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Are hydrologic-hydraulic coupling approaches able to reproduce Alex flash-flood dynamics and impacts on southeastern French headwaters?

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Key words: flash-flood, Alex storm, French Riviera, flood modeling, inundation mapping

Abstract: During the last 5 years, south-eastern France experienced four deadly Mediterranean flash-floods: one in October 2015, two in November and December 2019 and the last one in October 2020, caused by the Storm Alex. The 2015 and 2019 events mostly affected small coastal catchments of the French Riviera (< 50 km²), characterized by high density urban areas. These events were recently used as case studies for developing flash-flood real-time simulation methods, by coupling hydrologic and hydraulic models. The objective of this work is to test such hydrologic-hydraulic coupling for the simulation of the Alex event on the Vésubie catchment, one of the highly affected catchments. Two challenges will be tackled in this work, by testing the coupling (i) at the regional scale (catchment > 100 km²) and (ii) in the context of significant topographic changes due to the flood. A continuous semi-distributed rainfall-runoff model has been coupled with the Basilisk software, which is based on state-of-the-art 2D hydraulic modelling (well-balanced finite volume method for shallow water equations) with adaptive grid refinement. The streamflow series and inundation extents simulated have be compared with available observations gathered from post-event surveys with a particular focus on two places (Saint-Martin-Vésubie and Roquebilière).

1 Introduction

During the last five years, south-eastern France experienced four deadly Mediterranean flash-floods: 3rd October 2015 (20 fatalities, 600 million euros of insured damages), 23rd November and 1st December 2019 (13 fatalities, 390 million euros of insured damages), and more recently the 2nd of October 2020, caused by the Storm Alex (10 fatalities, 9 missing persons and 210 million euros of insured damages). The 2015 and 2019 events mostly affected small coastal catchments of the French Riviera (< 50 km²), characterized by high density urban areas. These events were recently used by Kirstetter et al. (2020) and Charpentier-Noyer et al. (2020) as case studies for developing a flash-flood real-time simulation method, by coupling hydrologic and hydraulic models. This coupling is mainly built on the open-source Basilisk (http://basilisk.fr/) software, developed by Popinet (2011). Basilisk is based on the resolution of the shallow water equations using a well-balanced finite volume method on an adaptive mesh: cell size is changing in time and space according to the calculation made. When studying a given catchment or a flooded region, the coupling approach aims firstly at splitting the computational domain into several "upstream" portions that are contributing to the flows of a single "downstream" portion (i.e. the high-stake area). Then, the hydrological response of the "upstream" portions is simulated by a dedicated rainfall-runoff model, which is very inexpensive in terms of calculation time. Finally, these simulated flows are injected as source terms into Basilisk, which simulates the hydraulic response of the "downstream" part of the computational domain, also considering rainfall on the "downstream" part. This approach was tested on the October 2015 flood on French Riviera coastal catchments and yielded interesting results in terms of computation time and reconstruction of observed data (Charpentier-Noyer et al., 2020).

Unlike 2015 and 2019 events, no significant damages were recorded on the coastal catchments during the October 2020 flood, while inland catchments such as the headwaters of the Vésubie and Roya rivers were devastated. Post-event aerial survey revealed huge sediment transport, and thus significant changes of river and flood plain's topography (ICube-SERTIT, 2020). In this context, the objective of this work is to test the hydrologic-hydraulic coupling originally developed for coastal catchments for the simulation of the Alex event on the upstream part of the Vésubie catchment, one of the highly affected catchments. The studied catchment drains 165 km², with elevation ranging from 531 to 3143 [m]. If the original coupling approach was developed considering an event-based rainfall-runoff model, this work aims to couple Basilisk with a continuous semi-distributed rainfall-runoff model, previously calibrated on available streamflow series. Moreover, three different coupling setups have been designed for the studied catchment, to compare the obtained results regarding computational times. In the following sections, the datasets used for the simulations are described, then the rainfall-runoff model, the hydraulic model and the coupling of the two models are described. Finally, obtained results and future work perspectives are presented.

2 Data

2.1 Digital Elevation Models

Two Digital Elevation Models (DEM) have been used in this study, both being aggregated at the 1 [m] spatial scale.

2.1.1 Pre-Alex DEM

A first DEM "pre-Alex", produced by the Métropole Nice Côte d'Azur in 2018 (referenced as "MNT LIDAR25cm©SIGMNCA") has been post-processed to produce a hydrologically conditioned DEM, (sub)catchment delineations and masks, and a stream network (here constituted by cells draining more than 1 km², cf. Figure 1).

2.1.2 Post-Alex DEM

A "post-Alex" DEM has been produced for this study by merging the pre-Alex DEM described in the § 2.1.1 subsection with another topographic dataset, produced by IGN thanks to a specific Lidar campaign, performed from 5 to 7 October 2020 (i.e. 3 days after the flood) and devoted to the impacted valleys (cf. https://alex.ign.fr/). The merging consists in using post-Alex topographic data for the cells within a 150 [m] buffer around the (pre-Alex) stream network, and pre-Alex topographic data everywhere else. Thus, only the geomorphological changes quantified within the river corridors are considered in this work.

2.1 Hydrometeorological datasets

2.1.1 Data used for Alex event simulation

In this study, the ANTILOPE (Laurantin, 2008) rainfall estimation has been used, and is available at 1 km² scale at the hourly timestep. This dataset is routinely produced by Météo-France each 24 hours, by merging precipitation estimated through radar mosaic with precipitation observed within the Météo-France available raingauges. For this specific event, this process has been expanded by the assimilation of around 40 raingauges data coming from Italia and non-Météo-France observations. The Figure 2 illustrates the total ANTILOPE rainfall cumulation during the 2nd of October 2020 over the most impacted French region, including the Vésubie catchment.

2.1.2 Data used for the calibration of the continuous semi-distributed rainfall-runoff model

Hourly rainfall estimations from COMEPHORE (Laurantin *et al.*, 2012) are used for the calibration of the semi-distributed rainfall-runoff model. They covered 1997 to 2018 and have a 1 km² spatial scale. Daily temperature estimations were extracted from the SAFRAN database (Vidal *et al.*, 2010). They were used to calculate daily potential evapotranspiration with the Oudin *et al.* (2005) formula. The daily values were disaggregated at the hourly time step following Lobligeois (2014). Hourly streamflow data available from 2010 at the Utelle streamgauge were extracted from the Banque HYDRO database (Leleu *et al.*, 2014).

2.2 Damages cartography

Post-flood impact cartography produced by the ICube-SERTIT (2020) has been used in this study to map the impacted areas located within the Vésubie catchment. This GIS dataset is composed by shapefiles of damaged buildings, roads and bridges, and polygons of "flooded areas" (cf. Figure 1). For this flood event, they have been produced by analyzing Péiades-1A and -1B images acquired on 5 October 2020.

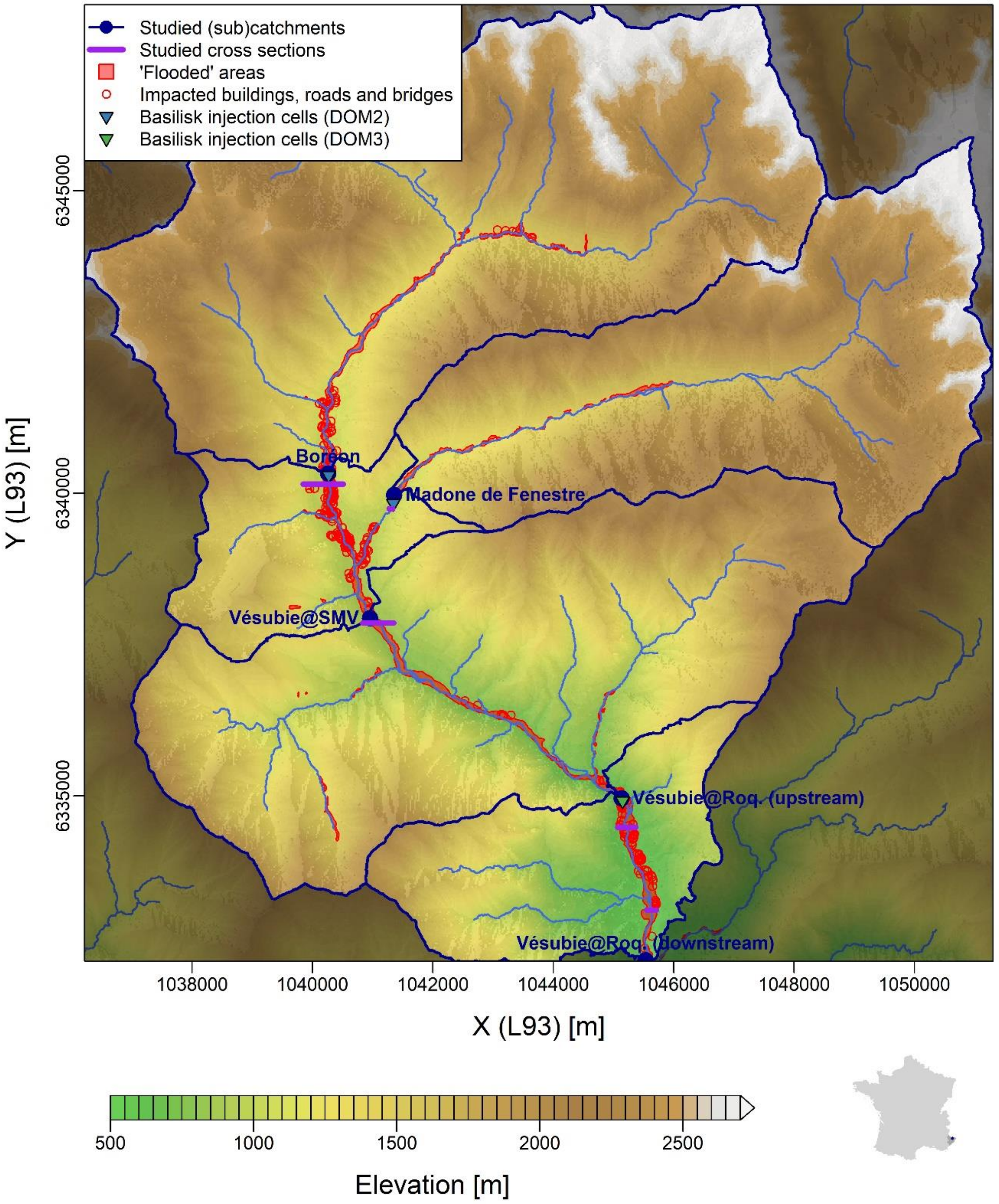

Figure 1: elevation and delineation of the studied sub-catchments. Red polygons and red crosses are ICube-SERTIT (2020) "flooded areas" and impacted buildings, roads and bridges, respectively.

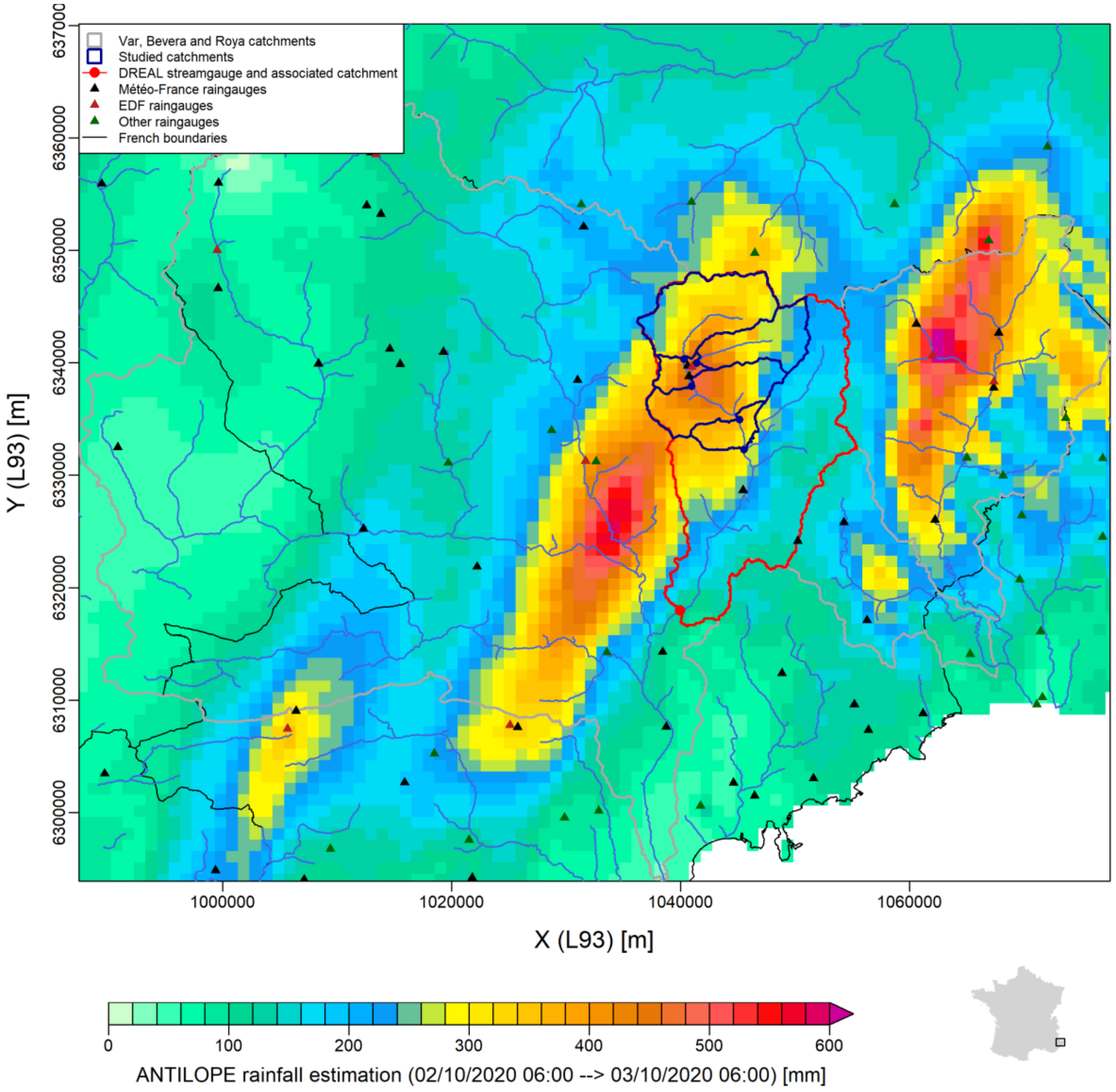

Figure 2: total rainfall amount estimated by the ANTILOPE database (from 2020-10-02 06:00 to 2020-10-03 06:00, UTC).

3 Method and models

3.1 General framework

This work is based on a hydrologic and hydraulic coupling at the catchment scale. In this context: the coupling is done by injecting outputs of rainfall-runoff models within a hydraulic model, as source terms in the mass conservation equation. The rainfall-runoff model outputs considered are (i) river streamflows temporal series (punctual source terms located within the river network) and (ii) net rainfall gridded temporal series, to simulate temporal and spatial evolution of water elevations on a given domain.

3.2 Hydrologically conditioning of used DEM

In this work, the two DEM considered have been hydrologically conditioned using TauDEM fonctions (https://hydrology.usu.edu/taudem/): topography have been automatically modified to obtain coherent flow patterns within the studied domain.

3.3 Rainfall-Runoff models

Two rainfall-runoff models have been considered in this study: (i) the distributed SCS-CN model has been used to produce temporal series of net rainfall grids, and (ii) the semi-distributed GRHM model has been used to produce temporal series of streamflows at several river outlet. These two models are described in the following sub-sections.

3.3.1 Net rainfall estimation through SCS-CN

Rainfall used as a source term within Basilisk is net rainfall estimated using the SCS-CN method. In this study, a spatially constant value of 70 as been considered for the CN parameter, coherently with the Kirstetter *et al.* (2020) study. Note that the net rainfall estimated thanks to hourly ANTILOPE dataset has been linearly interpolated at a 5 minutes timestep.

3.3.2 Discharge estimation with a semi-distributed GR hydrological model (GRHM)

A continuous semi-distributed rainfall-runoff model (note GRHM hereafter) has been used for the simulation of streamflow temporal series. The model derived from the work of Lobligeois (2014). It is based on the snow model proposed by Valéry (2010) and on a modified version of the GR5H hourly rainfall-runoff model (Le Moine, 2008) that integrates an interception store (GR5H-I), as formulated by Ficchì *et al.* (2019) and a modification of the production function to take precipitation intensity into account, as formulated by Peredo *et al.* (2021). A delineation of 8 sub-basins was used considering the Utelle streamgauge as the basin outlet (cf. Figure 2). The 5 parameters of the GR5H model were estimated by minimizing the KGE criteria (Gupta *et al.*, 2009) computed at Utelle streamgauge over the 2010-2018 period. The parameters are chosen to be identical for each sub-basin but with a scaling for the X4 parameters to take the size of each sub-basin into account, as done in Lobligeois *et.al* (2014). The values of the two snow model parameters were fixed according to previous studies.

3.4 Hydraulic model

Basilisk (http://basilisk.fr/) is an open-source calculation code developed by Popinet (2011) that allows the modelling of surface flows and thus to simulate water heights and flood extents on a given region. In this context, the hydraulic model is based on the resolution of the Saint-Venant equations using a recent well-balanced finite volume method (Buttinger-Kreuzhuber *et al.*, 2019) on an adaptive mesh. The implementation of an adaptive mesh is interesting for the modelling of surface flows because this principle allows to apply a low mesh resolution on areas of little interest and a higher resolution on areas with more interest. The choice of the mesh level is made by comparing the water height on the mesh with a refinement threshold set by the operator. The use of the adaptive mesh reduces the calculation time compared to the use of a fixed Cartesian mesh, more often used to solve the Saint-Venant equations. Kirstetter *et al.* (2020) used the Basilisk calculation code on the Brague basin at its outlet with the rainfall observed during the 2015 flood. Charpentier-Noyer *et al.* (2020) then coupled an event-based semi-distributed rainfall-runoff model with Basilisk, to reproduce the same 2015 flood on three French Riviera catchments (Riou de l'Argentière, Frayères et Brague rivers). Within this coupling approach, the rainfall-runoff model is run on the upstream part of the studied domain and feeds the hydraulic model applied in the downstream part. The rainfall-runoff model makes it possible to quickly simulate the streamflow temporal evolution, while the hydraulic model, although much slower when applied at high spatial resolution, makes it possible to have water level and velocity at any point of the downstream area. The obtained results on the three cathcments showed promising performances both in terms of calculation time and accuracy of the simulated flood areas and water levels. Thus, this coupling is used in this study.

3.5 Coupling setups

3.5.1 Three different simulation domains (and associated source terms)

Three different simulation setups have been designed for this work. The first simulation setup aims to only use net rainfall as source terms in Basilisk, and none streamflows. Thus, the domain to be considered for the flood simulation must be the entire studied catchment (here ~164 km²). This simulation setup is named "DOM1" hereafter. The two other simulations aim to use both net rainfalls and streamflows as source terms in Basilisk, and thus to mask several upper parts of the studied catchment. A second domain, noted "DOM2" hereafter, has been defined in order to directly inject streamflow series within two river sections – the Boréon tributary (area of ~59 km²) and the Madone de Fenestre tributary (area of ~35 km²), and to use rainfall series only on the "intermediate" sub-catchment (~70 km²) as source terms. For this DOM2 domain, an area of ~94 km² is masked from the hydraulic model, being simulated beforehand thanks to the rainfall-runoff model and trough the streamflow injection. Finally, a third domain, noted "DOM3" hereafter", has been considered, with a unique streamflow series injected close to the final outlet, upstream of the Roquebilière town (catchment area of ~150 km²). Net rainfall series are also considered on the intermediate catchment associated (~14 km²). Figure 3 presents the spatial extension of the three simulation domains considered.

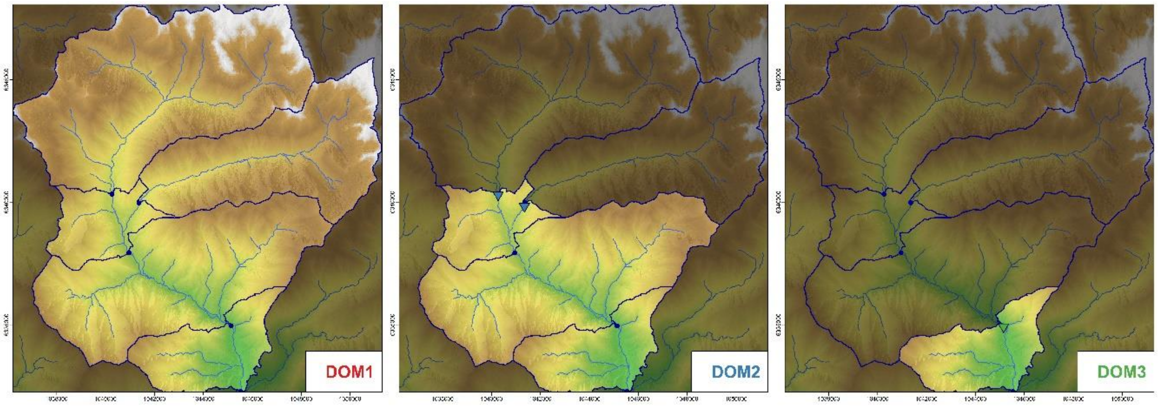

Figure 3: spatial extension of the three simulation domains considered in this study.

3.5.2 Domain impouding before the six reference simulations

An impounding of the river network has been done before any of the six reference simulations. This impounding consists, in this case, in injecting constant streamflow values in the upper part of the stream network during a sufficient time to reach the studied domain outlet. Here, respectively 8.3 and 6.4 m^3/s have been injected within the Boréon and Madone de Fenestre tributaries for 4 hours. Three scalar fields (the water height, the tangential and the normal velocity components) have been extracted from this first simulation and have then been used as initial conditions of each simulations.

3.5.3 Common simulation characteristics

Each simulation has been produced using the same following setups:

- the Manning coefficient is spatially uniform and equal to 0.05 [-], as in Kirstetter *et al.* (2020) simulation.
- the scalar field considered for refinement and coarsening is the water height, with a threshold equal to 20 [cm],
- the grid cell resolutions range from 4 [m] for the highest resolution to 128 [m] for the lowest resolution (at this resolution, the maximal number of cells within the studied domain is 17 M, if no masks are considered).
- The simulations are performed from 7:00 to 21:00 (TU), 3 October 2020 (14-hour event).
- The simulations were performed on a Linux virtual machine with 32 virtual processors and 64 Go RAM.

4 Results

4.1 Precipitation spatial and temporal variability

Figure 4 firstly presents the cartography of net precipitation estimated using SCS-CN rainfall-runoff model. The spatial variability of the rainfall accumulation is similar to the total rainfall accumulation (Figure 2), since a constant value of CN parameter has been considered in this study for the estimation of net rainfall. The highest rainfall accumulations are estimated in the intermediate part of the studied catchment (noted C2), with 274 [mm] of net rainfall. The precipitation estimated on the upper parts of the Vésubie catchments (noted C1) is less important, with around 208 [mm] of net rainfall in the Boréon and Madone de Fenestre headwaters. The last part of the studied catchment (noted C3) has a total of 237 [mm] of net rainfall. Figure 4 also shows subcatchment precipitation temporal series during the studied event. The temporal variability of the precipitation event is similar on the different subcatchments studied, with a first precipitation peak around 11:00 (UTC), followed by a smaller peak around 15:00 (UTC). Thus, the spatial variability of precipitation is limited on the studied region.

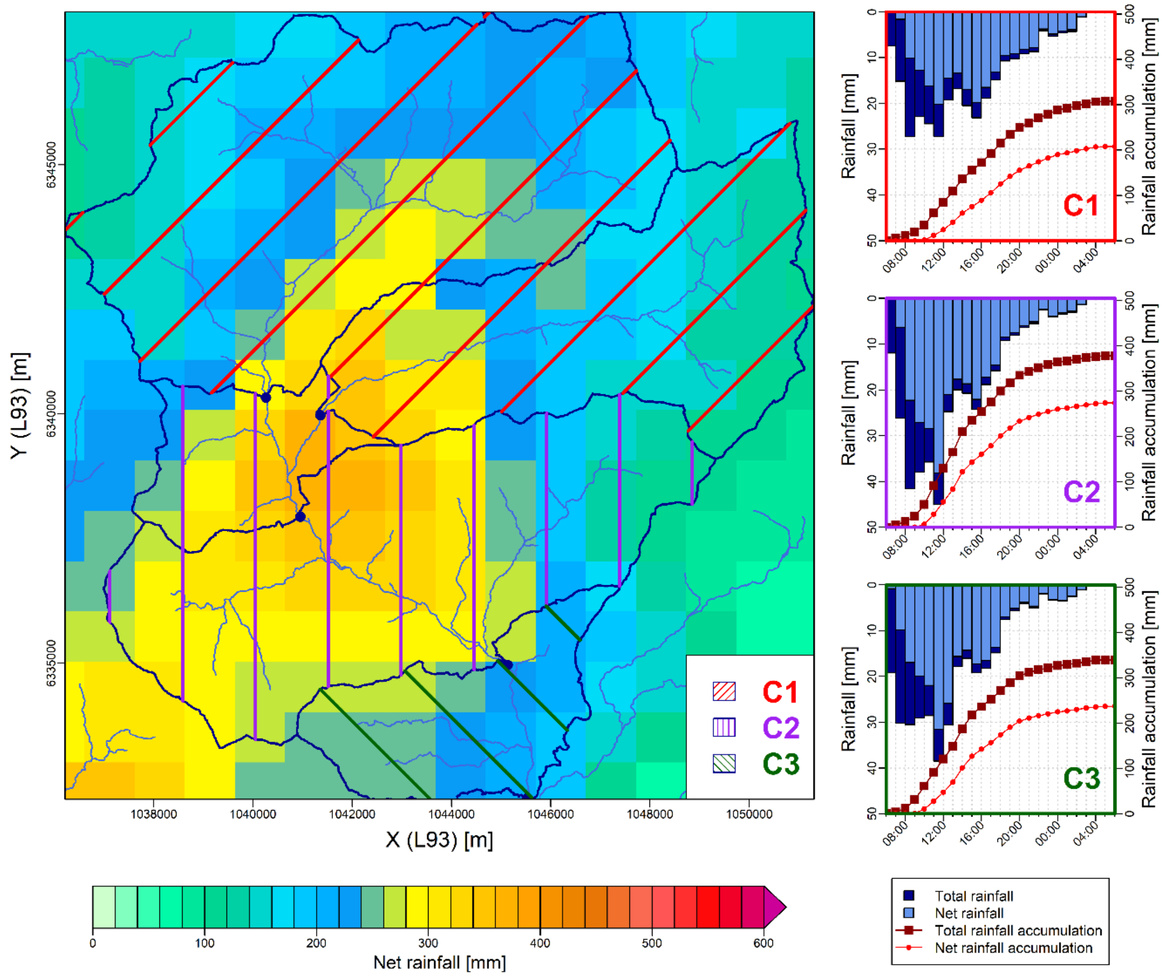

Figure 4: (right) net rainfall amount estimated by the ANTILOPE database during the 2020-10-02 06:00 to 2020-10-03 06:00. (left) Total and net rainfall temporal series over the three different part of the studied catchment.

4.2 Streamflow simulations

Figure 5 shows the GRHM streamflow simulated on the considered outlets, compared with streamflow estimated from Basilisk simulation. For the Boréon and the Madone de Fenestre subcatchments (Figure 5a,b), GRHM streamflow simulations are smoother than Basilisk outputs (DOM1 simulation), with a peak of ~240 and ~140 m^3/s simulated around 17:00 (UTC), corresponding to the second rainfall peak over these catchments (cf. Figure 4). None streamflows are simulated by Basilisk for the first simulation hours, due to the significant interception related to the SCS-CN production function (cf. Figure 4). After several hours, a sudden streamflow rising is simulated on the two catchments, producing two peaks of ~300 and 160 m^3/s respectively, around 13:00 (UTC). Uneven streamflow series are observed for the DOM1 Basilisk simulations. These oscillations seem to be related to the mesh refinement on upstream catchments, with sudden water releases when the refinement threshold (here water height difference of 0.20 [m] between two resolutions) is achieved.

Streamflows simulated for the different models have also been estimated after the two headwaters confluence (Figure 5c). For the DOM1 Basilisk configuration, two peaks are observed on this section, with around ~540 m^3/s and ~490 m^3/s simulated at 13:30 and 17:30 (UTC), respectively. DOM2 simulation, using GRHM streamflow outputs as source terms, produces a peak of ~370 m^3/s at 17:00 (UTC). The difference between GRHM streamflows series (sum of Boréon and Madone de Fenestre streamflows) and DOM2 streamflow series is due to the streamflow produced on the intermediate sub-catchment, between the injection cells and the studied section (~10 [km²]).

Two sections are considered around the Roquebilière town (Figure 5d,e). Again, two peaks are observed for all simulations, the highest peak being observed around 13:30 for DOM1 and DOM2 configurations (~860 and 660 m^3/s, respectively), and around 17:00 for GRHM and DOM3 configurations (~580 and 500 m^3/s, respectively). On the Vésubie at Roquebilière (downstream, Figure 5e) section, the DOM1 and DOM3 streamflow simulations appear to be incoherent, being lower than streamflow simulations on the Vésubie at Roquebilière (upstream, Figure 5f). These incoherencies are discussed in the discussion section.

Finally, available observations at the Utelle streamgauge (downstream of the studied catchments, cf. catchment delineation plotted on Figure 2) are compared with the GRHM simulation at the same outlet (Figure 5f). Again, GRHM simulation are smother than available observations, with an overestimation of streamflow during the first simulation hours (from 07:00 to 14:00). Unfortunately, the streamgauge was destroyed during the flood, and no estimation of peak streamflow values and timing are available on this catchment.

4.3 Flood simulations

4.3.1 Maximum simulated water height

Figure 6 and Figure 7 show the maximum simulated water heights around Saint-Martin-Vésubie and Roquebilière, respectively. Around Saint-Martin-Vésubie (Figure 6), the water heights simulated by the DOM1 configuration are higher than those simulated by DOM2, coherently with simulated streamflows (cf. Figure 5). Identically, the DOM1 configuration seem to produce slightly higher water heights than DOM3 configuration around Roquebilière (Figure 7). On the two domains, both DOM1 and DOM2 configurations produce high water heights on low-flow channels, and a limited number of overflowing on the flood channels. The flooded areas simulated by Basilisk and the flooded areas estimated by Icube-SERTIT (2020) are significantly different, highlighting potential multiple and massive deviations of the river channels during the flood. Finally, several thalwegs appear to be disconnected to the main river channel (cf. Figure 7, left bank of the Vésubie river, around Roquebilière Vieux), despite DEM hydrological conditioning. These disconnections may underestimate local water heights.

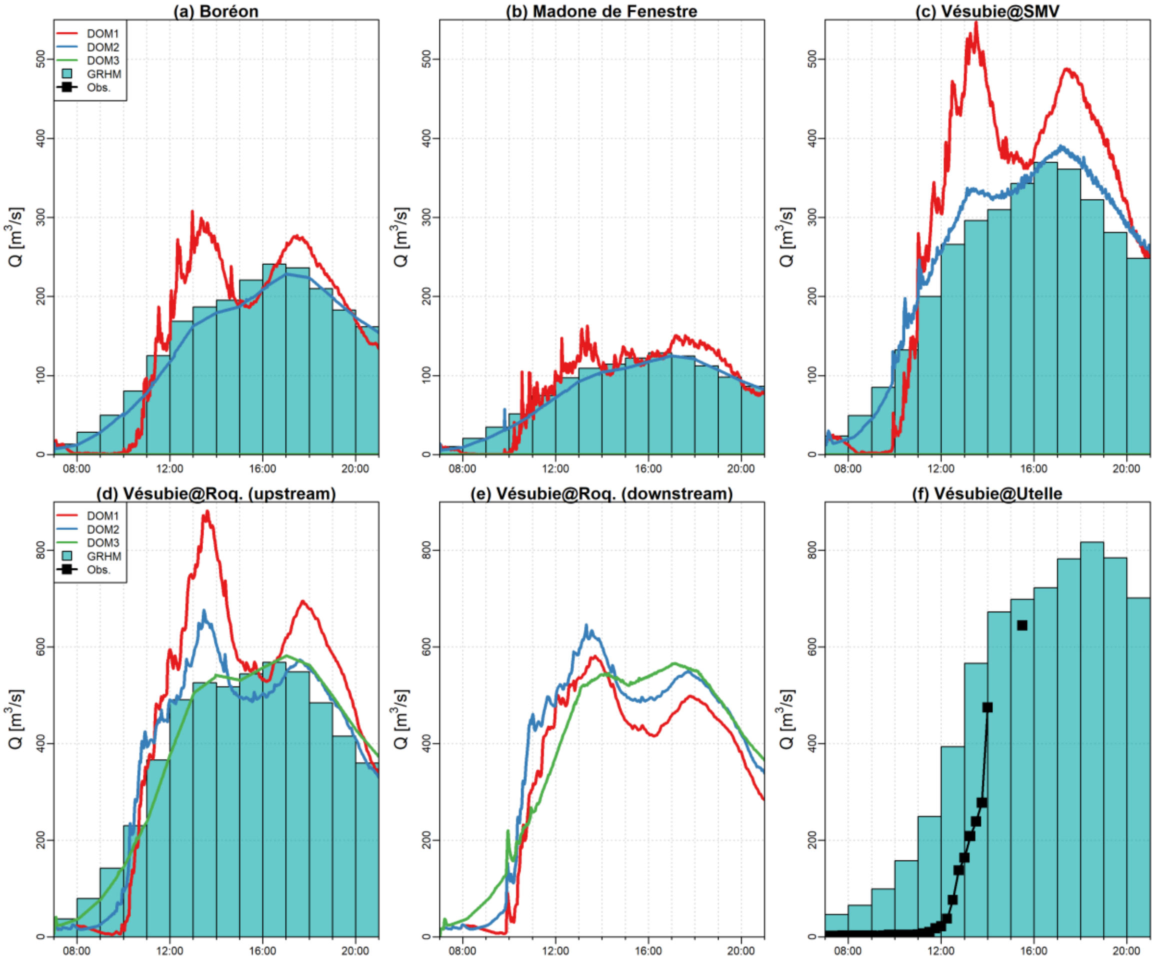

Figure 5: streamflow simulated at each subcatchments: colored bars represent mean hourly streamflows simulated by GRHM, and lines represent instantaneous streamflows simulated by the different Basilisk configurations. Available streamflow observations at Utelle are compared with GRHM simulation at this outlet.

4.3.2 Damages

Figure 8 compares the maximum water heights simulated on (4 [m] x 4 [m]) cells where damages have been estimated by Icube-SERTIT (2020), according to the different simulation configurations.

Around Saint-Martin-Vésubie, no water has been simulated on 63 and 125 of the 177 damaged sites, for the DOM1 and DOM2 configurations, respectively. Other sites are located on cells with maximum water heights between 0.1 and 1.5 [m]. When only destroyed sites are considered, these proportions go down 33 and 72 of the 106 destroyed sites. For the Roquebilière region, no water has been simulated on 15, 27 and 45 of the 72 damaged sites, for the DOM1, DOM2 and DOM3 configurations, respectively. When only destroyed sites are considered, these proportions go down to 6, 12 and 19 of the 34 destroyed sites.

4.3.3 Computational times

Computational times of 70, 28.7 and 4.5 [h] were obtained when simulating the 14-hour flood, from 07:00 to 21:00 (TU), for the DOM1, DOM2 and DOM3 configurations, respectively.

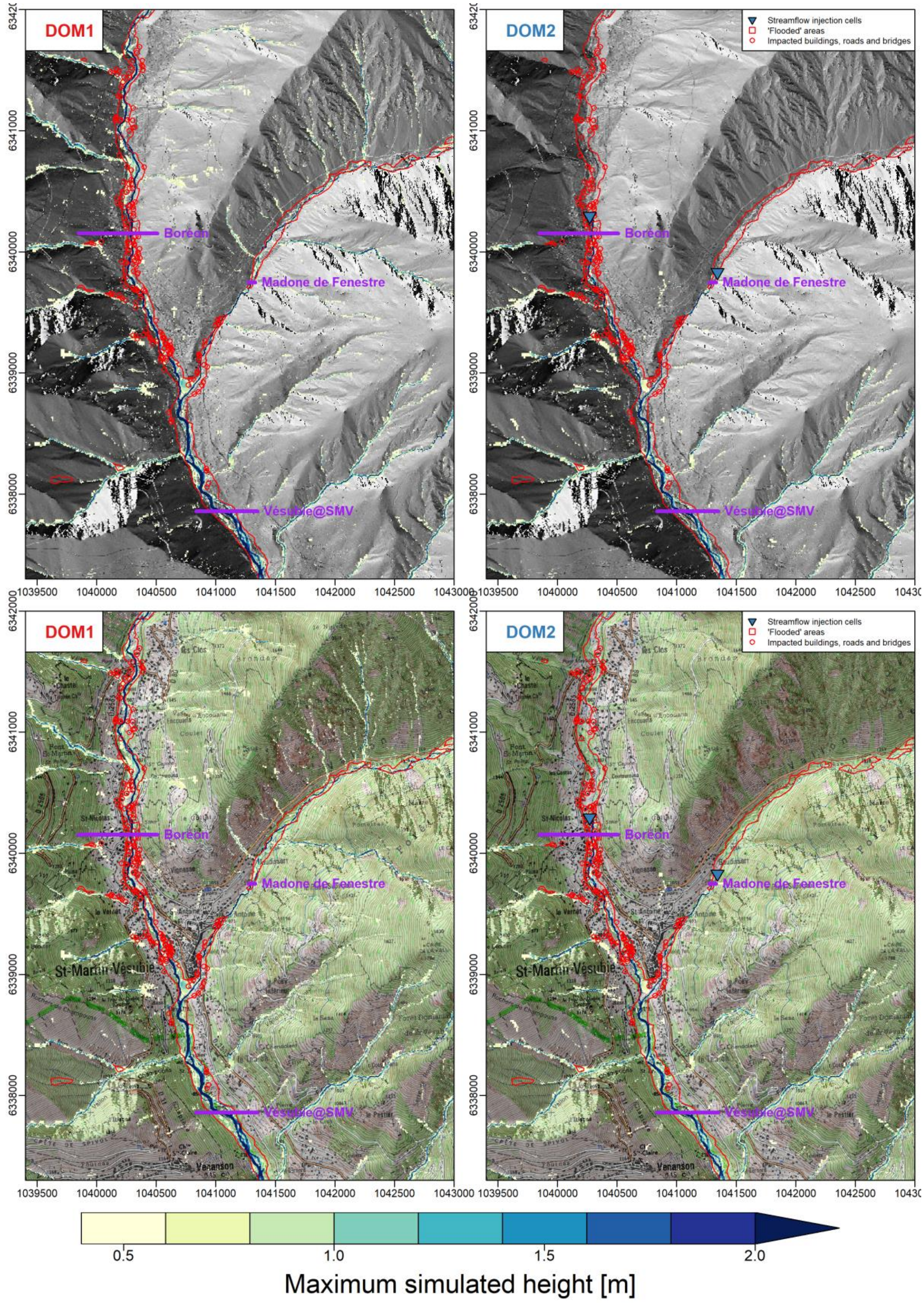

Figure 6: maximum simulated height around Saint-Martin-Vésubie, considering the "pre-Alex DEM" and the DOM1 (left) and DOM2 (right) simulation configurations; with DEM (first line) and SCAN 25® IGN maps (second line) as background images. Only the cells with more than 40 [cm] of water are highlighted here.

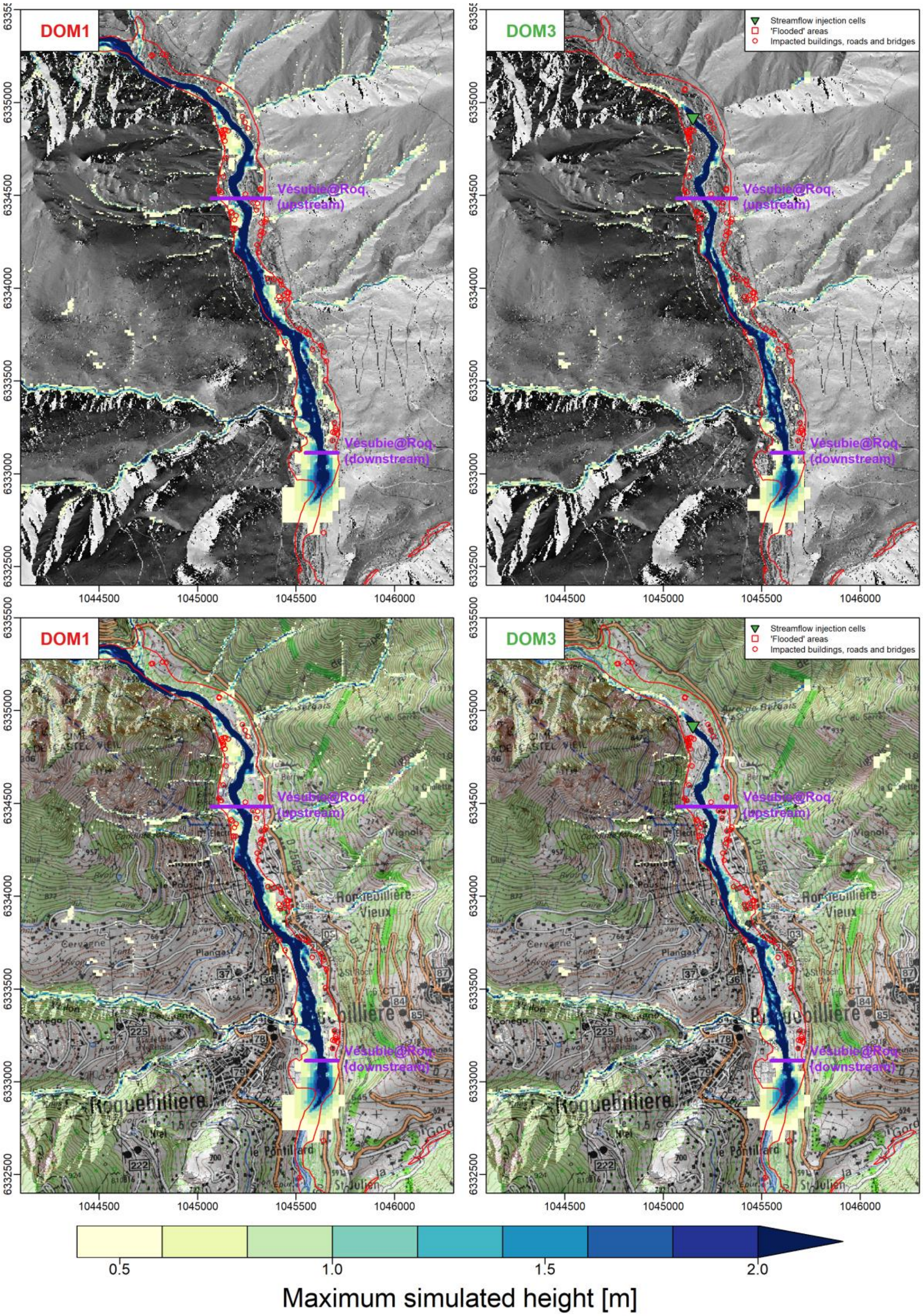

Figure 7: maximum simulated height around Roquebilière, considering the "pre-Alex DEM" and the DOM1 (left) and DOM3 (right) simulation configurations; with DEM (first line) and SCAN 25® IGN maps (second line) as background images. Only the cells with more than 40 [cm] of water are highlighted here.

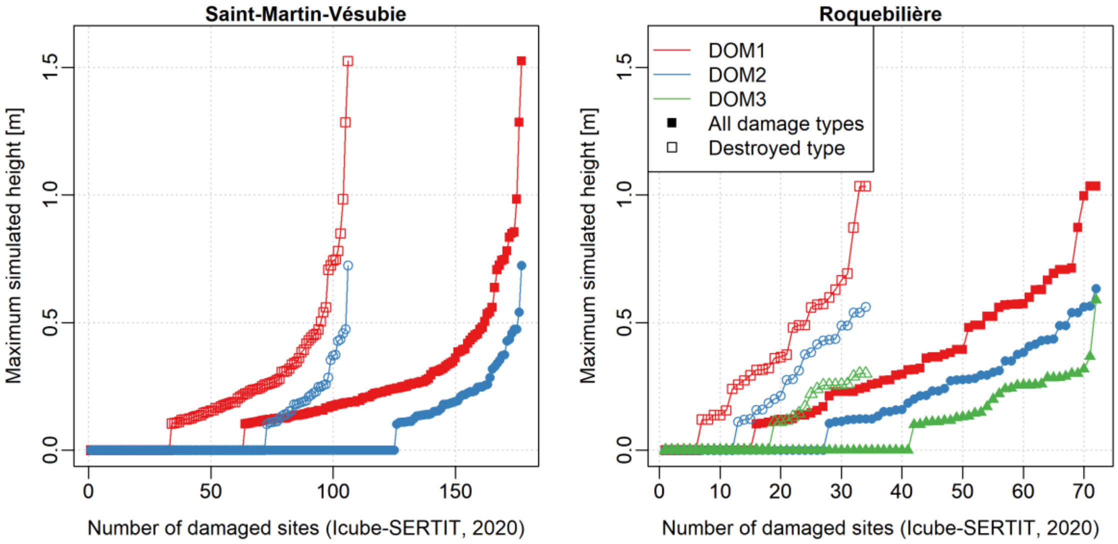

Figure 8: distribution of maximum simulated heights on cells containing damaged buildings, roads and bridges (Icube-SERTIT, 2020), for Saint-Martin-Vésubie and Roquebilière regions. For each simulation, two distributions are plotted: one considering all three damage types ("Possibly damaged", "Damaged" and "Destroyed") and one considering only "Destroyed" damage type.

5 Conclusions

In this work, we tested a hydrologic-hydraulic coupling method to simulate the Alex flash-flood event on the upstream part of the Vésubie catchment (Alpes-Maritimes, southeastern France), one of the highly affected catchments. The studied catchment drains 165 km², with elevation ranging from 531 to 3143 [m]. We coupled the continuous semi-distributed GRHM rainfall-runoff model with Basilisk, a 2D hydraulic modelling software with adaptive grid refinement. This approach allows to consider rainfall spatial variability to produce streamflows and water heights over the studied domain, described by squared cells of size ranging from 128 to 4 [m] here.

The main conclusion of this study is drawn from the comparison of flood extent simulation with the post-flood impact cartography produced by the ICube-SERTIT (2020). The simulated flood extents seem to be significantly underestimated when compared to the impact cartography, with numerous damaged structures being associated with dry cells within the simulations. If significant damages might be locally observed on non-flooded terrains (due to soil erosion or landslides), this underestimation might be induced by an underestimation of precipitation and streamflow used as source terms of the hydraulic model. Nevertheless, this underestimation mainly highlights the limitation of using fixed topography in this context of massive geomorphological changes of the flood channels. Figure 9 (right) highlights the geomorphological changes of the river corridor due to the Alex storm nearby Roquebilière. These changes are significant, with differences locally higher than 2 [m]. Using this post-Alex DEM within the DOM3 simulation configuration, flood extent is significantly wider (Figure 9 (left)) and close to the ICube-SERTIT (2020) flooded areas, raising the issue of potential impacts of floods in the coming years. In this context, using temporally variable topography within the hydraulic model is needed for the simulation of such event.

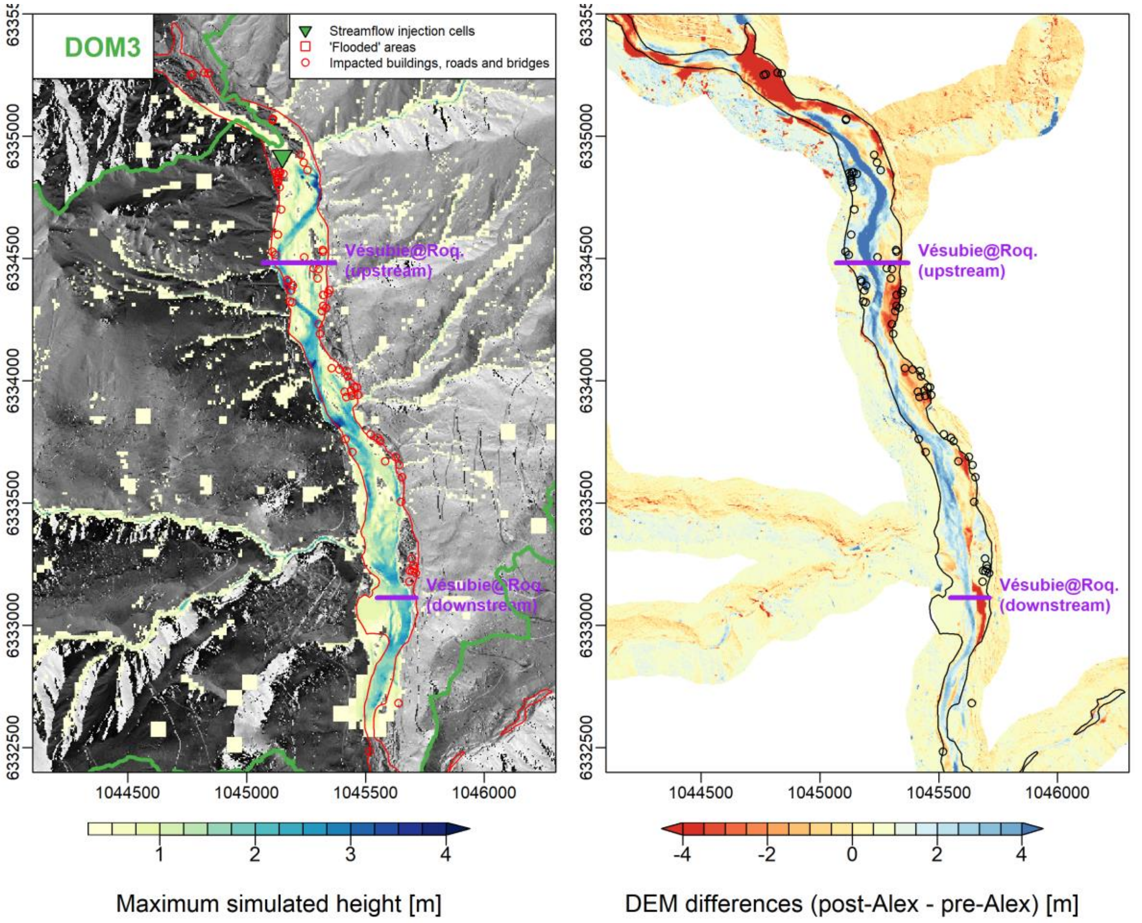

Figure 9: (left) maximum simulated height around Roquebilière, considering the "post-Alex DEM" and the DOM3 simulation configurations (only the cells with more than 40 [cm] of water are highlighted here); (right) DEM differences for Roquebilière area.

Several other limitations can be discussed. First, the very limited number of available observations on this catchment does not allow to validate the simulated streamflows. The comparison of simulations highlighted two different flood dynamics according to the considered models: GRHM simulations are smoother, with a streamflow peak around 17:00 (TU), while the SCS-CN and Basilisk combination produces highly energetic streamflow rises, with a peak around 13:00 (TU). The available streamflow observations on this catchment have been compared to the GRHM simulation (cf. Figure 5), showing a potential overestimation of the streamflow during the first flood event hours, induced by an early catchment response of the GRHM model. Thus, comparison of these simulations with onsite flood peak estimation and comparison of simulations performed on neighbor gauged catchments for the same flood event are needed to validate the tested approaches and the streamflow simulations.

The uneven characteristic of the streamflow series extracted from Basilisk also needs further investigations. This can be related to the sudden mesh refinement on upstream catchments, when the refinement threshold is finally exceeded. Moreover, the coarse resolution of rainfall inputs might explain these sudden streamflow rises, due to brutal spatial discontinuity between rainfall grids. Thus, a spatial interpolation of the rainfall grid might be needed, to limit the spatial discontinuity of rainfall source terms into the Basilisk simulation domain. Besides, several streamflow series estimated out of Basilik through particular sections appear to be incoherent, likely due to bad choice of sections, potentially crossing different channels and thalweg during the different refinement steps.

Finally, several thalwegs appear to be disconnected to the main river channel, despite DEM hydrological conditioning. This might be due to conditioning that is not preserved at the different refinement levels: in this study, the conditioning has been performed at 1 [m] scale, while Basilisk calculation were performed on cells ranging from 128 [m] to 4 [m]. Thus, development might be needed to produce a DEM with a consistent conditioning at the different considered grid levels.

6 Acknowledgments

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