ESTIMATION OF MORPHOLOGICAL IMPACT OF GROYNE LENGTHENING

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Abstract. Hydraulic-morphological calculations in open channel flows still cause problems for modellers, partially because of theoretical uncertainties and due to lack of sufficient data on sediment composition or sediment load. Though morphological changes in rivers can be precise described with 3D numerical models 2D models can be useful tools as well. Our aim was to study if a 2D calculation with the available data and computing capacities gives a reasonable estimation on how river training structures (in this case lengthening of a groyne) affect the river bed morphology.

Key-words: Hydrodynamic-morphological numerical model, groyne, sediment transport, bank-filtered aquifer.

1. Introduction, objectives

It is well known under which criterion numerical models can be used. The idea of a "perfect model" that can be used without calibration doesn't exist anymore. It is obvious that steady or unsteady flow field or water level calculations can be done with a 1D model, having the *Bernoulli Equation* or the *St. Venant Equation* as the mathematical bases. There are of course, cases when solving a hydraulic problem has to be done with an inappropriate method due to lack of sufficient data, tools or scientific background. This is the case in greatly developing fields such as **hydraulic-morphological calculations in open channel flows**. The modelling of sediment transport in a natural, alluvial river and taking the actual sediment composition into consideration **still cause problems for modellers**. Some physical phenomena are not yet precisely defined such as hiding and extension of a sediment particle, armouring of river bed, cohesive sediment transport or the effect of river bed formations, dunes. Besides theoretical uncertainties there are other difficulties such as lack of data on sediment composition or sediment load (as an upper boundary condition) etc.

Morphological changes occur slowly, except quicker changes of the river-bed morphology during floods. **River training solutions have a long term** (decades-long) **effect** on river bed topography so the effect of such an intervention **has to be estimated for 20 years**. Most of the numerical models use small time steps ($\Delta t < 60$ s or even 5 s) because of accuracy and stability reasons. If 20 years should be studied the **number of time steps would be 10^8** orders of magnitude, which cause problems even considering todays computational capacities.

The sediment transport is mainly influenced by geometric and hydraulic properties near the bottom (for example local slope, bed-shear velocity, turbulence) and so these have an effect on morphological changes. Technically speaking **morphological changes in rivers can only be precise described with 3D models** specially when modelling the near field of river training structures.

When having a hydraulic-morphological problem the following aspects should be taken into consideration:

- 3D characteristics of the process,
- very long simulation time (~20 years),
- small time step ($\Delta t \approx 5$ - 60 s),
- because of uncertain boundary conditions a long river section has to be modelled (up to 50 km),
- the needed data for the modelling such as the bed-load transport rate and sediment composition, or the grain size distribution of the bed material is not regularly measured,
- insufficient data for the calibration.

So it has to be examined if a 2D calculation with the available data and computing capacities gives a reasonable estimation on how river training structures affect the river bed morphology.

The following questions were kept in mind during this study:

a) If morphological changes caused by a groyne can be calculated with a 2D hydrodynamic-morphological model?
b) If the relative evolution due to the lengthening of the groyne can be estimated with a 2D model?
   Relative evolution means subtracting the developing bottom elevation in case of the shorter groyne from the developing bottom elevation of longer groyne.
c) If it is possible to give acceptable estimation of morphological changes using insufficient data and without calibration?
d) Which parameters have the greatest effect on the result, which parameters should be set more precisely?
   For some parameter a detailed sensitivity analysis was made.
e) Which area is affected by the lengthening of the groyne? How long river section should be taken into consideration – having in mind the uncertainties of the boundary conditions?

The answers to the questions a)-d) are more or less general.

For carrying out simulations there were two alternatives, the first one is to assume a regular, prismatic river bed and change the hydraulic and morphological parameters in a wide range; the second one is to study a specific river section. In the first case only known, general correlations could have been proven. In the second case time dependent hydraulic and morphological parameters had to be taken. But due to lack of sufficient data we were unable to study a specific river section. Some of the data are from one section of the river Danube others are from other sections, so the calculations are not valid for a specific river reach.

The simulations were made using **Telemac2D** and **Sisyphe v.6.1** hydrodynamic-morphological modelling software.

2. Basis for the mathematical approach

Hydrodynamic model

The basic equations were derived through depth averaging of the three dimensional *Reynolds Equations***,** which give the time averaged turbulent motion of viscous, incompressible fluid. The derivation of the *Reynolds Equation* from the *Navier-Stokes Equations* can be found in numerous articles or in university notes (such as *Németh 1963, Liggett 1975, Abbott-Basco 1989*). The following basic equations are valid for the **depth-averaged, open channel, two dimensional, unsteady flows**.

The equations stated here without source term, in non-conservative form are valid for incompressible fluid. (*Telemac-2D 2010*)

Conservation of mass:

$$\frac{\partial h}{\partial t} + \mathbf{v}\, grad(h) + h\, div(\mathbf{v}) = 0 \tag{1}$$

Conservation of momentum

x direction:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial Z}{\partial x} + F_x + \frac{1}{h}\mathrm{div}(h\ \nu_t\, \mathrm{grad}\, u) \tag{2a}$$

y direction:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial Z}{\partial x} + F_y + \frac{1}{h}div(h\ \nu_t\, grad\, v) \tag{2b}$$

Where **v** - velocity vector; u and v – time (t) and depth (h) averaged velocities in x and y directions; h – water depth; Z – water level; F_x and F_y – force per unit weight x and y directions; ν_t – eddy viscosity; g – gravitational acceleration.

In this case the force per unit weight taken into consideration is the bottom friction force. As the solution of the quadratic friction law *Strickler's* assumption was chosen.

$$F_x = -\sqrt{1 + \left(\frac{\partial Z_f}{\partial x}\right)^2 + \left(\frac{\partial Z_f}{\partial y}\right)^2}\ \frac{g}{h^{4/3}k^2}\, u\, \sqrt{u^2 + v^2} \tag{3a}$$

$$F_y = -\sqrt{1 + \left(\frac{\partial Z_f}{\partial x}\right)^2 + \left(\frac{\partial Z_f}{\partial y}\right)^2}\ \frac{g}{h^{4/3}k^2}\, v\, \sqrt{u^2 + v^2} \tag{3b}$$

where Z_f – bottom level; k – *Strickler* friction coefficient ($m^{1/3}/s$). The first term on the right takes the bottom slope into consideration

The closure problem of the in the *Reynolds-averaged Navier-Stokes Equations* were solved using the *Boussinesq' Eddy Viscosity Concept*. The used numerical model offers several methods to define the eddy viscosity. In this case the *Elder model* was used:

$$\nu_t = c_l\, u_*\, h \quad \text{or} \quad c_t\, u_*\, h \tag{4}$$

where c_l and c_t – longitudinal and transverse dimensionless dispersion coefficient with default values of c_l=6.0 and c_t=0.6; u_* – bottom shear velocity.

Morphological model (*Sisyphe 6.0, 2010*)

To calculate the bed evolution the model solves the *Exner Equation*:

$$(1-n)\frac{\partial Z_f}{\partial t}+\mathrm{div}(\mathbf{Q_b})=0 \tag{5}$$

Where n – is the bed porosity (n ≈ 0.4 for non-cohesive sediment) and $\mathbf{Q_b}$ – solid volume transport per unit width.

There are nine bed-load transport formulae that can be chosen in the program system. The following formulae were applied *Meyer-Peter-*, *Einstein-Brown-*, *Engelund-Hansen-*, *Soulsby-van Rijn-* and *van Rijn-formula*. In this article only results of the *van Rijn formula* (1984) are introduced.

The solid volume transport per unit width (in m^2/s) can be computed as:

$$Q_b = 0{,}053\left[(s-1)g\right]^{0,5} d_{50}^{1,5}\frac{T^{2,1}}{D_*^{0,3}} \tag{6}$$

where: s – specific density (density of particle divided by the density of water, $s=\rho_s/\rho_w \approx 2{,}65$); d_{50} – particle size, in case of mixed sediment the particle size of the actual fraction; T – transport stage parameter and D_* – particle parameter.

$$D_* = d_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{1/3} \tag{7}$$

$$T=\frac{(u_*')^2-(u_{*,cr})^2}{(u_{*,cr})^2} \tag{8}$$

in which ν – kinematic viscosity coefficient; u_*' – bed-shear velocity related to grains, $u_{*,cr}$ – critical bed-shear velocity according to *Shields*.

3. The numerical model and data

For an exact problem solving, the initial state and the main characteristics of the phenomenon should be known in advance. This means in our case geometric, hydrologic, hydraulic and morphological data is needed.

The available geometric and hydrologic data were sufficient for our needs. The bottom friction was calculated through hydrodynamic calibration. The morphological data posed some problems. For describing the initial morphological state, for morphological calibration and for morphological modelling the following data would have been needed:

- grain size distribution of the river bed material and its spatial distribution,
- total sediment transport rate, sediment composition, and its spatial distribution,
- the incoming, time dependent sediment load (rate and grain size distribution).

None of the above mentioned data were available on the studied section. That is why the grain size distribution of the bed material and the bed-load was estimated using available data on other, nearby sections of the Danube. The needed initial conditions were therefore only rough estimates.

Geometric data

The studied river section is located in the lower Hungarian section of the Danube. Cross sectional water depth measurements in every 100 m were used to create the digital terrain model and the mesh for the numerical calculations. The mesh used has triangular elements, the main characteristics are: 6610 nodes, 12812 elements, the sides of the triangular elements are 2.9–25.0 m long, in average 13.8 m. On the 2100 m long section there are four groynes where the mesh was refined. **Fig. 1. shows the digital terrain model**.

Hydraulic data and calibration of the model

An average – unsteady state – case was studied. Close to the studied section were the daily discharge (Q) values available for 18 years. An average hydrograph was calculated (by having the average discharge for each day of the 18 years data) and used as **upstream boundary condition**. The daily measured water level H(t) data was used to create the **Q-H curve** characteristic for that time period. Based on the Q-H curve the **downstream boundary condition** was calculated. **Fig. 2.** shows the boundary conditions, average discharge **Q(t)** and water level **Z(t)** values over time (days).

The hydrodynamic calibration was done with 1180 m^3/s discharge. The best fit free surface elevation was achieved with a roughness of $k_{st} = 37.5\ m^{1/3}/s$.

For the morphological calibration unfortunately no data was available.

Studied versions

Due to lack of sufficient morphological data, several transport formulae, sediment compositions and mean diameters were studied. The evaluation of the results was based only on technical and hydraulic speculation and experiences.

This method is of course arguable, but stayed as the only alternative when modelling without morphological data and calibration. Strictly speaking the data and methods resulting unrealistic bed evolution were rejected.

List of studied versions were as follows.

Type of sediment transport:

– suspended load and
– bed-load transport was investigated.

The following bed-load transport formulae were used:

– *Einstein-Brown-,*
– *Engelund-Hansen-,*
– *Engelund-Hansen + Chollet and Cunge-*
– *Soulsby-van Rijn-* and
– *van Rijn* method.

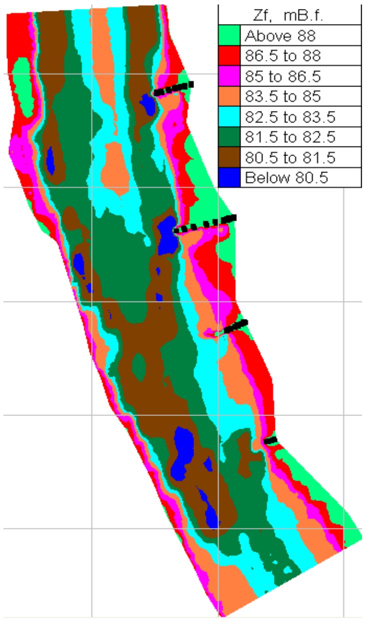

Fig. 1. Digital terrain model of the river section

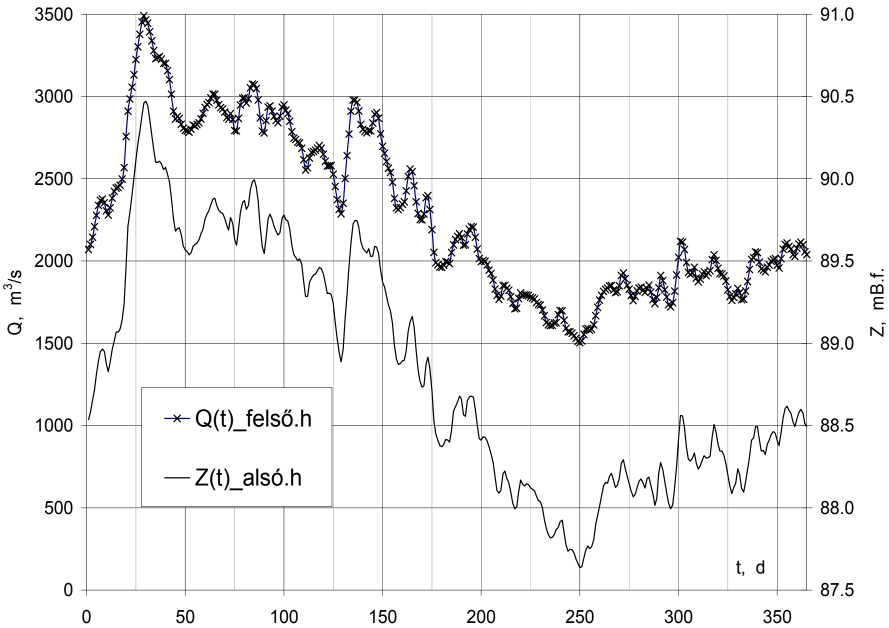

Fig. 2. Upstream Q(t) and downstream Z(t) boundary condition

After evaluating the first results the **bed-load transport** formula of ***van Rijn*** (*1984*) was chosen for further computations.

Several sediment compositions were studied. In this paper the following two variants are introduced.

– $d_{m,1}$ = **0.1 mm**, $d_{m,2}$ = **0.4 mm**, $d_{m,3}$ = **3.0 mm**
(assigned *'d_nonuni'* referring to the **nonuniform sediment composition**) and
– d_m = **0.8 mm** ('*d_uni*' referring to the **uniform grain size**).

Versions with different geometry: the version with the original topography of the four groyne was labelled "**short**" version. The third groyne (from upstream) was lengthened with 39 m, this version is the "**long**" version.

Several model parameters were changed to see their effect on the results. Some examples of the sensitivity analysis: different numerical solution methods were used, the weighting factors for depth and velocity were changed, different methods for turbulence modelling, different methods for calculating local slope, different hiding/exposure factor formulas, different equilibrium concentrations and different active layer thickness.

4. Evaluation of computational results

Fig. 3. shows the calculated depth averaged velocities (abs(v)) downstream of the third groyne. On the left side (*V_R_30_d0,8*) when modelling a short groyne; in the middle (*V_H_30_d0,8*) a long groyne and on the right side the difference of the velocities of the two (d*V_H-R_30_d0,8*). The area behind the groyne with lower velocities demonstrates the effect of the lengthening of the groyne. It is also considerable that the longer groyne causes an increase of the depth averaged velocity in the whole cross section. The area of the velocity increase greater than 3 cm/s (~219000 m^2) is twice the area of the velocity decrease of the same rate (~118000 m^2). This should draw the attention to the fact that the **lengthening of a groyne causes not only deposition but erosion as well**.

River training structures such as groynes result a deposition area behind the groyne and an eroding area in the narrowed cross section. Both phenomena are desirable for safe navigation. If the deposition area is connected hydraulically with the groundwater it could have an effect on the water quality of the dischargeable bank filtered groundwater. Studies dealing with groundwater quality are often neglecting the effect of erosion. Based on the calculations the deposition and erosion areas are stated compared to the whole studied river section in **Tbl. 1**.

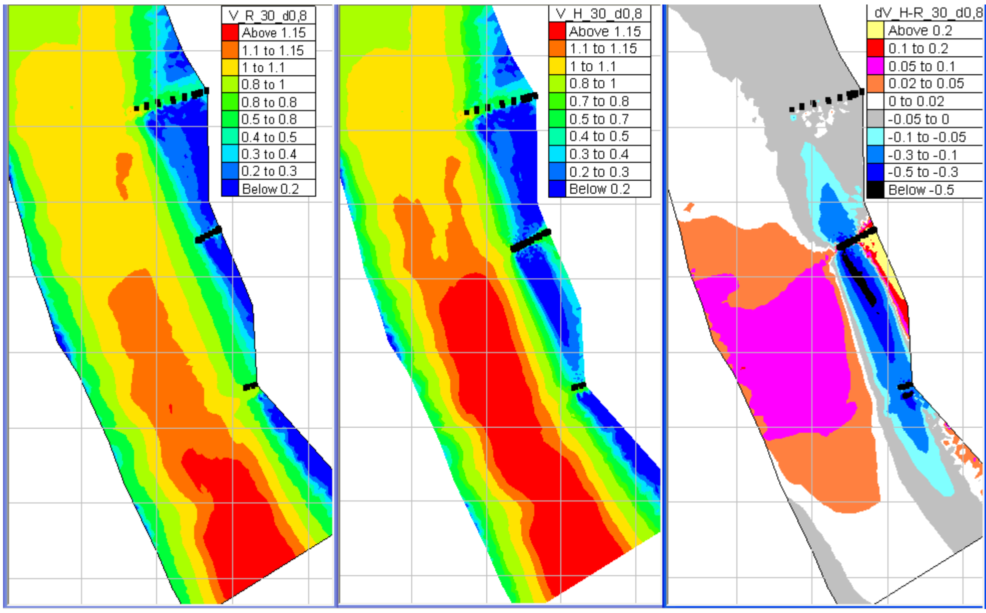

Fig. 3. Calculated depth averaged velocities in case of short and long groyne after 30 days

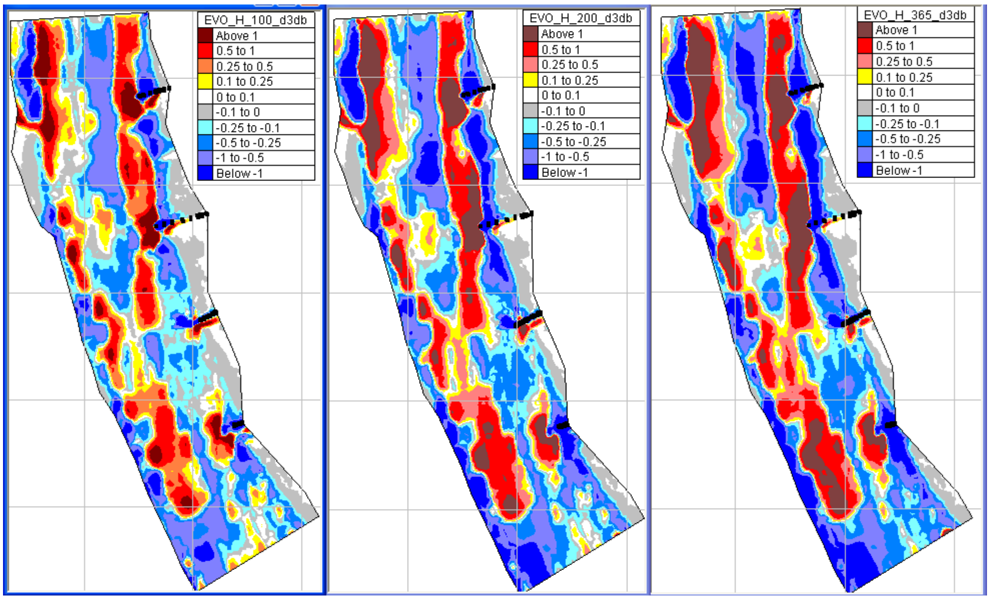

Fig. 4. Evolution after 100, 200 and 365 days in case of long groyne and nonuniform sediment composition

Looking at the column '*long groyne*' it becomes obvious that the eroded area is greater than the area where deposition occurs for all the studied times 100, 200 and 365 days. On the studied rivers section under the above mentioned conditions the area where erosion is calculated cannot be neglected, even if considering computational uncertainties. Based on the velocity distribution assumptions could be made that lengthening of **a groyne causes not only deposition but considerable erosion as well**. This assumption **was proven with hydrodynamic-morphological calculation**. Of course not only the size of the area of morphological changes is essential but its location as well.

	d_nonuni d_m = 0.1 mm 0.4 mm 3.0 mm						***d_uni*** d_m = 0.8 mm		
Total area 1 108 283 m^2	*'long groyne'*			*'difference'*			*'difference'*		
Simulation time, days	100	200	365	100	200	365	100	200	365
Area of deposition dZ_f > 3 cm, %	34.2	36.2	37.5	16.3	16.9	18.5	18.3	19.5	19.2
Area of erosion dZ_f < -3 cm, %	52.4	52.8	52.5	16.4	14.8	13.8	19.5	20.6	21.5
Deposition between 3 and 10 cm, %	4.4	3.8	2.9	11.0	11.2	11.1	9.3	10.0	9.2
Deposition between 10 and 25 cm, %	7.3	5.7	5.7	3.9	4.0	6.0	7.3	7.5	7.8
Deposition between 25 and 50 cm, %	8.7	7.9	7.7	0.7	1.2	1.1	1.2	1.5	1.7
Deposition between 50 and 100 cm, %	10.2	12.1	11.8	0.6	0.3	0.3	0.4	0.5	0.5
Deposition above 100 cm, %	3.7	6.6	9.4	0.1	0.1	0.0	0.2	0.1	0.1
Erosion between 3 and 10 cm, %	7.6	5.1	4.5	11.4	11.4	10.8	11.6	12.5	13.1
Erosion between 10 and 25 cm, %	13.0	9.7	8.2	3.8	2.0	1.5	5.5	5.8	6.2
Erosion between 25 and 50 cm, %	13.9	14.2	13.4	0.7	0.9	0.7	1.9	1.9	1.8
Erosion between 50 and 100 cm, %	13.8	14.2	12.7	0.2	0.3	0.5	0.2	0.2	0.2
Erosion above 100 cm, %	4.0	9.7	13.7	0.2	0.2	0.3	0.2	0.2	0.2
Unchanged area, %	13.4	11.0	10.0	67.3	68.4	67.6	62.2	59.9	59.3

Tbl. 1. Percentage distribution of the calculated evolution for 100, 200 and 365 days, for nonuniform and uniform sediment composition

Fig. 4. shows the evolution in the whole domain, compared with the initial bottom elevation (Z_f) in case of long groyne and nonuniform grain size distribution after 100 (left), 200 (middle) and 365 (right) days of simulation time (*EVO ≡ ΔZ $_f$≡ Evolution).* It is apparent that the areas of less evolution – deposition or erosion below 100 cm – do not change a lot over time (1-3%) see the column '*long groyne*' **Tbl. 1.** On the other hand the areas of extreme evolution – deposition or erosion above 100 cm – change extremely, 2 to 3 times between 100 and 365 days. Other versions (short groyne, uniform grain size distribution) were studied as well where the tendencies are similar to the ones mentioned above, that are not described in detail here.

It seems to be proven that **on the Danube discharges less than 2000 m^3/s have minor effect on the morphology** (see **Tbl. 1.** and **Fig. 1.**). This enables us to **reduce the simulation time**, taking into consideration only the discharges greater than 2000 m^3/s.

In **Tbl. 1.** the effect of the groyne lengthening can be seen in the columns labelled '*difference*' where the differences of deposition and erosion areas (in %) in the stated intervals are calculated. The differences were calculated for 100, 200 and 365 days for nonuniform and uniform sediment and compared to the total area (in %). Looking at the evolution over time in case of a long groyne it is evident that negligible error is made if the smaller discharges are not simulated. This is true for both uniform and nonuniform sediment composition. If calculating the relative evolution the **time periods of low discharge** – in case of the River Danube Q < 2000 m3/s – **can be ignored**, so the simulation time can be decreased. This means in our case 45% time saving.

The relative evolution (the difference of the emerging bottom by long and short groyne) at 200 days changes only slightly until 365 days. For example evolution greater than 10 cm evolves only on 0.88% (deposition) and 1.45% (erosion) of the total area. When evaluating the evolutions greater than 20 cm these areas are 0.18 and 0.45% of the total area. But it always have to be kept in mind when modelling morphological changes that greater errors have to be accepted because of uncertainties of the data and mathematical solution methods (*van Rijn 1984*).

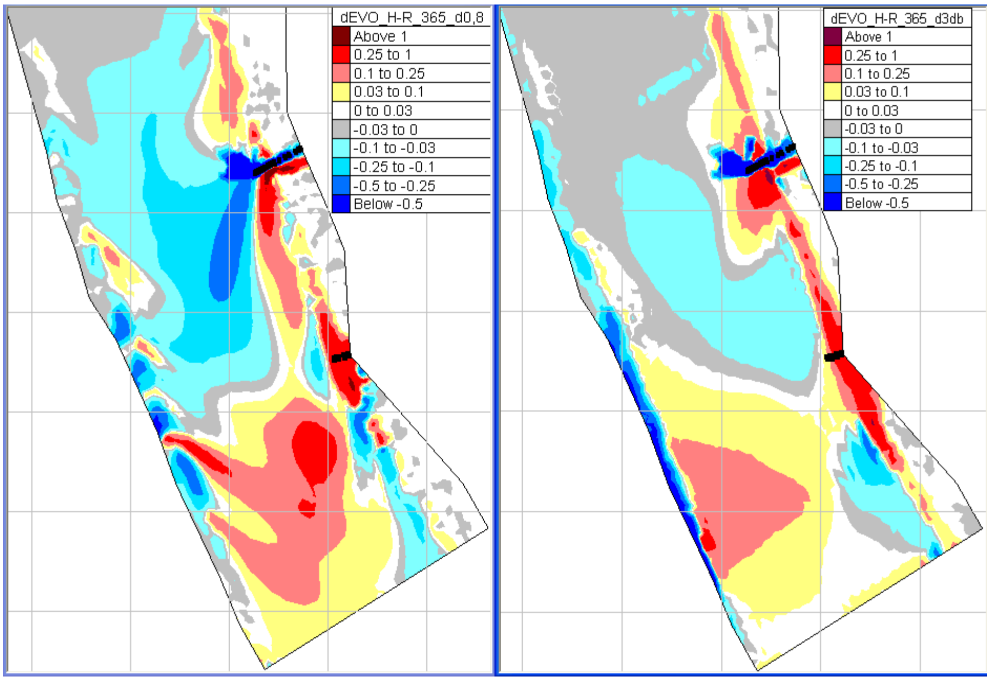

Fig. 5. Relative evolution in case of uniform (left) and nonuniform (right) sediment composition

The effect of the lengthening of a groyne emerges over a longer time period. **Fig. 5.** shows the **relative evolution after 1 year**: subtracting the change in bottom elevation in case of short groyne from long groyne [$dEVO = (Z_{b,365.day} - Z_{b,0.day})_{long} - (Z_{b,365.day} - Z_{b,0.day})_{short}$]. The spatial distribution of the relative evolution is to be seen on the left when modelling with uniform sediment, on the right with nonuniform sediment composition. It obvious, that the sediment composition greatly affects the evolution. When calculating with uniform sediment the extent of the eroded area is greater than that by nonuniform sediment composition (see **Tbl. 1.)**. As we have already mentioned there was no morphological calibration possible, so during evaluation technical thinking and some experience was also a useful basis. Downstream of the fourth groyne the spatial distribution of the evolution varies depending on the used sediment composition (see **Fig. 5.)**. This difference can be explained with the uncertainty of the downstream boundary condition, but not with the lengthening of the third groyne. The last part of the studied river section should therefore not be evaluated or a longer section should have been taken into consideration. In our opinion **a nonuniform sediment composition gives a more reasonable result than the calculation with uniform grain**.

When simulating nonuniform sediment composition the deposition area behind the lengthened groyne appear much more definite, which fits our experience. **Of course in nature the bed material and the bed-load composition are mostly nonuniform**.

The evolving bed material composition is also consistent with the natural bed composition. **On deposition areas the mean diameter of the sediment became less** than the initial d_m=0,86 mm, that means finer particles settled. **On eroded areas** the finer particles were washed away and the **bed material became courser.** There is a strong correlation between **Fig. 6.** – showing the mean diameter of the bed material – and **Fig. 4.** – showing the evolution after 365 days.

Of course spatial distribution of the mean grain size cannot be interpreted in case of uniform grain size.

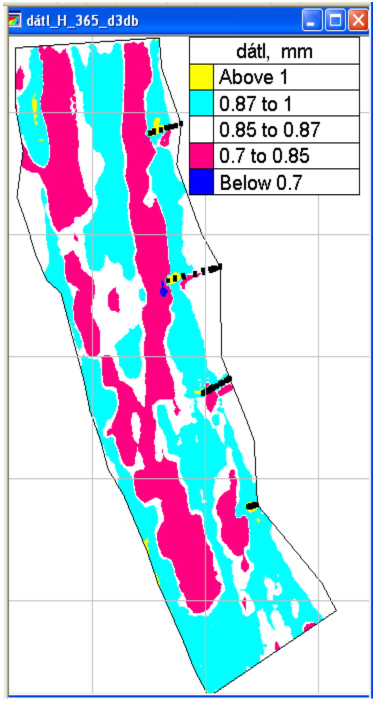

Fig. 6. Mean diameter of bed material

5. Summary

The **main results** of the study are as follows.

- It could be proven that under given conditions the **groyne lengthening causes** not only deposition but on an area of similar extent **erosion as well**. That has to be taken into consideration when studying its effect on a bank filtered aquifer.
- It could also be proven that under **low discharge conditions the morphological changes are not significant**. That means, in the studied case, discharges Q < 2000 m^3/s can be neglected during unsteady calculations. **This could decrease calculation time** significantly, up to 45%.

- It is obvious that a morphological calculation without calibration delivers only tendencies of changes or generalities as a result. It is surprising that even **relative morphological changes due to navigational interactions cannot be quantitatively calculated without morphological calibration**. The calculated difference of the elevations in case of long or short groyne does not give a reasonable result even though the same data and parameters were used in both cases.
- It was observed during sensitivity analysis when changing some **morphological parameters** (such as river bed material or bed-load grain size distribution, active layer thickness) **the relative evolutions differ greatly**. This problem could be solved by morphological calibration of the model.
- Despite known problems **2D modelling can be useful for morphological calculations**. In our opinion if the model is calibrated it gives reasonable results except in the near field of the groyne – where the gradients of the velocities and the turbulences are great.
- **The studied lengthening of the groyne has an effect over a 1 km river section**. Because of the inevitable errors of the boundary conditions about a **4 km river section should be modelled** in similar cases.

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