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The simulation tool DredgeSim – Predicting dredging needs in 2- and 3-dimensional models to evaluate dredging strategies

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ABSTRACT: Dredging along waterways has an impact on their topography, the sediment transport and the hydrodynamic regime. Furthermore, dredging causes high costs for the maintenance of the fairways. In order to model the effects of dredging in numerical simulations the software DredgeSim was developed. Coupled with different hydrodynamic and morphodynamic numerical models DredgeSim can be used to compute dredging needs and different strategies for the maintenance of waterways within complex models. The results can be evaluated concerning a possible reduction of dredging efforts. Typical use cases and different functionalities of this simulation package are illustrated in this article. The applicability of DredgeSim was tested successfully by computing a dredging strategy for a hydrodynamic-morphodynamic model of the Danube River to predict dredging needs.

Keywords: Dredging, Numerical modeling, Dredging strategies, Maintenance concepts

1 INTRODUCTION

The overall aim of using a software package to take into account dredging operations in numerical models is twofold. First, being able to model different dredging strategies allows an optimization with focus on a reduction of dredging efforts. This is an important task as high dredging costs are annually reported along German waterways (Tab. 1). Second, a detailed computer model about the evolution of a river section which is highly dredged can only be achieved by including dredging operations in the simulation, as the impact of such anthropogenic influences on the bed morphology and the topography can exceed those of natural sediment transport.

Table 1. Maintenance dredging costs along German waterways and harbors

Dredging costs per mill. €*	
1999	53.95
2000	70.91
2001	63.95
2002	80.57
2003	66.79

* Wasser- und Schifffahrtsverwaltung des Bundes (in Bundesministerium für Verkehr, Bau- und Wohnungswesen 2004)

Regarding these aims, the software package DredgeSim was developed at the University of the German Armed Forces Munich in cooperation with the Federal Waterways Engineering and Research Institute (BAW) (Maerker et. al 2006, Maerker & Malcherek 2008). It works in addition to common programs modeling the hydrodynamics and the morphodynamics. In DredgeSim a dredging operation can be defined for hindcast or forecast modeling purposes.

In a first practical application DredgeSim, coupled to the programs Telemac2D and Sisyphe, was used to evaluate different dredging strategies within a two-dimensional hydrodynamic and morphodynamic model of the river Danube, which was built up by the BAW. The river Danube is part of the important waterway connecting the North Sea with the Black Sea (Fig. 1). The part between the cities of Straubing and Vilshofen along the German section of the Danube River is a critical stage due to tight bends and naturally low water depths and is dredged regularly to fulfill the navigational requirements.

Results of predicted dredging needs along this stage, produced by the combined numerical models, are presented within this contribution. The achieved dredged volumes and dredging sites were compared with the real amounts of dredged material and the observed locations of dredging hot spots.

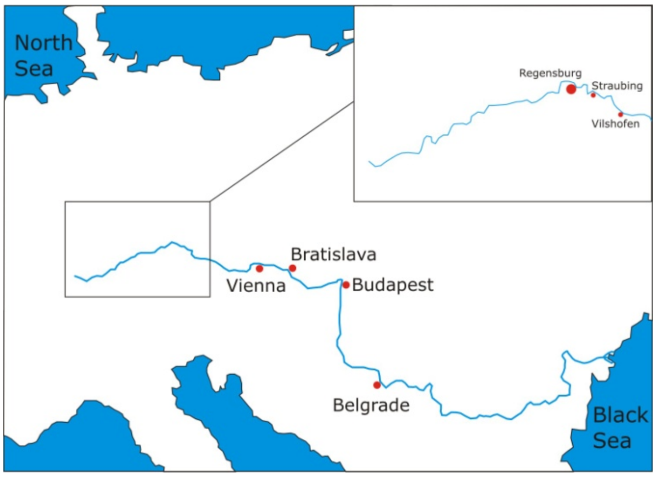

Figure 1. The Danube River and its German section

2 MODELING SYSTEM

The used modeling environment consists of the three components Telemac2D for the computation of the hydrodynamics, Sisyphe for calculating the sediment transport and DredgeSim for modeling the dredging operations. These modules need to interact with each other to exchange certain data, as each of them affects the results of the others and needs input data from their associates (Fig. 2).

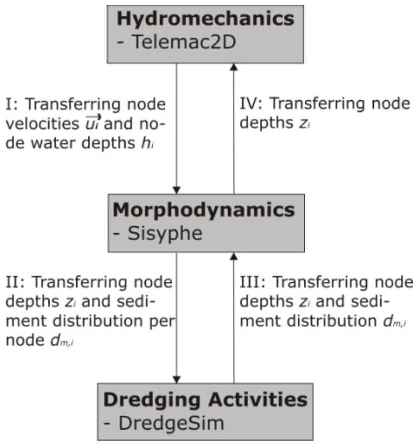

Figure 2. Used modular structure of the simulation environment

The structure of this software environment is arranged in a way that data is transferred between two components at a time. Hereby, the DredgeSim package is only coupled to the morphodynamic module Sisyphe, because dredging changes the topography of the riverbed first and foremost. Sisyphe on the other hand is also linked to Telemac2D. It receives hydrodynamic input data for the calculation of the sediment transport and updates in turn the bottom in Telemac2D, which has changed due to natural sediment transport and dredging.

2.1 *Telemac2D*

Telemac2D of Telemac system is based on the shallow water equations (Saint-Venant equations) (Hervouet, 2007).

$$\frac{\partial \vec{u}}{\partial t} + \vec{u}grad\vec{u} = -g\frac{dz_S}{d\vec{x}} + \frac{1}{h}div(hv_t\mathrm{grad}\vec{u}) + \vec{f}$$

$$\frac{\partial h}{\partial t} + \mathrm{div}(h\vec{u}) = 0 \qquad (1)$$

These equations are solved by specifying certain source terms and body forces to take into account e.g. surface influences like the bottom friction. Furthermore, different turbulence models can be used for modeling the momentum diffusion.

2.2 *Sisyphe*

The morphodynamic module Sisyphe solves the Exner equation which describes the bed evolution due to sediment transport. As the riverbed of the River Danube consists only of coarse particles, it is assumed that these particles are only transported by bed load. The Exner equation then reads

$$\frac{\partial z_B}{\partial t} + \mathrm{div}\vec{q_S} = 0 \qquad (2)$$

with $\vec{q_S}$ as the transport rate for each sediment fraction in *x*- and *y*-direction which is calculated from the bottom shear stress and a critical shear stress describing the initiation of sediment movement (Villaret, 2004).

2.3 *DredgeSim*

The dredging works are included in the simulation by using the DredgeSim package. This software allows the user to model dredging activities by two different possibilities. Either, dredging actions can be defined by giving a certain time and specific amount for dredging. Or a certain dredge criterion can be set to start a dredging operation automatically when too much sediment is detected within the fairway. Hereby, characteristic parameters like the water depths can be used as a measure to decide whether dredging is necessary as they should not fall below a critical value due to navigational requirements.

The first option allows hindcast modeling of dredging events in the past, whereas the second can be used in a forecast modeling to predict dredging needs as result of actual morphodynamics. Furthermore, both approaches can be used to either evaluate existing or develop new strategies.

The required steering data for the dredging operations is defined in two input files (Fig. 3). The DredgeSim steering file is used for the definition of pure dredging parameters whereas the IPDS-file is used for the geographical definition of operational areas. As a result, the amount of dredged material is printed on an output file for interpreting the simulation results and further postprocessing.

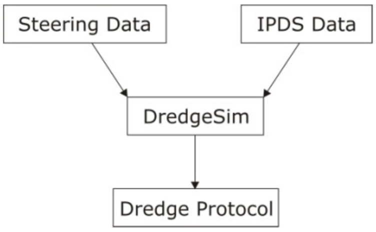

Figure 3. IO-Structure of the DredgeSim package

2.3.1 *Definition of operational areas*

In order to specify initial conditions for a numerical model an IPDS-file (Initial Physical Data Set) can be used. In this file, shape formats can be defined to distinguish regions where initial parameters vary from their global values, e.g. a local sediment distribution or a temperature field.

In DredgeSim this file is used to determine the location and size of possible dredging areas. For each of the defined areas distinctive dredging parameters can be set. E.g. it can be used to define critical water levels along the fairway (Fig. 4). This is a necessary input parameter for applying a dredge criterion on every node within the fairway in a forecast modeling. In case of a hindcast modeling the user can define precisely the extent of a dredging activity by marking this area with a dredge polygon following observations carried out along the dredging site.

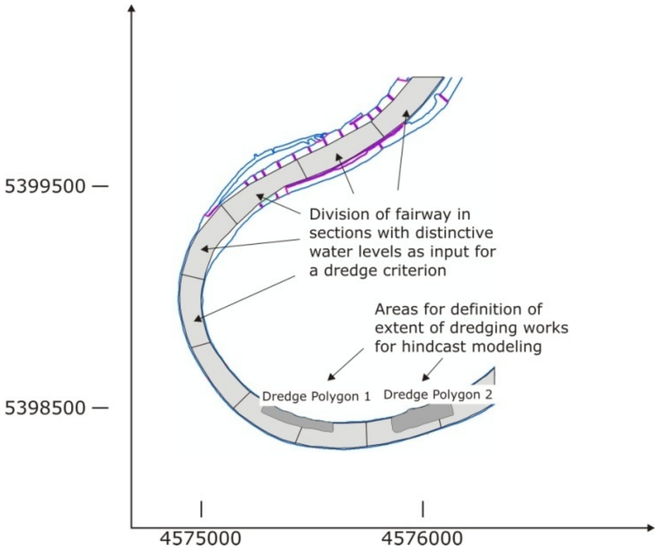

Figure 4. Definition of different critical water levels along the fairway and of the location and size of dredging areas.

2.3.2 *Hindcast modeling of maintenance operations*

Modeling dredging activities from the past in a hindcast simulation requires information about the place, the time and the extent of completed dredging events as input parameters. This data is usually well documented for dredging events along the fairways.

Hence, the user has the possibility to set a date and time of a dredging operation in DredgeSim. Furthermore, a dredge volume can be given, from which a new bottom depth for every node within the defined dredge polygons is calculated by the program (Fig. 5). Herein the total area of the defined dredge polygon is taken into account.

Modeling such a task is necessary to achieve the correct evolution of the riverbed if the modeled river section was dredged during the simulated time period.

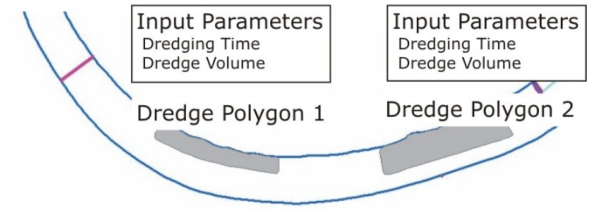

Figure 5. Definition of input parameters for dredging areas in case of a hindcast modeling.

Besides its application in hindcast models, a further use case for this type of steering dredging activities is the evaluation of the effect of expansion works on the hydrodynamic and morphodynamic regime. This reflects a form of capital dredging which can be modeled by defining a certain excavation volume.

2.3.3 *Forecast modeling of maintenance operations to predict dredging needs*

In order to predict dredging needs other parameters need to be specified. Hence, a conceptual model was developed by which a dredging operation is initiated automatically if the deposition of sediment is affecting the water depths which are required for save shipping. This model allows the user to specify different dredge criteria for different dredging areas.

In these dredge criteria, it is necessary to define critical values for e.g. the water depth itself. If a deposition of sediments is reducing the water depth up to this critical value, the troubling material is dredged (Fig. 6). This is a reaction on the actual morphodynamics. The dredging depth will be limited by a value the user has also to define.

This kind of dredge criterion was implemented in DredgeSim for scanning and dredging every node of a computing mesh which lies inside a dredge polygon. As a result the amount of dredged material is memorized at the end of a dredging operation. This allows conclusions about the efficiency and performance of a dredging strategy.

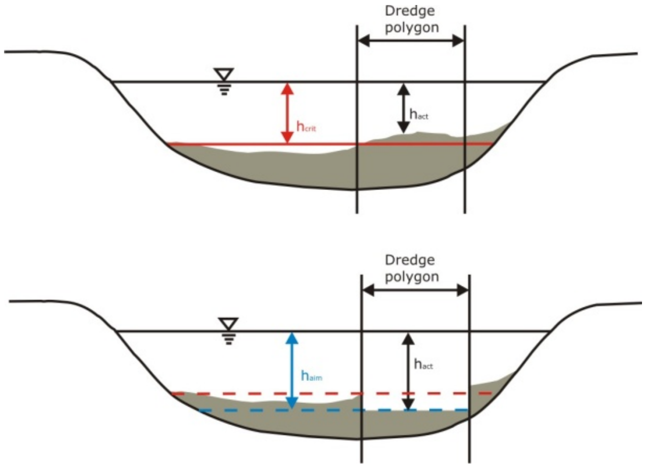

Figure 6. Dredge criterion for the initiation of dredging on a dredge polygon

There are three different dredge criteria available in DredgeSim, each referring to a special characteristic value to decide whether or not a node should be dredged. Either the bottom depth, the computed water depth, or the water depth related to a reference surface level can be chosen. The first can be used in coastal areas, where the bottom slope is rather flat and the water depths are influenced by the tide, whereas dredge criteria referring to the water depth are useful along inland rivers with steeper bottom slopes. The latter, taking into account a relation to a reference surface level, reflects the typical approach of planning and conducting building activities along German waterways and is therefore orienting on practical applications.

To improve the applicability in real projects certain sub-functionalities were included to DredgeSim. In order to avoid dredging of every single node which fulfils a dredge criterion, a minimum dredging volume can be specified. This minimum volume needs to be exceeded within a defined area by the sum of the dredged volumes of all affected nodes. Furthermore, in reality the riverbed is not observed continuously but periodically or dependent on the discharge. In DredgeSim the first can be respected by setting an initial time for observing the bottom and an observing period.

2.3.4 *Example application*

The following example should illustrate the use case of predicting dredging needs and evaluate a dredging strategy with DredgeSim. This test case consists of a channel with two bends and a plane initial bathymetry. The modeled morphodynamics induced by a stationary discharge shows deposition tendencies along the inner parts and erosion tendencies along the outer parts of the bends (Fig. 7, left). The water depths within this model were set to an initial value of 4m which are reduced due to the deposition of material along the bends.

To avoid a total siltation of these areas and to limit the reduction of the water depths a dredge criterion was defined in DredgeSim. If the water depth of a node is becoming lower than 2.5m this node is dredged. The new depth of this node is then calculated from an aim water depth of 4m which should be achieved due to dredging. Resulting from this dredge criterion a different bathymetry is obtained from a numerical simulation (Fig. 7, right).

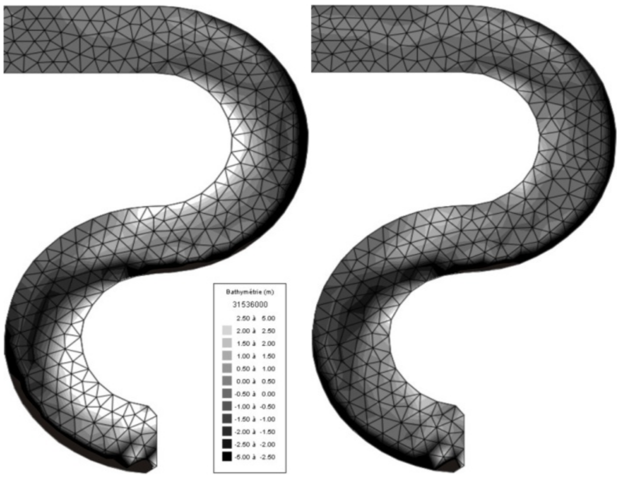

Figure 7. Test case of modeled change in bathymetry to illustrate a simulated dredging operation. The left picture shows the bathymetry affected by natural morphodynamics with depostion (black) and erosion (white) tendencies. The picture on the right shows the bathymetry after a dredging operation was initiated to remove deposited material.

Furthermore, the total dredging needs following this dredging strategy are obtained, if the dredged volumes are summed up for all nodes in total and per defined sediment fraction (Tab. 2). This is a measure for the dredging needs over a defined time scale to maintain an investigated river section and can be used to estimate the total storage capacity for dredged sediments.

Table 2. Dredged volumes in total and per modeled sediment fraction

Dredged volumes modeled by DredgeSim	
Sediment volume:	108878.42 m³
Sediment fractions	
Fine sand:	43551.37 m³
Very fine sand:	65327.05 m³

Furthermore, the time when a dredge criterion is fulfilled can be given as output as well. This shows, when exactly a dredging operation is required thus marking an important information for the real decisive process about the initiation of dredging.

2.3.5 *DredgeSim in 3-dimensional models*

As the DredgeSim package is communicating with the morphodynamic module, it only affects the bottom of a model. Hence, it can be applied in 3-dimensional models without further ado. The only input required for a DredgeSim application is the actual lateral discretization of the riverbed. Therefore, the component for the hydrodynamic simulation can easily be switched from 2- to 3D, which was tested by the BAW Hamburg.

3 APPLICATION ON THE RIVER DANUBE

The DredgeSim package was applied for the first time under project terms at the BAW Karlsruhe. The described modeling system consisting of Telemac2D, Sisyphe and DredgeSim was used to predict dredging needs in a model of the River Danube to test its applicability for future requirements.

In the test case presented here, a section of the Danube River between Straubing and Vilshofen was modeled by Glander et al. (2009). The considered part covers Danube km 2313 to km 2291 and lies within the stretch from the city of Straubing to the confluence of the rivers Isar and Danube (Fig. 8). It has a total length of about 22 kilometers.

Figure 8. Modeling area from Danube km 2313 to km 2291 along the stage Straubing to Vilshofen

Since modeling the bed evolution induced by the natural hydrodynamics and dredging operations over a relevant time frame requires a lot of computing capacity, a parallel computer was used for this task. The software is parallelized according to the MPI-method.

The first studies within this application focused on the calibration of the whole simulation package in order to reproduce correct dredging needs and reliable amounts of dredged material.

3.1 *Modeling terms and conditions*

The simulation period covered three years. As the presented test case is rather complex, detailed data is required for every part of the numerical simulation.

The hydrodynamic input data consists of a real time discharge curve from January 2000 to December 2002 at the inflow boundary and compatible water levels at the outflow boundary. The simulation mesh resembles the topography of this part of the river including groynes and longitudinal dams within this area. The used simulation mesh for the modeling area consists of 64541 nodes. Using 32 CPU led to a total computation time of round about 3.5 days for the defined simulation period. In Sisyphe the transport formula of Meyer-Peter and Müller was used to compute the bedload transport.

To predict dredging needs, the real decision making process whether or not dredging is necessary needs to be represented by DredgeSim. This is done by defining a dredge criterion considering a referenced water level authorized for maintenance measures. Within the dredge criterion, depths related to this referenced water level are compared with a critical value of 2.0 m at defined time steps. If the water depth is lower than the critical value, the affected node is dredged to a new value to reach which is calculated from a given depth of 2.05 m related to the reference surface (Fig. 9).

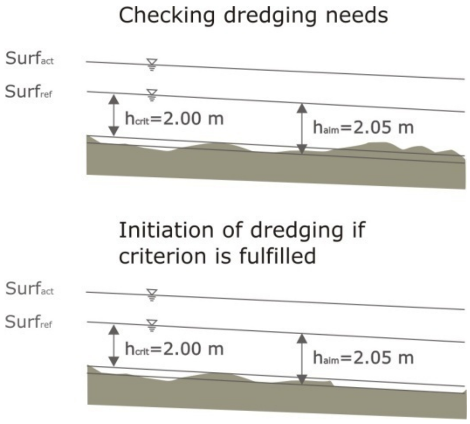

Figure 9. Applied dredge criterion

The illustrated procedure is very close to reality as nearly every construction measure on fairways is related to a referenced surface level. Furthermore, the used values for the dredge criterion are lying in a realistic range for this modeling area.

The dredge polygon covers the whole fairway to ensure that only nodes within this region are dredged if the dredge criterion is fulfilled (Fig. 10). Summing up the dredged volumes over the whole simulation period then indicates the total dredging needs within the fairway for this time.

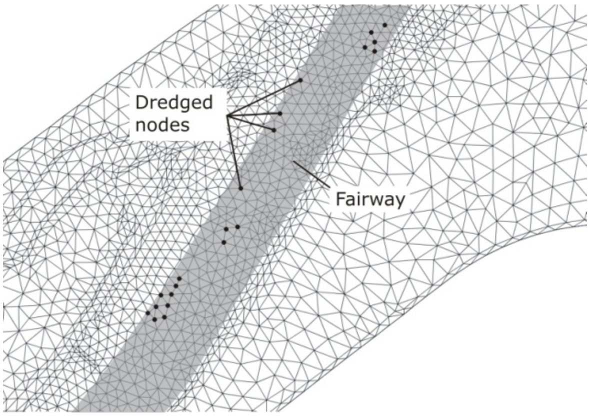

Figure 10. Dredged nodes within the fairway defined as a dredge polygon

3.2 *Computed dredging needs*

Due to this model setup a dredging operation is initiated on every node within the fairway which is affected by high deposition induced by natural sediment transport (Fig. 11).

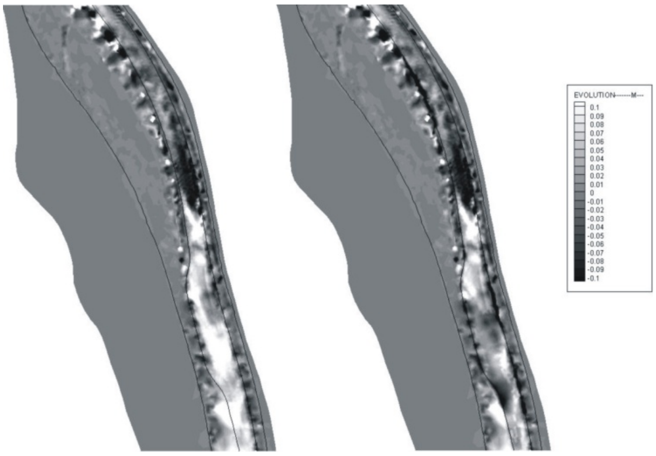

Figure 11. Modeled evolution of nodes within the fairway before (left) and after (right) dredging was initiated (Glander et al. 2009)

Resulting from this application of a dredge criterion, the amount of dredged material was computed by dividing the fairway in sections of 25 m length and summing up the dredged volumes on each section. This can be illustrated in a cumulative curve of all predicted dredged volumes over the length of the model. As data about the real dredged volumes for the simulated time period is available, a comparison of the simulated and the observed dredged volumes is possible (Fig. 12).

It can be seen that the predicted dredged volumes are higher than the observed. The factor between both is approximately 1.5 at the end of the compared time period. Since the morphodynamic model is well calibrated, this is mainly due to the applied dredge criterion. This was rather roughly defined. Every node which fulfills the dredge criterion is actually dredged within the simulation. This includes single nodes as well. In reality, this would not be the case, as a single deposition hot spot is normally not removed immediately and ships can avoid such resulting shallow water within wide fairways. Furthermore, the dredging depth along such a distance can vary according to local parameters, which is not considered in this dredge criterion, as one dredging depth was specified for all nodes.

On the other hand the shape of the computed curve fits the real curve very good. This means that the position of dredging operations is already well modeled, although the dredge criterion was specified roughly in this first approach. Furthermore, a numerical model is always dependent on its degree of discretization. Every node has an associated nodal area which is used to compute the dredged volume on a node. If the distance between two neighboring nodes is greater, the associated area is enlarging too, increasing the dredged volumes.

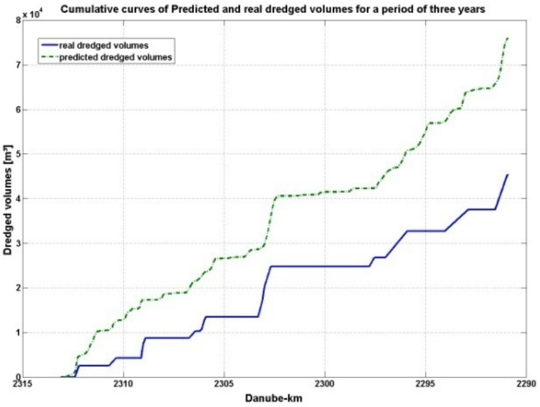

Figure 12. Cumulative curves of dredged material obtained by simulation and observation; a) in a long term simulation over three years, b) observed in reality over the same time period; modified from Glander et al. 2009.

As illustrated, DredgeSim already offers certain functionalities to refine the dredge criterion, which will be applied additionally. Particular cases like avoiding single nodes to be dredged or local differences in the dredging depths can be taken into account. As every numerical model, DredgeSim needs to be calibrated, which can be accomplished by these functionalities to increase the quality of the results.

4 CONCLUSIONS

It can be concluded that first applications of DredgeSim under project conditions showed good results. The deposition hot spots are reproduced fairly well within the morphodynamic model of the river Danube and removed according to a realistic dredge criterion. Hence, the modeled location of dredging areas is fitting observations. The dredge volumes were overestimated when predicting dredging needs and comparing the obtained results with observed data. Since DredgeSim offers certain possibilities to refine the dredging parameters, further simulations with a more detailed and calibrated dredge criterion will most likely increase the quality of the achieved results according to the amounts of dredged material.

Optimization of dredging strategies is necessary for a sustainable sediment management along fairways (Stamm et al. 2007). Numerical models which are able to take into account dredging and disposal actions can support this optimization process in the future.

REFERENCES

Bundesministerium für Verkehr, Bau- und Wohnungswesen (Ed.) 2004. Wirtschaftlich und umweltverträglich: Nassbaggerstrategien in Deutschland. Broschüre zum World Dredging Congress XVII.

Glander, B., Kopmann, R., Lege, T. 2009. BAW Karlsruhe, Personal communication.

Hervouet J.-M. 2007. Hydrodynamics of Free Surface Flows: Modelling with the Finite Element Method. John Wiley & Sons Ltd, Chichester.

Maerker, C., Deussfeld, N., Malcherek, A. 2006. Simulation von Bagger- und Verklappstrategien mit morphodynamisch-numerischen Modellen. 4. Rostocker Baggergutseminar.

Maerker, C., Malcherek, A. 2008. Die Bewertung von Unterhaltungsmaßnahmen mittels numerischer Modelle mit dem Programmpaket DredgeSim. 5, Rostocker Baggergutseminar.

Stamm, J., Wahrheit-Lensing, A., Schmidt, A. 2007. Nassbaggerstrategien – ein Beitrag zum nachhaltigen Management der Binnenwasserstraßen. Wasserwirtschaft 4/2007, 10-14.

Villaret, C. 2004. Sisyphe Release 5.4. User Manual. http://www.telemacsystem.com