NUMERICAL MODELLING OF SEDIMENT TRANSPORT IN CONNECTION WITH ARTIFICIAL GRAIN FEEDING ACTIVITIES IN THE RIVER RHINE

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Abstract: The bed evolution of the stretch of the River Rhine between km-812.5 and km-821.5 is characterised by general bed degradation as a result of the river training works and dredging activities of the last two centuries. The degradation of the river bed affects the water levels, and so the navigation conditions. To combat the erosion of the river bed with the aim to keep up the shipping traffic and to avoid the ecological system damages due to water level reductions, sand-gravel-mixtures were added to the river (so called artificial grain feeding activities). This paper presents the results of an application of a graded sediment transport model in order to study morpholodynamical characteristics due to artificial grain feeding activities in the river stretch. The finite element code TELEMAC2D was used for flow calculation by solving the 2D shallow water equation on non-structured grids. The sediment transport module SISYPHE has been developed for graded sediment transport using a multiple layer model. The needs to apply such graded sediment transport approaches to study morphological processes in the domain are discussed. The calculations have been carried out for the case of middle water flow and different size-fraction distributions. The results show that the grain feeding process could be well simulated by the model.

Keywords: Numerical Model; Graded sediment; Morphodynamical simulation; Rhine River

1. INTRODUCTION

One topic of the 5th International Symposium On River Sedimentation "Sediment Management" held in Karlsruhe during April 1992 was the artificial grain feeding in the Rhine downstream the Barrage Iffezheim. It was especially dedicated to the concepts and strategies concerning morphological problems in German waterways. Without grain feeding the completed service life of the Barrage Iffezheim is not to be guaranteed. Like a barrage the canalization of its tributaries too disturbs the bed-load balance of a river. The bed-load deficit downstream the measures leads to enforced erosion along the river. Faced to the problems of high erosion of up to 5 cm per year along the lower Rhine river and increasing maintenance costs along the river more recently, and particularly since the completion of a study on the erosion of the bed of the river Rhine, the Ministry of Transport, Building and Housing arranged a huge program of sediment management along the river.

The Wesel-Xanten stretch of the River Rhine between km-812.5 and km-821.5 is one of the Rhine stretches with complex geometrical and hydro-morphological characteristics. Due to the river training works and dredging activities of the last two centuries along the Rhine and especially in this stretch, the river bed is in a more ore less continuous degradation process. The bed degradation causes the reducing of river water levels, and so the hindering of navigation conditions. With the goal of achieving a "dynamic bed equilibrium" along the freely flowing Rhine in this so-called "Rhine bed erosion report" various stretch-specific measures were suggested with a special emphasis on artificial grain feeding. In order to prepare the artificial grain feeding at Wesel exemplarily for further supply measures along the Lower Rhine and to gain locally differentiated information on the reaction of the bed to artificially supplied bed load, in the period of March 2000 to July 2001 a pilot test was performed. By means of this in-situ test with its deepened monitoring of bed deformation and transport behavior and accompanying numerical models the relevant parameters and boundary conditions are to be compiled, which are necessary for an effective and efficient dimensioning of such dynamic bed-stabilization measures.

The demands from the sediment management on sediment transport modeling by means of numerical models are to be attributed to the fact that the influence of feeding or withdrawal of bed material on the development of the river bed is very small and effects of the measures on the bed deformation downstream not immediately are provable by instrumentation. Also, the uninfluenced bed development is not solely predictable on the basis of nature data. In order to be able to plan grain feeding measures more in detail, the employment of numerical sediment transport models offers itself. Such models predict the development of the river bed with and without feeding and can be inserted for the proof of the spacious and long-term effect of the measures or for the optimization of the operational business close to the construction site.

The TELEMAC system is a numerical simulation software using the finite element method, that was developed initially at the Laboratoire National d'Hydraulique, a department of the research branch of Electricité de France. It is now a joint effort of several research teams in Europe. The TELEMAC system consists of several programs dealing with various simulation purposes as e.g.:

- TELEMAC2D provides the hydrodynamics: depth-averaged velocity and water depth. It solves the 2D-depth-averaged shallow water equations coupled with transport equations for turbulence quantities.
- TELEMAC3D solves the 3D Navier-Stokes equations with a free surface. The program is able to deal with the effects of a vertical density resulting from temperature and salinity fluctuations.
- SUBIEF is a water quality module to simulate the transport of dissolved substances and suspended sediment.
- ESTEL deals with underground saturated and non-saturated flows.
- Programs ARTEMIS, TOMAWAC and COWADIS are used for wave simulation.
- SISYPHE is a sediment transport module to calculate bed elevation change due to bed-load transport for the case of quasi-uniform bed materials.

All the physical phenomena treated by the different modules of the TELEMAC system generally interact, e.g. the hydrodynamics may generate sediment transport, which modifies the topography and hence has an influence on the hydrodynamics. The system is one of the common platforms enabling industrial studies and multidisciplinary research. More details on the system and its applications can be obtained from Hervouet, et al. (2000) and LHF (1997).

This paper presents the results of the development of the coupled TELEMAC2D-SISYPHE system for graded sediment transport and an application of the model to study morphodynamical features, and then especially to analyse and control the grain feeding measures in this stretch of the Rhine. The works have been carried out within the frame of a co-operation research contract between the Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, and the Institute for Hydromechanics (IfH), University of Karlsruhe.

2. PILOT PROJECT "ARTIFICIAL GRAIN FEEDING AT WESEL"

The observed bed-load deficit as well as the proven mass losses of the bed of the Lower Rhine downstream the mine-specific lowering area up to the Dutch-German border amount to 120000 - 140000 m^3/a (BMVBW, 1997). In order to combat the river bed erosion and to improve navigation among others at the site Wesel an annual quantity of 50000 m^3 feeding material was supplied. Further, a pilot project has been set up to investigate the factors effecting on the artificial grain feeding in this river domain, to improve the so far obtained knowledge and gain more experience over a longer period of time. An amount of 150000 m^3 angular bed-load material was supplied for a 2-year-period in the project domain extending from Rhine km-814.2 to km-817.9.

Within the feeding range the partitioning in tracer (feeding range I) and main quantity (feeding range II), marked in Fig.1, was made. Within range I (from km-816.9 to km-817.9) 42600 tons of quarzporphyr as tracer and within range II (from km-814.2 to km-816.8) 202700 tons of Basanit and 7300 tons of hard limestone as real bed-load material were added.

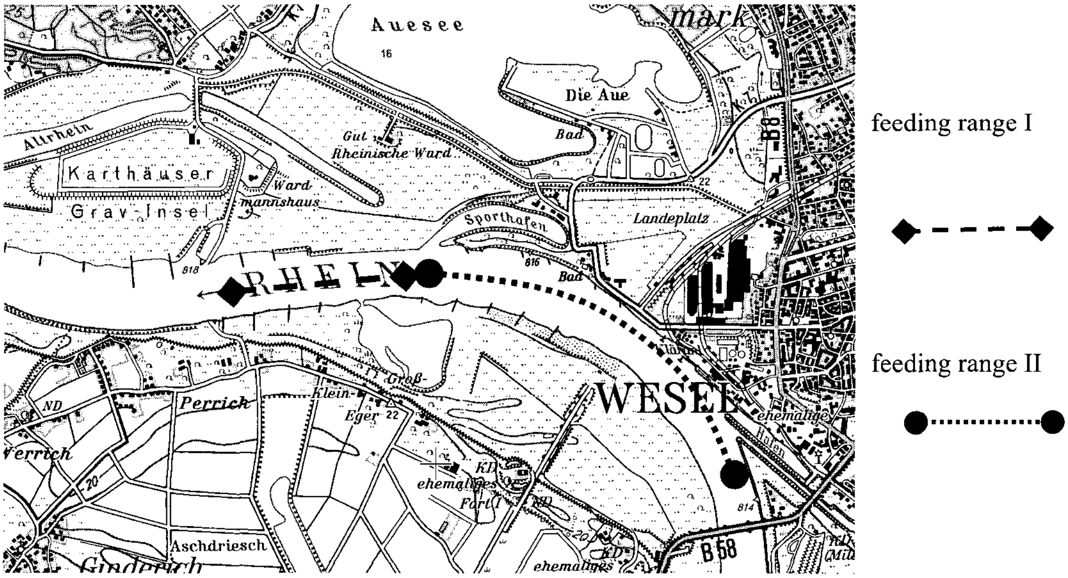

Figure 1. Map of the Rhine river near Wesel and artificial grain feeding location

3. NUMERICAL MODEL

The flow module TELEMAC2D is based on finite-element numerical schemes solving the 2D shallow water equations on triangular unstructured grids. A first-order approximation of time derivatives with a semi-implicit scheme is used in the program. TELEMAC2D solves the system of discretized equations at each time step using iterative preconditioned conjugate gradient method associated with element by element storage techniques in order to save core memory. In the model, bed roughness is represented by using the Strickler or Nikuradse formula respectively. For the calculation of the turbulent dispersion the so-called Elder model is recommended.

The sediment transport module SISYPHE uses the results of the flow computation to undertake simulation of bed-load transport and bed elevation change. SISYPHE offers various bed-load transport formulae, such as Van Rijn, Meyer-Peter and Müller, Einstein-Brown and Bijker, and others. The bed elevation change calculation is based on the mass-balance for sediment (LHF, 1997). The former version of SISYPHE assumed uniform bed material. In order to take into account the influence of grain size distribution of the bed-surface on the evolution of the bed topography and consequently also on the flow field, the SISYPHE was developed for fractional sediment transport using a multiple layer model, which is described in the later part of the paper.

In the coupled TELEMAC2D-SISYPHE system, the flow and sediment-transport modules communicate through a quasi-steady morphodynamic time-stepping mechanism: during the flow computation the bed level is assumed constant and during the computation of the bed level the flow and sediment transport are assumed invariant to the bed level changes. In general the time step for the bed level computation can be much larger than the time step for the flow computation. Furthermore, the bed level change after one time step is often small so that the modification of the flow field is so small that a simple flow adjustment model can be applied. An often used method is the continuity correction method. In this method the distribution of water discharge and the water level is assumed to be the same as those in the previous step. The water depth and the velocity field change only due to the bed level change (see Bui Minh Duc, 1998). The internal coupling between TELEMAC2D and SISYPHE has been based on these assumptions.

3.1 Modelling graded sediment

3.1.1 Multi-layer model

For graded bed material the sediment-transport rates depend on the bed-material composition, which itself depends on the history of erosion and deposition rates. In the model the bed is divided into an active layer and several substrate layers (Fig.2). The active layer and the first substrate layer (active stratum) constitute the so-called mixing layer. These layers may have different grain size distributions. Sediment particles are continuously exchanged between flow and the active layer. Sediment particles are exchanged between active layer and substrate when the bed scours or fills. When erosion occurs, some of the material that belonged to active stratum layer becomes part of the active layer, whose grain size distribution thus may change. On the contrary, deposition of sediment particles on the bed surface layer leads to an upward displacement of the active layer. Some of the material that belonged to active layer becomes part of the active stratum layer. The grain size distributions may change in the active and also in substrate layers.

3.1.2 Sediment transport capacity

The total bed load rate, Q_b for graded sediment is computed by using the formula :

$$Q_b = \sum_{j=1}^{N} Q_{b,j} \tag{1}$$

where N = number of size classes; and $Q_{b,j}$ = capacity for each size fraction. In SISYPHE $Q_{b,j}$ for a particular fraction of graded sediment is computed by using the bed load function of Meyer-Peter and Müller (1948) with some modifications by introducing a so-called hiding / exposure factor accounting for the reduction or increase of the transport rate of a particular size fraction when it is part of a mixture.

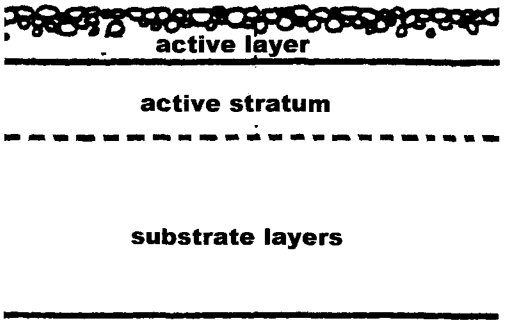

Figure 2. Multiple layer approximation of graded sediment transport

In the processes of graded sediment movement, the coarser particles on the bed have a higher chance of exposure to the flow. The situation is reversed for the fine particles on the bed due to the fact that they are more likely sheltered by coarse particles. This effect is called hiding / exposure effect. These effects result in a smaller critical bed shear stress for larger grains and a higher critical bed shear stress for smaller grains. Until now, most of the studies on graded sediment transport are based on introducing some kind of correction factors to account for this hiding / exposure effect and use these factors to modify the existing formulas of uniform sediment transport. Mostly they are based on experimental results. The hiding / exposure factors not only correct the critical bed shear stress but may take also some other effects of gradation into account. In this paper the hiding / exposure factor is computed by using the following function proposed by Karim and Kennedy, Holly et al. and others (see Holly and Odgaard, 1992):

$$Q_{b,j} = \beta_j \xi_j Q_{bt,j} \; ; \quad \xi_j = \left(\frac{d_j}{d_M} \right)^{\alpha} \tag{2}$$

where α = dimensionless coefficient of order one, that will be used later for model calibration; $Q_{bt,j}$ = theoretical bed load capacity for a bed containing only sediment of the size class j, evaluated using an appropriate bed load function such as proposed by Meyer-Peter and Müller (1948):

$$Q_{b,j} = 8 \left[\left(\frac{C}{C_{90}} \right)^{3/2} \theta_j - \theta_{cr} \right]^{3/2} \left(\Delta g d_j^{\,3} \right)^{-1/2} \tag{3}$$

$$\theta_{cr} = 0.047$$

in which C_{90} = grain related Chézy value; θ_j = fractional Shields parameter; θ_{cr} = critical Shields value; Δ = relative density; d_j = fractional grain size; and d_M = geometric mean grain size.

3.1.3 Variations of Streambed Elevation

The bed deformation due to the j -th fraction of sediment ($\partial Z_{b,j} / \partial t$) is calculated from the mass balance equation:

$$(1-P)\frac{\partial Z_{b,j}}{\partial t}+\nabla \cdot \vec{Q}_{b,j}=0 \tag{4}$$

where P = porosity of the bed material; and $\vec{Q}_{b,i}$ = fractional bed load flux. The total bed deformation ($\partial Z_b / \partial t$) is then determined by :

$$\frac{\partial Z_b}{\partial t}=\sum_{j=1}^{N}\frac{\partial Z_{b,j}}{\partial t} \tag{5}$$

3.1.4 Mixing Layer Composition

The key concept of multi-layer modelling is that of a mixing-layer, where the flow picks up the sediment to be transported and receives the sediment that the flow is unable to transport. The active-layer can be reduced into finite elemental volumes, of thickness E_m. The mass conservation for a size class j of particles in the active-layer volume is then:

$$(1-P)\frac{\partial(\beta_j E_m)}{\partial t}-(1-P)\frac{\partial Z_{b,j}}{\partial t}-S_{F,j}=0 \tag{6}$$

where $S_{F,j}$ = active-layer floor source term, which represents the exchange of sediment particles between the active-layer and the active-stratum control volumes due to active-layer floor movement.

The mass of a particular size class j in the active-stratum control volume may change only due to active-layer movement, i.e. due to exchange of material between the active-layer and active-stratum, while the active-stratum floor elevation remains unchanged. This is expressed by a mass conservation equation for a particular size class in the active-stratum control volume:

$$(1-P)\frac{\partial\left[\beta_{s,j}(Z_b-E_m)\right]}{\partial t}+S_{F,j}=0 \tag{7}$$

where $\beta_{s,j}$ = active-stratum size fraction j; Z_b = bed elevation; ($Z_b - E_m$) = active-layer floor elevation, i.e. active-stratum ceiling.

The active-layer floor source term $S_{F,j}$, again specific to the size class j, can be expressed using equation (7). When the active-layer floor descends, then

$$S_{F,j}\approx(P-1)\beta_{s,j}\frac{\partial(Z_b-E_m)}{\partial t} \tag{8}$$

gives the mass of the size class j, formerly comprising size fraction $\beta_{s,j}$ of the active-stratum control volume, which becomes part of the active-layer elemental volume. When the active-layer floor rises, then

$$S_{F,j}\approx(P-1)\beta_j\frac{\partial(Z_b-E_m)}{\partial t} \tag{9}$$

gives the mass of the size class j, formerly comprising size fraction β_j of the active-layer elemental volume, which becomes part of the active-stratum control volume.

The active-layer thickness E_m is evaluated by an appropriate empirical concept of the depth of bed material which supplies material for bed load transport and suspended-sediment entrainment. Usually the active-layer thickness is related to the flow and sediment conditions, as well as the instantaneous bed deformation. Researchers have considered the active-layer thickness to be a function of dune height or water depth (Armanini and Di Silvio, 1988; Rahuel et al., 1989, Langendoen et al., 2000), or grain size (Borah et al., 1982; van Niekerk et al., 1992; Cui et al., 1996), or model time scale (Rahuel et al., 1989, Langendoen et al., 2000). Throughout the last decades many new formulas to calculate the active-layer thickness have been proposed. However, all formulas were derived in a different way and a definition of the active-layer thickness based on physical processes in this layer has not been given yet. In the paper, the active layer thickness is assumed to be constant.

3.2 Model of grain-feeding

In order to simulate sediment transport in the case of grain-feeding, the following information on the grain-feeding domain must be given:

- number and index of grid points belonging to the domain;
- grain composition of particular fractions used as feeding-material (m);
- mean bed-evolution in the feeding domain (m/s); and
- grain-feeding time duration (s).

During the grain-feeding time, the bed changes at these grid points in the grain-feeding domain are defined by accumulating the bed change due to the grain-feeding and the bed deformation due to the flow.

4. MODEL APPLICATION

4.1 Model construction

The computational grid for the numerical model covers the Rhine stretch between km-812.5 and km-821.5 (Wesel-Xanten). The German Gauss-Krüger co-ordinate system is chosen as the local co-ordinate system (Fig.3). The computational grid has been made for the cases with discharges between low-water and middle-water. The grid system is non-regular and *consists of 5607 points and 10818 elements.* The grid size in the areas near groyne fields is refined with a minimal value of about 1m. The maximum grid size in the domains between two groynes is about 10m. On the floodplains, the cell length varies between 20 m and 60 m. A detail of the model grid for the river stretch nearby Wesel is given in Fig.4. Topographical data came from two sources: 1/2000 German Digital Federal Waterways Map and 100-m-profiles from soundings of the year 2000. Since the computational grid spacing was much denser than the spacing of the 100-m-profiles, an interpolation procedure was used to obtain the computation grid topography.

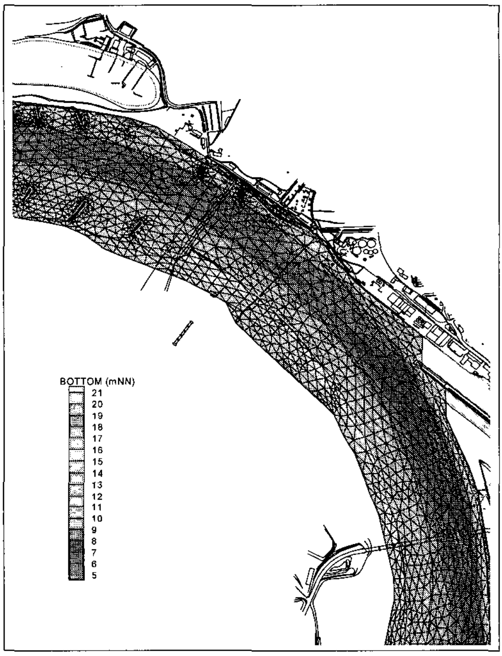

Figure 3. Computational grid

Sediment data collected at 18 profiles from 1983 to 1996 were initially used to extract size fraction distributions at bed-surface points. The data set was provided by the German Federal Institute of Hydrology (BfG). Further, based on the vertical and also horizontal locations of data-collection, mean values of size fraction and grain size have been extracted for bed-surface and substrate layers. The bed-load rate measurements have been carried out at only one profile, namely at km-818.2 (Wesel).

The computations require conditions for three types of boundaries: inflow, outflow and solid boundaries. Typically hydrodynamic computations require either free-surface elevations or discharges as boundary conditions at all open boundaries. However for sediment calculation, the boundary conditions are required only along inflow boundaries. Size-fraction distribution and time evolution of the bed elevation are prescribed for each computational point across the inflow boundaries. The assigned size-fraction distribution at each particular bed point must satisfy the basic requirement that the sum of all fractions must be equal to unity. For computations of grain-feeding to the bed, the bed-surface elevations and also size-fraction distributions at all points in the grain-feeding domain must be given.

As hydrodynamic boundary conditions the discharge of $Q = 2120\ m^3/s$ is given at Wesel as inlet-condition and the water surface of $\zeta = 14.24$ m+NN measured at km-812.5 as outlet-condition. The initial free surface is interpolated from measured profiles and the initial velocities are set to zero.

As mentioned above, bed-sediment samples were processed to obtain average bed-sediment size distribution in the domain. It has been shown that these bed-sediment samples generally contained a significant amount of sediment with a diameter between 0.6 and 60.0 mm. Based on these observations, the four size classes with average size-fraction distributions respectively in surface and subsurface layers were chosen to represent the natural bed sediment mixtures relevant to the model (Tab.1). We call these average size fraction distributions the default size-class distributions for the Wesel-Xanten model. Initial size-fraction distributions were then obtained by assigning the default size-fraction distributions to all bed points throughout the calculated domain. At the inlet boundary the bed level and fraction distribution were assumed to be constant with time. At the other boundaries, a zero-gradient condition was applied.

4.2 Calculation results and discussions

The calculations were made first for the flow with a fixed bed. The goal of these runs was to achieve a generally good agreement between the computed results and measured data throughout the domain by globally calibrating the model parameters. The TELEMAC2D hydrodynamics module has two major physical parameters that can be determined through the calibration process: the bed-surface friction coefficient and the horizontal eddy-viscosity coefficient used for the horizontal turbulent-diffusion terms. In the calculations, Elder's turbulence model was applied.

Table 1. Representative size classes for the Wesel-Xanten Model

Model size class	Diameter range (mm)	Geometric mean diameter (mm)	Percentage (%)	
			surface layer	subsurface layer
Sand	0.06 – 2.0	1.3	20.5	32.8
fine gravel	2.0 – 8.0	5.9	18.1	24.8
Medium gravel	8.0 – 31.5	23.3	44.5	34.6
Coarse gravel	31.5 – 60.0	50.0	16.9	7.8

Further, the Nikuradse friction coefficients of 0.07 has been chosen. A time step of 0.5 s was used in the hydrodynamic computation. A flow stabilisation period of 12 hours (86400 computational time steps) proved to be sufficient for the dissipation of the initially severe waves propagating in the domain. At the end of the flow stabilisation period, a steady state flow solution was achieved. The agreement between computed and measured free water surface elevations was checked throughout the model domain. After calibration, the predicted water surface elevation show generally good agreement with measurements (Fig.4). At the end of the flow stabilisation period, the computed water discharges at the outlet boundary were also checked. The difference in discharge between inlet and outlet boundaries was 1.02 %.

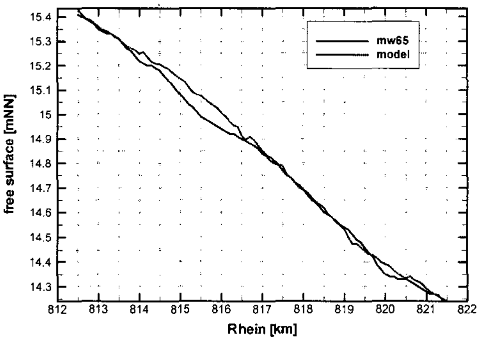

Figure 4. Comparison of simulated water surface and measurement

The calibration of the mobile-bed model comprised not only adjustment of boundary and initial conditions, but also the adjustment of certain physical parameters associated with various terms in the auxiliary sediment equations used in SYSIPHE. For graded sediment transport the bed load equation (2) and the mixing-layer-composition equation (6) contain two physical parameters: hiding / exposure factor, and active layer thickness, that can be used for model calibration.

Test calculations first were done using uniform grain size (uniform-transport model) for graded sediment processes without grain feeding activities. For these tests the single mean grain size was assumed to be constant throughout the computation domain and over the simulation time. Based on an analysis of measured data, a mean value of d_M = 20.1 mm for the bed surface was chosen. Applying the original Meyer-Peter & Müller formula in a uniform sediment approach with the proposed critical Shields value of 0.047 the simulated sediment transport under this middle-water flow condition turns out to zero. However, the prototype observations in this flow domain show that at lower discharges a substantial contribution of sediment transport rates can be expected. This is caused by sorting effects of graded sediment, through which fine sediment fractions can be transported over coarse sediment fractions during the lower discharges. As sediment transport occurs, the distributions of bed grain size may also change locally and with time. Uniform sediment concept cannot be expected to reproduce these graded-sediment mechanism. In order to account for this effect in uniform-transport model, some authors proposed to adjust the critical Shields value for initial motion of particles. Applying uniform-transport model for long-term morphological simulation in the Rhine stretch between km-849.0 and km-867.5, WL | Delft Hydraulics (2002) used different critical Shields values in a range of 0.02 – 0.083, which depend on the flow discharges. To account for the armouring effects in the Danube river, Hunziker et al. (2001) used a critical Shields value of 0.077. However, choosing such values seems to be relatively arbitrary.

Fig.5 shows the calculated distribution of the bed change after 30 days, using SISYPHE with uniform transport model and critical Shields values of 0.047, 0.04, 0.03 and 0.02. Using values of 0.03 and 0.02 the movement of bed material was obtained but the calculated bed load rates were quite different from measurements. As can be seen from equation (2), the bed load rate is a function of the effective bed shear stress and the mean grain size. In uniform transport model the mean grain size is generally constant during the simulation time, so that the bed load rate depends only on the bed shear stress. In our case with the constant middle water discharge, because of small change of the bed elevation during the simulation time, the velocity and so the bed shear stress field are mostly unchanged. Hence, the calculated bed load rates are also constant. This is quite different from graded-sediment transport model: since sediment transport occurs, the distributions of the bed grain size, and also the bed load rates change locally and with time. These shortcomings of uniform transport model become conspicuously in the case of grain feeding, where sorting effects of graded sediment and armouring effects have to be taken into account in the morphological simulation.

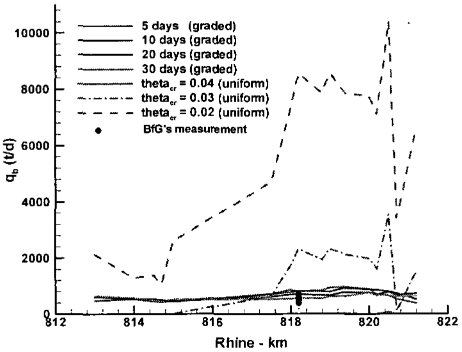

Figure 5. Bed load rate along the river stretch

By adjusting the two above mentioned parameters in graded sediment model and then comparing with measured data, the following selection of parameters was obtained for best fit between calculated bed-load rate and measurement under middle-water condition: hiding / exposure factor formula of Karim et. al with $\alpha = 0.85$; active layer thickness with constant value of 5 cm. In the model, four stratum layers below the bed surface were used. The stratum-layer thickness was assumed to be 25 cm throughout the model domain. A time step of 300s was used in the morphological computation.

As a further step of the work, the graded sediment model was tested by applying it to a middle water situation with grain feeding activities. Fig.6 shows the bandwidth and the prescribed limits of the particular grading curves of the supplied material. Additionally the boundaries of the model and the supply area representative for an idealized supply situation are shown. The grain feeding domain was assumed to be near Wesel. The following parameters for the grain feeding model were used:

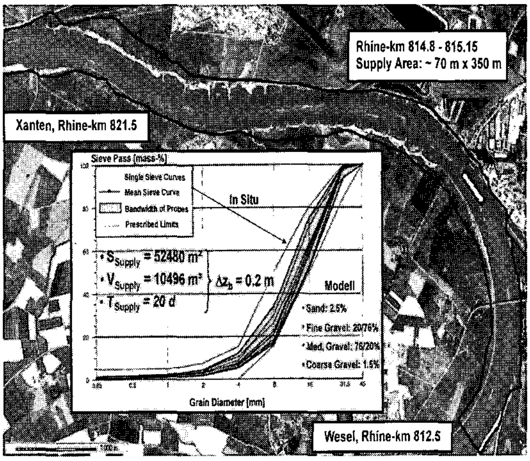

Figure 6. A real view of the model domain and the supply area

- volume of grain-feeding material: 4900 m^3
- grain feeding area: 24500 m^2
- grain feeding time: 20 days

Firstly we assumed that the grain-feeding material was a sand-gravel-mixture containing 2.5% sand, 20% fine gravel, 76% medium gravel and 1.5% coarse gravel, which correspond to the natural bottom grain composition in the domain. As the feeding material was distributed regularly in the grain feeding area, the bed level change due to the grain feeding was 20 cm at the end of the feeding time. In the model, the bed level change at all grid points of the grain-feeding area was then determined not only from the change due to grain feeding procedure but also due to hydraulics conditions.

Comparison for calculated bed load rates between the case with and without grain feeding show that under middle flow discharge condition, only two finest fractions used in the model (sand and fine gravel) participated in the bed movement Since in the model we used grain feeding material with a composition of dominant coarse fractions (medium and coarse gravel), which were not transported by middle flow discharge. These coarser materials remain on the bed and form an armour coat. In other words, the grain feeding procedure promotes an armouring effect in the supply area (Fig.7). The calculated results agree qualitatively well with the prototype observations in the river stretch.

For further test calculation, finer grain feeding material with a composition of 2.5% sand, 76% fine gravel, 20% medium gravel and 1.5% coarse gravel has been used. The other parameters of grain feeding process were the same.

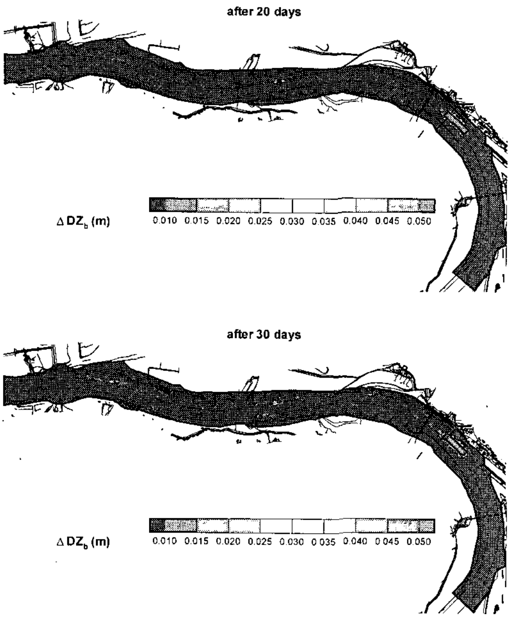

Figure 7. Difference of bed level change between the cases with and without grain feeding (coarse material)

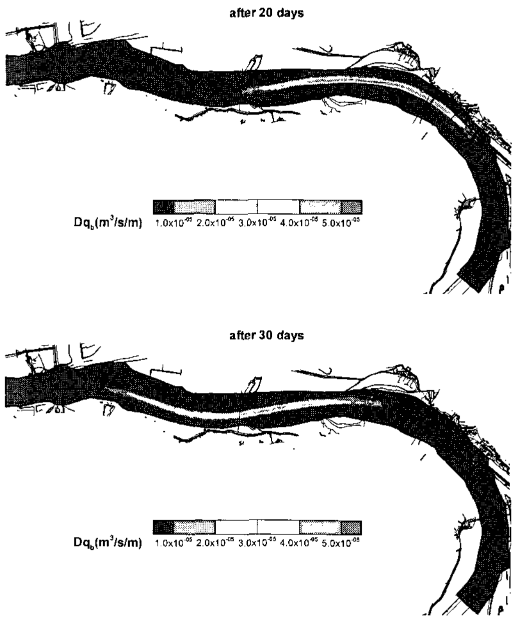

Figure 8. Difference of bed load rate between the cases with and without grain feeding (fine material)

Fig.8 shows the variations of calculated bed-load rates at different simulation times between the case with and without grain feeding after 20 and 30 days. After 20 days fine grain-feeding materials reached the place about 2 km downstream from the supply area. That agrees also with the prototype observations in the river stretch.

Fig.9 shows the calculated bed level change for the case with and without grain feeding after 30 days. As mentioned above, under middle flow-discharge conditions only the two finest fractions: sand and fine gravel could be washed out or transported as bed load transport. In this test case, these two fine fractions were dominant in the grain feeding composition so that the grain feeding procedure leads to a quicker bed material transport first within the grain feeding area and then gradually in the domain downstream of the supply area. The coarse fractions were not transported by middle flow discharge, that formed an armour layer on the bed in the grain-feeding area.

As mentioned above, uniform sediment transport models assumed that mean grain size is constant during the simulation time. Such models could not show any fractioned pattern. These morphological processes can be only reproduced by applying a graded sediment transport model.

The CPU times required for the 30-days-simulation of flow and sediment transport in the river stretch was about 7 minutes on 8 processors of an ORIGIN vector computer. The calculations have been carried out at the Federal Waterways Engineering and Research Institute (BAW), Karlsruhe.

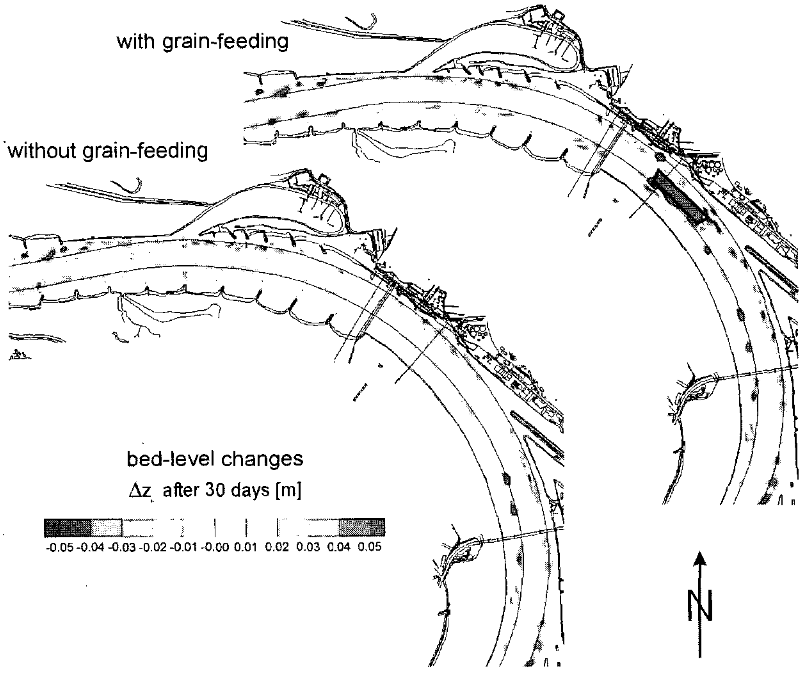

Figure 9. Bed level change for the case with and without artificial grain feeding after 30 days(fine material)

5. CONCLUSIONS

First experiences in the Rhine river suggested that artificial grain feeding and withdrawal of bed load material can be used as a directly effective instrument for a lasting dynamical bed stabilisation. To study morphodynamical characteristics due to artificial grain feeding activities, especially to analyse and control the grain feeding measures in this Rhine-stretch the sediment transport SISYPHE module in the TELEMAC system has been developed for graded sediment transport using a multiple layer model.

Based on the analysis of calculated results performed in this study and the comparison between predictions and measurements, and also prototype observations, the following conclusions can be drawn:

- For the investigation of the morphological processes within the project area it is absolutely necessary to use a graded sediment transport model.
- The artificial grain feeding process in the river stretch could be reproduced reasonably well by the numerical model.
- For a more detailed and more exact model calibration data of the bed level, the composition of the bed material and the bed-load rates at two different times with approximately the same discharge conditions are necessary.

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