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Kopmann, Rebekka

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Numerical simulation of dune movements during a flood event in River Elbe, Germany

R. Kopmann[a]

[a] Federal Waterways Engineering and Research Institute, Karlsruhe, Germany

Abstract: Dunes are major bed forms in waterways and significantly influence the local water depth which can affect the shipping capacity. The prediction of dune dimensions such as height and length is therefore of high interest for the Federal Waterways Engineering and Research Institute, Karlsruhe, Germany (BAW). An existing three dimensional hydro-morphodynamic numerical model was used to simulate the movement of bed forms in a 4 km long section of the River Elbe during constant discharge conditions. The model consists of 13 million elements with a maximum horizontal node distance of 2 m. This resolution is needed to directly represent bed forms (50-140 m length, 0.5-1.2 m height) in the mesh. The statistical dune parameters for a constant low water discharge could not be forecast precisely but the simulations show the correct trends for all parameters. An eight day segment from the subsiding part of a flood wave event was simulated and the dune parameters were compared to the measured ones. The correct trends for dune height, skewness and kurtosis could be simulated but highly overestimated the measured values so the prediction was not satisfying.

In principle, dune prediction with three-dimensional numerical RANS (Reynolds-Averaged Navier-Stokes) models and a proper turbulence model such as the k-epsilon model seems possible. However, more experience is needed to achieve this ambitious goal, firstly in the analysis of measurements and secondly in the numerical simulation of different discharge situations.

1 Introduction

Bed forms such as dunes generate considerable dredging costs in waterways every year. Therefore understanding the formation and movement of dunes and their interaction with water depth is an important topic for the Federal Waterways and Engineering Research Institute (BAW). In recent years two PhD theses have been written in close cooperation with the BAW (Henning, 2013), (Goll, 2017) touching on this topic. Henning conducted dune experiments in a BAW flume and performed multidimensional statistical analysis of the measured dune fields. In this study four statistical dune parameters calculated from measured or simulated bed levels were analysed: the mean dune length and height and the third- and forth-order distribution moments skewness and kurtosis.

Goll used these dune experiments for a three dimensional numerical simulation. She showed that considering turbulence in the shear stress calculation was essential for successful simulation of dune formation and movement. The numerical configuration found and proved at the laboratory dune experimental level was applied to a 4 km stretch of Elbe River near Lenzen. During the simulation of a 5 day period with constant mean water discharge the dune parameters (dune length and height, skewness and kurtosis) remained constant. Simulating the actual state was a great success and a necessary prerequisite for using numerical simulations to predict dune parameters.

Only for long periods of low or middle water conditions, the hydrodynamic situation in rivers can be treated as steady state. The dune movement, as opposed to the river water, happens on a much slower scale. Reaching an equilibrium (quasi-steady) state for dune movement in natural conditions with timely constant statistical dune parameters is therefore near to impossible. Dunes will always be influenced by the elapsed hydrodynamics and morphodynamics. Therefore any dune prediction must take this into account.

Usually the time span between sequential bottom scans for the investigated part of Elbe River is in the range of years. Such a long simulation period is still not manageable for the presented model. Consequently a continuous simulation which initiates at one bottom scan and ends at the next sequential bottom scan was not possible for most of the available measured data sets. Instead another procedure was chosen to investigate the dune prediction of the numerical model, knowingly being only second best. Assuming that a constant discharge would lead to dunes with constant statistical dune parameters, a numerical simulation was performed with the aim to reach constant dune parameters.

After a very short description of the numerical model and the used dune parameters in section 2, two test cases were applied to evaluate the dune prediction ability of the selected numerical model. In the first test case, one constant set of statistical dune parameters were simulated with a steady discharge and compared to measurements. The results are presented in section 3.1. In the second test case, a subsiding part of a flood wave event was simulated so that the previous hydrodynamic conditions were taken into account. The simulations are contrasted with the measurements in section 3.2. In section 4 the results are discussed and evaluated.

2 Methods

2.1 Numerical model

The three-dimensional simulations have been done with the open-source software TELEMAC-MASCARET (opentelemac.org). With Telemac-3D the Reynolds-Averaged Navier-Stokes equations are solved with a finite-element solver. The morphodynamic (bed load) is simulated with the module called Sisyphe which is coupled to Telemac-3D. Further details can be found in e.g. Hervouet (2007), Villaret et al. (2013).

Goll (2017) built a numerical model of a 4 km stretch of the Elbe River (El-km 480 to 484) near the city of Lenzen (Figure 1). The model consists of 13 million elements with horizontal node distances up to 2 m in the 3 km long evaluation reach. This resolution is needed in order to directly represent the bed forms with their luv- and lee-sides in the mesh, which have a length of 50-140 m, but a height of only 0.5-1.2 m. The model was calibrated for a discharge of 485 m^3/s which is slightly lower than the mean discharge (677 m^3/s). In this area dike relocation was realised between 2005 and 2009 in order to gain 420 ha of retention area. The investigated discharges in this study are not affected by this measure. The smaller discharges did not overtop the banks and the flood event occurred before the retention area was connected. Thus the new retention area is not included in the model area.

For the flood simulation the time step and the coupling period between the hydrodynamics and the morphodynamics needed to be reduced from 0.5 s to 0.1 s and 2 to 1 respectively. At the BAW one parallel cluster one-day simulation period needs a computing time of about 2.5 h in case of low water conditions and 16.5 h for flood conditions using 400 parallel processors.

In the following the most important parameters for the numerical model are listed. Detailed information can be found in Goll (2013).

10 vertical logarithmic distributed σ-layers

- k-espilon turbulence model
- equilibrium conditions for the sediment input
- 4 grain size classes
- bed load formula of Engelund & Hansen (1967)
- slope effect of Koch & Flokstra (1981) for the magnitude and Apsley & Stansby (2008) for the deviation
- calculation of the shear stress τ with consideration to turbulence after Goll (2013): $\tau = \rho u_*^2 + \rho r 2k$ (ρ: density, u_*: friction velocity, r: Newton-Taylor coefficient, k: turbulent kinetic energy)

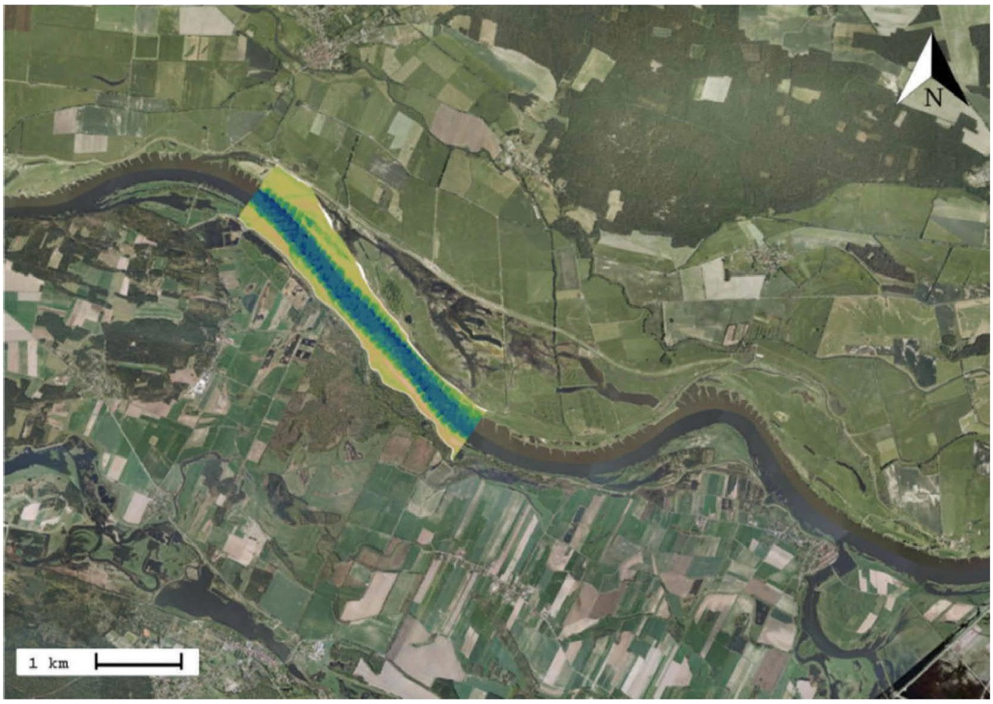

Figure 1: Aerial view of the computational domain between El-km 480.0 to 484.0 (source: Bundesamt für Kartographie und Geodäsie, 2016. Figure 8.5 from Goll 2017).

2.2 Dune parameters

Dunes can be described by their length and height. In dune analysis both of these parameters have been widely used (e.g. van Rijn, 1984; Yalin & Ferreira da Silva, 2001). Coleman et al. (2001) introduced three further parameters: standard deviation, skewness and kurtosis. Skewness and kurtosis are the third- and fourth-order distribution moments normalized by the variance. The skewness describes the deviation of the symmetrical shape. Zero skewness indicates a symmetric surface shape. Dune fields have usually flattened crests and steep, distinct troughs which give negative skewness values. The skewness is calculated by the quotient of the third order moment and the cube of the standard deviation σ. The third-order moment is the spatial averaged cube of the deviation z' to bottom elevation z:

$$sk = \frac{\langle z'^3 \rangle}{\sigma^3} \tag{1}$$

The kurtosis is the variation of the variance and is calculated by the quotient of the forth- order moment and the standard deviation to the power of four. The kurtosis value of a normal distribution is three, thus it is usually corrected by this value.

$$Ku = \frac{\langle z'^4 \rangle}{\sigma^4} - 3 \tag{2}$$

A positive kurtosis indicates more extreme values of the data set, whereas a negative kurtosis means less extreme values. Distinctive three-dimensional dune fields will have high positive kurtosis values.

3 River Application

The Leichtweiß Institute of Hydraulic Engineering (LWI 2012) calculated dune statistics for seven high-resolution bottom surveys of a stretch of the Elbe River near Lenzen. The dune parameters were calculated for a three kilometre long and straight section using the zero crossing analysis. The same statistic procedure is used for the simulation results. Detailed information about this processing can be found in Henning (2013) and LWI (2012).

3.1 Dune parameter prediction for constant discharges

Based on the assumption that a specific constant discharge generates a specific constant statistical dune parameter set, two discharges and their corresponding bed level measurements were chosen from the investigated ones in LWI (2012). One was used as the initial condition and the second for comparison. Both measurements should be made during a constant low or mean water period. So the dunes have enough time to evolve to their quasi-steady state. Ideally the two selected discharges should have the shortest time interval available between them, avoiding errors introduced by changes in river measures or from differences in measurement techniques. The best choice was two summer events in 2007 with 417 m^3/s and in 2011 with 368 m^3/s. Figure 2 shows the hydrographs from gauge Wittenberge for a 20 day period before the two discharges.

The measured bottom scan from 2007 was used as the initial condition and the bottom scan from 2011 was compared to the simulated bottom based on an artificial hydrograph shown in Figure 3. In order to keep the initial conditions consistent, the hydrograph also starts with the measured discharge of 417 m^3/s from August 2, 2007. After an adaptation period of one day the hydrograph provides the constant discharge corresponding to the bottom scan from June 8, 2011. With the previously described three-dimensional model the hydrograph was simulated. The constant part of the hydrograph was enlarged as long as the dune parameters reached a new equilibrium associated to the discharge of 368 m^3/s. The simulated, nearly constant statistical dune parameters were compared to the dune parameters calculated from the bottom scans in 2011 (Figure 4). Both the dune length and the dune height increased in nature with decreasing discharge. This trend could be predicted by the simulation whereas neither the level of the measured dune height nor the length could be reached (Figure 4 left).

The skewness of the measurements decreased with smaller discharge (Figure 4 right). Both measured skewness values are positive. As skewness was calculated without a high-pass

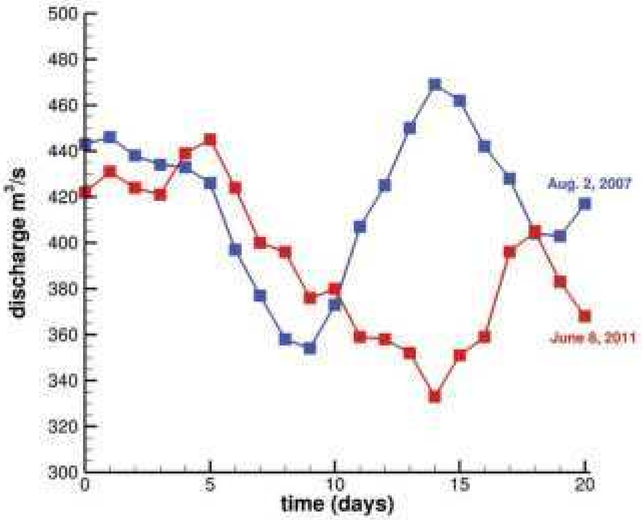

Figure 2: Hydrograph of gauge Wittenberge 20 days before the measured bottom scans at August 2, 2007 and June 8, 2011.

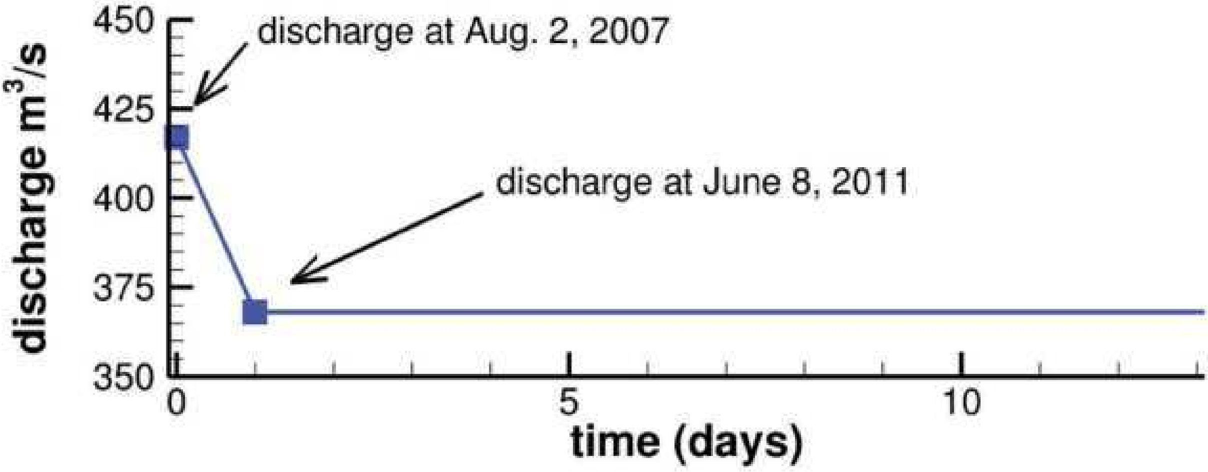

Figure 3: Used hydrograph for dune prediction for the constant discharge of $368 m^3/s$

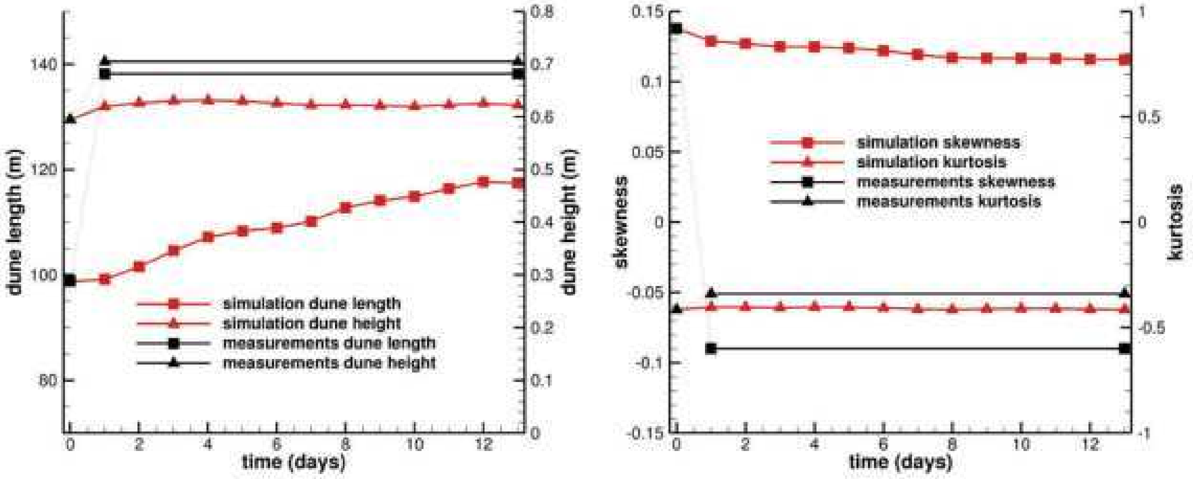

Figure 4: Simulated dune length and height (left) and skewness and kurtosis (right) for the artificial hydrograph presented in Figure 3 in comparison to the measured values for the initial conditions (at August 2, 2007) and the constant part (conditions at June 8, 2011) of the hydrograph.

filter the positive values suggest the existence of banks (Coleman 2011). The trend of the simulated skewness values is correct but the values from the measurements could not be reached.

The kurtosis values are slightly negative and do not change significantly. The negative kurtosis values indicate less extreme values which seems plausible for mean to low water conditions. The simulated kurtosis values increase minimally which fits adequately to the small increase in the values from the measurements.

Figure 5 compares the 3D views of the initial dune bed to the simulated dune bed after 13 days. When visually compared the resulting geometry is very similar to the initial dune structures, thus confirming the model can correctly generate dune movement. Even if the simulation does not forecast exact values for the four dune parameters, forecasting the correct trend is a valuable result. The time gap between the measurements, as well as the simplification through the removal of the elapsed hydrodynamics occurring during the time gap, influence the results and introduce uncertainties. These factors should be taken into account during the evaluation.

The adaption time for a new equilibrium is much longer for the dune length compared to the dune height. Assuming a similar adaption time of about 10-15 days in nature, the

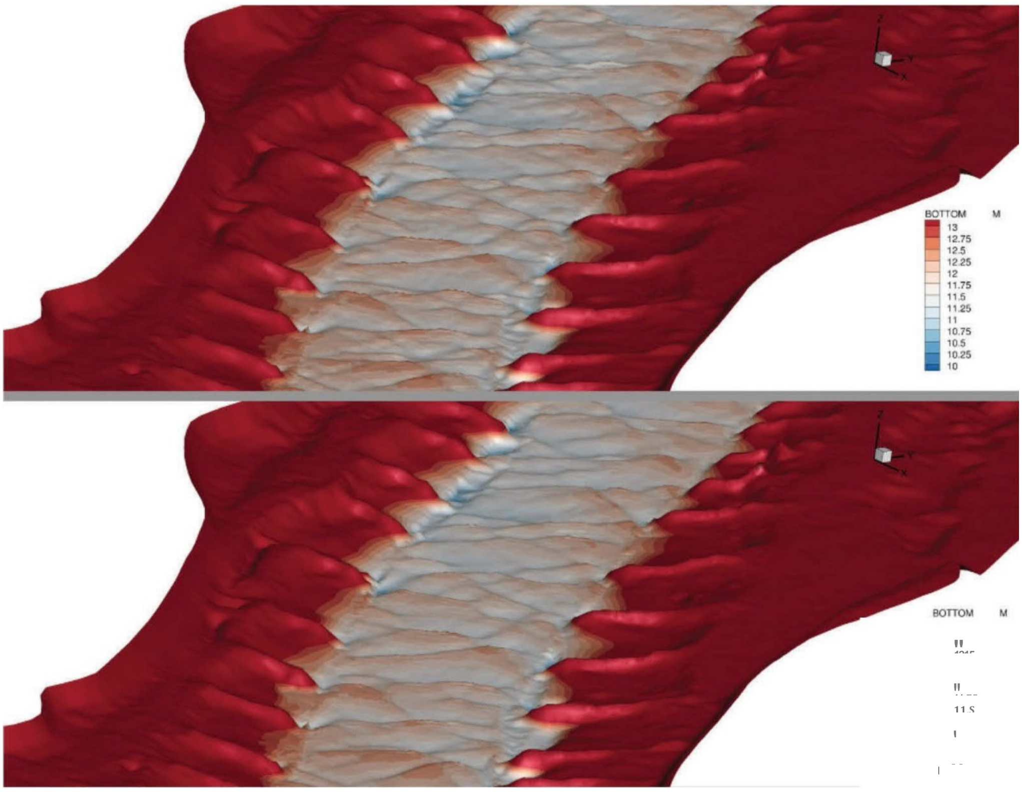

Figure 5: Initial bed levels (top) and simulated dunes after 13-days simulation period (bottom).

assumption of a quasi-steady state for the dune movement is not fulfilled. Figure 2 shows that in both previous 10-days-periods the discharge fluctuation is in the same range as the difference between the investigated discharges. It can be assumed that the measured dunes are not in a fully equilibrium state.

3.2 Dune parameter prediction for a flood event

The flood event was the only data set previously investigated in LWI (2012) where the elapsed hydrodynamics could be taken into account. As the numerical model was calibrated only for a mean water discharge, modeling a flood event is not ideal. Some further calibration work has been done for this study resulting in slightly different parameters (smaller angle of repose, adaption of sediment classes for an even distribution, slope effect of Apsley & Stansby for both, magnitude and deviation).

During the subsiding segment of the flood wave event three bottom scans were made and the dune parameters were calculated (LWI 2012). As the first bottom scan is too close to the peak, only the two latter ones were used. Figure 6 shows the hydrograph with the dates marked for the two latter bottom scans. The simulation starts on April, 13th 2006, the date of the first selected bottom scan, and ended 8 days later on April, 21st 2006. During this period the measured mean dune length increased by 16 m while the mean height increased by 10 cm. The skewness values are slightly positive and change not significantly. The high pass filtered values are negative which indicate a typical dune form of flattened crests and steep, distinct troughs. Also there are no notable changes in the kurtosis values. Both values are negative

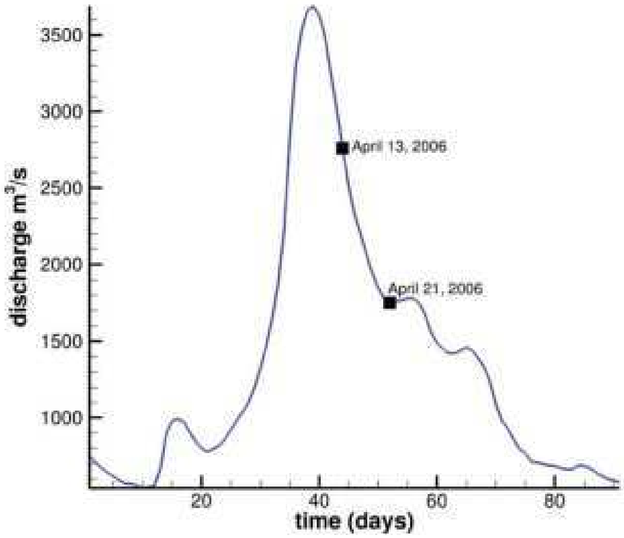

Figure 6: Hydrograph of gauge Wittenberge from March 1, 2006- June 1, 2006.

which indicate less extreme values but the values are higher than those for the low water conditions in section 3.1, which seems plausible.

In Figure 7 (left) the simulated dune lengths and heights during the simulation period are compared to the measurements. The simulated dune heights increased as in the measurements, but not by the measured 10 cm instead the simulated heights increased by 75 cm. No consistent trend was found in the development of dune length. In the first four days the dune length decreases. Starting at day six the length slightly starts to increase. The simulated skewness and kurtosis show the correct trend but overestimate the measured values (Figure 7, right). The strong increase in dune height creates more extreme values which increases the kurtosis and is probably also the reason for the overestimated skewness. In Figure 8 the initial state of the dunes (top) is compared in a 3D view to the dunes after the 8-days simulated flood event (bottom). The strong increase in dune heights and the change in dune shape can clearly be seen.

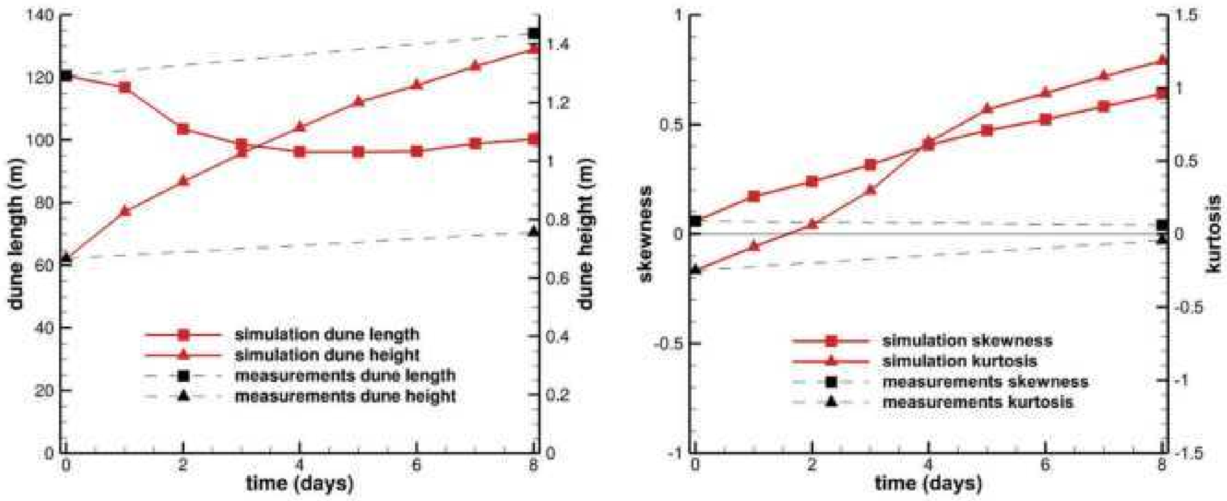

Figure 7: Comparison of dune length and height (left) and skewness and kurtosis (right) between the simulation and the measurements from April 13, 2006 to April 21, 2006.

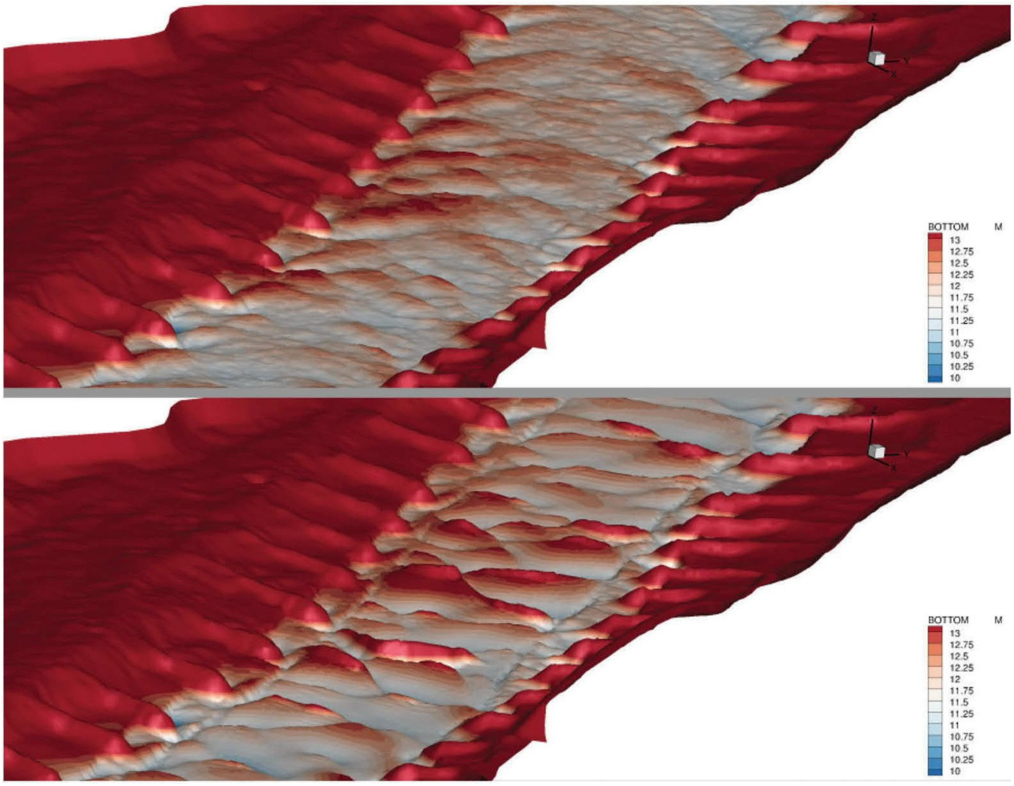

Figure 8: Initial bed levels (top) and simulated dunes after 8-days flood event simulation (bottom).

4 Conclusions

With the presented high-resolution three-dimensional numerical RANS model it is possible to simulate dune movement and evolvement. With the massive parallel and efficient numerical software

TELEMAC-MASCARET the computation time is tolerable. At the BAW one parallel cluster one-day simulation period needs from about 2.5 h up to 16.5 h of computing time depending on the hydrodynamic conditions, using 400 parallel processors. Simulation periods of days to months are possible. Thus the prediction of dune parameters with the presented numerical model needs further investigation. A prediction for steady state low to mean water conditions shows the correct trends but could not reach the right values. It is not verifiable, how much of this discrepancy is due to the fact that the measured dune parameters do not come from a fulfilled equilibrium state. Measurements with short time intervals for the entire discharge spectrum are needed for better examinations.

Simulations with high bed load transport rates have a high requirement for stable numerics. It can therefore already be considered a success that the numerical model, which was only calibrated for mean water conditions, was able to simulate the flood event. Nevertheless the results are not satisfying and further investigations are planned. First of all, it must be worked out whether the stability of the numerical model is sufficient for the flood conditions. One way to prove this is to simulate high water steady state conditions and reach plausible equilibrium dune parameters. Probably extensive calibration of the morphodynamic parameters and/or the numerical parameters will be needed for this.

Dune prediction with three-dimensional RANS numerical models seems possible in principle. More experience is needed to achieve this ambitious goal, firstly in the analysis of measurements and secondly in the numerical simulation of different discharge situations.

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Author:

Rebekka Kopmann
Federal Waterways and Research Institute (BAW)
Kußmaulstraße 17, 76187 Karlsruhe, Germany