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Simulation of embayment lab experiments with TELEMAC-2D/GAIA

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***Abstract*— For the inland river projects at BAW, sediment transport was usually considered as bedload only. This simplification was acceptable as long as the interest of investigations focusses to the main channel. However, lateral exchange between main channel, groyne fields, and floodplains is of increasing interest.**

Within a new BAW internal R&D project the capability of TELEMAC-2D / GAIA to simulate the lateral sediment exchange was examined by re-modelling the laboratory experiment conducted by [1]. In this experiment the distribution of suspended sediment and its deposits in different configurations of lateral embayment for three constant discharges were investigated. The embayment deposits and the concentrations at two significant locations were measured and were used to validate the numerical model. The numerical model could be calibrated reasonably to one embayment configuration and the lowest discharge. However, the calibration could not be transferred to the higher discharges or other embayment configurations. Furthermore, three differences between the numerical and the laboratory model made the comparisons difficult: the procedure of sediment recirculation, the loss of material in the pores of the laboratory model and the embayment pumping effect.

Further investigations are required to improve the hydrodynamics in an embayment using a 2D depth averaged numerical model. To account for the mainly 3D nature of the sediment transport in the embayment requires advances in 2D turbulence models and a numerical scheme that allows pumping effects. In any case it would be helpful to find or conduct an experiment with suspension and lateral sediment exchange that avoids the pumping effect and material losses in pores and provides measurements needed for validation of numerical models.

I. INTRODUCTION

For the inland river projects at BAW, sediment transport is usually considered as bedload only. The limitation due to this simplification is small as long as the interest of investigations focusses to the main channel. There, the main part of the suspended sediment is not involved in the river bed building process and is called “wash load”. However, the requirements of the European Water Framework Directive cause investigations at the floodplains and of the interaction between floodplain and main channel. Therefore, the focus of investigation is changing and suspended sediment transport becomes more and more important. At the floodplains, the deposition is dominated by suspended load. In the numerical model the simulation of the bed load is based on empirical formulations, but a lot of data are available in the main channel for calibration. Contrary to that, the suspended load is based on the advection-diffusion equation but data at the floodplains are rare. The simulation of the sediment processes at the floodplains and the interaction between main channel and groyne fields and floodplains are an interesting and challenging topic.

The aim of a new BAW internal R&D project is to demonstrate the numerical modelling capability of the lateral sediment exchange of non-cohesive material between floodplain or groyne field and main channel on German federal inland waterways and to improve long-term morphodynamic numerical modelling by considering suspension. For long-term morphodynamic modelling TELEMAC-2D/SISYPHE resp. TELEMAC-2D/GAIA is applied in BAW. The computer capacity and model efficiency are still not good enough to use three-dimensional models with the wanted space and time resolution.

From literature a laboratory experiment with lateral suspended sediment exchange was chosen for comparison with the depth-averaged numerical modelling. Reasons for the choice were the simple geometry, the presence of concentration and deposition measurements and the excellent description of the laboratory experiment. But even an intensive calibration process did not lead to a satisfying numerical simulation of the laboratory experiment. In this study it could not fully proven if a two-dimensional numerical model is generally able to reproduce the lateral sediment exchange found in the experiment.

Furthermore, the question needs to be answered whether the important processes of the laboratory experiment are also dominant in inland waterways. Nevertheless, the current state of investigation is presented as it is not only valuable to know the possibilities of numerical simulation, but also its limitations.

In section II the embayment flume experiment of [1] is presented. The numerical modelling with TELEMAC-2D / GAIA of this lab experiment is shown in section III. In section

IV the numerical results are compared with the measurements and in the section V the results are discussed and concluded.

II. EMBAYMENT FLUME EXPERIMENT

[1] investigated in a 7.5 m long and 1 m wide flume with a longitudinal slope of 0.1 % four different embayment configuration (see Fig. 1). Artificial sediments of polyurethane were recirculated and mixed in upstream and downstream tanks. With a mean grain size of d_{50} = 0.2 mm and a density of 1160 g/m^3 the artificial material corresponds to non-cohesive fine sediments with grain sizes 0.062 – 0.5 mm. [1] determined the settling velocity (0.00276 m/s). Each configuration was modelled with three different discharges. The initial concentration was determined experimentally to the maximum suspended capacity of the flow. The amount of recirculating sediment was calculated from the known water volume in the flume and the tanks, and the required sediment concentration. The values are summarized in Table 1. The recirculating sediment procedure did not produce a constant feed but a decreasing probably slightly oscillating feed. At the boundaries neither the concentrations nor the incoming sediment masses were measured. At two positions in the main channel orientated at the embayment configuration, (see Fig. 1) turbidimeters were installed which monitored the concentrations. The vertical position of the turbidimeters was experimentally chosen to the vertical averaged value of the concentration profile. The experiments were finished after 3, 4 and 5 hours reaching a quasi-equilibrium concentration state for low, medium and high discharges, respectively (see Table 1). Equilibrium was assumed when the bottom evolution in the lateral embayment were not measurable anymore.

The total sediment mass trapped in the embayment was collected, dried and weighed. The results were presented in Fig. 2 as trapping efficiency which is the mass divided by the total embayment area.

In the reference configuration without embayment (3.0) some sediments were trapped in small gaps between bricks and walls which led to a significantly decrease of sediment concentration (see Fig. 3). In this configuration no bed evolution appeared, so the loss resulted from the bricks and walls. For the low discharge nearly 80 % of the concentration was lost due to this phenomenon. For higher discharges it was only nearly 65 % (medium) resp. 40 % (high).

The measurements of the water levels show an oscillation phenomenon for all embayment configurations. This phenomenon is induced by a seiche, which occurs in dead zones of a flow like the embayment configurations 3.1 – 3.4 (e.g. [2], [3]). The seiche phenomenon is related to the geometry of the cavities and was observed stronger for configuration 3.1 and 3.2. The configurations differed in the roughness aspect ratio. This is defined as the lateral depth of the cavities (0.25 m) divided by the distance between two cavities. The configuration 3.1 has smaller roughness aspect ratio of 0.5 than configuration 3.2 which has one of 0.6.

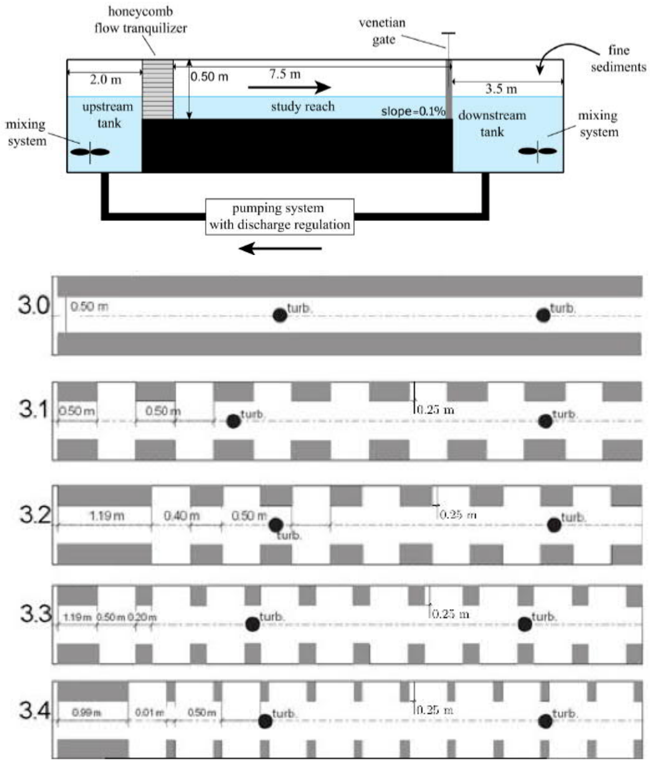

Figure 1: Side view of the set-up of the flume experiment (top) and topview on embayment configurations group 3 (bottom) (from [1]).

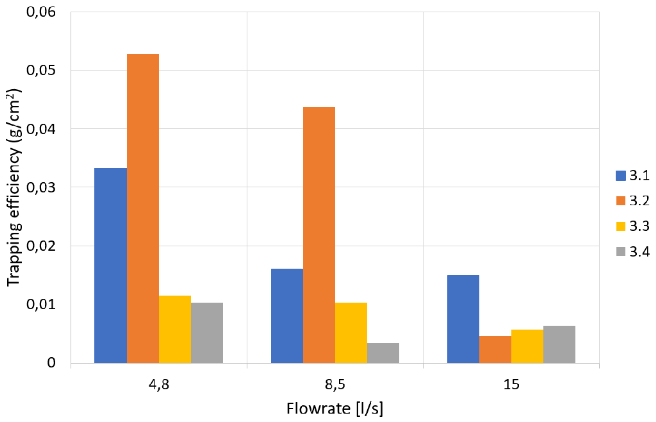

Figure 2: Measured trapping efficiency for all embayment configurations and all discharges (values are taken from [1]).

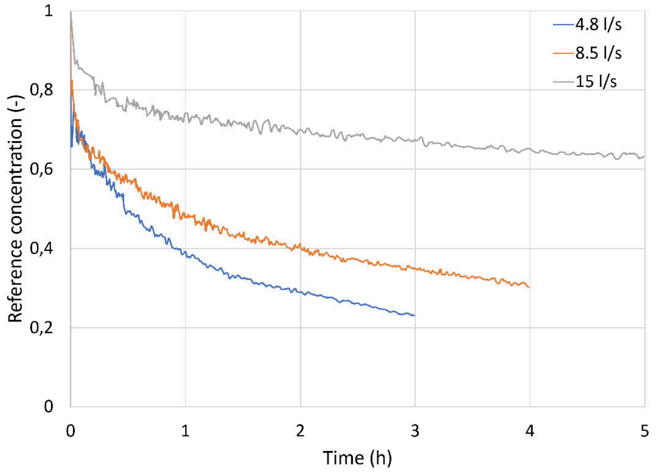

Figure 3: Measured concentration for the configuration without embayment (3.0) (values are taken from [1]).

III. NUMERICAL SIMULATION WITH TELEMAC-2D / GAIA

For long-term hydro-morphodynamic modelling of German federal inland waterways usually TELEMAC-2D/SISYPHE and in future TELEMAC-2D/GAIA is applied in BAW. Therefore, 2D models with a typical BAW resolution of about 10 grid points in the main channel was used for the simulations of the embayment lab models. The number of nodes for the five models are between 1454 and 2559 with maximum edge lengths of 5 cm. Fig. 3 shows the first 1.2 meters of the simulation grid for model 3.1. No increased resolution was chosen for the embayment areas as the embayment gyre could be simulated.

At the inlet boundary the discharge and the velocity distribution were imposed. The distribution was taken from the outlet boundary of a previous made steady state simulation. This procedure minimises the boundary impact. At the outlet boundary the water level was set.

Unfortunately, the boundary sediment concentration at the inlet was not measured and was not a direct recirculating due to the two tanks. After some investigations with sediment recirculating procedures, the best compromise was to use the measured sediment concentration as inlet boundary condition.

Applying the given initial concentration uniformly along the whole flume did not seem plausible. In order to fit best to the laboratory experiment, the initial condition was found as a steady state with a concentration distribution at the inlet according to the outlet. The sediment input flux was adapted to meet the initial concentration as an average value at the two measurement points. Fig. 4 shows exemplarily the initial sediment concentration for the embayment configuration 3.1. The initial and boundary conditions are summarised in Tab. 1.

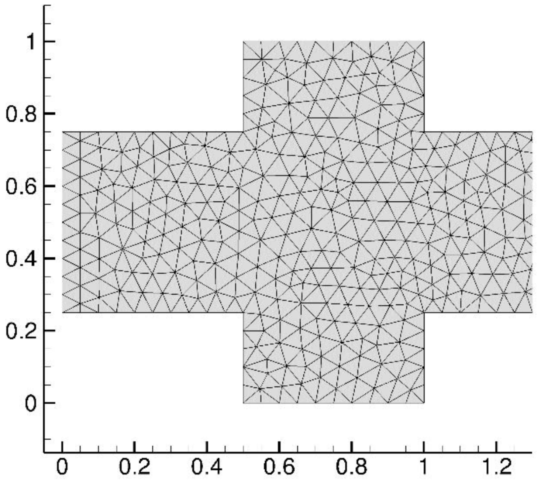

Figure 3: Part of the simulation grid for embayment configuration 3.1.

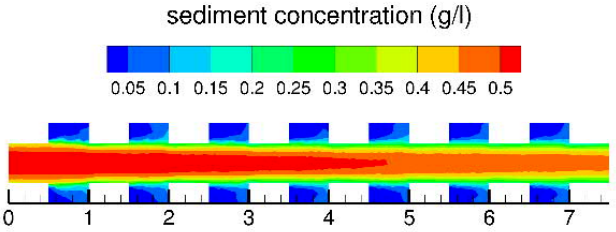

Figure 4: Initial concentration from a previous steady state simulation for embayment configuration 3.1 and the discharge 4.8 l/s.

TABLE 1: INITIAL AND BOUNDARY CONDITIONS.

Boundary conditions:			
Discharge (l/s)	4.8	8.5	15
Water depth (m)	0.035	0.05	0.07
Sediment concentration (g/l)	Measured concentration (see Fig. 3)		
Experiment duration (h)	3	4	5
Initial conditions:			
Velocities	Steady state from previous simulation		
Water depth			
Sediment concentration			
Initial concentration at the measurement points (g/l)	0.5	1.0	1.5
Recirculating sediment mass (kg)	2.75	5.5	8.25

Beside the unknown sediment boundary conditions another source of uncertainty in the measurements came from the loss of sediments in the small gaps between the bricks and walls. Both aspects lead to a high degree of uncertainty which prevents a good comparability between the experimental and numerical results. This fact was not so clear in the choosing process of the experiment. The structured simple geometry, the presence of concentration and deposition measurements and the excellent description of the laboratory experiment were good arguments for the choice.

A. Hydrodynamic calibration

The roughness coefficients were initially taken as Manning values from literature for wooden bottom (0.011 s $m^{-1/3}$) and for lateral bricks (0.014 s $m^{-1/3}$). For calibration the values were converted to Nikuradse roughness coefficients of 0.5 mm for the wooden bottom and of 2.1 mm for the lateral bricks. With both turbulence models, k-epsilon and horizontal mixing length, the embayment vortices could be reproduced. For further simulations k-epsilon model was chosen as it promised to apply better for complex flow situations. In Fig. 5 streamlines visualises the measured and simulated flow situation in the embayment for configuration 3.1. Measurements and also simulations show quite similar flow patterns for all discharges. In the measurements a vortex occurs with a centre moved in flow direction ($x/l \approx 0.7$). In case of high discharge, the size of the vortex seems smaller and a second small vortex could be interpreted at the upstream boundary. The numerical simulation calculated just one vortex which covers the whole embayment area. The vortex centre is only slightly upstream at $x/l \approx 0.55$.

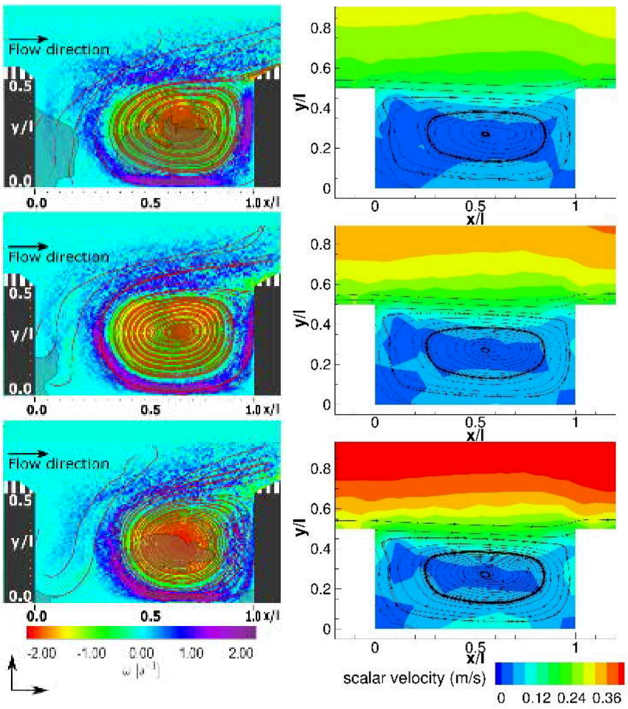

Figure 5: Comparison of measured vorticity and streamlines of the groyne gyre (left, from supplementary online data of [1]) and simulated scalar velocity and streamlines of the groyne gyre (right) for low (top), medium (middle) and high (bottom) discharges for configuration 3.1.

The uniformity of the flow was checked between the two concentration measurement points (see Figure 1). The water level slopes were found only slightly larger than the bottom slopes except for the largest discharge. The water level difference between the two measurement points and the uniform water depth was less than 1 % for the low and mean discharges but nearly 5 % for the high discharge. Tests were done using lower roughness for the high discharge, which led to the same hydrodynamic calibration quality as reached for the lower discharges. But this did not improve the sediment results significantly. Therefore, all results presented here used the same roughness coefficients.

IV. COMPARISON OF NUMERICAL RESULTS OF LATERAL SEDIMENT EXCHANGE TO MEASUREMENTS

The numerical model was calibrated using the offered sediment measurements of the embayment experiment. The settling velocity, the grain size and grain density were taken from the measurements. The following numerical and physical parameters were used for calibration:

- Reference height
- Bed shear stress
- Equilibrium concentration formulation
- Settling lag
- Diffusion of tracers
- Time step
- Numerical scheme for sediment (finite Element / finite volume / PSI-scheme / N-scheme)

The best calibration was found for the minimal reference height (1 % of the water depth), a bed shear stress which includes turbulence according to [4] with the parameter 2r=0.0119, van Rijn equilibrium concentration, settling lag, no diffusion of tracers, a time step of 0.05 s and PSI-scheme. For sensitivity studies the impact of the mesh resolution and the settling velocity were investigated as well.

The time evolution of the concentration averaged from the two measurement points and normalised by dividing with the initial concentration shows an exponential decrease until asymptotically reaching a constant value. Fig. 6 shows the comparison between the measurements and the calibrated numerical results exemplarily for embayment configuration 3.1 and all three discharges. The differences between the measurements which were also set as boundary conditions and the simulated concentration at the measurement points are very small. Therefore, no further adaption of the initial sediment concentration was done.

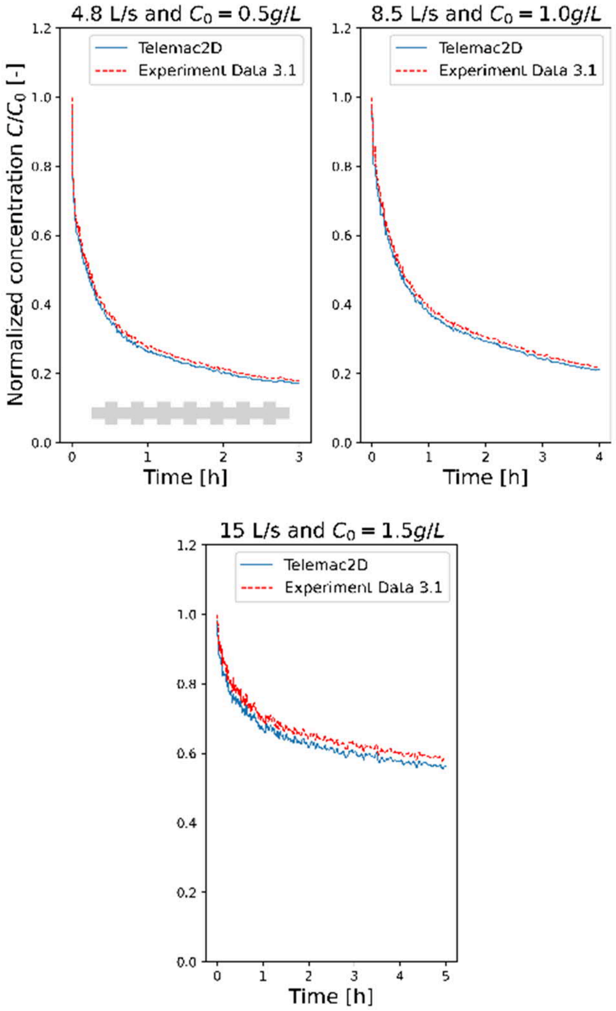

Figure 6: Simulated (blue) and measured (red) time evolution of the normalised concentration for embayment configuration 3.1.

In Table 2, the deposited masses are compared between the calibrated simulation and the measurements. Due to the recirculating procedure the temporal evolution of the sediment concentration corresponds to the deposited masses in the embayment areas of the experiment. A smaller final concentration implies a higher mass deposition. With increasing discharges, the deposition masses decreased in the experiment. Because of the set boundary condition instead of a recirculation in the numerical simulation, higher final concentrations did not lead to smaller masses. Contrary to the small differences between measurements and numerical results for the concentration the deposition masses fit only reasonable for low discharge. For mean discharge the masses were computed 5 times and for high discharge even 20 times too high. For the other configurations the behaviour for higher discharger is equivalent or even worse. The effect of smaller lateral sediment exchange for increasing discharges could not be captured by the numerical model at all.

A sensitivity study was conducted to investigate the range of deposition masses. Figure 7 presents the variation of deposition masses for several numerical and physical parameter settings for the low discharge and configuration 3.1.

From the physical parameters the settling velocity was the only one which decreased the mass compared to the calibration set up (red mark). But the chosen values are far from the measured ones and should not be taken for calibration. A finer grid resolution and a smaller time step decrease the numerical diffusion. This leads to less sediment input to the embayment areas. The fine grid with node distances of 1 cm instead of 5 cm cut the deposition masses roughly into half (258 g / 1018 g / 2203 g). Unfortunately, the trend that increasing discharges resulted in decreasing deposition masses could also not captured with a finer mesh.

Fig. 8 shows the comparison of the hydrodynamics and the final sediment concentration in the embayment area between coarse and fine grid for the mean discharge. The velocities are slightly higher in the main channel due to less numerical diffusion in the fine grid and the centre of the embayment gyre is moved more downstream like in the experiment with the finer grid. Moreover, the concentration is more mixed with the coarser mesh than in the fine mesh. Neither with the coarse mesh nor with the fine mesh the water level oscillated like in the experiment. In the experiment [1] reported water level oscillations between 1 and 3 mm.

TABLE 2: SIMULATED AND MEASURED MASSES DEPOSITED IN THE EMBAYMENT AREAS FOR CONFIGURATION 3.1.

	Measured deposition mass (g)	simulated deposition mass (g)
Low discharge	583	428
Mean discharge	282	1464
High discharge	262	5174

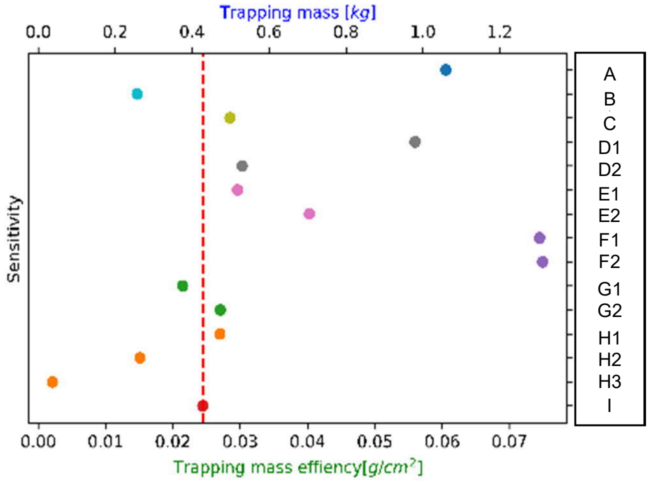

Figure 7: Simulated deposition masses for different parameter settings for low discharge and configuration 3.1 (A: settling lag, B: finer mesh, C: with diffusion of tracer, D1: equilibrium concentration Soulsy D2: equilibrium concentration Zyserman, E1: bed shear stress + TKE with 2r=0.119 E2: bed shear stress + TKE with 2r=0, F1: Finite Volume parallel F2: Finite Volume seriell, G1: timestep 0.01s G2: time step 0.1s, H1: settling velocity 0.005 m/s H2: settling velocity 0.001 m/s H3: settling velocity 0.0001 m/s, I: reference)

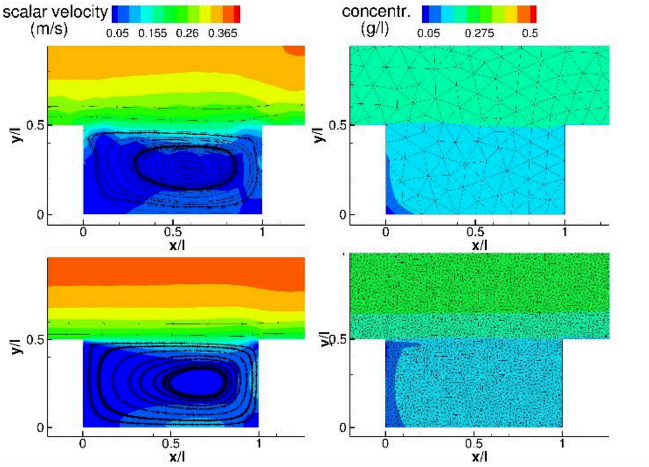

Figure 8: Comparison of the hydrodynamics and the final concentrations in the embayment area between the coarse (left) and the fine (right) mesh for mean discharge and configuration 3.1.

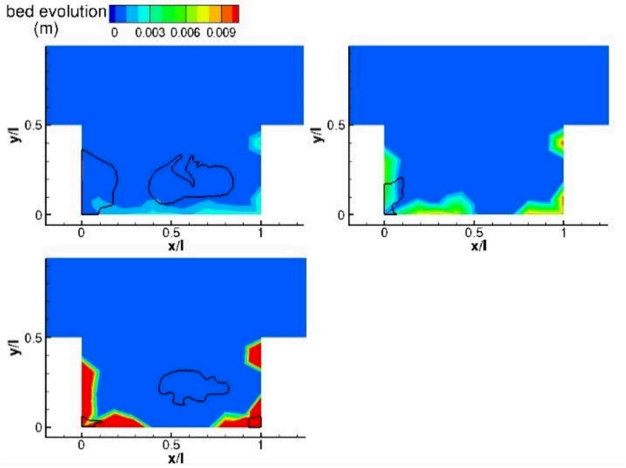

Figure 9: Comparison of simulated deposition to the measured deposition areas (black polygons) in the embayment for configuration 3.1 for low discharge (top left), mean discharge (top right) and high discharge (bottom left).

Furthermore, the transfer of the calibration to the other embayment configurations was investigated. In the experiments the deposits nearly doubled for configuration 3.2 and halved for configurations 3.3 and 3.4. Again, this was not predicted by the numerical model (see Table 3). At least the numerical model computed significant different values for configuration 3.3 and 3.4 but in the wrong direction. It must be stated that the calibration can neither be transferred to other discharges nor to other embayment configurations.

A qualitative comparison was made with the deposition areas. It is well known that sediment will be deposited in the middle of a vortex according to the spiral flow. The deposition pattern in the embayment areas show deposition in the middle of the embayment and additionally at some corners (see black polygons in Fig. 9). In the 2D simulation the deposition only occurred at the boundaries of the embayment where the velocities minimised (see Fig. 9). Again, the finer mesh did not improve the results. The missing deposition at the centre of the embayment gyre was expected because the secondary currents effect is a three-dimensional effect. An approximation exists in TELEMAC-2D but requires a slope in the free surface. The velocities of the embayment gyre are so small that no significant free surface flow appears.

TABLE 3: SIMULATED AND MEASURED MASSES DEPOSITED IN THE EMBAYMENT AREAS FOR THE LOW DISCHARGE AND ALL EMBAYMENT CONFIGURATIONS.

Embayment configuration	Measured deposition mass (g)	simulated deposition mass (g)
3.1	583	428
3.2	925	437
3.3	287	605
3.4	284	729

V. CONCLUSION AND OUTLOOK

At BAW the lateral sediment exchange between main channel and groyne fields is a topic of interest. The embayment experiment of [1] was chosen to investigate the capability of TELEMAC-2D / GAIA to simulate lateral sediment exchange. The numerical model was compared to the experimental results for four different embayment configurations and three different discharges. With some calibration it was possible for a single configuration and the lowest discharge to fit reasonable to the measurements. But with this calibration set up neither other embayment configurations nor higher discharges could be predicted. It is presumed that the numerical model missed significant physical processes. Of course, a three-dimensional simulation would enhance the numerical results. Deposits in the center of the embayment vortex are expected for a three-dimensional simulation (see e.g. [5]). But it is doubtable that the effect of decreasing lateral sediment exchange with increasing discharges can be captured by a 3D model with the same resolution.

Some aspects hinder the analysis of the present flume experiment. The procedure of sediment recirculation did not reproduce the boundary condition for the sediment concentration in the numerical model. Together with the loss of material in the pores of the laboratory model the masses can only be examined qualitatively. Additionally, in the experiment an oscillating water level was observed. Compared to the water depth the oscillating amplitude was high. Amplitudes of 1-3 mm were reported by [1] which correspond to 2 – 6 % of the water depth. Nevertheless, the simple geometry, the presence of concentration and deposition measurements and the excellent description of the laboratory experiment were good arguments using this experiment as a validation case for lateral sediment exchange. But it would be helpful to find or conduct an experiment with suspension and lateral sediment exchange that avoids the pumping effect and mass loss.

In the numerical model no oscillating of the free surface was simulated as it was observed in the experiment. This seiche effect producing low-frequency fluctuations in the water level is a typical phenomenon for embayment and groyne field hydrodynamics (e.g. [2], [6], [7]). Further investigations are needed to evaluate whether this effect influences the lateral sediment exchange significantly. In addition, it needs to be investigated whether this effect also plays an important role in groyne field morphodynamics. Investigations with oscillating boundary conditions could be proof whether these oscillations create a substantial amount of sediment exchange.

The "CAVITY" validation test case of TELEMAC-2D simulates a straight flume with one embayment and constant flow using a very fine grid [8] and Smagorinsky turbulence model. The flow was found unsteady and large and periodically small eddies were observed moving into the embayment. Although the configuration of the model is different to the investigated flume it seems promising that the pumping effect could be simulated even with a 2D very fine grid. Further investigations should be done with a very fine grid and different turbulence models.

Another idea to enhance the 2D simulation was an adaption of the secondary current approach. In TELEMAC-2D the secondary currents effect is classically using the free surface flow but could also take a given radius of the flow. For this experiment the radius could be set according to the radius of the streamlines of the embayment gyre. This should improve the position of deposition in the embayment areas. For the application to river stretches with groynes this idea needs some more investigations. Typically, the radius of a river stretch is constant. In case of overtopped groynes the gyre will disappear and the radius must be adapted.

Even if a wide range of calibration already have been done some further ideas could be followed like a modification of the settling velocity due to turbulence, other formulation for the reference level or other integration of turbulence in the shear stress computation.

Applying TELEMAC-3D/GAIA to this flume experiment will be the next step. Even if a three-dimensional model cannot be used for long river stretches and long time periods it would be helpful to see how far a three-dimensional simulation can improve the model results. Furthermore, the grade of resolution needed for a reasonable improvement would be of high interest. If applicable, a coarse resolution three-dimensional model could be used at least for medium-scale river stretches.

From a user perspective, GAIA needs to include some variables in the results file for a verification process of the suspended sediment calculation (e.g. equilibrium concentration) and new keywords to enhance calibration of the model (Schmidt number, reference elevation, user increase of bed shear stress, flux redistribution, etc).

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REFERENCES

[1] C. Juez, I. Bühlmann, G. Maechler, A. J. Schleiss, & M. J. Franca, Transport of suspended sediments under the influence of bank macro-roughness. Earth Surface Processes and Landforms, 43 (1), 271–284, 2018, https://doi.org/10.1002/esp.4243.

[2] I. Kimura, T. Hosoda, Fundamental properties of flows in open channels with dead zone, Journal of Hydraulic Engineering 123: 98–107, 1997.

[3] Y. Akutina, Experimental investigation of flow structures in a shallow embayment using 3D-PTV. PhD thesis, McGill University, Montreal, 2015.

[4] A. Goll, 3D Numerical Modelling of Dune Formation and Dynamics in Inland Waterways. PhD thesis, Université Paris-Est, École du Pont ParisTech 2017, https://hdl.handle.net/20.500.11970/104213.

[5] P. Ouro, C. Juez, M. Franca, Drivers for mass and momentum exchange between the main channel and river bank lateral cavities, Advances in Water Resources, 137, 103511. 2020, 10.1016/j.advwatres.2020.103511.

[6] C. Wirtz, Hydromorphologische und morphodynamische Analyse von Buhnenfeldern der unteren Mittelelbe im Hinblick auf eine ökologische Gewässerunterhaltung. PHD thesis, Freie Universität Berlin. 2004.

[7] C. Anlanger, Field-scale experiments and analysis of turbulent flow structures in a river reach with groynes. Master thesis at University of Natural Resources and Applied Life Sciences, Vienna, 2008.

[8] TELEMAC-2D Validation Manual, Version v8p2, Dec, 2020, http://wiki.opentelemac.org/doku.php?id=documentation_latest.

[9] J. I. Pérez Obreque, Modelling of lateral sediment exchange using TELEMAC2D/GAIA, Master thesis, Karlsruhe Institute of Technology, 2021.