

Sediment transport modelling in riverine environments: on the importance of grain-size distribution, sediment density and suspended sediment concentrations at the upstream boundary

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Abstract. Hydromorphodynamic models are powerful tools for predicting the potential mobilization and transport of sediment
10 in river ecosystems. Recent studies ~~even showed~~have shown that they are able to predict suspended sediment matter
concentration in small river systems ~~satisfyingly-satisfactorily~~. However, hydro-sedimentary modelling exercises often neglect
suspended sediment properties (e.g. sediment densities and grain-size distribution), ~~even though such properties which~~ are
known to directly control ~~the~~ sediment ~~partiele~~-dynamics in the water column during flood events. ~~This study has as~~The main
objective of this study is to assess ~~the importance of sediment characteristics (grain size distribution, densities, and suspended~~
15 ~~sediment concentrations imposed at the upstream boundary) in hydro-sedimentary modelling-whether a better representation~~
of such properties leads to an improved performance in the model. The modelling approach utilizes ~~existing~~a fully coupled
hydromorphodynamic ~~models:-model based on~~ TELEMAC-3D (v7p1) and an enhanced version of the sediment transport
module SISYPHE (based on v7p1), which ~~allow~~allows for a refined sediment representation- ~~(i.e. 10-class sediment mixtures~~
~~instead of 2-class, and distributed sediment density instead of uniform)~~. The proposed developments of the SISYPHE model
20 ~~enables~~enable us to evaluate and discuss the added- value of ~~the~~ sediment representation refinement for improving sediment
transport and riverbed evolution predictions. To this end, we used several model setups to evaluate the ~~sensitivity~~influence of
~~the model to~~ sediment grain-size distribution, sediment density and suspended sediment concentration at the upstream
boundary- on model predictions. As a test case, ~~the model is used to simulate~~we simulated a flood event in a small-scale river,
the Orne River in north-eastern France. ~~The~~Depending on the model setup, the results show substantial discrepancies in terms
25 of simulated bathymetry ~~evolution depending on the model setup-evolutions~~. Moreover, the ~~sediment~~-model based on an
enhanced configuration of the sediment grain-size distribution (~~40~~ten classes of particle sizes) and with ~~distributed sediment~~
densitydistinct densities per class outperforms the ~~model~~standard SISYPHE configuration, with only two sediment grain-size
classes, in terms of simulated suspended sediment concentration.

1. Introduction

In the last two centuries, many areas have undergone a rather fast demographic, industrial and urban development. This intense land occupancy has affected the quality of surface waters, which ~~become~~became the receptacle of anthropogenic effluents from various origins (Whitman, 1998; Heise and Forstner, 2007; Grabowski et al., 2011). In this context, several rivers in north-eastern France were strongly modified (e.g. rectification of river ~~bed~~beds, dam building) and received high amounts of ~~domestic and industrial and domestic~~effluents ~~duelinked~~ to ~~former~~steel-making activities ~~installed~~located near water ~~resource~~sources (Kanbar et al., 2017). As a consequence of these past effluent ~~inputs in the river, the riverbeds~~emissions, ~~riverbed~~ sediments often remain contaminated, ~~despite~~although part of the settled material ~~having~~has been dredged and removed ~~from them~~(Kanbar et al., 2017). ~~During flood events, the~~. The remobilization of these riverbed sediments ~~during~~ flood events can ~~strongly impact~~subsequently affect water ~~and even soil~~ quality ~~and contaminate floodplains~~ (Carter et al., 2006; Hissler and Probst, 2006; ~~Martínez Carreras et al., 2016~~). ~~In this context, the composition~~ and ~~status of these~~ contaminated sediments ~~require~~therefore ~~requires~~ thorough investigations (SEDNET, 2003) ~~and there~~. There is, consequently, a clear need ~~for predicting to predict~~ the potential resuspension and transport of sediment in these heavily polluted river systems. River sediments are ~~aggregates of~~heterogeneous ~~aggregates~~, composite structures composed of ~~mineral particles of~~amorphous or poorly crystalline ~~mineral particles~~, organic matter, and biological matter (biofilms, bacteria, virus and bio-macromolecules). While fresh sediment deposits are often close to fluid mud, older ~~and deeper~~ riverbed sediments ~~are affected~~ ~~by~~tend to be consolidated, with the ~~vertical gradient~~state of consolidation. ~~This higher for deeper sediment. These~~ vertical ~~differentiation of sediments complicates~~gradients ~~complicate~~ the modelling of sediment erosion, transport and deposition. Past studies have shown that hydromorphodynamic models are powerful tools for predicting ~~these processes, and are able to~~ simulate suspended sediment ~~mobilization and transport, especially~~concentration (SSC) satisfactorily. However, most studies ~~were conducted~~ in coastal, lacustrine ~~and~~ estuarial and fluvial areas (e.g., Villaret et al., 2013). ~~However, only a few modelling studies applied this type of model to~~, with much fewer studies done on small river systems (e.g., González-Sanchis et al., 2014; Hostache et al., 2014; Hissler et al., 2015). ~~Some promising results were shown with a rather satisfying capability to predict suspended sediment matter concentration, Barrière et al., 2015~~. Hydromorphodynamic models often simulate sediment dynamics according to three main processes, namely erosion, transport (via suspended load and ~~bed load~~bedload) and deposition. ~~Any transport formula assumes~~Transport equations assume that sediment ~~mobilization is triggered~~motion ~~begins~~ when the river ~~bottomed~~ shear stress goes beyond a threshold value that depends mainly on grain diameter and sediment density for non-cohesive sediment. Moreover, sediment density strongly influences sediment settling velocity and advection, which govern erosion and deposition via ~~the~~ sediment mass balance. In this context, Hostache et al. (2014) highlighted that simulated sediment transport, erosion and deposition are especially sensitive to particle fall velocity, which depends on grain diameter and sediment density. These two parameters therefore control the preferential ~~deposit~~zones ~~as of~~ ~~deposition, since~~ particles with lower/higher fall velocity will ~~be deposited~~settle in different ~~areas~~places. Most of the time, hydromorphodynamic models consider sediment as an ensemble of individual spherical particles. For evident reasons, these

models do not simulate sediment particles individually, but rather define the so-called sediment grain-size classes and simulate sediment transport separately for each class. Belleudy (2000, 2001), Lepesqueur et al (2009) and Guillou et al. (2010) emphasized the paramount importance of using an enhanced sediment grain-size distribution representation to accurately simulate sediment transport in both coastal and river environments. It has also been shown that a uniform grain size distribution for bedload transport can lead to an over-prediction in sediment fluxes by a factor of 5 (Durafour et al., 2014). Durafour et al. (2014) compared various empirical formulations of bed load~~bedload~~ during tidal cycles and found that distributing bed load~~bedload~~ fluxes over a larger number of grain-size classes significantly reduced differences between predictions and *in situ* observations. However, the majority of recent studies still consider only few (one or two) sediment grain-size classes with uniform density (e.g. Qilong and Toorman, 2015; Hostache et al., 2014) and, in many of them, even a unique median grain-size class of sediment is used (García Alba, 2014; Warner et al., 2010). A formal evaluation of model performance when using a larger number of grain-size classes and distributed sediment density is thus still missing.

Here, we further develop an existing hydromorphodynamic model based on the dynamic coupling of TELEMAC-3D and SYSIPHESISYPHE in order to consider an enhanced enhance the sediment grain-size distribution with distributed sediment and density representations. The objective is therefore to evaluate and discuss the benefit~~eventual benefits~~ of these developments~~considering a larger number of grain-size classes and a distributed sediment density~~ for improving sediment transport and riverbed evolution predictions. This paper is organized ~~in~~ into four sections: First, we present the hydromorphodynamic model and the our ~~developments that were made~~. Second, we describe the study area, the available observation dataset and the experimental design. Next, we present and discuss the results. Finally, we summarize the our ~~findings of this study~~ and propose perspectives for future developments in hydromorphodynamic modelling.

2. Modelling framework

The proposed modelling framework is based on TELEMAC-MASCARET (Hervouet, 2007). The fluid hydrodynamics are simulated using the TELEMAC-3D model, which solves the Navier-Stokes equations in a-hydrostatic mode. The morphodynamic~~Morphodynamic~~ and sediment transport modelling is carried out using the SISYPHE model (Villaret, 2010; 2013)~~model~~, an additional module of TELEMAC-MASCARET. This module. We adopted this modelling framework has the following interests~~for two main reasons~~: (i) the two aforementioned models are based on an unstructured mesh of finite elements, which is particularly suitable for modelling river and coastal area~~modelling areas~~ as it allows the simulation of complex geometry~~geometries~~, and (ii) they can be dynamically coupled. The dynamic coupling of the two models is especially relevant for sediment transport and morphodynamic modelling as it allows, at each simulation time step, to take into account the effect of the riverbed changes on the flow and vice versa to be taken into account. SISYPHE decomposes the dynamic sediment processes into sediment transport, erosion and deposition. Sediment transport is decoupled into the bed load~~bedload~~ and suspended load, which allows the computation of sediment concentrations in the water column ~~to be computed~~.

2.1 Friction and bed shear stress

The bed shear stress (τ) is the hydrodynamic variable that ~~mainly~~ controls sediment transport through erosion and deposition (Villaret et al., 2013). TELEMAC-3D uses a roughness coefficient for the bottom energy dissipation by friction. This friction is responsible for the bed shear stress that controls erosion and deposition. In this study, TELEMAC-3D and SISYPHE are coupled dynamically and the friction is calculated based on the Nikuradse law (Nikuradse, 1932). Previous studies on an estuary system (Lepesqueur, 2009) showed the importance of using spatially distributed friction coefficients instead of a single uniform coefficient in order to ~~obtain~~ yield more accurate predictions of current velocities and directions, especially in shallow water where ~~the~~ friction is controlled by the apparent roughness of the sediment and the bedforms.

The friction as a function of the bottom sediment grain size (Lepesqueur, 2009), according to the Nikuradse law, is computed as follows:

$$\tau_0 = \rho u_*^2 = \rho \left(\frac{\kappa}{\log\left(\frac{30z_1}{k_s}\right)} \right)^2 u_{z_1}^2 \quad (1)$$

In Eq. 1, ρ is the water density, u_* the friction velocity, z_1 the “altitude of the first horizontal plane above the bottom”, u_{z_1} the near bed flow ~~velocity~~ velocity, $\kappa = 0.4$ the von Kármán constant, $k_s \approx 2.5d_{50}$ the Nikuradse bed roughness, and d_{50} the median bottom sediment grain size.

2.2 Bed evolution

When TELEMAC-3D and SISYPHE are coupled dynamically, the latter computes the bed evolution using the Exner equation (Exner, 1920; 1925) and transmits the bed ~~level~~ state to the former at each time step ~~to the former~~. The bed evolution is taken into account by the hydrodynamic model to better predict the flow intensity and direction. It is computed based on the divergence of the bedload flux and the net deposition and erosion due to the suspended sediment transport:

$$(1 - n) \frac{\partial Z_f}{\partial t} + \nabla \cdot Q_b + (E - D)_{z=a} = 0 \quad (2)$$

In Eq. 2, n is the bed sediment porosity, Z_f the bottom elevation, Q_b the bedload flux per unit width, and E and D the erosion and ~~deposit~~ deposition rates at elevation $z = a$, corresponding to the interface between ~~the~~ bedload and suspended load.

2.3 Suspended sediment transport

~~The suspended sediment concentration~~ The SSC is computed using the following equation of advection-diffusion:

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} + V \frac{\partial C}{\partial y} = \left[\frac{\partial}{\partial x} \left(\gamma_t \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(\gamma_t \frac{\partial C}{\partial y} \right) \right] + \frac{(E-D)_{z=a}}{h} \quad (3)$$

In Eq. 3, C is the depth-average ~~suspended sediment concentration~~ SSC, γ_t ~~is~~ the diffusion coefficient, U and V ~~are~~ the depth-averaged flow velocities in the x and y directions, respectively, and h ~~is~~ the water depth.

2.4 Erosion and deposition rates

SISYPHE allows for the ~~consideration~~transport of cohesive/non-cohesive sediment mixtures ~~to be simulated~~ and is able to ~~estimate the evolution of~~consider these two ~~types of~~ sediment ~~types~~ separately. ~~This is a relevant point as the processes governing the erosion and deposition of these two types of sediment are markedly different (Villaret et al., 2010).~~ In SISYPHE, the distinction between cohesive (i.e., mud) and non-cohesive sediment is based on the sediment diameter: the sediment is considered cohesive below 63 μm (silts and clays) and non-cohesive beyond 63 μm . ~~This is a relevant point as the processes governing the erosion deposition of these two types of sediment are markedly different (Villaret et al., 2010).~~ For the cohesive sediment, a uniform suspended ~~mud~~ concentration across the water column is considered. ~~In this case, and~~ the Krone (1962) and Partheniades (1965) formulation (see Eqs. 4-5),) governs the erosion and deposition rates ~~of cohesive sediment~~:

$$E = \begin{cases} M * \left(\frac{\tau_0}{\tau_{ce}} - 1 \right) & \text{if } \tau_0 > \tau_{ce} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

In Eq. 4, M is the Partheniades constant set to $2.4 \cdot 10^{-5} \text{ kg} \cdot \text{s}^{-1} \cdot \text{m}^1 \cdot \text{m}^{-2}$, τ_0 ~~is~~ the shear stress and τ_{ce} ~~is~~ the critical shear stress. The critical shear stress of the mud ~~has been defined based on measurements was measured in-situ~~ using a scissometer: ~~the~~ ~~The~~ critical ~~shear strength of mud erosion value~~ was estimated ~~at to be~~ 0.48 Pa for the top layer and 0.84 Pa at 15 cm depth ~~(a~~ ~~A~~ linear interpolation is used to attribute ~~to each bottom layer~~ an individual critical shear stress), ~~value to each bottom layer~~.

$$D = \begin{cases} W_s * C * \left(1 - \frac{\tau_0}{\tau_{cd}} \right) & \text{if } \tau_0 < \tau_{cd} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

In Eq. 5, C is the suspended mud concentration in the water column, τ_{cd} the critical constraint of deposition (set at ~~0.001Pa~~001 Pa) and W_s the fall velocity computed based on sediment diameter according to Zanke's formulation (Zanke, 1977):

$$W_s = \begin{cases} \frac{(s-1)gd^2}{18\nu} & \text{if } d \leq 10^{-4} \\ \frac{10\nu}{d} \left(\sqrt{1 + 0.01 \frac{(s-1)gd^3}{\nu^2}} - 1 \right) & \text{if } 10^{-4} < d \leq 10^{-3} \\ 1.1\sqrt{(s-1)gd} & \text{otherwise} \end{cases} \quad (6)$$

20 In Eq. 6, $s = \rho_s / \rho$ is the sediment relative density, ~~withwhere~~ ρ_s ~~is~~ the sediment particle density and ρ the water density, g ~~is~~ the gravitational constant, ν ~~is~~ the fluid kinematic viscosity and d the sediment particle diameter.

Depending on the mud fraction (i.e., ratio between mud and total sediment ~~masses~~mass) in the top layer of the river ~~bottomed~~ sediment, SISYPHE treats ~~non-cohesive sediment~~ erosion ~~and deposition~~ according to ~~the~~ so-called non-cohesive and cohesive regimes. The formulation used for ~~sediment mixture~~the erosion ~~of sediment mixtures~~ follows the developments of Waeles (2005) ~~that~~, ~~which~~ are based on the model proposed by Van Ledden (2001) according to the observations made by Mitchener and Torf (1996), Panagiotopoulos (1997) and Mignot (1989). ~~According to the observations made by~~ Panagiotopoulos (1997),)

~~stated that~~ the critical shear stress of sand depends on the mud fraction: ~~with a~~ ~~at~~ ~~mud~~ ~~fraction~~ ~~fractions~~ lower than 30%, the critical shear stress of sand is ~~a little~~ ~~slightly~~ influenced by the mud content, whereas it reaches that of pure mud for ~~mud~~ fractions higher than 50%.

~~According to this~~ ~~Following these findings~~, in ~~SYSPHESISYPHE~~, the non-cohesive sediment is eroded as pure sand (non-cohesive regime) if the mass fraction of mud is below 30% and as mud (cohesive regime) if the mass fraction of mud is beyond 50% in the top layer of the river ~~bottomed~~ sediment. Moreover, following Waeles (2005) and Villaret (2010), a linear interpolation between the two aforementioned formulations is used when the mud fraction is between 30% and 50%. One could argue that such ~~a~~ linear interpolation is rather simplistic. For example, other authors (e.g., Mitchener and Torfs (1996) and Jacobs et al. (2011)) suggested applying ~~a~~ cohesive erosion regime from 30% of mud on. However, a linear interpolation may induce a smoother transition between cohesive and non-cohesive regimes. Consequently, we decided to keep the original formulation implemented in ~~SYSPHESISYPHE~~.

Moreover, in the non-cohesive regime, the non-cohesive sediment is eroded and deposited according to the formulation proposed by Célík and Rodi (1988) using the concept of a so-called equilibrium sediment concentration that is computed using the ~~formulae of~~ Smith and Mc Lean (~~formulation (Smith and Mc Lean, 1977)~~); see Eqs. 2 and 3):

$$E = \begin{cases} W_s * C_{eq} = W_s * \left(\frac{\gamma_0 T_s}{1 + \gamma_0 T_s} \right) & \text{if } \tau_0 > \tau_{ce} \\ 0 & \text{otherwise} \end{cases} \text{ with } T_s = \max \left(\frac{\tau_{skin} - \tau_{ce}}{\tau_{ce}}, 0 \right) \quad (7)$$

In Eq. 7, E is the erosion rate, W_s the settling velocity of a sediment particle in the water column, C_{eq} the equilibrium sediment concentration at the bottom of the water column, C_b the sediment bottom concentration ($C_b=0.65$), γ_0 an empirical coefficient, T_s the normalized excess of shear stress, τ_0 the bottom shear stress, τ_{ce} the critical erosion shear stress (i.e., the bed shear strength) and τ_{skin} the shear stress due to skin friction.

Considering a cohesive regime, with a mud fraction beyond 50% in the bottom sediment, the sediment mixture is assumed to ~~be behaving~~ ~~behave~~ as mud and ~~the~~ bedload is neglected. The erosion rate ~~for of~~ the non-cohesive sediment is therefore computed using the Partheniades (1965) formulation (Eq. 4). ~~Whereas~~ ~~Although~~ the erosion rate of the non-cohesive sediment is treated differently depending on the mud fraction in the bottom sediment, the deposition rate of the non-cohesive sediment is invariably computed using:

$$D = W_s * C_{ref} \quad (8)$$

In Eq. 8, D is the deposition rate and C_{ref} the reference sediment concentration at the bottom of the water column.

The vertical component of the flow velocity is neglected and the particle fall velocity is not directly used in the advection and diffusion of sediment (see Eq. 3). To compensate for this simplification, a vertical Rouse profile of ~~suspended sediment~~ ~~concentration~~ SSC, related to the particle settling velocity in the water column, is assumed for the non-cohesive sediment

concentration. This Rouse profile ~~therefore~~ allows the estimation of a so-called reference concentration C_{ref} close to the bottom of the water column that is used for calculating the non-cohesive sediment deposition flux.

In ~~this case, the~~ SISYPHE, erosion ~~flux~~ is assumed to be initiated only if the bottom shear stress becomes higher than ~~the~~ threshold value ~~(i.e., namely~~ the critical Shields number~~).~~ When the bed shear stress is below the critical Shields number, no motion occurs. On the contrary, if the bottom shear stress exceeds the critical Shields number, the sediment starts moving. Shields (1936) was the first author to ~~layput~~ stress on the initiation of sediment transport as a threshold process. For cohesive sediment, this threshold corresponds to the critical shear stress of erosion that is an intrinsic property of the mud and can be assessed using a scissometer. For the non-cohesive sediment, the threshold for initiating motion is ~~more empirical~~ determined empirically (Shields, 1936). In this study, the ~~Shields'~~ Shields parameter is introduced:

$$\theta_s = \frac{\tau_0}{(\rho_s - \rho)gd} \quad (9)$$

In Eq. 9, θ_s is the ~~Shields'~~ Shields parameter. The erosion of non-cohesive sediment is initiated if the ~~Shields'~~ Shields parameter exceeds ~~a so-called~~ the critical ~~Shields'~~ Shields number (Soulsby and Whitehouse, 1997), defined as:

$$\theta_c = \frac{\tau_{ce}}{(\rho_s - \rho)gd} = \frac{0.3}{1 + 1.2d_*} + 0.055(1 - e^{-0.02d_*}) \quad \text{with } d_* = d \left[\frac{g(s-1)}{v^2} \right]^{1/3} \quad (10)$$

In Eq. 10, θ_c is the critical Shields number and d_* the dimensionless sediment particle diameter.

The threshold for initiating the ~~initial~~ motion of non-cohesive sediment is based on the ratio of a critical bed shear stress and the submerged grain weight. Many studies proposed ~~a less empirical~~ parameterization parameterizations based on the weight and ~~the~~ (angular) surface of the sediment grain but eventually showed results quite similar to those obtained when using the original Shields curve (Zanke, 2003; Miedima, 2010). Consequently, one can argue that the Shields curve can still be considered a good means for assessing the ~~criterion for the mobility~~ threshold of ~~homogeneous~~ non-cohesive sediment mobility. Many studies proposed a modulation of the Shields curve based on experiments with heterogeneous sediments (e.g., Zanke, 2003). In this study, the formulation proposed by Soulsby and Whitehouse (1997) is used to calculate the Shields parameter. This is derived from the initial Shields curve with a better fit at ~~a low Reynolds~~ number numbers, therefore improving the accuracy for smaller particles diameters (see Eq. 4).

2.5 Bedload flux

As mentioned in Section 2.4, the bedload flux is neglected in a cohesive regime. However, in a non-cohesive regime, the ~~formulation of~~ Meyer-Peter-Müller formulation is used to compute the bedload flux:

$$Q_b = \begin{cases} \alpha_{mpm}(\theta_c - \theta_s)^{3/2} \sqrt{g(s-1)d} & \text{if } \theta_s > \theta_c \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

In Eq. 11, Q_b is the bedload flux and α_{mpm} the Meyer-Peter-Müller coefficient. The excess of bed shear stress responsible for the sediment mobilization is the difference between the skin friction (i.e. Shields parameter) and the critical bed shear stress calculated using the critical Shields number.

5 2.6 Sediment grain-size distribution and bottom sediment composition

In ~~its~~the original version, of SISYPHE ~~is limited to two class, the~~ sediment ~~mixture~~composition is represented by two classes (cohesive and non-cohesive sediment). To circumvent this limitation, we enable SISYPHE to run simulations for a 10-class sediment mixture: three classes of cohesive sediment and seven classes of non-cohesive sediment. As in the initial version of SISYPHE, each class is defined by a median grain diameter and a nominal density ~~in this study~~. Each sediment class ~~can be~~is treated separately ~~and~~. Accordingly, its characteristics (the Shields number and the settling velocity) and the nominal erosion, deposition and transport rates are computed separately for each class. Finally, the global sediment erosion, deposition and transport rates are estimated by summing the sediment class nominal contributions.

Over the model domain, the bottom sediment mixture is defined based on the volumetric fraction of each sediment class. Moreover, the bottom sediment is stratified in ten layers defined by their respective thickness as a function of the median sediment grain size:

$$ES(i) = i^2 * d_{50}(i) \quad (12)$$

In Eq. 12, $ES(i)$ is the thickness of the layer i and d_{50} the median grain size. The top layer ~~defines~~ is defined as the active layer. The second layer starts to be eroded when the coarser sediment of the first layer has been totally eroded, otherwise the flux of erosion of finest particles is limited to the first active layer.

20 3. Study area, available data, model set-up and experimental design

3.1 Study area

The Orne River, located in north-eastern France, drains around 1270 km² and flows into the Moselle River. Since 2014, the maximum recorded discharge ~~that has been recorded~~ is slightly higher than 200 m³/s, corresponding to a flood return period of approximately ten years. At low flow, the turbidity of the Orne River is particularly low (< 5 NTU). We selected a 4 km-long control section (Fig. 1) for this modelling exercise of suspended sediment transport. In the area of interest, the riverbed has an average width of 30 m and an average slope of 0.1%. The modelled reach is composed of two large meanders. Its downstream boundary is equipped with a dam. The streambed is mainly composed of pebbles, coarse gravel, sand and a small silt portion. The riverbanks are mainly composed of a sand-mud mixture with varying contents of mud and are covered by dense vegetation. ~~At~~In some ~~locations~~areas, the riverbanks are made of concrete or silted-up rockfills.

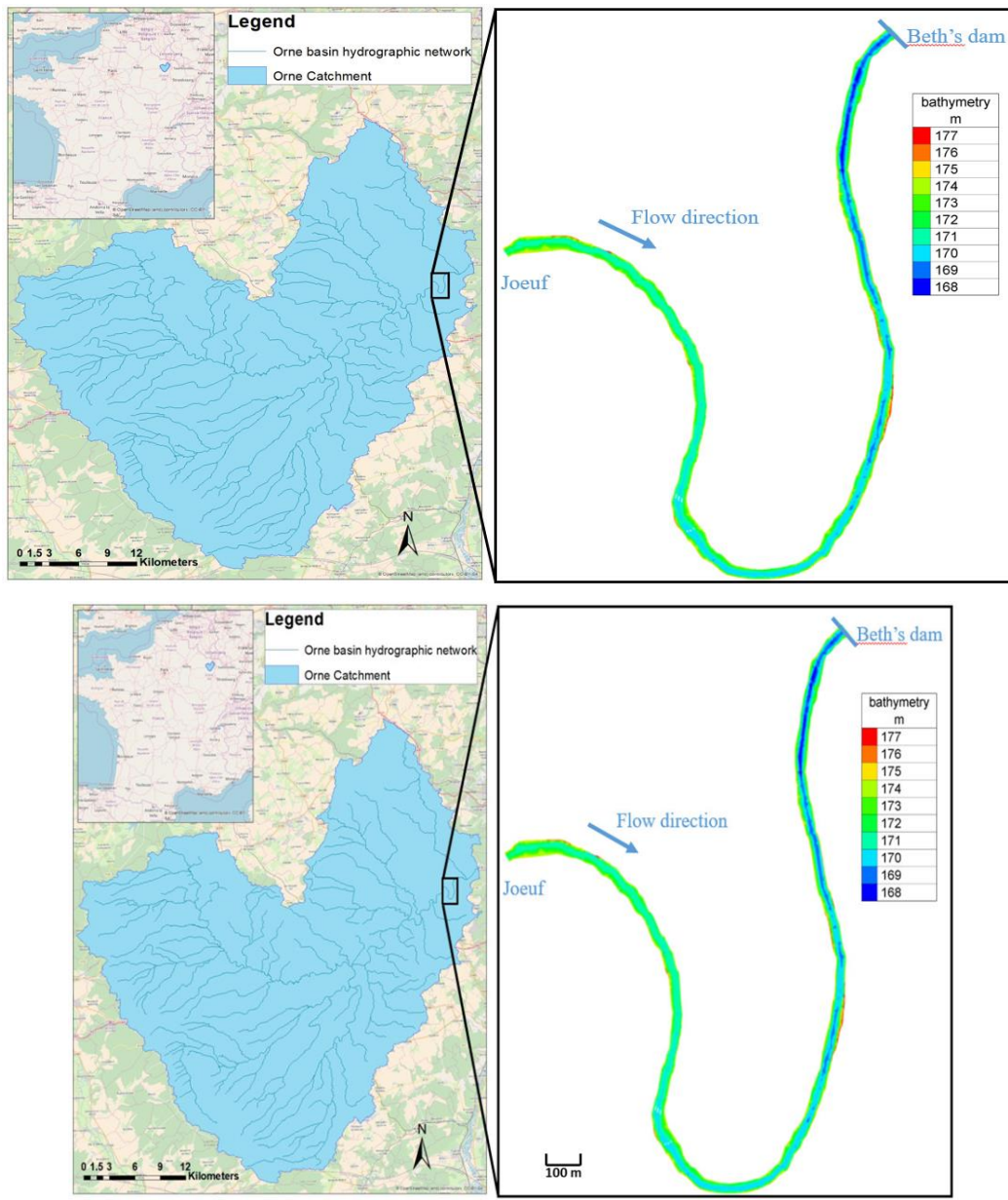


Figure 1: Study area and model domain (4 km-long control section of the Orne River)

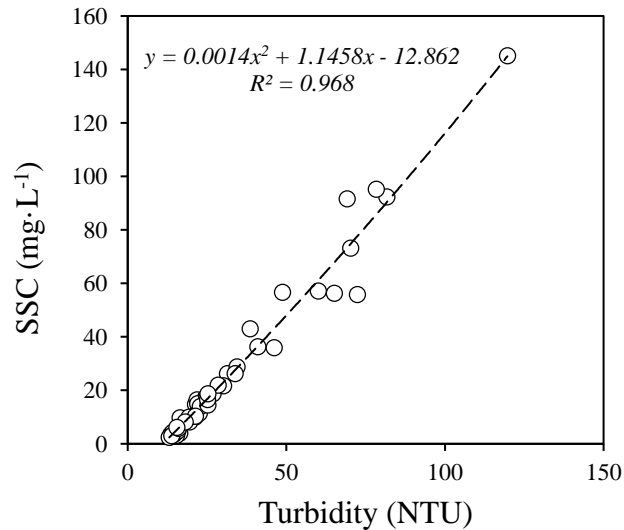
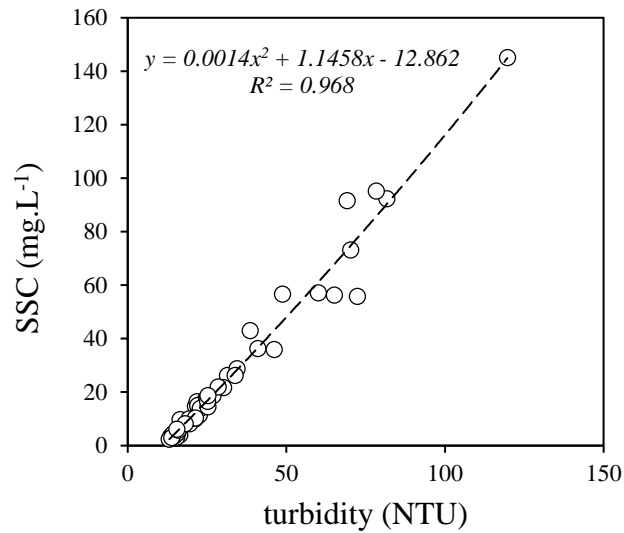
5 3.2 Available data

Since January 2014, we concentrated the monitoring efforts ~~have been concentrated~~ on continuously recording streamflow and water turbidity as a proxy of ~~suspended sediment concentration-SSC~~. Moreover, we monitored bathymetry (i.e. riverbed elevation) ~~and sediment deposition were measured more~~ episodically at selected locations on the riverbanks and the riverbed.

The continuous data used in this study were acquired during a moderate-magnitude flood event that occurred in March 2017. During this event, a peak discharge of $45 \text{ m}^3\text{-s}^{-1}$ was recorded and the turbidity did not exceed 150 NTU (Fig. 2).

3.2.1 Suspended Sediment Concentration (SSC)

SSC is generally measured ~~punctually~~occasionally whereas models require continuous input data time series. In this context, turbidity ~~data~~ is often recognized as a good proxy for ~~estimating~~assessing the continuous ~~the~~ time series of SSC (Martínez-Carreras et al., 2016). In this study, ~~the~~ turbidity ~~is monitored~~was measured every 5 minutes at the downstream boundary using an YSI 600 OMS turbidimeter. During the flood event that occurred in March 2017, turbidity values ranged from 0 to 150 NTU. These measurements are used to calibrate the relationship between turbidity and SSC ~~(Fig. 2)~~. The polynomial regression between the two datasets (e.g. Versini et al., 2015) exhibits a Pearson's correlation coefficient of 0.968 and a residual mean of $1.44 \text{ mg}\cdot\text{L}^{-1}$ (Fig. 2). ~~The calculated SSC is compared to the observation in Fig. 3.~~

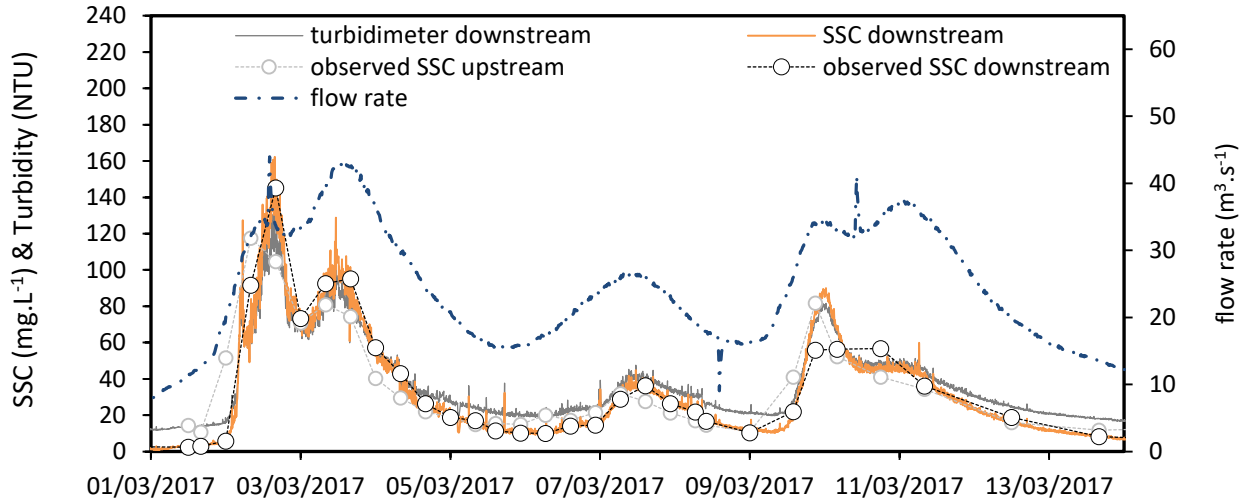


5 **Figure 2: Relationship between the river water turbidity and the suspended sediment concentration (SSC) measured at the downstream boundary in the Orne River section studied of the model domain (monitoring period: March 1-14 2017, n=31).**

Water samples were ~~automatically~~ collected every 6 hours using ISCO® automatic samplers at the upstream and downstream boundaries. The similarities ~~observed between measured~~ and ~~SSC-estimated~~ ~~SSC~~ at ~~various both~~ locations (Fig. 3) indicate that the sampling frequency is sufficient ~~to capture~~ ~~for capturing~~ the suspended sediment dynamics in the river section during this event. As a consequence, the ~~ISCO sample derived interpolation of the~~ ~~SSC~~ ~~punctual measurements~~ at the upstream ~~location~~ ~~is boundary are~~ used as an upstream forcing of the model. The SSC was measured by filtering ~~about 1L~~ ~~0.5 L~~ of river water through 1.2 µm Whatman GF/C glass fibre filters by means of a Millipore vacuum pump. All filters were previously dried at

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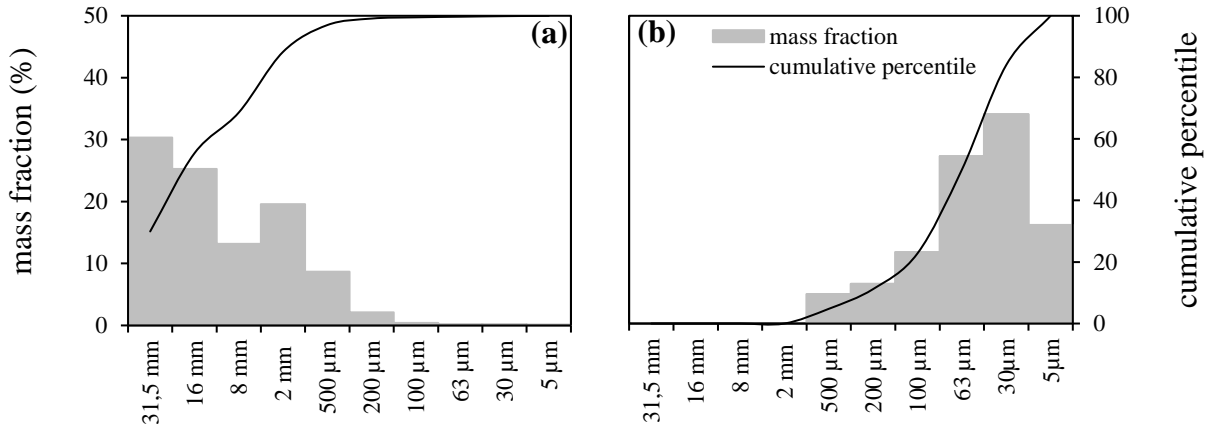
105 °C for 24 hours, cooled in a desiccator and weighed. After filtration, the filters were dried again at 105 °C and reweighed. The differences between weightings provided the total amount of sediment retained in the filters. We calculated the SSC by dividing the total amount of sediment retained in the filters by the volume of the filtered samples.



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Figure 3: Times series of flow rate, turbidity and calculated SSC. Punctual SSC observed measured at the upstream and downstream boundaries of the model domain are also plotted for comparison.

10 **3.2.2 Sediment grain-size distribution**



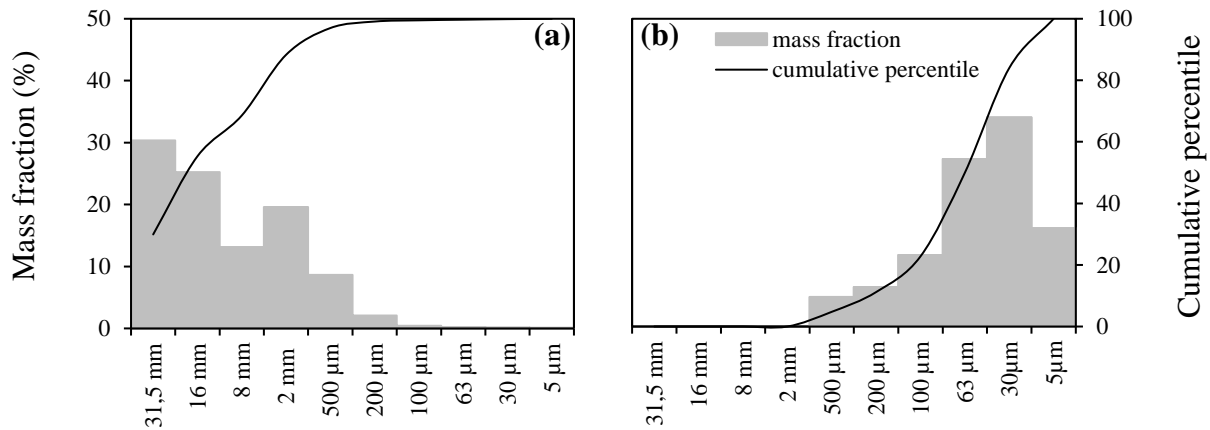


Figure 4: Sediment grain-size distributions estimated from the Orne River sediment samples collected in (a) the riverbed and (b) the riverbanks. (average value over 9 samples collected at three different river stations).

We estimated the grain-size distributions showed in Fig. 4 by sieving dried sediment samples collected in three different areas of the river section. Due to deep water at the downstream end of the river section caused by the dam, it was technically impossible to collect riverbed sediments in this part of the river. Moreover, as an extensive sampling of sediments along the river was not feasible, we ~~assume~~assumed, as ~~in-the-an~~initial ~~conditions-in~~condition of the ~~modelling-exercise~~model simulations, that the riverbed and riverbank sediment grain-size distributions ~~are~~were homogeneous along the river reach. ~~These initial~~Initial sediment grain-size distributions ~~are actually~~were estimated by averaging the three sediment samples.

3.2.3 Sediment density

- 10 In sediment transport modelling, the density of the sediment is usually set to $2600 \text{ kg}\cdot\text{m}^{-3}$ (Van Rijn, 1984). Here, we suggest considering a measured sediment density for each sediment class. To this end, we measured the variation of water volume in a 400 mL graduated flask while pouring a predefined mass of sediment into the water. The density measurements exhibit a spread of $1000 \text{ kg}\cdot\text{m}^{-3}$ and an average value of $2300 \text{ kg}\cdot\text{m}^{-3}$. The minimum density is $1800 \text{ kg}\cdot\text{m}^{-3}$ for the $63 \mu\text{m}$ sediment class (Fig. 5).

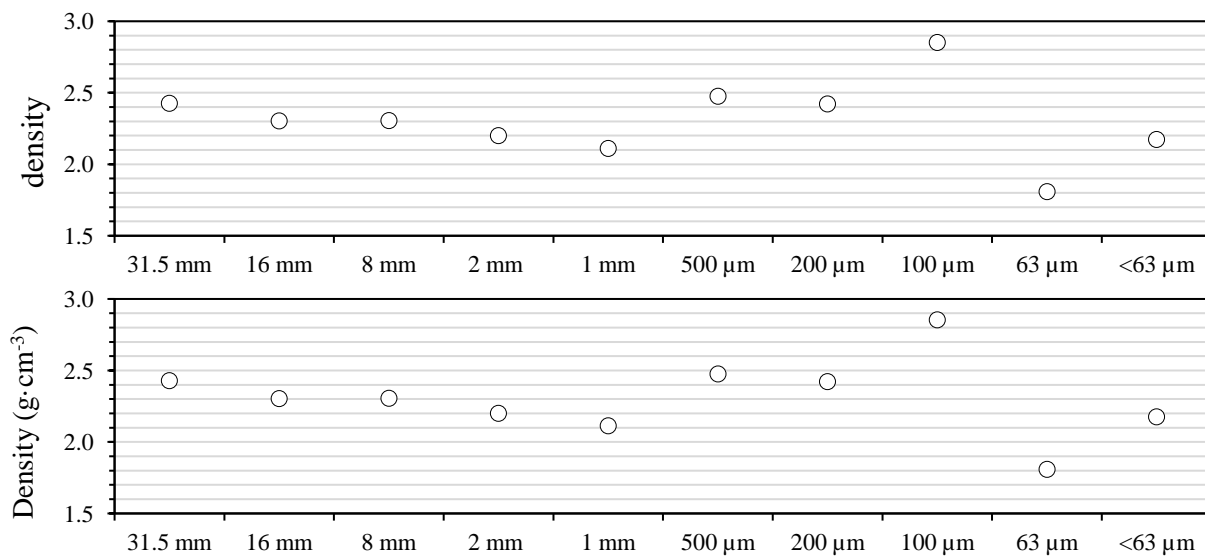


Figure 5: The Orne River ~~bottombed~~ sediment density measured for each of the 10 sediment size classes.

5 3.2.4 Riverbed bathymetry

The bathymetry of the riverbed and the lower part of the banks was carried out during two field campaigns ([in summer 2015 and summer 2016](#)) using a Differential GNSS system (vertical accuracy c.a. 1 mm) coupled with an echo-sounder (vertical accuracy c.a. 1 mm). The ground elevation of the upper parts of the banks was measured using a Differential GNSS system (vertical accuracy c.a. 1 mm) and a total station (vertical accuracy c.a. 1 cm) when the GNSS signal was not accurate enough
 10 due to the dense vegetation cover. These campaigns allowed us to measure riverbed elevation along the river cross section every c.a. 100 m.

3.3 Model ~~setup~~ and experimental design

Particularly well-adapted to simulate river hydrodynamics, TELEMAC-MASCARET is based on a finite element unstructured mesh allowing ~~for representing the representation of~~ complex ~~geometry~~ geometries (Hostache et al., 2014). For the study area,
 15 the unstructured mesh is composed of 16492 nodes ~~distanced from~~. ~~The distance between neighbour nodes ranges between 7 m up to and~~ 25 m. It was generated ~~with using~~ POLYMESH@ (developed by A. Roland, T.U. Darmstadt) ~~using a criterion on the bathymetry~~. The six bridge ~~piles lying~~ pillars located in the domain are represented in the model geometry. The riverbed and riverbank sediments are defined with two ~~distinct~~ different grain-size distributions (Fig. 4).
 20 ~~Four~~ We designed four model configurations ~~have been designed in order~~ to assess the ~~sensitivity~~ influence of the ~~model predictions to the~~ sediment grain-size distribution, the sediment particle density and the ~~SSC~~ boundary ~~conditions~~ condition on ~~model predictions~~ (Tab. 1). The SISYPHE and TELEMAC-3D parameter values remain identical for the four different

modelling configurations. The SSC distribution is assumed to be equal to the distribution of the erosion fluxes of each class at the boundary conditions. The settling velocity is calculated for each sediment class using the experimental sediment density values (Eq. 7 and Fig. 5). Moreover, due to the presence of vegetation on the riverbanks, the corresponding apparent roughness is fixed ~~to~~ 4 cm for the four modelling setups.

5

Table 1: Model configurations used in this study

Model configuration name	Suspended Upstream suspended Sediment classes	Bottom Sediment classes	Density
2CL	2	2	variable per class
10CL	10	10	variable per class
10CLD	10	10	2600 kg m ⁻³
10CL1CS	<u>21</u>	10	variable per class

The first configuration (2CL) corresponds to the standard ~~SYSPHESISYPHE~~ configuration, which only considers two classes of particle sizes with distinct densities. The second configuration (10CL) considers a riverbed ~~composed of~~ bottom sediment ~~with composed of~~ ten classes with distinct density values (Fig. 5) and an input ~~suspended sediment concentration~~SSC, at the upstream boundary condition, distributed over the same ten classes. The third configuration (10CLD) differs from ~~the 10CL~~ configuration ~~10CL~~ in terms of sediment density: the ten sediment classes have the same “standard” density value (i.e. 2600 kg·m⁻³). ~~Configuration 10CLD uses a density value of 2600 kg·m⁻³.~~ Note that the “standard” density value is higher than the ~~ones~~values we measured in the laboratory for all the sediment classes except for the 100 µm ~~class~~ (2850 kg·m⁻³; Fig. 5). The last configuration (10CL1CS) is identical to ~~the 10CL~~ configuration ~~10CL~~—except that the input ~~suspended sediment concentration~~SSC is imposed only on the sediment with the smallest particle size (<5µm).

10

15

4. Results and discussion

~~This~~In this section ~~presents, evaluates, we present, evaluate and discusses the~~discuss our results ~~obtained~~ based on the four model configurations (Table 1). In particular, ~~it aims~~we aim to evaluate the influence of the sediment size distribution, sediment density and ~~boundary condition~~ representation ~~of the upstream boundary conditions~~ on the simulated SSC and ~~the~~ bed evolution, respectively. To carry out this evaluation, the simulated SSC at the downstream boundary of the model domain is first compared with the corresponding ~~observed~~measured data.

20

25 4.1 Evaluation of the simulated SSC

4.1.1 Influence of the sediment grain-size distribution

The 2CL configuration required some additional effort for the model initialization and spin-up. Indeed, without a numerical adjustment of the initial bathymetry, the 2CL configuration was unable to ~~yield~~provide a satisfying fit with ~~observed~~the

~~measured~~ SSC data as spurious fluxes of SSC appeared (Fig. 6a). Some authors (e.g., Waeles, 2005) reported the need for long-term simulations (up to one year) in order to obtain a ~~satisfyingsatisfactory~~ initial state of the bathymetry and the sediment repartition. In our study, we successively simulated the same event several times. Five iterations (referred ~~to~~ as 2CL1, 2CL2, ~~..., ...,~~ 2CL5) were necessary in order to stabilize the initial bathymetry and avoid a systematic overestimation of the first SSC peaks (Fig. 6a and 6b). We took the fifth run of the 2CL configuration (i.e., 2CL5) as a reference ~~for the discussion~~ as it ~~yielded~~ the best results in terms of simulated SSC. Model initialization and spin-up were not necessary for the other configurations, namely 10CL, 10CLD and 10CL1CS.

Table 2 ~~clearly~~ shows that better model performances are ~~obtained~~ ~~yielded~~ when using a larger number of grain-size ~~fractions/~~classes. Indeed, not only are the error metrics substantially reduced in the 10CL configuration (in comparison to the 2CL5 configuration), but ~~also~~ the Pearson's correlation coefficient and the Nash-Sutcliffe efficiency (NSE) ~~increase~~ ~~are also~~ significantly ~~increased~~. Moreover, as shown in Fig. 6, the 2CL5 configuration tends to overestimate the first SSC peak (maximum absolute error: 118 mg·L⁻¹) and underestimate SSC for the rest of the simulation (mean error: -7 mg·L⁻¹). This highlights the limitations of a 2-class model that is not able to correctly predict SSC both at rather low and high flows. On the contrary, the 10CL configuration is able to ~~accurately~~ capture SSCs ~~accurately~~ as the mean and the maximum errors are 1.6 mg·L⁻¹ and -45 mg·L⁻¹, respectively.

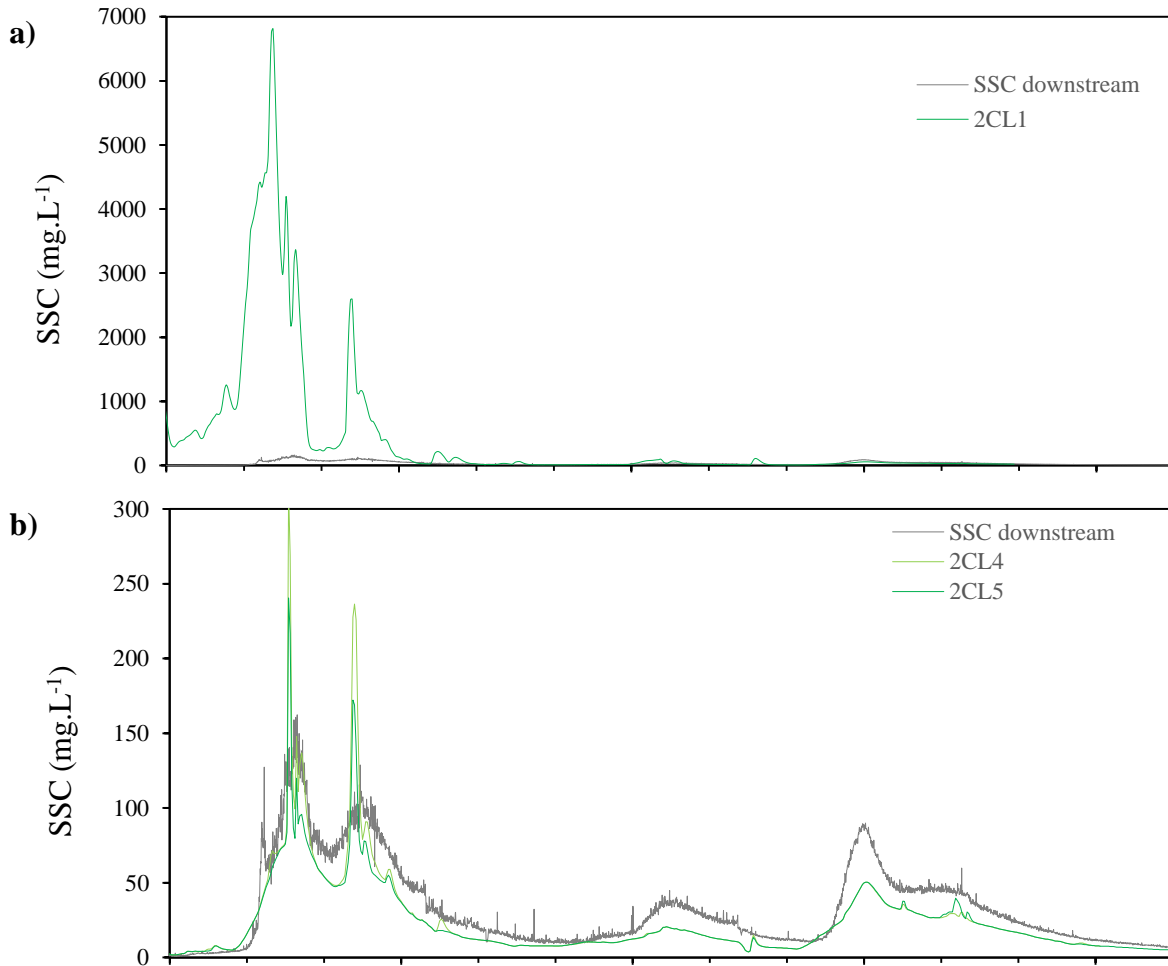
4.1.2 Influence of the ~~suspended~~ sediment density

As a reminder, in the 10CL model configuration, we use distinct densities for each class of sediment (Fig. 5), whereas ~~in~~ ~~10CLD~~, we use a unique value of density ~~in 10CLD~~ (2600 kg·m⁻³). During the simulated event, the contribution of the non-cohesive sediment to the SSC is ~~very small (in the order of)~~ ~~limited (c.a.~~ 1 mg·L⁻¹ at maximum). Both configurations ~~accurately~~ reproduce the ~~observed~~ ~~measured~~ SSC (Fig. 6c) ~~accurately~~. However, the 10CL configuration slightly outperforms 10CLD (Table 2) as the peaks of SSC are better predicted ~~in the 10CL configuration than in the 10CLD configuration~~. ~~Moreover, a substantial difference between the two model simulations is observed at~~ the first and ~~the~~ last peak of SSC ~~during the event~~ ~~exhibits a difference of~~ (10 mg·L⁻¹ ~~between the two models, which is not negligible as it represents for instance, representing~~ ~~c.a.~~ 10% of ~~SSC during~~ the last ~~SSC peak~~). The fall velocities are directly linked to the density (Eq. 6). As a result, overestimating sediment density can significantly reduce simulated SSC. ~~Although~~ ~~In our study~~, the effect of sediment density on model results is ~~nevertheless~~ slightly limited ~~in our experiment, mainly because~~ ~~due to~~ the ~~simulated event is of a~~ rather ~~moderate~~ ~~low~~ magnitude, ~~one could of the simulated flood event. We would certainly~~ expect ~~a higher sensitivity for~~ the effect of using measured nominal sediment densities to have a larger positive effect on simulated SSC time series when simulating larger flood events, ~~as larger sediment classes would be transported~~.

~~In this sediment transport modelling study, we chose to consider an average density value of 2600 kg.m⁻³ in the 10CLD scenario as this is the most commonly used value. One could argue that the average measured sediment density could also perform~~

satisfactorily. To evaluate this option, we carried out an additional simulation identical to 10CLD but using a sediment density of 2300 kg.m^{-3} (results not shown). The results obtained were similar to those obtained with the 10CLD configuration and different from the 10CL simulations, showing the added value of using nominal measured densities. This is arguably mainly due to the fact that only fine sediment classes are transported during this flood event and fine sediment classes have different nominal densities than the tested average values, namely 2300 and 2600 kg.m^{-3} (see Fig. 5).

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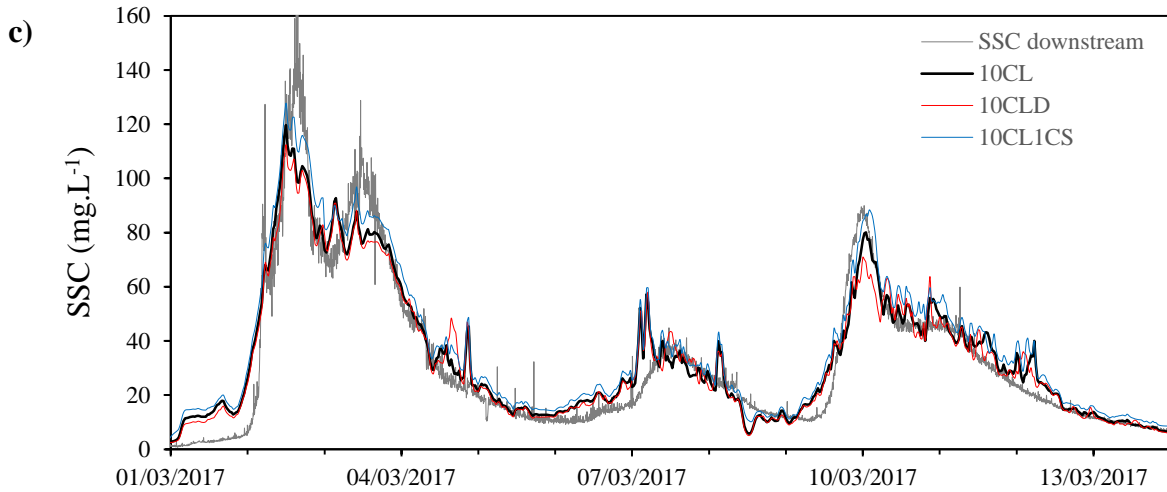


Figure 6: Simulated and ~~observed~~ measured suspended sediment concentration time series at the downstream boundary for configurations: a) 2CL (1st run); b) 2CL (4th and 5th runs); c) 10CL, 10CLD and 10CL1CS. SSC: suspended sediment concentration, 10CL, 10CLD, 10CL1CS, 2CL1, 2CL4, 2CL5: various modelling scenarios (please refer to Table 1)

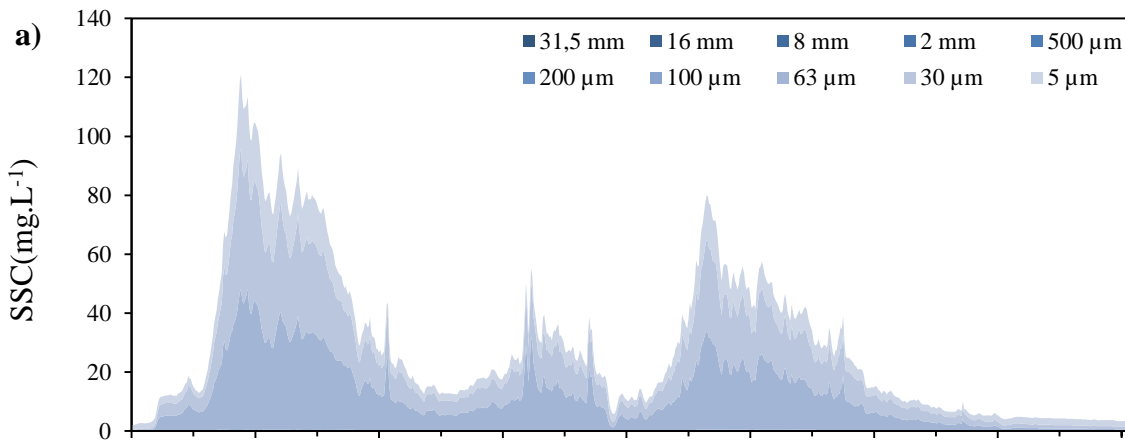
5 Table 2: Model performances computed for a 14-day simulation period (1-14 March 2017)

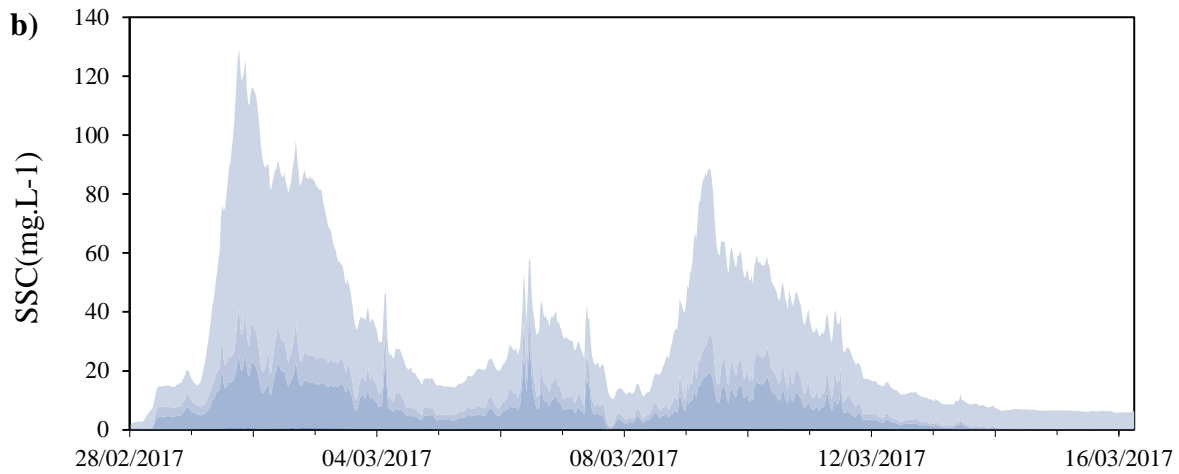
Model Configuration	Mean error (mg·L ⁻¹)	Max error (mg·L ⁻¹)	RMSE (mg·L ⁻¹)	NRMSE %	CORR	NSE
2CL	-7.86	118.99	14.74	37.67	0.89	0.72
10CL	1.60	-45.89	8.23	21.04	0.95	0.91
10CLD	0.84	-49.59	8.57	21.91	0.95	0.90
10CL1CS	5.22	-34.54	9.14	23.36	0.96	0.89

4.1.3 Influence of the suspended sediment size distribution ~~imposed~~ at the upstream boundary

~~In the 10CL1CS configuration, the~~ The simulated SSC is generally higher in the 10CL1CS scenario than in the 10CL (Fig. 6c). This is mainly due to the way the upstream SSC is imposed in the 10CL configuration. ~~Indeed, as the input SSC is (i.e., distributed over 10 ten classes). As a result,~~ coarser particles tend to settle more rapidly and the predicted SSC downstream ~~SSC is then~~ lower than in the 10CL1CS configuration. Overall, the error metrics and the skill scores reported in Table 2 show that the 10CL configuration slightly outperforms the 10CL1CS configuration as errors are lower and the NSE is slightly higher. ~~Overall, due to the rather moderate magnitude of the simulated event, the main processes controlling simulated downstream SSC appear to be advection and diffusion. Fig. 3 shows that the SSC time series have similar shapes and magnitudes at the upstream and downstream boundaries of the model. This indicates that erosion plays a limited role in the overall sediment transport budget when compared to advection and dispersion, during this rather low magnitude flood event.~~ To further investigate this, Fig. 7 shows the cumulative (starting from larger grain size) distribution of SSCs per sediment class simulated

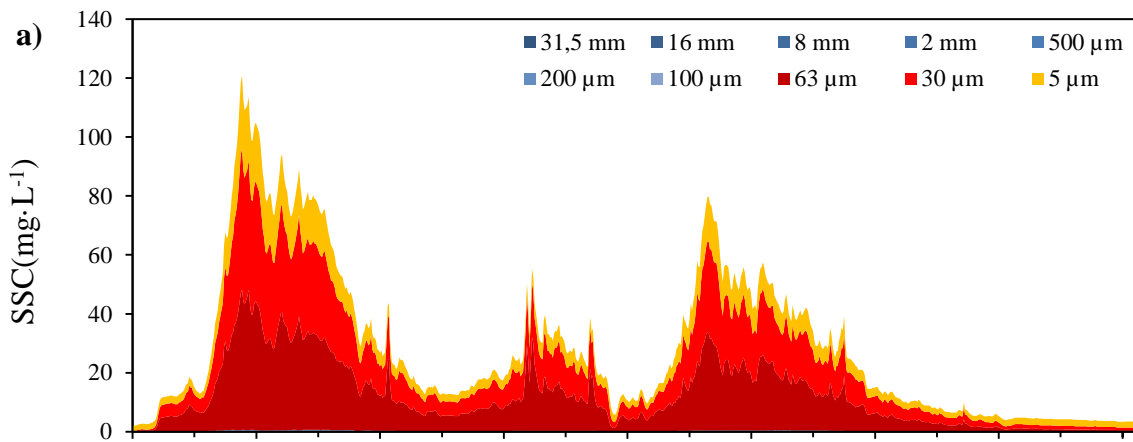
at the downstream boundary by the 10CL and 10CL1CS configurations. ~~As can be seen in this figure, the~~The contribution of non-cohesive sediments to the overall SSC is rather limited (in the order of $1 \text{ mg}\cdot\text{L}^{-1}$ at maximum). ~~Indeed, it) and~~ only contains the $100 \mu\text{m}$ sediment class for both models. However, as ~~is~~ visible in Fig. 7b, ~~erosion within the domain contributes slightly to the SSC as~~7b, the $63 \mu\text{m}$ and $30 \mu\text{m}$ -sediment classes are transported in ~~suspension in the~~10CL1CS~~the 10CL1CS~~ configuration whereas this configuration imposes SSC input only on the finest. This result shows that erosion within the domain contributes slightly to the sediment class ($5 \mu\text{m}$)-transport budget because these classes are not introduced into the model domain via the upstream boundary condition. Moreover, as ~~the~~these two configurations ~~considered produce~~yield markedly different results in terms of suspended sediment size distribution (Fig. 7), the way the upstream boundary condition is defined is shown to have a significant importance, especially on the advection and diffusion processes. We hypothesize that the difference between the SSC simulated with the two different configurations would be even larger when simulating higher magnitude flood events as the coarser and heaviest particles are more subject to sedimentation. Moreover, the dam affects circulation at the study site, reducing current velocity. Hence, the heaviest particles that can be transported at the upstream boundary, if the current velocity is high enough, might not reach the downstream part of the river due to the influence of the dam, ~~significant importance, especially on the advection and diffusion processes.~~





It is also worth mentioning that larger differences between the two configurations are expected in terms of simulated SSC for higher-magnitude flood events. Indeed, for such flood events, larger sediment particles are transported as a result of higher flow velocities. Distributing the upstream SSC over various sediment classes would then allow the transport of larger sediment particles via advection-dispersion in configuration 10CL.

5



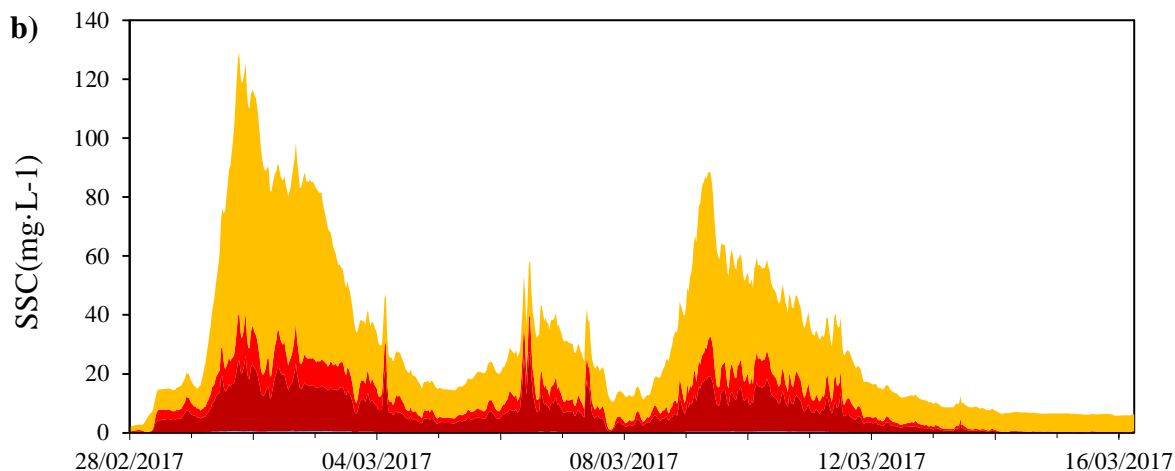


Figure 7: Downstream suspended sediment grain size cumulative distribution simulated by model configurations (a) 10CL and (b) 10CL1CS.

5 4.2 Cross-comparison of simulated riverbed evolution

~~Comparing~~To compare simulated bathymetry evolution maps showing changes in riverbed elevation is not straightforward for a moderate magnitude event on a small river. This is especially true because the evolutions are rather limited and local and it is difficult to collect sufficiently accurate ground truth data. To facilitate such a comparison, the evolutions of the riverbed elevation simulated by the various model configurations are compared via scatter plots (Fig. 8) using the 10CL configuration as a reference. Using bathymetry evolution instead of bathymetry itself not only allows a differentiation between erosion and deposition, but also an assessment of the thickness of deposited and eroded material. The bathymetry evolutions simulated by the 10CL configuration are separated as follows: erosion area (elevation change ≤ -5 mm), stable area (elevation change in $[-5\text{mm}; 5\text{mm}]$) and deposition area (elevation change $> 5\text{mm}$).

15 4.2.1 Influence of the sediment grain-size distribution

The comparison between evolutions obtained with the 2CL and 10CL configurations shows very low correlation coefficients (0.17 and 0.02 for ~~the~~ erosion and deposition, respectively). Moreover, stable areas in the 10CL configuration are unstable in the 2CL configuration (-0.11 of correlation). These substantial differences between the two configurations confirm that the number of sediment size classes implemented in the model plays a central role in the simulation of erosion/deposition processes. Overall, riverbed evolutions simulated by the 2CL model configuration are ~~almost inexistent~~very limited. This is mainly ~~due~~attributed to the model spin-up (~~see Section 3.1~~) that was necessary for stabilizing the bathymetry. (~~see Section~~

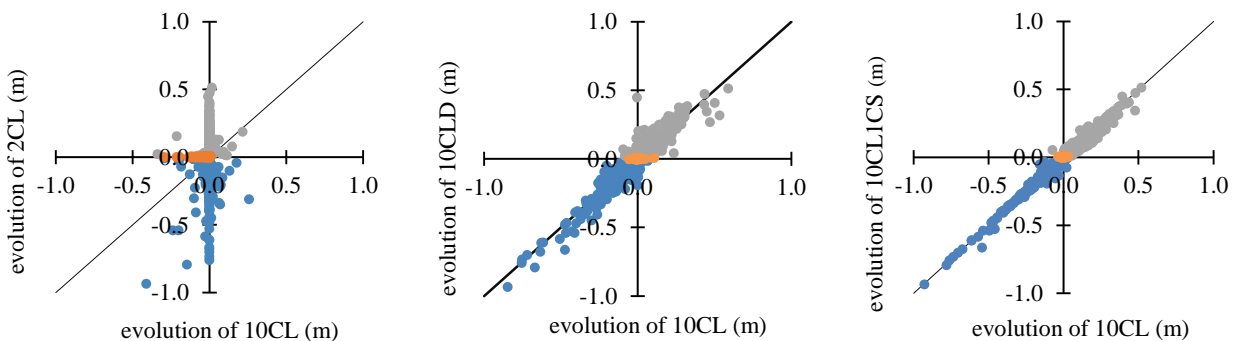
3.1). The simplified sediment size distribution (two classes) artificially amplifies the availability of the finest sediment class. This leads to a washout of this class during the spin-up simulation and at the beginning of the ~~event~~ simulation.

4.2.2 Influence of the ~~suspended~~ sediment density

The middle scatter plot in Fig. 8 shows a good correlation between riverbed evolutions simulated by the 10CL and 10CLD configurations. The correlation coefficients ~~computed on~~between erosion and deposition areas computed with both configurations are high with respective values of 0.97 and 0.92. ~~Therefore~~Moreover, we argue that the influence of sediment density ~~has some influence on the morphological changes occurring, especially for the deposition. Nevertheless, the correlation of the deposit should decrease as the flow rate increases, especially for more intense~~on model simulations would be larger when simulating higher-magnitude flood events. ~~The more SSC is composed as the range of different classes, the more~~ the transported sediment sizes would be broader. Indeed, during larger flood events, we might expect that coarser sediments are transported, eroded and deposited. Moreover, a change in sediment density would have an effect on deposition, as the density is directly linked to the ~~is~~ associated with a change in fall velocity ~~and the fall velocity induces the location, which implies changes in the transport processes: a higher density reduces transport and amount, on the contrary, a lower density increases it. Changes in density would therefore also result in the displacement of~~ deposition erosion and deposition areas for coarser sediment, making bathymetry evolutions more markedly different between 10CL and 10CLD configurations during higher-magnitude flood events.

4.2.3 Influence of the suspended sediment size distribution at the upstream boundary

The right scatter plot in Fig. 8 shows a good correlation between the 10CL1CS and 10CL configurations in terms of deposition and erosion areas, with respective values of 0.99 and 0.98. As ~~argued~~previously argued, the differences in bathymetry evolution between the two configurations (~~10CL and 10CL1CS~~) would likely be more important in the event of a higher flow rate.



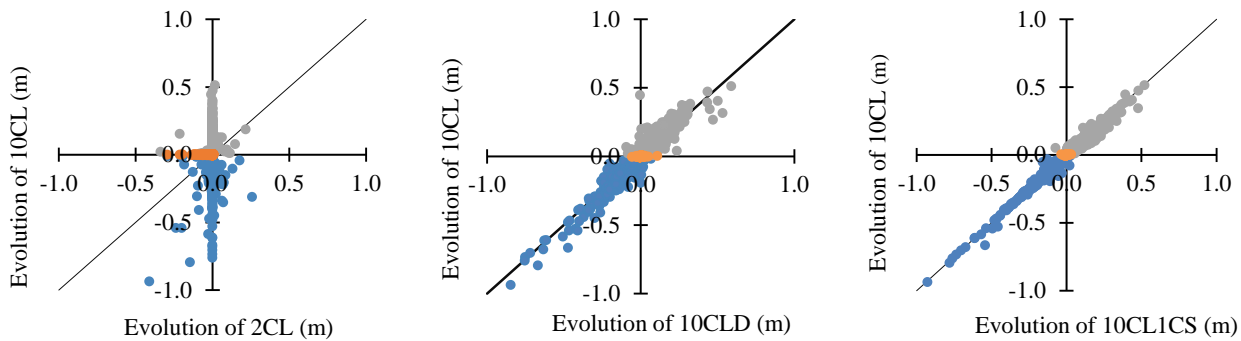


Figure 8: Cross-comparison of bed elevation evolutions (elevation final-initial) simulated for the 2CL, 10CL1CS and 10CLD configurations using the model configuration 10CL as a reference. The colours correspond to the 10CL's bathymetry evolution: the grey is the deposition, the orange is the stable bathymetry and the blue is the erosion.

4.3 Cross-comparison of simulated bottom sediment median grain-size evolution

- 5 ~~The median grain size of To further analyse the riverbed sediment at differences between the end of the simulation is analysed by various modelling configurations, we propose~~ cross-comparing the ~~evolution (final initial) evolutions of the riverbed sediment~~ median grain size (D_{50}) at each ~~model~~ grid node. The 10CL configuration is ~~taken again used as the~~ reference ~~(vertical axis).~~

4.3.1 Influence of ~~sediment~~ grain-size distribution ~~of the suspended sediment~~

- 10 Fig. 9 ~~(left-hand side panel)~~ shows ~~that there is~~ very limited correlation between the D_{50} evolutions when using the 10CL and the 2CL configurations (correlation coefficient of -0.05). The median evolution of the D_{50} in the whole area when using the 2CL configuration is about $70 \mu\text{m}$: the fine particles tend to leave the domain and the D_{50} increases. On the contrary, the median evolution of the D_{50} when using the 10CL configuration is ~~null~~ ~~close to zero~~: there is an equilibrium of the D_{50} in the domain, indicating that the ~~local~~ grain-size ~~sorting evolution~~ during the event does not ~~change~~ ~~modify~~ the ~~median~~ D_{50} over the
15 domain.

4.3.2 Influence of the ~~suspended~~ sediment density

- ~~The cross comparison (Fig. 9 (centre panel) shows a weak limited correlation between the evolution of the D_{50} evolutions when using the 10CL and 10CLD configurations (correlation coefficient of 0.32). The This shows that sediment density substantially influences bottom sediment distribution simulated is hence strongly impacted by the sediment density. The distribution of the points in the cross comparison is less spread out on the horizontal axis, suggesting that the distribution of the sediments is more stable grain-size evolution. The scatter plot exhibits a higher variance along the vertical axis (10CL configuration), indicating a more limited sediment grain-size evolution for the 10CLD configuration. The common value use of $2600 \text{ kg}\cdot\text{m}^{-3}$, which is higher than the mean nominal sediment density measured in our field study, densities tends to stabilize sediments increase the evolution of D_{50} during the flood event.~~
- 20

4.3.3 Influence of the ~~grain size distribution of~~ suspended sediment size distribution at the upstream boundary

The cross-comparison (Fig. 9 (right-hand side panel)) shows a high correlation between the D50 evolutions ~~of the D50~~ in the 10CL and 10CL1CS configurations (correlation coefficient of 0.87). The median (~~over the whole area~~) evolution of the bottom sediment D50 (~~over the whole area~~) in the 10CL1CS configuration is ~~null as well~~ also close to zero, suggesting that there is an equilibrium of the D50 all over the domain, as ~~for~~ in the 10CL configuration. This particular flood event was of ~~low intensity-moderate magnitude~~. Consequently, the fraction of suspended fine sand imposed at the upstream boundary condition ~~of~~ in the 10CL configuration was negligible and the suspended sediment was ~~distributed over~~ mainly composed of the three cohesive sediment classes. Hence, the ~~comparison of differences between~~ 10CL and 10CL1CS is ~~highly~~are limited ~~by~~ due to the moderate magnitude of the flood event.

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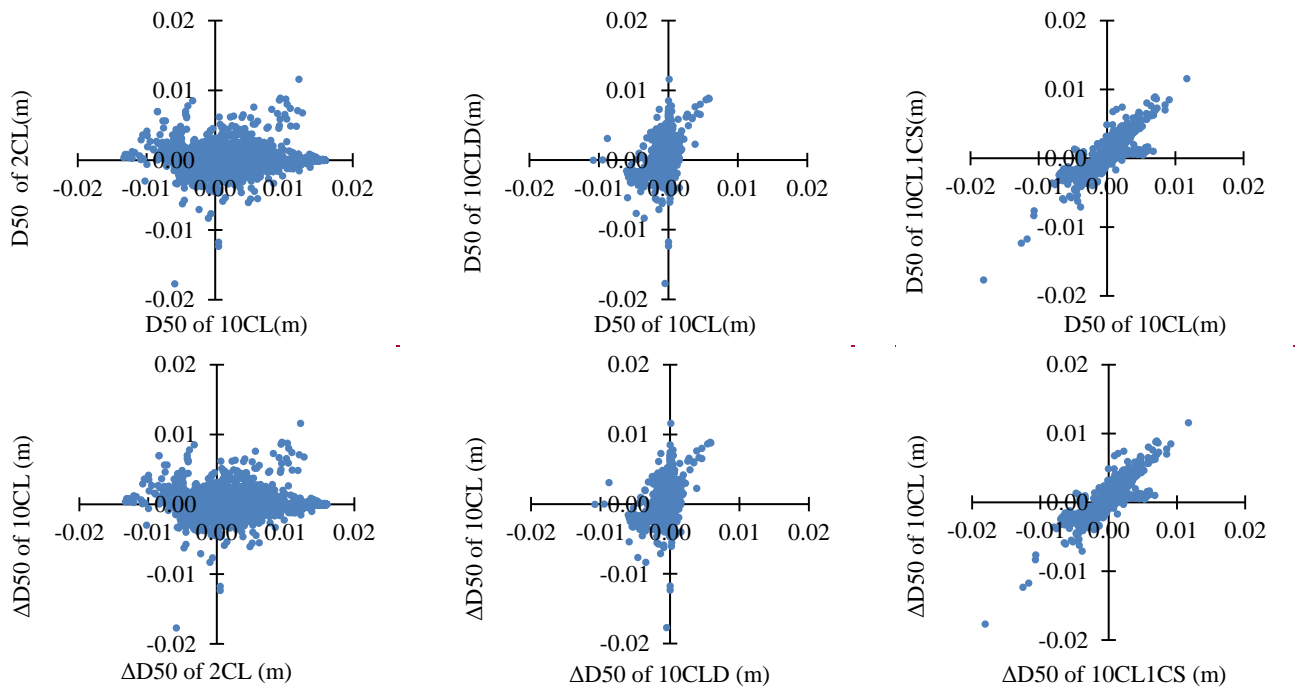


Figure 9: Cross-comparison of riverbed sediment median grain-size evolution (final-initial) simulated using the 2CL, 10CL1CS and 10CLD configurations using the 10CL configuration as a reference ~~model~~.

5. Conclusion

This study evaluates the influence of the sediment grain-size distribution, the sediment density and the upstream SSC representation on sediment transport/morphodynamic modelling. In this context, ~~the SYSYPHE model has been~~we further developed ~~in order the SISYPHE model~~ to integrate ten classes of sediment (mixture of sandcohesive and ~~mud~~non-cohesive sediment) with individual sediment densities (two sediment classes are implemented in the standard version). The physical

parameterization has also been rewritten, based on the parameterization proposed by Lepesqueur (2009), and has been adapted to the last release of SISYPHE (i.e. from version V5P8 to V7P7). The enhanced SISYPHE model is evaluated using a moderate magnitude flood event ~~of that occurred in~~ a small river (the Orne River, north-eastern France) as a test case.

The following conclusions are drawn from this study:

- 5 1. The simulated suspended sediment concentration (SSC) is markedly improved if the model takes into account 10 sediment classes instead of 2. The RMSE on SSC is reduced by a factor of 2 with 10 sediment classes. The simplified model, ~~including with~~ only 2 sediment classes appeared to simulate spurious sediment fluxes. Considering 2 or 10 classes of sediment in the model results in markedly different erosion/deposition areas.
- 10 2. The sediment density ~~is substantially influences model results~~, albeit to a smaller extent, ~~substantially influencing model results~~. Using a measured sediment densities (individually density for each sediment class) instead of a standard uniform value (i.e., 2600 kg·m⁻³) allowed for a slight gain in the model performance ~~on compared to~~ simulated SSC. ~~The area~~ Our analysis, based on a correlation of riverbed evolutions, also shows that using measured sediment densities instead of standard ones slightly changes the areas of erosion/deposition ~~slightly changed when using measured densities~~.
- 15 3. The way the input SSC is imposed at the upstream boundary also plays a role on the model performance, albeit a limited one in ~~this particular the simulated~~ flood event, ~~in the model performance~~. ~~However,~~ This was found to mainly influence advection-dispersion processes, whereas the influence on erosion/deposition ~~is was~~ not significant.

6. Future scope

20 ~~In the~~ The proposed sediment transport modelling framework with an improved representation is found to improve the accuracy of sediment properties (number the results. However, additional developments could be considered in order to integrate bio-physico-chemical processes. Indeed, the temporal variability of the bio-physico-chemical conditions in rivers plays a key role in shaping the sediment classes, densities and dynamics during flood events. In this context, we envisage implementing two important developments:

- 25 1. A new generation of high-frequency measurement sensors could be used to record the model input data. A LISST sensor (Fugate, D. C. and Friedrichs, 2002), which measures the size and concentration of particles suspended in water, or a combination of two acoustic doppler current profilers (Jourdin et al., 2014) could for example be used to monitor the SSC discretized over the classes of for each individual sediment), the numerical results proved to be class. This would provide more realistic model inputs and more accurate. However, improvements are of course still needed and this brings forward further processes validation data at the same time.
- 30 ~~+2. Flocculation processes could be integrated as they play a key role in sediment transport due to the fact that could be introduced in a future modelling framework: the density and the shape of flocs differ from those of individual~~

sediment particles. As a result, their displacement in the water column is different from that of isolated sediment particles (Parker, 1972; Van der Lee, 2009). The integration of flocculation process could be implemented by coupling a morphodynamic model with a flocculation model such as FLOCCMOD (Verney et al., 2009, Lepesqueur et al., 2018).

5 ~~The~~ In terms of longer-term developments, the erosion and deposition laws used in the morphodynamic model should also take into account ~~the overall~~ interactions between ~~the different~~ sediment classes ~~at the bottom~~, as argued for example by Starck (2014). Indeed, many ~~mechanisms due to heterogeneity in the bottom sediments~~, such as existing studies highlight the importance of the compaction of non-cohesive sediment (Swidersky, 1976), armouring (Egiazaroff, 1965), hiding/exposure (Ashida, 1973), filtration of fine particles by coarser sediment (Karim, 1982; Brunke, 1999; Herzig et al., 10 1970) and lubrication ~~induced by fine particles on coarser sediment~~ (Barry, 2006), together with biological processes ~~can either stabilize or destabilize the sediment, leading to a reduction or increase of the erosion fluxes~~ (e.g. Arthur et al., 1980; Widdows et al., 2000; Le Hir et al., 2007). ~~Integrating these mechanisms in morphodynamic modelling could contribute to further improving sediment transport predictions.~~

2. ~~In this study, the input SSC is numerically distributed over the sediment classes based on the riverbed sediment class distribution. However, it would be certainly beneficial to measure the SSC per sediment class directly to avoid introducing a bias and impose a more realistic sediment flux.~~

3. ~~Small particles in suspension can aggregate each other thereby creating flocs (Parker, 1972; Van der Lee, 2009). The flocculation process plays a role in sediment transport as the density and the shape of flocs is different from those of individual sediment particles. Their displacement in the water column is different from that of isolated sediment particles as a result of their different settling velocities and diffusion properties. As a consequence, taking into account flocculation could also help improve sediment transport modelling in the future.~~

Acknowledgments

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