Universitat de les Illes Balears

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NH1.6 – Extreme meteorological and hydrological events induced by severe weather and climate change

A forensic hydrometeorological and geomorphological reconstruction of the catastrophic flash flood occurred in Mallorca (Spain) on October 9th, 2018

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1. Motivations and background

- Climate change poses major challenges for current societies: impact on mean and extreme hydrometeorological regimes

- The Mediterranean region emerges as especially responsive to climate change and extremes: more frequent and intense heavy precipitations are projected

- The Spanish Mediterranean is a flash-flood prone region during late summer and early autumn. Highly-localized/mesoscale convective systems: high precipitation rates persist for several hours over individual catchments

- Densely urbanized coastal basins further reduce the hydrological response times

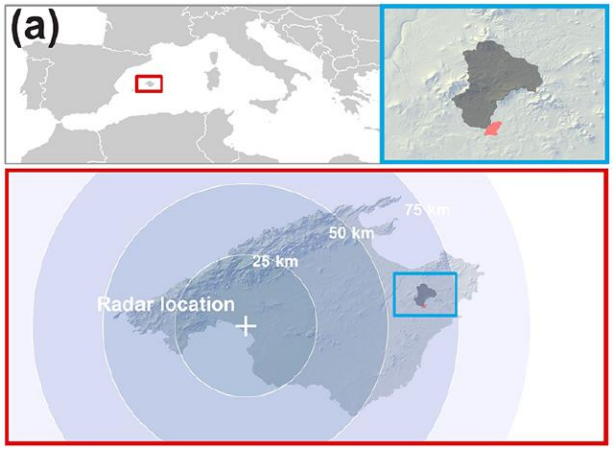
- To highlight the most relevant mechanisms and effects associated with the catastrophic 9 October 2018 flash-flood

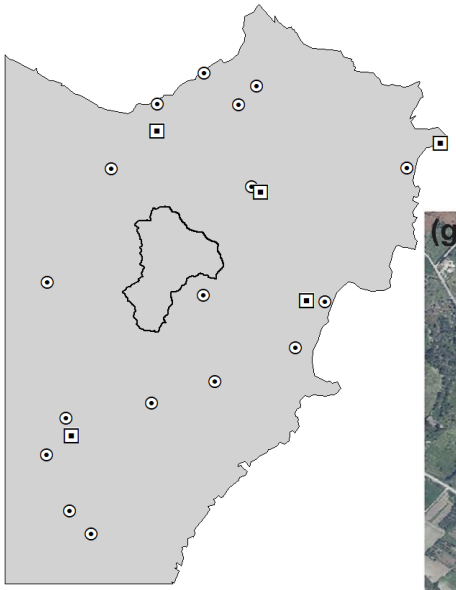
2. Underlying factors

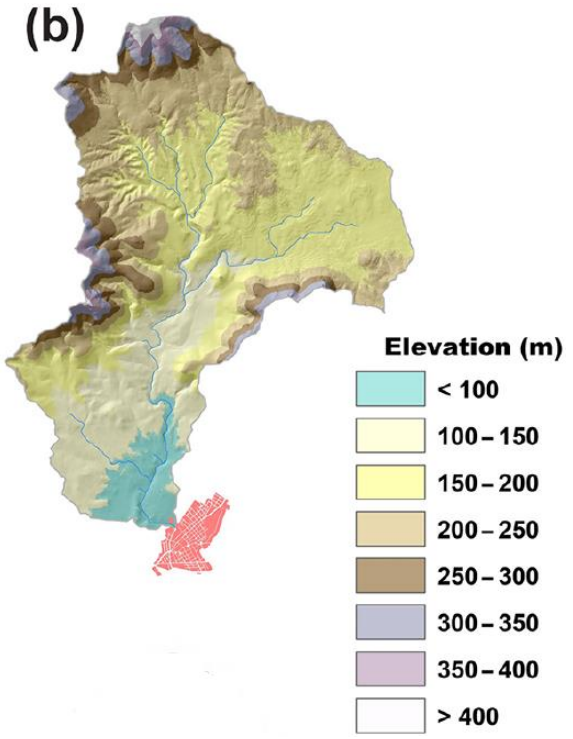
- Relative high sea surface temperature increases CAPE of the overlaying moist air masses through sensible and latent heat flux exchanges
- Intrusion of cold air aloft and presence of mesoscale vertical forcing mechanisms. Complex orography and acute land-sea contrasts
- All these factors promote lifting of low-level unstable air and triggering of deep moist convection
- Lasting convective activity and persisting high rainfall rates associated to prominent orography or quasi-stationary convergence lines
- Small-to-medium sized semi-arid basins are ephemeral and dominated by extreme events of low frequency but high magnitude: increase associated risks

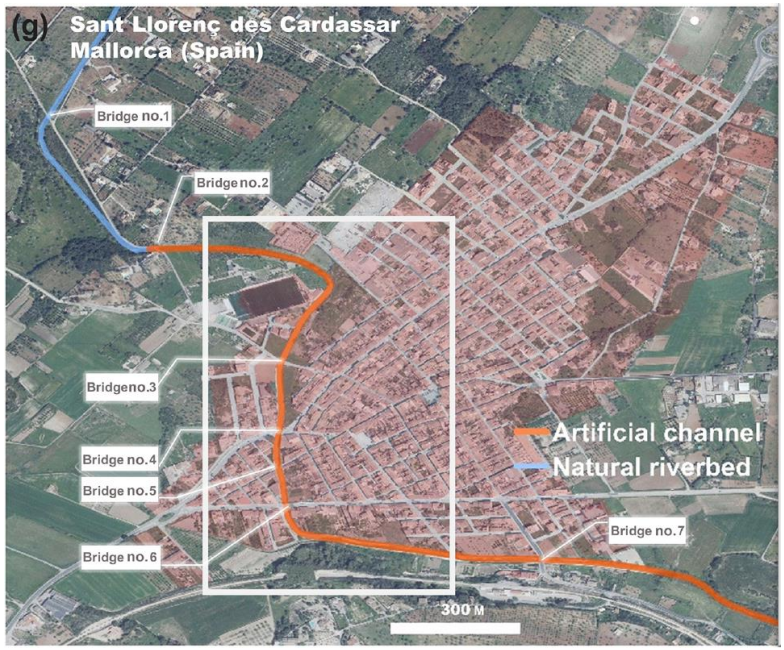
3. Catchment description

- Ses Planes is a small basin: 23.4 km^2 at the entrance of Sant Llorenç town
- Low vegetation density and thin soils. Persistence of low soil moisture contents
- Underlying karstic and dolomitic fractured bedrock
- 2 contrasting effects: fast hydrological responses to heavy precipitation and high infiltration rates
- No stream-gauges are deployed. 5 automatic rain-gauges (10-min). 17 additional pluviometers record daily amounts
- Doppler C-band weather radar located 60 km away from the catchment



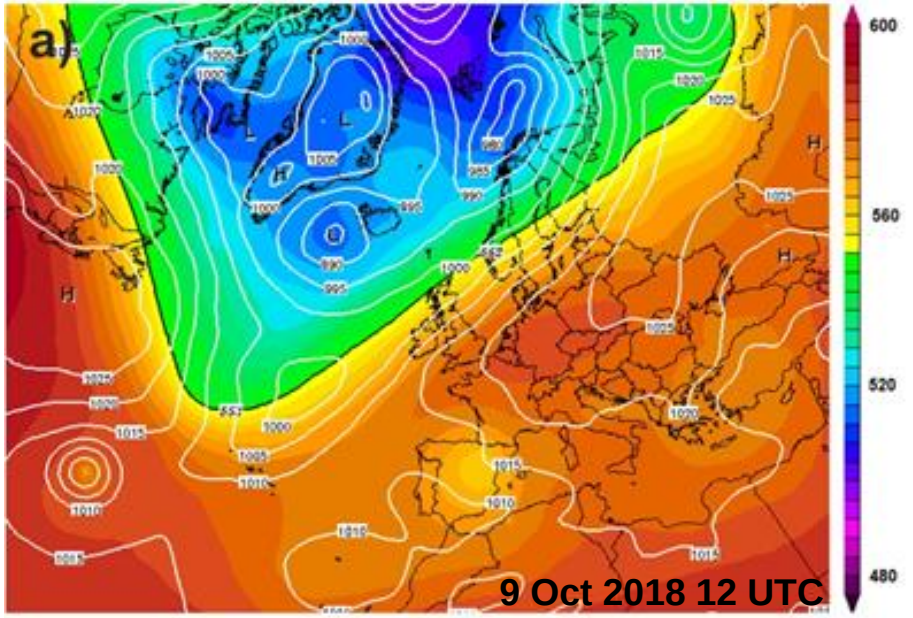


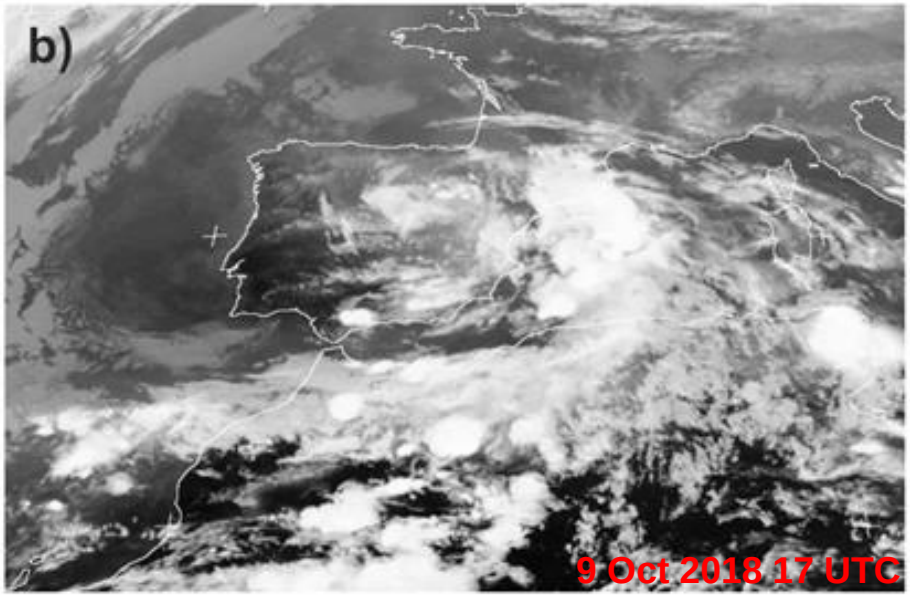




4. Synoptic situation

- Deep trough over the North Atlantic with a strong gradient of geopotential height inducing south-westerly flow towards western and northern Europe
- Small cold cut-off low over the Spanish Mediterranean coast. Southerly flow in its eastern flank.
- Anticyclone in central Europe determining a south-east flow in the Spanish Mediterranean region
- Genesis of stormy weather over the Balearic Islands.
- IR satellite image shows cloud structure associated with the upper-level cold low
- Plume extending along the Western Mediterranean with embedded intense convective nuclei
- Very cold tops to the south and above the Balearics. High depth of the convective cells





5. Precipitation analysis

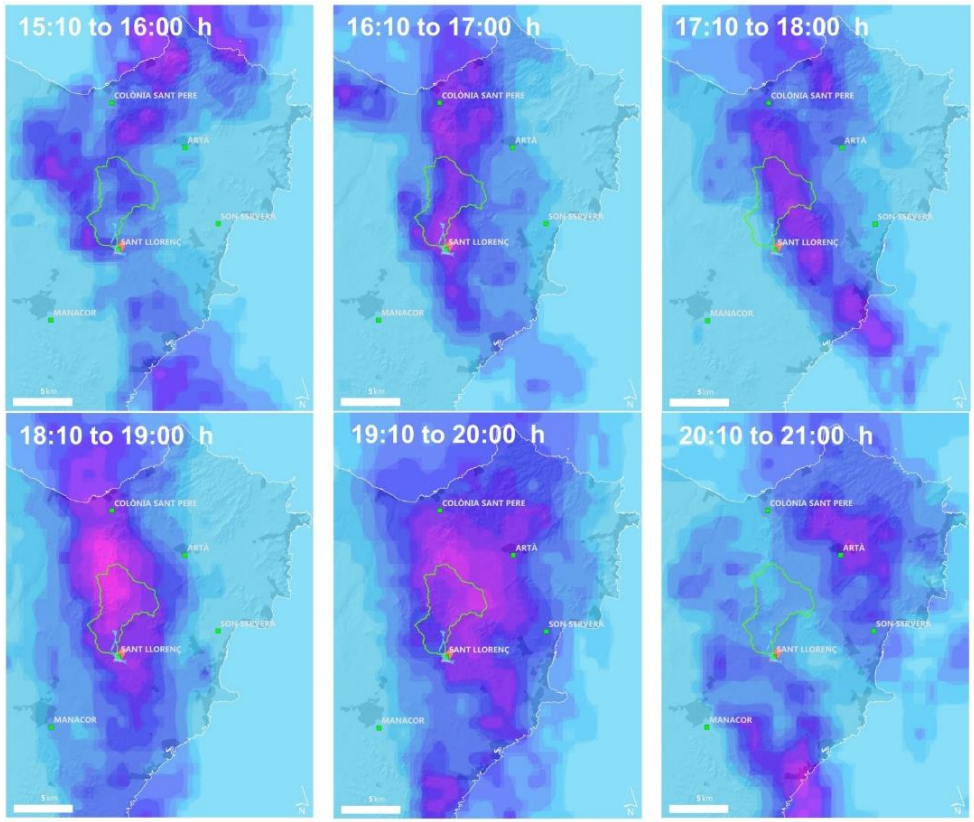
- Several convective clusters moved northwards from south over the Balearic Islands

- A train of mature storms repeatedly affected the east of Mallorca, following a southwest to northeast direction

- Convective systems formed east of the small cut-off low, over the sea

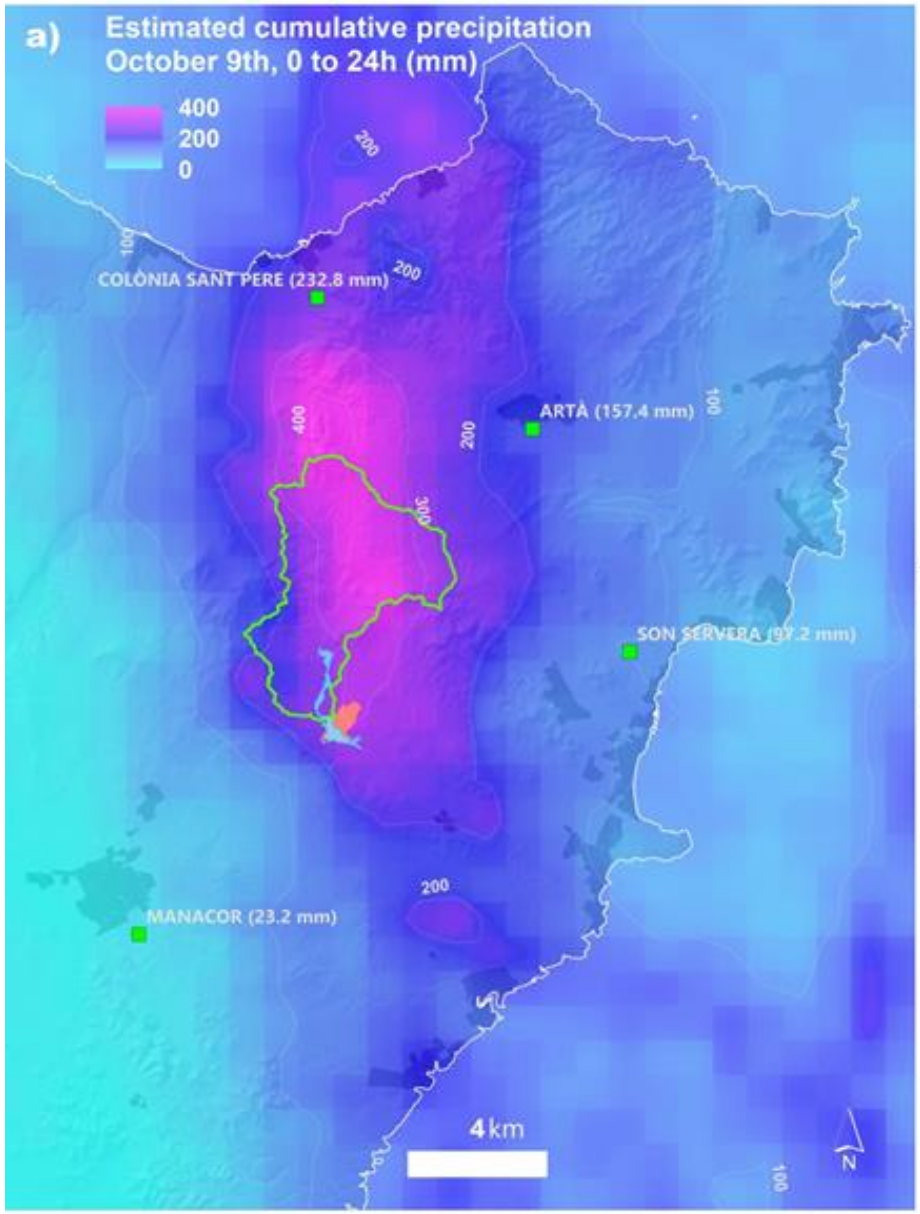
- Trigger mechanism most likely consisted of low-level convergence line

- No prediction weather system forecasted precipitation rates over eastern Mallorca anywhere near the recorded rainfall rates in their operational cycles



5. Precipitation analysis

- Quantitative rainfall estimations derived from 10-min reflectivity volume scans of the Palma radar at 1 km spatial resolution on 9 October 2018
- An area larger than 100 (10) km^2 were affected by 200 (350) mm
- Maximum rainfall amounts up to 400 mm in the upper parts of the Ses Planes basin
- Most intense precipitations lasted 4 hours (16:00-20:00 LT)
- Rainfall intensities of 140 mmh^{-1} between 18:40 and 19:40 LT



Spatial distribution of the total accumulated radar-derived precipitation

6. The 9 October 2018 flash-flood: in the aftermath

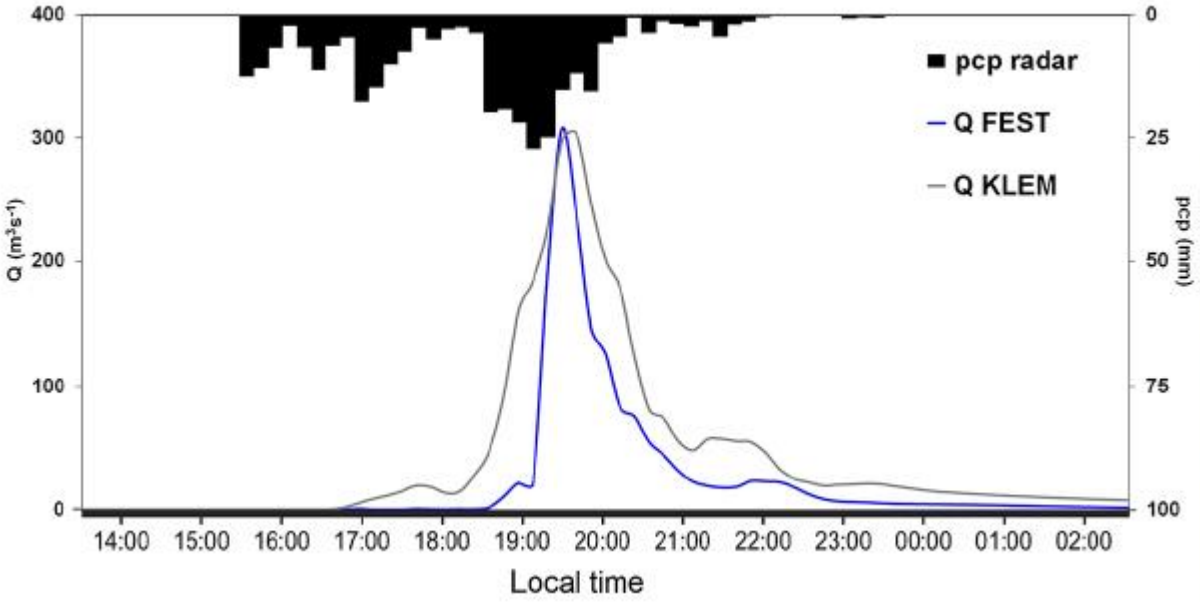
- Death toll: 13 people. 4 in Sant Llorenç town
- Damages in 300 dwellings, 30 stores and 324 vehicles
- Estimated total damage losses: 91 M€

7. Basin response and hydrological modelling

- Fully-distributed hydrological models: FEST and KLEM
- Loss rate: Soil Conservation Service-Curve Number (SCS-CN) method
- Initially dry soils and the existence of underlying karstic and dolomitic fractured bedrocks that promote deep percolation enhance a highly nonlinear hydrological response to intense precipitations

Catchment	Area (km^2)	Total rainfall (mm)	CN (II)	S_0 (mm)	λ	V_h ($m\,s^{-1}$)	V_c ($m\,s^{-1}$)
Ses Planes	23.2	316.7	63.4 (10.0)	431.8–457.2	0.35–0.40	0.36–0.40	3.3–4.1

- Estimated peak discharge about 305 m^3s^{-1} at 19:30-19:40 LT at the entrance of the town
- High inter-model consistency

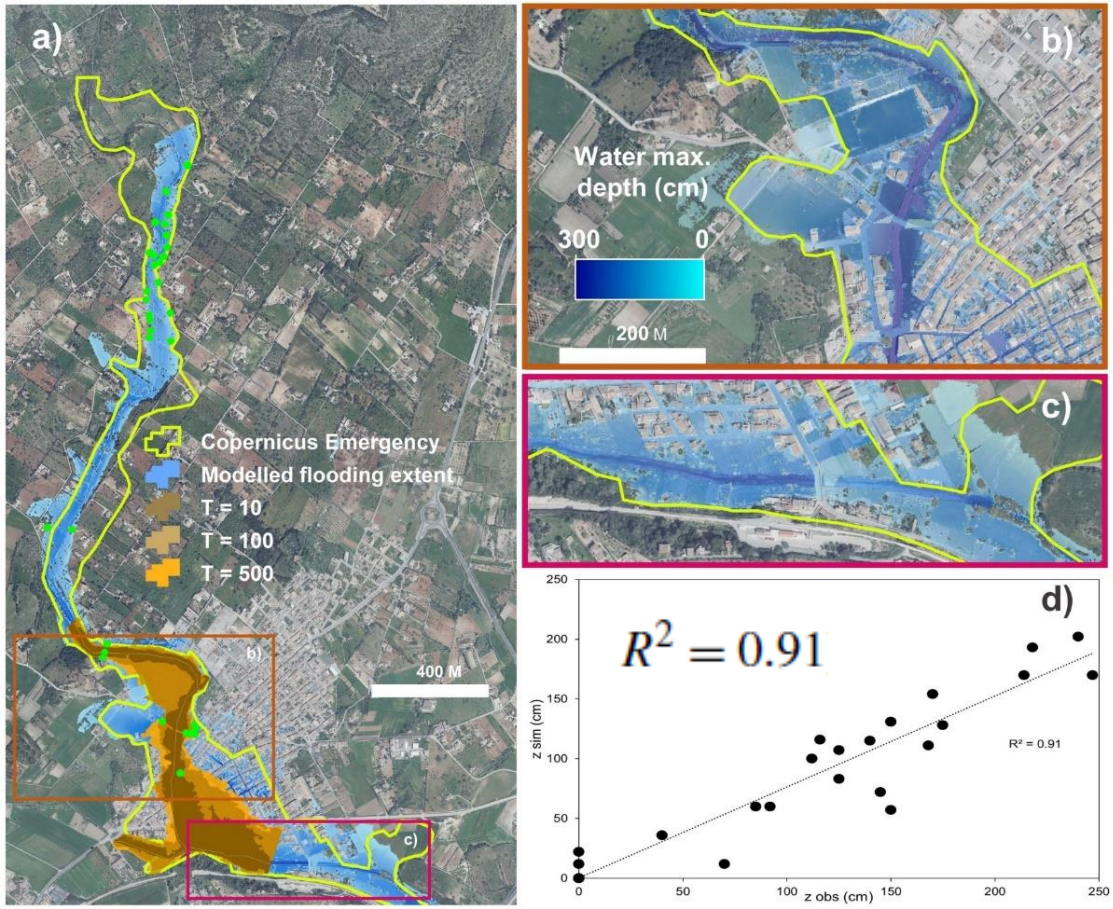


8. Hydraulic modelling and flood mapping

- HEC-RAS: unsteady flow analysis to obtain flooding water extent and timing, water maximum depth and velocity. HEC-RAS used 40 cross sections along more than 4 km of river reach

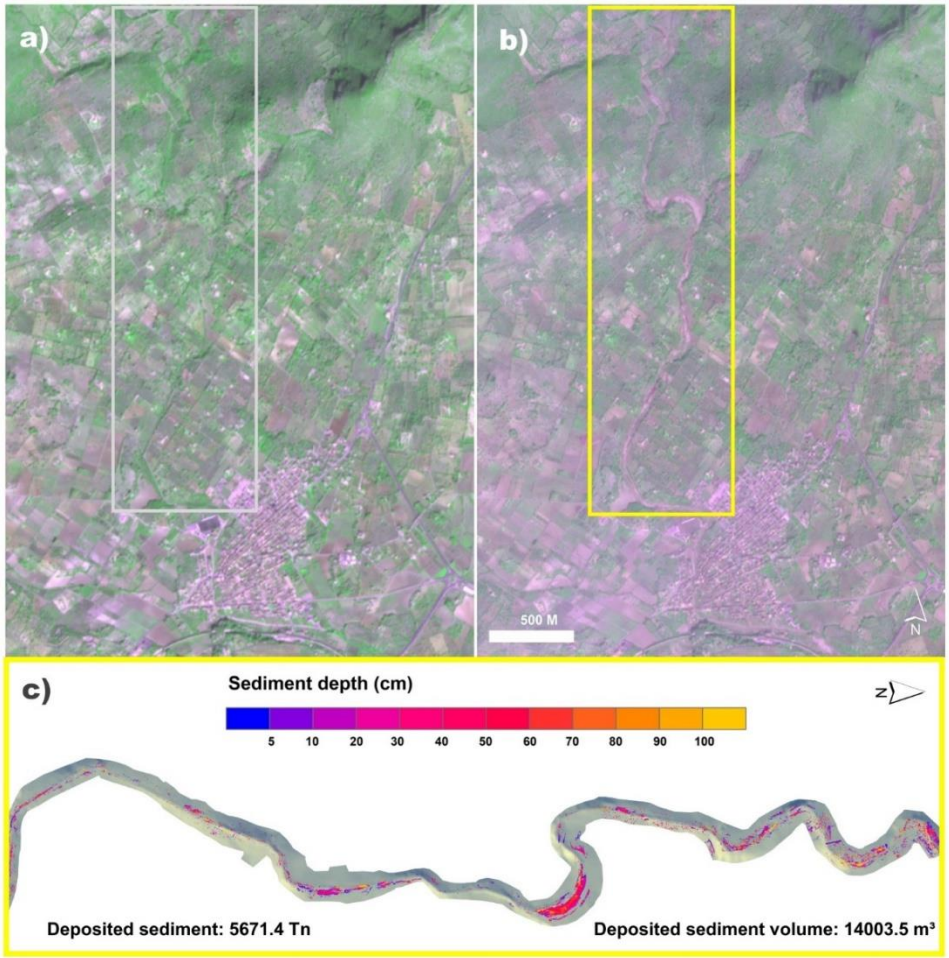
- Upstream boundary conditions coming from the hydrograph by FEST. Downstream boundary conditions imposed by the frictional slope calculated empirically
- Calibration of the hydrologic-hydraulic modelling chain:

1. comparison of the simulated flooded area with the observed event by the Copernicus Emergency Management Service (Sentinel-1 imagery)
2. Comparison of the modelled water depth against 23 flooding marks measured in situ (green dots)



9. Additional results

- Unit peak discharge: 13 $m^3s^{-1}km^{-2}$
- Runoff coefficient: 0.13-0.26
- Runoff volume: 1.0-1.9·10^6 m^3
- Lag time: 0.5-0.8 h
- Overland flow velocities: 0.35-0.40 ms^{-1}
- Flow velocities in the natural river channel: 3.3-4.1 ms^{-1}
- Flow velocities in the concrete artificial river channel: up to 7 ms^{-1}
- Water height: 1.5 m in the town center and close to 2 m near the concrete channel
- Unit stream power: 1110 Wm^{-2}. Changes in channel morphology
- Sediment volume: 1.4·10^4 m^3 deposited as new bars. Gravel and fine materials. Depths up to 1 m.



Effects of the catastrophic flash flood on the agricultural surroundings of Sant Llorenç town: sharpened false infrared RGB composites on 9 October (a) and 11 October 2018 (b) derived from Planet® high-resolution (3 m) imagery; (c) spatial patterns of sediment deposition and accumulation.

10. Discussion and conclusions

- Complex challenges faced by scientists, hydrometeorological forecasting, civil protection and policy making:

1. Small spatial and temporal scales of the multiple elements which contributed to the tragedy
2. Determinant precipitation structures at sub-kilometric scales in convective systems out of range of conventional precipitation forecasting methods
3. Inability of ensemble weather predictions to sufficiently forecast the location, intensity and timing of the precipitating systems that triggered the tragic flood outlines important challenges and research questions for the hydrometeorological research communities

- Limits in ensemble weather forecasting with lead times up to 12-24 h point out to the need that warning systems and civil protection activation protocols can cope with errors in the range of 30 to 50 km

- Reference and further details: Lorenzo-Lacruz et al. (2019): Hydro-meteorological reconstruction and geomorphological impact assessment of the October 2018 catastrophic flash flood at Sant Llorenç, Mallorca (Spain), NHESS, 19 (11), 2597-2617