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1D numerical modelling of the longitudinal profile evolution of riverbeds and reservoirs: application of COURLIS bedload on a real case

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Abstract – **The aim of this work is to reproduce the morphological evolution of a reach of an alpine river: the Buëch river. For that, a 1D modelling with the COURLIS bedload module is used. It allows the representation of bedload sediment transport in the riverbed. However, some limitations of the code were initially highlighted, and it was necessary to implement new features to have results corresponding to the bathymetric measurements.**

These developments, including among others a new transport formula, the possibility to vary longitudinally the size of the sediments, the possibility to represent dredging, are tested and validated and will be integrated in V8P4.

Results obtained with the latest implementations of COURLIS show that the code can satisfactorily reproduce the morphological evolutions observed in the field along the longitudinal profile. The computational times are also acceptable with 3 hours computational time to model a 5-years period. In addition, COURLIS results are close to those obtained with CAVALCADE, a model based on similar assumptions. These preliminary, and encouraging, results show that COURLIS may be used for future operational studies aiming at representing the longitudinal profile evolution of riverbeds and reservoirs on multiannual time scales.

Keywords: COURLIS, longitudinal profile, bed evolution, bedload.

I. INTRODUCTION

Modelling the morphological evolution of riverbeds and reservoirs is invaluable to better identify the control factors of hydro-systems, to predict evolutionary trends of riverbeds and to help define and optimize river management projects.

To meet this need, major developments have been made to improve the one-dimensional sediment transport module COURLIS of the TELEMAC-MASCARET system. For example, recent implementations have been carried out:

- to have a new scheme for energy slope calculation;
- to add new bedload formulas (Lefort formula);
- to simplify sediment supply management on the upstream boundary condition;
- to consider morphological widths in bedload transport rates calculations;
- to allow for a longitudinal evolution of the granulometry;
- to reproduce dredging during simulations.

The aim of this work is to develop a module that can faithfully reproduce the dynamics of suspended load and/or bedload as well as the morphological evolution of riverbeds and reservoirs. The objective is also to build a COURLIS code able to model, within reasonable computational times, bed evolutions at time scales ranging from the period of a flood to a decade.

A new version of COURLIS integrating the latest developments mentioned above has been tested on a reach of the Buëch river in the French Alps composed in its upstream part by a straight and embanked channel and in its downstream part by a reservoir. The objective of this application of the bedload model is to assess and validate its ability to reproduce correctly the spatial and temporal 5-year evolutions of a longitudinal profile observed on a real/operational case. The simulation results are also compared with the 1D hydro-sedimentary code CAVALCADE, which is developed and owned by ARTELIA. CAVALCADE solves the simplified shallow water equations in steady regime coupled to a bedload transport formula and a volume balance and has been used to study the longitudinal profile evolution of numerous (mostly) gravel-bed rivers [1; 2].

The article is organised as follows: the latest developments in the code are presented first, the study site and available data are then described, the parametrization of the COURLIS numerical model is detailed later, and finally, the model results are presented and compared with the measurements and the CAVALCADE simulations.

II. LATEST DEVELOPMENTS

A. New scheme for energy slope calculation

MASCARET supports steady and unsteady flow computations thanks to the three computational kernels: SARAP the steady flow kernel for subcritical, supercritical or mixed flow regimes (finite differences), REZO the unsteady subcritical flow kernel (finite differences), MASCARET the unsteady trans-critical flow kernel (finite volumes). These three kernels can be used with COURLIS and chosen according to the specificity of the study cases. Different ways to estimate the energy slope can be used in steady simulations. For the steady kernel (SARAP), the equation of the water line discretized between two successive sections 1 (upstream section) and 2 (downstream section) with no singularities originally implemented in MASCARET is given in Equation 1 (below [3]):

$$\frac{Z_2-Z_1}{\Delta x}+\frac{2}{\frac{1}{J_1}+\frac{1}{J_2}}=0, \tag{1}$$

with Z_i the free surface elevation on section i, Δx the distance between two sections, and J_i the energy slope at section i.

A new option is now proposed which can in certain configurations (Soni and Newton test-cases mainly) allow a faster mesh convergence (converged results with coarser meshes). The upstream slope J_1 is no longer taken into account to approximate the energy slope between two successive sections as presented in Equation 2 below:

$$\frac{Z_2-Z_1}{\Delta x}+J_2=0. \tag{2}$$

The option is used through the `<decentrement>true<\decentrement>` command in the MASCARET xcas file. Note that the morphodynamic results obtained with the new option for the Soni and Newton test-cases do not show significant differences with those modelled with the first method.

B. Upstream solid discharge through an equilibrium slope

To meet operational requests, a new option is also added to COURLIS to use an equilibrium slope instead of explicit bedload laws at upstream boundary conditions. The upstream solid discharge is then calculated from the chosen transport law considering a user-defined equilibrium slope and hydraulic variables calculated on the upstream boundary condition. This option is activated with the keyword `UPSTREAM SEDIMENT CONCENTRATION FROM EQUILIBRIUM SLOPE` set to `YES`. The equilibrium slope value is set in the steering file with the keyword `UPSTREAM EQUILIBRIUM SLOPE`.

C. Lefort formula

As "classical" bed load formulas are more adapted to 2D models [4], it has been decided to implement in COURLIS the Lefort formula [5] which is more dedicated to 1D models due to its formalism. The Lefort formula, which is frequently used on gravel bed rivers in French engineering studies, requires the introduction of the adimensional diameter d_m^* which writes:

$$d_m^*=d_m\left(\frac{gR}{\nu^2}\right)^{1/3}, \tag{3}$$

with d_m the actual particles average diameter, g the gravity constant, $R=\frac{\rho_s}{\rho}-1$ the relative density, considering ρ_s is the sediment density and ρ the water density and ν is the water kinematic viscosity.

The transition discharge Q_0 which separates partial bedload from general bedload is chosen such as:

$$\frac{Q_0}{B\sqrt{g(Rd_m)^3}}=C(d_m^*)\left(\frac{d_m}{B}\right)^{1/3}\left(\frac{K}{K_p}\right)^{-1/2}J^{-m_0}, \tag{4}$$

with $C(d_m^*)$ a function to describe the critical Shields stress variation with the mean grain diameter:

$$C(d_m^*)=0.0444\left(1+\frac{15}{1+d_m^*}-1.5exp\left(-\frac{d_m^*}{75}\right)\right), \tag{5}$$

B is the bed width, K the Strickler coefficient, K_p the skin friction coefficient and m_0 is an exponent corresponding to an increase of the shear stress with slope which writes:

$$m_0=1.6+0.06log_{10}(J). \tag{6}$$

The solid discharge is then estimated as:

$$Q_s=1.7QJ^m\frac{R+1}{R^{1.65}}\left[0.5\left(\frac{d_{84}}{d_{50}}+\frac{d_{50}}{d_{16}}\right)\right]^{0.2}C_d\frac{F(Q)}{(R+1)(1-n)}, \tag{7}$$

with n the bed porosity, Q the water discharge, $m=1.8+0.08log_{10}(J)$, d_{84}, d_{50}, d_{16} are respectively the 84th, 50th and 16th percentile of the grain size distribution and C_d is a dune correction coefficient which models the increase in friction due to the development and the transport of dunes. It is set for grain diameters above 0.6 mm. According to [5], it has little influence on the results.

$$C_d=\begin{cases}1-1.4\exp\left(-0.9\left(\frac{K}{K_p}\right)^2\sqrt{\left(\frac{Q}{Q_0}\right)}\right) \text{ if } d_m^*<14 \text{ and } \frac{K}{K_p}<0.63\\ 1 \text{ otherwise}\end{cases} \quad . \tag{8}$$

The discharge function F describes the partial bedload of fine particles and general transport, first bedload and then bedload and suspended load, via the following expression:

$$F(Q)=\begin{cases}0.06C_M\frac{Q}{Q_0} & \text{if} \quad Q<Q_0,\\ \left[6.1\left(1-0.938\left(\frac{Q_0}{Q}\right)^{0.284}\right)^{1.66}\right]^{m_z}\end{cases}, \tag{9}$$

with m_z the add-on exponent for solid discharge during the transition between bedload and suspension:

$$m_z=\begin{cases}1+\frac{0.38}{d_m^{*\,0.45}}\left(\frac{Q}{B\sqrt{gd_m^3}}\right)^{0.192} & \text{if} \quad Q>3.4Q_0,\\ 1 \quad \text{otherwise}\end{cases} \tag{10}$$

and C_M reduction factor of transport for partial bedload:

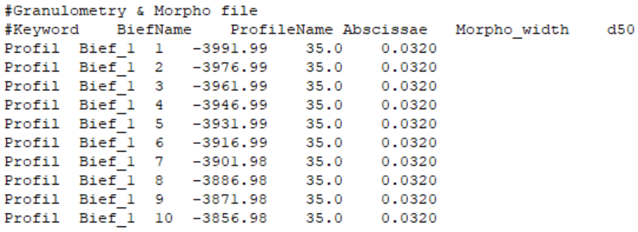
$$C_M = \begin{cases} \frac{1}{200}\left(\frac{Q}{B\sqrt{gJd_m^3}} + 2.5\right) & \text{if} \quad \frac{Q}{B\sqrt{gJd_m^3}} < 200, \\ 1 & \text{otherwise} \end{cases} \tag{11}$$

It is important to note that, when the ratio $\frac{K}{K_p}$ is unknown, an alternative is suggested by Lefort and can be activated in COURLIS with the boolean `ROUGHNESS RATIO WITH QSTAR FOR LEFORT`. When set to `TRUE`, the friction coefficient ratio is given by:

$$\frac{K}{K_p} = \begin{cases} 0.75\left(\frac{Q}{200B\sqrt{gJd_m^3}}\right)^{0.23} & \text{if} \quad \frac{Q}{B\sqrt{gJd_m^3}} < 200, \\ 0.75 & \text{otherwise} \end{cases} \tag{12}$$

D. Morphological width

It is possible to modify the morphological width B introduced in the Lefort formula by setting the keyword `OPTION OF VARIABLE MORPHO WIDTH` to `TRUE` along with the keyword `FILE FOR GRANULOMETRY AND MORPHO`. The latter should include the width information considered for each profile, and an example is provided in Figure 1. Although originally proposed by Lefort, the option of morphological width is available in COURLIS for all the bedload transport formulas.



```
#Granulometry & Morpho file
#Keyword    BiefName    ProfileName Abscissae   Morpho_width    d50
Profil  Bief_1  1   -3991.99    35.0    0.0320
Profil  Bief_1  2   -3976.99    35.0    0.0320
Profil  Bief_1  3   -3961.99    35.0    0.0320
Profil  Bief_1  4   -3946.99    35.0    0.0320
Profil  Bief_1  5   -3931.99    35.0    0.0320
Profil  Bief_1  6   -3916.99    35.0    0.0320
Profil  Bief_1  7   -3901.98    35.0    0.0320
Profil  Bief_1  8   -3886.98    35.0    0.0320
Profil  Bief_1  9   -3871.98    35.0    0.0320
Profil  Bief_1  10  -3856.98    35.0    0.0320
```

Figure 1. Granulometry and morpho file format.

The morphological width gives the effective width of the erodible area in each profile. In particular, this allows to calculate the solid discharge more precisely in rivers where active channels are less wide than the minor bed.

Note that the morphological width is usually a variable which can be adjusted during calibration procedures.

E. Longitudinal distribution of the grain size

The grain size distribution is considered constant on a cross section. However, it is possible to give each profile a different average sediment size. This option makes possible, for example, to represent numerically the sorting in granulometry upon arrival in a reservoir, and thus to more accurately describe the sediment transport that occurs there. Nevertheless, it is worth noting that the longitudinal distribution of grain size will remain constant during the computation (i.e., sorting processes are not solved).

This option can be activated through the keyword `OPTION FOR VARIABLE GRANULOMETRY = TRUE`, along with the keyword `FILE FOR GRANULOMETRY AND MORPHO`. The file format is shown in Figure 1.

Note that the average sediment grain size on each section is usually defined from field measurements. A calibration of this parameter can be eventually performed where data are missing or uncertain.

F. Dredging

During the calculations, in particular on long time series, it may be necessary to represent the dredgings which were carried out to be able to reproduce the morphological evolutions.

One or more dredgings can be performed using the keyword `NUMBER OF DREDGING`. Then the location of the dredgings should be set with the combination of keywords `ABSCISSAE OF THE BEGINNING OF THE DREDGING` and `ABSCISSAE OF THE END OF THE DREDGING`, giving one value for each dredging. Then, for each dredging, the depth must be set with the keyword `DREDGING DEPTH`. The time, in the simulation, during which dredging is desired must be filled in with the keyword `DREDGING TIME`, giving a value for each dredging. Note that a dredging can be carried out on one or several timesteps as a function of its duration.

III. STUDY SITE AND FIELD MEASUREMENTS

A well monitored complex site is selected to test the COURLIS bedload module and to show the relevance of the latest developments on real applications.

A. Study site

The study site is located in the southern French Alps, on a 4 km long reach of the Buëch river starting at the Serres bridge and finishing at the Saint Sauveur Dam (Figure 2). The upstream part of the reach corresponds to a straight and embanked channel of approximately 60 m wide with an alternate bar pattern. The riverbed slope varies between 0.004 and 0.006 m/m. The downstream part of the reach is composed of a reservoir. There, the bed width increases significantly to reach between 150 and 250 m. The upstream end of the reservoir has a braided morphology while further downstream the bed shows a sinuous single-channel layout, constrained by lateral bars located near the banks in areas of low bed shear stress. The slope of the bed in the reservoir varies according to its sedimentation level.

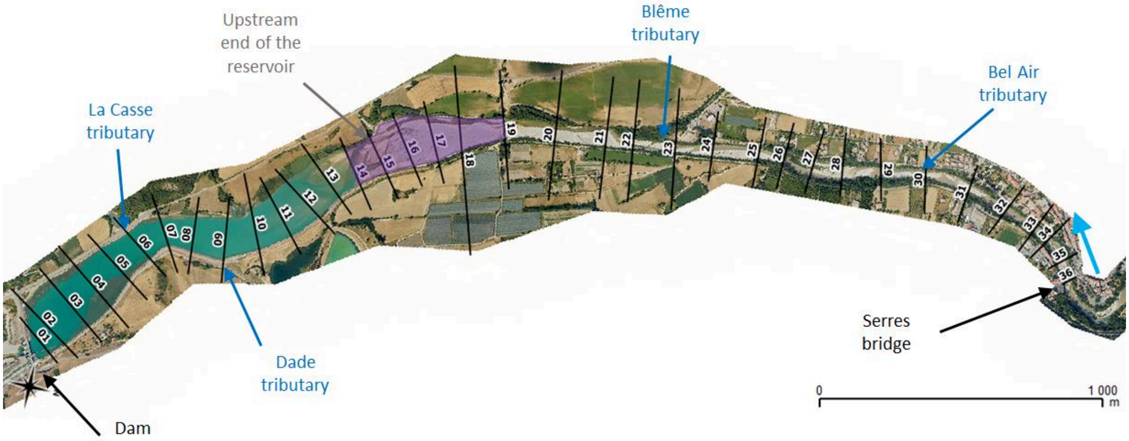


Figure 2. Presentation of the study site. The black lines indicate the cross-section locations of the bathymetric surveys. The purple polygon corresponds to the dredged area at the upstream end of the reservoir.

Several small tributaries flow into the Buëch between the Serres bridge and the dam. In terms of water supply, only the Blème river is a significant tributary.

The hydrological regime is pluvio-nival. The mean flow discharge is 16.3 m^3/s. The discharge values associated with 2-year, 5-year and 10-year floods are, respectively, 210, 320 and 390 m^3/s.

Buëch sediments are of two types:

- gravels with a D_m varying between 3 to 6.4 cm and a D_{50} of around 3.4 cm [6];
- fine sediments with a D_{50} of about 6 µm.

The annual gravel supply is estimated between 42,000 and 60,000 m^3/year [6]. The discharge for initial motion of gravels is roughly evaluated at 30 m^3/s. The annual fine sediment volume transported in suspension is assessed at 400,000 t/year.

The upstream end of the reservoir was dredged between 29th August and 4th November 2016 (see location of these works on Figure 2). Approximately 44,000 m^3 of sediments were extracted from the riverbed.

B. Field measurements

The hourly flow discharge of the Buëch ($Q_{Buëch}$) river is directly measured at the Serres bridge (Figure 3). The discharge of the Blème tributary ($Q_{Blème}$) is considered equal to $0.0644 Q_{Buëch}$ (based on the ratio of the two catchment areas).

The elevation of the free surface in the reservoir is measured directly at the dam only during normal operations as well as during the beginning and the end of floods when the gates are opened and closed (Figure 3). During floods, when the gates are totally open and not activated, the elevation of the free surface cannot be measured, so it is calculated from the theoretical valve capacity curves.

Four bathymetric surveys were performed in February 2015, December 2016, June 2019 and July 2020 along 36 cross-sections to observe the morphological evolution of the riverbed (Figure 2 and Figure 3).

IV. MODEL DESCRIPTION

A. Physical and numerical parameters

In both models (COURLIS and CAVALCADE), the Lefort transport law is used with calibrated morphological bed widths. A non-erodible substratum is found between 2,100 and 2,300 m upstream the dam and is modelled by a sediment layer thickness between 5 and 25 cm. Everywhere else, the sediment layer is supposed to be 3 m thick.

The mean diameter of sediment is set at 3.2 cm with a grain size gradient between the upstream end of the reservoir (at the longitudinal abscissae 1,450 m) and the dam from 3.2 to 2 cm respectively.

The dredging carried out in 2016 is numerically represented as a uniform extraction of sediment between 1,450 and 1,750 m upstream the dam.

The steady kernel SARAP of MASCARET is coupled with the COURLIS module with a ratio 1:1. The time step is set at $\Delta t = 10$ s and the Strickler bottom friction coefficient is uniformly chosen as $K = 30$ m$^{1/3}$/s. This value of bottom friction is defined arbitrary and not calibrated due to the lack of recent water surface elevation measurements.

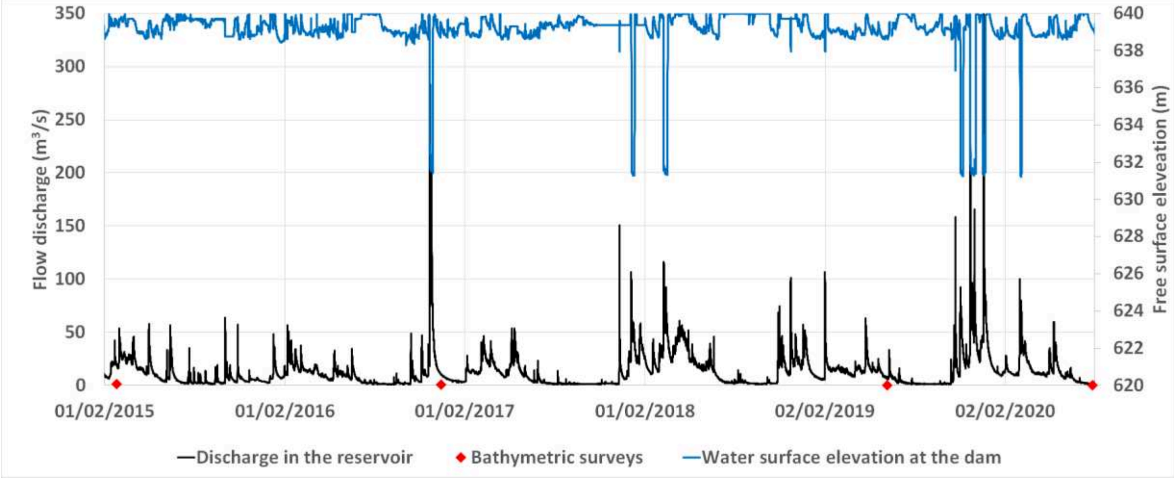


Figure 3. Flow discharge entering the reservoir and water surface elevation at the dam measured between 2015 and 2020. The bathymetric surveys are indicated in red.

B. Boundary conditions

At the Buëch inlet, the discharge is set from the Buëch hydrology measured between 2015 and 2020. Due to numerical difficulties to model low flows in large rectangular sections (see part IV. C), the physical time is cut off when the flow discharge drops below 20 m^3/s. This choice is motivated by an estimated threshold for initial movement of sediment of 30 m^3/s. The confluence with the Blème river at the abscissae 2,445 m is modelled through a liquid-only inflow.

The Buëch solid discharge is set by considering an equilibrium slope of 4.7‰ calibrated in order to reproduce the bed stability observed in the upstream part of the reach during the last years. Blème sediment supply is neglected.

At the dam, free surface levels are adapted from hourly water level measurements and calculations.

C. Initial conditions

The initial bed river is based on 2015 bathymetric measurements. Each cross section has been simplified to a rectangular cross section with a bed width calibrated to reproduce the main trends of erosion and deposition observed between 2015 and 2020. The 3 dam valves are modelled by an additional 36 m x 16 m cross section at the longitudinal abscissae 0 m. The longitudinal space step is chosen iteratively to smooth the Froude number at $\Delta x = 15$ m which allows to limit the instabilities observed for rougher meshes. Note that the effect of mesh resolution was not investigated during this study.

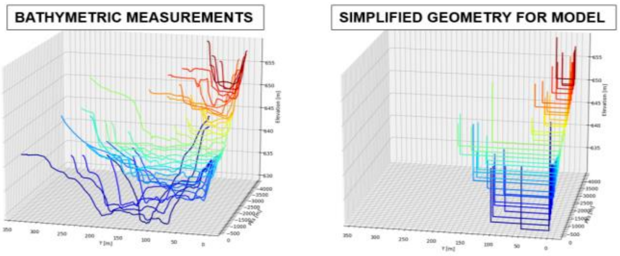


Figure 4. Simplification of riverbed in model.

V. RESULTS

The study starts with the model calibration step. As mentioned before, the first calibration procedure consists in adjusting the upstream sediment supply in order to reproduce the bed stability observed in the upstream part of the reach during the last years. Then, the rectangular cross-section width, the morphological width and the riverbed grain size are successively adapted profile by profile from field measurements (to avoid physical non-consistency) to model correctly the bed evolutions observed between 2015 and 2020. The final parameterization is identical in COURLIS and CAVALCADE models. Complementary simulations named "no options" in the following parts are also performed without the sediment size longitudinal variation, without the dredging, and with a morphological width in the Lefort formula equal to the rectangular cross-section. This allows to observe the influence of these functionalities.

Figure 5 presents the final longitudinal profiles observed and simulated in 2020. Bed evolutions measured and modelled from the initial bed geometry at the time of each bathymetries are shown in Figures 6, 7 and 8. Results demonstrate that the COURLIS calibrated model (with all the new options) can correctly reproduce the main bed evolutions observed between 2015 and 2020 which are characterised by a stability of the upstream part and a persistent erosion of the upstream end of the reservoir after the dredging of 2016. This observation is particularly true for the surveys of 2016 and 2020 for which the Root Mean Square Error (RMSE) reaches, respectively 17.1 cm and 19.3 cm. For these cases, the main difference with the measurements concerns an underestimation of the erosion in the dredging area. For the survey of 2019, the RMSE is higher (63.4 cm). However, this value is mainly due to the non-representation by the model of a large deposition of fine sediments in the reservoir (processes not considered in this current model application). Upstream this bed aggradation, the simulation results are good with centimetric errors on bed evolutions. Furthermore, the computational times are acceptable with 3 hours computational time to model the 5-years period.

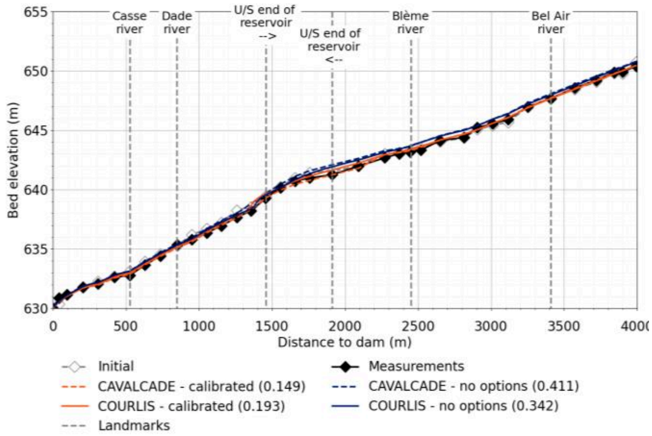


Figure 5. Longitudinal profile of riverbed in July 2020 - comparison between measurements, COURLIS results and CAVALCADE results under the same assumptions. RMSE (m) is computed between each model result and the measurements.

One can see a good agreement between COURLIS and CAVALCADE results (Figure 6, Figure 7 and Figure 8). In particular, the erosion and deposition patterns in the upstream part of the model are very similar, as are the erosions in the downstream part of the reservoir, near the dam. On the other hand, in the upstream end of the reservoir, some differences are observed with erosions clearly more marked for the CAVALCADE results, whereas the COURLIS results show some areas of deposit. Tests will be performed to better understand the origin of these differences. Despite this, the two codes stay relatively close to the measurements with maximum differences of about 20 cm.

Additional simulations are performed to quantify the effect of the grain size gradient, the dredging in 2016 and the use of morphological widths in Lefort formula with both COURLIS and CAVALCADE software. Results without aforementioned options are presented on Figure 5-8 (blue curves). As expected, the riverbed in the upstream end of the reservoir in December 2016 (Figure 6) is higher in simulation than what was measured on the field mainly because of the absence of the dredging carried out the same year. Compared with 2019 and 2020 measurements (Figures 7 and 8), the simulated riverbed shows similar patterns but remains higher all alongside the river because of this additional volume of sediment. Smaller bed widths in Lefort transport formula, using morphological bed widths, also permitted the limitation of the deposition all alongside the Buëch river. Finally, minor refinements of the solutions in the reservoir are done thanks to the implementation of a grain size gradient to approach the particle size distribution actually observed in reservoirs.

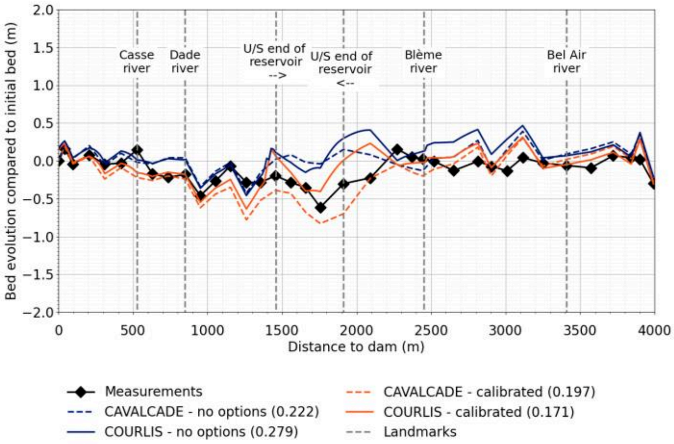


Figure 6. Longitudinal profile of bed evolution between February 2015 and December 2016 - comparison between measurements, COURLIS results and CAVALCADE results under the same assumptions. RMSE (m) is computed between each model result and the measurements.

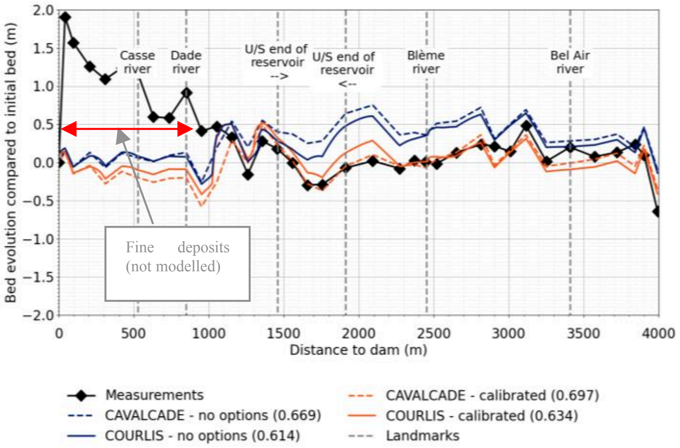


Figure 7. Longitudinal profile of bed evolution between February 2015 and June 2019 - comparison between measurements, COURLIS results and CAVALCADE results under the same assumptions. RMSE (m) is computed between each model result and the measurements.

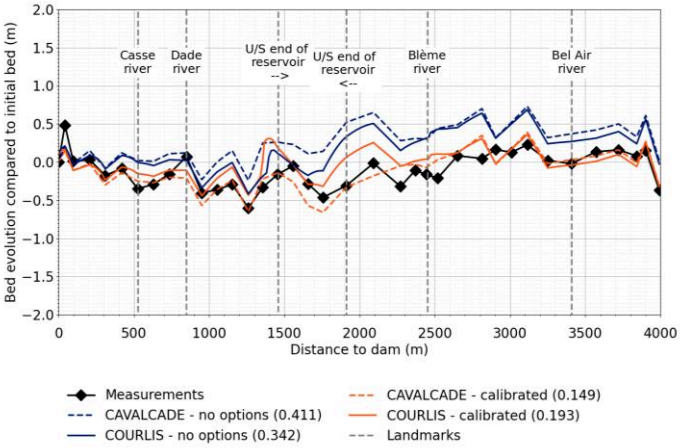


Figure 8. Longitudinal profile of bed evolution between February 2015 and July 2020 - comparison between measurements, COURLIS results and

CAVALCADE results under the same assumptions. RMSE (m) is computed between each model result and the measurements.

VI. CONCLUSION

The aim of this work is to reproduce with COURLIS bedload module the 5-year longitudinal profile evolution of a 4-km long reach of the Buëch river (Southern French Alps). The study site, which is a gravel bed river, includes a reservoir. The model is also compared with CAVALCADE, a similar calculation tool that can predict changes in river morphology due to bedload transport.

Several developments are made to be able to represent more accurately some processes. Indeed, a modification of the numerical resolution of the water level calculation in the kernel SARAP was carried out, as well as a new treatment of the condition at the sedimentary upstream boundary. Moreover, a new bedload transport formula is implemented, with the possibility to introduce the notion of spatialized morphological width along the river reach. The possibility to modify the size of the sediment according to its location along the river has also been added. Finally, a new option has been implemented to represent dredging during simulations. All these new functionalities, which will be integrated in the next version of TELEMAC-MASCARET (V8P4), are used to represent the morphological evolution of the study site.

Simulation results show that the COURLIS and CAVALCADE codes give similar results. This comparison provides a cross-validation of the algorithms implemented in both codes. The addition of new features in the code have greatly improved the results with simulation results that are closer to the observations. COURLIS, and its bedload module, allows to represent, with acceptable computational times, the main trends of the river and reservoir morphodynamics over a long period of time. These preliminary, and encouraging, results show that COURLIS may be used for future operational studies aiming at representing the longitudinal profile evolution of riverbeds and reservoirs on multiannual time scales.

Many features can still be added to the code to take into account other physical processes that can be relevant in some cases. For example, implementing a module of non-uniform grain size to the bedload part of the code would allow to better reproduce bed evolutions in some rivers. To model the behaviour of the river during extreme floods, it would also be interesting to take into account the possibility of having overflows on a major bed while keeping the possibility of having transport by bedload in the minor bed. The possibility of extending the application of COURLIS to a coupling with a multi-bief MASCARET model could also allow a wider spectrum of application for the code. Finally, modelling the transport of bedload and suspended load at the same time in the calculations would offer interesting possibilities to better reproduce the evolution of the bed in some real cases as the one presented in this study for which fine sediment deposition happens in the reservoir.

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