Improvements in the coupling interface between FEFLOW and MIKE11

*Bertram L. Monninkhoff**
bmo@dhi-wasy.de
DHI-WASY GmbH, Berlin, Germany /
Hohai University, Nanjing, China
*corresponding Author

Johan N. Hartnack
jnh@dhigroup.com
DHI, Copenhagen, Denmark

ABSTRACT: Since 2005 the coupling interface IfmMIKE11 has been available. The interface module couples FEFLOW to MIKE11 using the FEFLOW InterFace Manager (IFM). Its functionality covers the exchange of boundary condition data during runtime and the synchronization of the temporal and spatial discretization. The system has been applied to both simple benchmark cases and complex field conditions. In 2006 the coupling module was successfully extended for the coupling of polder areas and forelands. This option is also available in the present version of the module. Furthermore, this version includes a better representation of the exchange area between the river and groundwater body. This paper focuses on this topic. In FEFLOW rivers are mostly represented by Cauchy boundary nodes. The area enclosed by these boundary nodes describes the exchange area normally being applied to calculate the exchange discharge between the river and groundwater body. In most applications rivers are described by polylines along more than one slice (horizontal exchange) or by a boundary area only in the top slice (vertical exchange). The area can be changed during the simulation using a free and movable top slice. Using a phreatic or fixed top slice the exchange area will be held constant during the simulation. In none of these cases does the area represent the real exchange area, which depends both on the river profile and the water depth. To overcome this problem a new IFM function has been developed in FEFLOW, which enables the user to define not only the surface water reference level at a single boundary node, but also the exchange area represented by the node as well as a nodal transfer rate. This function can now be optionally used in IfmMIKE11. In that case, the cross section areas are used from the MIKE11 model. It also takes into account the case in which the groundwater drops below the bottom of the river. Finally, the coupling of mass transport will be introduced. For this coupling also some changes of the MIKE11 interface were necessary. In effect the coupling had to be changed from having the hydrodynamic and the transport equations being solved sequentially to solving them step wise.

INTRODUCTION

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

There are two general ways to describe a river in FEFLOW. If there is no resistance between the river and the groundwater body (for example caused by less permeable sediments at the river bottom), a boundary of the 1st kind (Dirichlet-type) can be assigned. In most cases however a certain resistance can be observed, so there is a difference between the ground- and surface water level and a boundary of the 3rd kind (Cauchy-type) has to be used. The latter boundary type is the only type supported by the coupling module. 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 will calculate as many as internal time steps 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. Each FEFLOW boundary condition node is assigned to the closest MIKE11 h-Point. So, every MIKE11 h-point can be assigned to more than one FEFLOW boundary node.
The FEFLOW feature “Reference Distributions” can be used additionally to control the spatial coupling, for example in areas with a dense river network. These distributions are also used for the representation of wetlands and polders. In that case, a complete polder can be given a single identification number, which is recognized by the coupling module and for which a special river can be

defined in MIKE11. This river should represent the characteristic water level – flooded area curve for that polder. Additionally, the surface elevation of every single point within a polder or wetland area should be defined in a predefined reference distribution ("Mike11_DTM"). If the surface water level in the polder is above of the surface elevation of a single FEFLOW polder node, a boundary condition at this particular node is set. The same is true in case the groundwater level is above of the surface elevation of a single FEFLOW polder node. A detailed description of this method can be found in (Monninkhoff, 2006).

In case of the polder coupling described above, boundary conditions are only set within the 1st slice of the model. This therefore represents a typical vertical (also areal) infiltration. The 2nd type of infiltration normally being applied in FEFLOW is the horizontal (also lateral) infiltration, in which boundary conditions are located in more than one slices but within a single slice only as a line element. The basic principle of the coupling is shown in the next figure.

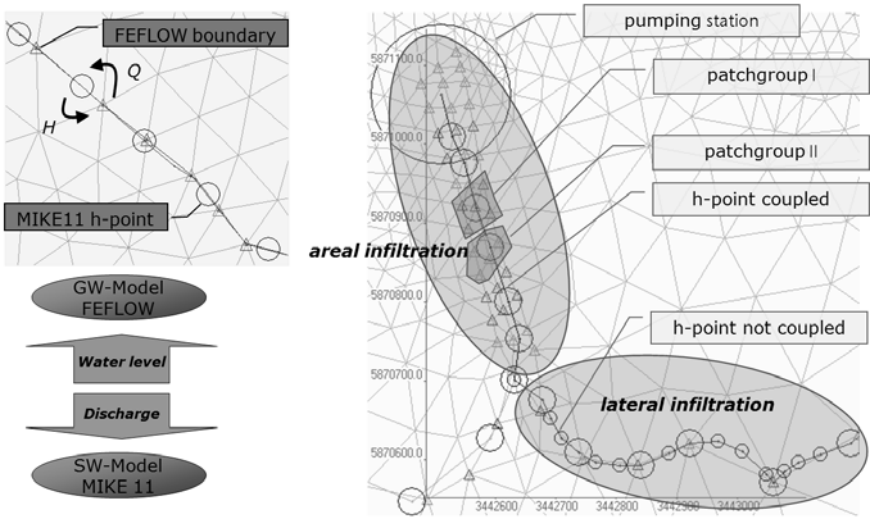

Fig. 1 Basic principle of the coupling.

PROBLEM DEFINITION

The exchange fluxes (q) between the ground- and surface water can be calculated within FEFLOW for each single boundary condition of the 3rd kind separately. The main parameter to control this flux is the transfer coefficient ϕ_h [d^{-1}]:

$$q = \phi_h (h_{ref} - h_{gw}) \qquad (1)$$

In which:

q = Darcy flux [md^{-1}] of fluid (positive from river to groundwater) and
h_{ref}, h_{gw} = heads [m] in the river and groundwater respectively.

In FEFLOW, the value of h_{gw} in Eq. 1 can be limited using **constraints**. Usually the bottom level of the river is regarded as the minimum head to calculate the flux and the term ($h_{ref} - h_{gw}$) can be replaced by wd_r [m], the water depth in the canal or river. For each boundary node a limiting minimum value for h_{gw} can be assigned additionally to the value representing h_{ref}. Using these constrains, in case of low flow or even dry conditions within the river the value for (h_{ref} - h_{gw}) is reduced to zero.

The flux (q) of each boundary finite element node is internally multiplied with the corresponding exchange area *A* [m²] represented by the node to determine the total ***discharge*** for each node $Q_{o,i}$ [m^3d^{-1}]. This area depends on the finite element stratigraphy within the model. The stratigraphy is subject to changes using the free and movable option in FEFLOW. In that case, the top slice of the model is located exactly on the position of the head of the first slice and all remaining slices are moved accordingly using the BASD (Best-Adaption-to-Stratigraphic-Data) technique (Diersch, 2005). To avoid this, an additional boundary option has been integrated. Using these ***integral*** boundary

conditions the exchange area of the boundary nodes is determined only once just before the simulation is started. But then the exchange area is surface water level independent! So in case that there is a lateral infiltration to or from the connected river there is no exact way in FEFLOW to represent the exchange area. In Monninkhoff (2008) it was therefore concluded that the exchange discharges between the surface and groundwater cannot be calculated by the module accurately for lateral infiltration conditions. In the next figure the results of a lateral infiltration simulation (for different FEFLOW stratigraphy options) are compared with the analytical solution of this problem. Here the "free & movable" result was retrieved using integral boundary conditions.

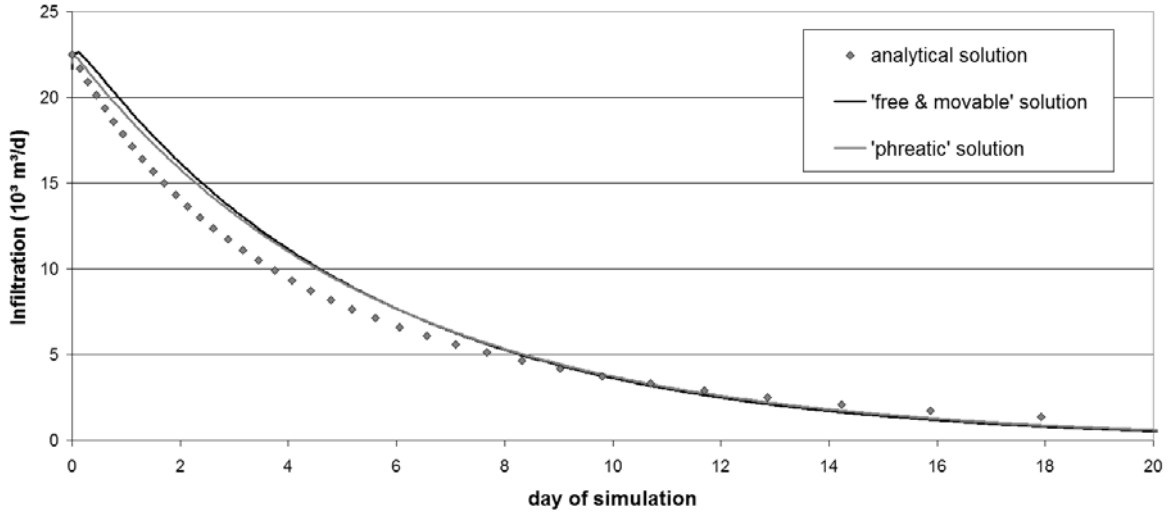

Fig. 2 Comparison between calculated results and the analytical solution for a lateral infiltration system.

In case of single vertical infiltration however, for example along a artificial channel with impermeable walls and a permeable bottom, the exchange area is in fact also water level independent in reality and can be represented by FEFLOW exactly. this was also verified by comparing mere vertical infiltration simulation results with the analytical solution of such a system. Results sufficiently close to the analytical solution can be retrieved if the maximum time step of FEFLOW is limited to less than 0.25 d. This was explained by the lack of an iterative approach in the module. In this paper it will be shown that it was succeeded to adapt FEFLOW and the coupling module in a way that now also lateral infiltration conditions can be represented.

ADAPTATION OF FEFLOW AND IfmMIKE11

In Monninkhoff (2008) it was already discussed that a new IFM function will be implemented in FEFLOW. This IFM function enables the definition of a new boundary condition type which has two main parameters; (1) surface water level (Hsurf [m]) and (2) a parameter representing the product of the transfer rate in [d^{-1}] and the exchange area in [m²]. This parameter is called **PHI** [m²/d]. The transfer rate can be defined at every node by using a predefined reference distribution. This approach has the advantage that all parameters are nodal and an overlay routine between elements (a transfer rate is normally defined as elemental characteristic in FEFLOW) and nodes doesn't have to be implemented. The function uses vector data, so that all relevant boundary nodes can be set at once. The definition of the function IfmSetCoupledRiverBndNodes is shown in the following figure. Note that there is no difference between outflow and inflow transfer coefficients and also no time dependent transfer rates can be defined. The boundary nodes created with this function are not visible or symbolized in any way in FEFLOW. They are only used internally.

```
int IfmSetCoupledRiverBndNodes
(
        IfmDocument pDoc,       Handle of document data
        int nNumb,              Number of boundary nodes to be set
        int *nod,               Vector of node-IDs of the boundary nodes
        double *Hsurf,          Vector of river water levels of the boundary nodes
        double *PHI             Vector of PHI values of the boundary nodes
);
```

Fig. 3 Definition of new IFM function.

The exchange area which has to be defined to calculate the PHI values at every time step and every relevant node are retrieved by multiplying the wetted perimeter of a FEFLOW boundary condition node and the length of the branch this node is representing. As said before, a FEFLOW boundary node is coupled to a single MIKE11 h-point, but not every MIKE11 h-point has a defined cross section. So a pre-analyses of the available h-points and cross sections is necessary to find the upstream and downstream cross section for each coupled h-point. From these analyses both the distances to the two adjacent cross sections as well as a table describing the wetted perimeter for each level point within those cross sections is derived. The wetted perimeter for every h-point at every time step can then easily be derived from the wetted perimeters at the two adjacent cross sections, using the water levels at that time step at those two points. The principle is explained more in detail in the next figure. The wetted perimeter w_p of a single h-point$_{1,2}$ is multiplied with the corresponding length ($½L_1+½L_2$) of the h-point. L_1 and L_2 are the distances from the coupled h-point to the up- and downstream cross section points. In the figure, each h-point has a cross section but it is also supported if this is not the case. This representative exchange area is then divided by the number of FEFLOW nodes coupled to the h-point. To the h-point$_{1,2}$ 6 nodes are coupled in the first slice and 6 nodes are coupled in the second slice. So PHI of the selected node in the figure in the first slice equals $½w_p \bullet \phi_h(L_1+L_2)/12$. As mentioned before, the transfer rate ϕ_h is defined by a specific reference distribution, called “Mike11_TRANS”.

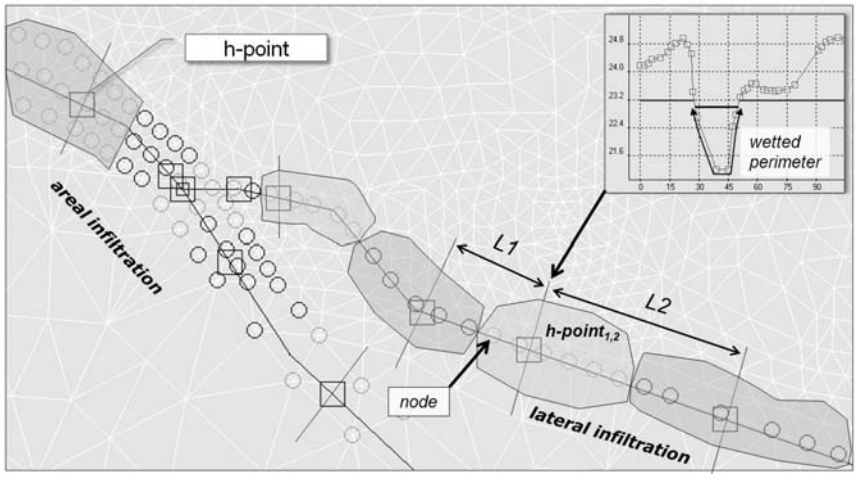

Fig. 4 Integration of the wetted perimeter in IfmMIKE11.

The user is free to decide if the river should be represented in just one or more than one slices, as a line element (even just in one slice!) or as an infiltration area, or a combination of both. The exchange area is defined by the module, not by the locations of the boundary conditions. In contrast to regular FEFLOW 3rd kind boundary nodes, even single nodal boundary points can be used to represent the interaction between the ground- and surface water. By defining infiltration areas rather than lines, the exchange rates can be divided along more than one nodes, by which the natural situation can be represented in a more realistic way. By using more nodes (horizontal or vertical) the user additionally has the possibility to define different transfer rates within a single cross section. This can be useful if, for example, an aquitard is connected to a part of the river bed. The default module setting assumes that the transfer rates of the first slice are also valid for all remaining slices, but an option has been integrated which allows the user to define the nodal transfer rates in every single slice separately.

The new function doesn’t offer an ***integral*** option (yet). The difference between ground- and surface water level is always the driving force for the resulting exchange rate, even if the groundwater level is below the river bed. In cases were the groundwater is below the bottom of the river, like the first benchmark example presented in the next section, the infiltration rates will be overestimated. To overcome this problem, IfmMIKE11 checks the conditions along the coupled boundary nodes at the beginning of the FEFLOW time step and in case that the groundwater level is below the river bed, instead of using the new function IfmSetCoupledRiverBndNodes, boundary conditions of the **4th kind** are set (wells). The extraction rates of these boundary conditions are calculated from the PHI values multiplied with the water depth in the river at the beginning of the time step.

To use these new functionalities in IfmMIKE11 a transfer reference distribution should be available and the corresponding checkbox in the IfmMIKE11 options dialog has to be activated. Using these new kind of boundaries, the integration of tributaries (rivers which are available in the FEFLOW mesh but are not present in the MIKE11 setup) is no longer supported. Furthermore, the user has to decide for the complete model which coupling method will be used for the regular river branches. A mix of regular and the presented new coupling method is not possible for regular river courses. However, the combination of the coupling of regular river branches using the new method and the coupling of polder or wetland areas as discussed in the introduction of this paper as well as the option that deactivates dry h-points is supported.

BENCHMARK DEFINITIONS

For benchmarking the coupling, a simple system has been modelled, representing an initially full rectangular canal with no other in or outflow than the fluxes to or from the connected groundwater. In MIKE11 this was realised by integrating a constantly-closed control structure just upstream of the downstream boundary condition. The upstream boundary condition inflow was set to zero. The conservation of mass equation for this canal can be written as follows:

$$\frac{\delta h_{ref}}{\delta t} = -\frac{Q_o}{A_r} \tag{2}$$

In which t represents time [d] and A_r represents the cross section area of the canal [m^2].

In this example it was assumed that the groundwater is initially way below the bottom of the canal and that even after the canal has been drained completely, the groundwater still has no direct contact to the surface water.

In case that the canal is rectangular, the time T_e [d] to empty the canal from a water depth wd_{r1} to a depth wd_{r2} can be found relatively easy. Substituting equation (1) in (2), taking into account that the width of the canal (B_r [m]) is water level independent, infiltration takes place along the complete wetted perimeter of the canal (bottom and lateral infiltration) and h_{gw} is limited to the bottom of the canal (constraint in order to have a groundwater level independent exchange flux), T_e can be calculated by:

$$T_e = -\left[\frac{B_r(\ln(wd_r) - \ln(B_r\phi_h + 2\phi_h wd_r))}{B_r\phi_h}\right]_{wd_{r1}}^{wd_{r2}} \tag{3}$$

In case that the canal is triangular with a constant slope of the banks $1/\eta$ [-], the solution of T_e can be expressed in a slightly more convenient way:

$$T_e = -\left[\frac{\eta}{\phi_h\sqrt{(1+\eta^2)}}\ln(wd_r)\right]_{wd_{r1}}^{wd_{r2}} \tag{4}$$

Both types of canal cross sections have been tested. In Figure 5 an example of the two cross sections for the benchmark setup is shown.

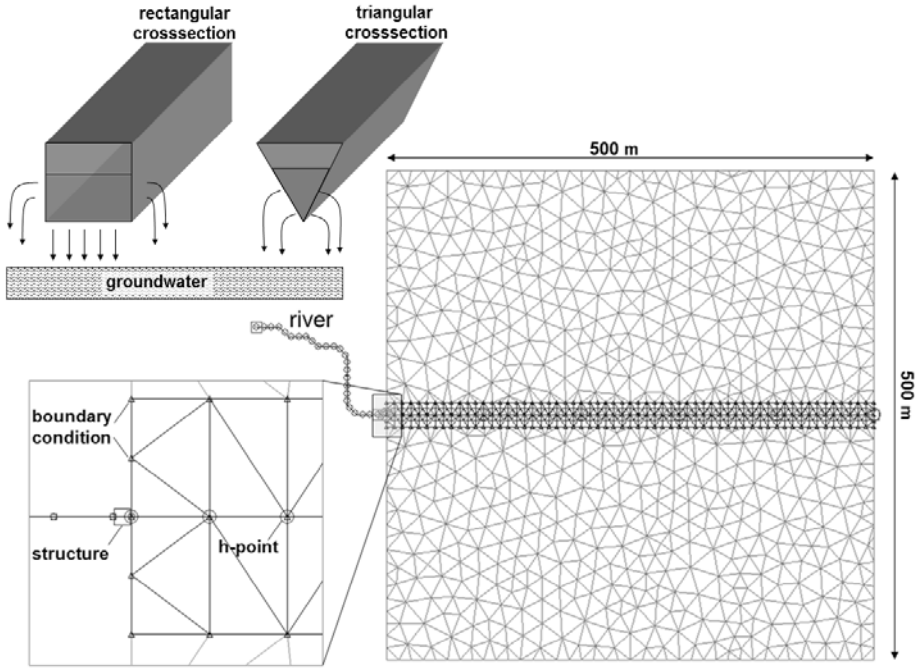

Fig. 5 Setup of the benchmarks examples to analyse the influence of different cross sections.

It was also intended to provide a benchmark in which the groundwater level is initially above or reaches a level during the simulation which is above of the bottom of the canal. In that way, also the two way interaction between the surface and groundwater could have been analyzed. Unfortunately, such an example could not be found, despite of intensive literature research. Most of the publications provide stationary solutions, like (David, 1998), or transient solutions for rivers which fully penetrate the aquifer (Barlow, 1998). An example which comes close to the intended system is based on the Theis solution (Theis, 1941). Hunt (1999) derived a solution, which in additionally to Theis' solution also takes into account the situation in which a river only penetrates partially into the aquifer system, the river has a semi pervious sediment layer and the river is not necessary located at the boundary of the model. The system Hunt describes gives a instationary solution for a phreatic aquifer system in which a well extracts groundwater and this extraction causes inflow from the river into the groundwater. The system he describes as well as the IfmMIKE11 model which was set up to represent this system are shown in the following figure.

Hunt presents a solution for the drawdown of the groundwater, both in space and in time, as well as a solution for the discharges from the river into the groundwater. The equations he provides for these two solutions are given in Eq. 5 (drawdown $\omega(x, y, t)$ [m]) and Eq. 6 (ratio between the infiltration and the extraction rate $\Delta Q/Q_w$):

$$\omega(x,y,t) = \frac{Q_w}{4\pi T}\left\{W\left[\frac{(\ell - x)^2 + y^2}{4Tt/S}\right] - \int_0^\infty e^{-\theta} W\left[\frac{(\ell + |x| + 2T\theta/\lambda)^2 + y^2}{4Tt/S}\right] d\theta\right\} \tag{5}$$

where λ [m/d] is a constant of proportionality between the seepage flow rate per unit distance (in the y direction) through the streambed and the difference between river and groundwater levels at x = 0 (location of the river). W is the Theis well function (for example in Barry, 2000) and S [-] stands for the porosity and T [m²/d] for the transmissivity of the aquifer.

$$\frac{\Delta Q}{Q_w} = erfc\left(\sqrt{\frac{S\ell^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda\ell}{2T}\right) erfc\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{S\ell^2}{4Tt}}\right) \tag{6}$$

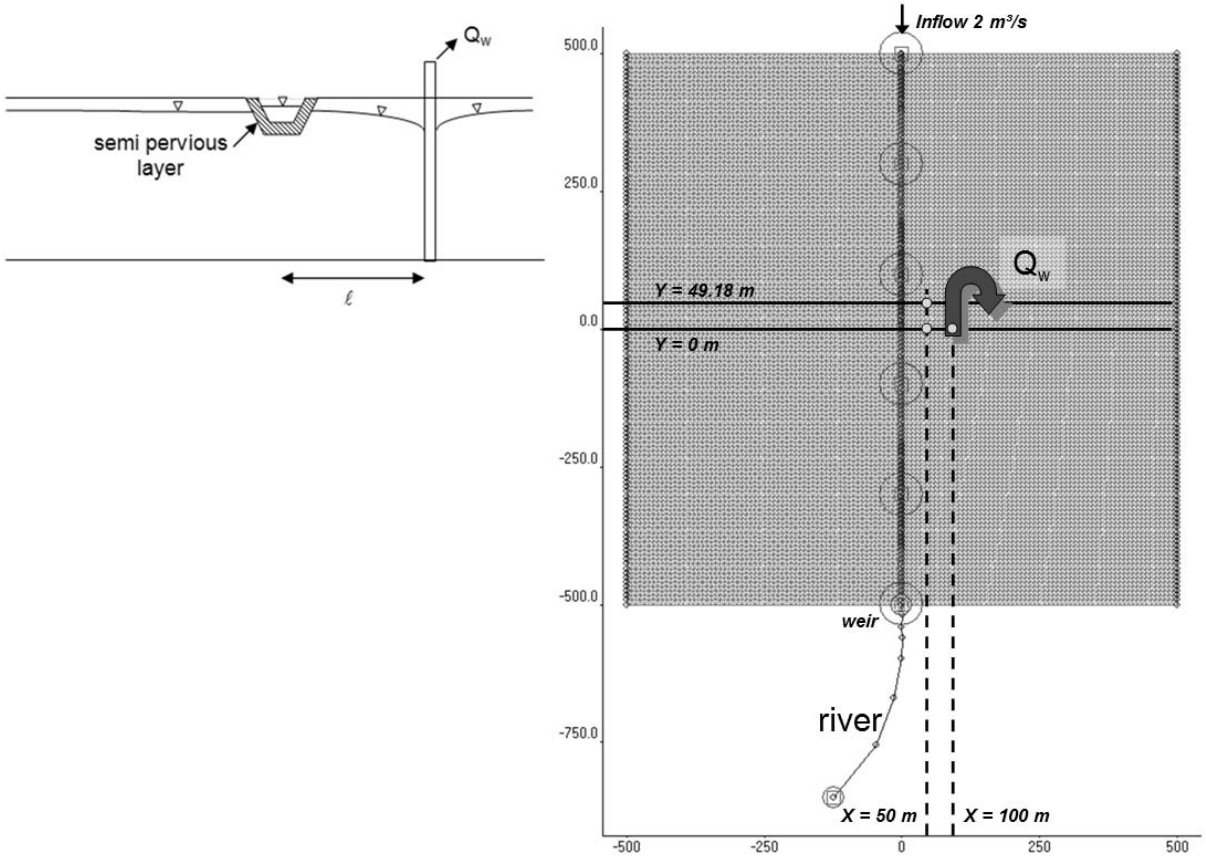

Fig. 6 The problem considered by Hunt (1999) and the benchmark setup in IfmMIKE11.

Unfortunately, also Hunt assumes that the water level in the river does not change in time and as a result of the infiltration into the groundwater. A combination of the two benchmarks mentioned in this section would provide a perfect base to verify any model simulating the interaction between ground- and surface water systems. Nevertheless, the benchmark Hunt has published was used to verify the model and the results will be shown in the next section.

SIMULATION RESULTS

In the next figure a comparison is shown between the analytical solutions and the simulated results of the first benchmark presented in this paper. In the figure both the exchange discharges between the river and the groundwater and the water depth in the river are included. The figure contains the results for the rectangular as well as the triangular cross sections. The initial water depth of the river in both models is 10 m, the river width of the rectangular cross section is 25 m and the slope of the bank of the triangular cross section amounts 1:2. The transfer coefficient for both models is equal to 0.1 d^{-1}. The length of the river is 500 m and the maximum allowed time step of FEFLOW is 0.05 d. Both the exchange discharges and the water depths fit perfectly to the analytical solutions, for both cross sections. It was also tested that the simulated results do not depend on the stratigraphical settings in FEFLOW; the results are identical using a phreatic or a free & movable top slice and also the use of integral boundary conditions shows no effect. Due to the shape of the cross sections, the water depth declines slower in case of the triangular cross section. At a water depth of 10 m, the wetted perimeters of both cross sections are almost identical (44.7 against 45 m). In case of a water depth of 5 m, the wetted perimeter of the rectangular channel (35 m) is clearly larger than the one of the triangular channel (22.4 m). Consequently, the exchange rates are also higher for the rectangular shape at a water depth of 5 m. In the figure also the exchange rates for a free & movable top layer using integral boundary conditions and the regular coupling method (s. also Fig. 2) are included. It is clearly distinguishable that the new coupling routine shows far better results. It has to be noted however, that due to the low ground water table, in this benchmark example in fact no new boundary conditions were used; at all time steps and all boundary nodes a boundary condition of the 4th kind

with exchange rates calculated according the actual wetted perimeter were set. This has been explained already in one of the previous sections.
Also with the new coupling method the influence of the maximum allowed time step of FEFLOW was tested. This is shown in Fig. 8. Also for this method it has to be concluded that the lack of an iterative coupling causes discrepancies between the analytical and numerical solution if the FEFLOW time step exceeds a length of approximately 0.25 d.

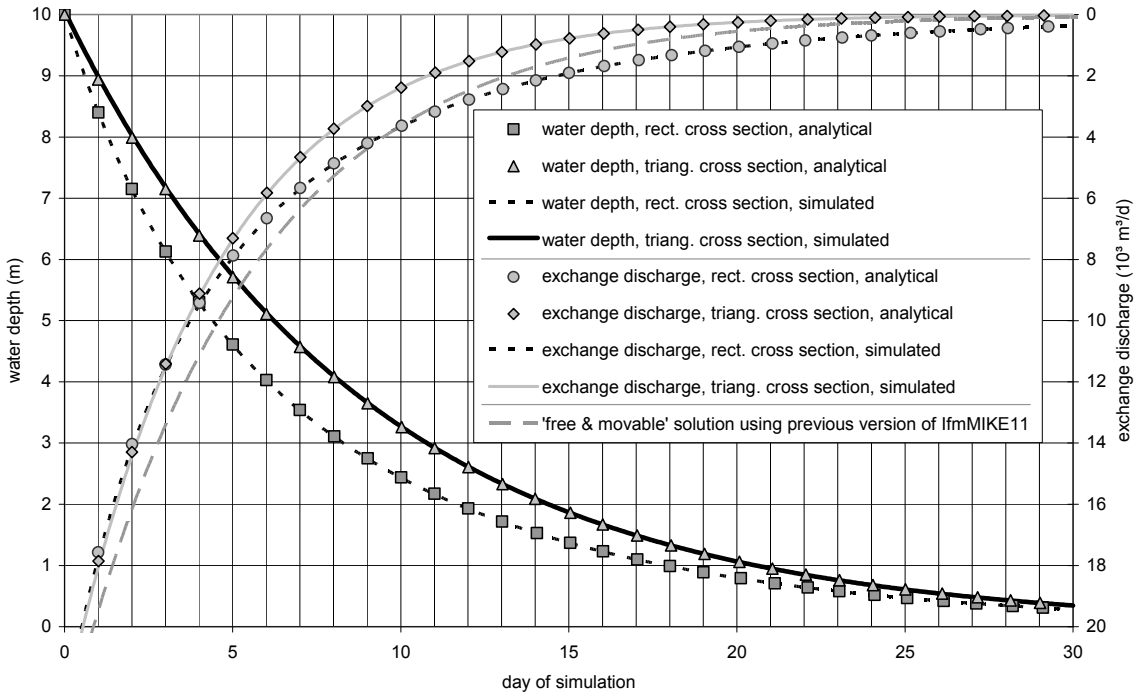

Fig. 7 Comparison between the analytical solutions and simulated results for a rectangular as well as a triangular river cross section using a maximum FEFLOW time step of 0.05 d.

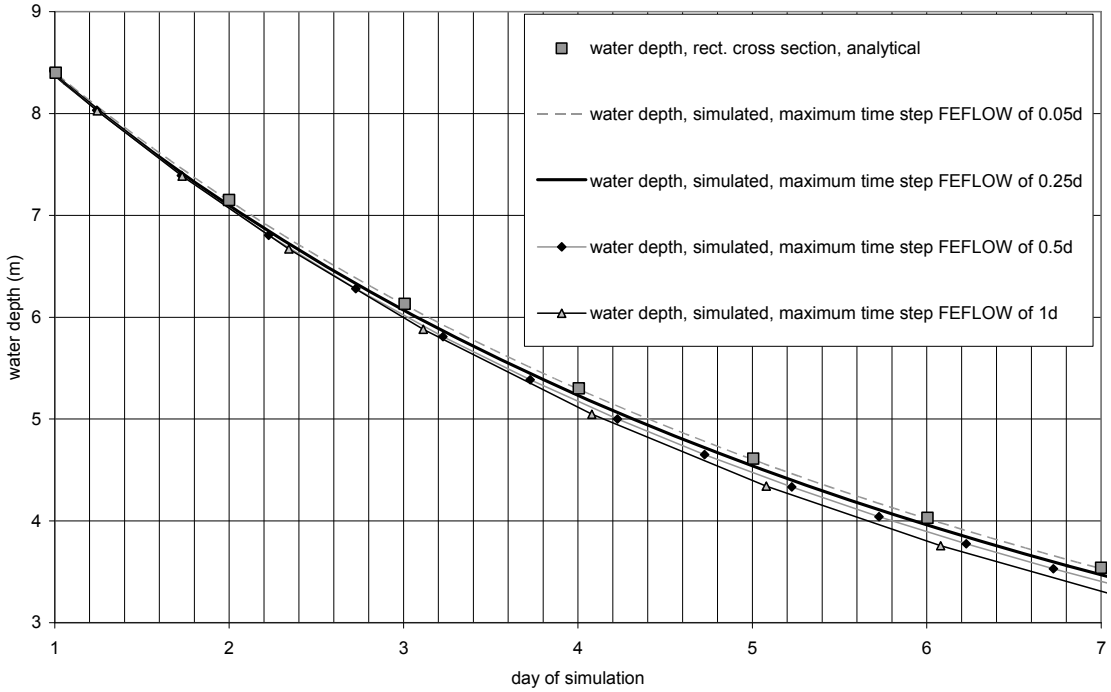

Fig. 8 Comparison between the analytical solutions and simulated results for a rectangular river cross section using different maximum FEFLOW time step lengths.

The setup of the Hunt benchmark was already shown in Fig. 6. For this example the MIKE11 model had to be build in a way that the river water level would not or hardly change as a result of the infiltration. For that purpose a rather wide (200 m) and very smooth river bed (K_{st} = 80 $m^{1/3}/s$) has been defined. Furthermore, a constant upstream inflow rate of 2 m³/s and a weir level of approximately 10 m at the downstream end of the coupled region ensured that the water level in the river along the FEFLOW model was infiltration rate independent as well as constant along the river itself.

MIKESHE has been verified using the Hunt benchmark as well (Illangasekare, 2001). For that verification λ in Eq. 6 was set equal to $1*10^{-5}$ m/s. With a 200 m wide rectangular channel with a constant water depth of 2 m (the river bed was set at 8 m) an identical value for λ can be achieved using a global transfer coefficient equal to $42.353 * 10^{-4}$ d^{-1}. With furthermore a porosity of 0.2, a transmissivity of 0.001 m²/s, a distance ℓ between river and well of 100 m and an extraction rate Q_w equal to 10 000 m³/a exactly the same conditions could be tested with IfmMIKE11. In the next two figures both the simulation results for the infiltration rate along the coupled river as well (Fig. 9) as the drawdown along the line y = 0 and y = 49.18 m in Fig. 6 at day 23 of the simulation (Fig. 10) are shown. Within the figures also the analytical solutions presented by Hunt are included. The values have been calculated using a software tool which is available at the website of Hunt (see also Hunt, 2008). The analytical solutions and the IfmMIKE11 results are nearly identical.

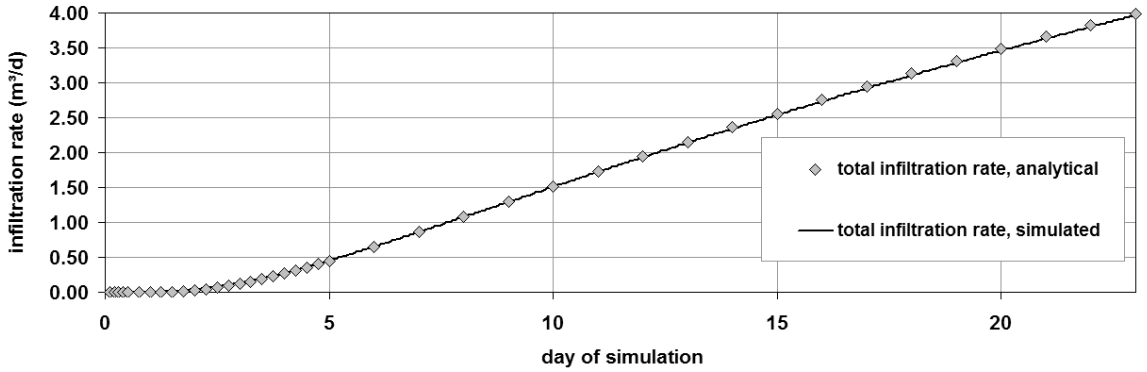

Fig. 9 Comparison between the analytically solved and simulated total infiltration rates in time along the coupled river branch.

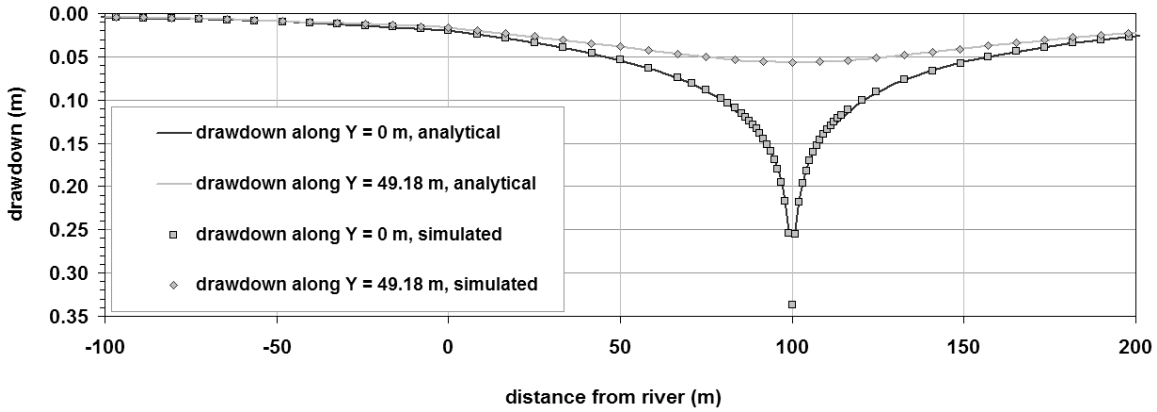

Fig. 10 Comparison between the analytically solved and simulated drawdown along Y = 0 and Y = 49.18 m at day 23 of the simulation.

Finally, the drawdown in time has been analysed at two points, both halfway river and extraction well, but with different Y coordinates (0 and 49.18 m). Also this comparison showed that the analytical solutions and the simulated results with IfmMIKE11 match excellent. Finally, it was also successfully verified that the infiltration rates shown in Fig. 9 are also distracted from the MIKE11 model and that despite this additional outflow the river water depth upstream of the implemented weir remains constant at 2 m during the complete simulation. This benchmark showed therefore that the new IFM function IfmSetCoupledRiverBndNodes was successfully implemented in IfmMIKE11.

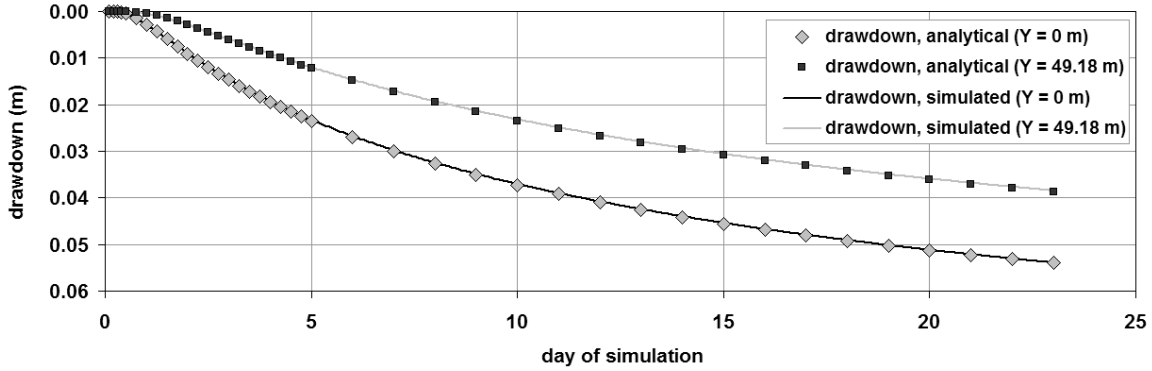

Fig. 11 Comparison between the analytically solved and simulated drawdown in time at the points (50, 0) and (50, 49.18).

FURTHER DEVELOPMENTS

QUALITY MODELLING

It is intended to extend the coupling between MIKE11 and FEFLOW 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. The flow field is the output of the hydrodynamic solver (HD simulation) and the transport equation solver in MIKE 11 utilizes this flow field in either a coupled mode (one time step at a time) or in a decoupled mode where the flow field is read from a hydrodynamic result file. The latter option has been implemented in the MIKE11 interface during the past few months, but has not been tested completely yet. With respect to the FEFLOW coupling and in contradiction to the MIKE11 – MIKESHE coupling, the hydrodynamics and the transport equations 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 flow and concentrations 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.

In FEFLOW the boundary conditions for flow and mass transport are set independently. Like the flow boundaries also the mass boundaries can be set in four different types. From these, only the 1st and 4th kind seem to be useful for the intended coupling. Furthermore, 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 (Diersch, 2007). In general it can be stated that the former 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 the groundwater); the mass transport boundary condition would then assume that the value being set represents the dispersive mass flux. The total mass flux will however be enlarged by the inflow from the flow boundary condition multiplied with the concentration at the node, so that the total mass flux into the model would be higher than the user could presume from the boundary values (kg/d) being set at the 4th kind mass boundary node. 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. The mass flux flowing from the river to the groundwater and vice versa can be controlled adequately. Mass boundary nodes of the **1st kind** (boundary values are defined as concentrations) on the other hand are ideal to use with the convergence form. The model would be more stable and the resulting

parameters of the MIKE11 time step can be transferred directly to the FEFLOW model (both concentrations). This would however automatically mean 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 automatically is generated. This error can be reduced by assuring that the elements around the mass boundary nodes of the 1st kind are small, preferably smaller than the volume which flows into the element during a single time step, but nevertheless this remains difficult to control. Summarized, both mass boundary conditions of the 1st and of the 4th kind have advantages and disadvantages and it is therefore intended to implement this choice as an option in IfmMIKE11. If mass boundary conditions of the 4th kind are used, only the divergence form will be supported and if mass boundary conditions of the 1st kind are used, both forms can be used. It is intended that the mass boundary nodes are generated automatically in FEFLOW at those locations which have coupled flow boundary conditions as well.

During the coupling 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 is pointing towards the river, then the mass boundary condition at that node should be deleted. As the coupling routine will automatically assure that there is a flow boundary condition at the same node, FEFLOW will take out water with the same concentration as the concentration at that node. Knowing the discharge at that time step, the mass flux boundary condition for the coupled MIKE11 h-point can easily be defined and set.
If at a single coupled node the flow direction at the end of the FEFLOW flow simulation time step is pointing towards the groundwater, a mass boundary condition (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 actual discharge rate calculated from the flow simulation. 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 this, the FEFLOW ***mass simulation*** can be started with the new mass boundary conditions. It has not been decided yet, whether the FEFLOW mass simulation will be run before or after the MIKE11 combined flow and mass simulation; both options seem to be possible. The resulting water levels of the last MIKE11 time step will be set just before the next FEFLOW flow simulation. This concept is shown in the next figure and will be implemented within the coming months.

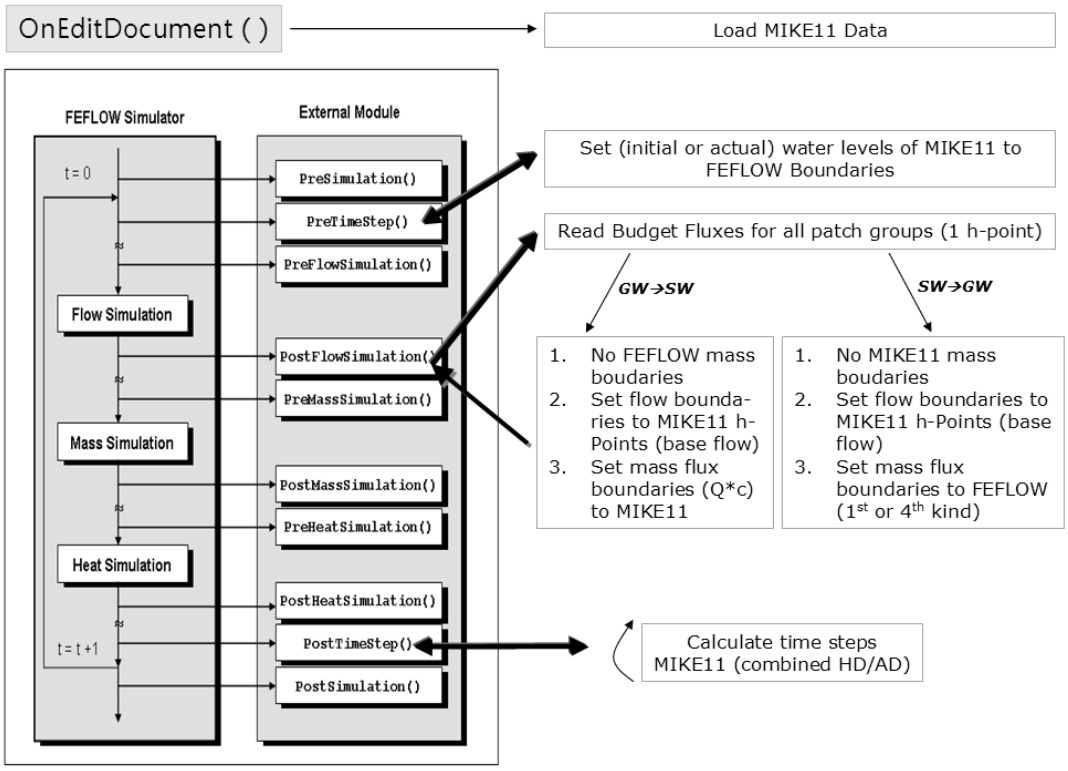

Fig. 12 Concept of the implementation of mass transport coupling in IfmMIKE11.

CONSTRAINTS IN FLOODAREAS

Already implemented is an improvement of the coupling of polder, wetland and foreland areas. In the actual version of IfmMIKE11 constraints can be optionally set automatically to the boundary conditions within those areas. The minimum value of h_{gw} in Eq. 1 for each node within a polder, wetland or foreland will then automatically be set to the surface level at that node. This level can be retrieved from the reference distribution “Mike11_DTM” or can automatically be taken from the Z coordinate of the first slice at the location of the node.

REFERENCES

Barlow, P.M., A.F. Moench, Analytical Solutions and Computer Programs for Hydraulic Interaction of Stream-Aquifer Systems, U.S. Geological Survey, Open-File Report 98-415A, Marlborough, Massachusetts (1998)

Barry, D.A., J.-Y. Parlange, L. Li, Approximation for the exponential integral (Theis well function), Journal of Hydrology 227 (2000), 287-291

David, J., Grundwasserhydraulik: Strömungs- und Transportvorgänge / Joan David. – Braunschweig; Wiesbaden: Vieweg (1998), ISBN 3-528-07713-1

Diersch, H.-J., Finite Element Subsurface Flow and Transport Simulation System, Reference Manual, FEFLOW Version 5.3, WASY GmbH, Berlin, Germany (2005)

Diersch, H.-J., About the difference between the convective form and the divergence form of the transport equation in FEFLOW White Papers Vol. I, DHI-WASY GmbH, Berlin, Germany (2007)

Hunt, B., Unsteady stream depletion from ground water pumping, Ground Water 37, no. 1 (1999), 98–102

Hunt, B., Groundwater analysis using Function.xls, Civil Engineering Department, University of Canterbury, http://www.civil.canterbury.ac.nz/staff/bhunt.shtml, last update 15 August (2008)

Illangasekare, T.H., MIKE SHE Code Verification and Validation for RFETS Site-wide Water Balance Model, Colorado School of Mines, Golden, Colorado. In collaboration with Robert Prucha, RMC Consultants and DHI-Water and Environment for Kaiser-Hill Company, L.L.C., September 28 (2001) (www.integratedhydro.com/reviews.html)

Monninkhoff, B., K. Kernbach, Coupled surface water – groundwater modelling for planning of flood retention in the Lower Havel area, In: Proceedings of the International FEFLOW User Conference, Sept. 10-15 (2006), Berlin, 115 – 124

Monninkhoff, B., S. Kaden, Coupled modelling of groundwater and surface water for renaturation planning in the National Park Lower Odra, Groundwater-Surface Water Interaction: Process Understanding, Conzeptualization and Modelling (Proceedings of Symposium HS 1002 at IUGG2007, Perugia, July (2007), IAHS Publ. 321

Monninkhoff, B., P. Schätzl, Coupled Modelling of Groundwater and Surface Water for Integrated, Sustainable Water and Flood Management in Polders, Proceedings of the "International Groundwater Symposium- Flow and Transport in Heterogeneous Subsurface Formations: Theory, Modelling & Applications", held in Istanbul, Turkey from June 18-20 (2008), 180-188.

Theis, C.V., The effect of a well on the flow of a nearby stream. American Geophysical Union Transactions 22, no. 4 (1941), 734-738

ACKNOWLEDGEMENTS

Thanks to Bruce Hunt to provide useful VBA macros to calculate the analytical solutions he published before. Thanks also to Douglas Graham, DHI Denmark, who provided information to the verification of MIKESHE using the solution given by Hunt.