Simulation of the Brague Flood of October 2015 in Southeast of France

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December 1, 2023

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IN SOUTHEAST OF FRANCE

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KEY WORDS

Flash floods, 2D hydraulics, numerical modeling, TELEMAC-2D

ABSTRACT

The Brague watershed (Alpes-Maritimes) is recurrently subjected to flash floods known as "Cévenol" events, which result in flooding and damage. In October 2015, the municipalities of Biot and Antibes were particularly severely affected. The *hydrometric station of the Brague river was damaged during the flood and did not provide a complete record. This flood event was previously studied using hydrological approaches or 2D hydraulic modeling tools with adaptive mesh refinement. Here, we propose to model and simulate this event in the downstream area of the Brague, based on a 2D approach on an unstructured mesh using the TELEMAC-MASCARET modeling software.*

1. INTRODUCTION

The Mediterranean coastline is very often affected by episodes of intense rainfall and rapid flash floods that result in loss of human lives and destruction of infrastructures. These episodes are studied within the framework of various research efforts and research projects, including the recently established HyMeX program [1,2] and [3].

The south-eastern part of France often experiences rapid and severe flash floods in the late summer and autumn. These are typically caused by slow-moving convective storms that draw moisture from the Mediterranean Sea, with the region's topography amplifying the rainfall [4]. Notable catastrophic flash floods occurred in September 2002 in the Gard region [5], in June 2010 around Draguignan city [6], and more recently in October 2015 on the French Riviera [7,8], particularly affecting Cannes city [9] and the downstream part of the Brague river, on eastern part of Antibes. The latter is a coastal torrential river located in the Alpes-Maritimes department. It flows for about twenty kilometers and collects the waters of several tributaries, mainly the Valmasque and the Bouillide. It originates in the municipality of Châteauneuf-de-Grasse and flows into the Mediterranean Sea near the town of Antibes. Its watershed covers approximately 70 km^2 and is quite steep which induces short hydrological responses. The watershed includes 10 municipalities. During Mediterranean weather events, the Brague often experiences bank overflow, causing catastrophic floods. Since 1970, it caused about fifteen floods recognized as natural disasters by ministerial decrees. These floods resulted in millions of euros in damage, claimed several human lives, and affected the psychological well-being and the health of the local population [10]. Today, the Brague watershed is even more under pressure due to population growth and urbanization.

Among the last three recent floods (November 5-6, 2011; October 3, 2015, and November 23, 2019) of the Brague, the one of 2015 was the most significant. Indeed, rainfall and flow rates in some places reached values with a return period of more than a hundred years, causing catastrophic damage in urbanized areas (tens of thousands of claims and several million euros of insured damage), with 9 casualties in the Brague watershed. The 2015 event has been subject to several recent studies [7,11,12,8,13,14,15], and more particularly on the hydraulics perspective: with a flood excess volume method [16], with HAND/MS, caRtino 1D and Floodos 2D [17], with Basilisk [18] and with HEC-RAS 1D-2D [19]. To our knowledge, up to now no numerical approach has considered an unstructured mesh to simulate the hydraulics of this event.

In this work, our objective is to establish a numerical model with intentionally coarse mesh to assess its ability to replicate and comprehend the key elements of the 2015 flood (flooded areas, dynamics, and orders of magnitude). To achieve this, it is necessary to better understand the influence of physical and numerical parameters for the configuration of this specific case study. The model will be further refined to assess the possibility of real-time forecasting, testing scenarios, modifications within the watershed, and designing a physical model following the idea of [20]. To do so, we propose here a preliminary work to model this flood event on an unstructured mesh using the TELEMAC-MASCARET modeling software (http://www.opentelemac.org/).

In what follows, we will first present the geographical and meteorological context. Then, the data used for the modelling will be introduced (DEM and input hydrographs). In the methodological part, we will describe TELEMAC-2D and the implementation of the model (mesh generation, parameters setup). Finally, we will present and analyze the results. The results will be compared with the ones obtained thanks to HEC-RAS 1D-2D modeling software [19] and with the observed flood extent [21,22].

2. GEOGRAPHIC AND METEOROLOGIC CONTEXT

This part presents the Brague watershed (Figure 1) and the studied domain (Figure 2), which is located in the downstream part.

2.1 The Brague river and watershed

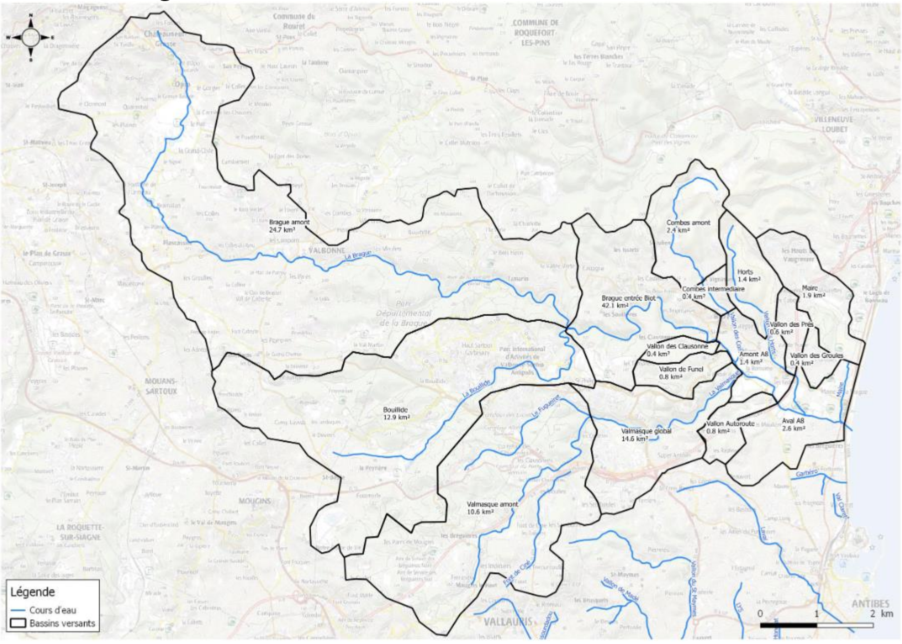

Figure 1: The watershed of the Brague river and its main tributaries (source: [23]).

2.1.1 The watershed

The Brague watershed (Figure 1) area covers a surface area of 70 *km²*, with around 100 *km* of watercourses. It also covers ten municipalities: Antibes, Biot, Châteauneuf, Grasse, Mouans-Sartoux, Mougins, Opio, Le Rouret, Valbonne and Vallauris, and encompasses a variety of land uses. In particular, there are three departmental parks (Brague, Valmasque, Vaugrenier), seven golf courses, the Sophia-Antipolis business park, leisure activities in the lower floodplain (Marineland, campsites), and a large amount of residential housing, particularly in the floodplain [24].

The Brague river rises at an altitude of 340 *m NGF* in Châteauneuf-de-Grasse. It stretches for around twenty-one kilometers before flowing into the Mediterranean Sea at Antibes. Major tributaries, such as the Valmasque (8 *km*) and the Bouillide (7 *km*) on the right bank, and the Vallon des Combes (5 *km*), the Vallon des Horts (4 *km*) and the Maïre (< 1 *km*) on the left bank, add water to the river. However, the smallest tributaries are dry for part of the year.

Carrying a low flow (around 0.4 m^3/s) but continuous throughout the year, the river flows until it reaches the alluvial plain that extends over the municipalities of Biot and Antibes. It is at this point that the slope becomes milder, with an average slope of 0.4 %, encouraging flooding.

The frequent and intense flash floods that occur in this watershed reshape the watercourse. That was the case during the flood of October 2015, with, among others, a widening of the main channel and erosion.

Faced with the risk of flooding, the multi-year intervention program [25] provides a range of protection strategies. These include conventional civil engineering measures and measures based on nature, such as preventing logjams (logjam traps), bank protection and action on hydraulic structures crossing the river.

2.1.2 The studied domain

The studied domain (Figure 2) focuses on the downstream part of the watershed which corresponds to the Brague plain. It extends over the municipalities of Biot and Antibes, where the outlet is located. The area is heavily urbanized with some vacant lots situated in the direct vicinity of the riverbanks such as golf courses and campsites.

The development length of the Brague river is around four kilometers. In this part of the watershed, the river has gentle curves and a mild slope. Along its course, the watercourse intersects with four tributaries: the Valmasque, the Vallon des Combes, the Vallon des Horts, and the Maïre. Each of the rivers encounters various hydraulic structures, such as bridges and culverts. A highway divides the estate in two, crossing both the Brague and the Vallon des Horts.

Depending on the season and the weather, some of the tributaries, such as the Vallon des Combes, are dry. One hydrometric station, located upstream of the domain at Biot, monitors the river's flow rate and water level. The Brague's mean annual flow is 0.4 m^3/s.

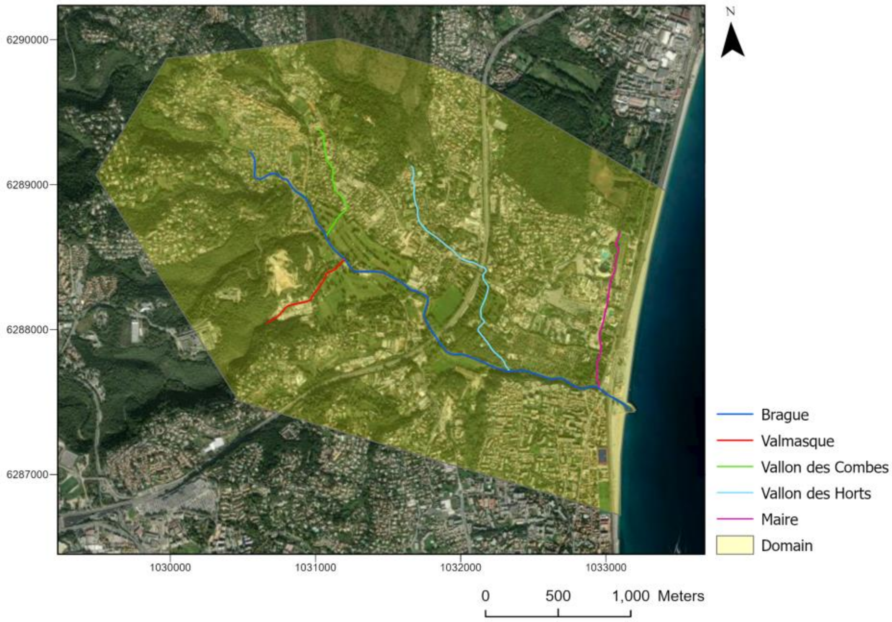

Figure 2: Delimitation of the study area with the Brague river and its tributaries.

2.2 The 2015 flood event

Between 2 and 3 October 2015, the Côte d'Azur was affected by intense rainfall (Figure 3). The cities of Cannes [9], Mandelieu, Biot and Antibes experienced flash flooding. In one hour, it rained 115 and 109 *mm* respectively in Mandelieu and Cannes. In the Brague basin, it rained 160 *mm* in 3 hours. The event was the result of a combination of factors. The major one is a low-pressure system born in the Mediterranean Sea. The unusual feature of this low-pressure system is that the epicenter of the rains was concentrated in the same zone for more than three hours. Added to that, on October 2, precipitation lasted all day. The rain was light but continuous. Water was therefore able to infiltrate, saturating the soil [7].

Both human and economic damage was caused. The flood caused twenty casualties, including nine in the Brague watershed and three just for the municipality of Biot. Material damage in the downstream part of the Brague watershed is estimated at 200 million euros [13]. From a hydrological point of view, the event exceeds the 100-year return period. As a result, the flood of October 3, 2015 becomes the reference flood for the watershed. The plan for flood risk prevention (Plan de Prévention des Risques naturels d'inondation – PPRi in french) is therefore revised for ten municipalities, including Biot and Antibes [22] as illustrated in figure 4 within the 2015 flood extent.

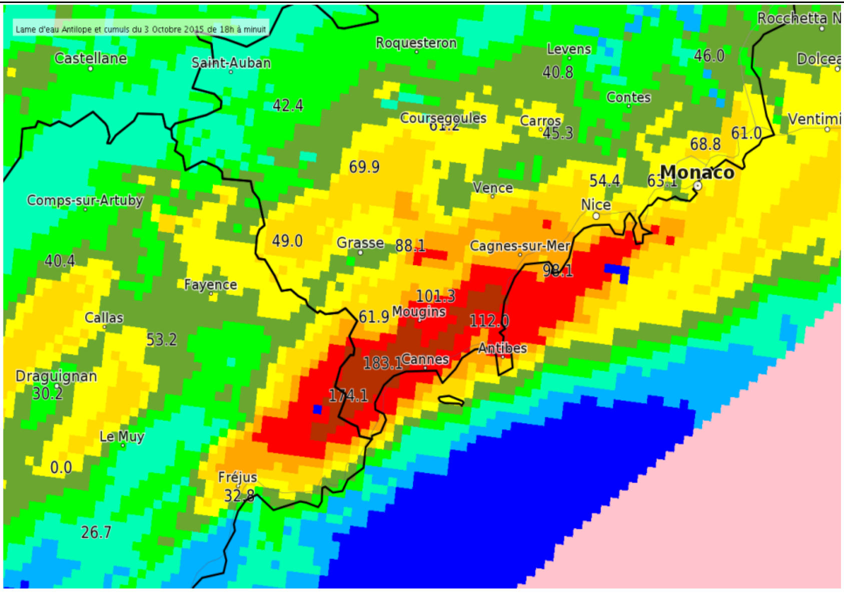

Figure 3: Rainfall map for 3 October 2015 between 6 pm and midnight on the Côte d'Azur – in red: 100 to 150 *mm*, in brown: more than 150 *mm* (source: MétéoFrance) from [26]).

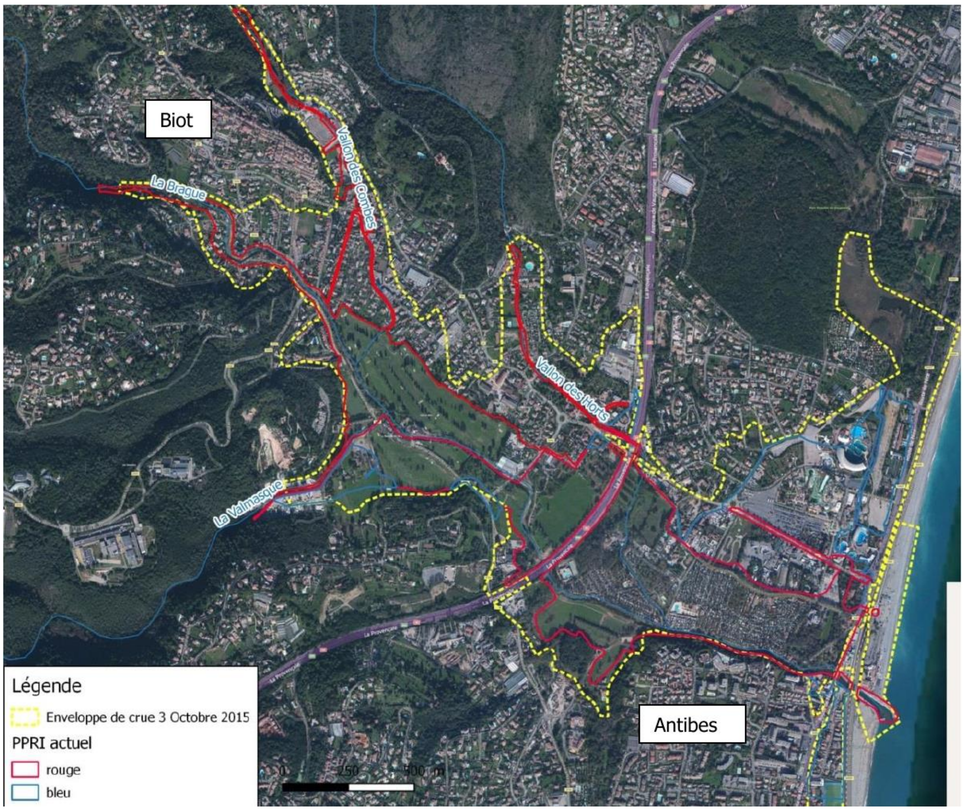

Figure 4: Envelope of the current natural flood risk prevention plan (PPRi in french) and the extent of October 3, 2015 flood in the Brague plain (source: [21]).

3. DATA

This section first presents the data used in our TELEMAC-2D model: the domain DTM from IGN, improved in [19] and the inflow hydrographs. Following that, the key elements pertaining to the HEC-RAS 1D-2D model are provided based on [19].

3.1 DTM & inflow hydrographs

The TELEMAC-2D numerical model requires input data. Nevertheless, as the model is relatively simple, only the basic data are required for its development, namely a digital terrain model (DTM) and upstream and downstream boundary conditions.

The DTM is provided by the French National Geographic Institute (IGN) and has a resolution of 1 *m* [27]. The initial DTM requires improvements at certain levels: local interpolations of main channel, obstruction of watercourses by hydraulic structures, underground sections not represented. These improvements have been made by Ah-Woane et al. [19] to enable a better representation of the river hydraulics.

Hydrographs of the Brague and its tributaries are available (Figure 5). These hydrographs have been simulated [13], given that the hydrometric station on the Brague at Biot was destroyed during the event and was therefore unable to record water levels, and that the tributaries have no hydrometric stations. Downstream, the Mediterranean Sea enters the river estuary. This creates a downstream control, making the river flow subcritical at this location.

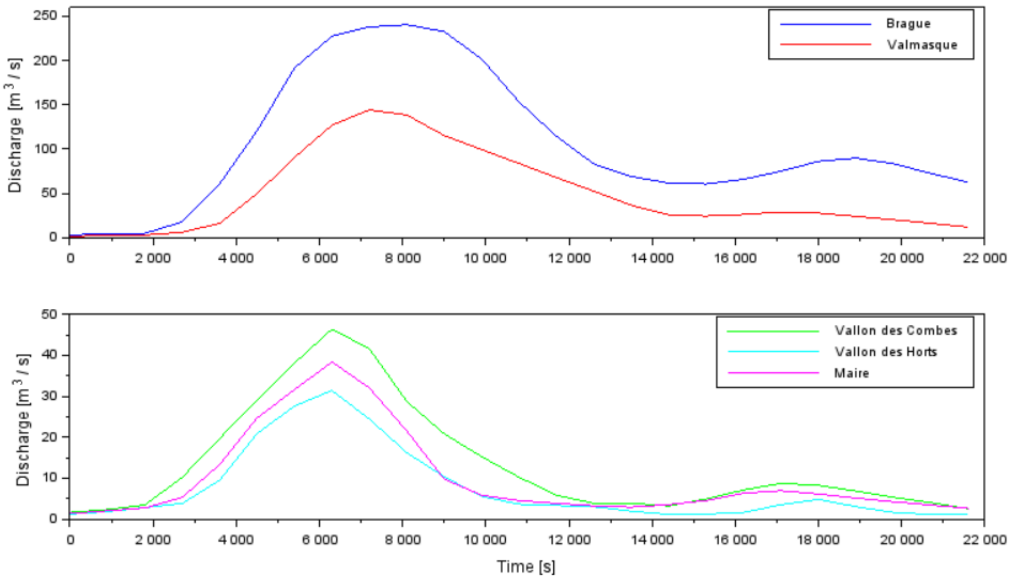

Figure 5: Simulated hydrographs of October 3, 2015 flood for the Brague and its tributaries.

3.2 Existing numerical model

A coupled 1D-2D HEC-RAS model was developed to study the October 2015 flood [19]. Several key features and elements of the HEC-RAS 1D-2D model are described hereafter (Figure 6).

The study area covered by the HEC-RAS 1D-2D model is similar to that of the TELEMAC-2D model, suggesting a comparable geographical scope and environmental context. The HEC-RAS 1D-2D model focuses on the Brague and Valmasque rivers, as these two watercourses usually have the most impact on flooding.

Three hydraulic structures are considered: two bridges located near the Brague hydrometric station in Biot and culverts located on the highway crossing the Brague. These structures play an important role in influencing flooding and river hydraulics. The HEC-RAS model integrates buildings directly from the DTM. This integration of buildings suggests a global approach that considers the impact of structures on the region's hydraulics.

The model considers Manning's law. The main channel of the two rivers, defined by the 1D Saint-Venant equations, have a friction coefficient set at n=0.035 $s/m^{1/3}$. The floodplain, defined by the 2D diffusive wave equations, has a friction coefficient of n=0.06 $s/m^{1/3}$.

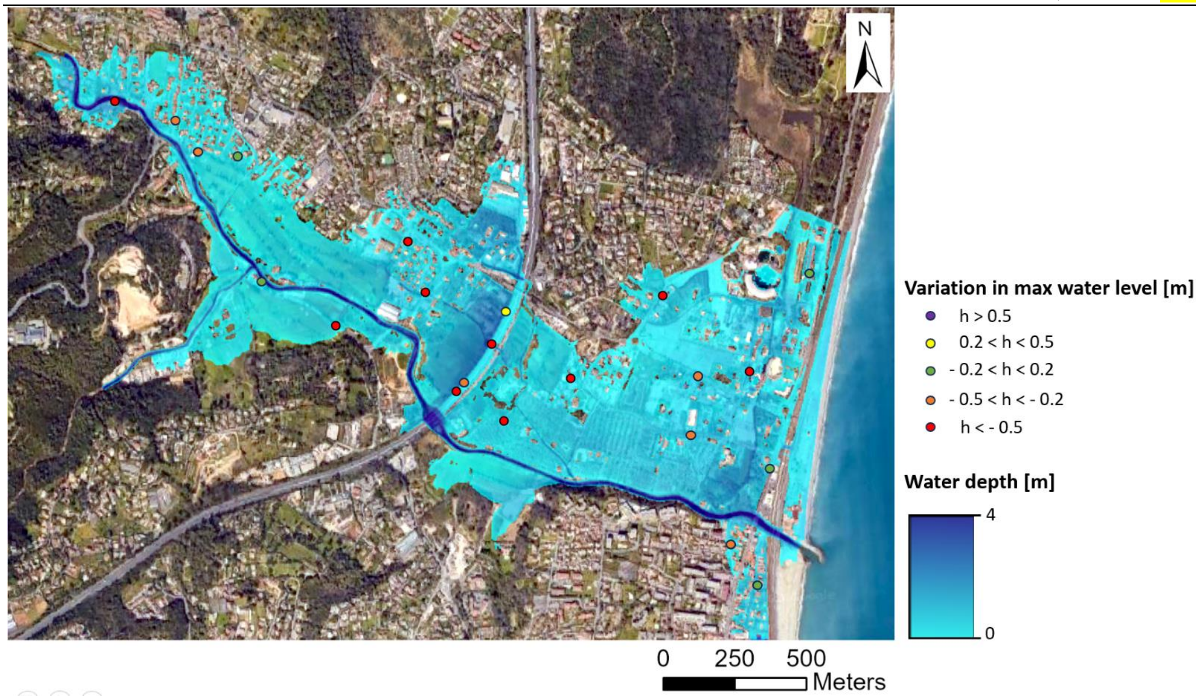

Figure 6: Flood map and comparison of max water level of the HEC-RAS 1D-2D model and the flood marks of October 2015 flood (source: [19]).

4. MATHEMATICAL AND NUMERICAL MODELS

This part presents the mathematical and numerical models used in the purpose of this study. With the aim of testing the ability of a relatively coarse model to reproduce the observed main flooding patterns (water levels, floodmap, arrival times, etc.), useful information on the construction of this model are given here.

More details on TELEMAC-2D numerical code and numerical options can be found in the user reference manual (www.opentelemac.org).

4.1 Modelling tool

TELEMAC-2D v8.4 was used in this study. It is a hydrodynamic code of the TELEMAC-MASCARET suite of solvers, solving the Saint-Venant equations in two dimensions. It solves the two-dimensional Shallow Water Equations in their non-conservative form [28].

4.2 Model set-up

4.2.1 Physical parameters

The friction law of Strickler (K=1/n) is used as a closure model for the bottom friction. As a first (and relatively strong) assumption, the coefficient of Strickler is considered to be uniform over space and invariant in time with a value of K=35 $m^{1/3}/s$.

The hydraulic structures such as culverts and bridges piers are not accounted in the present numerical model; bridges or culverts are removed from the terrain model in order to open the way to water flows. In the same way, buildings are not accounted for in the current model and are not represented in the DTM.

Flow rates are injected upstream (Figure 7), close to the water level station in the Brague river, and in tributaries (la Maïre, Vallon des Horts, Vallon des Combes, la Valmasque). The downstream boundary is set in the sea, parallel to the coastline, with an imposed water level of 0 *m NGF*. The last allows an easy and sufficiently accurate representation of the downstream boundary during such flooding events, which is assumed to not influence the flood dynamics in the downstream watershed.

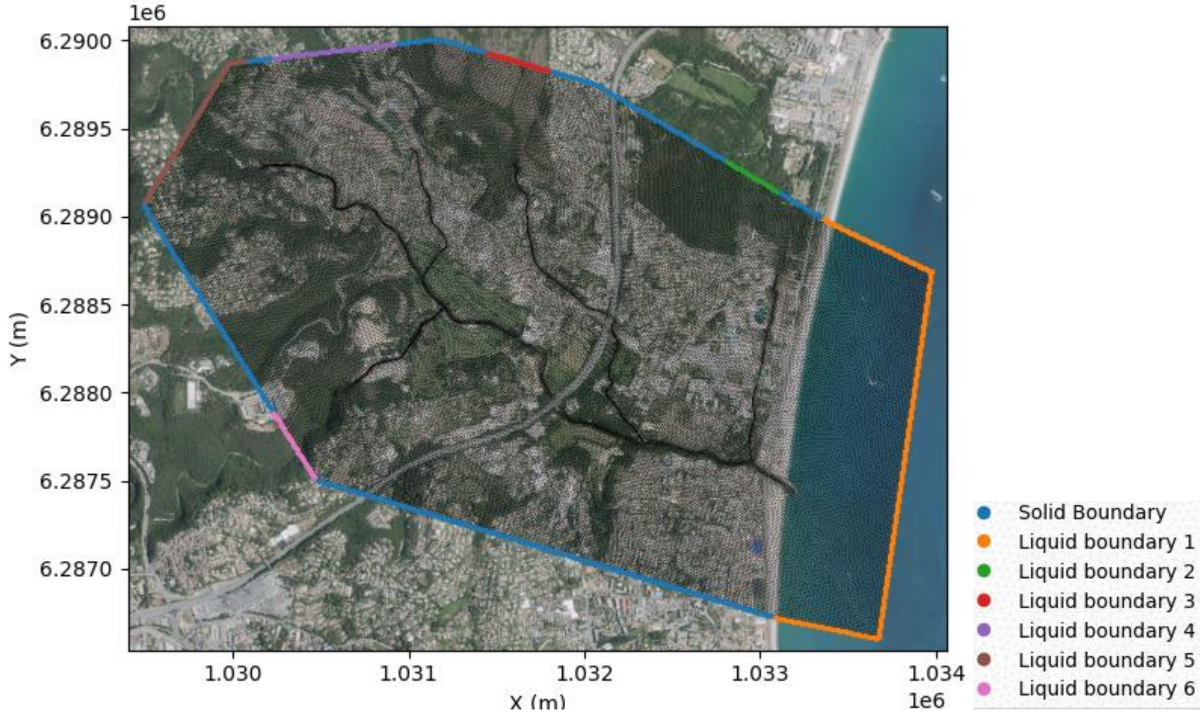

Figure 7: Aerial views of model catchment with the solid boundaries plotted in blue and the six boundaries plotted with the other colors and (bottom) zoom on the mesh with the confluence between the Brague river and tributaries.

The initial condition assumes fully-saturated soil and karst, which seems in fact relevant regarding the rain data which shows repeated rainfall events starting several weeks before the flood event [7]. The hydraulic model is initialized by injection of permanent inflows at the upstream boundaries. To initialize the model before propagating the flood of 2015, the permanent flow imposed at each upstream boundary is equal to the flow measured before the flooding event, which means at the start of the 2015 hydrograph (i.e. at t=0 *s*, in Figure 5). Initializing the flow in the main channels aims at increasing model realism by reproducing satisfactory initial water volumes in the domain. Moreover, it ensures the flood wave to spread on wet domain, while not accounting for it – assuming a dry domain – would lead to irrelevant flow dynamics.

4.2.2 Numerical parameters

The finite elements method is used to solve the Saint-Venant equations in their non-conservative form (for more details see [28,29,30] and the TELEMAC-2D user manual including references therein). The computational mesh is composed of unstructured triangular elements, of mean size of 10 *m*, 5 *m* in the Brague river and 3 *m* in its tributaries, and 15 *m* in the floodplain, totalizing 51,708 nodes for 102,437 elements (Figure 8). The mesh is built using the software programs BlueKenue (https://nrc.canada.ca/). Channels banks are defined thanks to constraint lines, with mesh nodes positioned along them, allowing to capture sufficiently well the transition between the floodplain and the channels (Figure 8). As a common practice in fluvial models, in these channels, the longitudinal mesh size is higher than the transverse one, in order to reduce the number of used computational nodes and eventually reduce computational times. The model uses a deliberately coarse mesh with fewer nodes to test if it can accurately reproduce the main flooding patterns observed in the field, such as water levels, floodmaps, and arrival times.

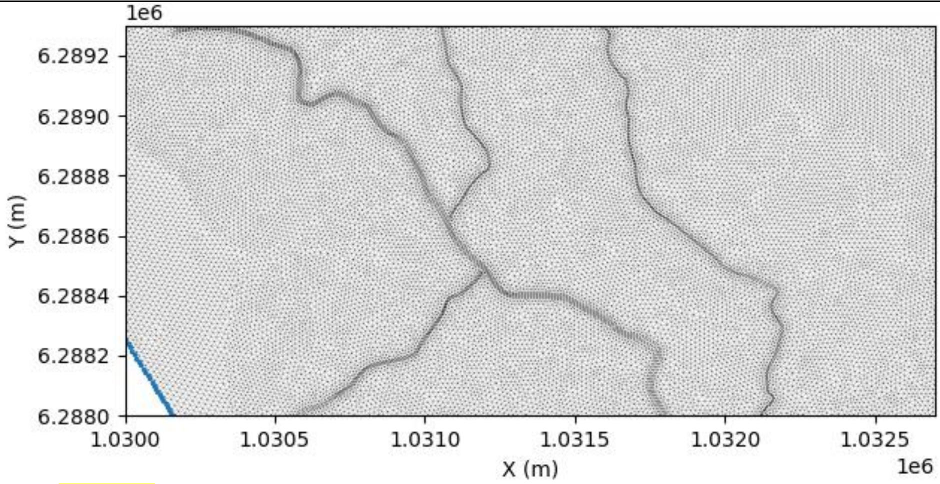

Figure 8: Zoom on the mesh with the confluence between the Brague river and tributaries.

The flow velocity components along x and y cartesian coordinates, U and V, are solved with the NERD scheme (code=13). The GMRES solver with the minimum error method is used. A computational time step of 1s is retained for the present study, which corresponds to the maximal time step used in HEC-RAS 1D-2D simulations of Ah-Woane et al. [19]. Turbulence terms are closed using the constant eddy viscosity model, with a turbulent viscosity equal to 10^{-4} $m.s^{-2}$.

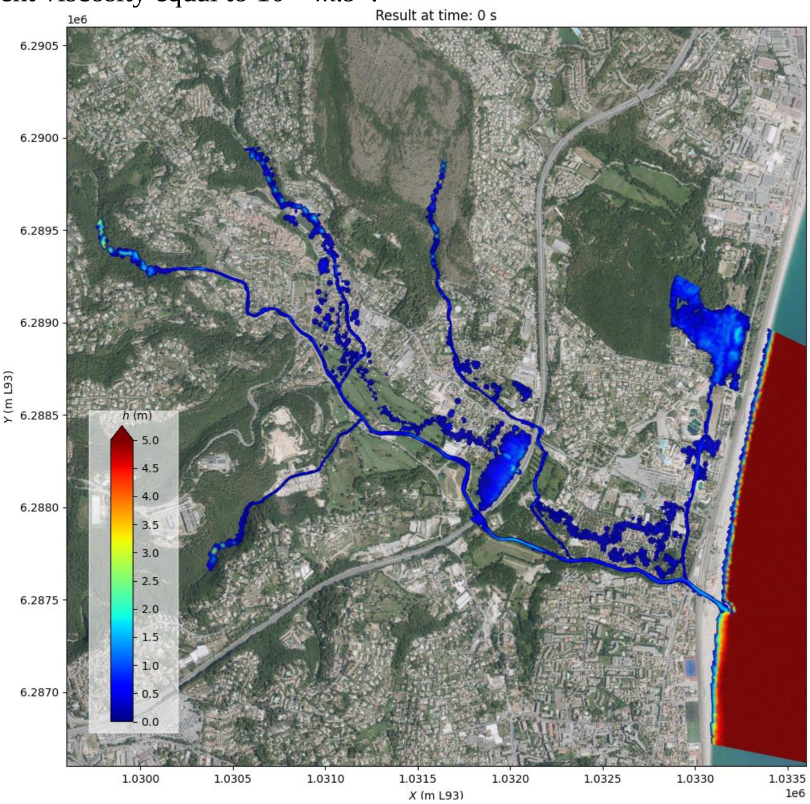

Figure 9: Aerial views of the steady state simulated as initial condition before the flood.

4.RESULTS AND DISCUSSION

The steady state used as initial condition of the flood (hot start) is obtained after approximately 15 *h* of simulation, hence the initial condition for the flood simulation is chosen after this time, at t=20 *h* (Figure 9). According to this result, the model is relatively well initialized as the water mainly flows in the Brague river and its tributaries. There is no water blockage due to remaining hydraulic structures (e.g. bridge decks) that might behave as walls, which was possible thanks to the manual pre-treatment of the DEM [19].

However, after initialization, it is possible to identify a multitude of areas which are filled with water in the floodplain, even if they should not in reality (Figure 9). This result can be explained quite easily, as the current model is voluntarily coarse and somehow over-simplified: due to the coarse mesh size, some tributaries are directly connected to the floodplain because banks slopes cannot be accurately modeled (e.g. they might be weakly porous); in a less notable way, some numerical pumping may occur when the banks are not described with a sufficient high number of cross-sectional nodes. The last points could be improved in the near future by increasing the mesh resolution and correcting manually the elevation of banks and dikes when the DTM resolution is not sufficient to capture realistic slopes.

Despite of the previous multiple assumptions presented in section 3 and the limitations exhibited by the initial condition, the main results (Figure 10) are quite satisfactory and in relatively good agreement with observations (Figure 4). Indeed, the inundation maps obtained numerically and observed after the flooding event are reasonably comparable. This result also suggests that the initial condition (the current hotstart) does not play – under the present configuration – a significant role on the flooding patterns in comparison with other controlling factors, such as the flood hydrograph itself.

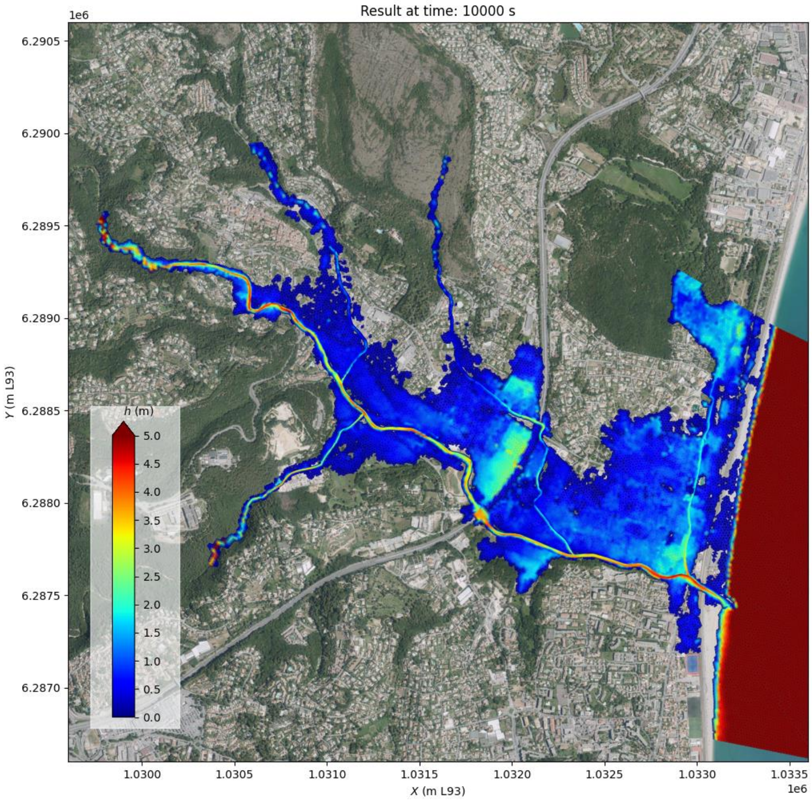

Figure 10: Aerial views of the inundation extent at t=10,000 *s*.

By comparing with HEC-RAS 1D-2D results (Figure 6, see [19]) for more details on HEC-RAS 1D-2D model), we notice that the flooding maps obtained from the two models are comparable, although the models are notably different. Indeed, the HEC-RAS 1D-2D model accounts for a finer description of the geometry such as buildings, but also of hydraulic structures such as culverts, even if the downstream boundary is constrained by the coastline with imposed normal depth (friction slope = 0.0065). This comparison highlights that model calibration is possible at this relatively coarse scale, and motivates to consider another flooding event to validate the TELEMAC-2D model at this scale.

It is also worth noting that as it was expected, the numerical simulations were quite fast and cost effective, as it required only 28 *min* of computation on a single CPU. This point sheds light on the opportunity of using such an approach to model flooding events under this type of configuration to provide preliminary/prospective results, or increase model accuracy and realism in the future by enriching its complexity, to the detriment of increased computational times. It is noteworthy that the computational time could be even reduced using multiple CPUs.

5.CONCLUSION AND PERSPECTIVES

5.1 Conclusion

A TELEMAC-2D model is successfully built to simulate at a coarse scale the flooding event of 2015 in the downstream Brague river. Despite inaccuracy due to coarseness, the first results show the model ability to reproduce the main flooding patterns (flood extent and dynamics, water depths). It is possible – under this configuration – to use this approach to get preliminary results fastly, to get prospective outcomes for many purposes (general understanding and model improvements) and it opens the door to future and technically feasible real-time prediction. The last results offer many perspectives as suggested below.

5.2 Perspectives

In the general framework of better understanding and later forecast flooding of the downstream part of the Brague watershed, the TELEMAC-2D numerical model implemented in this work will be improved in the future. Through several studies currently in progress, the model will be progressively enriched, to improve i) the actual knowledge on the importance of accounting for some parameters/factors under this specific study case, ii) model accuracy, realism and predictability, and iii) possible code improvement (e.g. flow in culverts). The use of HPC will be of crucial help to deal with increased model complexity.

Among these topics, a closer look to the following points is expected soon:

- Assess the importance of bottom roughness spatialisation and temporal evolution on flood dynamics
- Influence of hydraulic structures such as culverts on the flood dynamics, and the relative importance of accounting of them accurately
- Relevance of accounting for a fine description of tributaries’ geometry, or small-scale geometries such as buildings
- Impact of numerical model parametrization (e.g., mesh size/time-step, numerical schemes, solvers).

In the future, the following points should be addressed:

- Possibility of generalizing the flooding model for a wider range of flooding events (shape of flow hydrograph with various intensities and durations, initially unsaturated karsts, etc.)
- Possibility to use the numerical model as a tool to test the relevance of defining experimental models set-ups
- Extending the model catchment area to simulate runoff within the whole watershed or couple the current model with a hydrological model.

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