Simulation of the Brague Flood of October 2015 Using HEC-RAS with a 1D-2D Approach.

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ABSTRACT

On the evening of October 3, 2015, the southern coast of the Alpes Maritimes region was hit by a particularly intense and rapid flash flood episode. The municipalities of Biot, Antibes, Cannes, Mandelieu (non-exhaustive list) were extensively flooded and suffered significant damage. The death toll from these floods reached 20, with substantial material and economic losses (approximately 600 million euros in insured damages according to FFSA). The three main rivers that caused these floods were the Brague (70 km²), the Grande Frayère (22 km²) and the Riou de l'Argentière (48 km²). Among these rivers, only the Brague had a hydrometric station, which was damaged during the flood and did not provide a complete record. This flood event was studied using hydrological approaches or 2D hydraulic modeling tools. Here, we propose to model and simulate this event in the downstream area of the Brague river, using a 1D-2D approach enabled by the HEC-RAS modeling software.

1. INTRODUCTION

The Mediterranean coastline frequently faces severe rainfall and rapid flash floods, resulting in casualties and infrastructure damage. Ongoing research initiatives, such as the HyMeX program [1,2] and [3], have extensively studied these incidents.

The southeastern part of France experiences regular flash floods, primarily in late summer and autumn, driven by slow-moving convective storms from the Mediterranean Sea, amplified by topographic factors [4]. In particular, on the evening of October 3, 2015, heavy rains swept across Provence from west to east, intensifying on the French Riviera. The western part, especially between Villeneuve-Loubet and Mandelieu, was submerged by water on an already saturated ground, resulting in a heavy human toll (20 deaths) and phenomenal damage [5,6]. This event particularly impacted the city of Cannes [7] with a cumulative precipitation of 196 *mm* and also the downstream part of the Brague, from the municipality of Biot to the eastern part of the city of Antibes, with a cumulative precipitation of 128 *mm*. The downstream Brague River is originating in Châteauneuf-de-Grasse and flowing into the Mediterranean near Antibes. Its watershed, covering 70 km^2 with steep terrain, induces rapid hydrological responses, encompassing 10 municipalities. Mediterranean weather often causes Brague to overflow, resulting in catastrophic floods recognized as natural disasters since 1970. Among the recent floods of the Brague (November 5-6, 2011; October 3, 2015; November 23, 2019), the 2015 event stands out as the most significant. With rainfall and flow rates in some areas surpassing values with a return period of over a hundred years, it caused catastrophic damage in urbanized areas, resulting in numerous insurance claims and millions of euros in insured damage, along with nine casualties in the Brague watershed. Several recent studies have delved into the 2015 event [5,6,8,9,10,11,12], particularly focusing on hydraulics through various methodologies such as flood excess volume method [13], HAND/MS, caRtino 1D, and Floodos 2D [14], Basilisk [15], and TELEMAC-2D [16].

In this work, our objective is to model the event of October 3, 2025, using a 1D-2D approach with the HEC-RAS modeling software. To our knowledge, this has not been done before, except in a regulatory study using the MIKE software [17].

In what follows, we will first present the geographical and meteorological context. Then, the data used for the modeling will be introduced (the inflow hydrographs, the DEM and its treatment). In the model part, we will give the equations that we have chosen to use in our HEC-RAS 1D-2D model and its setup. Finally, we will present and analyze the results. The results will be compared with the observed flood extent [17,18].

2. CONTEXT

In this section is presented the Brague watershed, particularly affected by flash floods. Between 1970 and today, 15 main flood events occurred with the latest one in 2019 and the most powerful one in 2015. And then we will present the meteorological context of this event.

2.1 Domain: Brague river and its watershed

The Brague is a torrential coastal river in southeastern France, flowing into the Mediterranean Sea at Antibes. It has its source at an altitude of 340 *m NGF* at Châteauneuf-de-Grasse. This 21-kilometer-long river flows through five municipalities which are from upstream to downstream: Châteauneuf-de-Grasse, Opio, Valbonne, Biot and Antibes. The Brague collects water from two main tributaries located on its right bank: the Bouillide (7 *km*) and the Valmasque (8 *km*).

Its 70 km^2 watershed (Figure 1) concerns ten municipalities. The basin can be split into two parts: the hinterland and the alluvial plain. In the hinterland, the Brague runs for 17.5 *km* from its source to the start of the alluvial plain. The average slope is relatively steep (5%). The landuse is mainly residential. On the alluvial plain, which extends over the municipalities of Biot and Antibes, the slope becomes gentler, averaging 0.4%. The Brague runs for 3.5 *km* before discharging into the Mediterranean Sea. The landuse is more varied. There are golf courses and campsites, the Sophia-Antipolis technology park, various natural and leisure parks and a dense residential area. The karstic attributes of its watershed favor water infiltration and losses over a large part of its hydrographic network [20].

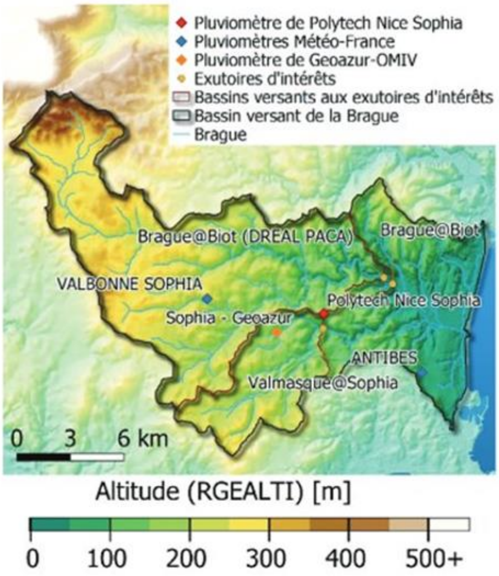

Figure 1: Outline of Brague watershed at the outlets studied and the position of the rain gauges (source: [19]).

These characteristics (surface area, slope, location, soil imperviousness) are favorable to flash floods and associated flooding. To prevent the various risks, a number of initiatives have been implemented, such as river restructuring (Figure 2), tributary development (Vallon des Combes rectangular main channel), and destruction or improvement on hydraulic structures [21].

Figure 2: Photo of restructuring of the Brague main channel taken on 11/29/2023 near the hydrometric station at Biot.

The study area corresponds to the Brague plain (Figure 3). This area stretches from the town of Biot to the Mediterranean Sea at Antibes. The Brague crosses the entire zone and meets four of its tributaries. These are the Valmasque, the Vallon des Combes, the Vallon des Horts and the Maïre. The main river flows through a diverse landscape, encompassing both rural and urban areas [15]. Its flow rate and water level are measured at its single hydrometric station located upstream of the zone of interest. Along the way, the watercourses encounter hydraulic structures such as bridges and culverts. These and other factors, such as the state of the karst, have a significant impact when it comes to flooding.

The mean annual flow of the Brague is 0.4 m^3/s at Antibes. This is more than 120 times less than its largest neighbor, the Var. Its course is characterized by gentle curves and occasional rapids. The basin has attracted a great deal of interest, particularly since the floods of October 2015, which caused severe damage. A new flood risk prevention plan (Plan de Prévention des Risques d'inondation - PPRi in french) was put in place following this event. In our study, this document is used as a basis for producing the numerical model.

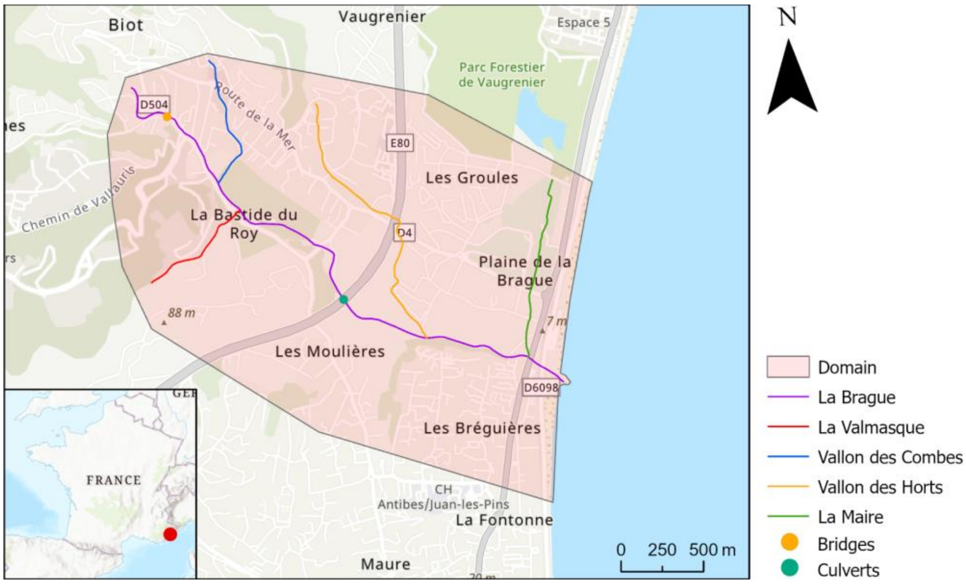

Figure 3: Delimitation of the study area with the position of the Brague and its tributaries and the main hydraulic structures.

2.2 Meteorological context of October 3, 2015 event

Although the flow of the Brague is low, it is no less dangerous. Flash flooding is a recurrent phenomenon in the region, particularly in the Brague watershed. Over the last 20 years, 3 floods have followed this type of event. In 2011, in 2019 and the most catastrophic, in 2015. It is this last one that interests us. On the evening of the 3rd of October 2015, a flash flood affected several towns on the Côte d'Azur, including Cannes, Mandelieu, Antibes and Biot. Over a period of 3 *h* and across the whole of the Brague watershed area, cumulative rainfall reached up to 160 *mm*. The rain was the result of a meteorological depression at sea level.

Both human and economic damage resulted from the flooding that followed the rain. The human toll was 20 deaths, including 9 in the Brague watershed. The estimated material damage in the watershed was €200 million [10]. The rainfall and flow rates during the event exceeded 100-year values. As a result, the flood of the 3rd of October 2015 became the reference flood, particularly for the Brague and its tributaries. The PPRi, drawn up in 1998 for the municipalities of Biot and Antibes, was then revised based on this event [17].

In addition, the river's only hydrometric station was destroyed during the flood, leading to the loss of all flood data. However, [9] have reconstructed the peak flows of the flood from field measurements: cross-sections, longitudinal profile, high-water marks. The flows were obtained using the Manning-Stricker formula. The rainfall-runoff method confirms the consistency between observed rainfall and calculated peak flows. The authors also provide hydrographs for different curve number (CN) values and different locations, for the Brague at the entrance to Biot, and for the Valmasque. The peak flows determined as part of the PPRi revision by Cabinet Merlin [17,18] and the work done in [9,10,13] are consistent. The latter provides the October 3, 2015 flood hydrographs used in this report.

Another study using the Basilisk tool and an adaptive mesh refinement provided results via a numerical model [15]. These results highlight the weakness of the downstream part of the basin regarding flooding. The study also shows the most sensitive areas, in particular the A8 highway and the bridge over the departmental road D6007 near the outlet.

3.DATA

In order to simulate flash flood phenomena, numerical modeling software requires a certain amount of information. This information is needed to create reliable models. The amount and quality of this information are therefore essential for the model to work properly.

3.1 Hydrological data

Different types of input data for constructing the flood are used. Firstly, we have input data for the 2015 event. These include hydrographs for the Brague and its tributaries (Figure 4), as well as additional data on flooded areas [17]. Downstream conditions and peak discharges (Table 1) are also available. However, this information is not sufficient to run any model satisfactorily. It is also necessary to have digital data on the ground: the digital terrain model (DTM). This is a representation of the Earth's surface that captures information about the elevation of the terrain in digital form. It is generally created by sampling elevation data at regular intervals across a geographical area. In hydrology, hydraulics and water management, DTMs play a crucial role in hydrological modeling, flood mapping and resource management.

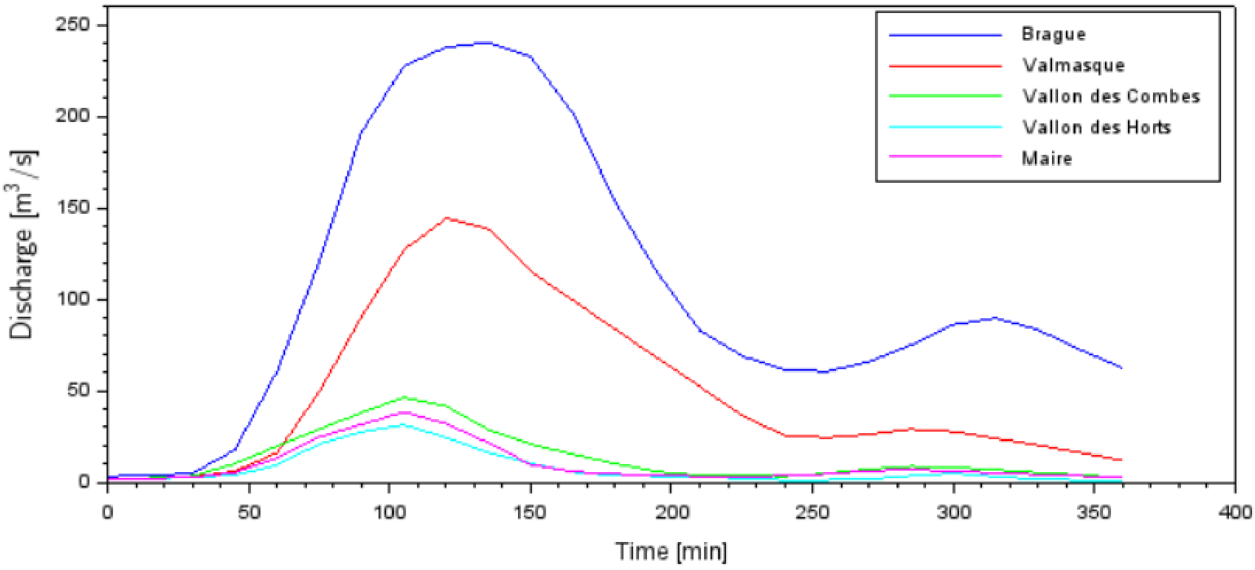

Figure 4: Hydrographs for the Brague river and its tributaries for the October 3, 2015 flood.

River	Peak discharge [m^3/s]			
Brague	250	240.4	240	240
Valmasque	145	144.3	145	-
Vallon des Combes	52	46.4	40	-
References	Blanc et al., 2018 [17]	Piton et al., 2018 [10]	Lebouc and Payrastre, 2017 [9]	Bohkove et al., 2019 [13]

Table 1: Comparison of peak flows for the flood of the 3rd of October 2015 estimated for the Brague and its tributaries.

3.2 DTM and treatment

The DTM provided by the French National Geographic Institute (IGN) is used as the basis for the hydraulic model. The resolution of the DTM is 1 *m* [22]. While this dataset is a valuable resource for a variety of applications, in the case under study, it does not accurately represent rivers. In particular, it lacks precision regarding tributaries and the presence of underground sections. Hydraulic structures such as bridges and culverts have been removed by interpolation. These interpolations do not respect the river topography. As a result, the DTM cannot be used immediately to develop the hydraulic model.

To remedy the limitations of the IGN DTM, several corrective measures have been implemented. The aim of these corrections is to ensure a more realistic representation of the streams and to remove obstacles likely to prevent the water flow. They are carried out using ArcGIS Pro software and the Hydrologic Engineering Center's River Analysis System (HEC-RAS). These corrections are based on both aerial photographs taken from Géoportail website (www.geoportail.gouv.fr/) and field trip measurements.

Two field trips were carried out on the Brague river. The first trip took stock of the situation at the Brague hydrometric station in Biot and at the bridges at the river's outlet, mainly where the DTM was faulty. The second trip focused on the outlet of the river, where measurements were taken of the height of the free surface and the banks. These measurements were carried out using a 2.5 *m* long graduated stick (accuracy 0.1 *m*), upstream for 300 *m* from the Brague outlet.

This method does not provide a complete survey of cross-sections. Nevertheless, the measurements obtained played a crucial role in refining the corrected DTM. They also provide additional information for the numerical model. There is a downstream control that leads to a subcritical flow at the outlet. The elevation of the free surface is theoretically 0 *m NGF*, as the sea enters at the outlet.

The watercourses were then fully smoothed to eliminate residual noise. The digital elevation model (DEM) is obtained by adding the buildings, also taken from the IGN, to the corrected DTM. This improved DEM now provides a more reliable basis for developing the hydraulic model of the study area.

4.MODEL

None of the rivers studied shows issues with sediment transport. This phenomenon is therefore not studied here. In this section, we concentrate on the development of a 1D-2D coupled model using HEC-RAS [23]. Additional information about HEC-RAS software can be accessed on the website (www.hec.usace.army.mil/software/hec-ras/).

4.1 HEC-RAS equations

HEC-RAS (chapter 4 in [23]) solves the system of 1D transient Shallow water equations within the main channel. It includes a continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_t , \quad (1)$$

and momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} = gA(S_0 - S_f), \quad (2)$$

with A - wetted area of a cross-section, $[m^2]$; Q - volumetric discharge, $[m^3]$; q_t lateral inflow per unit length (not considered in model setup for this study), $[m^2/s]$; h - water depth, $[m]$; $S_0 = -\partial z/\partial x$ - opposite to the slope and S_f - friction slope.

Friction slope is defined by the Manning friction law:

$$S_f = \frac{n^2}{2.208} \frac{Q\,|Q|}{R^{\frac{4}{3}} A^2}$$

with n - Manning friction coefficient, $[s/m^{1/3}]$; R - hydraulic radius, $[m]$.

For the flood plain flow simulation, 2D diffusive wave equation (chapter 4 in [23]) is used:

$$\frac{\partial H}{\partial t} - \nabla \cdot (\beta \nabla H) + q = 0, \quad (3)$$

with $H = h + z$ - water surface elevation, $[m]$; q - source / sink flux term (not considered in model setup for this study), $[m]$ and $\beta = \frac{(R(H))^{\frac{5}{3}}}{n\,|\nabla H|^{\frac{1}{2}}}$

The diffusive wave equation [24,25] is a simplified approach to the shallow water equation without inertial (advection) terms. For initial calculations, choosing the diffusive wave equation allows for faster computations and provides greater stability properties than with the Shallow Water equations [26].

The connection between 1D and 2D zones/models is done by “normal 2D equation domain” overflow computational method [26]. It imposes inflow discharge into related 2D cells. The velocity contribution is not considered through 2D boundary. Among the four methods proposed in HEC-RAS to model bridges, we have chosen to calculate the flow through the bridges thanks to the energy-based method with standard step method [23,27,28]. For the culverts, the flow is computed with the FHWA full flow equations (chapter 8 in [23] and [29].

4.2 Model setup

The model only considers the Brague and Valmasque as these two rivers usually contribute the most when it comes to flooding. The main channel of both rivers as well as the hydraulic structures are defined in 1D. The Brague and Valmasque are respectively defined by 53 cross-sections with an average distance of 68.4 *m* and 11 cross-sections with an average distance of 71.5 *m*. The digital model developed incorporates three hydraulic structures: two bridges at the Brague hydrometric station in Biot (Figure 6A and 6B) and culverts (Figure 6C and 6D) on the Brague, where the highway crosses the watercourse. These structures are the most likely to become overloaded during floods.

The 2D model is an almost uniform square mesh of 10 *m* resolution which corresponds to the floodplain. Cells at the edge of the 2D area adapt their shape to fit the form of the region. The mesh is made up of 25,503 cells. The finest cells measure 50 m^2 and the largest measure 314 m^2. Lateral structures allow the junction between 1D and 2D domains (Figure 5).

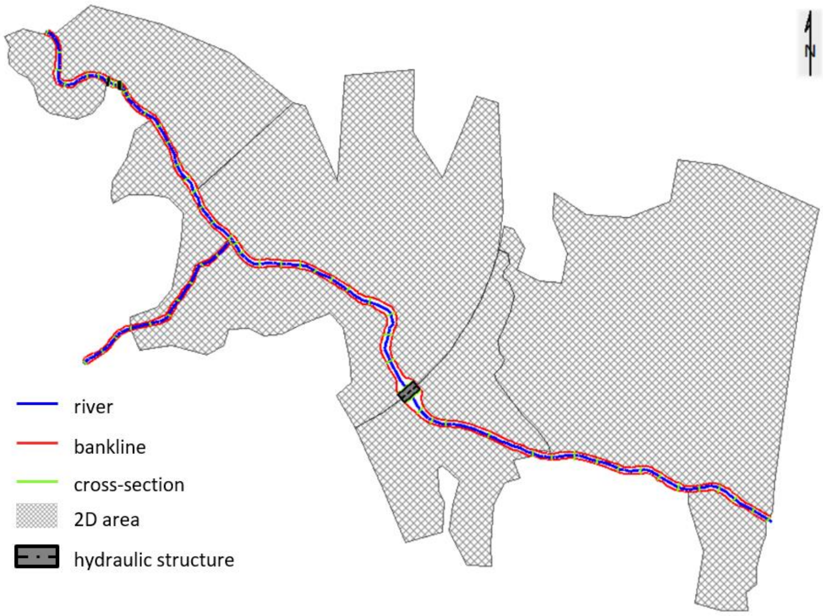

Figure 5: Final structure of the 1D-2D HEC-RAS model.

The friction law used is Manning. The friction coefficient n is uniformly set to n=0.035 $s/m^{1/3}$ in the main channels and n=0.06 $s/m^{1/3}$ in the 2D areas.

The model is initialized with a baseflow of 3.2 m^3/s for the Brague and 1.6 m^3/s for the Valmasque. The downstream boundary condition is set to normal depth with a friction slope of 0.0065. Also, the initial water level in the 2D zones is set to 0 *m*.

To ensure the model stability, we must consider the following Courant-Friedrichs-Lewy (CFL) condition:

$$CFL = \max(|u| + c)\frac{dt}{dx} < 1, \qquad (4)$$

where $c = \sqrt{gh}$ is the celerity, [*m/s*] ; g - the flow mean velocity, [*m/s*] ; g - the gravitaty acceleration, [m/s^2] ; h - the water depth, [*m*] ; dt - the time step, [*s*], and dx - the mesh size , [*m*]. In our case, the relation above is valid with a time step of less than 0.6 *s*. During the simulations, the precision of this mesh size makes it possible to obtain consistent results while having a reasonable computation time. The simulations are completed in about 17 *min*, considering a time step of 0.5 *s*.

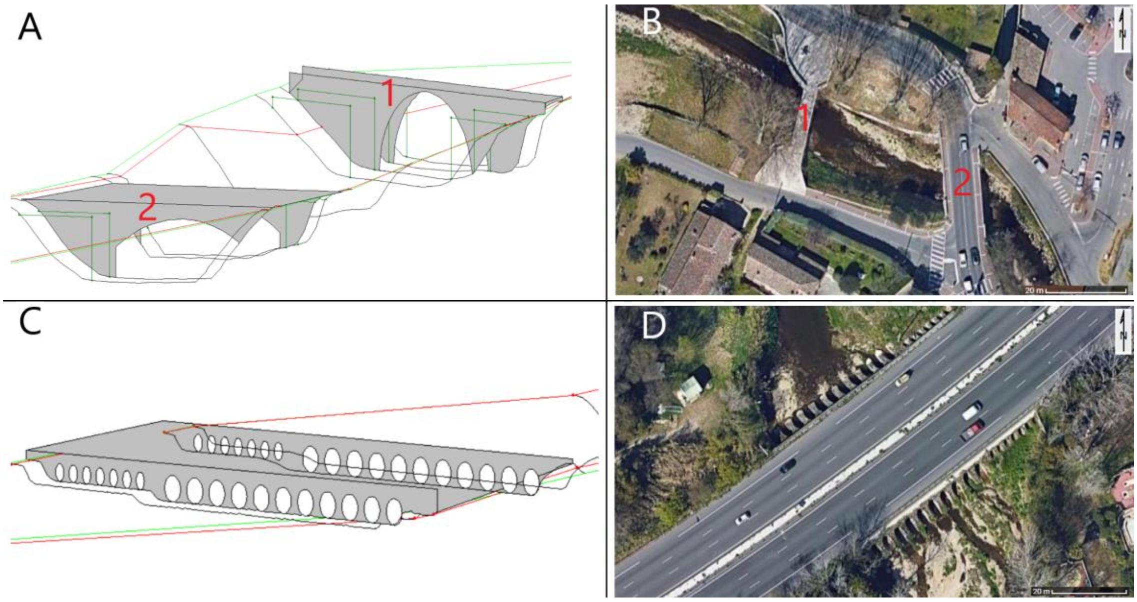

Figure 6: Hydraulic structures defined in the model and their satellite photographs. A and B represent the two bridges upstream close to the hydrometric station at Biot. C and D represent the culverts on the A8 highway.

5. RESULTS AND DISCUSSION

5.1 Simulation

As the soil was saturated with water, all the precipitation from the hinterland flowed towards the downstream part of the catchment. This allows injections to be introduced directly upstream of the watercourses to reproduce the 2015 flood event. These injections correspond to the flood hydrographs mentioned in section 3.1. Once the simulation has been completed, the maximum water depth and the main flood flow axes are extracted (Figure 7).

The flood extent covers almost the entire floodplain. Characteristic features of the 2015 event are represented such as the flooding of the neighborhoods around the hydrometric station or the flooded Marineland. The flood flow axes indicate that the right bank upstream of the highway is mainly flooded by the Valmasque. On the left bank, the upstream flood flows along the plain without returning to the main channel of the Brague. The water submerges the highway and then floods the whole plain downstream as far as Marineland.

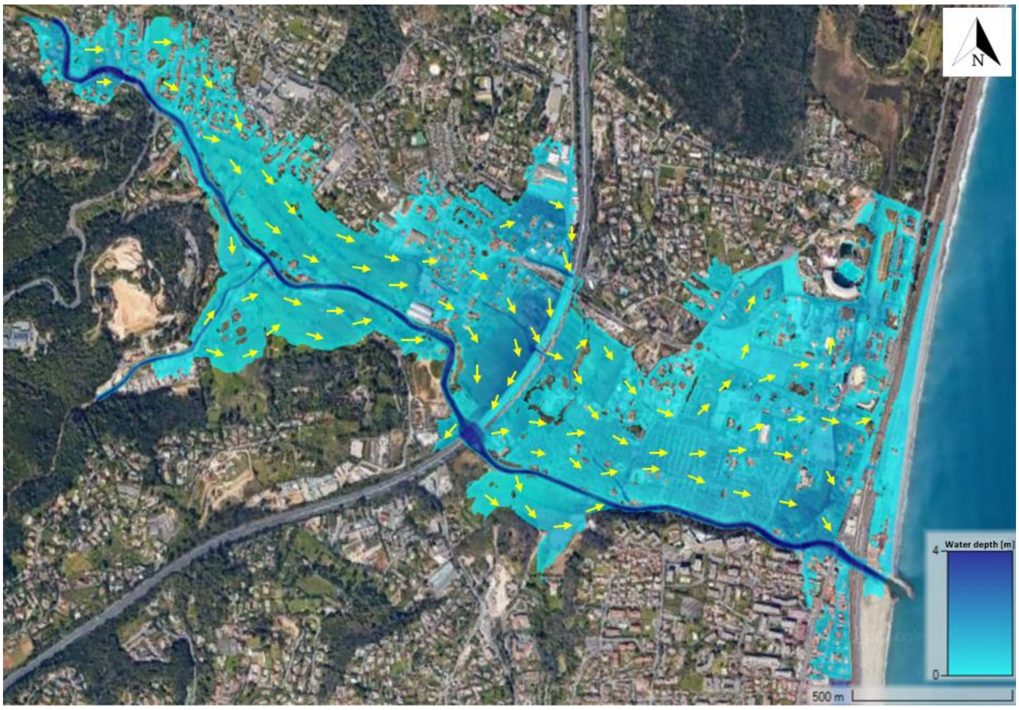

Figure 7: Flood extent and main flow axes of the October 3, 2015 event.

5.2 Analysis

The results of the HEC-RAS model show that the flood extent is underestimated compared with the results of the PPRi model (Figure 8), particularly in the Combes and Horts valleys. A comparison between water levels and flood marks shows underestimation as well. A difference of more than 50 *cm* appeared over most of the domain. Nevertheless, the water level is acceptable at the downstream part close to the sea and at some local point (Figure 9).

These differences are mainly due to the simplicity of the HEC-RAS model. During the flood of October 2015, a greater number of hydraulic structures than those considered in our model were overloaded. The PPRi model, developed with MIKE software, provides more relevant results given that it includes 38 hydraulic structures, additional water inflows from other tributaries and valleys and logjams [17]. The uncertainties regarding flood marks must be considered. The backwater effects can increase the level of the flood mark. The accuracy of the calculated water altitude must also be taken into account.

It is interesting to note that the flood flow axes (Figure 7) between the two models are relatively similar, except for the highway. The incorporation of culverts outside the Brague main channel would improve our model accuracy.

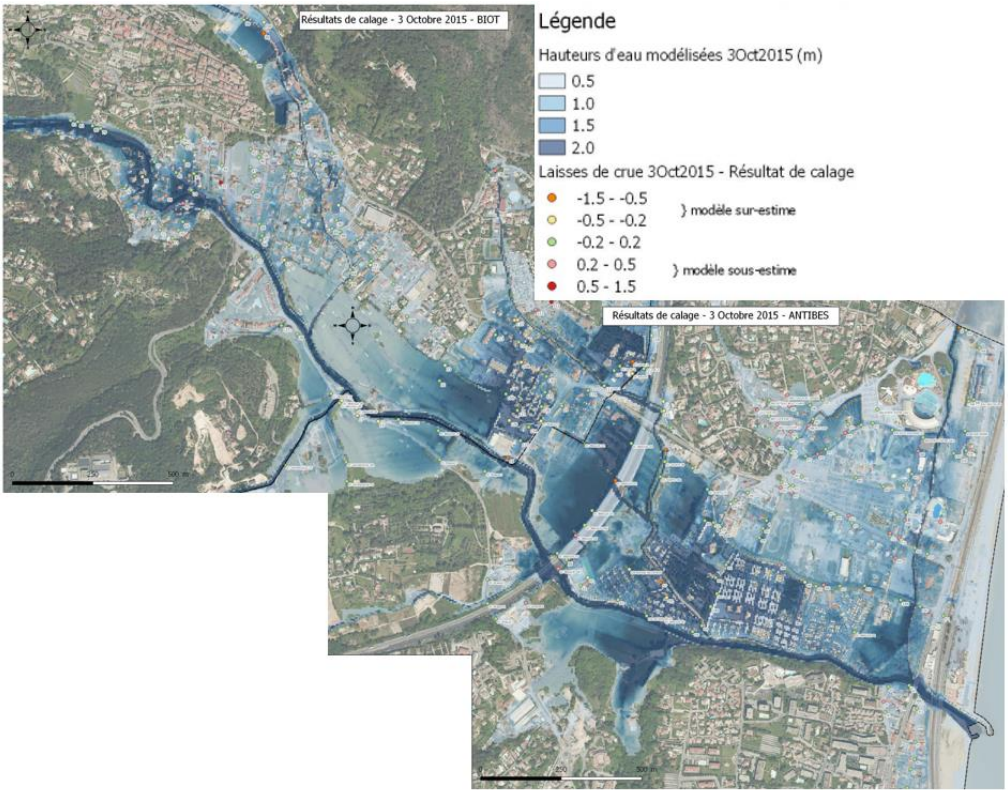

Figure 8: Flood extension and flood marks of the October 3, 2015 event from the PPRi model (source: [17]).

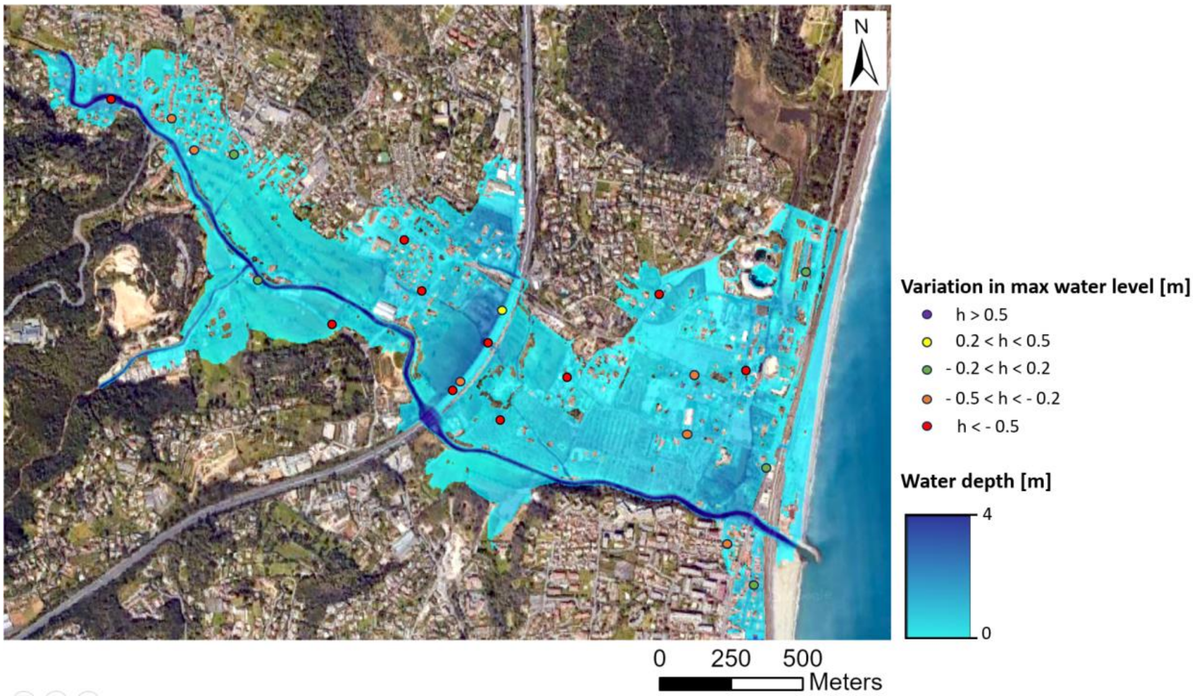

Figure 9: Comparison of max water level of the HEC-RAS model and the flood marks of October 2015 flood.

6. CONCLUSIONS AND PERSPECTIVES

A coupled 1D-2D model (HEC-RAS) was developed to simulate the flood of October 3, 2015 in the downstream part of the Brague catchment. The aim of this paper is to present the results obtained and to suggest ways of improving and using the model.

6.1 Conclusions

The application of a simple model, assuming saturation of downstream karst zones during flash floods, has proven to be a valuable tool for representing the basin's response. Through this approach, a comprehensive understanding of the hydraulic functioning of the watershed has been acquired, discerning the relative importance of each watercourse during flood events. The model has demonstrated consistency in predicting flood extents and flood flow axes. The results confirm the pivotal role played by the Brague and Valmasque rivers in determining the extent of flooding on the plain.

The simulation has revealed that high water levels are generally underestimated, emphasizing the need for careful consideration of such factors in flood risk assessments. The incorporation of three hydraulic structures into the model has enhanced its accuracy, particularly in predicting water heights at the level of these infrastructures. This highlights the importance of accounting for man-made elements in hydrological models to better capture the intricacies of real-world scenarios.

Importantly, despite the simplicity of the model and limited hydrological data, the results have been satisfactory. This underscores the model's utility in situations where detailed data may be scarce. In essence, the study showcases the effectiveness of this model in offering insights into the hydraulic behavior of the downstream Brague watershed, with the potential for practical applications in the study of future flash floods.

6.2 Perspectives

Several perspectives have emerged from this study. The improvements to the model and simulations discussed below will further our understanding of flood dynamics and improve flood risk assessment.

It is imperative to extend the model to other tributaries in the study area. The incorporation of additional water sources will contribute to a more complete representation of the hydrological network, capturing the influence of the various factors contributing to flood dynamics.

The inclusion of variable friction across the entire domain will provide a more realistic representation of the influence of the landscape on flood propagation, enabling a nuanced simulation that considers different surface characteristics.

The identification and integration into the model of missing hydraulic structures, both on rivers and on the highway, is essential. The integration of these elements will contribute to a more accurate representation of the physical infrastructure that plays a crucial role in water dynamics (loading, logjams).

The efficiency of the model can be further enhanced by exploring the injection of water through valleys. Taking into account natural water flow paths in valleys will improve the model's ability to simulate the dynamic interaction between topography and hydrological processes during floods.

To validate the model's robustness, it is recommended to test its performance across a spectrum of hydrological events. Examining a variety of flood scenarios will help to assess the model's versatility and its ability to accurately predict outcomes under different conditions.

Of particular interest is a comparison of the different systems of equations that can be used with HEC-RAS for flood propagation. This comparative analysis will highlight the strengths and limitations of the different mathematical formulations, helping to select the most appropriate equations for accurate flood simulations.

Incorporating these perspectives into future projects will undoubtedly contribute to improving the numerical model. This progress is essential if we are to develop a reliable tool that can inform flood risk management strategies and improve our ability to mitigate the impact of floods on the vulnerable communities and infrastructures concerned.

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