Spatial and temporal analysis of the sand dynamics in alpine rivers for 3D numerical modelling

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ABSTRACT: Hydraulic structures can impact the sediment continuity of the river and can create a sediment imbalance downstream of dams according to the different sediment classes (silt, sand, gravel). For operators, one important issue is the presence of sand (d>63 µm), which can lead to exploitation difficulties, issues for flushing or emptying operations as well as to ecological, industrial or safety issues. It was recognized that the percentage of sand particles that is transported by suspension compared to bedload transport can often prevail. However, today it is still a real challenge to evaluate the spatial and temporal variability of these sand concentrations in gravel-bed rivers since sand dynamics are generally supply limited.

Using 3D hydro-sedimentary modelling could help to better understand processes of sand transport in rivers. In this article, we will present results from experimental monitoring that will then be used for 3D numerical modelling (TELEMAC 3D + Gaia) on engineered rivers in the Northern French Alps.

1 INTRODUCTION

Hydroelectric facilities constitute an obstacle to flows that can lead to the total or partial storage of sediment transport. The result is the impact of sediment transport on the operational management of hydroelectric facilities and, reciprocally, the effect of dams and water intakes on the sediment continuity and therefore on the river morphology. In particular, the presence of sand can lead to operating difficulties, such as difficulties in carrying out flushing or emptying operations and potential impacts on the environment downstream of the dams.

Good knowledge of the sand dynamics in engineered Alpine rivers is crucial. There are many socio-economic issues at stake, including ecological, industrial and safety aspects. One challenge is to evaluate continuous sand fluxes in such gravel-bed rivers. A solution would be to use the concentration index by measuring at a single point on the cross-section and relating it to the cross-sectional average (Camenen et al., 2023). However, depending on the hydraulic conditions, sand particles can be transported by bedload and/or suspension (Török et al., 2019). Today, there are measurement and modelling challenges for this grain size. Sand transport volumes are determined both by the transport capacity of the flow and the availability of materials (upstream contributions, bottom, banks).

EDF DTG (Direction Technique Générale of Electricité de France) is monitoring many stations measuring suspended sediments using turbidimetry and automatic bank sampling. It has been found that the proportion of sand (>63µm) in these suspended sediments is not negligible and is even sometimes prevailing compared to the proportion of silt and clay (<63µm). However, this measurement method is only partially adapted to measure the transported sand flow: unlike fines, sand is often distributed heterogeneously over the measurement section, and turbidity meters respond less well to sand than to fines (Thollet et al., 2013).

In order to better predict sand fluxes, a continuous monitoring of the overall sand flow passing through these stations should be achieved, including time scales ranging from floods to hydrological years. As a first step, comprehensive field campaigns are carried out at three different Alpine rivers (Isère, Romanche, Arc) in the northern French alps in order to improve measurement methods and to better understand transportation processes. In this article, we will focus on measurements from the Romanche river.

It is tried to measure the sand transport with occasional suspended-sand discharge measurements over the entire section, as well as with other measurement techniques such as continuous bank measurements. The possible relationship between bank measurements and the sand fluxes passing through the section (index method) is investigated for different experimental conditions (flow rates, sediment sources and grain sizes etc.).

Three-dimensional hydro-sediment modelling will then be used to explore in detail the question of sand distribution in the section. Only few studies exist that try to investigate the sand repartition in engineered rivers by the means of numerical modelling (Wright et al., 2009; Reisenbüchler et al., 2020; Bui et al., 2019). Exploring sand dynamic modelling requires a comprehensive data set.

2 MATERIALS AND METHODS

The Romanche River is located in the Northern French Alps. It is a secondary tributary of the Isère River with a respective surface area of the catchment of 1222 km^2. The mean annual water discharge is around 37 m^3/s, and the river is characterized as a gravel bed river with a nival hydrological regime.

The target model section of the Romanche River is located in between two hydroelectric dams in a system of successive reservoirs. The Clapier reservoir and the Saint Guillerme hydroelectric power station, which are supplied by the higher located Chambon reservoir, are situated around 12 km upstream of the section, on the other hand the Livet dam (and reservoir) is located around 5 km downstream. The Saint Guillerme power station (Clapier dam) has a maximum power of 115 MW and the Livet dam supplying the Romanche-Gavet power plant, which has a maximum power of 97 MW. Around 1 km downstream of the Clapier dam is the confluence with the Veneon River. The Veneon River and the Clapier dam, via flushing, are the two main sources of sand

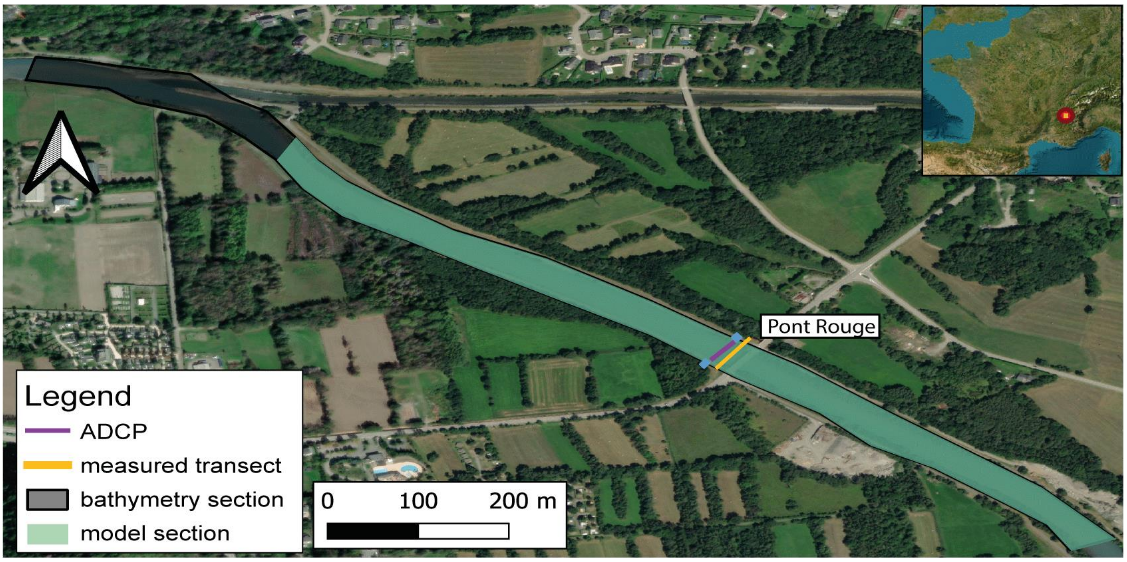

__Figure 1.__ Map showing the study site of the Romanche River with the measuring station Pont Rouge, the targeted model section and the covered bathymetric area. The yellow line marks the measured transect of the suspended sand-discharge measurements and the blue diamonds represent the bank measurement.

input to the Romanche River, which is then transported further along and can pose silting problems in the Livet reservoir. The new Romanche-Gavet hydropower plant was commissioned at the end of 2020 after ten years of construction works. Comprising the new Livet dam as well as a new underground powerhouse, they replaced 6 previous plants and 5 old dams.

Hence, the high quantity of sand transport implies several questions and challenges for a better understanding of the sand dynamics in this section. Different methods are used to obtain information on the sand distribution at each site. Therefore, automatic sampling from the bank (ISCO), suspended sand-discharge measurements (Delft bottle, distributed pumping) and turbidimetry measurements are performed several times per year as well as for specific hydrological events (flushing, flood). However, all these measurements only show the sand distribution in one part of the river section. An overview of the sand repartition of the entire section is required. For this analysis other data such as discharge measurements, bathymetric information, velocity field measurements (ADCP), as well as granulometric information from suspended sand-discharge measurements samples were collected and will be used.

The measurement transects for the suspended sand-discharge measurements, locations of ADCP and ISCO measurements as well as the covered bathymetric area are shown in Figure 1. The suspended-sand-discharge measurements were carried out at the measuring station “Pont Rouge” (Figure 1).

Numerical modelling is carried out using the three-dimensional code system TELEMAC 3D, modules of the open source system Telemac-Mascaret (http://www.opentelemac.org/). TELEMAC3D solves the Navier-Stokes equations and the free surface flow equations, including the velocity in all three directions ate each point of the 3D mesh. To solve the questions of the sand transport in the above-described model section TELEMAC 3D is coupled to the sediment transport module GAIA, which solves the advection-dispersion equation for the sediments using finite element schemes (Tassi et al., 2023). The targeted model section is shown in Figure 1.

3 RESULTS

3.1 *Sand repartition from experimental monitoring*

A first analysis of the existing experimental data is currently taken out to select most adequate data for the numerical modelling. Therefore, all the available data and different measurements are gathered and then checked for completion and adequacy. Other measurements such as suspended sand-discharge measurements were carried out for different hydrological events to obtain the most

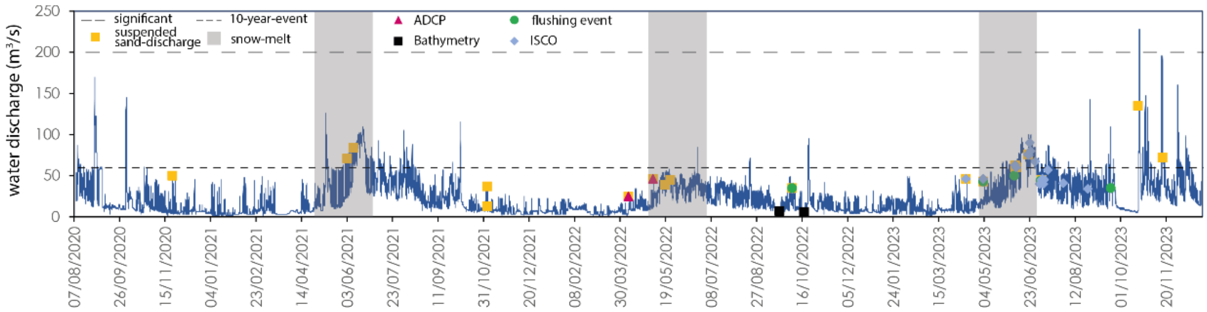

Figure 2. *Water discharge time-series of the Romanche River for the period between April 2021 until October 2023 at the station of Bourg d’Oisans, upstream of this section. The measurements carried out during this period are marked with different symbols. The grey highlighted areas mark the respective snow melt period of spring (may-june).*

complete picture of the sand repartition in the river section, including normal stage (discharge Q~37 m^3/s), flood periods or flushing events (Q >60 m^3/s) to determine the sand flux difference between normal discharge and “event” discharge. The water discharge of the Romanche River at Bourg d’Oisans, a measuring station upstream of the targeted model section is shown in Figure

2. This shows the discharge of the hydrological year for the Romanche River, with slightly higher discharge rates during the snow melt periods, especially in 2021 and 2023. For a flood event in October 2023 discharge rates of up to 220 m^3/s were measured. As the sand transport is supposed to increase with discharge, measurements are usually performed during the snow melt periods or flood season. Suspended sand-discharge campaigns at the Romanche River are generally carried out as quick as possible as the discharge rate can fluctuate significantly during the day. Therefore, one measurement often includes only few measuring points (usually 3) per vertical. Nevertheless, on hydrological events, measurements are carried out several times to obtain an idea of the sand distribution during different water discharge rates. Examples of two suspended sand-discharge measurements for different events and discharges are shown in Figure 3. The measurement shown in Figure 3a was taken in October 2022 during a flushing event of the Clapier reservoir upstream. Figure 3b shows the suspended sand-discharge results during a flood period in November 2023. Both measurements were taken at the same measuring station (Pont Rouge).

First, it can be highlighted that sand flux is in general much more homogeneous during the flushing event especially between the abscissas 8-16 (Figure 3a) than during the flood event. The analysis of the velocity fields shows that the velocities are highest close to the water surface and on the right side of the bridge pillar which corresponds to the zones with the lowest sand fluxes. The daily discharge rates before the flushing event (Figure 3a) varied between 15 to 50m^3/s. However, an important factor is the water level, which is much lower for the flushing event and which can possibly influence the sand repartition.

The flood event shown in Figure 2b had its peak in terms of water discharge rate two days prior to the measurement ($Q \sim$ 200 m^3/s), the discharge rate during the measurement was around 74

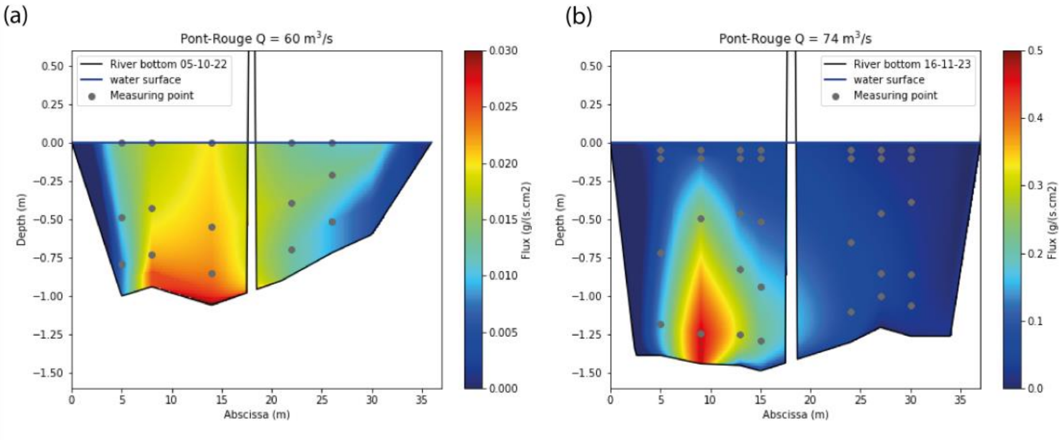

Figure 3. *Sand flux distribution throughout the river cross-section from suspended sand-discharge measurements at the Romanche River a) during a flushing event in October 2022 with discharge rates of around 60 m^3/s and b) during a flood period in November 2023 with a slightly higher discharge rate of 74 m^3/s. The difference in depth is due to different water levels during each event. The white bar in the middle of the section represents the bridge pillar. The grey dots mark the measuring points.*

m^3/s and hence not significantly higher than the discharge during the flushing in Figure 3a. Nevertheless, the sand repartition varies significantly for the two events. The sand repartition during the flood event is highly concentrated close to the river bottom and on the lefthand side of the river.). The analysis of the discharge rates of the Veneon River, a tributary upstream of the section, showed that the flood event was transmitted from this river as high discharge rates were measured only a few hours preceding the flood event at the Romanche River.

For the flushing event (Figure 3a) particle grain size data were available and the Rouse number $R_o = W_t/(\kappa u_*)$, with W_t being the particle settling velocity, $\kappa = 0.41$ the von karman constant and u_* the shear velocity, could be estimated for this event. The sand particle size distribution varied from 75 to 360 µm; hence the Rouse number was calculated for the smallest (75 µm) and for the largest (360 µm) particle size. The estimated Rouse numbers were 1.2 and 2.4, respectively, which suggests a prevailing suspension for all particles. However, for the coarsest particles ($d = 360$ µm, $R_o = 2.4$), bedload should not be negligible anymore.

Both events are highlighted as scenarios for the numerical modelling. The suspended sand-discharge measurements are time-consuming and cost intensive. Even though important information can already be obtained from these measurements and other monitoring data, these results only show the sand distribution throughout a river cross-section and the spatial and temporal repartition of these sand flows is still very little understood. To obtain a more accurate image of the sand repartition in the Romanche River and under different hydrological conditions, we will use numerical modelling.

4 PERSPERCTIVES FOR THE NUMERICAL MODELLING

The model is calibrated using a combination of different direct measurements achieved in the three studied rivers in the French Alpes (Romanche, Isère, Arc) for various hydrological conditions and sediment concentrations. Based on these results, the spatial heterogeneity of sand flows in the measurement sections is investigated. Then the model is used to evaluate the possibility of using the concentration index method (Camenen et al., 2023).

An important objective is to identify if the model is able to reproduce the same sand repartition for the measured transects shown above. The two selected hydrological events are key events that should be reproduced to better understand the evolution of the sand repartition in a larger section for such events. The analysis of the existing data showed that these two events not only originated under very different conditions, one under natural conditions (flood event) and one under artificial conditions (flushing event) but also that the sediment source was completely different. Numerical modelling is therefore indispensable to recreate these conditions and test other (sediment sources, discharge rates, sediment fluxes) to obtain a better knowledge of the entire system.

The main objectives of the numerical modelling are hence to obtain answers about the distribution of suspended sand in the river section for different hydrological events, the representativeness of the bank measurements, as well as the representativeness of point measurements from the suspended sand-discharge measurements. Furthermore, an inter-comparison of the results from different sites is planned as well as to investigate the impact of upstream sediment stocks.

At each site, we plan to simulate the distribution of sand fluxes for different permanent flows and different upstream sand concentrations. In addition, a simulation of the impact of the presence of banks and a greater or lesser stock of sand within the model on the results and the distribution of sand. Another configuration will be the simulation of the distribution of sand concentrations over the section during non-permanent events such as flooding or flushing events.

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