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# Numerical Modelling of Sediment Transport at Weirs

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***Abstract*—A weir is a barrier across the width of a river or stream, which is commonly used to measure or regulate flow and water elevation. Constructing a weir can alter the characteristics of the flow and sediment transport in the river reach. In order to capture complex local patterns of the flow and sediment transport near structures, three-dimensional (3D) modelling is needed. However, two-dimensional (2D) morphological simulations are frequently carried out to investigate the long-term effect of such structures on morphological alterations at larger scales due to their lower computational effort. It is thereby important that the physical processes around such hydraulic structures need to be simulated with a reasonably accurate model in these situations. At present, the clear water module TELEMAC-2D of the model system TELEMAC-MASCARET has only offered the possibility to simulate water flow at unregulated weirs in a computationally efficient manner. The present paper shows, how the sediment transport module SISYPHE of the system is adapted and extended in order to integrate weirs in hydromorphological simulations with minimal modelling effort. Analogous to the implementation in TELEMAC-2D, the boundary condition at the weir nodes is defined internally in the main program sisyphe.f as liquid boundary in a way that bedload flux can be considered. Subsequently, the bedload flux coming from the upstream side of the weir is transferred to the downstream one by modifying the subroutine conlit.f according to the proportion of each grain fraction. Conducting simulations in a study case verifies the correctness of the new implementation, where the sediment fluxes are compared as well as the total volumes of the present sediment evaluated.**

## I. INTRODUCTION

Watercourses worldwide have been shaped by numerous hydraulic engineering interventions over the last decades or even centuries. However, river regulations and the construction of transverse structures for riverbed stabilization have fundamentally changed the transport of sediment in terms of quantity and quality. For better understanding the patterns of large-scale hydromorphological processes in large model areas with transverse structures, the use of numerical simulations is necessary [1]. As flow and sediment transport at or close to hydraulic structures in rivers have complex three-dimensional (3D) features, 3D numerical models provide in general more accurate results than two-dimensional (2D) approaches [2]. However, since these hydromorphological processes are very complex to model and 3D-models are computationally expensive, an easy-to-implement 2D approach for sediment transport at weirs should be developed.

The open source TELEMAC-MASCARET modeling environment only offers the possibility to simulate water flow over unregulated weirs in the clear water module TELEMAC-2D. Hereby, the weir is not constructed directly in the grid mesh. Thus, the water fluxes are calculated using empirical equations instead of using the depth-averaged SWEs [3]. Therefore, the water flow in large scale modeling areas with several weirs can be simulated accurately with little modeling and calculation effort. The present paper shows, how the sediment transport module SISYPHE is adapted and extended in order to integrate the bedload transport at weirs in hydromorphological simulations. This approach ensures minimal modelling effort of bedload transport for large consecutive domains, delimited by weirs.

The main idea for modifying the sediment transport module SISYPHE is somehow in an analogous manner to the implementation of flow calculation at weirs in the clear water module TELEMAC-2D. The boundary conditions of sediment transport at the nodes of the weir, upstream and downstream, are adjusted internally in the main program sisyphe.f as liquid boundaries, so that a bedload flux can take place there. Subsequently, the bedload flux coming from the upstream side of the weir is transferred 1:1 to the downstream one according to the proportion of each grain fraction by modifying the subroutine conlit.f. The correctness of the new implementation is verified by simulations in a study case, where the bottom elevation at different time steps is compared as well as the total volumes of the present sediment evaluated.

## II. WEIR TREATMENT IN TELEMAC-2D

The water flow over weirs is calculated in the clear water module TELEMAC-2D using the subroutines clsing.f and clhuvt.f. The process is described below.

The discharge Q is calculated using the Poleni formula in the subroutine clsing.f. Then the flow velocity perpendicular to the weir UNORM on both sides of the weir is determined based on the discharge and the flow depth known at each node. This flow velocity is transferred to the subroutine clhuvt.f. Here the tangential flow velocity at each node of the weir is calculated. Using the orthogonal and tangential flow velocity, the components of the flow velocity in x- and y-direction at the boundaries UBOR and VBOR are then calculated for both sides of the weir. These values act as transfer parameters at the new boundaries.

The boundary conditions for flow depth LIHBOR and flow velocities LIUBOR and LIVBOR at the weir are defined in the Subroutine clhuvt.f in such a way that water flow over these boundaries is possible. Per default, the boundary conditions at the border of the domain and thus at the weirs are defined as solid wall (boundary code = 2). At the weir nodes, the subroutine adjusts the boundary condition of the flow depth as a free boundary condition (KSORT = 4), while the flow velocity is assigned a boundary condition with prescribed value (KENTU = 6). Thus, the water level on the upstream and downstream side of the weir is variable. The components of the flow velocity in x- and y-direction are assigned the fixed values UBOR and VBOR, which are calculated in the previous. The orthogonal flow velocity UNORM present at the weir serves as a decision criterion for the implementation of permeable boundary conditions at the weir. Only when the flow velocity perpendicular to the weir is greater than zero, the boundary conditions at the weir are defined as permeable and a flow over the weir takes place.

Since the boundary conditions at the weir are not registered as liquid boundaries, the flux over these boundaries is not included in the mass balance. Therefore, it must be ensured that the mass flux added to the model area downstream of the weir corresponds to the absolute value of the mass flux leaving the upstream model area. The calculation and correction of the fluxes across the boundaries of the weir are handled in the subroutine propag.f. In order to ensure continuity, the fluxes over the boundaries of weir are balanced in such a way that their amounts are equal. Water masses are not generated artificially at the weir.

## III. NEW IMPLEMENTATION IN SISYPHE

In this work, the modified morphological version of SISYPHE developed by Reisenbüchler et al. (2016, TUC) [4] is used. The implementation of sediment transport over weirs is carried out in an analogous manner to the treatment of the clear water flow in TELEMAC-2D. For this purpose, both an appropriate place of embedding the code as well as a suitable transfer variable have to be identified. In SISYPHE, sediment is separated in two components, namely bedload and suspended load. It should be noted that only bedload transport over weirs is considered in this paper, which is explained in the following.

### *C. Boundary Conditions*

The boundary conditions of the sediment transport rate LIQBOR and the bed evolution LIEBOR at weirs are defined in the main program sisyphe.f before calling the subroutine front2.f. The subroutine front2.f is used to identify and number liquid and solid boundaries of a model area. Consequently, the boundary conditions at the weir are also registered as liquid boundaries. Thus, a bedload flux can take place across these boundaries, which is automatically included in the mass balance. If the boundary conditions were defined in another subroutine after calling the subroutine front2.f, no bedload flux can take place across the boundaries and the bedload would therefore not be able to leave the upstream model area.

If the model area contains a weir, which is defined in the steering file, the boundary conditions for the sediment transport rate LIQBOR and the bed evolution LIEBOR are redefined at each node of the weir. At the nodes on the upstream side of the weir, free boundary conditions are assumed for both the sediment transport rate and the bed evolution. This allows the bedload to leave the area upstream of the weir freely. However, at the nodes on the downstream side of the weir, the bedload transport rate LIQBOR is defined as a Dirichlet boundary condition, while the bed evolution LIEBOR is assigned by a free boundary condition. This ensures that an imposed value of bedload is added to the downstream side of the weir. The exact allocation can be found in table I.

TABLE I. ALLOCATION OF BOUNDARY CONDITIONS ACCORDING TO THE WEIR SIDE

| | **Upstream Boundary** | **Downstream Boundary** |
|---|---|---|
| **LIQBOR** | 4 = KSORT | 5 = KENT |
| **LIEBOR** | 4 = KSORT | 4 = KSORT |

### *D. Bedload Transport*

As the implementation of the clear water flow over a weir in TELEMAC-2D shows, either a mass flow over a boundary must be transferred or the continuity must be ensured later. In SISYPHE, the sediment balance is ensured by solving Exner's equation for sediment transport.

Considering only bedload transport, the subroutine bedload_solvs_fe.f is applied to calculate the bed elevation change due to gradients of the mass fluxes of the fractional bedload flux FLBCLA. As can be seen in the subroutine, these fluxes are defined based on the bedload discharges at boundaries QBOR as well as flow directions there. At Dirichlet boundary conditions, which are usually used for inlet boundaries, the fractional bedload flux FLBCLA is calculated as a negative value of QBOR for each grain class and at each time step. Since the boundary conditions at the weir are registered as liquid boundaries, the bedload flux FLBCLA is calculated for each grain class and at each time step at the outlet boundary condition upstream of the weir. As the bedload fluxes at the upstream side of the weir are fully transferred to the imposed solid transport rate QBOR at the downstream side of the weir, the sediment conservation is ensured without any additional extension of the code.

First, the subroutine conlit.f is modified for implementing bedload transport over a weir. Assuming that the upstream side of the weir contains NPSING nodes, we define the fractional bedload flux $Q_{CLOUT}$(K) through this cross section as follows:

$$Q_{CLOUT}(K) = \sum_{IA=1}^{NPSING} FLBCLA(K, IA) \tag{1}$$

Where FLBCLA(K,IA) is the fractional bedload flux for grain class K through node IA.

The total bedload flux $Q_{OUT}$ through the upstream side of the weir is then calculated by summing up the fractional bedload fluxes $Q_{CLOUT}$(K) of all grain classes (NSICLA):

$$Q_{OUT} = \sum_{K=1}^{NSICLA} Q_{CLOUT}(K) \tag{2}$$

To determine the fractional bedload fluxes through the downstream side of the weir, we define the ratio of the fractional bedload flux $Q_{CLOUT}(K)$ to the total bedload flux $Q_{OUT}$ at the upstream side of each weir:

$$RATIO(K) = \begin{cases} 0, & if\ Q_{OUT} = 0 \\ \frac{Q_{CLOUT}(K)}{Q_{OUT}}, & otherwise \end{cases} \quad (3)$$

Assuming that this ratio is constant along the weir, the continuity of sediment transport over the weir can be ensured.

In the subroutine conlit.f the function QGL(IFRLIQ,AT) is applied to prescribe the sediment discharges for imposed liquid boundaries, where bedload rate SOLDIS(IFRLIQ) is defined externally. In the subroutine disimp.f the total bedload rate is then distributed to the nodes at the downstream boundary of the weir. The bedload rate for each node is passed to the subroutine conlit.f, where the variable QBOR is determined considering the values of RATIO and sediment discharge.

This concept of modelling bedload transport can be applied for a number of weirs constructed along a river reach.

## IV. RESULTS

The functionality of the implementation of bedload transport at weirs is verified by a hydromorphological simulation for a simple test case. The simulation area comprises a 304 m long and 30 m wide trapezoidal flume, in which two weirs are constructed (see figure 1). The first weir is located 100 m downstream of the model inlet, which indicates the left side of figure 1. The height of the channel bed at the inlet of the model area is 10.0 m while the height of the channel bed in front of the first weir is 9.9 m. The weir crest is at 13.0 m and the channel bed immediately after the first weir is at 8.9 m. The second weir is located 97 m downstream of the first weir. The channel bed in front of the second weir is at a height of 8.8 m, the weir crest at 12.0 m and the channel bed immediately after the second weir at 0.0 m. The bottom slope of both the first canal section and the canal section between the two weirs is therefore 0.1 %, while there is no inclination of the third channel section between the second weir and the outlet. The numerical mesh consists of 2381 nodes and 4510 elements with an average edge length of 2 m. This setup allows a fast simulation in approximately 1 h and 26 min on a normal work station using one processor given a time step of 1 s and a total simulation period of 9 days.

For the hydrodynamic simulation, a stationary discharge at the inlet of 50 m³/s and a constant water elevation at the outlet of 10 m are chosen. The first weir has its crest at 13 m and the second at 12 m. The runoff-coefficient for both weirs amounts to 0.7. Initially the riverbed is defined completely as non-erodible, without any movable sediments. The morphological boundary condition at the inlet is defined as a constant sediment rate of 0.006 m³/s (without porosity). There is no sediment transport at the outlet. This ensures, that the material does not leave the model area. Thus, the bedload present in the area at the end of the simulation corresponds to the bedload added over the simulation period, which is important for the code validation. The simulation is conducted using two mobile grain fractions and a third non-movable grain class. Due to the use of several grain classes, the functionality of the code is also shown for the transport of multiple grain classes. Table II shows the sediment diameters and the fraction for the particular size classes.

TABLE II. INITIAL SEDIMENT COMPOSITION

| **Size class i** | **1** | **2** | **3** |
|---|---|---|---|
| **Diameter $d_{m,I}$ [m]** | 0.001 | 0.002 | 0.003 |
| **Fraction [-]** | 0.40 | 0.60 | 0.00 |

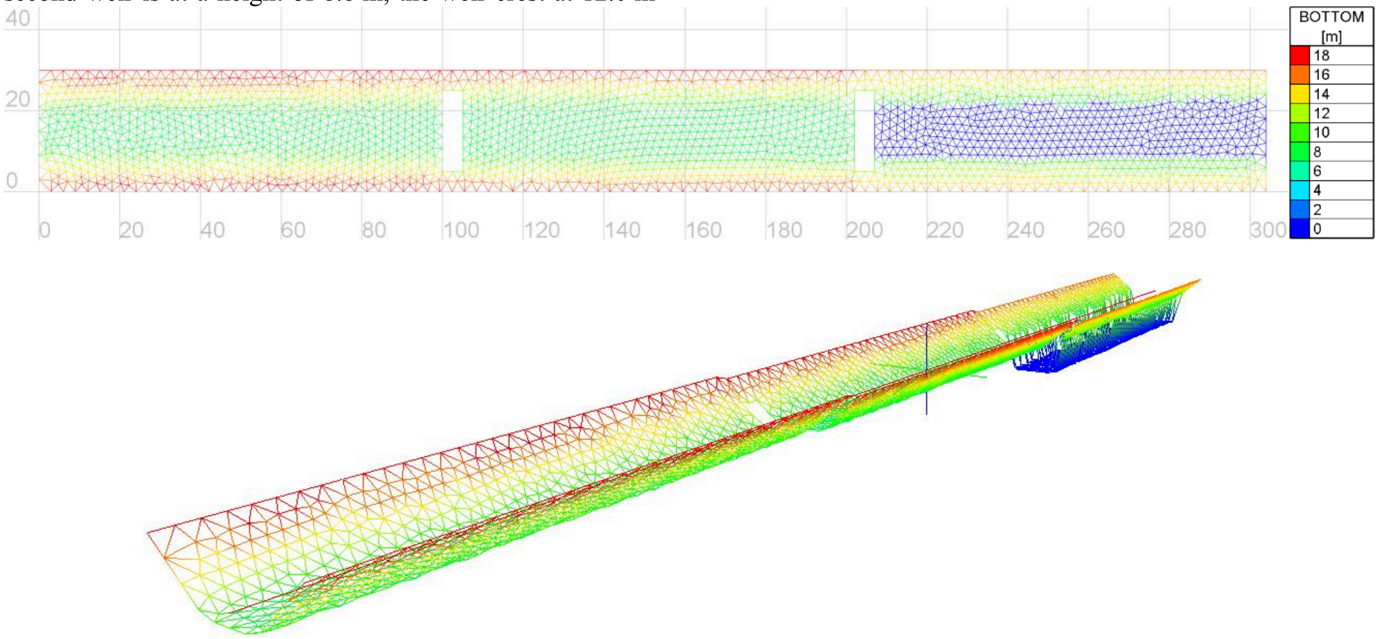

Figure 1. Plan view and 3D view of the test model area

The simulation results are analyzed regarding the development of the bottom elevation along a longitudinal section at the center of the channel, the bedload rate over a cross-section, which is located 150 m downstream of the inlet of the model area between the first and second weir, and the bedload volume present in the model area.

Figures 2a-2c show the development of the bottom elevation along a longitudinal section at the center of the channel per channel section every 24 hours of simulation time. With the help of this illustration, the development of the channel bed over the entire simulation period is clearly visible. Thus, the sediment transport and the development of the river bed can be traced. The sediment is transported over the two weirs and deposited in the third channel section between the second weir and the outlet with progressing simulation time (see figure 2c). In this settling zone, the expected deposition takes place due to the large water depth (up to 10 m) and due to the missing outlet boundary for sediment discharge. In the respective areas in front of the two weirs, stationary conditions of the channel bed are established (see figure 2a and 2b). An equilibrium of sedimentation and erosion is created here. This state is reached before the first weir after two days of simulation time and in the section between the weirs after approximately three days of simulation time.

In addition, the average bedload rate that passes a cross section in midway between the two weirs is evaluated over the simulated time. The course presented in figure 3 is maintained by a moving average analysis of the original result data. The bedload rate significantly increases after about one day of simulated time. After about 2.5 days of simulated time, the bedload rate behaves almost stationary. The development of the bedload rate corresponds to the development of the river bed in this area. As already mentioned, after a simulation period of about three days an equilibrium state of the river bed is reached in this section. The constant bedload rate at this cross section also corresponds to the constant sediment discharge at the inflow boundary of the channel.

Finally, the accumulated sediment volume in the model area at the end of the simulation is calculated and compared with the sediment rate added over the simulated time (see figure 4). At the model inlet, a constant sediment rate of 0.006 m³/s is added over a simulation time of 9 days (777,600 s). Including the porosity of 0.4, a sediment volume of 7,776 m³ must therefore be present in the model area at the end of the simulation, since no outlet boundary exist for the sediment transport at the channel outlet. The graph of the accumulated volume in the model area shows the expected linear increase and the total accumulated volume at the end of the simulation. This amounts to 7,776 m³ as expected. An additional analysis of the grain composition of the total sediment volume shows the same grain composition as the grain fraction of the added bedload shown in table 2. Here, the volume of the first grain class makes up 40 % and the second grain class 60 % of the total volume. This evaluation shows that sediment volume is neither destroyed nor artificially generated when transported over the weirs. The mass balance is thus maintained.

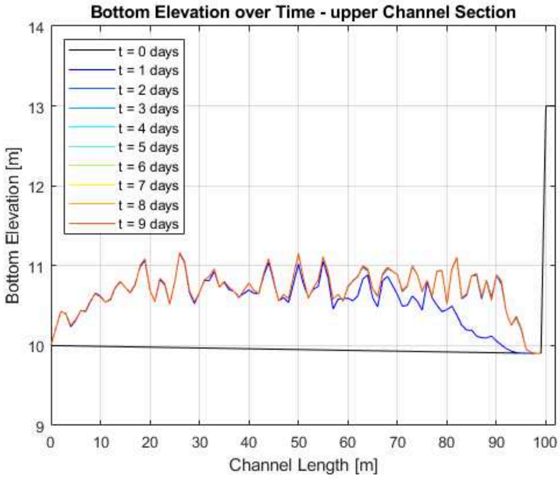

Figure 2a. Development of bottom elevation over time in the first channel section

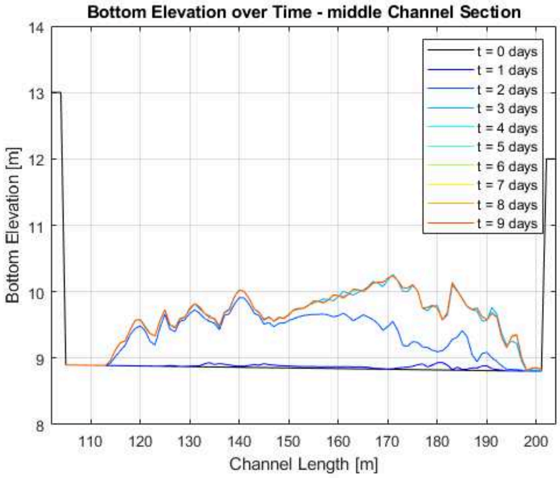

Figure 2b. Development of bottom elevation over time in the second channel section

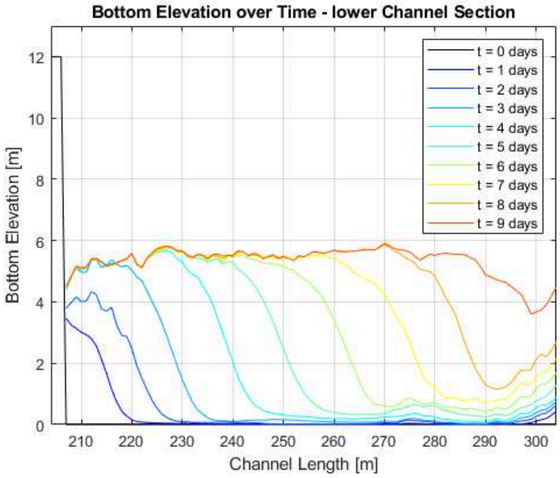

Figure 2c. Development of bottom elevation over time in the third channel section

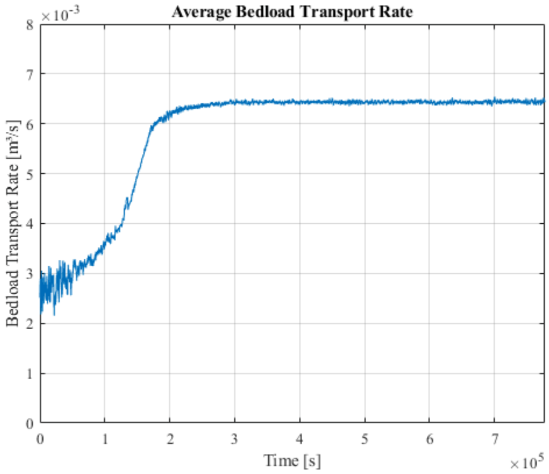

Figure 3. Average bedload transport rate over a cross section 150 m downstream of the inlet between the first and second weir over time

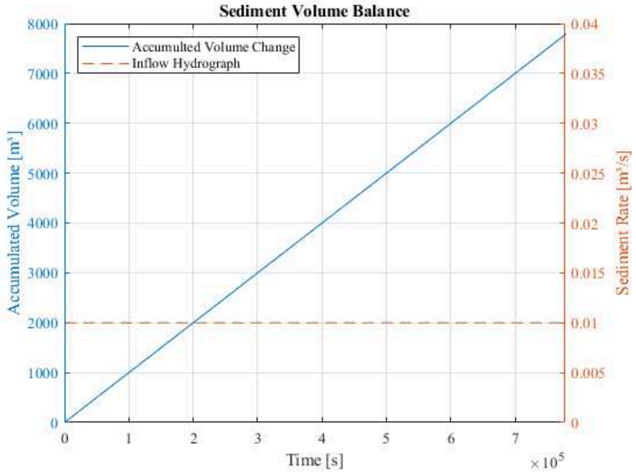

Figure 4. Comparison of the accumulated sediment volume over time and the sediment inflow hydrograph

Since the code of the bedload transfer from upstream to downstream of the weir is structured in such a way that the added bedload flux downstream is always offset by one computational time step from the bedload flux at the upstream boundary, a certain amount of bedload flux is buffered for one time step. However, this intermediate storage does not affect the correctness of the calculation results. In fact, the temporarily stored bedload quantity is only lost in the last simulation time step. For the preceding steps, the bed load quantity downstream of the weir only lags behind the bed load flow upstream by one time step, which does not lead to a distortion of the mass balance. It should also be noted that numerical models always picture only a simplified representation of reality and in no case a 100 % realistic representation of nature is possible. Within the overall accuracy of numerical models, we assume that this lag is acceptable.

## V. CONCLUSION

Until now, no numerical method has been available in the TELEMAC-MASCARET modelling environment to simulate sediment transport at weirs in a time and modelling efficient way. The new developed code offers an easy to implement, realistic and computationally efficient way to calculate sediment transport in large scale, numerical model areas. The code was verified by a simple test area, where the results regarding the deposition of bedload over time and the sediment balance were very satisfactory and met the expectations. The code can, therefore, be applied to real model areas. It will allow the combination of previously disconnected river reaches and models into one consecutive model [5]. This extension of the sediment transport module SISYPHE represents an important tool for the investigation of large-scale hydromorphological transport processes both over long runoff periods and during flood events.

The implementation of sediment transport at weirs refers to the coupling of TELEMAC-2D with SISYPHE. For the application of the above presented method for 3D simulations of the existing code has to be further modified, since a different handling of structures in the flow model is necessary.

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