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Christensen, B.; Jirinec, P.; Larsen, Ole; Paetsch, M.

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MIKE 21C – Morphological and Hydrodynamic Modeling Software and its application on River Loire and Labe

B.B. Christensen[1], P. Jirinec[2], Ole Larsen[3], Matthias Paetsch[3]

1   Introduction

The modelling and simulation of hydrodynamic and morphological conditions of inshore waters requires the implementation of an advanced mathematical modelling system. With MIKE 21C a quasi-3D generalized mathematical modeling system for the simulation of the hydrodynamics of vertically homogenous flows, and for the simulation of sediment transport has been developed. The modeling system has the capability of utilizing both a rectilinear and a curvilinear computational grid. The developed solver makes it feasible to carry out detailed long-term morphological simulations in two dimensions.

The paper presents the numerical techniques and examples of application of the model for the river Loire in France and the river Labe in Czech Republic.

2   Theoretical background

The MIKE 21C model has been developed specifically to simulate 2D-flow, sediment transport and morphological processes in rivers. It is a curvilinear model based on a structured orthogonal grid description of the area of interest. The hydrodynamic part of the model is based on the Saint-Venant equations for 2D depth-integrated flow. Convection, viscosity, pressure gradients, and bed friction are all included. The equations are solved in a curvilinear form in the hydrodynamic model. The curvilinear form is based on a transformation, whereby the velocity field is kept in a Cartesian base, which requires that the variables are co-located in the cell-centre. A semi-implicit pressure-velocity coupling is applied for the solution of the continuity equation.

A separate module accounts for the presence of helical flow. The deviation angle, δ_s, of the bed shear stress from the direction of the mean flow is specified as:

$$\tan \delta_s = -\beta \frac{h}{R_s}$$

See e.g. Rozovskii (1957), Engelund (1974) and Struiksma et al. (1985). R_s is the radius of the curvature of flow streamlines, h is the flow depth, and the coefficient β is defined as:

$$\beta = \alpha \frac{2}{\kappa^2}\left(1 - \frac{\sqrt{g}}{\kappa C}\right)$$

where $\kappa = 0.4$ is the von Karman constant, C the Chezy number, and $\alpha = 1.0$ a calibration constant. For the present model the coefficient β typically varies from 9 – 11.

The relatively weak adaptation in space of the helical flow is accounted for through the solution of an adaptation equation. The physics expressed by the adaptation equation is simply that the helical flow will adjust towards equilibrium over a length scale λ_{sf}, which characterizes the process, i.e.:

$$\lambda_{sf}\frac{\partial(\tan\delta_s)}{\partial s_s} + \tan\delta_s = -\beta\frac{h}{R_s}$$

In regions of changing curvature of the streamlines the secondary flow will adapt gradually. The adaptation of the secondary flow profile is considerably faster near the bottom (where the bed shear stress act) than further up in the water column. Thus, the process of adaptation cannot be characterized by one length scale only. The adaptation length is a function of the water depth and friction number. The following differential length scale λ_{sf} is applied (Struiksma et al. (1985) and Olesen (1987), in the present morphological model of river Loire.

$$\lambda_{sf} = \frac{1.2hC}{\sqrt{g}}$$

The bed material is rather coarse e.g. in the investigated part of the Loire River. This implies that the sediment transport mechanism is completely dominated by bed load, i.e. that the influence of suspended load can be ignored in the modelling. The sediment transport is described by the Engelund and Hansen (1967) formula:

$$S_{BL} = 0.05\frac{C^2}{g}\theta^{\frac{5}{2}}\sqrt{(s-1)gd_{50}}$$

where $s = 2.65$ is the specific density of the bed material, d_{50} is the median grain size, and θ is the Shields parameter. The Engelund and Hansen formula is

originally formulated as a total load model. However, due to the non-presence of suspended load, it can be used directly for the bed load transport.

The transverse component of the bed load transport S_n is calculated, so that it includes the effects from the helical flow and the sloping bed, i.e.:

$$S_n = \left(\tan \delta_s - G \theta^{-a} \frac{\partial z^*}{\partial n} \right) S_{BL}$$

$G = 1.25$ and $a = 0.5$ are the calibration parameters and $\partial z^* / \partial n$ the transverse bed slope.

Along the banks where groynes are present a special formulation is needed for the sediment transport, as the groynes will suppress the sediment transport and keep the sediment fixed. The formulation is based on a supply-limited method. This method requires the definition of a supply-map, i.e. a map that specifies the amount of available sediment given as a thickness Δ_{supply}, and an equilibrium layer thickness Δ_{eq} that defines the threshold for full sediment transport capacity, i.e.:

$$S_{BL}^* = \frac{\min(\Delta_{supply}, \Delta_{eq})}{\Delta_{eq}} S_{BL}$$

where S_{BL}^* is the bed load transport adjusted for the supply-limited effect. The thickness of the supply layer is updated in connection with the morphological update of the bed. The morphological calculations are carried out on the basis of the sediment transport using the Exner equation, i.e.:

$$\frac{\partial z}{\partial t} = -\frac{1}{1-n} \left(\frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} \right)$$

where z is the bed level, t is time and e.g. $n = 0.35$ is the bed porosity.

3   Model application – River Loire

The lower part of the Loire River has groynes and guide walls along the banks. The presence of these structures, in combination with extensive sand mining is responsible for the degradation of the riverbed and the associated decrease in low flow water levels of 2-3 meters over an extended length of the river, primarily due to sand mining. This chapter describes a study of how the hydraulic conditions at low flow can be improved by a reduction in height and the extension of the groynes, i.e. how sediment can be forced to resettle in the main channel and increase low flow water levels.

The modelling is carried out using the two-dimensional curvilinear morphological model MIKE 21C. For the most favourable scenario examined,

where the groynes are modified over a reach of 10 km, an increase of 0.35 meters is obtained for the low flow water levels.

The model area covers a reach of 14 km starting at La Pointe (upper right-hand corner), located just downstream of the confluence of the Loire River and the Maine River, and ending at Chalonnes-sur-Loire (lower left hand corner on the photo mosaic shown in Figure 1).
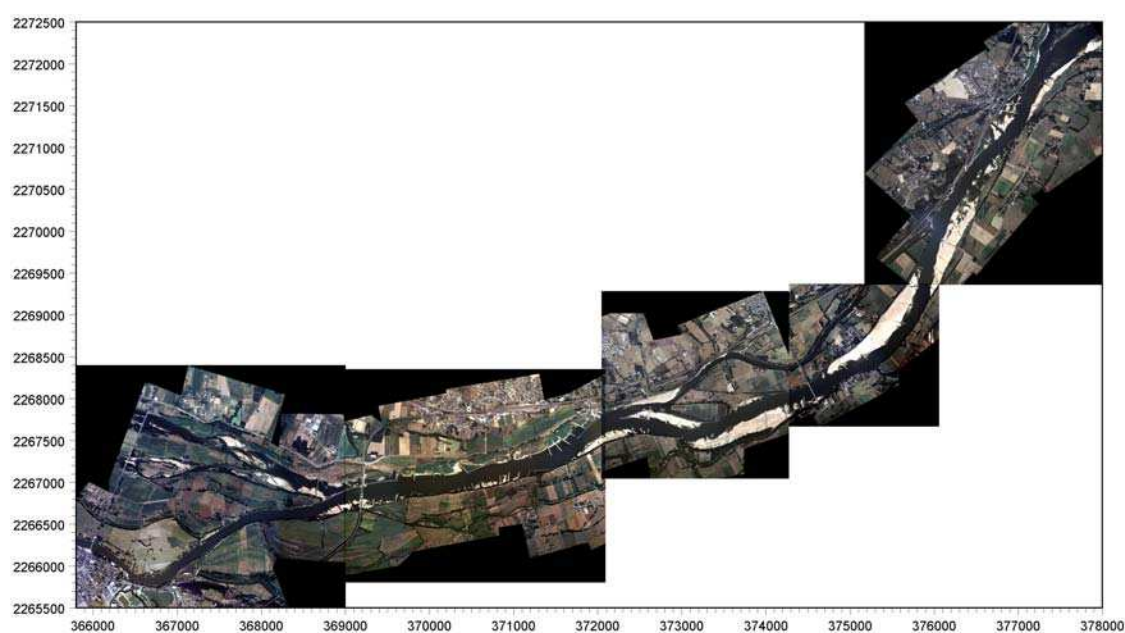

Figure 1: Mosaic of aerial photos of the model area (1999).

The morphological model is run for the selected five-year hydrological period for each scenario in order to investigate and compare the effects of the morphological changes.

The two-dimensional model is primarily established for a study on how a modification/ reduction of the groynes can increase the low flow water levels, without affecting the hydraulic conditions for high flows. The grid resolution is chosen so that the typical meander wave length consists of about 40 points and that a morphological simulation of a five years period can be finished within a reasonable time.
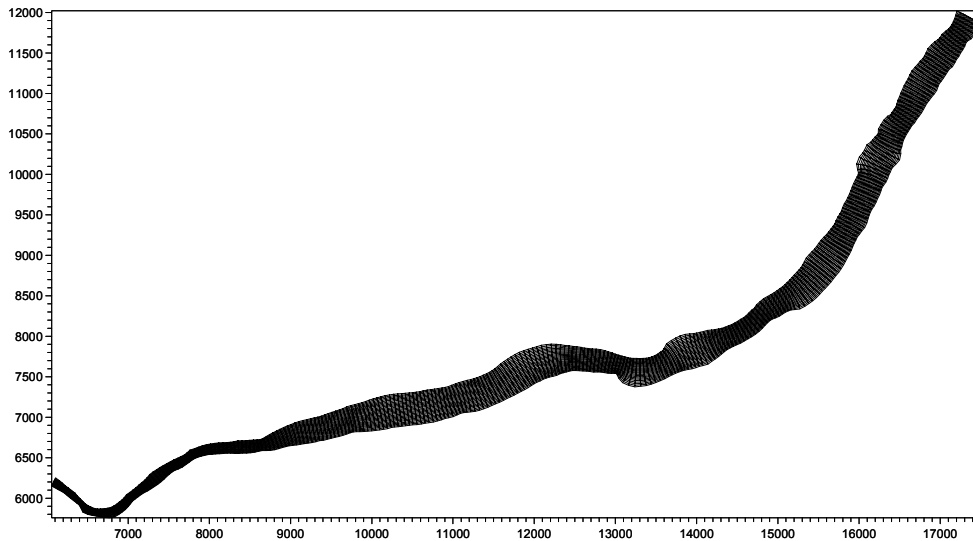
Figure 2: Curvilinear grid used for the 2D model, 297 x 26 grid points.
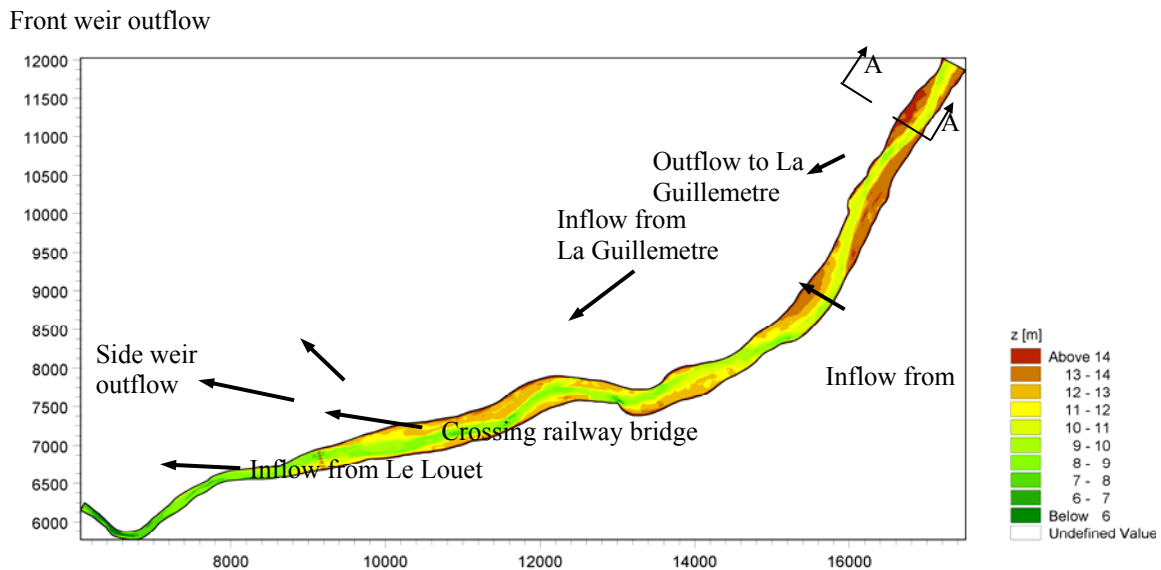
Figure 3: Initial model bathymetry.

The bank lines in the model have been created from digitalized data obtained from the geo-referenced photos. The orthogonal curvilinear grid used for all simulations is shown in Figure 2. The initial bathymetry is created on basis of a bathymetric survey from 1999 and level data from the groyne fields obtained during the summer of 2001. In grid cells with no observations bed levels were obtained by elliptic interpolation of the surrounding points. The base bathymetry that is used as the initial condition for all scenarios is shown in Figure 3. The

locations along the bank lines at which water either flows in or out of the model domain are also shown.

The groyne fields consist of 52 groynes with a total length of 11.1 km along the left riverbank and 47 groynes with a total length of 10.9 km. along the right riverbank.

The sediment in the model is described by single grain size d_{50} = 1.4 mm, which is a reasonable assumption for this part of the Loire River. In the areas where groynes are located a supply-limited formulation is used to describe the sediment transport due to the fact that the sediment is maintained in these regions.

Four morphological scenarios(1-4) have been defined in order to investigate the impact from modified groyne extension and height on the hydraulic conditions, i.e. water levels at low flow. The first scenario (1) simulates the existing conditions, which are used as reference case. In the second scenario (2) the extension of the groynes has been reduced so that the width of the main channel will grow from a typical width of 130 meters to a width of 180 meters. The third scenario (3) is identical to the second scenario except for the groyne height, which is reduced by 0.5 meters. The fourth scenario (4) simulates a system where all groynes and guide walls have been removed on the first 10 km of the modeled reach.

The morphological development and adaptation to the modified groyne field is illustrated in Figure 4 showing cross sections obtained after one and two years for all four scenarios. The location of the cross sections is marked by A-A in Figure 3. From the plots, it is seen that the river only needs one flood season to adapt to the modified groyne field, and that the impact from the succeeding floods has only a modest influence on the shape of the cross section. For the free system where all groynes have been removed, it is seen that the transverse bed slope decreases with time. This is due to migration of the alternating bars, which are free to move. The third scenario is expected to have a more favorable effect on the low flow water levels than the second scenario. The reason for this is that the modest reduction in the groyne height allows a larger amount of sediment to be released from the groyne fields without affecting the width of the low flow channel.
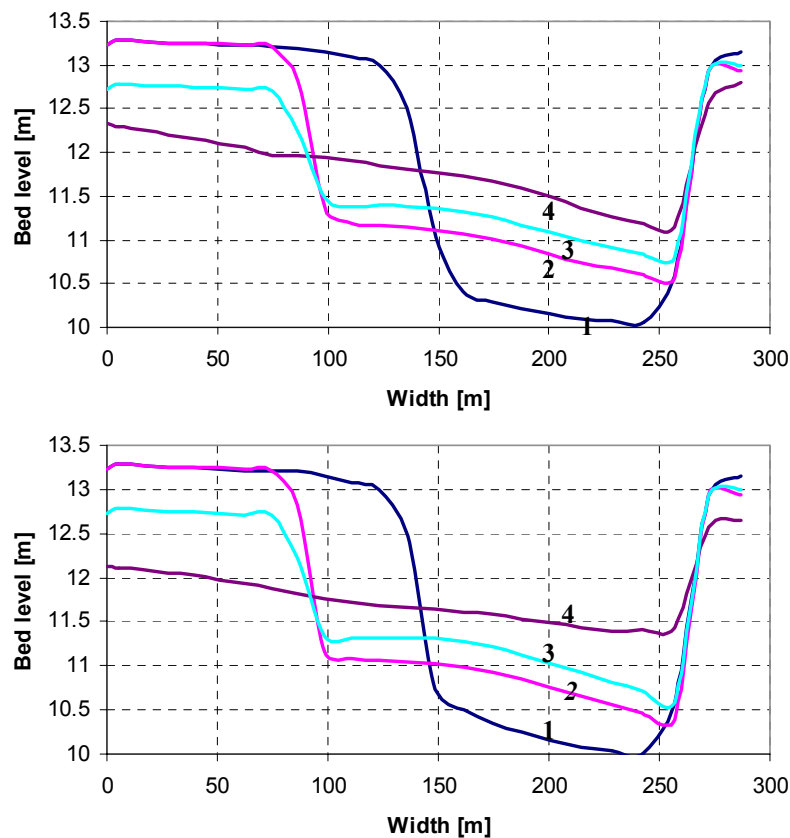
Scenarios 1-4

**Figure 4:** Cross sections obtained after one year (top) and two years (bottom).

The migration of the alternating bars in the free system can also be seen in Figure 5 that shows contour plots of the obtained bed levels after three years. From the plot it is seen how the river responds to the changes of the groyne fields. It is seen that the width of the main channel increases as expected in scenario two and three contemporary with the deposition of sediment in the old main channel.

For the free system, it is seen that the alternating bar pattern gets more pronounced. This implies that the flow in the low water channel in general runs a longer distance than the water in the three other systems.

An estimate of the effect on the Q-H relation can also be obtained from a simple analytical approach. This approach is based on a resistance equation, e.g. Manning or Chezy, and assumes equilibrium sediment transport in compound rectangular channels. Basically, it compares the resistance in a typical cross section in the existing system and a groyne modified cross section. However, the problem with this kind of analysis is that it typically exaggerates the effects on the longitudinal water surface profile. This is mainly, because it does not include the impact from spatial depth-variations on the conveyance, or helical flow and

gravity effects on the sediment transport. Another ignored effect is the weaker meandering of the main channel (caused by the wider channel), which is responsible for a shortcut effect, i.e. the flow will have to run a shorter distance in order to get from point A to point B. All the above mentioned effects are included in the two-dimensional morphological model.
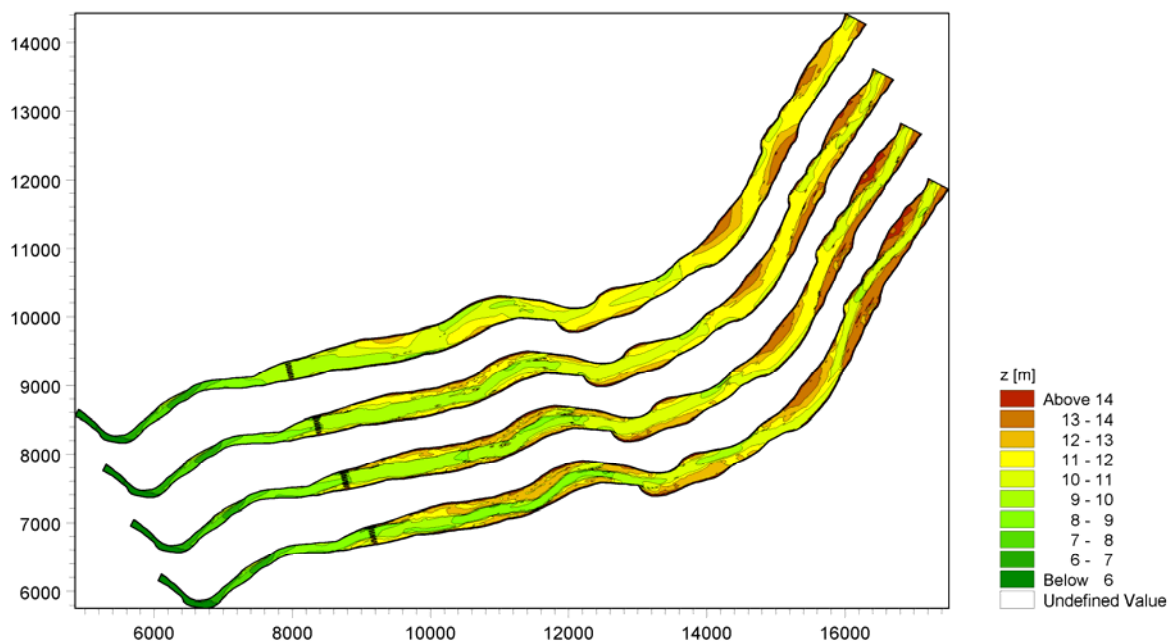

Figure 5: Bathymetries obtained after three years. From top: system where groynes have been removed completely (4), system with reduced extension and height of groynes (3), system with reduced extension of groynes (2), and system with existing conditions (1).

In Figure 6 the low flow part of the Q-H relations are presented for the four systems after one year and three years, respectively.

It is seen that the modification of the groyne fields has a favorable impact on the Q-H relation for low flows, but also for high flows where water levels are slightly lower than in the existing system.

By comparison of the Q-H relation obtained after one and three years, it is seen that the most significant Q-H adjustment takes place during the first flood period. However, some minor changes are seen on the Q-H relations in Figure 6.b. This indicates that the system is adjusted by two time scales. A short time scale for the lateral exchange between the groyne fields and the main channel (of the order one year), and a longer time scale for the time it takes to bring the longitudinal system in equilibrium by adjustment of the sediment flow passing through the system.
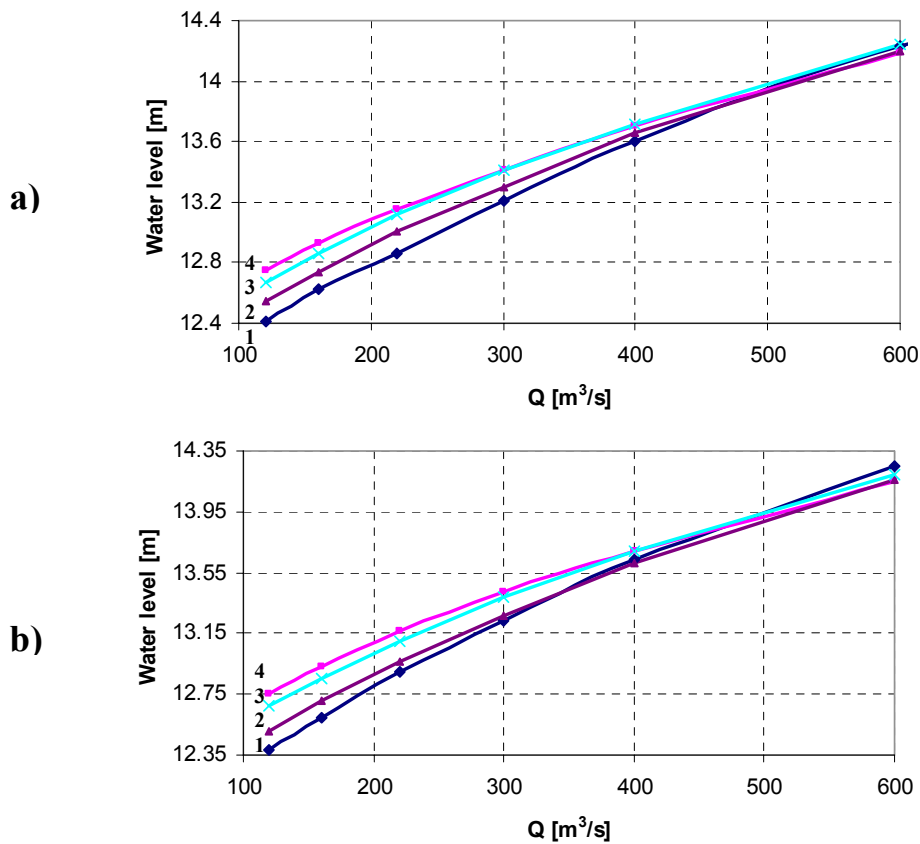
Figure 6: Q-H relations obtained for the four scenarios at La Pointe, a) after one year, b) after three years. 1: existing system, 2: reduced extension of groynes, 3: reduced height and extension of groynes, 4: free system.

Summarizing it can be stated that three model scenarios with modified groyne fields were examined and compared with a model scenario of the existing system. For all three systems a more favorable Q-H relation was obtained with an increase in the low flow water levels up to 0.37 meters. This height corresponds to an increase in the water surface slope from $2.22 \cdot 10^{-5}$ to $2.56 \cdot 10^{-5}$ or a 15 % increase.

The best result was obtained for the free systems where all the groynes have been removed. However, scenario three where the extension and height of the groynes are reduced obtained almost as favorable results, and this scenario must be considered as the most applicable.

4   Model application – River Labe

A detailed flood flow model was created for Labe River and in its flood plain in 265 km long river reach between Hradec Kralove and Czech Republic/Germany

border. The whole modeled area (including 24 barrages and other water constructions) was covered by curvilinear computational grid of size 26 348 x 400 points (with grid density from 2 to 15 m) and was divided into 8 sub-models. Basic inputs for the model construction were digital elevation model and detailed channel shape from measuring boat. Flow parameters (e.g. surface elevation, depths and velocity distribution) were calculated for flood discharges from HQ_1 to HQ_{100}. Simulation results are presented in maps in scale 1 : 10 000, which completely cover the whole flooded area and in detailed longitudinal profiles. Based on calculated hydraulic characteristics conceptual proposal of flood protection was prepared.

The similar detailed model was used for flood flow study (reconstruction of severe flood from August 2002) on Vltava River in Prague. Many different variants of flood protection measures were evaluated on this model. Based on calibrated model the "set of flooded area maps" for emergency operations during various flood events was created. In other studies the most probable scenarios of flood protection measures collapse were taken into account and suddenly/continuously flooding of the city was simulated.
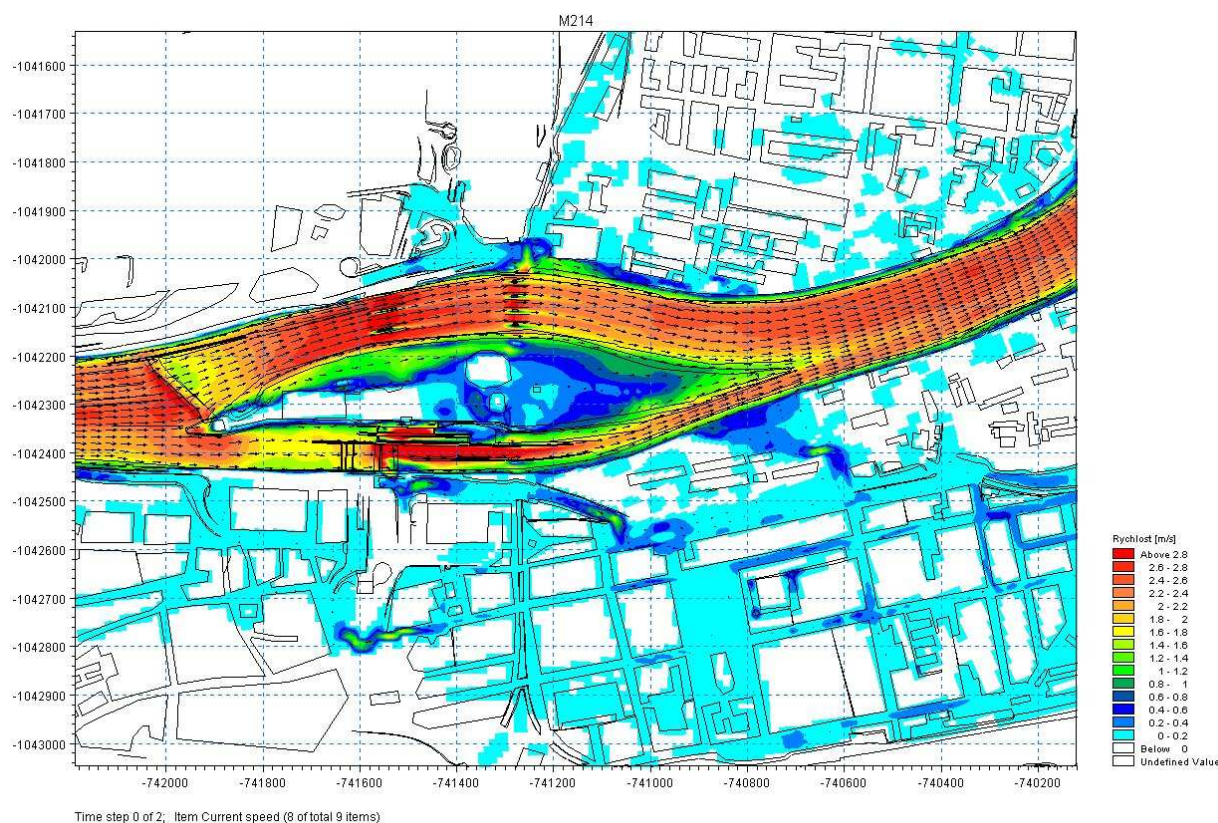
Figure 7: An example of the velocity fields – flood mapping in Prague

The following examples of the results are presented (Fig. 7 - Fig. 9) showing that MIKE 21C 2D technology definitely increased the predicative ability of

models because the combination of flood depths maps with velocity fields predefined more or less exactly the risk zones during the floods and these results are very valuable for preparation of flood management plans and evacuation planning maps.
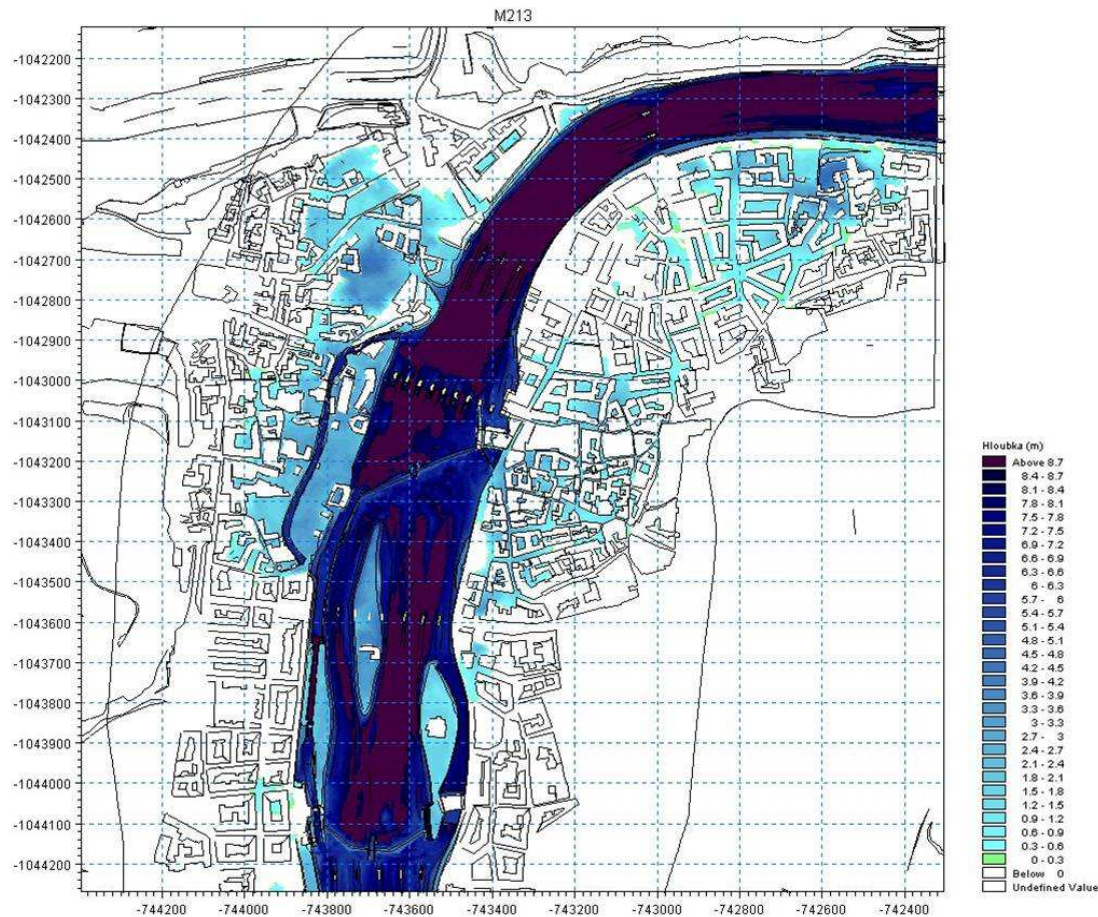

Figure 8: An example of the depths mapping in Prague

As a disadvantage of 2D approach could be taken the fact, that the length of computational time was so enormous, that it made the fully dynamic computations actually impossible.

Nevertheless the benefit of the 2D approach was undoubtable and it was obvious, that it is only question of time, when the hardware development enables fully dynamic simulations as well.

Flood line simulated by the model was compared with a real one (from aerial photographs from August 2002 – See Fig.9). Both lines are very close, so we can state, that mathematical model simulation was successful.
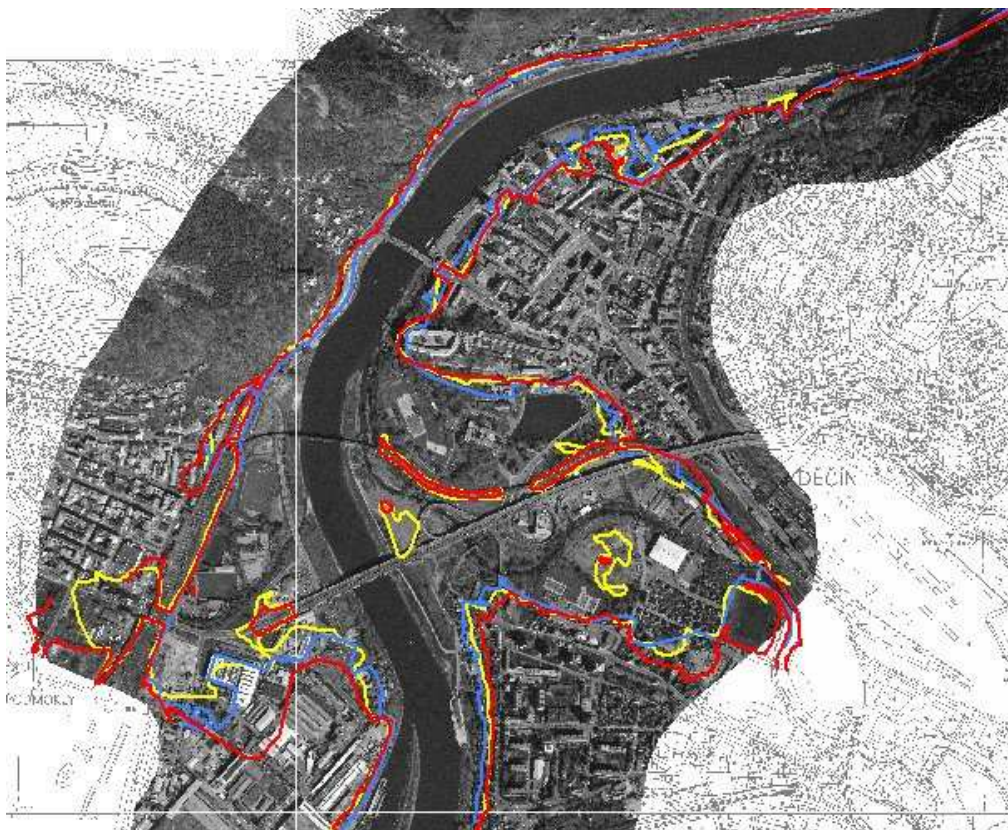
Figure 9: The comparison of real flood extension - water levels (red line – simulated line for predicted discharge, blue line - the reality of flood 2002/8, maximum flooding envelope evaluated from airborne photogrametry) – source the Elbe River Basin Authority – 2002

The 2002 flood fully proved the usefulness of mathematical models for flood protection at any stage, for the flood measures design process, for improving the flood forecasting , for producing easily understood maps and charts for improving the rescue activities. Mathematical model MIKE 21C now have became an integral part of Flood Protection scheme in Czech Republic.

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Autoren:

B.B. Christensen[1], P. Jirinec[2], Ole Larsen[3], Matthias Paetsch[3]

[1]DHI Water and Environment, River and Flood Management Department, Agern Allé 11, 2970 Hørsholm, Denmark; email: bbc@dhi.dk

[2]DHI Hydroinform a.s. Na Vrších 5/1490, 100 00 Praha 10, Czech Republic, email: p.jirinec@dhi.cz

[3]DHI Water and Environment, Wiesenstrasse 10a, 28857 Syke, Germany, email: ola@dhi-umwelt.de