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Development of a hydro-morphodynamic Model for Sediment Management in the Rosenheim Reservoir

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***Abstract*— In this study, a hydromorphological model of the Rosenheim reservoir, one of the impoundments formed by a chain of run-of-river power plants along the Inn River (Germany), was developed by coupling TELEMAC-2D and SISYPHE. Available bathymetry surveys, conducted after the high magnitude flood events in 2005 and 2013, were used for calibration and validation respectively. The implementation of the subroutines modified by the Chair of Hydraulic and Water Resources Engineering of the Technical University of Munich together with the selection of a low angle of friction of the sediment for the secondary currents correction produced a good match between the measured and simulated cross-section profiles. The model's ability to predict the bed variation after the event was evaluated using the Brier Skill Score (BSS) and considering the initial bathymetry as the baseline prediction. Applying this technique, the three following parameters were considered: (i) phase error to assess the accuracy of the location of erosion and deposition processes, (ii) amplitude error to evaluate the bed evolution magnitude and (iii) mean map error to estimate the bias of the simulation against the measurements. The model was successfully calibrated and validated with BSS values being in the category of excellent and good together with a high number of cross-sections featuring low phase, amplitude and mean map errors. The calibrated model is presently applied to other flood events in the reservoir.**

I. INTRODUCTION

Human settlements along the floodplains of the Inn River have led to canalization, river training and construction of hydropower plants that have modified its natural hydromorphological and ecological characteristics [1, 2]. Throughout the operational years of the chain of hydropower plants (HPP) along the Inn River, a large amount of sediments have been trapped near the dams resulting in a strong alteration of the natural slope of the river [1]. The selection of a proper sediment management strategy for reservoirs is of great importance to avoid the loss of storage capacity, to manage floods safely, and to achieve a Good Ecological Status (GES). Calibrated hydro-morphological models can predict sediment transport processes realistically and thus be used as powerful tools in the decision-making process. Apart from the impact to the ecological environment and habitat connectivity, previous studies of the Inn River have concluded that the fine particles that form the bed have a highly dynamic response to the increasing of flow discharge during flood events [1] and therefore, a hydromorphological approach should be used in order to perform flood modelling. To this goal, the application of the 2D numerical model, TELEMAC-2D (T2D), coupled with the sediment transport module, SISYPHE (SIS), from the TELEMAC-MASCARET System [3] is applied to the case study of the Rosenheim Reservoir as part of the Project of Development and Application of an Integrated Mathematical Model for Reservoir Sediment Management (NEREID). This project is part of the Programme for the Promotion of the Exchange and Scientific Cooperation between Greece and Germany IKYDA 2018.

II. STUDY AREA

The study area is the Rosenheim Reservoir, one of the 16 impoundments formed by the dams of the chain of run-of-river HPP along the German side of the Inn River. The 11.2 km long river segment is bounded at the upstream by the Nußdorf HPP, at the Inn kilometer (rkm) 198.7, and at the downstream by the Rosenheim HPP at the rkm=187.5. The catchment area at this point of the Inn River is approximately 10,000 km^2 and the mean flow discharge 316 m^3/s. Fig. 1 shows the location of the study site with respect to the city of Munich.

III. MATERIALS AND METHODS

A. Numerical model

The TELEMAC-MASCARET System has proven to be a powerful tool for the integrated river engineering projects. Specifically, the implementation of coupled numerical models between the 2D hydrodynamics module, TELEMAC-2D, and the sediment transport module, SISYPHE, have been successfully carried out for several case studies performed by

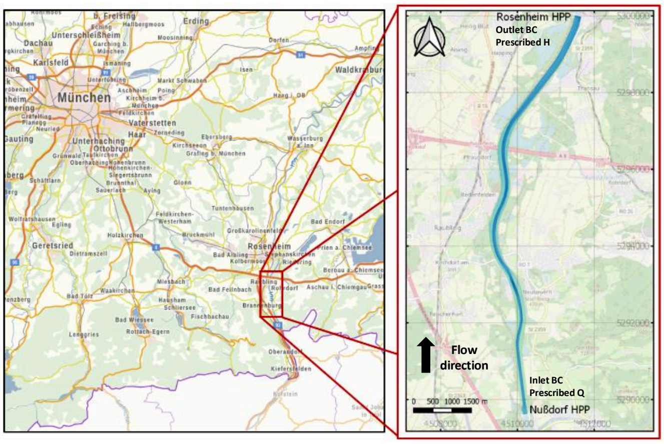

Figure 1. Location of the Rosenheim Reservoir (Adapted from [4,5])

the Chair of Hydraulic and Water Resources Engineering of the Technical University of Munich (TUM) [6–8]. The TELEMAC-2D module solves the depth-averaged free surface flow equations giving the user the possibility to select between different numerical schemes, solvers and physical parameters. On the other hand, the SISYPHE module solves the sediment balance equation to simulate the bed evolution and grain sorting. Depending on the application, the user can select between a range of sediment transport equations for bedload and suspended load. In addition, this module is capable of simulate non-uniform sediment transport, cohesive sediment and mixed sediment.

B. Model set-up

We built an unstructured triangulated mesh using the software BlueKenue [9] paying special attention to the use of break lines to obtain a precise implementation of the river shape while maintaining a constant element size through the domain. The resulting mesh for this 11.2 km long reach had 26,034 elements with average edge lengths of approximately twelve meters.

The bed elevation at the grid points within the flood plains were interpolated using topography surveys obtained by airborne laser scans with resolution of one square meter. The implementation of different bathymetries depending of the event of interest was possible due to the existence of bathymetry surveys measured as cross-sectional profiles each 200 meters in different years.

C. Hydrodynamic model

The model was configured to solve depth-averaged Saint-Venant Equations by using the fractional step method implemented in T2D, where the advection terms are solved using the method of the characteristics; and the propagation, diffusion and source terms by the finite element method [10]. Additionally, the k-ε turbulence model with the default value for turbulent quantities was selected. To guarantee stability of the simulations and accuracy in the results, we chose a time step of one second. As in previous models [1] the bottom roughness was defined by the Strickler coefficient.

The information for the boundary conditions was obtained from the water stages and flow discharge measurements made by the HPP operator at the upstream and downstream of the weirs of the dams every 15 minutes. For the inlet boundary condition, we used the above-mentioned measurements at the downstream of the Nußdorf HPP as the prescribed flow discharge. In the same manner, for the outlet, we used the stage hydrographs at the upstream of the Rosenheim HPP weirs as a prescribed elevation boundary condition (see fig. 1). The flow discharge and stages hydrographs used for the simulations are depicted in figs. 2 to 4.

To determine the feasibility of using certain flood events as hydrodynamic calibration and validation periods, the availability of water level recordings at gauging stations located within the domain was analyzed.

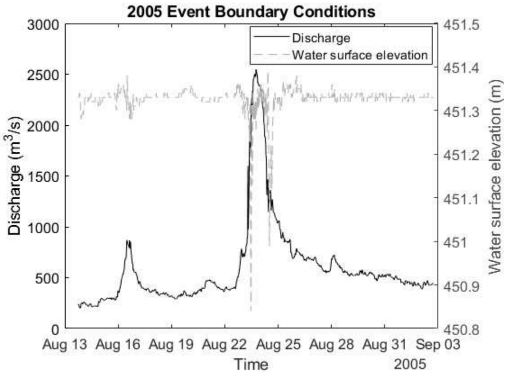

Figure 2. Boundary conditions for the 2005 event.

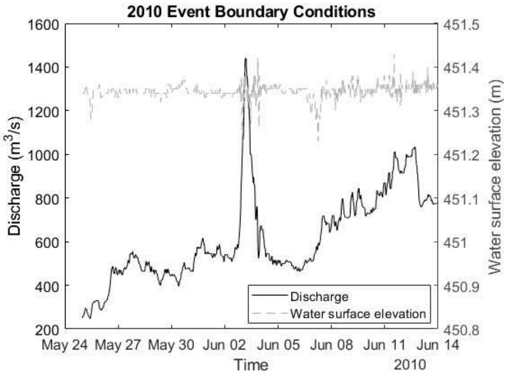

Figure 3. Boundary conditions for the 2010 event.

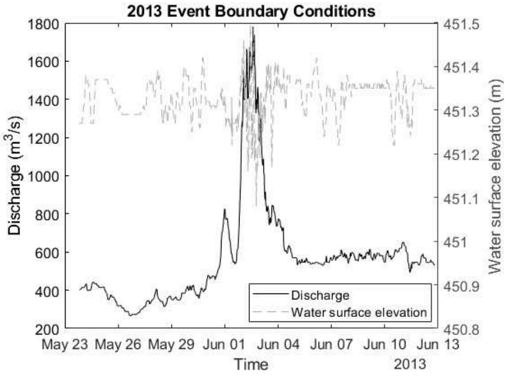

Figure 4. Boundary conditions for the 2013 event.

We concluded that the events of 2005 and 2013 would serve for the calibration period while the event of 2010 would to be used for validation. The reason behind this decision is that only the upstream gauge was operating during the 2005 flood event. Fig. 5 presents the river stations where these data were recorded.

The bathymetry used for the calibration events was measured in 2003, which is considered the equilibrium bed elevation. In contrast, for the validation process, the implemented bathymetry was surveyed in 2009 since no high magnitude events were registered before the one of 2010.

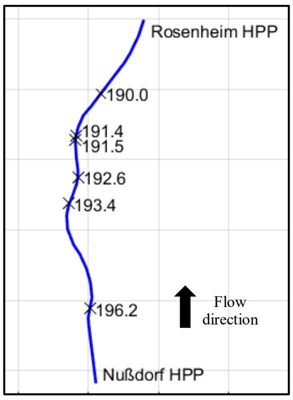

Figure 5. Location of the intermediate gauging stations used for the hydrodynamic calibration expressed as rkm.

D. Hydro-morphodynamic model

For the calibration and validation of the hydro-morphodynamic model, the boundary conditions for the fractional sediments were modified to allow a prescribed solid discharge at the inlet of the domain, as well as free open boundary for the sediments at the outlet. In order to generate the sediment discharge time series, concentration measurements taken in an upstream reservoir (rkm=211.0) were used to generate a sediment rating curve which is shown in fig. 6. Sieve analysis along the Inn River at the German side showed that there were two predominant sediment sizes: 0.16 and 0.40 mm in fractions of 0.4 and 0.6 respectively.

For calculating the sediment transport, formulas for total load were considered. The bed structure was discretized in two layers according to the modified subroutines for fractional sediment transport developed by the Chair of Hydraulic and Water Resources Engineering of the TUM [11], with a constant active layer thickness of 0.9 mm. Sediment slide, secondary currents, skin friction and slope effects were included in the sensitivity analysis. The elements outside of the riverbanks were set as non-erodible.

The availability of cross-sectional bathymetry surveys after the high magnitude flood events of 2005 and 2013 allowed choosing these as calibration and validation periods respectively. The summary of the calibration and validation periods used for the hydrodynamic clear water model and for the hydro-morphodynamic model is shown in table 1.

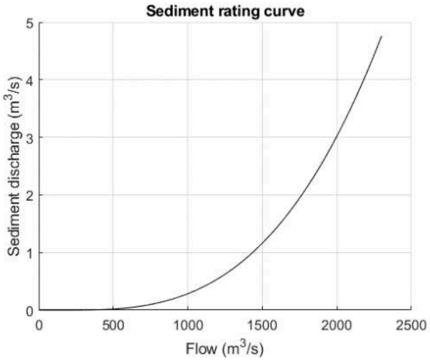

Figure 6. Sediment rating curve used for the inlet boundary condition.

TABLE 1: SUMMARY OF THE CALIBRATION AND VALIDATION PERIODS SELECTED FOR THE HYDRODYNAMIC AND HYDRO-MORPHODYNAMIC MODELS.

Period	**Hydrodynamics**		
	Event	***Bathymetry***	***Modules***
Calibration	2013 and 2005	2003	T2D
Validation	2010	2009	T2D
Period	**Hydro-morphodynamics**		
	Event	***Bathymetry***	***Modules***
Calibration	2005	2003	T2D+SIS
Validation	2013	2003	T2D+SIS

E. Model evaluation

The use of the goodness-of-fit parameters as recommended by [12] is well established in the calibration of hydrodynamic models and has been widely used for 1D parameters such as hydrographs or maximum water surface elevation along river profiles [6]. Therefore, the Nash-Sutcliffe Efficiency (NSE) was used for the assessment of the Hydrodynamic clear water model calibration. However, using a single parameter to determine the performance of a model to predict riverbed evolution processes might not be appropriate to perform a holistic evaluation. This makes the task of evaluating the results rather complicated. For this case study, we applied the Brier Skill Score (BSS) to evaluate the quality of the results as in the work of [13]. This method has been originally used in weather forecast models and uses a baseline prediction in order to quantify the skill of the new prediction of the model [14]. In hydromorphological models it is possible to use the initial river bed elevation as the baseline prediction [13]. Equation (1) shows the formula for the BSS, the set of observed values is X, the set of simulated values is represented by Y and the baseline predictions is B. Note that the angle brackets (⟨⟩) signify the mean value as indicated by (2) where n is the number of elements in X.

$$BSS=1-\langle(Y-X)^2\rangle/\langle(B-X)^2\rangle \tag{1}$$

$$\langle X\rangle=(X_1+X_2+\ldots X_n)/n \tag{2}$$

The use of the BSS allows the comparison of the skill of the model to simulate the sediment erosion and deposition processes along the whole domain depending on the availability of observed data. A perfect agreement between the simulation and observed values leads to a BSS equal to one, while any value of the BSS below zero stands for a simulation worse than the baseline prediction. Table 2 shows he recommended model performance classification ranges for the BSS by [13].

TABLE 2: RECOMMENDATION FOR MODEL PERFORMANCE CLASSIFICATION ACCORDING TO BSS (ADAPTED FROM [12])

Category	**BSS Value**
Excellent	1.0 – 0.5
Good	0.5 – 0.2
Reasonable/fair	0.2 – 0.1
Poor	0.1 – 0.0
Bad	< 0.0

The BSS can also be represented as a function of four parameters as shown in equation (3). Three of these parameters, namely α, β and γ, give further information of the skill of the model while measuring the phase error, amplitude error and map mean error respectively. The fourth parameter (ε) is a normalization term [13]. Table 3 contains the ranges and the perfect agreement value of these parameters. Equations (4) to (7) show the formulas for calculated the parameters of the decomposition of the BSS. Note that these equations contain Y´ and X´, which are the difference between the observations or simulations and the baseline prediction, see (8) and (9).

$$BSS = (\alpha - \beta - \gamma + \varepsilon)/(1+\varepsilon) \tag{3}$$

$$\alpha = r^2_{Y'X'} = ((Y' - \langle Y' \rangle)\ (X' - \langle X' \rangle)/\sigma_{Y'}\ \sigma_{X'})^2 \tag{4}$$

$$\beta = (r_{Y'X'} - \sigma_{Y'}/\sigma_{X'})^2 \tag{5}$$

$$\gamma = ((\langle Y' \rangle - \langle X' \rangle)/\ \sigma_{X'})^2 \tag{6}$$

$$\varepsilon = (\langle X' \rangle/\sigma_{X'})^2 \tag{7}$$

$$X' = X - B \tag{8}$$

$$Y' = Y - B \tag{9}$$

We applied this methodology for the calibration and validation of the hydro-morphodynamic model comparing: (i) the mean bottom elevation profile to evaluate the skill of the model for simulating the erosion and deposition processes along the domain, and (ii) the cross-sectional profiles to measure the capabilities of this model to represent the morphological processes in the direction parallel to the main flow.

IV. RESULTS AND DISCUSSION

A. Hydrodynamic Calibration

The calibration process in TELEMAC-2D was carried out by modifying the Strickler coefficient, i.e. the bed roughness. We aimed to maintain physical values for this coefficient considering that lower velocities develop at the downstream of the reservoir, near the weirs of Rosenheim HPP, resulting in deposition of finer particles at the upstream. Fig. 9 shows the discretization of the calibrated Strickler coefficient along the domain.

As previously concluded by [1] it was not possible to find a set of roughness coefficients that could fulfill the water stages elevations for base flow and high flow conditions, this behavior can be observed in figs. 7 and 8. Therefore, we perform a calibration for base flow expecting that the hydromorphological model could simulate the highly dynamic riverbed evolution. Reaching NSE values falling within the categories of “satisfactory” and “very good” (according to [12]) for calibration and validation periods during base flow conditions, we considered that the clear water model was able to adequately simulate flow velocities and water depths along the domain.

TABLE 3: DEFINITION OF THE DECOMPOSITION PARAMETERS OF THE BSS (ADAPTED FROM [12])

Parameter	Measure	Range	Perfect agreement
α	Phase error	[0, 1]	1
β	Amplitude error	[0, +∞)	0
γ	Map mean error	[0, +∞)	0

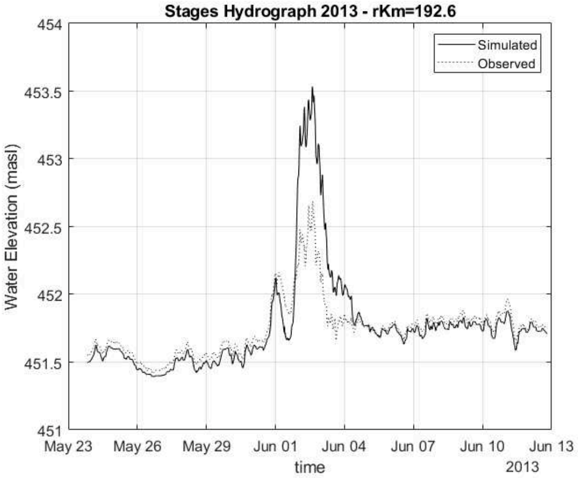

Figure 7. Stages hydrograph example for the calibration period reaching NSE=0.78 for base flow conditions

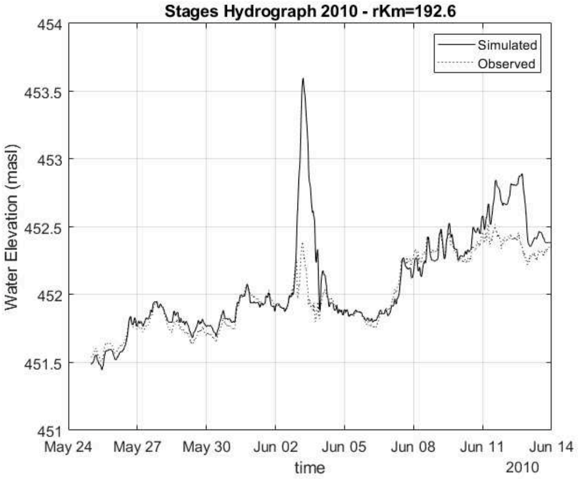

Figure 8. Stages hydrograph example for the validation period reaching NSE=0.90 for base flow conditions

B. Hydro-morphodynamic Calibration

After performing a sensitivity analysis with different sediment transport formulations it was considered that the Engelund-Hansen equation [15] for total load was adequate to represent the hydromorphological processes in the study area. Other total sediment transport formulations as the modified Engelund-Hansen Equation by [16] and the equation of Wu [17] were implemented leading to unsatisfactory results. For the calibration process, the skin friction correction factor (μ) was implemented as a variable to be read from the Selafin file. In this manner, the value could be modified locally to alter the effective shear stress (τ'_0) and therefore the transport capacity of the domain as shown in (10).

$$\tau'_0 = \mu\tau_0 \tag{10}$$

During the calibration process, we intended to discretize the different values of the skin friction correction factor in the same segments as for the Strickler coefficients since in the boundary friction is associated to the skin friction [18]. However, the some of these zones were further discretized in order to improve the results of the model. The discretization for this calibration factor is presented in fig. 9.

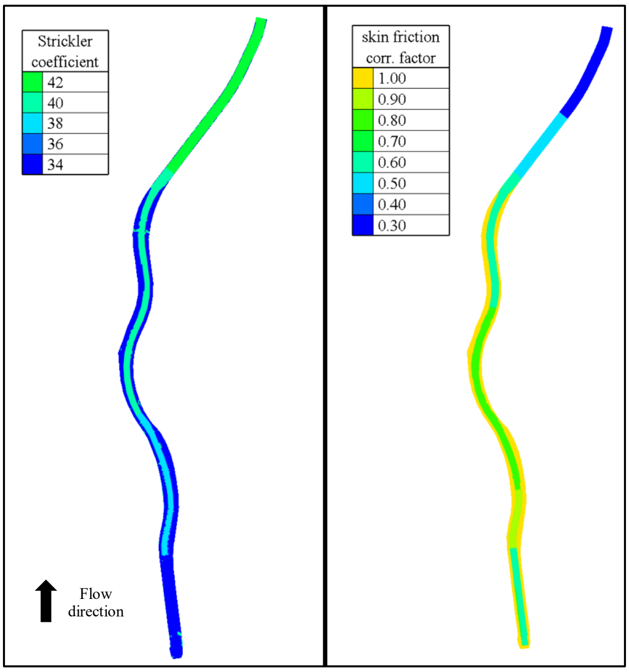

Figure 9. Calibrated Strickler coefficient (left), Calibrated skin friction factor (right).

Fig. 10 and fig. 11 are presented to assess the quality of the simulation along the domain by comparing the observed and the simulated mean bottom elevation profile (MBE) at the end of the event for the calibration and validation periods, this value was kept within a range of one meter for the majority of the surveyed cross-sections. For each figure, the gray indicates line the MBE of the river before the event (i.e.: from the bathymetry of 2003 used as baseline prediction), while the red and the blue lines represent the observed and simulated MBE respectively. Furthermore, the absolute difference between the simulated and observed MBE is shown in figs. 10 and 11. Additionally, table 4 presents the BSS and the skill parameters for both the simulated periods.

An overall good performance of the developed numerical model is supported by the BSS values falling within the categories of "excellent" and "good" for calibration and validation respectively. However, the simulation of the event of 2005 led to lower phase, amplitude and map mean error results. By contrasting the α, β parameters for the calibration period with the graphical results showed in fig. 10, the model shows that it is capable of predicting erosion and deposition process at the correct location and by accurate volumes along the domain. This also leads to a low map mean error represented by a γ of 0.03.

The simulation of the event of 2013 showed a low model skill to estimate the right amount of sediment eroded and deposited along the domain even when these processes occurred in the correct locations except from some segments between rkm= 195.6 and 194.0. This behavior is reflected in a relatively high value of the phase error (β). It is possible that 2003 bathymetry do not represent the real conditions of the morphology of the river before 2013 event.

TABLE 4: BSS FOR CALIBRATION AND VALIDATION OF THE HYDRO-MORPHODYNAMICS MODEL.

Event	*BSS*	*α*	*β*	*γ*
2005 (calibration)	0.59	0.51	0.02	0.03
2013 (validation)	0.38	0.43	0.32	0.10

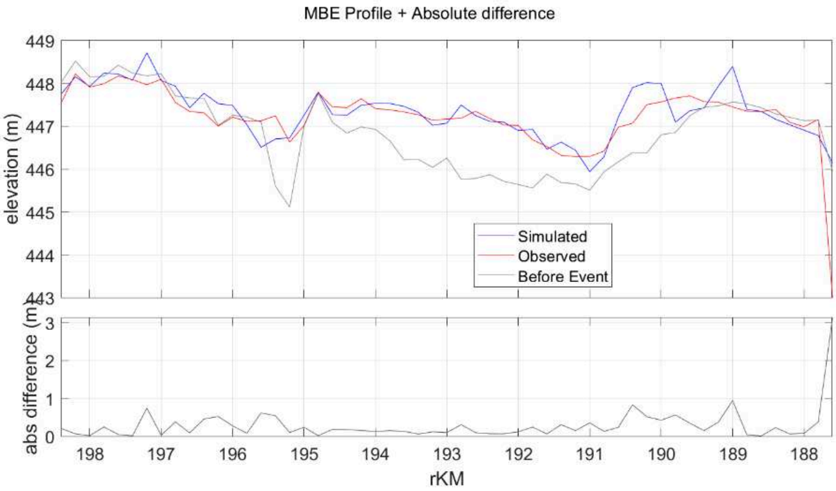

Figure 10. Comparison between observed and simulated MBE for the calibration period (top), Absolute difference (bottom).

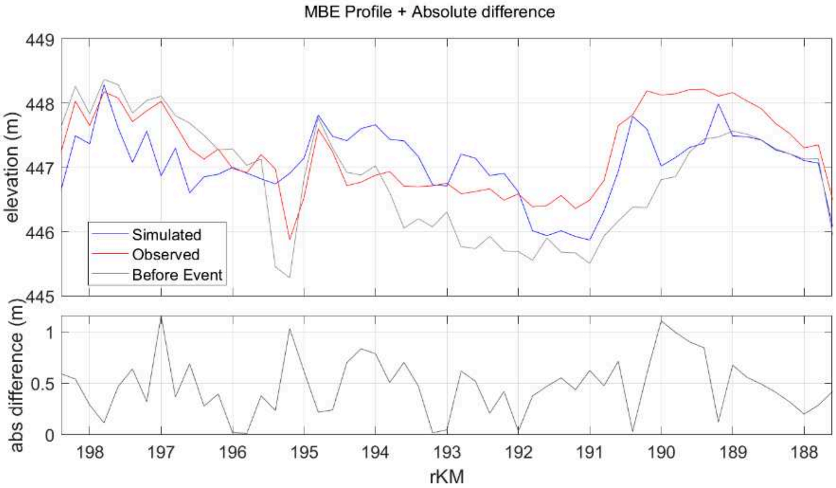

Figure 11. Comparison between observed and simulated MBE for the validation period (top), Absolute difference (bottom).

Along with the analysis of the MBE profiles, each cross-section was examined to evaluate the model capability to simulate sediment transport processes in the direction perpendicular to the main flow. Fig. 12 depicts some preliminary results at a cross section located at a river bend (rkm=192.6) for the simulation of the 2005 event. This result was not consistent with the observation, nor with the expected scour at the outer bank of the bend. This could be due to the hypothesis of the shallow water equations, which produce depth-averaged velocities that do not account for the decrease of the magnitude at the bottom caused by the slope effect and secondary currents.

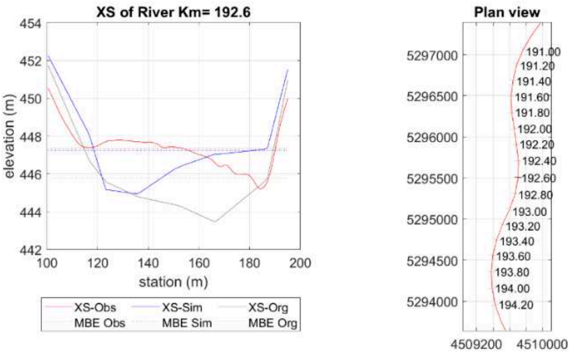

Figure 12. Results of a cross-sectional profile without considering the slope and secondary current effects.

To address the misrepresentation of the riverbed at the bends, we activated the consideration of the slope effect in the SISYPHE steering file using the Koch and Flokstra equation [19] and included the secondary currents effects to correct the intensity of the bed load transport rate. Additionally, we set a non-physical sediment friction angle of 3° to improve the results by limiting the element slope within the cross section. Therefore, since the banks were set non-erodible, the subroutine *maxslope.f* did not affect the shape of the channel. Fig. 13 shows the improvement of the cross-sectional profile simulation at the same cross-section (rkm=192.6) applying the corrections previously discussed.

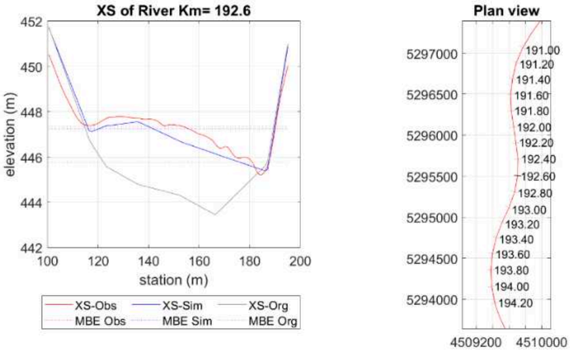

Figure 13. Results of a cross-sectional profile considering the slope and secondary current effects.

As in the MBE profile analysis, we applied the BSS skill criteria to all the 55 cross-section profiles of the reservoir. As expected, for the calibration period, the majority of the cross-sectional profiles were in the range of “reasonable” to “excellent” with a third of the total number of cross-sections in the highest category (18 out of 55). The river stations that resulted in high skill values were mostly found within the segment rkm=194.4 to 190.6, showing consistency with the plots presented in fig. 10. On the other hand, the majority of the cross-sectional profiles obtained from the simulation of the event of 2013 were considered worse than the baseline prediction. This is mainly due to the large amplitude error in most of the cross sections as it can be noted in fig. 14. Even if the erosion and deposition processes at the banks developed as expected along the cross-section, the model produced an overestimation of the total sediment accumulated in this section of the reservoir in the main direction of the flow. Table 5 summarizes the results of the skill of the model in the direction parallel to the main flow by indicating the quantity of cross-sections falling in each of the categories proposed by [13].

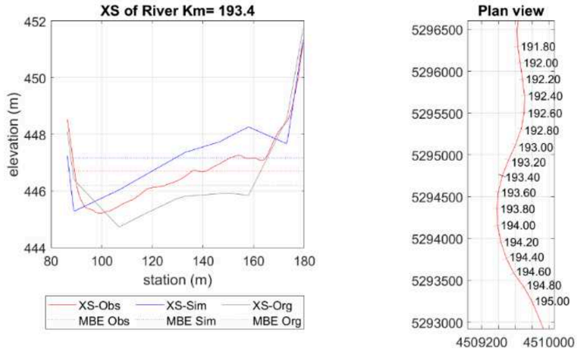

Figure 14. Poorly simulated cross-section profile due to excessive sedimentation.

TABLE 5 SUMMARY OF THE PERFORMANCE EVALUATION ALONG THE CROSS-SECTION PROFILES

Event	**Number of cross-section profiles falling under:**				
	Excellent	***Good***	***Reasonable/ fair***	***Poor***	***Bad***
2005	18	9	3	1	24
2013	12	7	2	3	31

C. River stages prediction by the hydro-morphodynamic model

At the stage of the developed model, the simulation of water levels at high flows was not improved. The overestimation attributed to highly dynamic particles at the bed was not confirmed by this case study. However, at some locations, the stage hydrograph for base flow conditions after the event presented better performance than the clear water model. This can be observed at the last third of the stage hydrograph depicted in fig. 15, where it is evident that the dashed red line maintains a constant offset with the observed values while the continuous black line, that shows the results of the hydro-morphodynamic model, fits almost perfectly to the observations. The river morphology after the simulation is closer to the observed one than the initial bathymetry (i.e.: 2003 survey) as demonstrated by the model performance evaluation based on the BSS parameters.

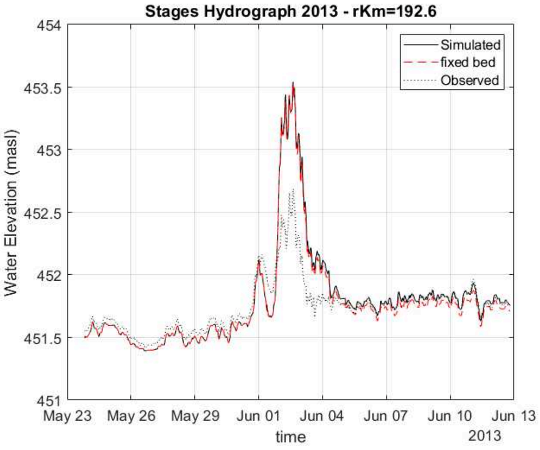

Figure 15. Poorly simulated cross-section profile due to excessive sedimentation.

V. CONCLUSIONS

In this study, a hydro-morphodynamic numerical model using the TELEMAC-MASCARET system was developed and calibrated based on the information recorded during large magnitude flood events that occurred within the last 20 years. In general, the model provided a high performance for simulating hydromorphological processes within the domain by: (i) applying the total load sediment transport formula of Engelund-Hansen, (ii) implementing the improved fractional sediment transport subroutines by [11], and (iii) using a low friction angle of sediment for sediment transport in the main flow direction. Results from this model can be used for further studies to generate adequate sediment management strategies to improve the river ecological conditions.

A comprehensive analysis of the sediment balance of the upstream reservoir (Nußdorf Reservoir), where a turbidity gauging station is located, could lead to a definition of a better inlet boundary condition for this domain. Additionally, by replacing the total load sediment transport equation by an approach that considers bed and suspended load separately might reproduce the sediment transport processes more accurate. Finally, the improved model will be applied to study floods in this alpine catchment and give guidance for river management strategies.

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