Integrated analyses of MAR techniques in Shandong, China

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Abstract
The Huangshui River, located in the Northeast of Shandong Province, China, shows an outstanding example for water conflicts caused by a fast growing population, industry and agriculture. To tackle these problems, a joint Chinese-German project was launched in 2008. An important part of the project is the optimization of the existing MAR facilities along this river. Here, eight dams reduce the outflow into the Bohai Sea. The water which is stored in front of these dams infiltrates into the underlying aquifers. This process is accelerated by the construction of 2500 infiltration wells. The main objective of these facilities is to reduce the sea water intrusion caused by overexploitation of groundwater. To prevent groundwater outflow into the sea and to increase the storage capacity of the reservoir, an underground dam of six km length has been constructed. Within the scope of the project a coupled surface and groundwater model has been developed which describes the reservoir and all relevant physical processes as part of a complete and interactive system. For this reason, the module IfmMIKE11, which couples FEFLOW and MIKE11, has been extended for mass-transport processes. A model has been constructed which uses this module and covers the complete river basin.

Keywords
Keywords: IWRM, MAR, China, intrusion, groundwater, IfmMIKE11

INTRODUCTION
The Shandong Province, especially the Huangshui River Basin and Longkou County, is an outstanding example for water conflicts caused by a fast growing population, industry and agriculture. In the coastal catchments of the Shandong province water scarcity is further increased due to salt-water intrusion, reducing the usability of available water resources. Already in the 1990’s many measures against saltwater intrusion problems were implemented. In 1995 for example, an underground dam was finished in the downstream part of the Huangshui River, 1.2 km from the seaside, with a total length of approximately 6 km (Liu et al., 2003). The average depth of the dam is 26.7 m. On the one hand, the dam prevents the ground water from flowing into the sea. On the other hand, it can stop sea-water intrusion. Even after this project was finished, the area affected by salt water intrusion continued to increase. It is part of the project presented here to investigate the impact of this dam and to analyse whether its effectiveness can be increased. The general objective of this project however, is to combine German expertise in water management and research efforts in the coastal area of Shandong Province to find ways to relieve the desperate water scarcity situation.

The total water consumption within the project area (ca. 1560 km²) during the years 2000 until 2007 was about 207 million m³/a. This number was derived from various sources delivered by our Chinese partners (Water Resources Bulletins for the years 2000 – 2007 for Longkou, Penglai, Zhaojuyan and Xixia as well as GIS land-use analyses between the different countries within the model area). It is composed by: agriculture (irrigation) 73 %, domestic 10 %, industry 16 % and environment 1 %. With a usable yearly runoff of about 193 million m³ for the same period, the water demand exceeds the water resources, on average by about 7 %. This problem is even more severe considering the monthly and annual distribution of water resources and water demand.
The main areas of extraction are located in the groundwater reservoir along the downstream end of the Huangshui River and in the plain area between Huangcheng and Longkou in the western part of the model area. This is also the area in which the largest actual groundwater depression has been observed. After further assessment of the present situation and the many abatement measures tried with, especially to stop salt-water intrusion, it was found that there is a tremendous potential to improve the situation by appropriate integrated water-resources management (IWRM). The basic IWRM concept applied in this project makes use of a GIS-based Decision Support System, which fully integrates the simulation models which are needed to analyze and compare the effects of implementing different measures. This concept is explained in more detail in the next section.

In this paper not so much the IWRM concept being applied in the project, but much more a specific tool developed to describe the relevant interaction processes between the surface and groundwater bodies will be discussed. This tool couples the groundwater model FEFLOW (Diersch, 2009) and the surface water model MIKE11 (DHI, 2010). This paper focuses on the integrated mass-transport coupling options, by which also salt-water interaction between rivers and groundwater can be simulated.

IWRM METHOD

The steps and components applied in this project can basically be separated in four parts. First of all, a so-called measures catalogue was set up. From the analyses of the present situation, all potential measures for the project area, especially in the fields of water saving, groundwater recharge, water recycling, as well as measures against salt-water intrusion and institutional measures were collected, sorted and combined in a logical and functional measures catalogue. Secondly, a Decision Support System (DSS1) was developed to find the most promising combinations (measures scenarios) of these potential measures, only partially taking into account their geographical location. Thirdly, a GIS based information system was developed which basically incorporates:

- Information to all selected measures scenarios from DSS1 and the possibility to specify each measure according to its location, intensity or size.

- A number of hydrological models, which together describe all relevant hydrological processes and which are coupled on the fly or by automatic data exchange. These processes include runoff, evaporation, recharge, surface-water flow and groundwater flow. This integrated model represents the fourth part of the overall IWRM concept.
× Tools which automatically implement the measures within the geographical setup of each hydraulic model (for example weirs, land-use changes, reservoirs or subsurface dams).

× Criteria and multi-criteria evaluation routines to analyse the simulated measures scenario (DSS2). The basic criteria are similar to the ones of DSS1, but they are separated into a number of components which each can be evaluated by automatic routines using the results of the models together with relation tables representing the socio-economic situation in the area.

The integrated hydraulic model concept includes two different model approaches; a relatively coarse and a detailed model. The coarse model is used to verify the general feasibility of the water usage proposed in the selected measures scenario. This model consists of the simulation packages SIWA and WBalMo (both DHI-WASY). SIWA is a 1D empirical soil-water model, based on land use, soil, slope and groundwater depth data. The model provides a fast and robust way to calculate spatially distributed monthly groundwater recharge and runoff rates. WBalMo (Water Balance Model) is a simulation system for river basin management. By recording relevant system characteristics, probability estimates of water deficits for each of the catchments or users in the region can be provided. If the resulting deficits for all water users of a coupled WBalMo and SIWA simulation are within the limits set in the GIS environment, the specified measures can be accepted and relevant results can automatically be transferred to the detailed model. This detailed model also consists of two modules; FEFLOW (DHI-WASY) and MIKE11 (DHI). FEFLOW provides an advanced 3D environment for performing complex groundwater flow and contaminant transport modelling and can also simulate density dependent flow processes. MIKE11 is a powerful surface-water model to simulate 1D flow problems. The software offers to simulate unsteady flow in river networks as well as looped systems. MIKE11 and FEFLOW can be coupled using the module IfmMIKE11 (Monninkhoff and Schätzl, 2008). The detailed model gives information about the impact of the proposed measures on groundwater levels and salinity values. All models have been set up and calibrated, and their results could already be used to support the development of the water balance in DSS1.

COUPLED MASS-TRANSPORT MODELLING WITH IfmMIKE11

Since 2005 the coupling interface IfmMIKE11 has been available. The interface module couples FEFLOW to MIKE11 using the FEFLOW InterFace Manager (IFM). From 2006 to 2009, the coupling module was successfully extended for the coupling of polder areas and forelands (Monninkhoff & Li, 2009; Monninkhoff & Kaden, 2007).

Quantity modelling

In FEFLOW rivers can be described by boundaries of the 1st kind (Dirichlet-type) or boundaries of the 3rd kind (Cauchy-type). The latter boundary type is the only type supported by the coupling module IfmMIKE11. At the end of each FEFLOW time step the discharges to these FEFLOW boundary nodes are calculated by the module within FEFLOW. The resulting values are transferred to the MIKE11 calculation points (h-points) as single point source inflow boundary conditions. Then, MIKE11 calculates as many internal time steps as needed to reach the actual time of FEFLOW. This process is ended by transferring the calculated water levels at the end of the FEFLOW time step from the MIKE11 h-points to the FEFLOW boundary nodes. The internal time step of MIKE11 is controlled by the interface. This time step can be constant or adaptive to the dynamics of the model. The time step of the groundwater model is controlled by FEFLOW. The spatial overlay of both meshes is automatically integrated within IfmMIKE11. The exchange discharges \( Q \) between the ground- and surface water can be calculated within FEFLOW for each single boundary node of the 3rd kind separately. The main parameter to control this discharge is an elemental parameter called transfer coefficient \( \phi_h \) [d\(^{-1}\)]:

\[
Q = \phi_h A(h_{ef} - h_{gw})
\]

In which:
\( Q \) = Discharge \([m^3d^{-1}]\) of fluid (positive from river to groundwater),

\( A \) = nodal representative exchange area \([m^2]\) of the boundary node and

\( h_{\text{ref}}, h_{\text{gw}} \) = heads \([m]\) in the river and groundwater respectively.

The nodal representative exchange area depends on the finite-element stratigraphy within the model in FEFLOW. Moreover, the stratigraphy is subject to changes using the free and movable option in FEFLOW. In that case, the top slice of a 3D model is located exactly on the position of the head of the first slice and all remaining slices are moved accordingly. To avoid an uncontrolled and unrealistic exchange area in this case, an additional boundary option has been implemented. Using these integral boundary conditions the exchange area of the boundary nodes is determined only once just before the simulation is started. Nevertheless, in most cases, the exact exchange area between the river and the groundwater cannot be described by the stratigraphy of the mesh.

From the stratigraphy point of view, rivers can be defined in FEFLOW by a typical vertical (also areal) or horizontal (or lateral) infiltration scheme. In the first case boundary nodes are only set to the 1\(^{st}\) slice of the FEFLOW model and in the latter case boundary conditions are located in more than one slice but within a single slice only as a line element. The basic principle of the coupling is shown in the next figure.

![Figure 2: Basic principle of the coupling.](image)

In case that the groundwater level drops below the bottom of a river, the above equation indicates that the calculated discharge will continue to increase. Brunner et al. (2009) show that this is not the case in reality and the discharge is limited to a certain maximum. In FEFLOW additional constraints can be set to approximate this process. Using these constraints, a user-defined minimum for \( h_{\text{gw}} \) is introduced in the above equation, usually equal to the bottom of the river.

Monninkhoff & Hartnack (2009) showed a third mechanism to describe rivers in FEFLOW which is only available within the FEFLOW internal programming interface (IFM). In IfmMIKE11 these boundaries are called special boundaries. It is basically the same as a 3\(^{rd}\) kind boundary, but both the exchange area and the transfer coefficient can be defined externally and for each single node. Using this function IfmMIKE11 could be improved by updating the exchange areas according the actual
water levels and the profile data available in MIKE11. It was shown that both for triangular and rectangular cross river sections this approach gives results which fit reasonably with analytical solutions of the same problem.

**Quality modelling**

For the project presented here, the coupling between MIKE11 and FEFLOW was extended also for mass transport. The numerical solution of the transport equation of MIKE11 (AD simulation) requires, like FEFLOW also, a temporally varying background flow field. With respect to the FEFLOW coupling, the hydrodynamics and the transport equations in MIKE11 are solved in a coupled mode i.e. MIKE11 calculates the river flow field and the concentrations within the same time step. The coupling between FEFLOW and MIKE11 is explicit i.e. FEFLOW completes a time step and then exchanges values with MIKE11 which in turn takes a time step. The exchange of water and mass is calculated by FEFLOW based on values from the previous time step. This approach in turn requires that every time a MIKE11 time step is calculated FEFLOW must pass the following values for each coupling point:

- Flow (in- and outflow to the river in separate parameters)
- Mass flux (kg/s) for each chemical species (in case there is inflow to a river h-point)

In return MIKE11 passes

- Water level at the h-points
- Concentrations (kg/m³) for each chemical species at the h-points

back to FEFLOW.

Like the flow boundaries also the mass boundaries can be set as different types in FEFLOW. From these, only the 1st (defined concentration) and 4th (defined mass) kind are useful for mass coupling processes.

If MIKE11 automatically generates mass boundary nodes at those FEFLOW nodes which also have coupled flow-boundary conditions. It is therefore not necessary to set mass boundary conditions to the coupled nodes at the beginning of the simulation. The type of boundary is defined by the user settings. Both single and multi-species processes can be coupled. Despite the fact that the mass coupling is mostly automatical, it is useful to be familiar with the basics of mass transport in FEFLOW to be able to couple MIKE11 and FEFLOW also for mass-transport processes.

In that context it is important to know that FEFLOW can run a mass-transport problem applying one of two different formulations of the transport equation; the *convective* or the *divergence* form. In Diersch (2009) the difference between the divergence and convective form of a mass-conservation equation is explained in detail. The main difference lies in the convective terms in the transport equations applied to both forms. The divergence form has a divergence expression \( \nabla \cdot (q_c) \) and the convective form involves a more convenient gradient relationship \( q_c \cdot \nabla c \) for the convective term in the general mass-transport equation. The convective form can be derived from the divergence form by applying the general continuity equation for porous media. Both transport equations are physically equivalent, but they lead to different formulations of boundary conditions. When using the divergence form of transport, the mass fluxes prescribed at a boundary denote the sum of both advective and dispersive fluxes. Using the convective form, only the dispersive part of the flux is prescribed. In that case the total flux will be calculated internally as a result of the governing concentration at a node and the fluid flux across the flow boundary located at the same node.

In general it can be stated that the convective method ensures a higher degree of stability, especially at outflow boundaries. This form, however, is rather unsuitable for using mass boundary conditions of the
4th kind in case that there is also a flow boundary condition at the same node (inflow into groundwater). So, if mass-boundary nodes of the 4th kind will be used for the coupling, it is obligatory to use the divergence form, accepting possibly less stability at outflow boundaries. To ensure stability, the mesh discretization around the boundary conditions should then be rather dense and using well-shaped finite elements. The main advantage of this method, however, is that the mass balance is guaranteed. Mass-boundary nodes of the 1st kind (boundary values are defined as concentrations) on the other hand are ideal to use with the convective form. The model is more stable and the resulting parameters of the MIKE11 time step can be transferred directly to the FEFLOW model (both concentrations). This would however imply that the finite-element volume represented by a mass boundary node of the 1st kind would get the same concentration as the concentration at the coupled h-point of the river. The original groundwater concentration within this volume would be neglected and a discrepancy in the mass balance is automatically generated. This error can be reduced by ensuring that the elements around the mass-boundary nodes of the 1st kind are small.

Besides these two options, also an IFM internal option has been implemented, similarly to the special boundaries available for quantity coupling, which can be accessed by the function IfmSetCoupledMassTransBndNodes(). This function enables the definition of a new boundary-condition type which has two main parameters; (1) surface-water reference concentration ($c_{ref}$ [mg/l]) and (2) a parameter representing the product of the mass-transfer rate in [m/d] and the exchange area in [m²]. This parameter is called PHI [m²/d]. In chapter 6.8 of the FEFLOW White Papers, Volume 1 (Diersch, 2009), it is explained, that a 3rd kind mass-boundary node in the convective form gives the same results as a 2nd kind mass-boundary node in the divergence form, if a suitable set of parameters has been defined. This principle can also be followed for the special boundary (which is in fact nothing else than a 3rd kind mass-boundary condition with a nodal transfer value and a representative exchange area). Using suitable parameters, the result of a special boundary in the convective form will give the same results as a 4th kind boundary in the divergence form. The value of a 4th kind boundary [g/d] for inflow into groundwater can be calculated by multiplying the fluid flux with the concentration in the river. Using this fluid flux [m³/d] for PHI and setting the river concentration as $c_{ref}$ [mg/l] for the special boundary in the convective form, an equivalent boundary condition will be defined. The practical consequence is that input mass-flux boundary conditions can also easily be simulated by using the standard convective form without resorting to the more complex divergence form of the transport equation. In this way, a defined mass flux into the model will be generated. Furthermore, it is guaranteed that the concentration of the FEFLOW nodes beneath the river eventually will approximate the concentration of the river.

**Quantity-Quality modelling**

With IFM the user can interfere with FEFLOW at certain entry points (also call-backs), enabling the user to read, change or delete parameters, boundary conditions or initial values inside FEFLOW before, while or after simulating. While simulating the relevant call-backs are PreTimeStep(), PreFlowSimulation(), PostFlowSimulation(), PreMassSimulation(), PostMassSimulation() and PostTimeStep(). Between Pre- and PostFlowSimulation() the actual flow equations are calculated for the current time step. The resulting velocity and flow field is then used between Pre- and PostMassSimulation() to solve the mass transport equation.

To be able to define which mass boundaries are to be set, it should be continuously checked if there is water flowing from the river to the groundwater or vice versa. If at a single coupled node the flow direction at the end of the FEFLOW flow simulation time step at PostFlowSimulation() is pointing towards the river, then the mass-boundary condition at that node should be deleted. In fact, internally a zero flux 2nd kind boundary will be set. As the coupling routine will automatically ensure that there is a flow boundary condition at the same node, FEFLOW will remove water from the groundwater with the same concentration as the concentration at that node. The mass flux can then be retrieved by the IFM budget operator. This mass flux is then forwarded to the coupled MIKE11 h-point.
If at a single coupled node the flow direction at the end of the FEFLOW flow simulation time step is pointing towards groundwater, a mass-boundary condition (special, 1st or 4th kind) should be set in FEFLOW. In case of a 1st kind mass-boundary node, the concentration of the previous MIKE11 time step is directly set in FEFLOW and in case of a 4th kind mass-boundary node this concentration is multiplied with the discharge rate calculated from the flow simulation (budget). In this case, no mass-boundary condition in MIKE11 is needed. The water which flows out of the river will have the same concentration as the river itself. After these steps, the FEFLOW mass simulation can be started with the new mass boundary conditions.

During the implementation of this concept it was found, that, although the flow simulation has been finished, the budget calculated in PostFlowSimulation(), or even PreMassSimulation(), is not necessarily the final budget that will be calculated in PostTimeStep(). This can be explained by the fact that in some cases, the heat or mass simulation is influencing the flow simulation, for example in case of density dependent modelling. This is the reason that FEFLOW internally does not finalize the budget before PostTimeStep(). This implies that the original concept could not be implemented completely. Because the budget components are not ready in PostFlowSimulation() or PreMassSimulation(), also the direction of flow as well as the boundary flux at every coupled node cannot be analysed or calculated within that call-back. It was decided to use the direction of flow as well as the nodal boundary budget from the budget in PostTimeStep() of the previous time step. This direction of flow defines if a mass boundary has to be set in FEFLOW or MIKE11 and which mass flux has to be transferred from MIKE11 to FEFLOW or vice versa. The adapted concept is shown in detail in the next figure.

The waves in the middle of the figure indicate that FEFLOW is running the mass simulation here. It can also be seen, that a certain mass error is inherent to this adapted concept, but only for an inflow into the groundwater. In that case in PreMassSimulation() IfmMIKE11 sets the mass boundaries in FEFLOW according the fluid fluxes and also the river concentrations of the previous time step. In case 4th or special kind of boundaries are used, the mass flux set to the boundary condition (a combination of PHI and cref in case of special boundaries) will also be calculated by the internal mass-boundary budget.
in PostTimestep(). The fluid flux nodal budget however will be different due to the conditions of the actual time step. This actual budget at the end of the time step however is used to set the actual outflow fluid flux boundary to the coupled h-point of MIKE11 (QBaseMIKE11 at the left side of PostTimeStep() in the figure). Even if the concentration will stay constant during the actual time step of MIKE11, the mass flux flowing out of the river calculated by MIKE11 at the end of PostTimeStep() will therefore automatically be different from the mass flux set to the FEFLOW boundaries in PreMassSimulation(). Until the problem of the incomplete fluid flux budget in FEFLOW has been solved, this mass balance error cannot be avoided. Under relatively stationary conditions however, the magnitude of this mass error will be acceptable. A second mass balance error, which is automatically introduced because of the non-iterative character of the coupling is optionally balanced out during the simulation.

Example
Different simple models have been set up to test the mass coupling presented in the above section. Both for inflowing and outflowing conditions as well as combinations of both realistic results could be obtained. Also for the standard FEFLOW demonstration site for mass transport, an example has been developed, introducing a non-polluted river close to a contamination site. This is shown in the following Figure. After a certain period, the concentration in the river starts to increase and the river discharges the mass out of the model area. Furthermore, the entry point of the main concentration is moving with the general groundwater flow direction towards the south (downstream). In the figure both concentrations (bottom right) and discharges (bottom left) along the river for different time steps (July 2000 and December 2004) as well as time dependent concentrations at 2 points of interest (figure at top right) and the distribution of the groundwater concentration in December 2004 (top left) is shown. The dilution in the river is clearly visible in the figure at the bottom right. The moving front is obvious from the figure at the top right.

Figure 4: Example of an arbitrary application of mass-transport coupling.

APPLICATION WITHIN THE SHANDONG PROJECT
This module was also used to calculate salt-water intrusion as a result of the groundwater abstractions and the effects of surface-water infiltration into the groundwater reservoir. It was found that the original period of eight years is too short to notice any significant changes. The initial values of the
salt-water intrusion model were taken from the measured values delivered by our Chinese partners. Both the initial salt-water distribution as well as the distribution after 80 years of simulation are shown in the next figure. It can be seen that within the area of the groundwater reservoir, salinity concentrations stay relatively constant, but the main part of the remaining plain area is heavily affected by the salt-water front, especially in the western plain areas. These kinds of figures can easily be produced by the GIS-based DSS. Additionally, salinity curves can be presented at single measurement points. Both features can be used to evaluate the proposed measures and can also be compared to previously analysed measures.

Figure 5: Development of salinity front after 80 years of simulation.

CONCLUSION AND OUTLOOK
The module IfmMIKE11 was successfully extended for mass-transport processes and has already been applied within the project presented in this paper. Focus is now put on how the preferred measures from DSS1 can be implemented best, taking into account both spatial and temporal characteristics. Here, the module can be used as well, for example to analyse the influence of additional weir and infiltration fields, especially in the western model area.

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