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Development of a hydro-morphodynamic model for simulation of bed load and morphological changes of flash-floods (Têt River, France)

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Abstract— **Mediterranean coastal rivers are subject to the climate hazards. Most of the year, they present low water levels with low flows and during intense and short rainy events, their flow increases sharply. These "flash-floods" comprise an intense advancing water wave that induce considerable sediment loads. Most of the solid flows through coastal rivers take place during these brief events. Besides, the materials transported by the river significantly impact the river morphology. These changes may promote floods, destabilize hydraulic structures and disrupt their operations. To analyse the amounts of sediment bed loaded by the Têt River (Gulf of Lions, France) and their effects on the river morphological changes during floods events, we implemented a hydro-sedimentary model (hydrodynamic and sediment transport processes, TELEMAC-2D-GAIA) over the last 12.5 km reach (up to the river mouth). Hydrodynamics calibration was performed on two recent floods events over Manning coefficients. Validation on a third event led to a NSE (coefficient of Nash–Sutcliffe efficiency) of 0.66. Despite several simplifications, the morpho-dynamics model provided reasonable performance regarding the bed load transport. A test of sensitivity on the transport formulae conducted to choose the Meyer-Peter and Müller formula. After investigations on model limitations, we examined the morphological impact of a flash flood on the river. Further researches will focus on simulation of the 100-year flood induced by the 2020 Gloria event.**

I. Introduction

River floods are essential processes in the land-to-sea transfer of sediment. They can be classified into two different types: seasonal floods and flash-floods. The former are generally associated with large systems such as the Amazon and characterised by a seasonal flood pulse [1]. Occurring during several weeks or months, meteorological conditions that have caused these floods are not directly linked with coastal conditions. Conversely, flash-floods are short and intense events occurring during a few hours or days, and provoked under intense meteorological conditions. Flash-floods are common features in Mediterranean watersheds. They are associated with small mountainous catchments influenced by brief meteorological marine storm events during which depressions over the sea induce rapid and extreme rainfall over coastal relief. The result is a sudden river discharge of fresh water and sediment to the coastal zone. In this case, hydrology in the inner-shelf are closely linked with local meteorological conditions.

Due to the event-driven nature of the discharge in small rivers, most sediment reaching the sea from them usually does so during flash-floods. Small rivers are estimated to account for more than the half the annual suspended sediment load to the Mediterranean Sea [2]. Hence, it is important for global sediment flux studies to investigate flash-floods in which steep basin topography can give rise to a high potential sediment discharge [3]. Sediment delivered to the sea during such floods may be stored in prodeltas or bypass these to reach the canyon region and then the abyssal plain [4].

Due to their small spatio-temporal scale, flash-floods require specifics sampling and modelling strategies. Hence, studies about flash-floods have focused on the dynamics and the fate of sudden river inputs to the coastal zone [4], the river system (runoff, fresh water and solid fluxes) [5], suspended sediment balance [6]. Coupling hydrodynamics and transport sediment models allows investigating the sediment dynamics [7], the link between flash-floods and river morphology [8]. However, researcher face major shortcomings: i) morpho-dynamics model are very sensible to sediment transport law [8], ii) unlike suspended load, bed load has been hardly estimated.

The aim of the study is to model the bed load and morphological changes that occurred during three major recent floods over the Têt River (southwestern Gulf of Lions, France). We firstly present the study zone, the modelled reach and events. The following section describes the material (models and data) and methods. The results and discussion sections include model reliability, modelling limitations, bed load estimation and morphological evolution.

II. Study zone and Modelled Hydrologic Events

The Têt River discharges into the south-western part of the Gulf of Lions (Figure 1). The Têt catchment (1396 km^2) has a mean altitude of 1023 m and a mean slope of 12 [9]. Its maximum headwater elevation is at 2100 m and the river length is about 100 km [10]. Over the 1980–2000 period, the averaged annual precipitation for the entire basin is 757 mm.

The rainfall pattern is characterised by long dry periods interrupted by short, violent marine events that can result, within a few hours, in flood events. The average liquid discharge at the gauging station at Perpignan, 12.5 km upstream from the mouth, is 10.82 $m^3.s^{-1}$ Instantaneous discharge can reach more than 1000 $m^3.s^{-1}$ during major floods associated with extreme rainfall events [11]. Extreme floods with a discharge peak of 540 $m^3.s^{-1}$ have a 5-year return interval, whilst relatively smaller flood events with a discharge peak of 180 $m^3.s^{-1}$ have a return interval of 2 years. To reduce the intensity of peak floods, a retention dam was built in 1978 at Vinça, 50 km upstream from the mouth, on the border between the mountainous part and the alluvial plain.

In the present study, modelled domain is a 12.5-km reach from Perpignan up to 500 m from the Têt River mouth (Figure 1). The study period (2018-2019) encompasses three extreme flood events whose main characteristics are resumed in Table 1.

TABLE 1. CHARACTERISTICS OF STUDIED FLOOD EVENTS

Event	Dates (beg*- end)	Peak d** (m3/s)	Peak date	Return period (years)
Flood1	2018/10/14 2018/10/21	237	2018/10/15	2-5
Flood2	2018/11/17 2018/11/22	159	2018/11/18	2-5
Flood3	2019/10/22 2019/10/26	241	2019/10/24	2-5

Beg*=beginning; d** = discharge.

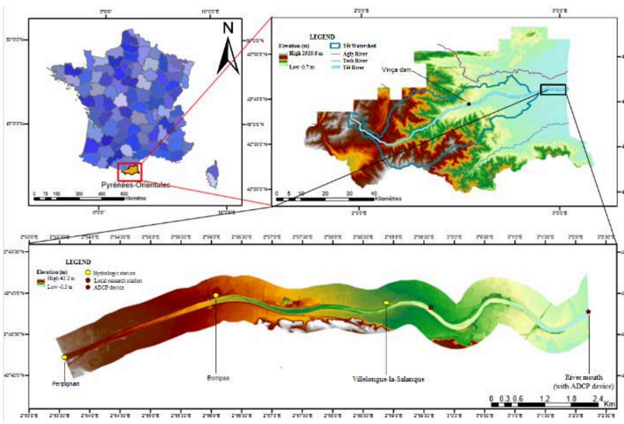

Figure 1. Study zone

III. MATERIAL AND METHODS

The TELEMAC-MASCARET SYSTEM is freely available at www.opentelemac.orgv and was designed for computational fluid dynamics [12] and associated processes. The morpho-dynamics modelling consists in coupling an hydrodynamic model with a module of sediment transport and riverbed evolution.

A. Hydrodynamics modelling and settings

The two dimensional (2D) hydrodynamic module (TELEMAC-2D v8p1) simulates free-surface flows in the two dimensions of horizontal space. For more details, readers are referred to the TELEMAC-2D user manual [13].

TELEMAC-2D model offers several numerical options for calculation. Here, we chose the method of characteristics to simulate velocity advection for its stability and the propagation step is solved by the conjugate gradient method with a diagonal preconditioning which ensures numerical stability. We used default values for viscosity (10^{-6} $m^2.s^{-1}$) and water density (1000 $kg.m^{-3}$). For reasons of model stability, we set the hydrodynamic time step to 2 s. Bottom friction was based on the Manning coefficient map. We used the Blue Kenue software [14] to generate a mesh of 71733 triangular elements with sides ranging from 10 m to 100 m. Channel sub-mesh presents higher resolution (10 m) (Figure 2).

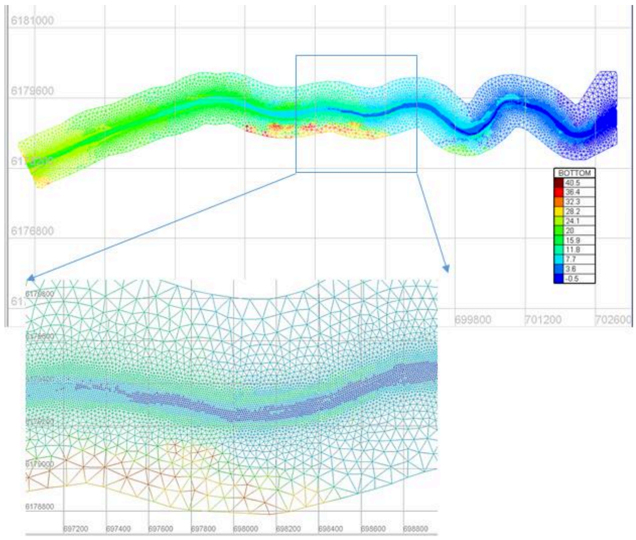

Figure 2. Mesh for modelling

The hydrodynamic model requires three boundary conditions: at upstream two water-inflow boundary conditions and at downstream a water level boundary condition. The two former are the *in situ* Perpignan and Basse discharges. The water level is the one observed at river mouth. The model also included rain and evaporation during simulations.

The hydrodynamic model was run during all the floods events (Table 1). It was initialized by a pre-simulation over a period of 10 days starting with constant water level (29 m), and constant velocity (0 $m.s^{-1}$). The selected constant water level corresponded to the river bottom elevation at the upstream boundary condition with a shift of +3 m.

B. Morpho-dynamics modelling settings

Based on the historical sediment transport module SISYPHE, GAIA [15] is a recently developed module of the TELEMAC-MASCARET SYSTEM for modelling of sediment transport and bed evolution. It simulates a large number of complex physical processes (different sediment classes, sand-mud mixtures) commonly found in river and estuarine modelling. It offers several formulae available for sediment transport and solves riverbed evolution with the sediment mass conservation equation. Second currents and effect of bed slope associated with the influence of gravity can be included. In addition, vertical stratification of sediments and non-erodible riverbed is possible to set up in the model. For more details, readers are referred to the GAIA user manual [15].

The boundary conditions for the fractional sediments were modified to allow a prescribed constant solid discharge at the inlets of the domain, as well as free open boundary for the sediments at the outlet. The prescribed constant solid discharge was derived from literature estimation of annual discharges ($1.5x10^{-6}$ $kg.s^{-1}$) [6].

For estimating the sediment transport of two classes of non-cohesive sediments (D50 of 200 µm and 500 µm), several formulae for bed load (Meyer-Peter and Müller, Van Rijn) and total load (Engelund-Hansen, Engelund-Hansen modified by Chollet-Cunge) were tested. The bed structure was discretized in two layers: an active sediment layer (thickness of 0.15 m) and erodible layer (thickness of 2 m). Sediment slide, secondary currents, skin friction and slope effects were excluded with the aim of simplify the model.

C. Calibration and validation assessment

A first calculation with the hydraulic model TELEMAC 2D was conducted to determine the variations of hydraulic parameters during the floods events. We calibrated the hydrodynamics model in terms of water height and velocity from both first floods event (i.e. Flood1 and Flood2) adjusting Manning coefficients in the channel by a trial-and-error method. Accuracy is controlled against reference datasets: water level measured at Bompas and Villelongue-la-Salanque, and velocity recorded by the ADCP at the river mouth. Once the model calibrated, we performed the hydrodynamics model validation. Accuracy is controlled at same locations than the calibration.

Regarding morpho-dynamics, due to control data lack, model calibration and validation consisted in sensibility tests in relation with sediment transport law, bed structure and sediment distribution (fraction and D_{50}). Within the view to calibrate the model, for each simulation, we computed the simulated quantity of sediment transported by bed load, and compared it with estimations of annual total load of sediment from literature.

Several classical statistics served to appraise model accuracy: the Pearson correlation coefficient, the RMSE (m), the Nash-Sutcliffe efficiency (NSE, [16]).

D. Available datasets

Hydrologic data

At upstream, the French Ministry of Ecology, Sustainable Development and Energy provides hourly water discharges of the Têt River at the Perpignan gauging station, 12.5 km upstream from the river mouth (42°42'13"N, 02°53'32"E). Data are available at http://www.hydro.eaufrance.fr/. Due to the lack of data and according to [6], discharges of the Basse Affluent of Têt River has been computed as 10% of the measured discharge at Perpignan gauging station.

Along the studied reach, the same institution provides hourly time series of levelled water level at Bompas (42°42'58"N, 2°56'4"E) and Villelongue-de-la-Salanque (42°42'53"N, 2°58'53" E) gauging stations.

At downstream, an Acoustic Doppler Current Profiler (ADCP Aquadopp Profiler 2 MHz, Nortek) provides 10-minutes times series of vertical-averaged velocity (intensity and direction) and depth. This device is located 500 m from the river mouth (42°42'47"N, 3°02'13"E). Pre-processing necessitate to turn depth data into water level. It is noteworthy that depending that depending on hydrologic condition, this gauge receive both marine and inlands influence.

Rainfall and evaporation data

Hourly rainfall data are originate with two sources: *in situ* and satellites. The French national meteorological service (*Météo-France*, https://donneespubliques.meteofrance.fr/) provides the observed local rain at Perpignan airport (45°44'14"N, 2°52'22"E). Gaps in the data (<2%) are filled with remote sensing rainfall. The product PERSIANN-Cloud Classification System is a real-time global high resolution (4km) satellite precipitation product developed by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (UCI) [17]. Satellite data are available at http://chrsdata.eng.uci.edu/.

The local meteorological station does not provide evaporation. We use hourly evaporation issued from 8-km gridded dataset SAFRAN. It is a mesoscale atmospheric analysis system for surface variables [18]. In this dataset, both observations from meteorological stations and surface analyses from numerical weather prediction systems are used. Data are freely available at *Météo-France* portal.

Bottom friction map

We use the Corine Land Cover Edition 2018 to define zones with same cover assumed to reflect similar friction properties. The European Environment Agency provides this product through the Copernicus Land Monitoring Service (https://land.copernicus.eu/). From a 44-items classification, we built a simplified land cover map: riverbed, crops, and urban. Following literature advises [19], different values of Manning roughness coefficient were assigned: 0.09 for the crops area, and 0.01 for the urban. Over the riverbed, we tested several manning coefficients within the range 0.03-0.05.

Topography data

The French National Geographic Institute provides a Digital Terrain Model at https://geoservices.ign.fr/. This raster (RGE ALTI), derived from LiDAR data, has a 5 m spatial resolution and 15 cm vertical accuracy. It is noteworthy that that this DTM rely on data acquired before the studied event (unknown date). Topographic features (cross-sections, slope map) are collected from the digital elevation model.

Sediment data

Literature review provides estimations of annual load of suspended sediment for the Têt River. Knowing that, for Mediterranean rivers, the total transported sediments can be divided into 80% suspended sediments and 20% bed-loaded sediments [8], we can estimate the amount of bed-loaded sediments during one year.

TABLE 2. SUSPENDED AND BED-LOADED SEDIMENT QUANTITY FOR THE TÊT RIVER.

Study	Study period	Transported suspended sediment ($t.yr^{-1}$)	Transported bed-loaded sediment ($t.yr^{-1}$)
[20]	1980-1999	53 546 ± 15 796	13386 ± 3160
[4]	1977-2004	61 000 ± 18 000	15250 ± 4500
[6]	1977-2013	45 000 ± 35 000	11250 ± 8750

IV. RESULTS

A. Hydrodynamics model performance

The hydrodynamic model was poorly sensitive to the choice of the Manning parameter when exploring the whole range of Manning values in the riverbed. We finally selected the channel value giving the lowest RMSE: 0.04 $s.m^{-1/3}$.

Regarding the hydrodynamics validation (Figures 3a-b), the simulated and observed water levels are in good agreement at all gauges. Averaged RMSE, NSE and correlation coefficient at the both stations were 0.76 m, -1.2 and 0.96, respectively. The velocity comparison (Figure 3c) leads to RMSE of 0.19 $m.s^{-1}$, NSE of 0.57 and correlation coefficient of 0.96. Difference between the indicators at both location suggests that model accuracy has spatial variations. Visual investigation of graphics shows that vertical and velocity accuracies have temporal variations. RMSE, NSE and correlation coefficient presented the lowest values at the beginning of flushing, respectively. Best scores should be obtained during rising waters.

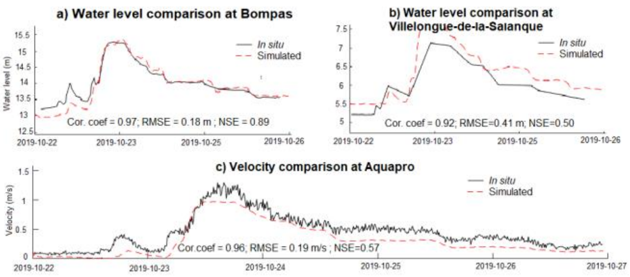

Figure 3. Hydrodynamics validation (Flood3)

B. Sediment transport

Bed load estimation

We performed several simulations tests to investigate the influence of the different transport laws in bed load estimation. Figure 4 presents the simulated bed load discharges at downstream location for Flood1. We can observe that difference between simulated discharges are important. Apart from the bed load induced from Van Rijn formula, the simulated bed load discharges are closely related.

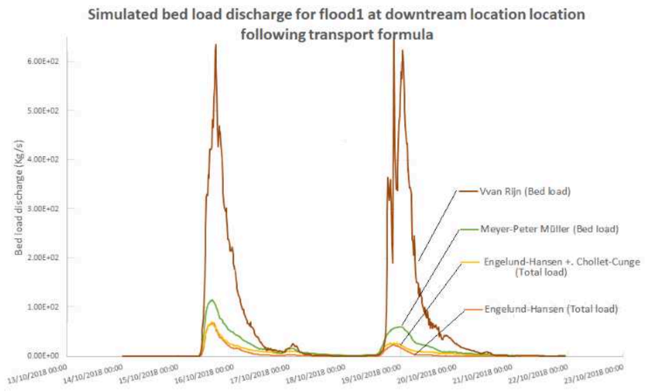

Figure 4. Bed load discharge for Flood1 at the downstream boundary condition according different transport formulae.

Table 3 gives an overview of the simulated quantity of the bed-loaded sediment during the Flood1 according to the transport formula. As expected, the quantity of sediment is highly variable. Both original and improved Engelund-Hansen formulas seems to underestimate the bed load, while Van Rijn formula likely overestimates the bed-load. Comparing with literature-derived quantity of annual bed-loaded sediment (Table 2), best accuracy is obtained with the Meyer-Peter and Müller formula. Hence, all the following results have been performed using this formula.

TABLE 3. SIMULATED QUANTITY OF BED-LOADED SEDIMENT DURING FLOOD1 FOR THE TÊT RIVER ACCORDING TO THE TRANSPORT FORMULA.

Formula	Transported bed-load sediment (t)
Meyer-Peter and Müller	10321
Van Rijn	45587
Engelund-Hansen	3454
Engelund-Hansen+Chollet-Cunge	5617

Bed evolution

We present here the bathymetry evolution during the Flood1 (Figures 5a-c). For comparison facility, vertical scale have be limited from -1 m to 1m. However, Figure 5c presents erosion and deposition values superior to 4 m. The analysis shows a spatio-temporal alternation between both processes of erosion and deposition. Between the peak and the end of the peak (Figures 5b-c), there is a notable difference in the magnitude and the zone of erosion/deposition. At the end of the event (Figure 5c), erosion is more important in the upstream reach, while deposition occurs in the downstream part of the river.

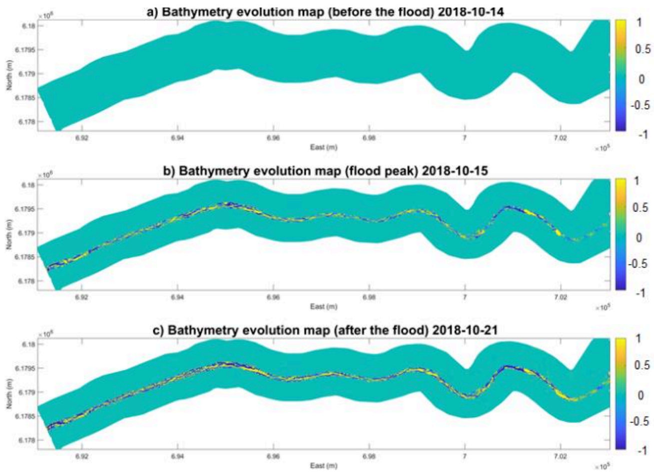

Figure 5. Maps of bathymetry evolution

To analyse the morphological evolution, a comparative analysis of several cross-sections (Bompas, Villelongue-de-la-Salanque and the downstream reach) was conducted before the floods, one day after the peak and at the end of the floods. In this study, for clarity reasons, we only present these results for the Flood1 (Figure 6). The temporal superposition of the cross-sections at the same zone indicates silted sections (deposition) and erosion sections.

We observe that changes in cross-sections are not spatially and temporally uniform. Indeed, upstream cross-sections are subject to intensified phenomena of erosion and deposition. Hence, after Flood1 simulated deposition and erosion can respectively reach 2.0 m and 1.1 m (Figure 6a), while at downstream location erosion is null and averaged deposition remains low (<0.5 m) (Figure 6c). Depending on the cross-section location, erosion and deposition do occur on the same way (Figures 6a-b). At last, we also observe that between the peak flow and Flood1, there are notable bed evolution.

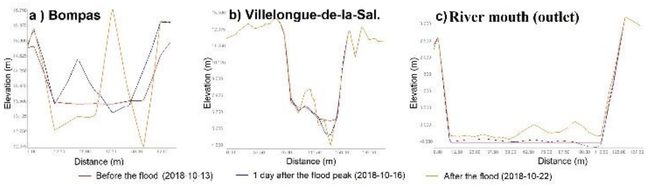

Figure 6. Simulated morphological evolution of the perpendicular cross-sections during the Flood1 at a) Bompas, b) Villelongue–de-la-Salanque, c) River mouth.

The investigation of the evolution of longitudinal riverbed profile reveals large variations of deposition (>4 m) and erosion (> 2 m). Overall reach slope remains the same, despite large local variations.

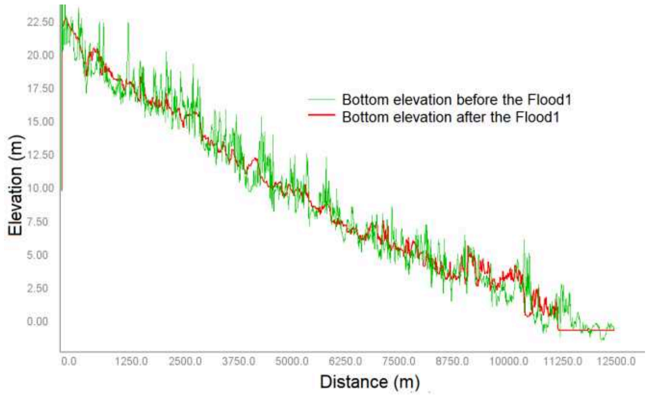

Figure 7. Simulated morphological evolution of the longitudinal profile during the Flood1

V. DISCUSSION

A. Model reliability

Hydrodynamics model performances

The validation performed on Flood3 event showed that simulated water levels were in good agreement with the observations. Comparing with the amplitude of the flood wave (3 m at Perpignan), the RMSE (<0.41 m) value remained low. At Villelongue-de-la Salanque, accuracy is lower and we can note there is a continuous shift of nearly 0.50 m. This suggests that gauge reference could be false. Indeed, gauges can be subject of landslide that can be induced by flash-floods.

The model was able to simulate the river velocity variations with a slight under-estimation. It also reproduces the flow reversion during marine floods (i.e. when see water level rise before inland waters at the beginning of a floods). Apart from Manning coefficient uncertainty, the velocity underestimation can be linked with unadjusted topography errors. Indeed, several years (without knowing how many) separate topographic surveys and modelled events. Hence, the numerous annual floods have redesigned the braided river. Hence, 2018 riverbed could actually be narrower and higher than in the used RGE-Alti riverbed.

Study results highlights that accuracy is lower during flushing waters. This is mostly due to uncertainty propagation [21], an under-representation of the inner-drainage channels and moreover the importance of actual morphological changes. Indeed, they are essential to reproduce flash-floods events [8].

Morpho-dynamics model performances

Morpho-dynamics model performance has only been assessed by comparing bed load discharge at the river outlet with bed load estimations derived from suspended discharges values encountered in the literature (limitations of this method are discussed hereafter)

Model limitations

The analysis of the hydrodynamics model performance showed the importance of topographic controls. Hence, modellers should take into account both the accuracy and the resolution of input topography. Here, UAV orthoimages evidence a braided bed whose channels width remains inferior to the minimum mesh edge size (10 m). In addition, greenfield banks and river bed with a pronounced micro-topography (hummocks and hollows) and hydraulic structures (weirs) should affect the local water velocity field. With a 10m-mesh resolution, the model does not capture such fine-scale topographic controls. However, these features are taken into account through the roughness coefficient that is adjusted during the model calibration.

Calibration and validation steps suffer from a lack of control data. Indeed, regarding hydrodynamics, horizontal accuracy (flood extent) has not been controlled and velocity fields cannot be fully spatially checked.

Control and input data for the morpho-dynamics suffer from a lack of sediment and bed evolution information. Phillips traps that capture bed load sediment were difficulty suitable for assessment. Indeed, simulation and period of sampling collection were different. During a flood event, the traps were filled or sandbagged. Entrance of the Philips traps were also clogged. Further field works and connection with local collectivity (that own cross-section elevation datasets) are needed to increase the data exchanges and the *in situ* knowledge in terms of bed-evolution, bed load, sediment distribution, cover and layers (thickness, number).

Models could have been more sophisticated. By instance, TELEMAC-2D can include wind effect. Depending on the type of the rainy event (marine or inland), local wind magnitude can vary. However, regarding the floods velocity magnitude, if winds may have impact on our results, the topography, sediment layers characteristics and transport law remain the primary sources of models uncertainty. Several options in GAIA have not been activated: sediment slide, slope effect and secondary currents. The latter could explain misrepresentation of the riverbed at the bends. *In situ* device (LISST-Streamside) shows the presence of non-cohesive sediments that we did not take into consideration.

Model calibration and validation are assessed through three classical statistics. However, using these parameters to determine the model performance in predicting riverbed evolution might not be appropriate. New skill scores, such as Brier Skill Score [22], should be computed.

Despite these limitations, the good agreement between observed and simulated data suggests the morpho-dynamics model is sufficient to capture the flow and the sediment transport within the river.

B. Sediment transport

The use of several sediment laws highlights the model sensibility to this parameter. Both of total load methods (Engelund-Hansen, Engelund-Hansen modified by Chollet-Cunge) overestimate bed load transport. Engelund-Hansen equation [23] overestimates the transport of the finest sediments in comparison with other sediments. It may also be because these equations are designed for grain of larger size. Meyer-Peter and Müller, Van Rijn methods are adapted methods regarding the size of the simulated sediment.

C. Morphological evolution

The process of sediment transport (erosion, transportation and sedimentation) may change the riverbed topography [22]. Erosion agents include flowing water, waves, wind or gravity. Eroded material is eventually dropped at another location (deposition). Low waters are associated with deposition and slowly modify the landform [24], whereas during flash-floods both phenomena intensively occur causing changes on the river morphology.

Our results suggest that once the flood wave passed, erosion and deposition continue. During the flood, there is always an alternation between both processes. Spatial repartition of these phenomena depends on local conditions: slope, meanders, presence of hydraulics structures or vegetation [8]. These conditions explain why we observed at the end of the Flood1 a higher erosion in the straight upstream reach (Figures 5c, 6a and 7) and a higher deposition in the downstream meandering and over the flat part of the river(Figures 5c and 7). Looking at the longitudinal and perpendicular profiles of the outlet (Figures 6c-7), one may note low deposition at the outlet and enhanced deposition and erosion in the first part of the reach. Above-mentioned local conditions together with the increase of the river width (+166 % between Bompas and the river mouth) could explain such an organisation of phenomena.

VI. CONCLUSION

In this study, we implement a hydro-sedimentary model within the view to analyse the amounts of sediment bed loaded by the Têt River (Gulf of Lions, France) and their effects on the river morphological changes during recent flash-floods (three in all).

Hydrodynamics model is successfully calibrated against the two floods and validated against the third one (NSE of 0.66). Water velocity are slightly under-estimated.

Despite several simplifications, the morpho-dynamics model provides reasonable performance regarding the estimation of bed load transport. A test of sensitivity on the transport formulae conducts to choose the Meyer-Peter and Müller formula. After investigation on model limitations, we examine the morphological impact of a flash flood on the river.

In January 2020, the Gloria storm generated a 100-year floods event. The downstream device could not recorded the full event and has been taken out during the flood. Further researches will focus on i) improving the current morpho-dynamics model ii) using neural network to reconstruct the downstream water level condition to simulate sediment transport during this 100-year floods event.

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