

Simulation of natural levee laboratory experiments with TELEMAC-2D/SISYPHE

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Abstract—Natural levees are wedge-shaped sediment deposits which are formed along the banks of alluvial channels. They define a longitudinal borderline between the main channel and the floodplain and impact the interaction of the flow between the main channel and floodplains. They are hence of importance for river management, e.g. in terms of flood protection, overbank sedimentation, and transport of pollutants. The processes involved in levee formation were investigated in flume experiments performed by the Leichtweiß-Institut für Wasserbau (LWI) within the BMBF-project “In_StröHmunG”. In the framework of a Master thesis conducted at the LWI in cooperation with the BAW, data of these experiments were used to investigate the capabilities of the TELEMAC-MASCARET system to simulate the evolution of these morphological features. In particular, the aim of the master thesis was to figure out which processes can be reproduced with a depth-averaged model and which parameters are significant to reproduce levee formation. A total of six experiments with different sediment transport rates and configurations of vegetation on the floodplain were simulated with TELEMAC-2D/SISYPHE considering both suspended and bed load sediment transport. Numerical results showed that levee masses could be successfully calibrated and validated. The simulated levee geometry had the typical shape characteristics, but the deposition locations differed from those observed in the physical model. This preliminary investigation showed that depth-averaged models are able to capture the main levee formation processes.

I. INTRODUCTION

Flood events can lead to considerable sediment deposits on the floodplains and form so-called natural levees. Natural levees define a longitudinal borderline between the main channel and the floodplain and are hence impacting the interaction of the flow between the main channel and floodplains. Such interactions are important for river management, e.g. in terms of flood protection, overbank sedimentation, and transport of pollutants. The processes governing natural levee formation are of ongoing research. Therefore, flume experiments were carried out in the framework of the BMBF-project at LWI laboratories in Braunschweig (Germany) to get insight into the formation of natural levees [1].

According to [2] the formation of natural levees can be related to two different lateral sediment transport mechanisms, through which suspended sediment from the main channel is conveyed onto the adjacent floodplains. Fig. 1 compares both

concepts: a) transport of sediments to the floodplains induced by a shear layer between the channel parts due to different flow velocities, and b) advective transport resulting from water level differences between the main channel and the floodplains.

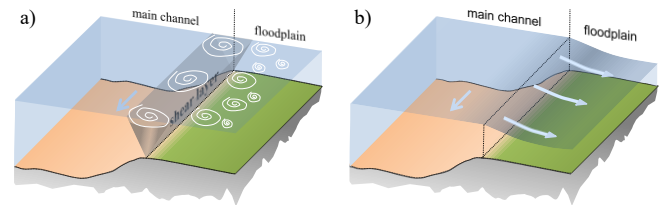


Figure 1: Turbulence induced sediment transport (a), advective sediment transport (b). (according to [2])

The laboratory experiments focused on the turbulence induced transport mechanism which is influenced by the shear layer between the main channel and the floodplain. This shear layer leads to a rapid decrease of turbulence over the floodplain. As a consequence, sediment cannot longer remain in suspension and deposits at the floodplain edge so that natural levees are formed exhibiting a steep slope towards the main channel and a milder slope towards the floodplains [2].

Natural levee formation can also be observed on Federal waterways and is therefore of interest for the Bundesanstalt für Wasserbau BAW. First investigations about modelling of natural levees were carried out in the framework of a master thesis [3] and are presented in this paper. The laboratory experiments were simulated with TELEMAC-2D and SISYPHE (www.opentelemac.org). The aim of the master thesis was to investigate which processes can be simulated with a depth averaged model (TELEMAC-2D coupled with SISYPHE) and which parameters are most sensitive.

II. Laboratory experiments

The laboratory experiments were conducted in a 2 m wide and 30 m long, sediment recirculating tilting flume in the hydraulic laboratory at LWI. A 20 m long section of a half trapezoidal compound channel was built in the flume starting at a distance of 4 m from the flume inlet (Fig. 1). The section had a 10 cm high floodplain with a width of 130 cm and a channel bed width of 60 cm connected to the floodplain via a 1:1 sloped bank. Artificial grass mats of 3 cm height were used to simulate roughness on both the bank and the floodplain. The

main channel bed was built from film faced plywood plates with a single layer of fixed polystyrene granulate grains as roughness ($d_{50} = 2.06$ mm). The granulate was also used as surrogate sediment in the experiments to accelerate morphodynamical development. The polystyrene grains were of cylindrical shape and had a solid density of $\rho_S = 1058$ kg/m³. The sediment was recirculated using the sediment recirculation circuit of the flume.

Data of six experimental runs were utilised for the numerical simulations. The experiments were conducted in two experimental series, hereafter referred to with the same names as used in [1]. All experiments were carried out with a discharge of 32 l/s, a water stage of 16 cm in the main channel, a constant bed slope of $S = 0.0005$, quasi uniform flow conditions and over a period of 19.5 h. Sediment transport rates were controlled by the amount of sediment in the flume and monitored via calibrated turbidity meters installed in the recirculation circuit. It is important to note that sediment was mainly transported in suspension, i.e. no bedforms were

developed. After each experiment the final levee configuration was documented. The material forming the levee deposits was collected in 60 cm long sections over the measurement section and weighted to determine the mass of deposited sediment. Further details of the model setup and experimental program can be found in [1].

Experiments of the “T-series” used herein were initially designed to investigate the impact of bedforms on levee formation but also featured two experiments without bedforms as reference used in this study. Experiments of the “MB-series” used herein focused on the effect of additional emergent vegetation simulated by a 12 cm wide strip of rigid cylinders with a diameter of 3 mm arranged in staggered arrays with a spacing of 2 x 2 cm, placed along the floodplain edge. This strip of vegetation was investigated in a continuous and in an intermitted configuration. For the latter the vegetation strip was reduced to vegetation patches of 120 cm length separated by gaps of 180 cm length in between. Fig. 2 gives an overview of the model setup and geometry.

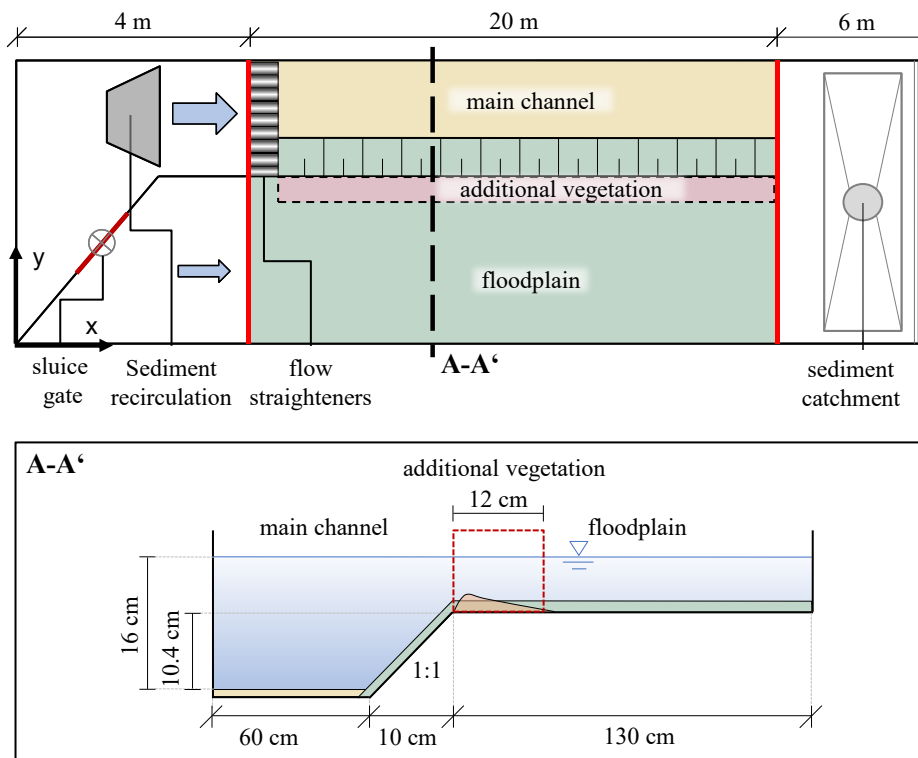


Figure 2: Top view and cross section of the flume model ([1]).

III. NUMERICAL SIMULATIONS

For the numerical simulations the modules TELEMAC-2D and SISYPHE were chosen. The aim was to investigate which processes of the natural levee formation can be simulated with a depth averaged model as well as to investigate the limitations of the approach.

Initially, the hydrodynamic simulation was performed with the BAW's standard steering-file configuration, which includes the N-type MURD advection scheme, Nikuradse roughness law and as turbulence model either the horizontal mixing length model or k- ϵ model [4]. This parameterization was later enriched with the Baptist's roughness law to account for vegetation-induced friction [5].

The model domain was discretised with a fine unstructured finite element mesh with typical size of approx. 3 cm, resulting in 57412 nodes and 112564 elements (Fig. 3). Due to instabilities at the start of the simulation period, a very small time step of 0.05 s was set for some configurations which led to Courant numbers of approx. 0.5 in the main channel.

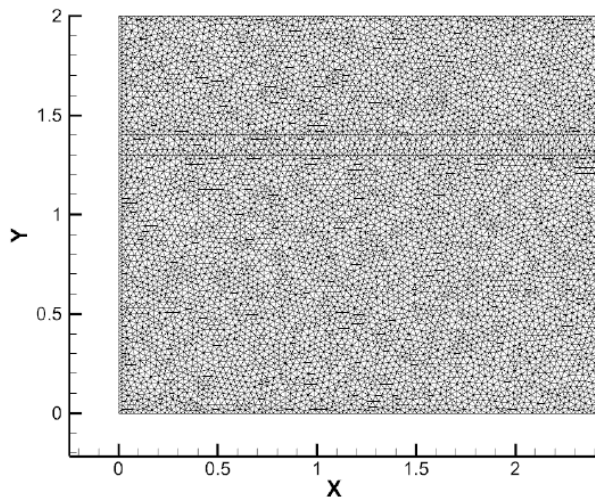


Figure 3: Mesh detail at the inlet. (from [3] page 19)

A. Hydraulic calibration

The hydraulic calibration was performed by comparing the model results with velocity measurements conducted in laboratory experiments without sediments. Uniform flow conditions were reached by the boundary conditions shown in Fig. 4. During the calibration process the roughness parameters for the two roughness zones (main channel and floodplain) and the turbulence model were selected.

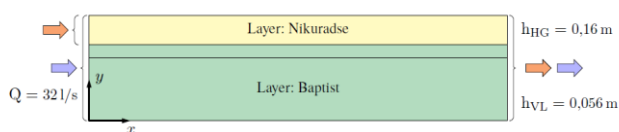


Figure 4: Boundary conditions and roughness layers for the hydraulic calibration. (from [3] page 20)

For the glass walls of the flume the Nikuradse roughness was set to 1 mm. At the floodplains the vegetation formulation from Baptist [5] is used as the grass height is about half of the water depth. The bottom roughness was chosen to 5 mm, the vegetation height to 2.5 cm and the vegetation diameter to 0.8 mm. The roughness coefficient in the main channel was calibrated to 6.18 mm which equals 3 times the median grain diameter. In order to ensure a proper velocity distribution at the inlet the velocity distribution was taken from the outlet for a fully developed flow.

Fig. 5 shows the comparison of the measured and simulated depth averaged velocities. At the floodplains the velocity could only be measured above the artificial grass which means that values in between the grass blades are missing. The velocity profile inside the blades of grass is assumed to decrease linear to zero. Nevertheless, the values at the floodplains are not as reliable as in the main channel.

Using the original k- ϵ model the roughness coefficients at the main channel needed to be increased to $k_s = 5 \cdot d_{50} = 10.3$ mm. If the turbulence is mainly caused by bottom roughness and not by geometry structures, experiences at BAW indicate that the k- ϵ model produces lack of turbulent viscosity. Adding additional turbulent viscosity of 10^{-3} m²/s to the calculated values from the k- ϵ model the new values are in the same order like the turbulent viscosities from the horizontal mixing length model. With this, the smaller roughness coefficient ($k_s = 3 \cdot d_{50}$) can be used. The steep velocity gradients in the shear zone were better captured by the original k- ϵ model than by the horizontal mixing length model or the modified k- ϵ model. But as shown in Fig. 5 the overall agreement of all models is very similar. The modified k- ϵ model was chosen for further use because the roughness coefficients in the main channel were in a better agreement with roughness prediction formulas and the more complex turbulence model promised a better representation of the turbulent flow.

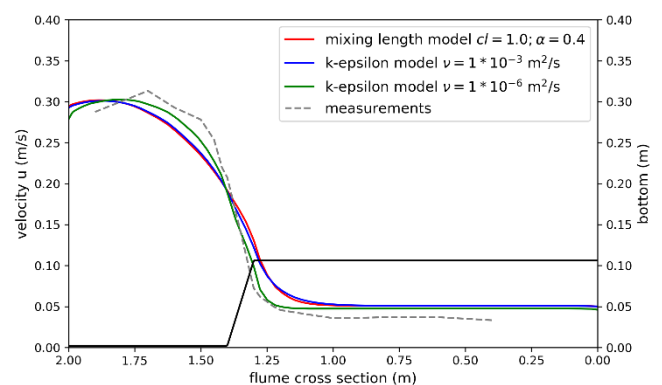


Figure 5: Comparison of measured and simulated time and depth averaged velocity along the cross section at 15m.

B. Morphodynamic configuration

As there was no experience in modelling natural levee formation the general configuration and the numerical parameters needed to be investigated. First it had to be decided

whether bedload and/or suspended load should be considered. In literature the initiation of suspension is assumed if the ratio of the critical bed-shear velocity u_{*cr}^* and the settling velocity w_s equals 0.25 (Engelund), 0.4 (van Rijn) or 1.0 (Bagnold) [6]. According to this the sediments in the flume experiments should be in suspension for shear velocities above 0.0075 ... 0.031 m/s. The bed-shear velocity in the main channel $u_* = \sqrt{\frac{\rho g h_{HG} I}{\rho}}$ can be calculated from the water depth h_{HG} and the bed slope I to 0.028 m/s. As the value is nearly at the top of the range for initiation of suspension it is most likely that most of the material in the main channel will be transported in suspension.

Deposits at the floodplains only occur if sediment was transported as suspended load. Thus, the calibration of the levee masses could only be done with parameters of the suspended load. Without bedload the sediments tended to aggregate in the main channel. Therefore, the combination of bedload and suspended load worked best. For the bed load transport Meyer-Peter & Müller bed load formula with MPM factor of 3 is used.

Defining the sediment boundary condition was not trivial. According to the laboratory model the sediment transport concentration was uniformly imposed at the main channel. In the model this boundary condition led to sediment aggregation over time at the inlet. Therefore, a concentration distribution along the inlet was calculated from the equilibrium concentration. With this procedure no deposition occurred in close proximity to the inlet.

Another challenge was that the vegetation height on the floodplain could not assumed to be constant over time due to high sediment deposition in the artificial grass (see Fig. 6). This was solved by a modification that corrected the vegetation height used in the vegetation formulation by the height of the deposited sediments.

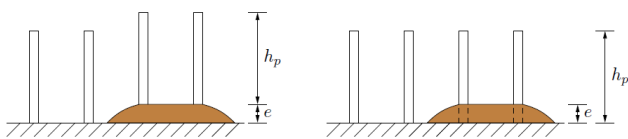


Figure 6: Vegetation height (h_p) without (left) and with (right) adaption to sediment aggregation(e). (from [3] page 35)

C. Morphodynamic calibration

For the morphodynamic calibration the laboratory experiment T4 was chosen. The boundary conditions (water (Q) and sediment discharge (Q_{sed}) and water depth at the main channel (h_{HG}) and the deposited levee mass (m_{levee}) are summarised in table 1. The calibration was only done with the levee mass, whereas the width and position of the levees were compared afterwards.

TABLE 1: MEASUREMENT DATA FOR LABORATORY EXPERIMENTS T4 AND T5

	Q (l/s)	h_{HG} (m)	Δt (h)	Q_{sed} (m^3/s)	m_{levee} (g/m)
T4	32	0,16	19.5	$2.38185 \cdot 10^{-5}$ = 42 g/(sm)	56.4
T5	32	0,16	19.5	$3.10208 \cdot 10^{-5}$ = 54.7 g/(sm)	117.1

The settling velocity, the porosity and the density, were set to the values of the sediment used in the flume experiments (respectively equal to $w_s=0.031$ m/s, $p=0.379$, $\rho_s=1058$ kg/ m^3). The critical Shields parameter Θ_c and the reference height z_{ref} were calculated according to the formulas from van Rijn [6,7] using the dimensionless grain diameter $D^*=15$, the water depth h and the equivalent roughness coefficient ks .

$$\Theta_c = 0.04 D_*^{-0.1} = 0.04 15^{-0.1} = 0.0305 \quad (1)$$

$$z_{ref} = 0.01 h < 0.5 ks < 0.2 h = 3.09 \text{ mm} \quad (2)$$

After all other parameters were determined from measurements, the only calibration parameter left was the sediment dispersion. In SISYPHE three calculation options are available to account for dispersion: setting a constant value, using the turbulent viscosity calculated by the turbulence model of the hydrodynamics or using the Elder approach. Setting a constant value was not investigated as it seems too simple. Using the turbulent viscosity values from the hydrodynamic calculation resulted in very low natural levee masses. For the Elder approach [4] two parameters can be calibrated which define the longitudinal α_l and transversal α_t dispersion together with the friction velocity u_* and the water depth h .

$$\epsilon_t = \begin{cases} \alpha_l u_* h \\ \alpha_t u_* h \end{cases} \quad (3)$$

Elder determined the longitudinal parameter to 6 and the transversal to 0.23, but with this parameter combination levee masses were largely overestimated. With a much smaller transversal parameter of 0.06 the levee masses were in perfect agreement to the measurements. The longitudinal parameter had nearly no influence on the resulting masses as the lateral sediment transport to the floodplains is decisive.

The validation was done with a similar laboratory experiment T5, which featured a 30% higher sediment concentration than in T4 (see Table 1). With the same parameter configuration, the computed levee masses ($m_{levee}=95.9$ g/m) were underestimated by 18%.

In the flume experiment the masses were determined in the 6 m long evaluation section in order to avoid influences from the inlet and outlet. The behaviour at the inlet and outlet was not comparable between flume experiment and numerical model. For the hydrodynamics of the numerical model the boundary conditions were chosen in such a way that the flow conditions did not vary significantly with flume length. The

inlet boundary condition for the suspended sediment was also defined with the help of the equilibrium concentration which also minimised the influence of the inlet. Therefore, levee masses were computed over the whole domain. In Fig. 7 the distributions of the simulated levee masses along the flume are presented. It can be seen that the levee masses decreased over the flume length. This trend was in general also observed in the laboratory model (see Fig. 9) despite this cannot be shown with T4 and T5 as in these experiments only a mean value for levee mass was measured. The evaluation section of the laboratory model was located nearer to the outlet than to the inlet which would lead to smaller masses. This must be due to the different evaluation procedures the numerical model underpredicts the masses per flume length.

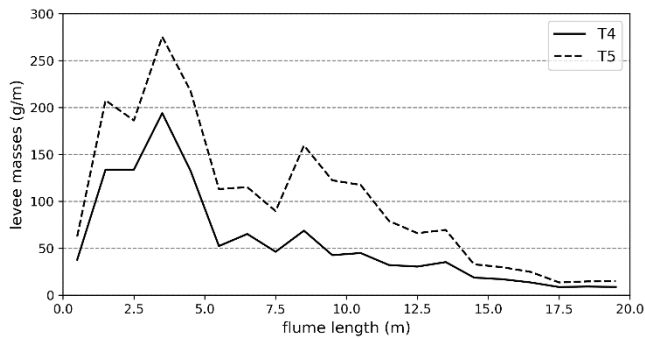


Figure 7: Development of levee masses along the flume for T4 and T5.

The evaluation of the simulated levee geometries was performed between the flume section 10 to 15 m. Fig. 8 presents the simulated levee cross sections for T4 and T5. In general, the typical geometry of natural levees with a steep slope towards the main channel and a slowly descend towards the floodplain can be observed. Along the flume length the height of the levees decreased, whereas the width was more or less constant. Additionally, levees were higher for T5 due to higher sediment input. In the laboratory model only sediment deposits higher than the artificial grass were able to be measured reliable. For that reason, the comparison between laboratory and numerical model for T4 and T5 was limited to levee width, position and mass.

The maximal levee width of about 10 cm is in good agreement to the measured ones (11.1 cm for T4 and 11.7 cm for T5). The position of the simulated levees was 10 cm from the edge of the slope. In the measurements the levees were located directly at the floodplain edge. With a better representation of the shear zone able to capture the 3D flow field, an improvement of the solution would be expected.

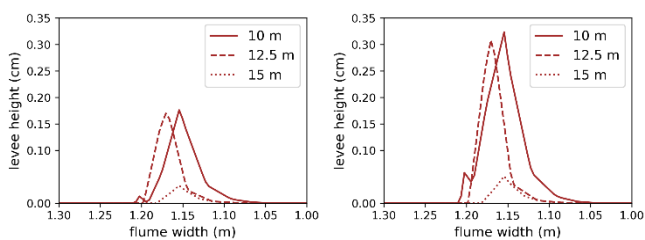


Figure 8: Form and width of simulated levees for T4 (left) and T5 (right).

The simulated masses increased over time and asymptotically approached a maximum value, which, however, was not reached even after 19.5 hours. This behaviour has been observed in similar experiments performed in the laboratory model.

D. Sensitivity to sediment parameters

The sensitivity of the settling velocity w_s and the critical Shields parameter Θ_c to the calculation of the natural levee masses were investigated. Because the settling velocity is precisely known from measurements it should therefore not be modified during the calibration process. Nevertheless, it is important to understand its influence to the natural levee formation.

Table 2 shows the parameter values, their investigated ranges and their influence on the levee masses. Lower settling velocities but higher critical Shields values produce increasing levee masses. Both parameters have a considerable impact to the levee masses although even for small parameter value changes. In the last table row a scaled sensitivity S is calculated with the mass change Δm divided by the parameter change Δw_s resp. $\Delta \Theta_c$ and multiplied by the calibrated parameter w_s resp. Θ_c .

$$S = \frac{\Delta m}{\Delta w_s} w_s \quad (4)$$

TABLE 2: SENSITIVITY DUE TO w_s AND Θ_c

	w_s (m/s)	Θ_c
calibrated value	0.031	0.0305
investigated range	0.028 – 0.033	0.02 – 0.04
difference to reference value	-0.003 / +0.002	-0.0105 / +0.0095
mass change Δm (g/m)	+42.2 / -18.1	-48.3 / +101.7
scaled sensitivity S (g/m)	+654.1 / -187	-140.3 / +326.5

With the scaled sensitivity the influence of both parameters to the levee masses can be compared. All values are in the same range which means that both parameters have approximately the same influence. The largest value was reached for the decreased settling velocity value.

E. Experiments with medium vegetation

Four further experiments were simulated which investigated the influence of additional vegetation strips on levee formation. Two experiments (MB10, MB11) featured continuous vegetation strips while the vegetation strip was intermitted in the other two experiments (MB23, MB25).

In Table 3 the boundary conditions and the resulting levee masses of the laboratory experiments featuring additional vegetation are summarised.

TABLE 3: MEASUREMENT DATA FOR THE VEGETATION LABORATORY EXPERIMENTS

	Q (l/s)	h _{HG} (m)	Δt (h)	Q _{sed} (m ³ /s)	m _{levee} (g/m)
MB10 continuous vegetation	32	0,16	19.5	1.9905 10 ⁻⁵ =35.1 g/(sm)	54.6
MB11 continuous vegetation	32	0,16	19.5	2.4953 10 ⁻⁵ = 44 g/(sm)	110.2
MB23 intermitted vegetation	32	0,16	19.5	3.10208 10 ⁻⁵ =54.7 g/(sm)	117.1
MB25 intermitted vegetation	32	0,16	19.5	2.38185 10 ⁻⁵ =42 g/(sm)	56.4

Simulation results of the levee masses along the flume at the end of the experiment are compared to the measurements in Fig. 9 and Fig. 10. For the continuous vegetation the simulated levee masses fit well to the measurements. But the behaviour at the inlet is completely different between the laboratory model and the numerical model. It seems that after approx. 10 m flume length the differences due to the inlet can be neglected.

For the intermitted vegetation the development of the levee masses along the flume exhibit a pulsating behaviour. Obviously, the numerical model reacted to the vegetation sections with increasing levee formation. The higher roughness due to the vegetation roughness immediately decreased the velocity and thus led to sediment deposition.

For the laboratory model it is the other way around. The levee masses are higher in the sections without vegetation. This can be related to gradually decreasing flow velocities in the particular vegetated sections where the minimum velocity was reached at the downstream end. As a consequence, the vegetated sections sheltered parts of the downstream unvegetated gaps, too, and thus more sediment deposited in these sections. Probably only a three-dimensional model is able to reproduce the complex flow situation due to this intermitted vegetation.

Comparing Fig. 9 and 10 it can be seen that with intermitted vegetation the levee masses are decreased. Experiment MB11 and MB25 had approximately the same sediment input. The levee mass measured in MB25 (intermitted vegetation) was only the half of the mass measured in MB11 (continuous vegetation). In the numerical

model the levee mass was stronger reduced due to intermitted vegetation to approx. 40%.

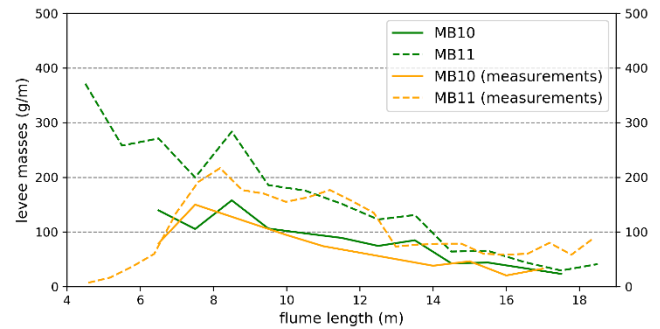


Figure 9: Comparison of the development of levee masses along the flume for the continuous vegetation experiments.

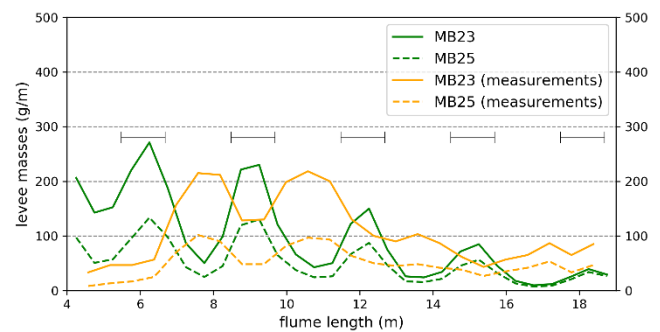


Figure 10: Comparison of the development of levee masses along the flume for the intermitted vegetation experiments.

IV. CONCLUSIONS

The numerical simulation of natural levee formation laboratory experiments with TELEMAC-2D and SISYPHE showed promising results. By calibrating only the sediment dispersion parameter, the levee masses could be simulated in a good agreement to the measurements. The simulated levee geometry showed a typical steep slope towards the main channel and a slowly descent towards the floodplains, whereas the position of the levees was shifted onto the floodplain. This difference can be related to the artificial grass used in the laboratory model which behaved like a sediment trap and explains the earlier deposition of the sediments. However, the maximal width of the simulated levees was comparable with the measured ones.

The numerical simulation of the physical experiments accounting for vegetation showed good results as long as the vegetation was continuously arranged. For intermitted vegetation the flow and transport processes were too complex to be captured with a depth-averaged model. Nevertheless, the general behaviour of pulsating levee masses along the flume was simulated satisfactorily.

Further investigations are planned with TELEMAC-3D coupled to SISYPHE (or the brand-new sediment transport module GAIA). This should allow a better reproduction of the shear zone and consequently a more precise capture of earlier sediment deposition processes.

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