Very high resolution numerical modelling for inland waterway design

Regina Patzwahl, Jacek Jankowski, Thomas Lege
Department of Hydraulic Engineering in Inland Areas, Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany

ABSTRACT

The paper discusses the advantages and disadvantages of numerical modelling of rivers with a grid of very high resolution using the new MPI version of UnTRIM as the computational engine. The main aim of the investigation is to assess the economy of this approach taking especially into account the effort required for the mesh generation and its modification, which is usually laborious in the case of coarser meshes requiring exact reproduction of structure lines defining the flow. In the first step the results of a low-resolution Telemac-2D grid are compared to the results obtained for the same river stretch topography with a high-resolution UnTRIM model. In the second step the results of two- and three-dimensional modelling applying a high-resolution mesh based on a high quality digital terrain model are studied. It is concluded that under the assumption of appropriate computational resources readily available, the high-resolution modelling reduces significantly the effort required for the initial model set-up and for adjustments due to changes in the model topography. The calibration, parametrisation and validation of the models is simplified without affecting the accuracy, freeing the engineer to concentrate on the project aims and not bypass the weak points of the methodology.

Keywords: UnTRIM, high-resolution numerical modelling, three-dimensional modelling

1 INTRODUCTION

1.1 *Situation of German lowland rivers*

Since centuries, the big free flowing lowland rivers of Germany have always been important inland waterways for commercial navigation. They flow mainly through alluvial plains and are presently almost completely regulated by river training works (mainly groynes, longitudinal dykes and riprap) in their navigationally relevant stretches. Large areas of the original floodplains are transformed into dyke-protected farmland eliminating the otherwise existing possibilities of lateral erosion. The upper sections and the tributaries are often cut off by barrages, usually leaving the lower parts of the river with a deficit in sediment supply. In the long term, the resulting imbalance in the natural sediment transport causes erosion in the main river channels. These problems are interleaved with flood-protection and agricultural aspects as well as environmental issues concerning free-flowing rivers and their adjacent areas. A well-known example of these issues is the fact that in the eyes of present-day society the percentage of fluvial areas in their natural state is too small, leading to e.g. renaturation of agricultural land or realignment of straightened river courses.

In order to balance these manifold, seemingly competing interests of the modern society, detailed planning and expert consultancy based on the forecasts of the hydraulic consequences of waterway engineering and management are necessary. Therefore, the need for further optimisation as well as improving the efficiency of the waterways maintenance and development methodology is caused not only by the needs of modern commercial shipping, but also by nature conservation requirements. In consequence, this is connected with a growing responsibility for assuring the quality of forecasts. In this field, BAW (Federal Waterways Engineering and Research Institute) performs model investigations and renders expertise for the Federal Waterway and Shipping Administration of Germany and conducts applied research aimed to improve the required methodology.

1.2 *Aims and methods*

The aim of this contribution is to assess critically the advantages and disadvantages of the high-resolution computational fluid dynamics (CFD) modelling approach based on engineering applications concerning the works on stretches of the River Elbe (Germany). For these stretches adequate sets of reference data from in-situ measurements, results of other modelling approaches, recent digital terrain models as well as experiences from century-long consultancy work are readily available. This combination allows a multifaceted assessment of the achieved results and applied modelling procedures, also taking into account the economy of an engineering project in terms of reducing unnecessary work time expenditure.

Our investigation for this purpose is structured as follows. First, a comparison between an existing two-dimensional model of lower resolution and a high-resolution model of the same area is made. Then, two- and three-dimensional model runs concerning another stretch of the River Elbe with adequate reference data are performed. Additionally, the study is aimed for validation of the new parallel version of the code we use, UnTRIM.

1.3 *Motivation for high-resolution CFD modelling*

The growing availability of high performance computing in combination with the efficient implementation of parallelisation methods in simulation programs allow the application of a very fine spatial discretisation to facilitate new, modern inland waterway design. The terrain topography is represented with the very high resolution necessary to resolve all hydraulic relevant structures. Very high resolution means that for modelled waterway stretches of about 10 km length meshes with a horizontal discretisation of approximately 2 m (i.e. smaller than the width of groyne ridges) are generated, resulting in about a million of computational cells for the two-dimensional and a few million cells for the three-dimensional hydrodynamic modelling.

Although the mesh is unstructured, the cell dimensions are kept as equal as possible all over the computational domain in order to obtain a very high mesh regularity diminishing the spatial discretisation error of the applied mathematical scheme. Additionally, this meshing approach has advantages by pre-processing the geometrical data simplifying drastically the treatment of any structure lines describing e.g. river training structures like groynes or longitudinal dykes. They can be adequately represented in this high resolution without the necessity to lose the mesh regularity there. The topography of the mesh can be obtained directly and in an efficient way from digital terrain models (DTM) of the study area.

Because all structures relevant to hydrodynamics are represented by the mesh itself, changes in topography (e.g. due to modifications in river training measures in combination with flow optimisation for ecologic reasons) do not cause disturbances in the regular grid structure, which means eliminating grid effects from the list of undesired influences on numerical modelling results. Moreover such a topography independent grid saves work time resources of the project engineer assessing a choice of river training measures by the application of a hydrodynamic numerical model.

1.4 *Introduction to UnTRIM*

UnTRIM is the result of a long-term, systematical research concerning computationally efficient, robust and stable numerical algorithms for studies of hydraulic environmental problems, conducted by V. Casulli and his co-workers in the last two decades. UnTRIM is a practical mathematical scheme for solving the three-dimensional Navier-Stokes equations with a finite difference/volume spatial discretisation, a semi-implicit, fractional time step integration with a semi-Lagrangian treatment of advection using an unstructured, orthogonal staggered grid with horizontal levels (Casulli, 2002). The application domain of UnTRIM are the geophysical, three-dimensional, non-hydrostatic, transient environmental free surface flows with its appropriate boundary conditions.

The orthogonality of the base horizontal mesh of UnTRIM means that the segments joining the circumcentres of adjacent mesh polygons - in the present implementation triangles or quadrilaterals - must have an orthogonal intersection with their common sides. The severity of this purely geometrical condition is diminished by the existence of well-optimised and sophisticated generators for orthogonal meshes (Lippert, 2006) and the fact that if the meshes are kept regular (when mesh polygon dimensions vary gradually in the domain), the user is rewarded with a second-order discretisation error in space. The highest accuracy is achieved when the grid is additionally colinear with the expected net flow streamlines and the semi-implicit scheme is equally balanced between time levels.

Paired with the overall computational efficiency, the numerical properties indicate UnTRIM as a well-designed scheme for this specific kind of high-resolution modelling, in which unstructured meshes are required. This fact spawned efforts for parallelising the code using the mesh decomposition methods and the message passing interface (MPI, 1995) for the communication between the mesh partitions (Jankowski, 2007), well-designed for massively parallel computers. The achieved speedup encourages UnTRIM application for highly resolved river models.

It must be mentioned that due to its algorithmic structure, UnTRIM is equally applicable for both three-dimensional non-hydrostatic or hydrostatic as well as two-dimensional, vertically averaged flows just by changing a few numerical parameters, but still using the same horizontal base mesh.

2 COMPARING A LOW-RESOLUTION TO A HIGH-RESOLUTION MODEL

The first aim is to find out what the differences in handling, post-processing and overall model behaviour of a high-resolution CFD model in comparison to a "standard" low-resolution one are.

2.1 *Model set-up "Coswig"*

For this purpose an orthogonal quadrilateral, flow aligned grid (≈ 2m edge length) of a 13km-long stretch of River Elbe in Germany is set up. In this area an elaborate and well-calibrated two-dimensional mesh for the CFD code Telemac-2D (Galland et al., 1991, Hervouet, J.M. and Bates, P. (Eds.), 2000) with an edge length ranging from 10 to 20m already exists (see *Acknowledgements*). The 2x2m grid, covering the last 13km of the 25km-long Telemac-2D model, is generated with the grid generator JANET (Lippert, 2006, smile consult, 2007) and the topography of the actual Telemac-2D mesh interpolated onto it. The resulting mesh consists of 740000 polygons. It should be mentioned, that while the generation of a coarser grid (including reproduction of structure lines defining the flow) is a matter of weeks, the generation of a high-resolution mesh, a high-quality digital terrain model provided, is a matter of days.

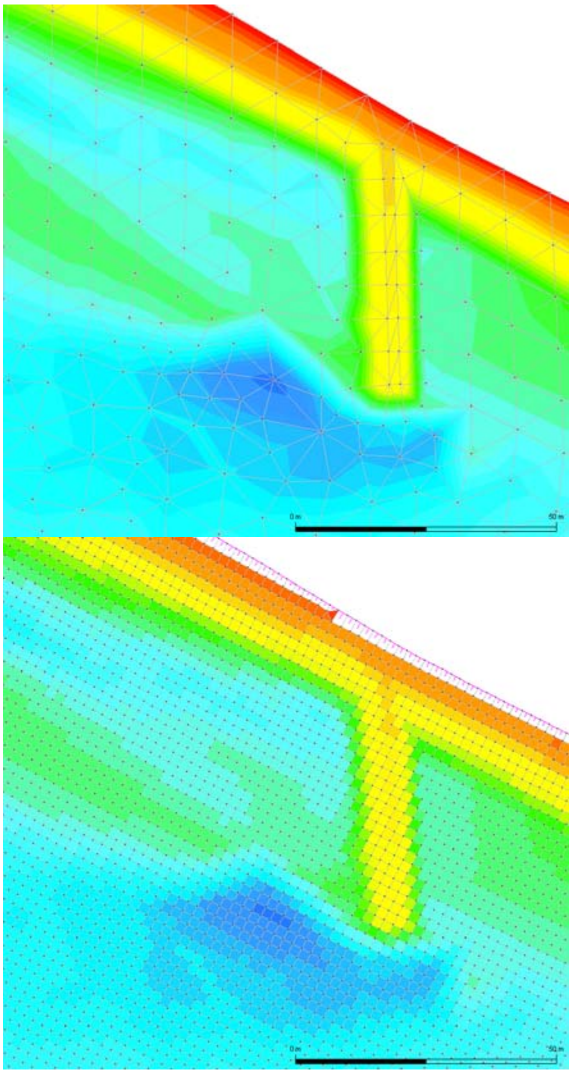

Figure 1. A cut-out of grid for Telemac-2D (≈10-20m edge length, above) and orthogonal quadrilateral, flow aligned grid (≈ 2m edge length, below). Note the scale.

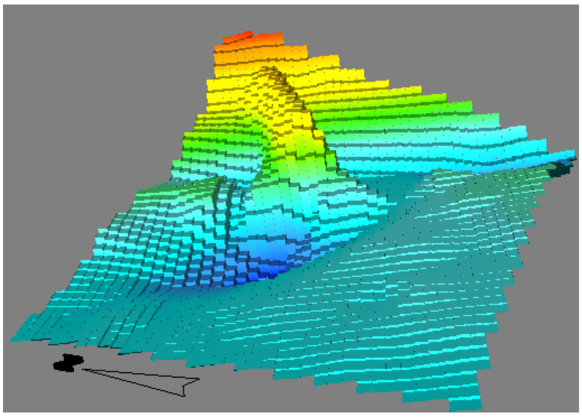

Figure 2. A 3D-view of a groyne and its scour in the River Elbe bed. Direction of flow from right to left.

2.2 *Roughness distribution*

In exact analogy to the investigations with Telemac-2D three discharge scenarios (denoted GlQ, MQ, 2MQ; see table 1 for parameters) were computed applying UnTRIM in two-dimensional mode. To start with, a constant Nikuradse roughness coefficient k_s for the whole model area was applied.

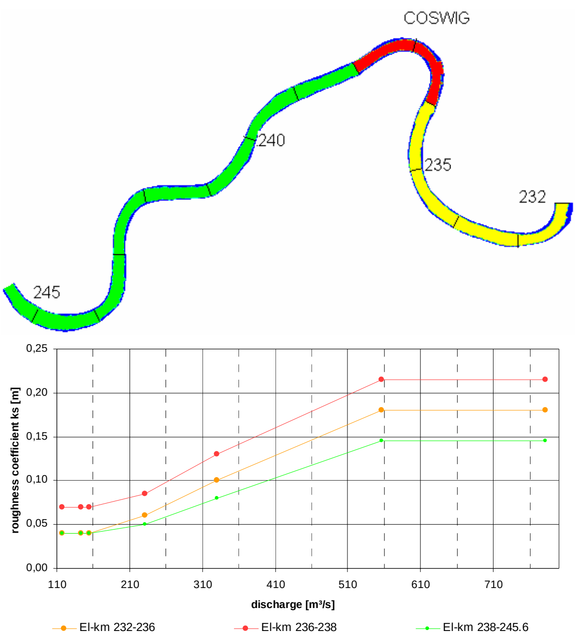

Figure 3. Zonal (above) and discharge dependent Nikuradse roughness coefficient k_s (below) for Telemac-2D model of the River Elbe kms 232 – 245.

The values were taken from the elaborate roughness distribution for the coarser Telemac-2D model (figure 3). The adequate calibration of the coarser mesh with water level measurements requires a spatial distribution of roughness to parameterise the insufficient representation of form and volume as well as to diminish the effects of simplifications due to the two-dimensionality of the model.

2.3 *Discharge dependent roughness*

As discharge and therefore flow velocity and energy in the system increase, turbulence increases as well. The two-dimensional simulation cannot take into account the increased need for energy dissipation. The Nikuradse roughness coefficient (k_s) has to be increased in both cases in order to fit the measured water level. Table 1 lists the characteristic parameters for low, mean and twice the mean discharge (GlQ, MQ, 2MQ).

Name	Discharge [m³/s]	k_s (Nikuradse) [m]	Time step Δt [s]	CPU time/ Δt [s]
As-is state, Variant 2a, steady-state bound. condition				
GlQ	143	0.04	1.5	0.4
MQ	360	0.125	1.5	0.5
2MQ	720	0.18	1	0.5

Table 1. Computing parameters for the two-dimensional numerical studies on River Elbe kms 232 - 245. 64 partitions (eq. processors) were used and steady-state was reached after 8h simulation time.

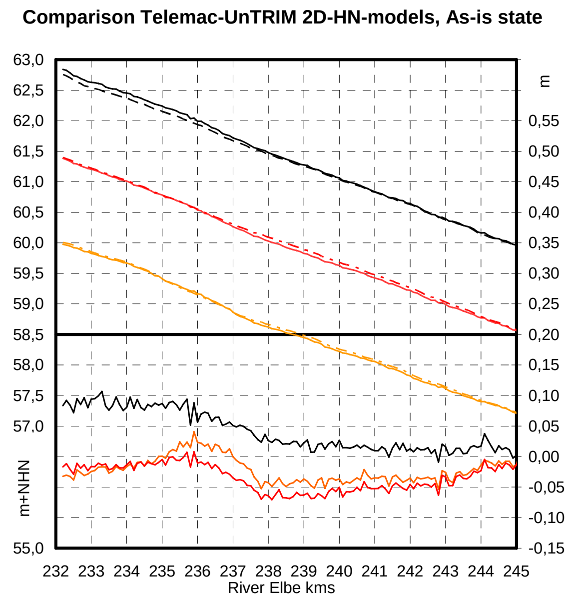

Figure 5. Result for Telemac (solid line) and UnTRIM (dashed line) model. Yellow: GlQ, red: MQ, black: 2MQ. Above: total water level computed, below: the difference between the two models.

Figure 5 shows the resulting water level extracted along the river axis for a better comparison. If we accept a deviation of 5cm as within the limits of measuring accuracy the results obtained from the UnTRIM high resolution model are comparable with the results obtained from Telemac. The most important deviation results from the fact that the inlet of the UnTRIM model is close to the hydraulic demanding bends following River Elbe km 232. For highest discharge rates the influence of secondary currents and sloped elevation cannot be sufficiently taken into account by the two-dimensional model.

2.4 *Grid independent changes in river topography*

In order to test the assumption that implementation of river measures to be assessed in the model is less costly in terms of labour as no grid adjustments should be necessary, a variation of a group of groynes extending from River Elbe kms 232,5 to 236 which was already fully implemented in a Telemac-grid was interpolated onto the 2x2m-UnTRIM grid.

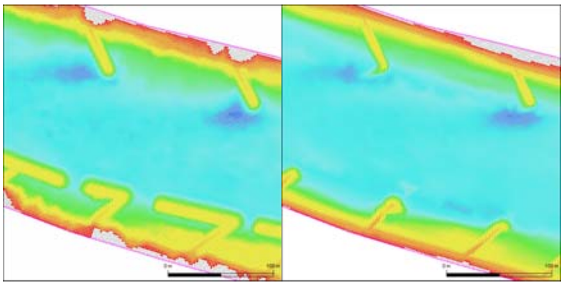

Figure 6. Detail of the as-is state (to the left) and implemented groyne modification (to the right).

The river training measure was designed to equalize flow conditions along the bend. The amount of change in water-level does fit the results obtained by the Telemac computation within an acceptable range for the lowest and medium discharge rate. The as-is-state UnTRIM model under-estimates the water level compared to the Telemac results at the highest discharge rate for the strong influence of three-dimensional effects in the bend, not covered by the chosen constant roughness coefficient in the whole area.

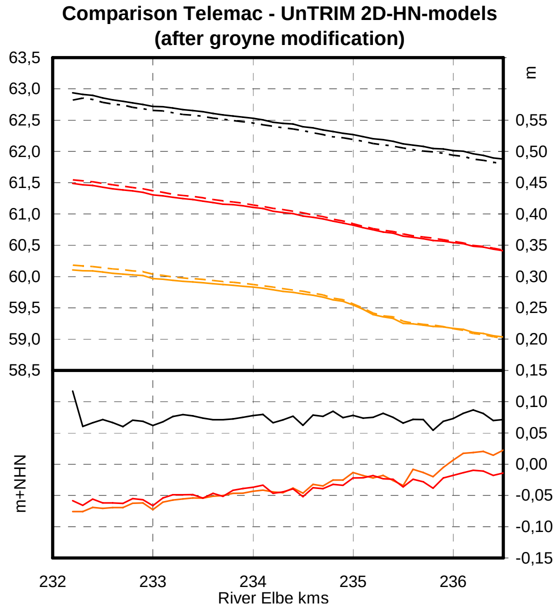

Figure 7. Result for Telemac model (solid line) and the UnTRIM model (dashed line) for Variant 2a. Yellow: GlQ, red: MQ, black: 2MQ. Above: total water level computed, below: the difference between the two models.

3 COMPARING TWO-DIMENSIONAL AND 3D-MODELLING

3.1 *Model set-up”Klöden”*

The numerical model covering the Elbe up- and downstream the village of Klöden extends from Elbe kms 185.5 to 196.6 and includes the lowland. The lateral model boundaries are defined by the dykes. The grid is designed as unstructured, mainly quadrilateral, orthogonal grid. The model is divided into three zones of grid resolution: river channel extended by a belt 30m wide, area of proposed small scale measures as e.g. groyne adjustment is represented in a very high resolution 2x2m flow aligned grid (A), lowland, area of proposed large scale measures as e.g. re-activation of river backwater is represented in a 5x5m grid (B), the remaining part of the lowland is represented by 10x10m polygons (C).

Figure 7. Application area between the River Elbe kms 185.5 and 196.6.

The seams between areas of different mesh discretisation are realised using belts of triangular elements. A digital terrain model (DTM) provided by the BfG (2007) for the River Elbe is the base for topographic interpolation onto the grid. Its resolution amounts to 2x2m. Hydraulic effective structures, e.g. groynes, are to be completely reproduced by 2x2m mesh polygons, no further structural adjustment was made. Dykes are represented by mesh elements. However in order to meet the hydraulic requirements of a training measure, the dykes are revised by a tool supplied by the grid generator JANET (Lippert, 2006, smile consult, 2007), which marks the dykes as hydraulic routing structure. Unlike the Coswig grid, where river bed topography is already smoothed by the coarser Telemac grid, the river bed topography for the Klöden grid is reproduced exactly as scanned by depth-sounding and therefore very rough in itself. The overall model consists of 1,3 million mesh polygons, the 2x2m-zone contains about 750000 mesh polygons. The volume for the river bed represented by the UnTRIM mesh differs from the volume determined by the DTM by only 500m³ resulting in a mean deviation in depth of 0.1mm.

3.2 *Two-dimensional modelling*

In order to save execution time and to keep files as small as possible for discharge rates lower than bank-full discharge the 2x2m grid was cut out and applied for model runs.

Three representative discharge rates and according water level measurements which are in good accordance with the period of time of river bottom sounding were chosen. The shortcuts MNQ, MQ and 2MQ are applied to distinguish between low water, mean-flow and double the mean flow discharge. See table 2 for further details on numerical parameters and discharge rates.

Name	Discharge [m³/s]	k_s (Nikuradse) [m]	Time step Δt [s]	CPU time/ Δt [s]
two-dimensional, steady-state boundary condition				
MNQ	165	0.009	1.5	0.4
MQ	398 (360)	0.04	1.5	0.5
2MQ	734	0.07	1	0.5
3D non-hydrostatic, steady-state bound. condition				
GlQ	121	0.033	1.5	1.5
	165			
MQ	285		0.8	1.7
	312			
	360			
2MQ	734		0.5	2.4
	837			

Table 2. Computing parameters for the 2D and 3D non-hydrostatic numerical studies on River Elbe kms 185.5 - 196.6. 64 partitions (eq. processors) were used in general and steady state was reached after 8 h simulation time.

Two-dimensional runs for all three discharge rates with a constant, discharge dependent Nikuradse roughness coefficient k_s for the whole model area confirm what is implied by the studies with the “Coswig”-grid: the better river bottom topography and volume are represented in the grid, the lower the roughness coefficient and simpler the zonal roughness distribution employed.

While the water level is well fitted to the measured water level in the northern half of the model (figure 8), in the southern half of the model, where flow conditions are much more extreme the water level is constantly under-estimated. The difference increases of course with increasing discharge, as pointed out in 2.3.

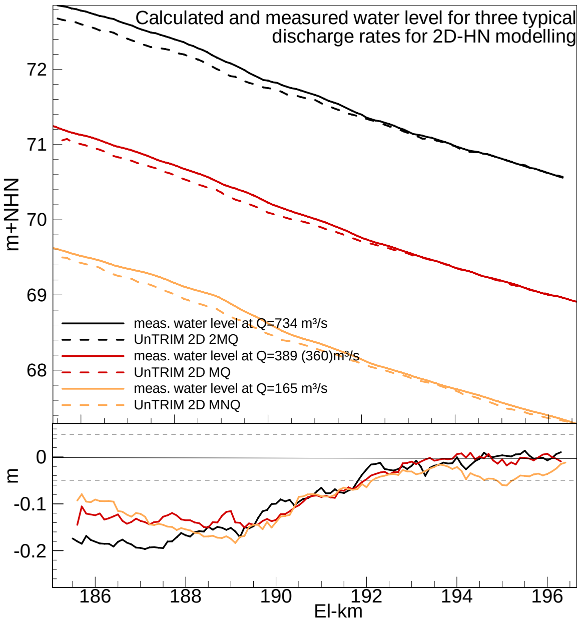

Figure 8. Above: Calculated (dashed line) and measured water level (solid) for three discharges, k_s(MNQ)=0.009m, k_s(MQ)=0.04m, k_s(2MQ)=0.07m. Below: Difference between calculated and measured water level.

In order to proceed the two-dimensional modelling, a discharge dependent zonal roughness model analogue to what is discussed in 2.3. has to be set up. However, as the misfit obviously is connected to that part of the model where 3D flow is dominant, applying 3D-dimensional non-hydrostatic modelling in order to avoid any kind of roughness distribution lies at hand.

3.3 *Non-hydrostatic 3D modelling*

The basic parameters for 3D non-hydrostatic computing with UnTRIM are: a set of horizontal layers (Δz=0.5m), a turbulence model based on mixing length leading to depth-dependent vertical eddy-viscosity, a constant horizontal eddy-viscosity set to ν_{hor}=0.4m²/s and the Nikuradse roughness coefficient k_s=0.033m for all discharge rates, which accords to 2D90 for this stretch of River Elbe. See table 2 for more numerical parameters.

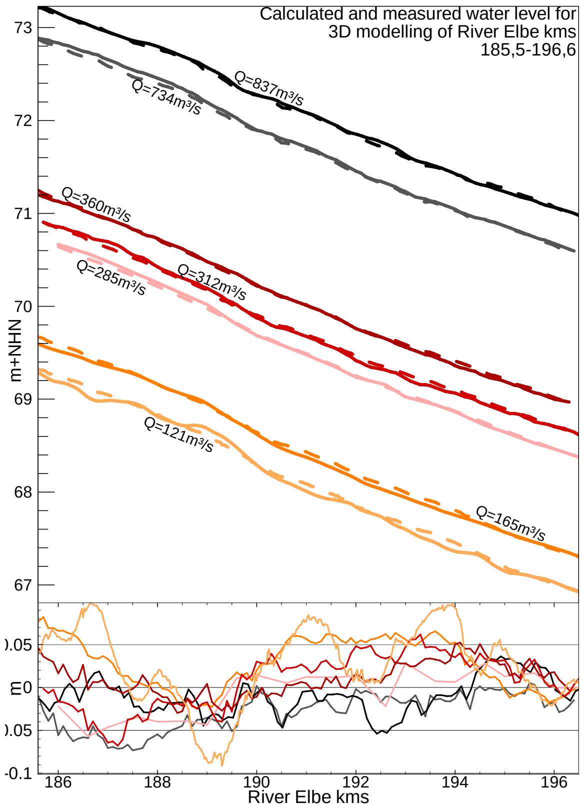

Figure 9. Above: Calculated (dashed line) and measured water level (solid). Below: Difference between calculated and measured water level.

Figure 9 shows the results for the 3D-computation for various discharge rates. For the lowest discharge rates the fit is not as good as for higher ones but mostly within the limits of 5cm deviation from measured water level. It is an approved fact that river bed morphology of the River Elbe changes with discharge. The higher discharge rates, the coarser the bed-form. The river bed echo-sounding was preceded by a period of discharge rates of MQ to 2MQ. A river bed not suiting low discharge rate and thus a slightly too high roughness coefficient might be an explanation.

Tying the roughness coefficient to a constant and physical meaningful value leads to better data constraint. Inconsistencies in the boundary conditions show up early during calibration.

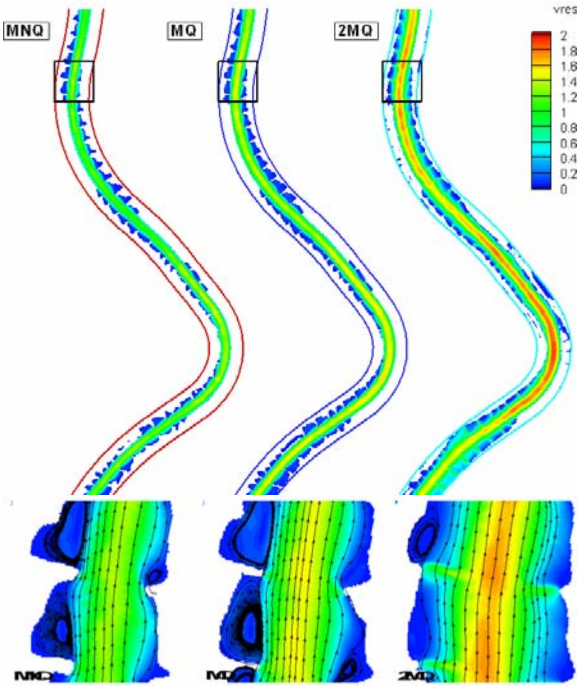

Figure 10. Above: Depth-integrated velocity from post-processing for MNQ, MQ and 2MQ for 3D-HR-HN computation. Below: Streamline traces. Values for water depth h < 0.05m are blanked.

Figure 10 shows the distribution of the depth-integrated velocity (from post-processing) for the three discharges and a zoom into the flow field.

3.4 *Applying changes in topography*

Figure 11 shows a simplified possible connection of River Elbe backwater. The grid remains unchanged whereas the depth assigned to the polygon edges is modified.

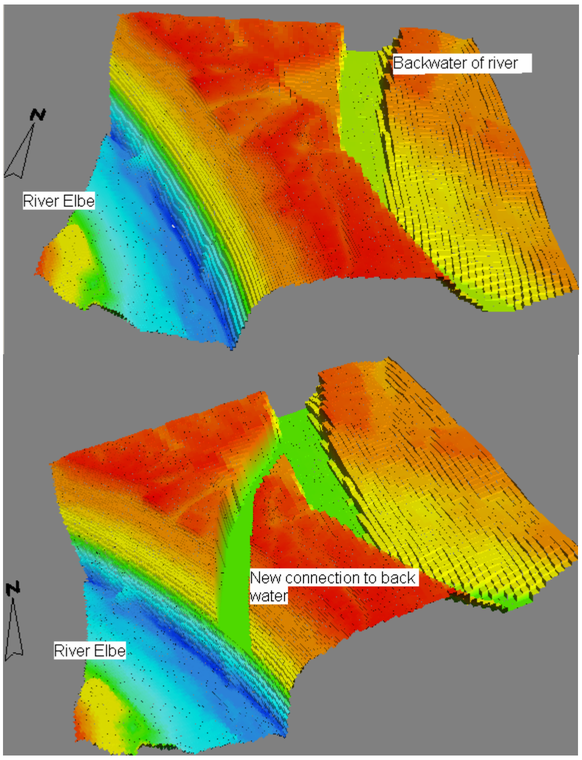

Figure 11. A simplified example for implementation of large scale river design into the HR-grid. Length of connection amounts to 210m.

4 DISCUSSION

The two-dimensional computational results for the high-resolution “Coswig” model lie within reasonable limits of the results of a thoroughly calibrated Telemac-2D model with lower resolution. While the mesh with lower resolution needs to be calibrated by zonal and discharge dependent roughness coefficient the high-resolution model provides reasonable fit of water-level with one discharge dependent k_s for the whole model.

Two- and three-dimensional modelling of the high-resolution grid “Klöden” lead to reasonable results for water level employing a constant Nikuradse roughness coefficient k_s for the whole river bed (2D) and for all discharges (3D).

In the two-dimensional computation the value is much lower than for coarser models. This is due to the fact that form drag and insufficient volume representation no longer need to be parameterised by roughness.

What is left of actual roughness can be ascribed to grain drag, provided that 3D flow is not dominant in the section as can be observed in the results for the two-dimensional modelling of "Klöden". Water level fit is very good where flow conditions are moderate.

Three-dimensional computation of the flow field provided reasonable results for all discharges and additionally for those areas where the river is characterised by strong bends with strong 3D flow-influence.

Reducing roughness to one mean value for the whole river bed stretch and for all discharge rates means less working expense in calibrating using zonal roughness distribution and gives better constraint to data and computing results. In consequence, the computing of time dependent boundary conditions which is important for flood assessment becomes a straightforward task.

The most important advantage from the point of view of a practitioner is the fact that any river training measure under assessment can be easily implemented into the grid. The grid remains unchanged and one escapes the obnoxious question whether the obtained result is due to river training measures or a simple grid effect.

The only noticed disadvantage compared to dealing with coarser meshes is size of files to be handled by pre- and post-processors and the graphic software for analysis and presentation of the results.

5 CONCLUSION

A high-resolution grid for CFD modelling means less effort in mesh generation, less effort in calibration and, in consequence, needs lower expenditure of human labour, but increased need for computational efficiency and power, which must be readily available. Running a 3D-modell requires less detailed modelling experience of hydraulic processes prevailing in the actual river model. The professional focus can be set on solutions and their assessment instead of parameterisation and its validation.

ACKNOWLEDGEMENTS

The authors thank Birgit Bleyel (BAW), who applied the Telemac-2D model for the River Elbe kms 220 - 245 (near Coswig) in the framework of an ongoing consulting project, for making her results available for this contribution.

REFERENCES

Casulli, V., Zanolli, P. 2002. Semi-implicit numerical modelling of non-hydrostatic free-surface flows for environmental problems. *Mathematical and Computer Modelling,* 36:1131 – 1149.

Galland, J.-C., Goutal, N. and Hervouet, J.-M. 1991. TELEMAC: A new numerical model for solving shallow water equations. *Adv. Water Resources*, 14 (3), 138-148.

Jankowski, J.A. 2007. Further developments of UnTRIM: parallel implementation and its verification. *Proceedings of the Fifth International Symposium on Environmental Hydraulics (ISEH V),* Tempe, Arizona, USA.

Lippert, C, Sellerhoff, F. 2006. Efficient generation of orthogonal unstructured grids. *Proceedings of the Seventh International Conference on Hydroscience and Engineering (ICHE 2006),* Philadelphia, PA, USA.

Message Passing Interface Forum. *MPI: A Message Passing Interface Standard.* University of Tennessee, Knoxville. Version 1.1, June 12, 1995, http://www-unix.mcs.anl.gov/mpi/.

smile consult GmbH, 2007. http://www.smileconsult.de.

The German Federal Institute for Hydrology (BfG) 2005. Aktuelle Fernerkundungsprojekte an der Elbe. *Praxisorientierte und vielseitig nutzbare Fernerkundungseinsätze an der Elbe.* Kolloquium, Magdeburg, Germany.

The TELEMAC Modelling System, 2000. Special issue of: *Hydrological Processes*, Vol. 14 (13). Eds.: Hervouet, J.-M. and Bates, P.