

Simulation of Flood Scenarios with Combined 2D/3D Numerical Models

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ABSTRACT: To determine flooded areas in case of failure or revision of a weir in combination with a coincidental 100-year flood event, extensive water level calculations have to be done. The Federal Waterways Engineering and Research Institute was commissioned to estimate the hazard potential for this situation at the Main river. In close vicinity to the barrage the flow is characterized by a three-dimensional velocity field. In contrast to these three-dimensional small-scale effects, the flow in the far field of the barrage and over the wetlands can be approximated as two-dimensional. In order to simulate the variety of effects correctly with an appropriate effort of time 2D- and 3D-models were built. Neither the two- nor the three-dimensional model can reproduce all the relations in a sufficient way. Furthermore the parametrical correlations of boundary conditions of the two models highly influence each other. The approach of joining a two- and a three-dimensional model in order to create a hybrid model will be shown.

Keywords: Hybrid modeling, Flood, Weir, OpenFOAM

1 INTRODUCTION

In the first half of the 20th century, 34 barrages were built at the river Main between Kostheim and Viereith. The Federal Waterways and Shipping Administration commissioned the Federal Waterways Engineering and Research Institute to estimate the hazard potential due to failure of a weir gate. The calculated water levels were compared to existing water levels of a 100-year flood event. Thus the impact on the flooding situation caused by failure of a weir gate can be judged.

According to the German Association for Water Management and Environmental Construction distinctions between failure and revision of a weir gate have to be made. In case of a failure a weir gate cannot be moved out of the flow cross section at the time of an arriving flood. In case of a revision an inspection cover blocks a weir field. Considering failure of a weir gate the upstream water level of the barrage needs to be estimated for a 100-year flood event. In all scenarios the most powerful weir is considered. Real-life examples are chosen to demonstrate the creation of a hybrid model and the processing of the given task respectively.

In case of failure or revision of a weir gate the flow regime in close vicinity to the weir is characterized by a three-dimensional flow intensified by the small number of weir fields. Hence, the application limits of one- and two-dimensional numerical approaches will be exceeded. To limit the computing costs a three-dimensional multiphase model is set up with OpenFOAM covering only areas where vertical acceleration cannot be neglected.

Since the flow in the far field of the barrage and across the wetlands can be approximated as two-dimensional, a 2D-model was used. It stretches over several kilometers of the river valley estimating the consequences of the failure for the region.

In order to compute the upstream water level in case of failure with respect to all two- and three-dimensional effects both models are necessary. The hydraulic boundary conditions and results of the two models influence each other.

A flow around the barrage (over the wetlands) has to be taken into account in case of a 100-year flood event. Hence, the 100-year discharge will split up into a branch over the wetlands and another through the weir. The partition of the 100-year discharge depends on the upstream water level.

The tailwater level highly depends on this partition and on the point where the flow over the wetlands returns into the river Main additionally. Furthermore the tailwater level affects the backwater at the weir and in consequence the upstream partition of the 100-year discharge. Neither the two- nor the three-dimensional model can reproduce sufficiently all the relations listed here independently. This explains why a hybrid model is necessary for these kinds of scenarios. Investigating both failure and revision of a weir, detailed information about the water levels was obtained.

2 2D MODEL

Several different engineering companies were assigned by the Bavarian Environmental Agency to build two-dimensional depth-averaged hydrodynamic models in order to create flood risk maps for Bavaria. They consider that all gates of the weir are in operation in case of a 100-year flood event. The flood risk maps show the water elevation in such a case. Concerning the water level calculations in case of failure of a weir, the Bavarian Environmental Agency provided the Federal Waterways Engineering and Research Institute with those two-dimensional depth-averaged hydrodynamic models, which are covering the whole Bavarian part of the river Main.

The models were created with the software Surface-Modeling System (SMS) of Aquaveo LLC. They contain the river channel and are wide enough to simulate an extreme flood. The wetlands are meshed with a triangular grid and the river channel with a rectangular grid as shown in figure 1. The cell size in the river channel is 25 m (in flow direction) by 10 m. The cell size on the wetlands depends on the topography and is up to a maximum of 25 m. The geometry of the model is based on a digital terrain model of the Bavarian part of the river Main. The digital terrain model was created by the Federal Institute for Hydrology during the years 2005 to 2009. Its height accuracy is 0.15 m, its positional accuracy 0.20 m.

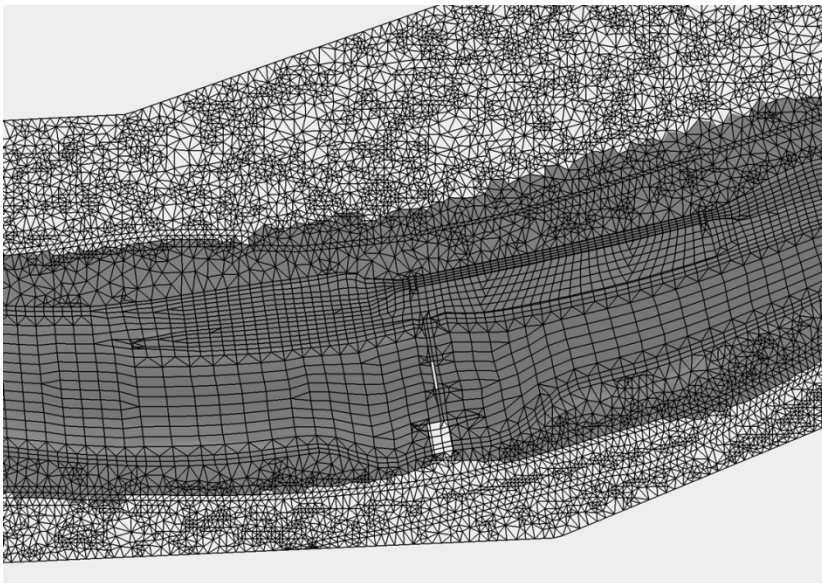


Figure 1. 2D mesh: Detail of the two-dimensional depth-averaged hydrodynamic model of the weir Rothenfels [Bavarian Environmental Agency]

The calculation engine HYDRO_AS-2D of the engineering company Hydrotec is used for the hydrodynamic-numerical computations (Nujic 2006). At the inflow boundary condition, the 100-year discharge which corresponds to the simulated river reach was used. Serving as hydraulic boundary condition at the outflow, a relation between discharge and downstream water level was established. The defective weir gate is simulated as a wall with the same height. The flow over the wall depends on an overflow coefficient μ , which will be adapted as described in chapter 4.

3 3D-MODEL

The geometry of the weir originates from laser scan data of the Federal Waterways and Shipping Administration. It was supplemented by existing plans of the paved weir floor and the radial gate. The geometry of the riverbed of both models (2D and 3D) is obtained from the same data for reasons of comparability. Microstation 8.11 was used to edit and merge all geometries.

The geometry used for the simulation is not the same for each barrage but depends on local conditions: If the flap gate can be lowered without any external source of energy it will be used for flood water to pass. Hence, the top of the weir gate is crucial for the backwater. Where the area of the navigation lock represents a flow sensitive cross-section, it will be integrated into the 3D-model (e.g. if the navigation lock is appropriate for flood discharge).

Using the grid generator SnappyHexMesh integrated in OpenFOAM a mesh is generated. It consists mostly of isotropic hexahedral cells. The dimensions of the model are adapted to the flow conditions. The 3D-models are about 500 m long, 100 – 200 m wide and 20 m high, containing 7 – 10 millions of cells, depending on the barrage which is investigated (figure 2). The average cell size is 1.00 m. In close vicinity of the weir pier the cells are refined four times to an average size of 0.06 m.

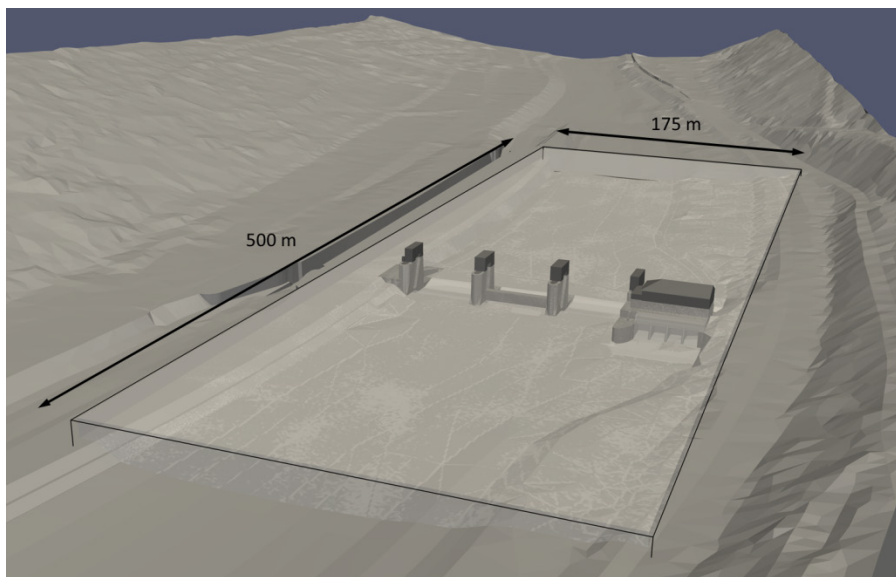


Figure 2. 3D model: Overview of the dimensions and geometry of the 3D-model of the weir Rothenfels

A flow rate is prescribed at the inflow boundary which is consistent with the partial discharge of a 100-year flood flowing through the weir (main cross-section of river Main). This percentage depends on the geometry of the weir, the tailwater level and the resulting backwater. A certain water level is assigned at the outflow boundary. Tailwater level and flow rate distribution upstream of the weir influence each other. An atmospheric boundary is given for the top. The simulation time is set to 500 s in order to obtain a quasi-stationary flow and a sufficient period of time to measure the average water levels.

OpenFOAM version 2.2.0 with the solver interFoam was used for the hydrodynamic calculations. The approach is based on the three-dimensional, instationary and incompressible Navier-Stokes equations (Jasak 1996). Due to the geometric discretization small scale turbulences cannot be considered. Hence, a k-Omega turbulence model was used for the simulation. The two-phase Navier-Stokes equations are solved with the volume of fluid method which allows the determination of the water surface (Hirt and Nichols 1981).

4 HYBRID MODELLING APPROACH

Considering lateral inflows into the model area the 2D model is aimed to represent the large-scale flow regime. Furthermore, the overflowing river Main and the resulting flow over the wetlands are simulated. Hence, a statement about the ratio of flow over the wetlands and total discharge can be made which depends on the upstream water level. The tailwater level and flow through the weir resulting from the calculations of the 2D model are used as hydraulic boundary conditions in the 3D model.

Since the vertical acceleration is neglected in two-dimensional modelling it is the aim of the 3D model to represent the hydraulic capacity of the weir more exactly, e.g. the relation of flow through the weir,

tailwater level and backwater. This correlation is in fact unknown at the beginning of the investigation. Accordingly, temporary results of the 2D model must serve as hydraulic boundary condition. On the other hand, correlations found by the 3D model are integrated into the 2D model.

The 3D model can be seen as addition to the 2D model considering the more exact simulation of highly turbulent flow in close vicinity to the weir where the assumption of a two-dimensional flow is no longer valid. The procedure for coupling the two models in general can be done as follows (see figure 3): To gain an overview over the flow regime around the weir a first calculation run of the 2D model is carried out. Results of this calculation are the discharge through the weir and the tailwater level. Furthermore the difference between upstream and downstream water level can be calculated. Nevertheless, the water level difference is quite inaccurate due to the two-dimensional character of the model. To verify the water level difference the resulting discharge and tailwater level of the 2D model are transferred to the 3D model as hydraulic boundary conditions. Taking these hydraulic boundary conditions into account, the result of the three-dimensional model provides more detailed information about the backwater. Comparing the estimated backwater values of the two models, a statement can be made whether the hydraulic capacity of the weir in the 2D model is accurate. Accordingly the overflow coefficient integrated into the weir of the 2D model needs to be adapted to the flow conditions of the 3D model.

After the adaption of the 2D model another simulation run is carried out. The relation of flow over the wetlands and discharge through the weir changes due to the adapted overflow coefficient. The newly estimated values for flow through the weir, tailwater level and backwater are controlled by another simulation of the 3D model. This iteration course is repeated until an acceptable deviation between the two- and the three-dimensional model is reached.

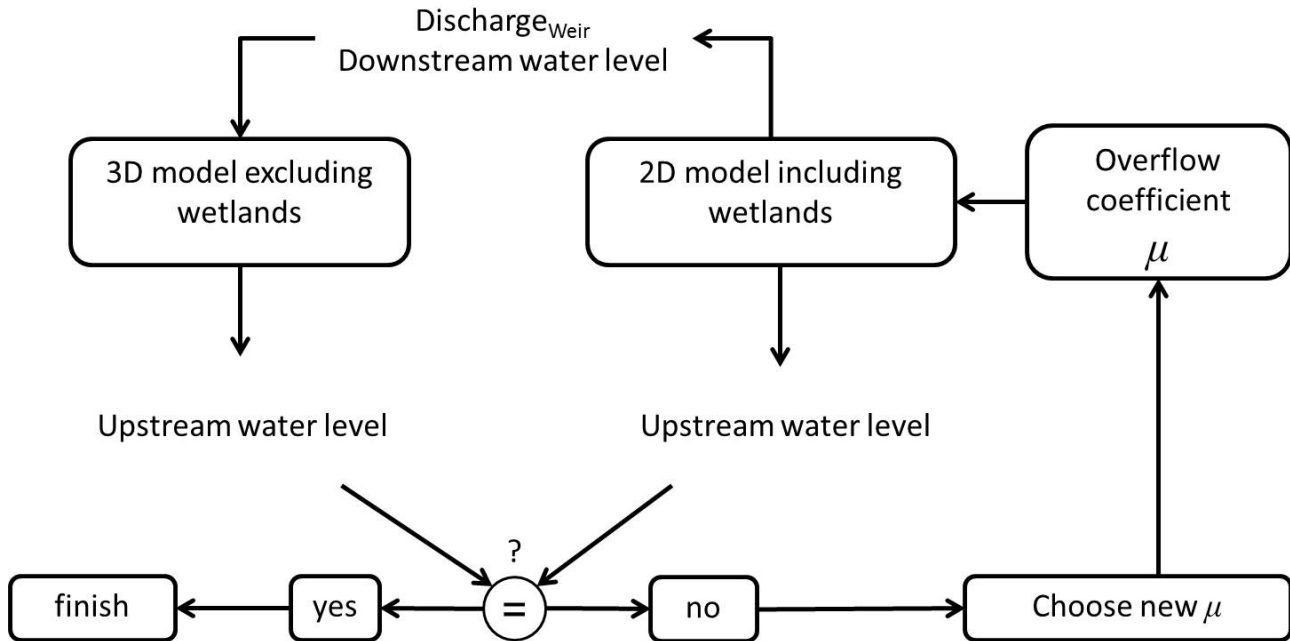


Figure 3. Iteration: Iterative procedure of coupling the 2D- and 3D-model

Since the necessary amount of iteration steps and occurring range of boundary conditions are unknown at the beginning of the investigation, an approach is needed to limit the number of simulation runs of the 3D model. A functional correlation between “discharge through the weir”, “tailwater level” and resulting “backwater” of the 3D model is wanted. Here, a mathematical function with two variables representing a three-dimensional surface in space was chosen. Using a polynomial of second order in x- and y-direction, an equation with nine unknowns results. Hence, nine simulations of the 3D model with different combinations of hydraulic boundary conditions are needed to solve the equation.

The equation is given as:

$$ax^2 + by^2 + cxy^2 + dx^2y + exy + fx^2y^2 + gx + hy + i = z \quad (1)$$

Value ranges of the parameters “discharge through the weir” and “tailwater level” can be estimated based on the first simulation run of the 2D model. E.g. in case of failure of a weir gate at the weir Rothenfels it was decided to set the range of the discharges from 1975 to 2175 m³/s and the range of the tailwater levels from 149.05 to 150.05 m a.s.l. The results are nine different combinations of boundary conditions considering a minimal, average and maximal discharge and tailwater level respectively within the parameters ranges.

By means of trivial matrix algebra the coefficients of equation (1) can be found. While solving this equation it has to be taken into account that the parameter “tailwater level” is not the value specified at the boundary condition but a measured value on the downstream side. Due to the distance between the boundary and the measuring points deviations between the two values can occur. After the model has reached a quasi-stationary condition the tailwater level is evaluated on the basis of 60 measuring points and time related-averaging. The same approach is used for the evaluation of the upstream water level.

The solution of equation (1) is given in figure 4. For the sake of clarity, the upstream water level was classified in steps of 0.1 m. By analyzing the result of equation (1) (figure 4) it can be concluded that a linear approximation is also adequate for the functional correlation between the parameters.

By means of equation (1) it can be checked right after a simulation run of the 2D model whether the calculated backwater at the weir corresponds with the backwater estimated by the 3D model. If the value differs too much from the value of the 3D model, the 2D model can be adapted by the overflow coefficient. After the iteration is finished, water levels are obtained representing the two-dimensional flow regime of the far field and the highly turbulent three-dimensional flow through the weir. By calculating the difference between the water levels obtained by the iterative simulation and existing water levels of a 100-year flood event (calculated with the identical 2D model), the aggravation of the flood situation can be quantified.

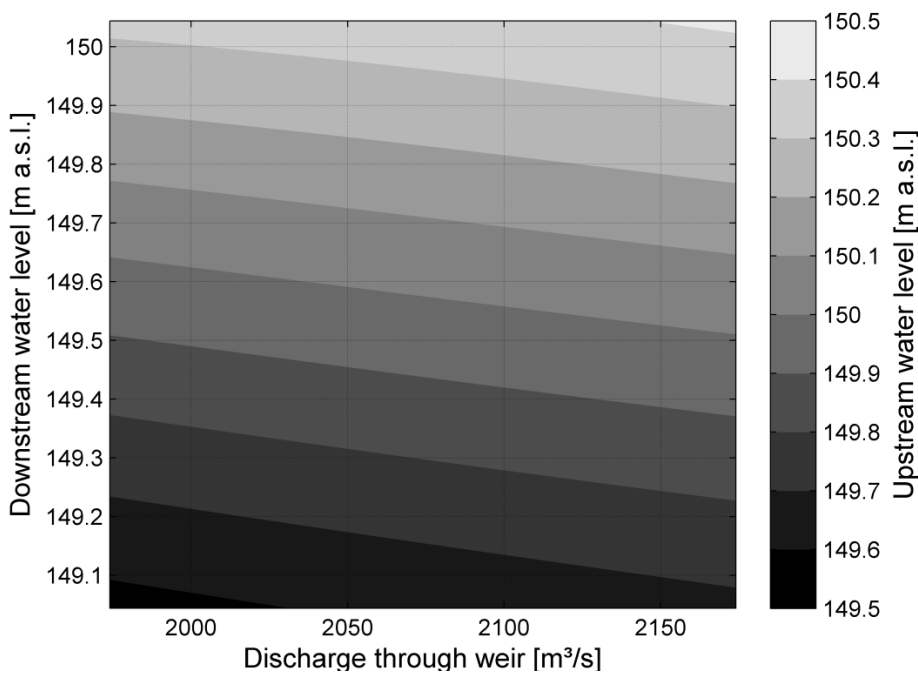


Figure 4. Results of the 3D model: Graphical description of the functional correlation between discharge through the weir, downstream and upstream water level (weir Rothenfels)

5 REAL-LIFE EXAMPLE

As a real-life example the barrage Viereth at the river Main is chosen. The aim of the investigation was to determine the hydraulic capacity of the barrage in case of revision. The barrage contains two weir fields, each 30 m wide, and one lock chamber. The lock cannot be used for the flood release. Since the weir was built in 1925, complex and costly maintenance work needs to be done during the next years. In this process the roller weirs will be replaced with radial weirs. Placing the inspection cover, blocks 50% of the effective flow cross section. Hence, large backwater will occur in case of a 100-year flood event during the construction measure.

First, in order to mitigate the situation, the construction measure is planned to be done in the months May to October which have a lower flood risk. Second, a revision cover is constructed which allows the passage of water in case of a flood (figure 5). By moving the construction measure to the months May to October the design discharge can be reduced from 2000 m³/s to 1180 m³/s. At the same time, the revision cover offers the possibility to enlarge the effective flow cross section by lifting six integrated weirs. This unique type of revision cover was developed by the engineering company ‘Ingenieurbüro Rapsch und Schubert Stahlwasserbau Consulting GmbH’. Of course the downstream revision cover allows the passage of water as well. If a critical water level is reached the construction pit will be vacated and flooded

safely in order to decrease the upper water level. In case of the placed revision cover with lifted weirs and a discharge of $1180 \text{ m}^3/\text{s}$, the resulting upstream water level had to be estimated.

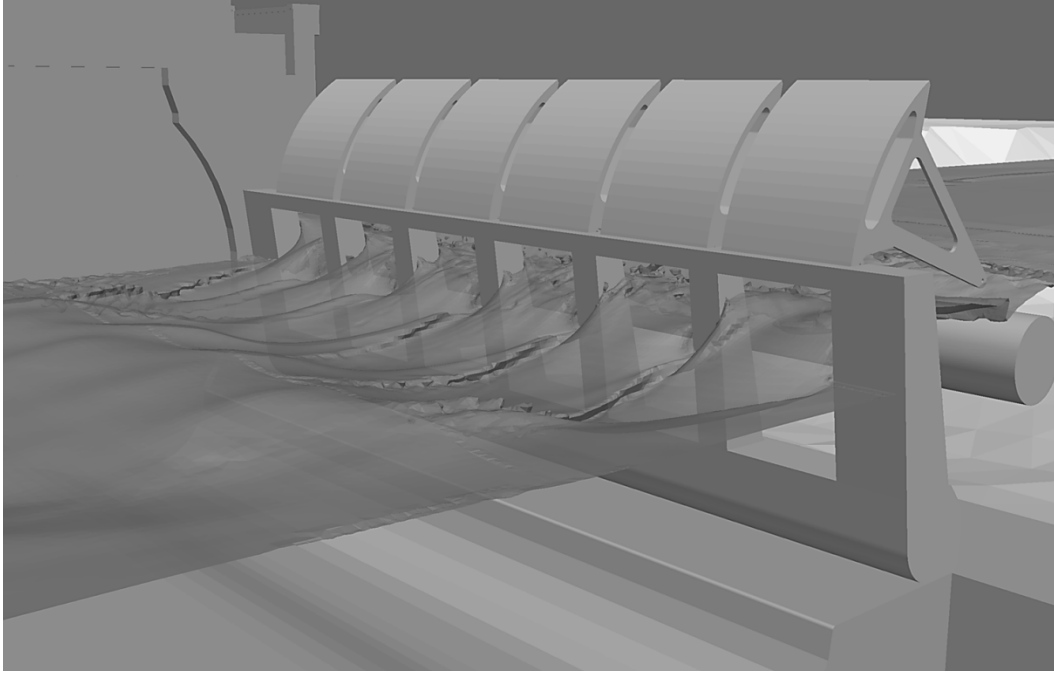


Figure 5. Revision cover Viereth: Revision cover used for the construction measures at the weir Viereth (developed by Ingenieurbüro Rapsch und Schubert Stahlwasserbau Consulting GmbH)

The approach of solving the given task is consistent with the procedure described in prior chapters. Simulating the flow through the partially closed weir a three-dimensional k-Omega model was set up by the Federal Waterways Engineering and Research Institute. In this specific example a private engineering company was in charge of the 2D-model. Value ranges of the parameters “discharge through the weir” and “tailwater level” can be estimated based on a first calculation run of the 2D-model. Afterwards a mathematical function was found for the case of the placed and opened revision cover as described in chapter 4.

The use of the formula simplifies the communication with external partners. The number of data exchanges is limited to handing over of the results of the first simulation run of the 2D-model and the return of the formula. Multiple exchanges of parameters and boundary conditions are reduced to one exchange of a compact formula. As another advantage, the formula is still valid in its domain of definition if the design discharge changes.

The outcome of the investigation is the upstream water level which results from the placed and opened revision cover and the design discharge. Compared to the upstream water level arising from the design discharge without the revision cover, maps showing the water level increase caused by the placed and opened revision cover can be developed.

6 CONCLUSION

Considering failure of a weir gate at a barrage, the upstream water level needs to be estimated for a 100-year flood event. The flow regime in close vicinity to the weir is characterized by a three-dimensional flow whereas the flow in the far field of the barrage and across the wetlands can be approximated as two-dimensional. To limit the computational costs only areas where vertical acceleration cannot be neglected are considered in the three-dimensional multiphase model, which was set up with OpenFOAM. In order to compute the upstream water level in case of failure with respect to all two- and three-dimensional effects a two- and a three-dimensional model are necessary. But the hydraulic boundary conditions and results of the two models influence each other.

Due to the consideration of vertical acceleration, the 3D-model can calculate the hydraulic capacity of the weir in a more exact way than the 2D-model. Hence, the 3D-model is used to find a mathematical function for the correlation between discharge through the weir, tailwater level and resulting backwater. The estimated function is used to adapt the overflow coefficient of the weir of the 2D-model to the hy-

draulic correlations of the 3D-model. The adapted 2D-model combines the advantages of both models, the dimension of the 2D-model and the accuracy of the 3D-model.

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