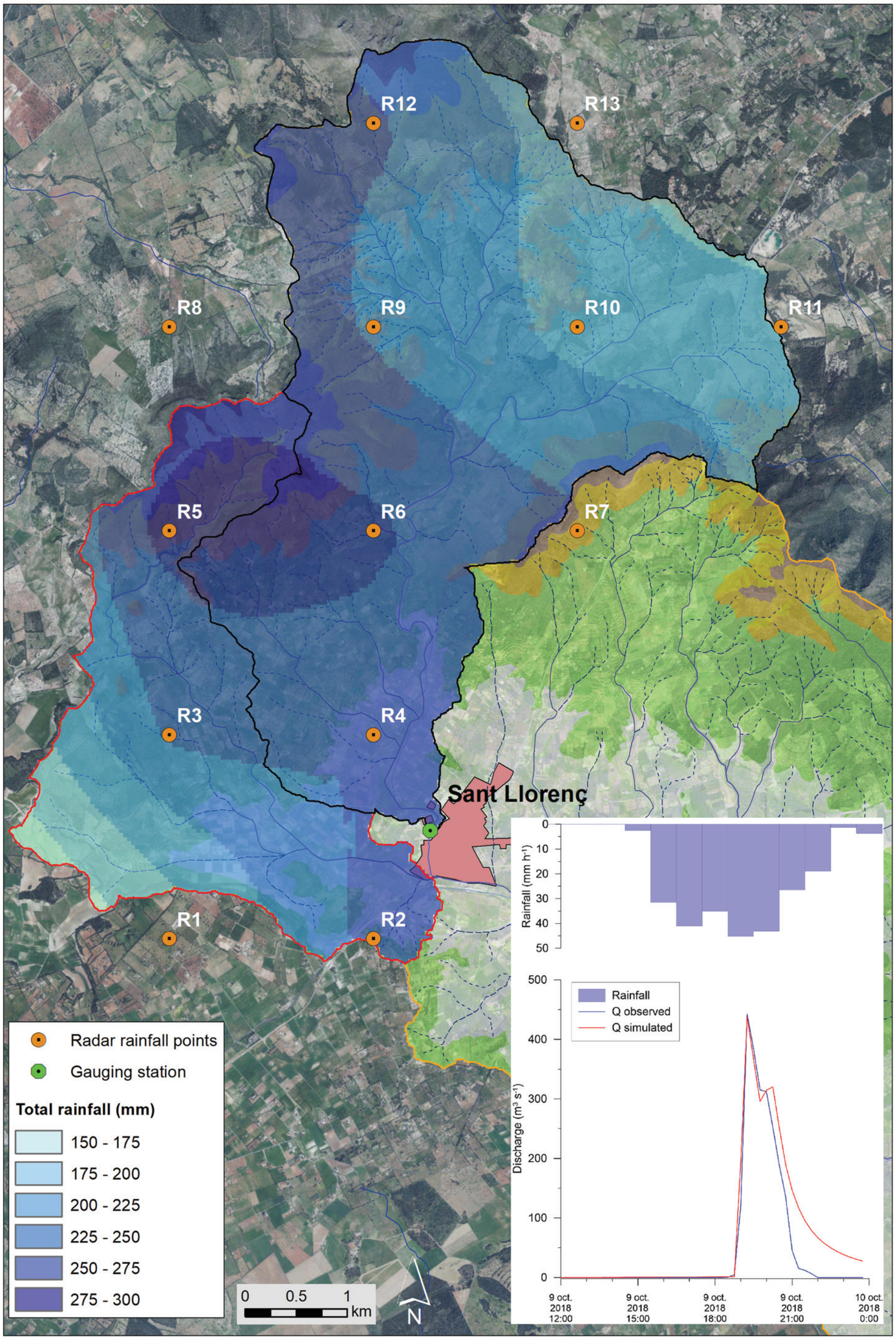


Figure ~~6~~7 Map of isohyets of the rain storm ~~occurred~~ of 9th October 2018 in the two headwater catchments of the Ca n'Amer River; i.e.~~,~~ the Blanquera and Begura de ~~Saumà~~Salma rivers. Source: 10-minute radar images obtained from the web https://opendata.aemet.es/. The inset figure illustrates the observed discharge measured at the MEDhyCON hydrometric station as well as the result of the rainfall-runoff simulation using a modified version of the GR3 model. Background: aerial photography and DEM data (PNOA, 2015).

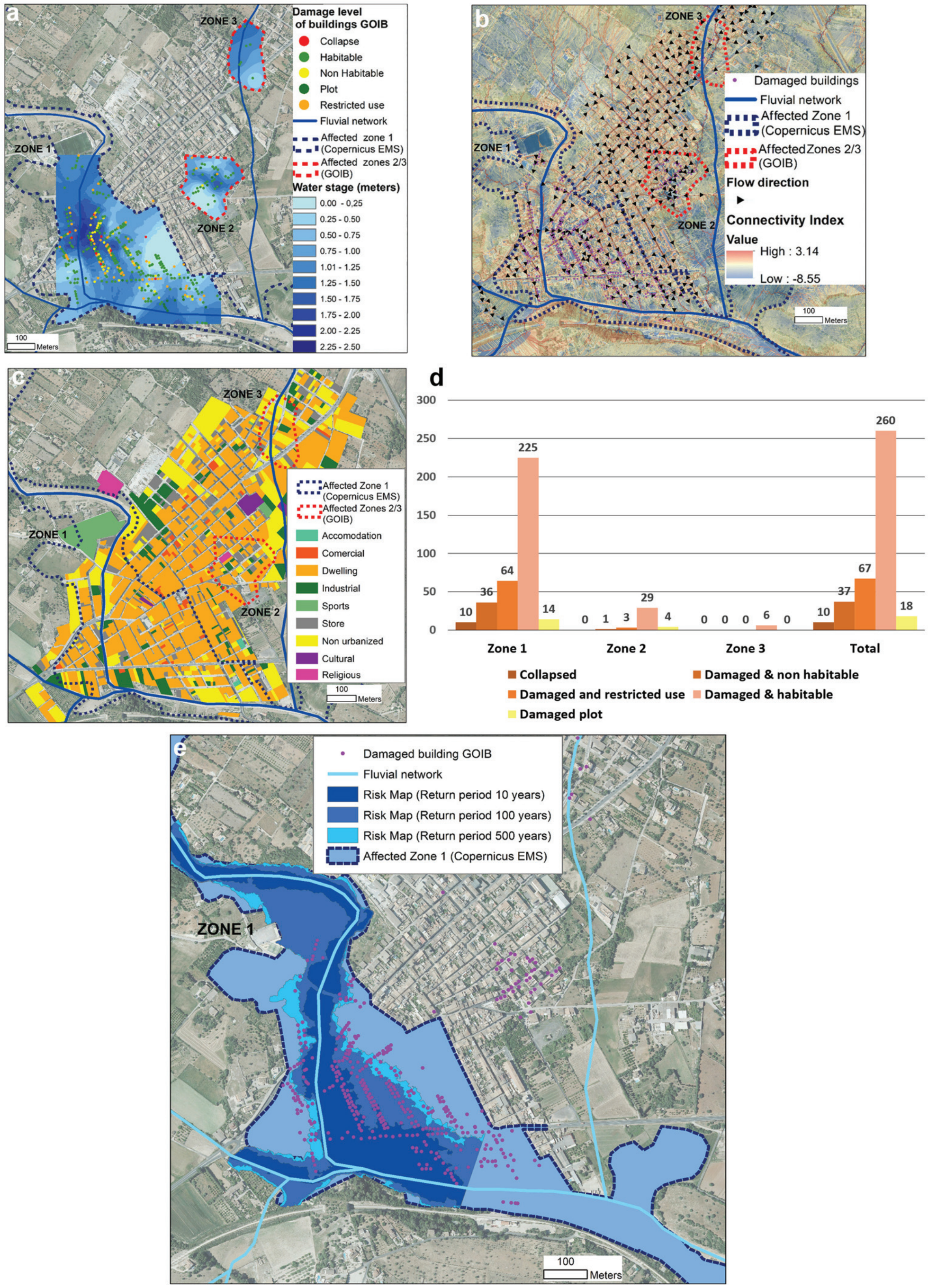


Figure 8~~7~~ (a) Map of the damage level classification of buildings and water stage reached in the different affected zones at Sant Llorenç des Cardassar according to the Balearic Islands Autonomous Government in comparison with the flood delimitation ~~carried out~~ by Copernicus EMS. Flow direction and hydrological connectivity in the affected zones (b) 1, ~~and~~ 2, ~~as well as (c)~~ and 3 in the Sant Llorenç des Cardassar urban network. (c~~d~~) Economic activities at building scale in the urban area of Sant Llorenç des Cardassar and the delimitation of affected zones by the flash-flood. (d~~e~~) Damage level classification of buildings in the different affected zones at Sant Llorenç des Cardassar. ~~(f) Damage level of the buildings and plots by zones.~~ (e~~f~~) Official flood risk maps and flood delimitation by Copernicus EMS at the Sant Llorenç des Cardassar village with the location of buildings affected ~~buildings~~ by the flash -flood ~~occurred~~ of 9th October 2018. Background: aerial photography (PNOA, 2015). In Fig. 7d, the source of land uses at the urban plot scale is the General Directorate for the Cadastre (http://www.sedecatastro.gob.es/).

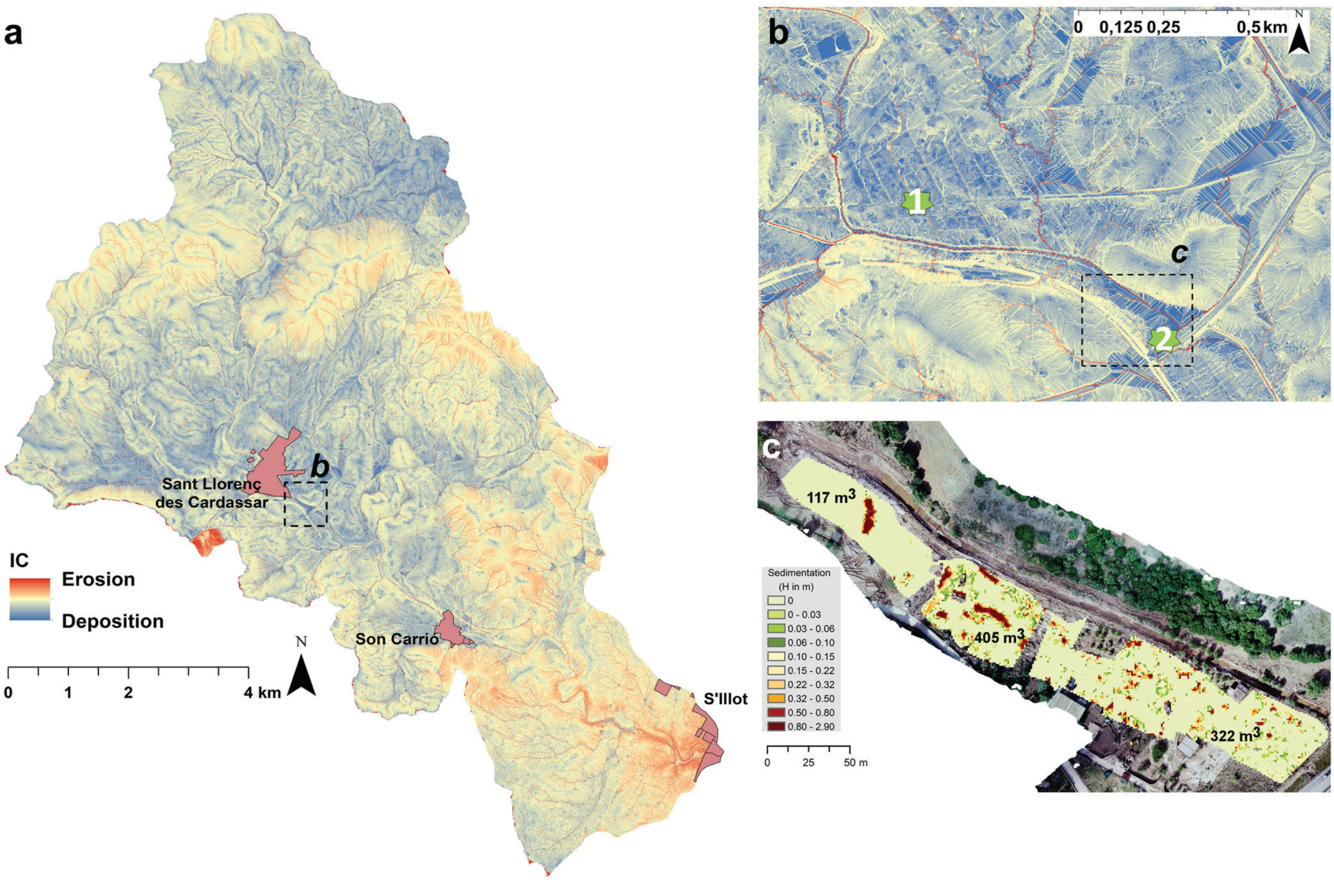


Figure 98 Spatial patterns of hydrological and sediment connectivity (deposition zones in blue colours) (a) in the Ca n'Amer River basin, (b) in the south-east part of Sant Llorenç des Cardassar with numbers indicatinge (1) the point where the missing person was last seen and (2) where- this person was found by using with the application of this connectivity index from a digital terrain model (MDT) of 2 m resolution (Instituto Geográfico Nacional, 2014). (c) Overbank sedimentation estimated after the flash-flood from a DEM performed with SfM from a UAV flight (15th October 2018) in relation to the ground points of the 2014 LiDAR data. Back ground aerial orthophotography of ca. 2 cm resolution obtained also from the drone images. Numbers indicate the total volume of deposited sediments in the three measured areas.

Supplementary material

INTERNATIONAL	Media
Thte New York Times	Majorca Flash Flood Kills at Least 10 https://www.nytimes.com/2018/10/10/world/europe/flash-flood-majorca-spain.html
Al Jazeera	Flash floods in Spain's. Mallorca kill 9, many missing: Two British nationals among the dead as cars are swept away by raging, muddy waters in the Spanish island https://www.aljazeera.com/news/2018/10/flash-floods-spain-mallorca-kill-9-missing-181010100342382.html
EUROPE	
The Telegraph	Majorca floods: Two Britons among eight dead amid 'biblical' scenes https://www.telegraph.co.uk/news/2018/10/09/majorca-flooding-leaves-two-dead-amid-biblical-scenes/
The Guardian	Mallorca floods: at least 10 dead, including British couple https://www.theguardian.com/world/2018/oct/10/uk-couple-reportedly-killed-mallorca-spain-flooding
BBC	Majorca flash flood kills at least 10 on Spanish islands https://www.bbc.com/news/world-europe-45807978
The Sun	A mum is believed to have been killed rescuing her eight-year-old daughter from the floods which ravaged the holiday island of Mallorca las night https://www.thesun.co.uk/news/7456969/majorca-floods-2018-latest-weather-updates-victims-sant-llorenc/
European Flood Awareness System (EFAS)	Flash floods in Mallorca, October 2018 https://www.efas.eu/en/news/flash-floods-mallorca-october-2018
Le Parisien	Inondations à Majorque: au moins neuf morts, Rafael Nadal au secours des sinistrés http://www.leparisien.fr/faits-divers/espagne-inondations-mortelles-a-majorque-10-10-2018-7915314.php
L'independant	Inondations à Majorque: le bilan passe à dix morts et un enfant porté disparu, la video d'un sauvetage en pleine rue https://www.lindependant.fr/2018/10/10/majorque-au-moins-cinq-morts-dans-les-inondations,4726940.php
Le Figaro	Inondations à Majorque: bilan alourdi à 13 morts http://www.lefigaro.fr/flash-actu/2018/10/17/97001-20181017FILWWW00220-inondations-a-majorque-bilan-alourdi-a-13-morts.php
Bild	Land unter im osten Mallorcas https://www.bild.de/news/ausland/news-ausland/unwetter-drama-auf-mallorca-suche-nach-vermissten-laeuft-57758938.bild.html
NATIONAL	
El País	Doce muertos y un niño desaparecido en la tromba de agua de Mallorca https://elpais.com/politica/2018/10/09/actualidad/1539116387_575481.html Las ramblas de Sant Llorenç estaban catalogadas de máximo riesgo de inundación https://elpais.com/politica/2018/10/11/actualidad/1539255702_359602.html Rafael Nadal dona un millón de euros a los afectados por la torrentada de Sant Llorenç https://elpais.com/tag/sant_llorenc_des_cardassar/a/
El Mundo	Al menos 10 muertos en Sant Llorenç y otros puntos de Mallorca por las fuertes lluvias e inundaciones https://www.elmundo.es/baleares/2018/10/09/5bbd0ee4e2704e405b8b4635.html

ABC	Al menos doce muertos en municipios de Mallorca tras las inundaciones por las tormentas https://www.abc.es/sociedad/abci-lluvia-deja-mas-120-litros-agua-mallorca-y-provoca-graves-inundaciones-sant-llorenc-201810092235_noticia.html
REGIONAL	
Última Hora	Graves inundaciones en Sant Llorenç tras desbordarse el torrente https://www.ultimahora.es/noticias/part-forana/2018/10/09/1030853/graves-inundaciones-sant-llorenc-tras-desbordarse-torrente.html
Diario de Mallorca	Las tormentas causan graves inundaciones en Sant Llorenç https://www.diariodemallorca.es/mallorca/2018/10/09/tormentas-causan-graves-inundaciones-sant/1354754.html
Ara Balears	Deu morts pel temporal de pluja a Mallorca https://www.ara.cat/societat/desborda-Sant-Llorenc-arrossega-vehicles_0_2103389890.html
Majorca Daily Bulletin	Hundreds take part in massive clean-up operation in Sant Llorenç https://www.majorcadailybulletin.com/news/local/2018/10/12/53423/hundreds-take-part-massive-clean-operation-sant-llorenc.html

Table S1 Disaster press coverage of the storm occurred in the 9th October 2018 in Mallorca Island.

Damaged items	**Case file number**	**Amount Paid in €**
Commercial, stores and others	~~114~~22	567,886~~338,045~~
Industrial	~~8~~1	~~12,193~~72,786
Offices	~~10~~4	~~2,762~~49,660
Cars	~~887~~507	~~1,812,312~~2,577,950
Dwellings	~~811~~240	~~3,227,225~~3,574,186
Total	**~~1830~~774**	**6,842,468~~5,392,540~~**

Table S2 Compensation payments in the village of Sant Llorenç des Cardassar for damages caused by the flash-flood in 9th October 2018. Source: Insurance Compensation Consortium (CCS, 2018).

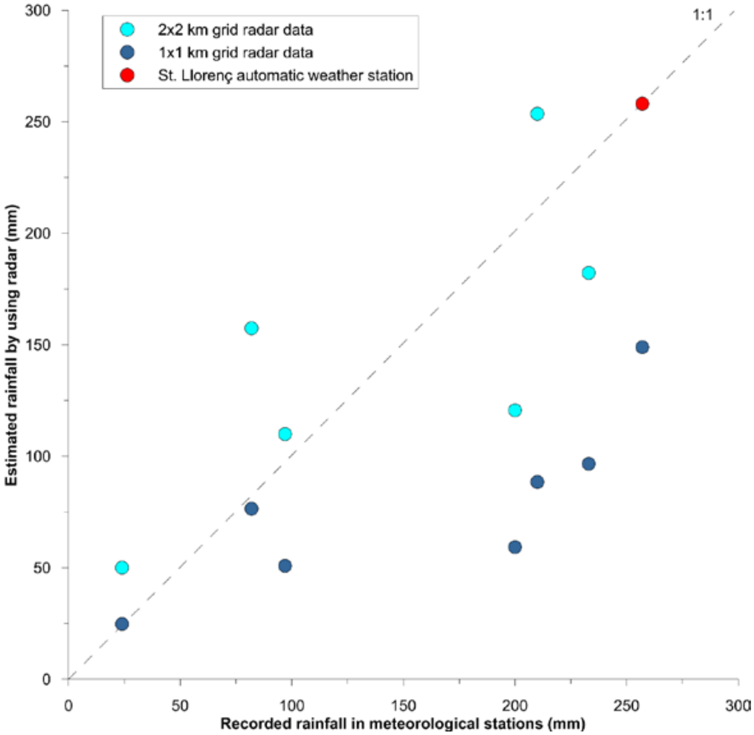


Figure S1 Scatterplot of recorded rainfall in meteorological stations and estimated rainfall by using different grid radar.

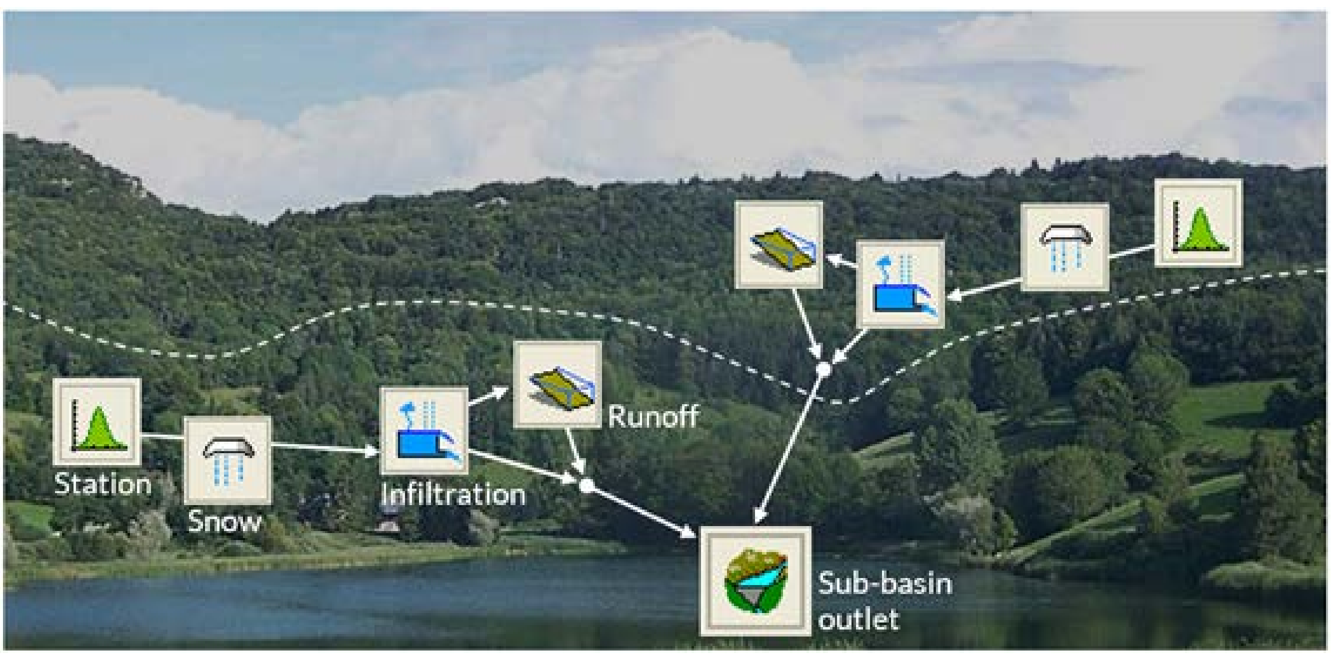


Figure S2~~1~~ Semi-distributed rainfall-runoff modelling with GSM-SOCONT. The sub-basins is divided in two elevation bands in this example.

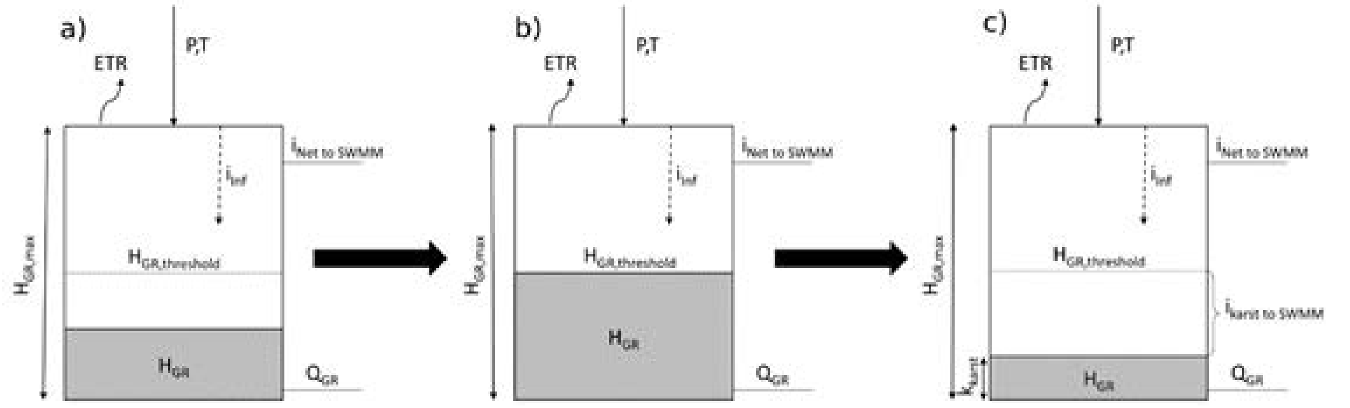


Figure S32 Scheme of the modified infiltration model including a karstic component. Only the relevant parameters are shown, being Q_{GR}: outflow from the infiltration reservoir; H_{GR}: level in infiltration reservoir (State variable); $H_{GR\_threshold}$: height of the onset of karstic behaviour; H_{GR_max}: Maximum height of infiltration reservoir i_{karst}: karstic release coefficient; ETR: Evapotranspiration; i_{Inf}: Infiltration intensity; $i_{Net\ to\ SWIMM}$: surface runoff intensity; P,T: Precipitation, Temperature