Bleyel, Birgit; Kopmann, Rebekka

Influence of the layer model on a 2D sediment transport model: Hirano-Ribberink versus C-VSM

Influence of the layer model on a 2D sediment transport model: Hirano-Ribberink versus C-VSM

Birgit Bleyel, Rebekka Kopmann
Hydraulic Engineering in Inland Areas, Bundesanstalt fuer Wasserbau (BAW), Karlsruhe, Germany
birgit.bleyel@baw.de; rebekka.kopmann@baw.de

***Abstract*— With the possibilities introduced by the new C-VSM layer model, which provides continuous vertical grain sorting, it is essential to identify its impact on simulation results in comparison to the classical Hirano-Ribberink layer concept, which is the default layer model implemented in SISYPHE. To this goal, comparisons between field observations and numerical results obtained with both models are proposed.**

The comparisons were done with a two-dimensional sediment transport model consisting of a 46.5 km reach of the river Rhine. Numerical results using the Hirano-Ribberink layer model for a time period of six years (2000 – 2006) was not fully satisfying. Simulated evolutions were considerably underpredicted in comparison with the field measurements and the computed mean sediment diameter becomes coarser over time. Consequently, the transport rate prediction decreases.

Numerical results performed with the C-VSM model show no tendency to coarsen the mean grain diameter and the sediment transport is increased compared to the Hirano-Ribberink layer model. On the other hand, the computing time is quadrupled using C-VSM. This disadvantage could be damped by using twice as much parallel processors which leads to a doubled computing time.

I. Introduction

In morphodynamic modelling of inland rivers, the vertical distribution of the sediments influences the sediment transport behaviour. This is obvious in case of armouring, when coarse grains which cover the underlaying finer sediments prevent further erosion. Furthermore the sediment distribution in the uppermost sediment layer (the so called active layer) determines the current sediment transport. It is assumed that the hydrodynamic influences this active layer in such a way that it can be handled as fully mixed. A thinner active layer will speed up the process of armouring more than a thicker one. Several approaches calculating the active layer thickness are available e.g. [1]. Based on the authors' experience calculated active layer thicknesses often leads to numerical issues. Therefore constant values for the active layer thickness are preferred for practical applications. Furthermore active layer thickness is one of the most sensitive parameters behind the roughness parameter and the sediment grain sizes e.g. [2].

As morphodynamic is a slow process compared to hydrodynamics also the vertical distribution of sediment changes slowly. On the other hand the sediment distribution in the active layer adapts relatively fast to the simulated current hydrodynamics. The sediment distribution in the deeper layers also referred to as "sediment memory" stores the sediment distribution for a long time. Only in case of deep erosion the layers beyond the first two layers are modified. This means that the initial vertical sediment distribution influences the sediment transport significantly over a long period usually longer than the simulation period. So it is important to start with a best guessed initial distribution. The longer the simulation period the more decreases the influence of the initial vertical distribution and the more increases the influence of the numerically build vertical sediment distribution. Too much mixing processes or too less vertical resolution due to an insufficient modelling of the vertical sediment distribution can result in e.g. too coarse mean grain sizes. But modelling a proper vertical distribution is important especially for long term simulation.

In the following section, the two layer models available in SISYPHE (Hirano-Ribberink and C-VSM models), are presented briefly. In section III the 46.5 km Rhine model is introduced. This model was calibrated using Hirano-Ribberink model. The results are compared in section IV with simulations using the C-VSM model.

II. Vertical Layer Modelling in Sisyphe

A. Hirano-Ribberink model

The Hirano-Ribberink layer model [3], [4] is the default option in SISYPHE. The basic concept behind this model is a fully mixed top most active layer which interacts with the hydrodynamic. With the current sediment distribution a bed load discharge for each sediment class is calculated which can result in sedimentation or erosion per class. The sediment body below the active layer up to the rigid bed can be discretised by a selectable number of additional layers. The layer below the active layer is called stratum. The height of the active layer can be set as constant or it can be dynamically computed. The stratum is increasing or decreasing according to the sediment deposition or erosion processes. The underlaying layers are not involved in the sediment transport processes. If a layer is destroyed due to erosion processes it cannot be built again except for the active layer and the stratum.

In case of sediment deposit (Fig. 1) the new sediment is mixed into the active layer, which is temporarily enlarged by the height of the deposit. The newly mixed active layer is split into the height of the active layer and the enlarged part. The enlarged part is combined with the stratum. This procedure enlarges the stratum layer. In case of erosion (Figure 2) the eroded sediments are taken out of the active layer. This can result in a new sediment mixture of the active layer. To restore the calculated or constant height of the active layer part of the stratum is mixed into it. If the cumulated erosion is larger than the stratum the former layer 3 becomes the new stratum.

B. Continuous Vertical Sorting model (C-VSM)

The C-VSM is based on the work of Astrid Blom et al. [5], [6] and was adapted and implemented in SISYPHE by Uwe Merkel. It is available since version V6P3. Detailed information can be found in [7], [8] and [1]. Each sediment class has its own continuous vertical grain sorting profile, which is discretised by a user defined maximum number of sections.

For the interaction with SISYPHE the current sediment distribution over the active layer thickness is temporarily mixed at every time step. As for the Hirano-Ribberink model bed load discharges per sediment class and sedimentation or erosion per class are calculated.

In case of sedimentation (Figure 3) the new sediment is added on top of the vertical sediment stratification. The vertical profile of each deposited class gets a new section on top. If the maximum number of section is reached sections are combined with a modified version of the line generalization algorithm proposed by Douglas and Peuker [9].

In case of erosion (Figure 4) the eroded classes are taken from the vertical sediment stratification.

An advantage to this model is that the only mixing process in the C-VSM model is the mixing of the active layer. But this mixing is only temporarily and does not modify the original vertical distribution. This is preserved and all sedimentation or erosion processes base upon this distribution.

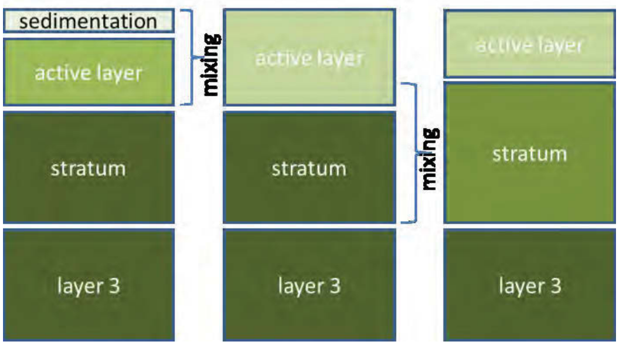

Figure 1: Sedimentation procedure for Hirano-Ribberink model in SISYPHE.

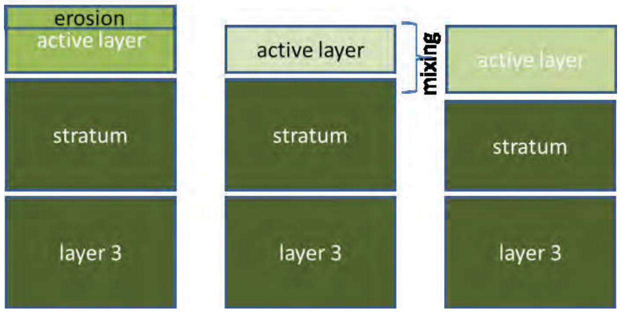

Figure 2: Erosion procedure for Hirano-Ribberink model in SISYPHE

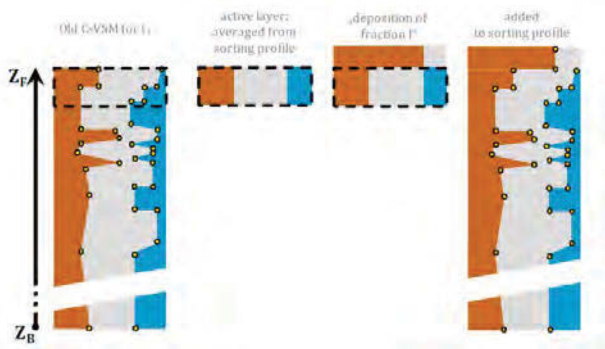

Figure 3: Sedimentation procedure for C-VSM model in SISYPHE. Figure taken from [7].

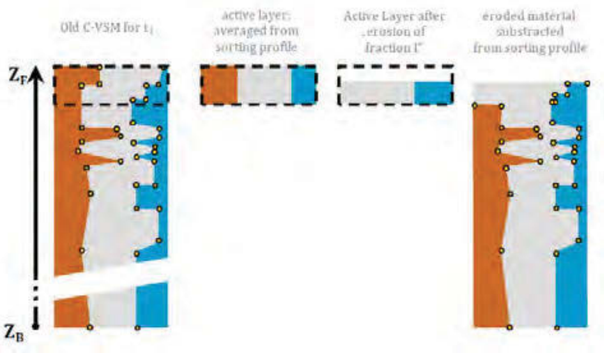

Figure 4: Erosion procedure for C-VSM in SISYPHE. Figure taken from [7]

III. Rhine Model

The comparison between the two layer models have been done with a 46.5 km long TELEMAC2D-SISYPHE model for the middle Lower Rhine from Rhine-km 730 near Neuss to 776.5 near Duisburg (see Figure 5). The model consists of about 260,000 nodes and was calibrated for a period of 6.5 years of the natural hydrograph 1.1.2000 - 22.6.2006. On a parallel cluster at BAW (Intel(R) Xeon(R) Gold 6138 CPU) the computing time is about 1.5 days for this simulation period using 160 processors respectively subdomains.

The grid resolution with node distances between 5-50 m allows a proper reproduction of the groyne geometry as well as the analysis of artificial bed load supply, bed evolution and bed-load transport.

The most important parameters for the hydrodynamic and morphodynamic simulations are listed below.

- Hydrodynamic time step: 4 s, morphological factor 4
- Nikuradse friction law, four different friction zones
- Elder turbulence model
- Multi-grain (10 sediment classes for bed load transport and if necessary 10 sediment classes to follow the artificial bed load supply), Hirano-Ribberink multi-layer model (3 layers, constant active layer thickness: 0.1 m)
- Meyer-Peter und Müller transport formula; Karim, Holly, Yang hiding exposure formulation
- Soulsby and Talmon slope effect formulation
- Secondary currents approach for hydrodynamics and morphodynamics, with the radius of curvature provided in an additional file
- Bed load management module NESTOR to consider artificial bed load supply and dredging procedures
- The sediment distribution is initialized by a pre-simulation over a period of 6.5 years starting with equal fractions for all sediment classes. The time averaged sediment distribution of the active layer is transferred to the other layers.

IV. Comparison Hirano-Ribberink vs C-VSM in SISYPHE

The Rhine model described in section III using the default layer model was taken as base scenario for the comparison between the Hirano-Ribberink model and the C-VSM model. The only difference between the two models is the choice of the layer model. The initial vertical distribution of the sediment body was the same for both models. For the C-VSM the influence of the vertical discretisation was investigated. A set of three different maximum sections numbers (25, 100 and 200) were tested. All are less or just even to the recommendation of 200 – 500 [1].

The smallest sections number produces instabilities of the bottom evolutions (peaks). The highest sections number took too much computation time for project needs. The results with 100 maximum sections number look plausible. Therefore this choice seems a good compromise between computation time and quality of results for this investigation.

No extra calibration was done for the C-VSM model even though the results are not in a good agreement with the measurements as this was not the aim of this study. Of course this must be done if the C-VSM model should be used instead of the Hirano-Ribberink model for project purposes.

Figure 5: Model area in the middle Lower Rhine. The flow direction is from South to North.

The hydrograph of the simulation period is shown in Figure 6. The annual averaged discharge (red line) illustrates that the years 2000 and especially 2001 - 2002 are wet years followed by four dry years 2003 - 2006.

In Figure 7 the simulated bottom evolution for the simulation period (2000 – 2006) is compared with field measurements. The simulated and measured bottom evolutions were averaged over the sounding width and along 1.1 km of the river stretch. The simulated bottom evolutions fit acceptable to the measurements considering measurement uncertainties and the comparably small changes. For the regions with bed load management actions (grey areas) the agreement is less satisfying as the simulated evolutions are mostly too big. Additionally the erosion area between Rh-km 755 and 765 which is the cause for the artificial bed load supply cannot be correctly represented in the numerical model.

A reason for that could be the coarsening tendency of the model which results in less erosion. Figure 8 shows the averaged grain size distribution in the active layer for the initial state and after 6.5 years simulation period. All fractions for all sediment classes were initialized equally. But at some regions only the largest grain size was available due to scour protections measures. This leads to a slight increase of the averaged initial fractions for the coarsest sediment class.

The coarsening tendency after 6.5 years is clearly visible. The fractions of the smaller sediment classes were decreased while the coarser sediment classes were increased. The mean grain size in the active layer averaged over the bed load active area increased from 20.1 to 24.6 mm during the total simulation time.

Varying nearly every calibration parameter did not enhance the results significantly. E.g. a refined discretization of the vertical structure of the sediment body produced an even stronger coarsening effect. In Figure 9 the simulated annual solid discharges 2000 – 2006 with 3 and 5 layers using the Hirano-Ribberink model are compared. In both cases the active layer (constant 0.1 m) and the last layer (initially 98.9 m) are the same. For the 3-layer variant the stratum is about seven times larger (1 m instead of 0.15 m). The small thickness of the stratum promoted the coarsening effect. The layers 3 and 4 as possible new stratum layers if the original stratum is destroyed have also smaller thicknesses (0.3 and 0.55 m). With the refined vertical discretization of 5 layers the calculated annual solid discharges along the river stretch (dotted lines) were significantly smaller than for the 3-layer model (solid lines). Instead of enhancing the model the coarsening was increased by using more and finer layers.

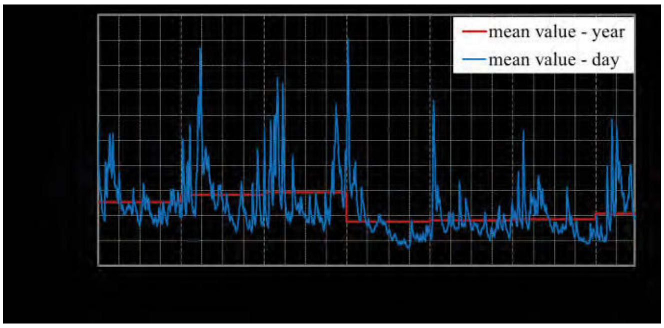

Figure 6: Hydrograph of simulation period

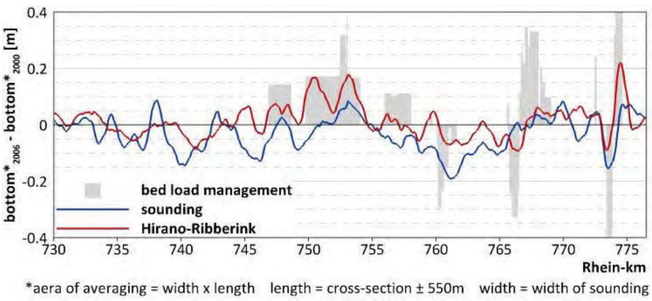

Figure 7: Measured and simulated bottom evolution for the simulation period (2000 – 2006) averaged for the width of the sounding and 1.1 km along river stretch.

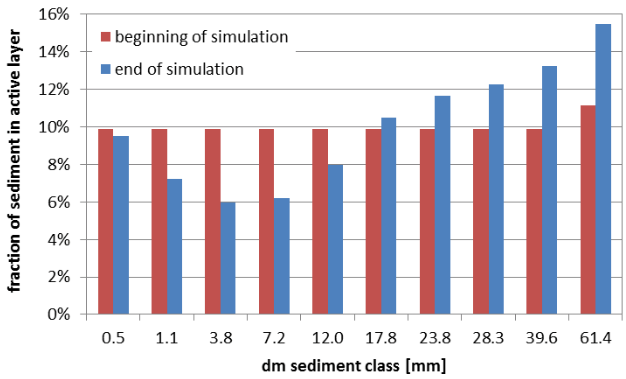

Figure 8: Simulated mean fraction of sediment classes for the active layer.

The development of the coarsening effect and the problem for long-term simulations can be seen in Figure 10. As expected the solid discharge is higher for wet years and smaller for dry years (compare the annual averaged discharges in Figure 6). A clear coarsening tendency due to simulation duration could not be proven. For better evidence the same hydrograph is used for a second simulation. This simulation is identical with the first run except for the sediment fractions in the beginning, which derive from the final vertical sediment distribution of the first run (dotted line). All annual discharges of the second hydrograph have smaller values. Also the variation of the solid discharge along the river stretch decreases with the simulation duration. These results confirm the coarsening tendency by simulation duration of the Hirano-Ribberink model.

This behavior of the Hirano-Ribberink model in SISYPHE hinders successful long-term simulation in the present project. For project studies simulation periods of 10 to 20 years or longer are needed. In order to solve this problem the second layer model C-VSM was tested.

With C-VSM a successful simulation run of the 6.5 years simulation period could be managed. Again the averaged grain size distribution in the active layer for the initial state and after 6.5 years simulation period was analyzed (Figure 11). The averaged fractions applying C-VSM doesn't change much within the simulation period. Instead of a coarsening as with Hirano-Ribberink the initial mean grain diameter of 20.1 mm decreases minimal to 19.7 mm during the 6.5 years.

Figure 12 shows the results of the first and second simulation period analogous to the simulations for Figure 10 with the C-VSM model. The annual solid discharges simulated with C-VSM but the same parameter set as the original model are generally higher than with the Hirano-Ribberink model. The annual solid discharges do not differ much between the first or second simulation run. The variation of the solid discharge along the river stretch is higher compared to the Hirano-Ribberink results. All three observations confirm that the C-VSM model has no coarsening tendency.

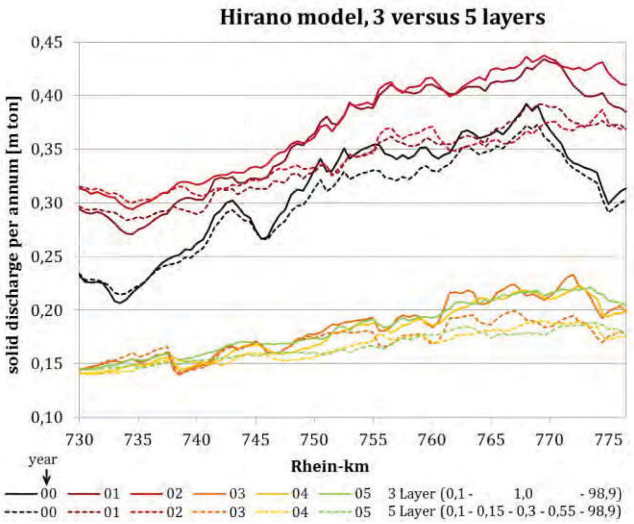

Figure 9:Comparison of simulated annual solid discharge with Hirano-Ribberink model using 3 and 5 vertical layers

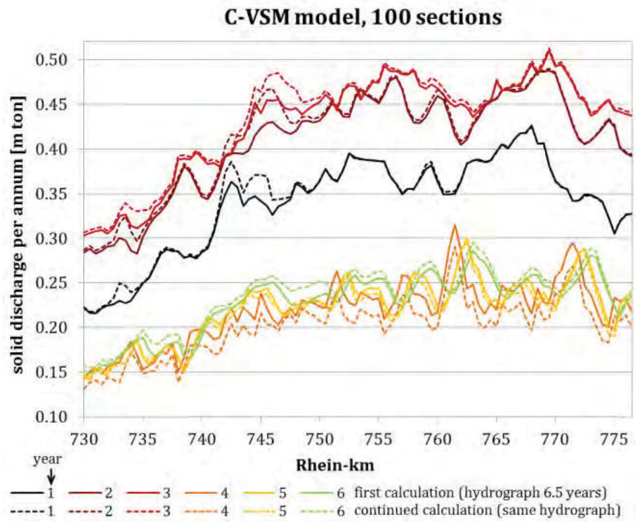

Figure 12: Simulated annual solid discharge with C-VSM model (dotted lines: started with sediment fractions from the end of the first run).

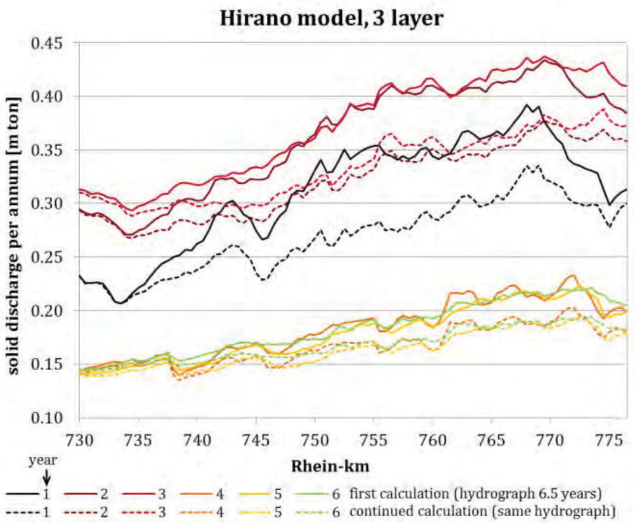

Figure 10: Simulated annual solid discharge with Hirano-Ribberink model (dotted lines: started with sediment fractions from the end of the first run).

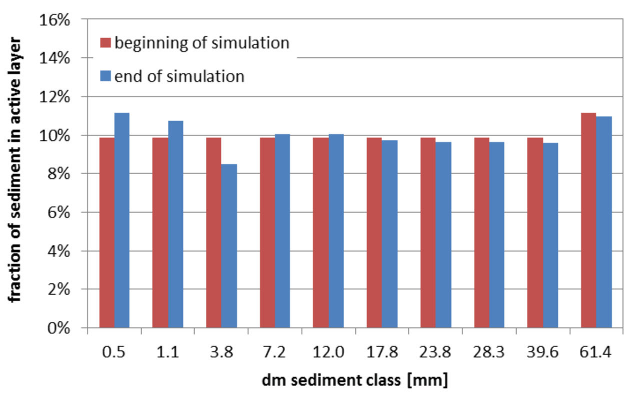

Figure 11: Simulated mean fraction of sediment classes for the active layer using C-VSM.

V. CONCLUSIONS AND OUTLOOK

The default layer model in Sisyphe (Hirano-Ribberink model) tends to coarsen the sediment distribution in time. Especially for long-time simulation the calculated mean grain sizes correspond not longer to the natural conditions and the sediment transport decreases in time. This tendency cannot be compensated by calibration.

First investigations with a 46.5 km Rhine model could not detect a coarsening tendency with the C-VSM model. So this model could be a better choice for long-term simulations in SISYPHE than the Hirano-Ribberink model. Nevertheless much more experiences have to be collected with the new layer model to verify its usability for project work. Next steps will be the calibration of the C-VSM model to the measurements. Even if there is no numerically driven coarsening there is no automatically mechanism that the C-VSM model is able to reproduce the erosion region between Rh-km 755 -765.

Furthermore the C-VSM model is computationally costly. It needs about four times more computing time than the Hirano-Ribberink model using a maximum sections number of 100. This could be reduced to two times if the number of processors is doubled. This increase in computation time is barely possible for long-time simulations. Further investigations are needed to proof that 100 maximum sections number produce comparable results than the recommended 200 – 500. The expected computation times can only be handled using restart functionality as the parallel cluster queues at BAW are limited.

VI. ACKNOWLEDGEMENT

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