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Sensitivity Analysis of Numerical Solving Techniques for Modeling Sediment Transport under Tidal Conditions

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ABSTRACT: The sensitivities of numerical solving techniques (MIKE21 and RMA2/SED2D-WES) for modeling hydrodynamics and sediment transport in tidal environments were studied. For comparative analysis an existing model for sedimentation in the tidal harbour of Bremen (Weser estuary) was evaluated. This „real world case“ shows capabilities and limitations of actual 2D modeling systems solving problems in a „dynamic“ flow and sediment regime. It is pointed out which modeling capabilities are necessary and how they are implemented. Limiting functions for boundary and critical flux conditions in model subdomains during specified tidal phases, continuity problems resolving node equations, wet/dry checking with different approaches (marsh porosity for RMA2 versus flood/dry depth for MIKE21), and the influence of viscosity parameters are presented topics. Friction and viscosity parameters are also defining, among other model parameters, the quality of simulations. Restrictions in the parameter identification process, building a full integrated simulation approach, are specified.

1 INTRODUCTION

A large number of transport models have been developed as tools to give specific answers in coastal and estuarine environments. Numerical simulation of sediment transport processes is of vital importance in the assessment of long-term management strategies for dredging.

Quality of model results strongly depends on (a) knowledge about the basic physical processes, which is limited but not discussed here, and (b) code implementation of the mathematical description for the designated problem class. In fact, the last topic is critical, because it reflects on the applicability of well know models.

The work presented is a comparative analysis of the FD-model MIKE21 and its FE counterpart SMS (RMA2 and SED2D).

2 MODELING TECHNOLOGY

Underlying differential equations describing the physical phenomena are proposed to be known. Due to the well known models choosen here, we skip the theoretical background and refer to literature.

2.1 MIKE21 Version 2.6

2.1.1 Hydrodynamic Module (HD)

The node centered FE algorithm of MIKE21 to solve the unsteady 2D flow equations is a stable and efficient scheme.

From the numerical point of view, ADI techniques, as the one by Richtmeyer & Morton (1967) used here, accumulate the numerical error in the center of the grid to be solved. They are described as "oscillations" or "zig-zagging", but they are specific to the scheme. ADI techniques, breeded for speed, apply special measures (e.g. up/down sweeps in different directions) to compensate this phenomena.

According to many FD solving techniques, stability is obtained by limiting the "numerical momentum" ($C_R = u\Delta t/\Delta x$). The operator-splitting method with its optimized handling of different terms launches the user some flexibility to go up to C_R=20. Flexibility ends if setting up models with high discretisation in space (Δx<5m, e.g. to evaluate scour near structures), which leads to Δt=2s-10s.

2.1.2 Mud Transport Module (MT)

The multi fraction mud transport module solves the 2D equation for advection-dispersion (suspended-load dominating with settling, deposition and erosion for up to 8 fractions, each with $d \leq 60\mu m$) using the QICKEST scheme (Ekebjaerg & Justensen, 1991). Forcing function is currents.

Thus, parameters describing the physical process are dispersion coefficients (constant or proportional to the current) and critical velocities for erosion/deposition, mean settling velocities, initial bed composition (a very restricted view to reality by giving the percentage of every fraction) and erosion coefficients. This is the classic approach to define interaction of suspension, were transport is modeled, and the bed model. It shows clearly the dilemma to model mass transport caused by erosion defining erosion coeffecients ($\tau_{bottom} > \tau_{crit}$ is only a criterion to initialize the subprocess; compare Matheja, 2000).

2.1.3 Discretisation of Space and Time

Flexibility of implemented space discretisation (staggered grid with Δx=Δy=const.) is limited, although nested grid functionality is available.

All modules are working with Δt=const. (using a real world format, JJ:MM:HH:SS).

2.2 RMA2/SED2D

2.2.1 RMA2 Version 4.3

RMA2 is a 2D FE scheme for subcritical free-surface flow, solving the Reynolds form of the Navier-Stokes equations (e.g. King & Norton, 1978). Derivatives in time are replaced by a nonlinear finite difference approximation. The solution is fully implicit, solved by Newton-Raphson non linear iteration.

Turbulence is modeled by eddy viscosity (constant for materials or coupled to velocities by Peclet-number).

Stability of the method is critical, due to explizit linearization of advective terms without upwinding and in cases of high Peclet-numbers.

2.2.2 SED2D-WES Version 1.2

SED2D-WES can be applied to cohesive (clay-ey) and non cohesive (sandy) sediments (Ariathurai, 1974; Arithurai et al., 1977).

The model considers a single grain size solving the 2D convection-diffusion equation. Processes can be grouped into motion (diffusion coefficients), erosion (erosion rate for particle by particle erosion and mass failure of a bed layer), and deposition. In difference to MIKE21 the model assumes transported mass in suspension even that part in motion close to the bed. Thus, the implemented equations and approaches are equivalent to MIKE21. Only the solving techniques (FE) and some details are different.

2.2.3 Discretisation of Space and Time

Space discretisation is based on several FE types (one dimensional elements or two dimensional either triangular or rectangular). This FE-solution can lead to extremely dense meshes. Due to mesh quality, stability and job times, this is limited in practice.

The time scaling (Δt=const., starting at zero) ignores present concepts (common format, comp. *2.1.3* having an elegant concept).

3 DESCRIPTION OF THE TEST CASE

The test case was extracted from a "real world" model with an accurate data base. It covers sediment dynamics in the Bremen harbour area (Weser estuary, Fig. 1).

During periods of mean discharge material accumulates in the harbour, while during periods of high discharge it is flushed through the area. Thus, different discharge conditions were examined. The discharge at the non-tidal gage "Intschede" (33km above weir “Hemelingen” - 4,5km upstream the model boundary) was transferred to the upstream model boundary by a mass conservation model taking velocity information from a 1D model for the non-tidal part and water levels from tidal gages in and nearby the model area into account (Fig. 2). Tidal water levels at the downstream boundary were calculated from field measurements adequate for the discharge class to be modeled (Fig. 3).

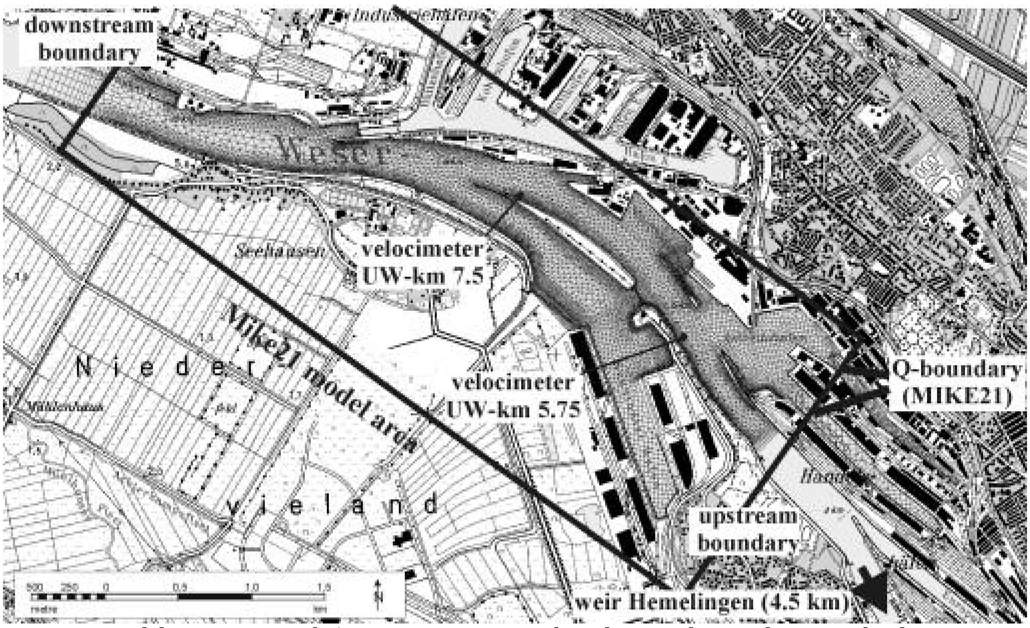

Figure 1: Model Area: FE-Mesh (RMA2/SED2D: combined triangular/quadratic mesh, element size 25-3200m^2, 16078 elements) and FD-Mesh (MIKE21: starting point: 3482900,5884200; grid dimension: nx=500, ny=1090; grid resolution: dx=dy=5m; rotation against north=305°).

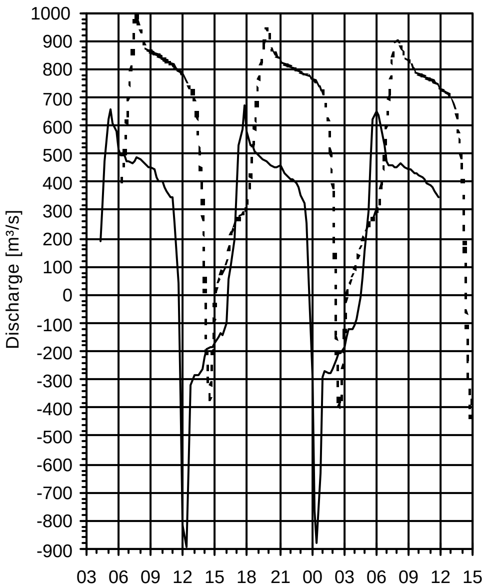

Figure 2: Tidal Discharge at upstream Model Boundary for the Discharge Class Q=150m^3/s (02.12.1997 4^{15}–03.12.1997 11^{45}) and Model Calibration (17.03.1990 6^{00}–18.03.1990 15^{00}).

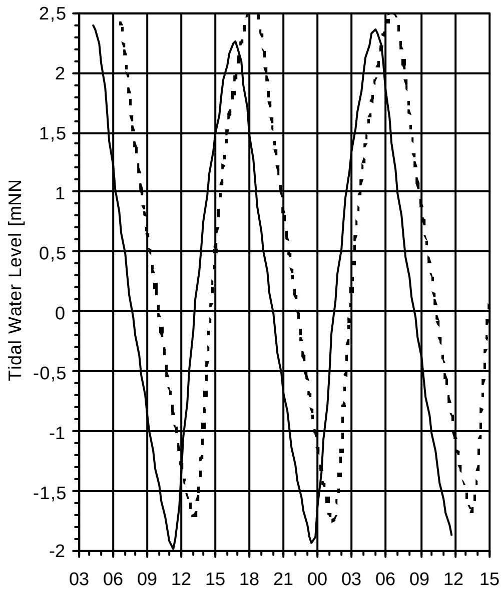

Figure 3: Water Levels at downstream Model Boundary for the Discharge Class Q=150m^3/s (02.12.1997 4^{15}–03.12.1997 11^{45}) and Model Calibration (17.03.1990 6^{00}–18.03.1990 15^{00}).

Model calibration and validation were based on four velocimeters placed during a flood event for three weeks, different gages and results of a physical model.

Originally the model was set up to examine the placement of structures (current deflecting walls) and to find optimized geometries to minimize sedimentation in access channels and harbour entrances.

It shows dependencies in a dynamic estuarine environment, influenced by flood runoffs, tidal discharge and tidal water levels caused by severe storm events. Thus, it builds the ideal base to evaluate the models RMA2/SED2D and MIKE21 under practical conditions ("real world case").

4 HYDRODYNAMIC MODELING

4.1 Calibration

4.1.1 RMA2 and MIKE21 Parameter Sets

The hydrodynamic part is evaluated by giving a view to selected model results (calibration). Validation for an extreme event shows the same accuracy and is not discussed here. System geometry and friction of the MIKE21 model were created by direct export from RMA2 data sets <u>without</u> modification (search radius=20m). Boundary conditions are the same (Fig. 2 and Fig. 3).

Peclet-number and friction (Tab. 1) were obtained using boundary conditions mentioned above and checking resulting eddies for different time steps with results from an earlier physical model.

Table 1. Model parameters after calibration and validation (RMA2).

Area	Peclet-Number [-]	Manning-Number [-] (d<2m)	d>2m
River	20	0.030	0.030
Harbours	20	0.030	0.025
Embankments	20	0.030	0.035

Flood/dry check (8cm/18cm) was switched on. Time step length was set to 15min.

The MIKE21 model used the same parameter set. Only the time step length was set to 5sec. and 2.5sec. to satisfy Courant-Criterion. For turbulence modeling the formulae of Smagorinsky (1963) with c_s=0,5 and in comparison a constant eddy viscosity (velocity dependant, E=500m^2/s) was evaluated. The Smagorinsky approach was much more stable and subsequently used for later investigations.

4.1.2 Comparison of Model Results

Evaluation of model results shows only slight differences predicting tidal water levels (Fig. 4: max. ±2cm for RMA2 and MIKE21 with Δt=5s during periods of high ebb/flood discharge).

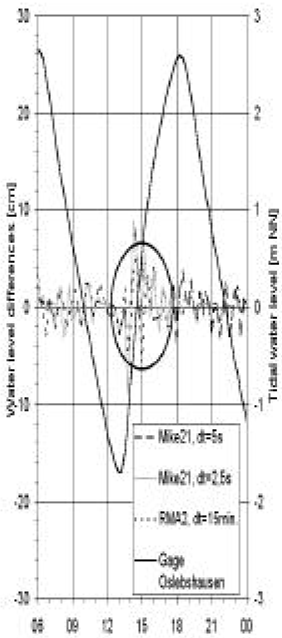

Figure 4: Water Levels/Differences at Gage Oslebshausen UW-km7.5 (17.03.1990 6^{00}-17.03.1990 0^{00}).

Differences in velocity distribution are mainly visible at slack water, where every model (especially MIKE21 with short Δt) has it's difficulties to handle periods with low momentum and mass transport (Fig. 5). Nevertheless, the ranges of velocity distribution (ebb: 0.37-0.4m/s; flood: 0.1-0.25m/s) are reproduced.

Considerable differences exist for flow directions. They are caused (a) by laziness of flow measurements near slack water (k_f and k_e) and (b) known problems of RMA2 and MIKE21 to change flow direction (marked points in Fig. 6, compare Matheja et al., 1997; Matheja & Stoschek, 1998). It must also be recognized that point measurements can only document the hydrodynamic situation nearby the velocimeter.

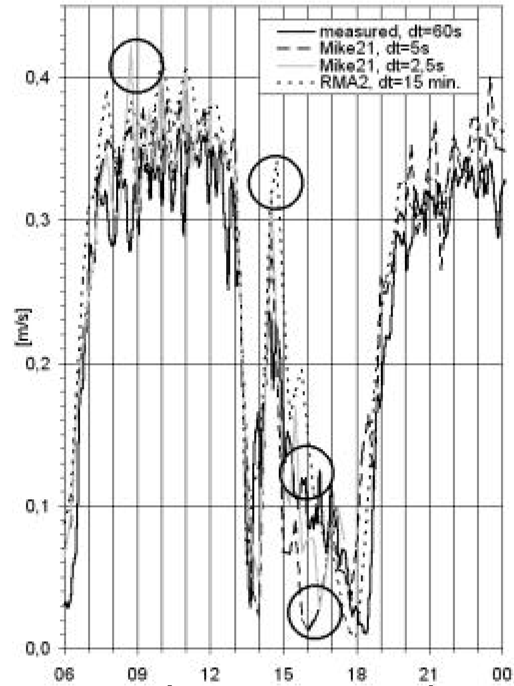

Figure 5: Velocities at Station UW-km 7.5 (17.03.1990 6^{00}-18.03.1990 0^{00}).

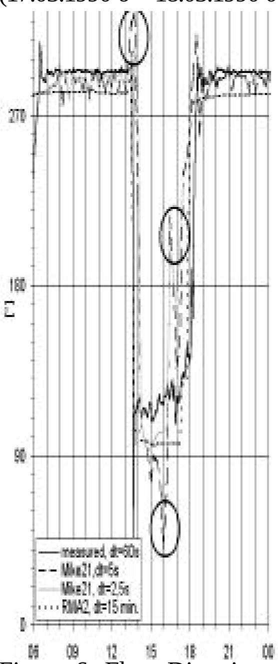

Figure 6: Flow Direction at Station UW-km7.5 (17.03.1990 6^{00}-18.03.1990 0^{00}).

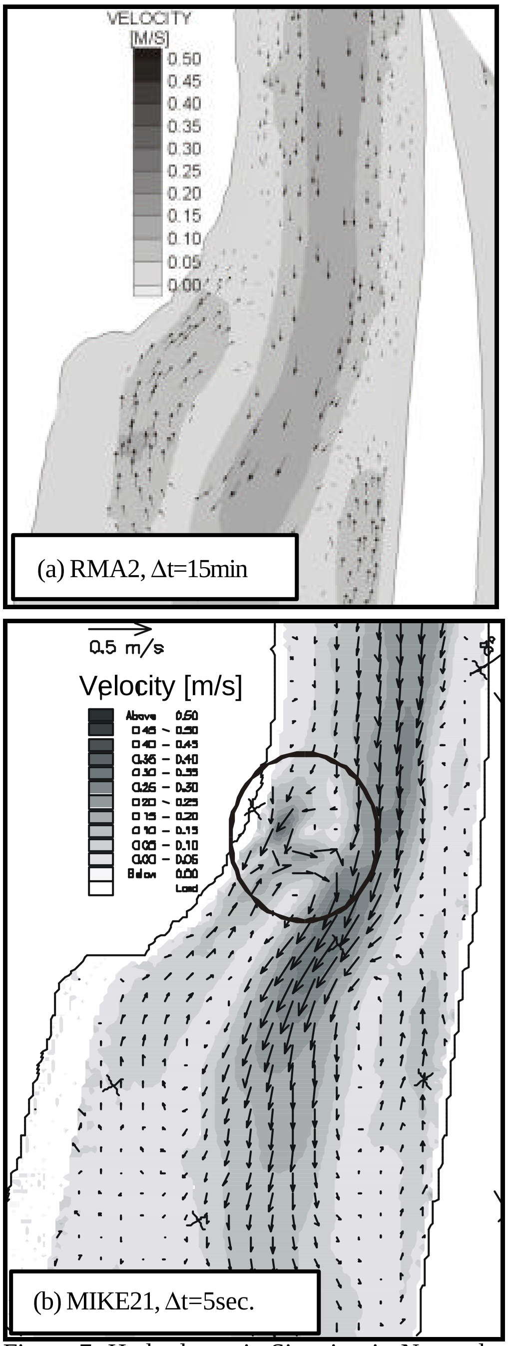

Figure 7: Hydrodynamic Situation in Neustadt Harbour for identical Boundary Conditions (17.03.1990 15^{30}, compare Fig. 3 and Fig. 4): (a) RMA2, Δt=15min; (b) MIKE21, Δt =5sec.

4.2 Turbulence Modeling

Practical turbulence modeling (large eddies modeled by mean turbulences, stable over simulation time steps, e.g. Δt=5s in MIKE21 to 15min in RMA2) is nowadays restricted by available data (normally measurements at distinct points spreaded over the model area). Under these conditions, tests carried out here, can only evaluate numerical aspects.

The implemented eddy viscosity concept (RMA2) is reacting sensitive (70% of all stability problems) in dynamic tidal environments. To predict turbulence for different turbulence phenomena (harbour areas with large eddies and turbulence near structures) it is imperative to use Peclet-numbering to reproduce dimension, rotation and speed of macro eddies [1].

It can be stated, that the Smagorinsky approach (MIKE21) is more stable and efficient (in comparison with eddy viscosity concepts of RMA2). Taking c_s-values from other estuaries (Elbe estuary, Ems estuary, Hamburg harbour) into account, a range between 0.4 - 0.7 results in a good fit of eddy diameter and dynamic behaviour (drift, rotation, velocity). A comparison with physical model results gives the same view (e.g. Franzius-Institut, 1996). Time discretisation in MIKE21 offers a way to calculate smaller eddies with higher energy dissipation, and thus creates a more rough picture of the hydrodynamic situation (Fig. 7).

This shows that turbulence modeling requires (a) results of physical models as used here for calibration or (b) ADCP-measurements or multiple "DGPS-drifters" (Nasner, et al., 1996) in different depths over longer tidal periods.

4.3 Discretisation of Time

Time step length in RMA2 (required time step length Δt=15min to get the model stable) leads to a more smooth calculation, neglecting momentum exchange during extremely dynamic tidal periods. The model is not able to start a dynamic run without preparing a "hot start situation" by hand, which is automatically handled by MIKE21.

MIKE21, satisfying Courant-Criterion, creates a more "complex" picture of hydrodynamics (compare Fig. 7).

4.4 Flood/Dry Checking

Algorithms to model flooding/drying are essential in tidal environments (mean tidal range in the project area 4.06m).

Flood/dry check of RMA2 limits stability of the model enormously ($\approx$23 runs to get the model stable). On condition that elements are rectangular and parallel to bottom isolines (to avoid "death zones" and abrupt "zig-zagging" of geometry during flooding/drying between single iterations) stability can be obtained. RMA2 is not able to model pond areas and thus is not suitable for flat coastal regions (wadden areas). Parameters for the marsh porosity concept (Roig, 1995) were difficult to obtain (especially AC0 - mean bed elevation and AC3 - minimum wetted surface area factor). Simulations were extremely unstable, so simple flood/dry check were used in this environment (upper part of the estuary with maximum bottom slopes in the tidal range). In fact, this concept offers a fast and efficient scheme unless water reaches flood plains, where vegetation plays a keyrole.

MIKE21 offers only the flood/dry concept (depths) to model tidal influenced areas. The implemented algorithm is very stable ($\approx$5 runs to obtain stability for calibration, neglecting velocity distribution in boundary areas, caused by high Q shifting during flooding). Getting far from default values causes local stability problems, which can easily be managed by slight geometry modifications. MIKE21 can handle pond areas, which releases the user from modifying system geometry when modeling flood plain areas.

5 SEDIMENT TRANSPORT MODELING

Sediment transport modeling was evaluated for one hydrological year for different discharges at gage Intschede and associated tides.

For this purpose the Neustadt Harbour area (Fig. 1, Fig. 8) was divided in several sub areas. Only the sand fraction (d=0.1mm) is discussed here.

[1] Remark: Velocities in RMA2 and thus turbulence patterns are difficult to control "on screen", due to missing reference vectors.

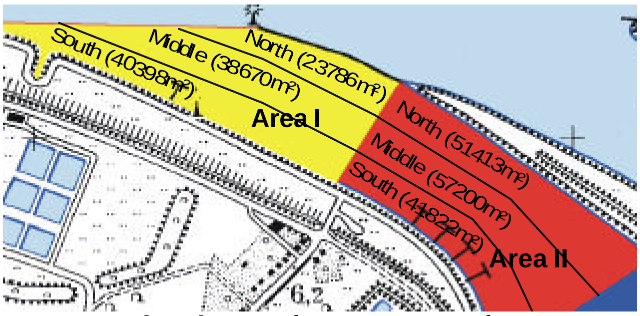

Figure 8: Selected Areas for Comparison of Sediment Transport Results.

5.1 RMA and MIKE21 Parameter Sets

Main parameters are documented in Tab. 2. Sensitivity of single parameters in SED2D and MIKE21 will be discussed in a future publication.

Table 2. Sediment transport parameters after calibration/validation (Gage "Intschede": Sand Fraction, Q=150m^3/s,).

	MIKE21	SED2D
critical velocity for deposition [m/s]	0.1	-
critical velocity for erosion [m/s]	0.3	-
sand grain size for transport [m]	-	0.08
sand grain size for roughness [m]	-	0.5
deposition length [-]	-	0.3
relative height of centroid [-]	0.3	-
erosion coefficient [kg/sm^2]	0.005	-
dispersion coefficient in x/y[m^2/s]	1	5
initial boundary conc. [g/m^3]	8	8
mean settling velocity [m/s]	0.007	0.007

5.2 Comparison of Model Results

It can be stated, that after hydrodynamic calibration, the influence of specific sediment parameters is considerable (Fig. 9).
Besides rebuilding the hydrodynamic situation, its characteristics by means of hydrologic boundary conditions (mean conditions derived from long-term characteristics[2]) and superposition of sediment transport results under these conditions, the availability of sedimentological data[3] is essential to forecast multi-fraction

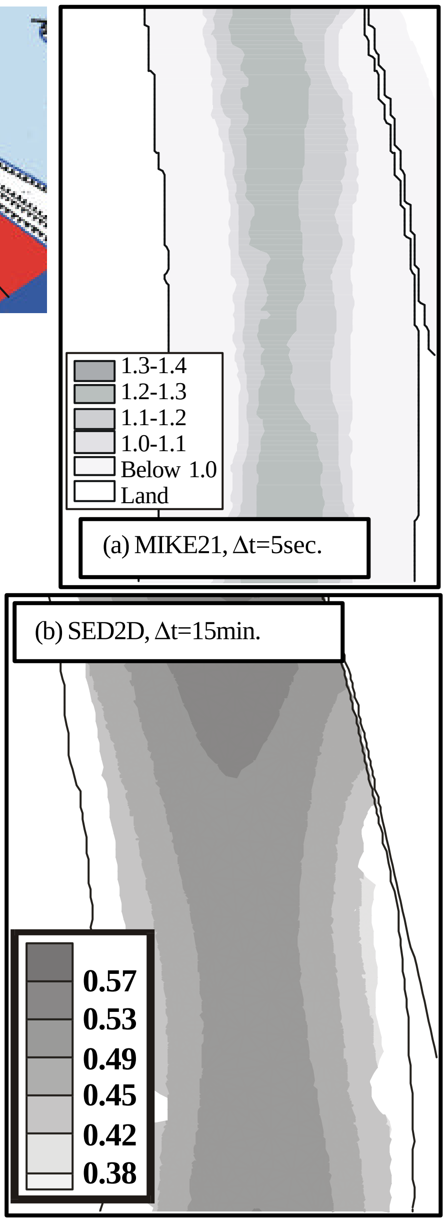

Figure 9: Sedimentation [m/year] in Neustadt Harbour (Entrance) for identical Boundary Conditions during Calibration Tests: (a) MIKE21, Δt =5sec. (b) SED2D, Δt =15min.

sediment transport processes. Model results

[2] Remark: Characterisation of hydrologic situation for long-term forecasts (splitting in different discharge classes and selection of adequate tidal boundary conditions for the upstream boundary) is not described here.

[3] Parameters documented in Tab. 2 and: (a) distribution over the depth and model area, (b) input function related to different discharges, (c) sedimentation and erosion during extreme events (floods and storm events) and (d) influence of ship traffic.

(Tab. 3, sand fraction) for the actual situation (without current deflecting wall) after calibration/validation document their comparability.

Both models show extreme influence of model boundaries (upstream and downstream boundary with imprecise results), where closed concepts to describe in-/outflow of sediment are not available. Thus, the distance between boundaries and area of interest should be more than two times the range of tidal sediment movement during flood period.

Table 3. Sedimentation for one hydrological Year (mean Conditions) in Neustadt Harbour (Situation without Current Deflecting Wall).

		Sedimentation/Erosion [m/year]	
Area	**Sub-Area**	**RMA2**	**MIKE21**
I	North	0.12765	0.11865
	Middle	0.14013	0.12981
	South	0.04402	0.04299
II	North	0.01478	0.01389
	Middle	0.02822	0.02564
	South	0.00969	0.00943

Evaluated scenarios showed that forecasts of sediment transport regime over longer periods are limited by available data **and** existing model technology. State-of-the-art modeling techniques as MIKE21 and SED2D are missing efficient concepts to model (a) in-/outflow at model boundaries, (b) multi-fraction transport (including all cohesionless/cohesive fractions), and (c) cohesive sediment properties[4] included in parameter sets).

6 RUN-TIME STATISTICS

Run-Time statistics for isolated runs (no network usage to save results) are documented in Tab. 3. System tasks (printing, nfs-jobs etc.) during execution were not documented. Other user access during execution was quoted to jobs smaller 2min. of CPU time.

All jobs were calculated on SUN ULTRA1 machines (1GB-RAM, 140Mhz, saving results on local disks).

[4] For example: Sodium Adsorption Ratio (S.A.R.), salinity, Atterberg Limits, organic content, dynamic viscosity and cation exchange capacity (CEC).

Table 3. Run-Time Statistics for one Model Tide with identical Boundary Conditions.*

	MIKE21*	RMA2/SED2D**
Comp. Times/job	≈377h	≈39,6h
Required RAM	80MB	796MB
Disk Space***	886MB	408MB
Stability	++	+

* MT-Module, Δt=5sec / ** Addition of RMA2 and SED2D jobs; versions require no swap, Δt=15min. / *** Results were saved every 15min.

7 CONCLUSION

Each modeling system is difficult to use, but provides users the necessary functionality (with a few cuts) to handle systems such as the one under investigation.

MIKE21 is a stable system, with a fast solver and a very robust algorithm for wet/dry checking. Required disk space and computing times are neglectable if the whole project life cycle is investigated. For symmetric systems or extra large problems (shelf modeling) it is the adequate solution. Its capability to model flow around structures (e.g. current deflecting walls) is limited. Its sediment transport suite of programs offers a solution for a wide range of practical problems. Nevertheless, simulation of multi-fraction transport is the same as modeling each fraction and superposition the solutions afterwards.

RMA2/SED2D with its sensitive FE-algorithms needs further development (e.g. time management, stability, visualisation in SMS). Sediment transport modeling in tidal environments is limited (e.g. bug using dried elements in SED2D, managing ponds and single fraction approach).

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