Modelling the interaction of surface-water and groundwater flow by linking Duflow to MicroFem

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Abstract Duflow is a computer program for one-dimensional hydraulic modelling of surface water. MicroFem is a finite-element model that simulates saturated groundwater flow in multiple-aquifer systems. Both model codes simulate steady-state as well as transient flow. A method is presented to couple the flow systems in Duflow and MicroFem. The results of both models are exchanged to bring the flow systems in equilibrium with each other in an iterative way. The coupling software is verified with several analytical solutions. To demonstrate its use a regional coupled model is built of a water-supply well field with induced surface-water infiltration. Compared to individual surface-water and groundwater flow models, coupled models have a surplus value in all situations where the flow systems have a significant mutual interaction.
Key words saturated groundwater; surface-water; finite-element groundwater modelling; one-dimensional surface-water modelling; surface-water/groundwater interaction modelling

INTRODUCTION

When groundwater flow is modelled, the exchange with the surface-water system is based on assumed boundary conditions. The same applies to the groundwater system when surface-water flow is modelled or a simple empirical rainfall-runoff model is used. In most cases this simplification is a defendable choice. In certain situations, when the interaction between the surface-water system and the groundwater system plays an important role, it can be an advantage to combine the surface-water model and the groundwater model for an integrated calculation.

In this paper a method is presented to couple a surface-water model built with Duflow, and a groundwater model built with MicroFem (Smits, 2002). The coupling software brings the results of both models in equilibrium with each other in an iterative way.

DUFLOW

Duflow is a computer program to model steady-state and transient surface-water systems (EDS, 1995; STOWA, 2000). The surface-water flow is modelled in a one-dimensional network of nodes connected by sections with a certain length and hydraulic resistance. For each section the bottom height and the dimensions of the cross-section have to be specified. Within the network several types of hydraulic structures, like weirs, culverts and pumps can be included.

Duflow solves the Saint-Venant equations for conservation of mass and momentum, using the initial and boundary conditions, such as an incoming flow at the upstream part of the model and a measured downstream water level. For each section and for each time step Duflow calculates the discharge, water level and mean velocity. Supply or removal of water takes place at the nodes of the network.

Fluxes between the groundwater system and the modelled watercourses can be defined as known boundary conditions or a special module in Duflow, the RAModule, can be used for a transformation of rainfall to discharges at the sections. This module makes a distinction between processes for open water, paved and unpaved surfaces. The used equations, in which several linear reservoirs are linked in a parallel and/or sequential mode, have a strong empirical character. In the coupling with MicroFem this RAModule is not used; the flux to each section is calculated by MicroFem.

MICROFEM

MicroFem is a finite-element model code for multiple-aquifer saturated groundwater flow modelling (Hemker & Nijsten, 1996; Diodato, 2000; Hemker, 2004). Within MicroFem there are several options to model the top boundary condition. The river-type of boundary condition is used for the link with Duflow. The drainage or infiltration flux depends on the resistance of the bottom of the watercourse, and the difference between the surface-water level and the calculated hydraulic head in the top aquifer, as is shown in Fig. 1 and equations (1-4).

$$\text{if} \quad h1 > rh1: \qquad q_{out} = a \times (h1 - rh1) / rc1 \tag{1}$$

$$\text{if} \quad h1 < rh1: \qquad q_{in} = a \times (rh1 - h1) / ri1 \tag{2}$$

$h1$	hydraulic head of the top aquifer, directly under the watercourse (m)
$rh1$	given level of the surface-water (m)
$q_{in/out}$	flux between the groundwater and the surface-water system (m^3 d^{-1})
$rc1$	inflow resistance (in case of drainage) (d)
$ri1$	outflow resistance (in case of infiltration) (d)
a	nodal area (m^2)

The inflow and outflow resistances are defined by the equations:

$$rc1 = (Dr / Krc) \times (a / LW) \tag{3}$$

$$ri1 = (Dr / Kri) \times (a / LW) \tag{4}$$

Dr	thickness of the streambed sediments (m)
Kr	vertical hydraulic conductivity of the streambed (m d^{-1})
LW	wet surface of the watercourse per node (m^2)

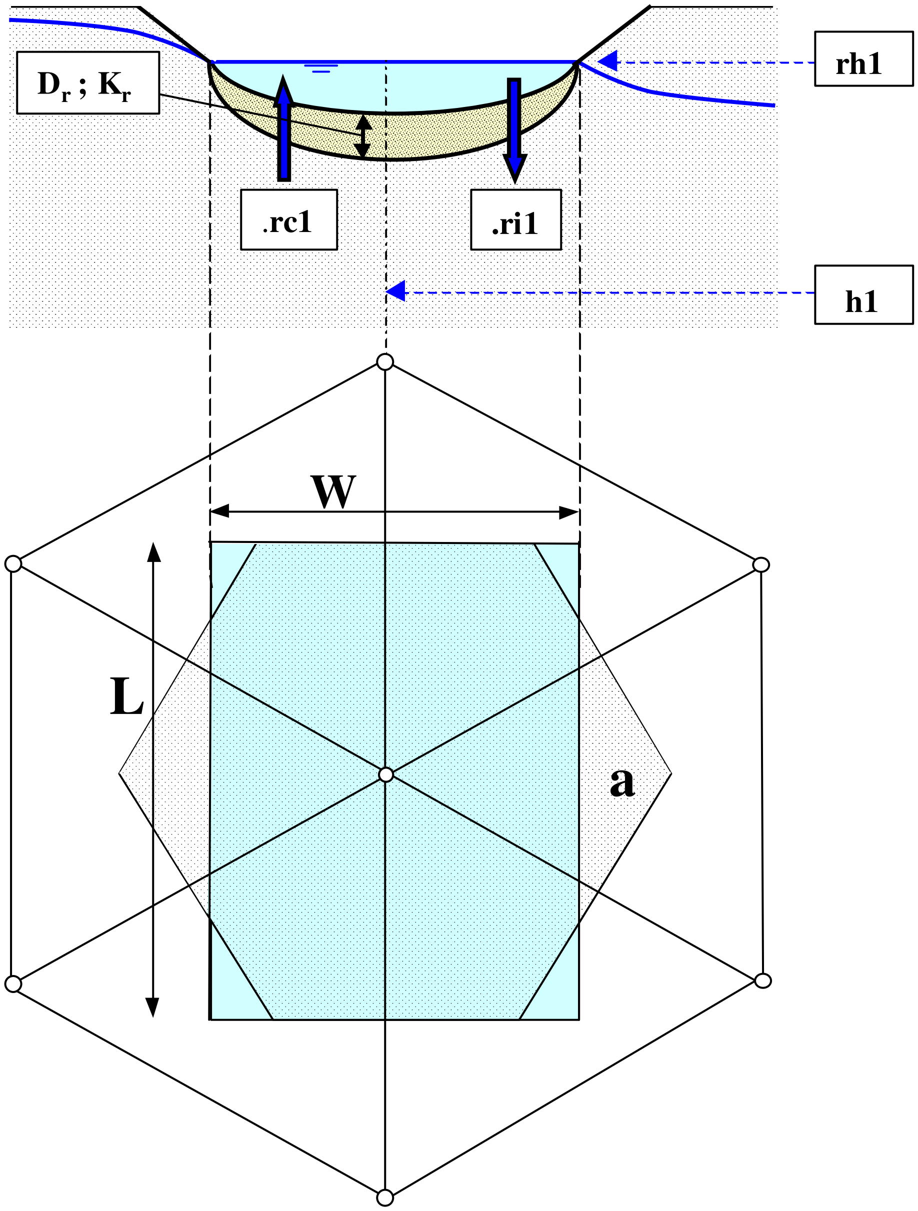

Fig. 1 Infiltration and drainage with the river-type condition at a MicroFem node.

For the river-type boundary condition the level of the surface-water, the wet surface of the watercourse and the inflow and outflow resistances are specified in MicroFem. In a coupled calculation the level of the surface-water and the wet surface of the watercourse is calculated by Duflow and transferred to MicroFem for every coupled MicroFem node.

COUPLING IN SPACE

The surface-water and groundwater models are built in Duflow and MicroFem respectively. Some initialisation routines help to collect the required data for a coupled calculation and to place MicroFem nodes right below the sections of the Duflow model. The number of MicroFem nodes that are coupled with each Duflow section can be chosen freely. The example shown in Fig. 2 couples three MicroFem nodes to a single Duflow section. The MicroFem nodes are coupled to the central parts of the Duflow sections. They do not coincide with Duflow nodes, because hydraulic structures with two different water levels may be located here. Also, more than two sections can be connected at a Duflow node and the wet surface of a watercourse may change in the transition from one to another section. It is easier to calculate and transfer only a single water level and a single wet surface for each node and each time step.

The coupled MicroFem nodes are equally spaced over the Duflow sections. The distance between the first MicroFem node and the beginning of a Duflow section is half the nodal distance at that section. The same holds for the other end of the Duflow section. In this way the network of coupled MicroFem nodes belonging to adjoining Duflow sections will be more regular.

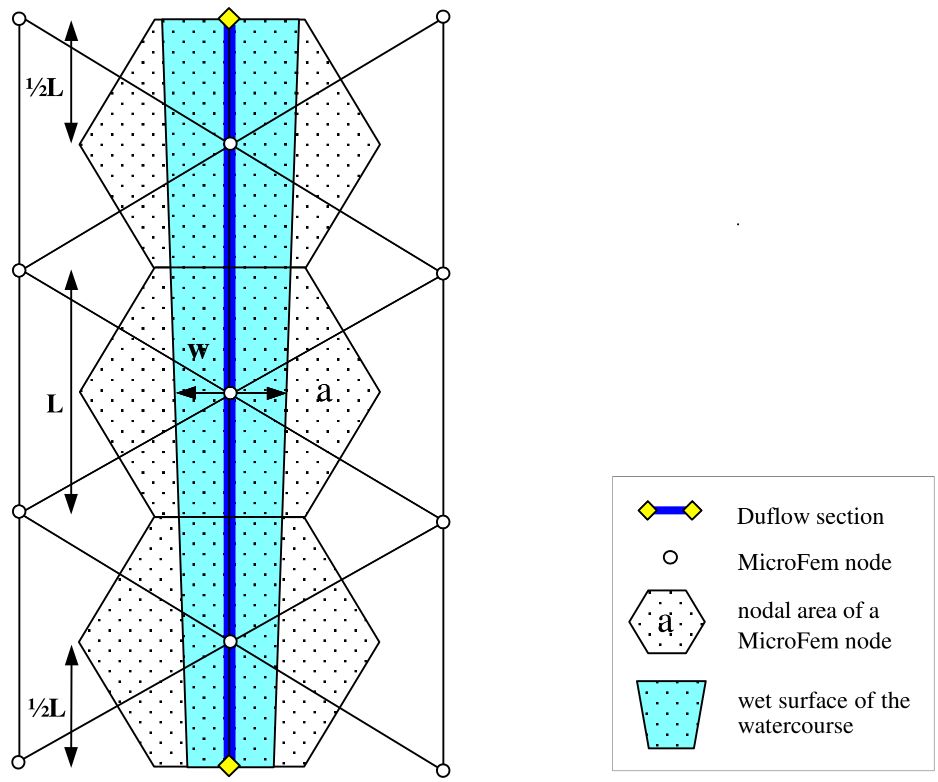

Fig. 2 Coupling in time: Three MicroFem nodes and one Duflow section.

For each coupled MicroFEM node the bottom height and the dimensions of the cross-section of the coupled Duflow section are obtained by interpolation.

COUPLING IN TIME

The dynamic character of surface-water and groundwater flow is very different. Groundwater flow is relatively slow and the response to changing boundary conditions is also slow compared with surface-water. This affects the lengths of the chosen time steps in both models. In a surface-water model time steps of one to several minutes are used. In a transient groundwater flow model time steps are often one to several days.

The modelled period is usually divided into several time intervals. In each time interval the coupling module brings the results of both models in equilibrium with each other. The lengths of these intervals can be chosen freely. The number of Duflow and MicroFem time steps within each interval can be chosen independently. However, the length of an interval should be a multiple of the time step length in Duflow as well as in MicroFem (Fig. 3).

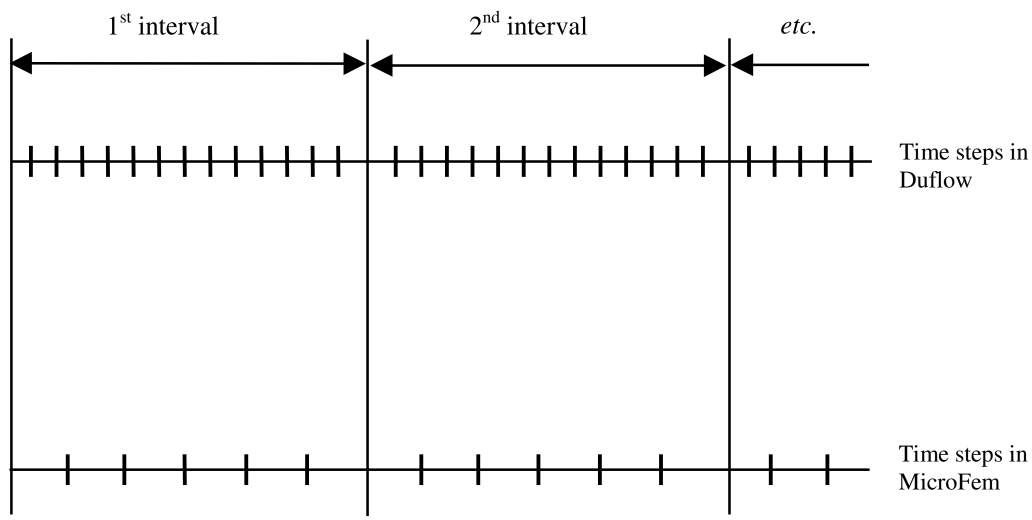

Fig. 3 Coupling in time. The vertical lines represent the time steps.

In this way a certain degree of flexibility exists for the modeller to select the length of the intervals and time steps for both models. For example, the time step can be set to one minute in Duflow, to one day in MicroFem and also to one day for the interval in which the heads and flow rates of both models are balanced. Other possibilities are, for example, one minute, one hour and six hours respectively, or ten minutes, six hours and half a day. In most cases the length of the interval will be chosen equal to the time step in MicroFem.

SOME CHARACTERISTIC ELEMENTS

Going dry of a watercourse

A section in Duflow can run dry, for instance if the upstream inflow stops. The numerical routines in Duflow cannot cope with dry cross-sections. To solve this problem a so called low-flow routine will come into action at low water levels. This low-flow routine works with a fictitious, thin and deep groove under the real cross-section (Fig. 4).

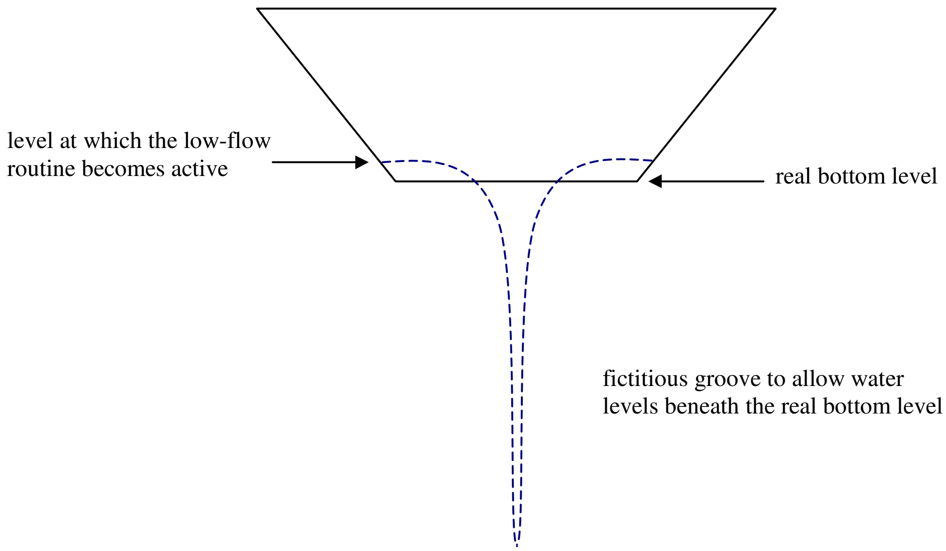

Fig. 4 Sketch of a cross-section with the low-flow groove of Duflow.

The groove does not affect the calculated discharge significantly, because the cross-sectional area is kept unaltered. When the water level drops beneath the bottom level, some water will be kept in the groove and the Duflow calculation will not crash. Because the wetted cross-sectional area is small, the amount of discharged water will be small as well.

The coupling module takes the low-flow routine of Duflow into account by checking whether the modelled water level in a Duflow section drops beneath the real bottom level. The outflow resistances of such MicroFem nodes are then set to infinite to avoid infiltration from the groove to the groundwater system. In this way the coupling module can cope with watercourses that run dry and are rewetted again.

Maximum infiltration

If the water table drops to a low level, the difference between the surface-water level and the hydraulic head of the groundwater (*rh1-h1*) becomes large. According to equation (2) the infiltration rate will be large as well. In case the water table looses hydraulic contact with the watercourse an unsaturated zone develops between the surface-water and the groundwater system. Because of the reduced permeability of this zone the infiltration rate will be less than computed with equation (2). For such circumstances a maximum infiltration capacity can be defined for each coupled node and the coupling software makes sure that this maximum value is not exceeded.

Definition of sub-catchments

In many cases only the important watercourses will be modelled in Duflow. The minor watercourses will be disregarded by the surface-water model, but the drainage by these small watercourses can be modelled in the groundwater model as a top boundary condition. This will be explained in the following example. In a model of the polder *de Zeevang* (Fig. 5) only the river *d'IJe* is part of the Duflow model. Other watercourses in this polder are modelled by MicroFem as a drainage top boundary condition. The small watercourses actually discharge at the river *d'IJe*. If this water is only removed from the groundwater system by MicroFem, it is not discharged to the Duflow sections and the water balance of the river *d'IJe* will not be modelled correctly.

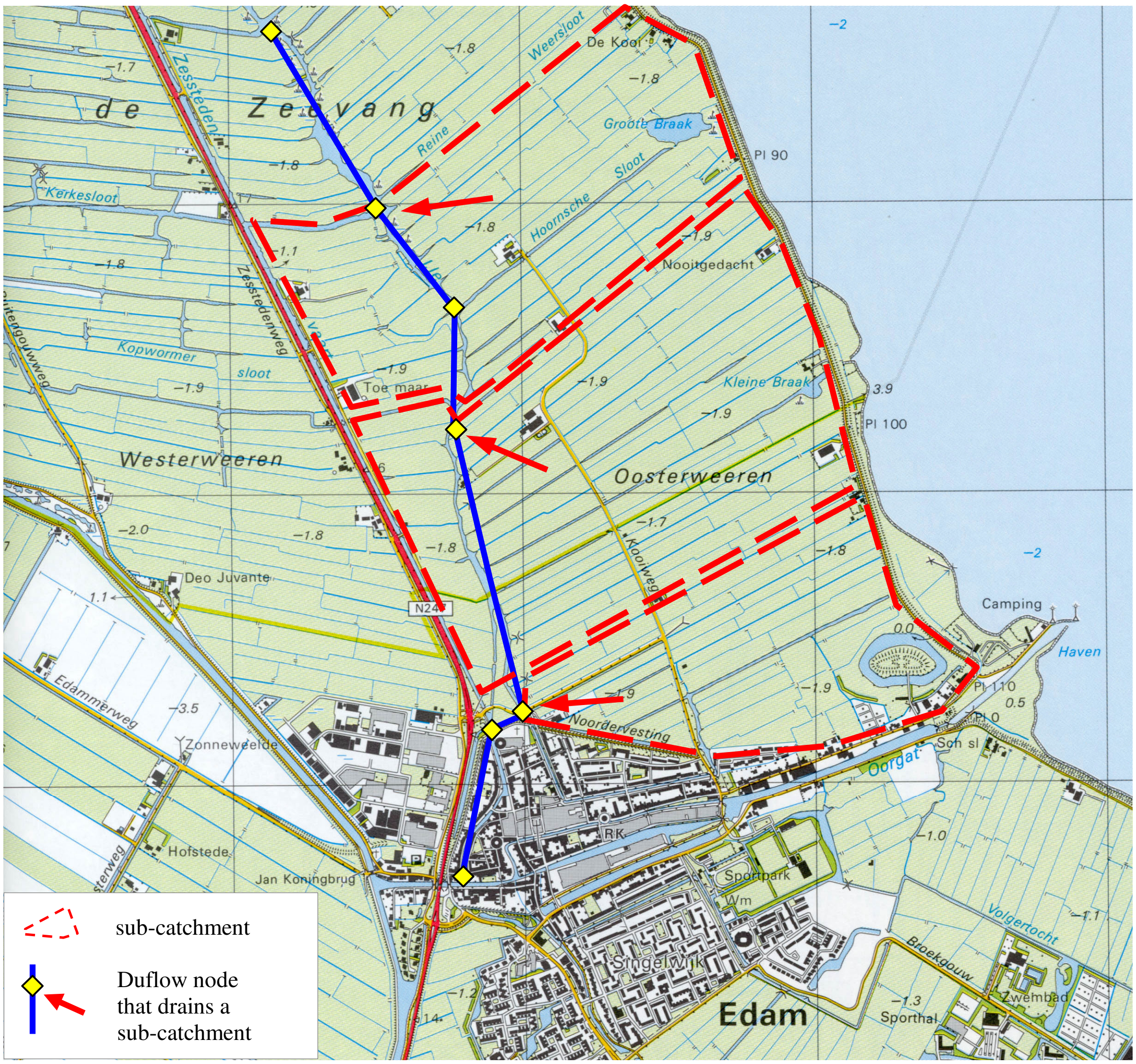

Fig. 5 Example of the coupling of sub-catchments to Duflow nodes.

MicroFem nodes can be grouped with a label. The draining flux of grouped nodes can be directed by the coupling module to a particular node of the Duflow model. By using this option it is possible to build coupled models at a regional scale.

The technique of dividing a model into sub-catchments is similar to the use of the RAModule in Duflow for the transformation of rainfall to runoff. However, instead of this empirical model with linear reservoirs, the physical-based groundwater model MicroFem is used. It is possible that the quick component of the direct runoff from paved areas is too slow in coupled models. Further research is needed to find out whether the application of the RAModule for paved surfaces will enhance the results.

SETTING UP A COUPLED CALCULATION

Based on the layout of the Duflow network a MicroFem network can be generated automatically. All the data for the coupled calculation are stored in a so called coupling file. The required data are: the names of the input and output files for both models, the dimensions of the cross-sections, the bottom levels and lengths of the Duflow sections, the *x* and *y* coordinates of the Duflow and MicroFem nodes, the Duflow section numbers with the coupled MicroFem nodes, the inflow and outflow resistances for each section, and the nodal areas of the MicroFem nodes. The data in this coupling file are used during the coupled calculation to find and write the matching input and output in the Duflow and MicroFem files.

RUNNING A COUPLED CALCULATION

The coupling module is controlled by a batch file containing a series of commands. It repeatedly starts the Duflow code and the MicroFem code. Between the calculations the coupling module reads the results from the output files of one model and writes it in the correct format to the input files of the other model. The Duflow and MicroFem calculations are only linked by their files.

The coupling module runs the Duflow model for the first interval with a zero flux from the groundwater system. For each coupled node the calculated mean water level (*h*) and the calculated mean wet surface (*LW*) are transferred to the MicroFem model. The coupling module runs the MicroFem model for the first interval with *h* and *LW* as a river boundary condition. MicroFem calculates for each coupled node the flux between the surface-water and groundwater system. For each coupled section the mean calculated flux is transferred to the Duflow model. With these mean fluxes as boundary conditions the coupling module runs the Duflow model again for the same interval. The coupling module repeats the successive model runs of Duflow and MicroFem for the same interval (Fig. 6) until the calculated water levels in all Duflow sections do not change more than a user-defined value. The results of both models are in equilibrium and the coupling module continues with the next interval. This procedure is repeated until all intervals are calculated.

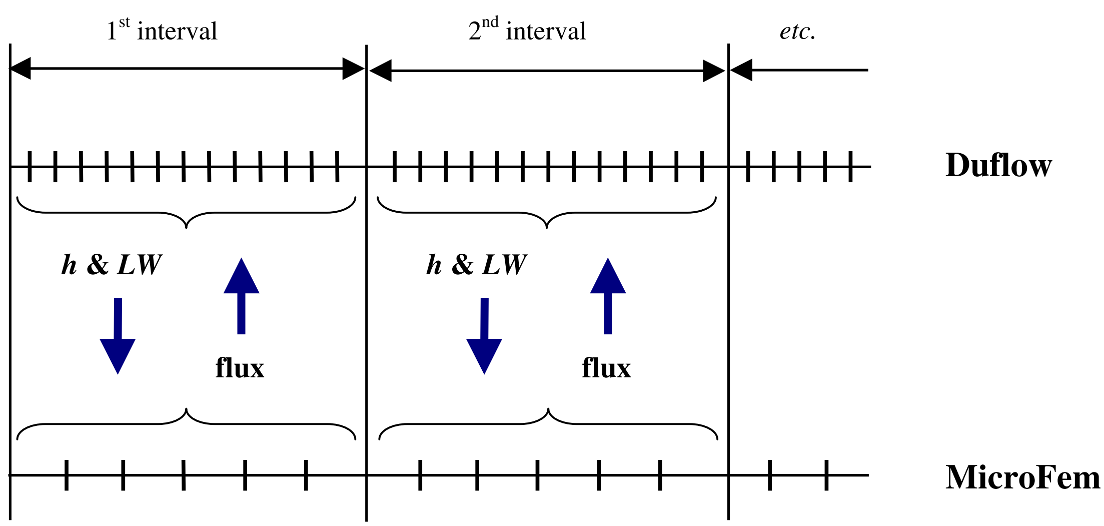

Fig. 6 Coupling in time, showing the parameters that are brought in equilibrium with each other for each interval. The vertical lines represent time steps.

The number of iterations that are needed depends on the required accuracy of the calculation and on the model conditions. In case of a relatively low hydraulic resistance between both systems and considerable fluctuations of the surface-water level, more iterations are needed than in situations with high resistances and slowly moving surface-water levels. Stopping criteria for the accuracy and the minimum and maximum number of iterations per time interval can be specified by the user.

VERIFICATION

A number of simple coupled models were set up for code verification. Some of these models used the transient water balance as a check, while others were compared with analytical solutions. At first simple models with fully penetrating canals were tested. De Ridder and Zijlstra (1994) presented analytical solutions for the flux between a canal and the adjacent aquifer and for the hydraulic head in the aquifer as a function of distance and time for different regimes of the water level in the canal. As initial condition the water level in the canal is taken the same as the hydraulic head in the aquifer. For the same base model, but each time with different time steps and intervals, the following conditions of the water level in the canal were applied:

- no fluctuation, a steady water level
- a sudden drop of one meter
- a sudden rise of one meter
- a linear drop of one meter
- a linear rise of one meter
- harmonic fluctuations.

As an example the linear drop condition is presented in Fig. 7. Here q is the flux from the groundwater system to the canal, $s_{0,t}$ the level in the canal as a function of time and $s_{x,t}$ the hydraulic head in the aquifer as a function of the distance to the canal and of time.

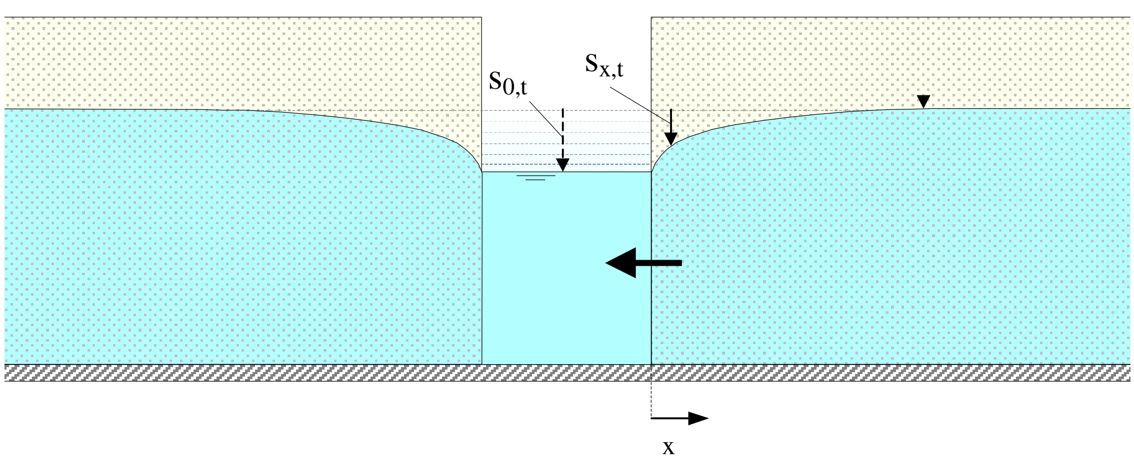

Fig. 7 Linear drop of the water level in the canal.

Some analytical and numerical results for the sudden rise case are presented in Fig. 8. Similar results are given for the linear drop case in Fig. 9. The results from the coupled model and the analytical solution are practically the same. This also applies to the results of the other test cases.

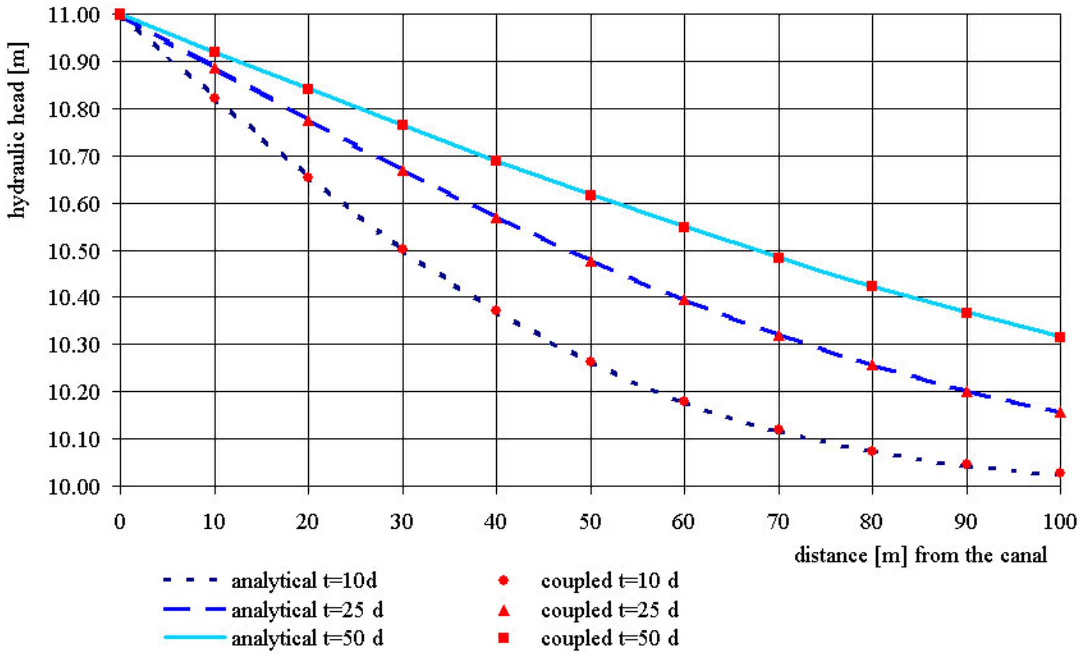

Fig. 8 Analytically and numerically computed hydraulic heads after a sudden rise of the canal level from 10 to 11 meter.

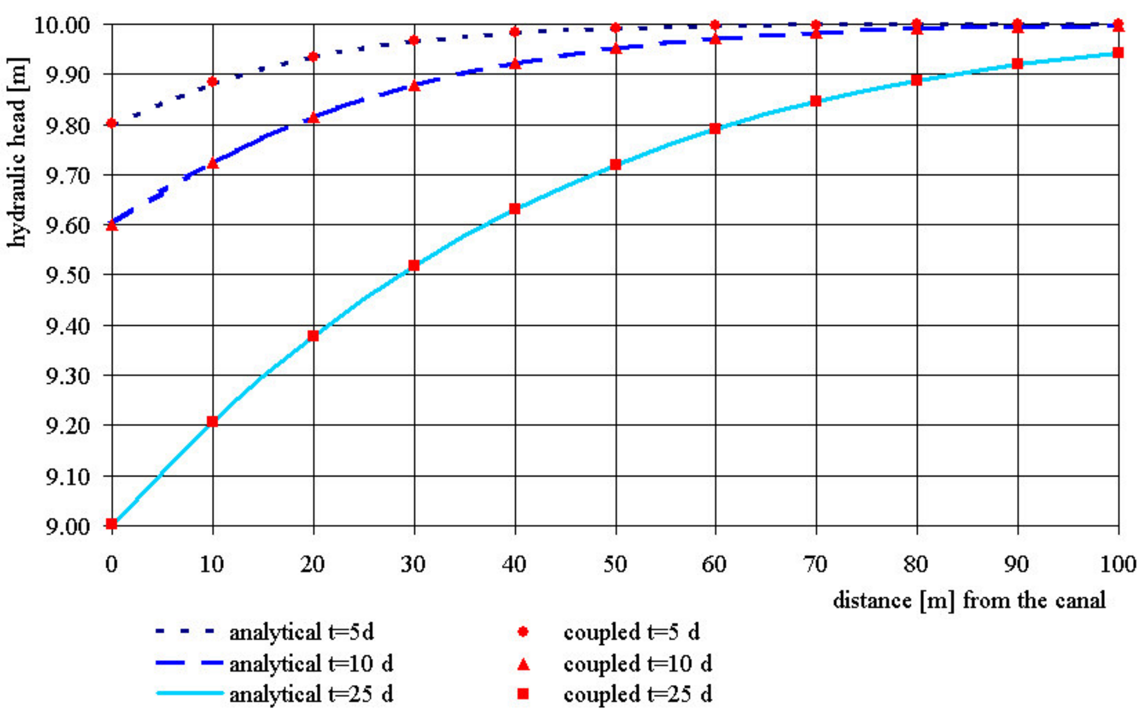

Fig. 9 Analytically and numerically computed hydraulic heads after a linear drop of the canal level from 10 to 9 meter in 25 days.

The coupling software is also tested for several other problems:

- a watercourse that runs dry
- an isolated lake with flow from and to the groundwater system
- a polder with seepage and precipitation
- a model with different sub-catchments.

All tests gave good results for hydraulic heads, water levels and fluxes.

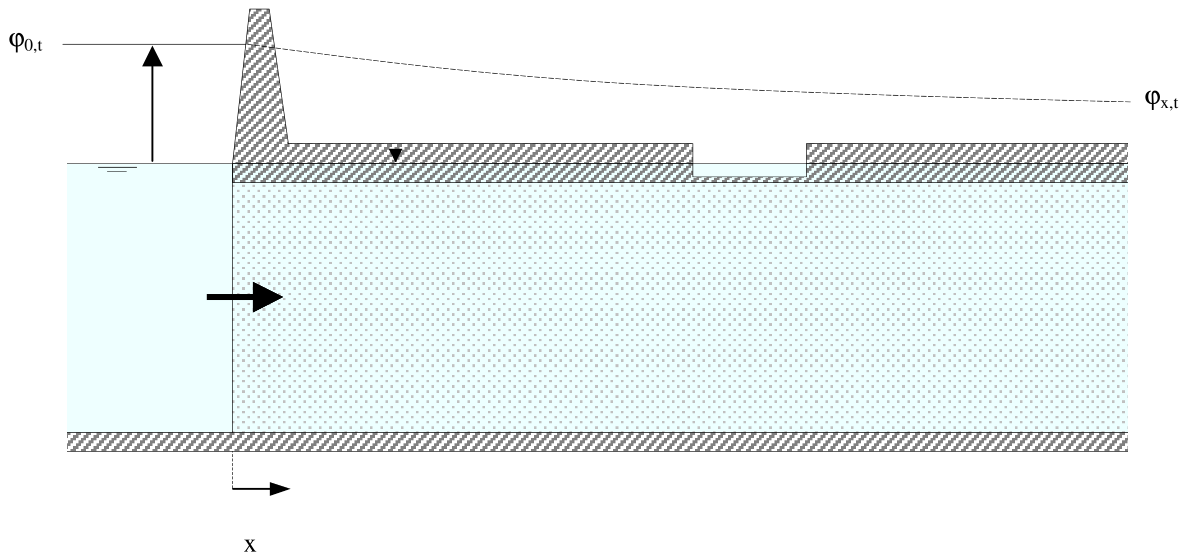

Fig. 10 Cross-section of an infiltrating river and a lake in a flood plain.

Finally a coupled model was set up that simulates a lake in a flood plain (Fig. 10). The river level $\varphi_{0,t}$ rises 3 m during a four-days flood, as shown in Fig. 11.

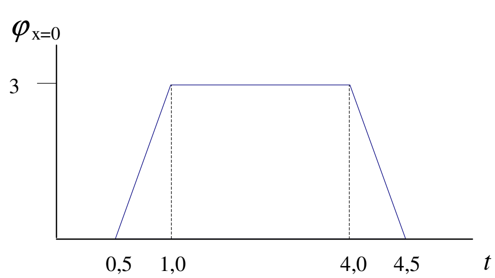

Fig. 11 River level fluctuation during a flood.

Both the lake and the river were modelled in Duflow. The coupled model was used to compute the lake level response to the river flood. The results were compared with the analytical solution published by Ramaker (1998). Some results of the coupled model are presented in Figs 12 - 14.

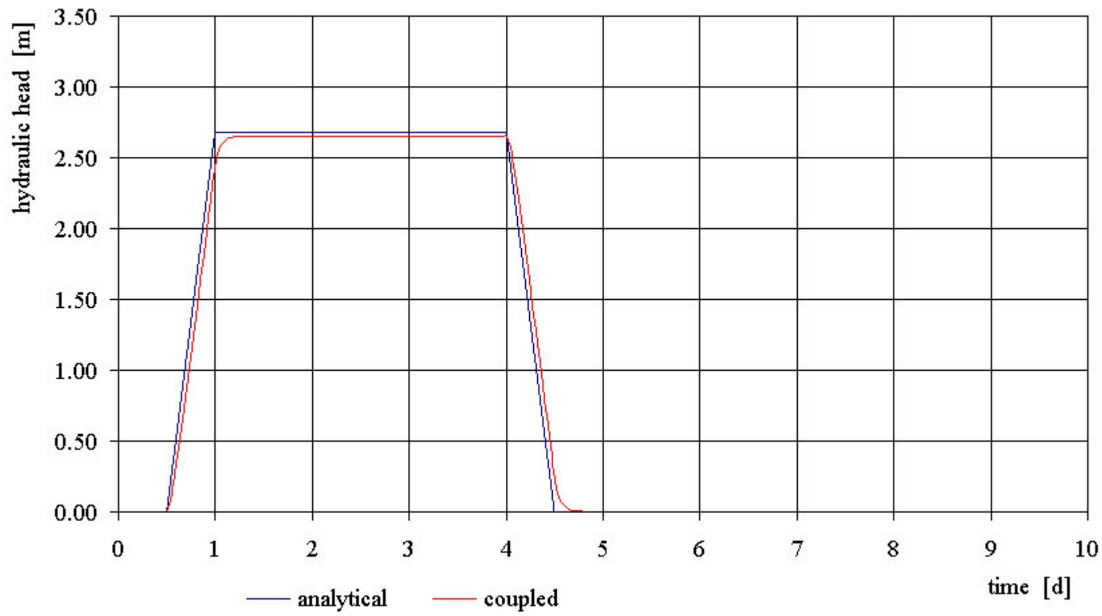

Fig. 12 Analytical and coupled model hydraulic heads under the lake.

The slight difference between the computed heads in Fig. 12 can be explained by the neglected hydraulic resistance between the river and the aquifer in the analytical solution, while this resistance is set to a small value of 0.1 day in the coupled model.

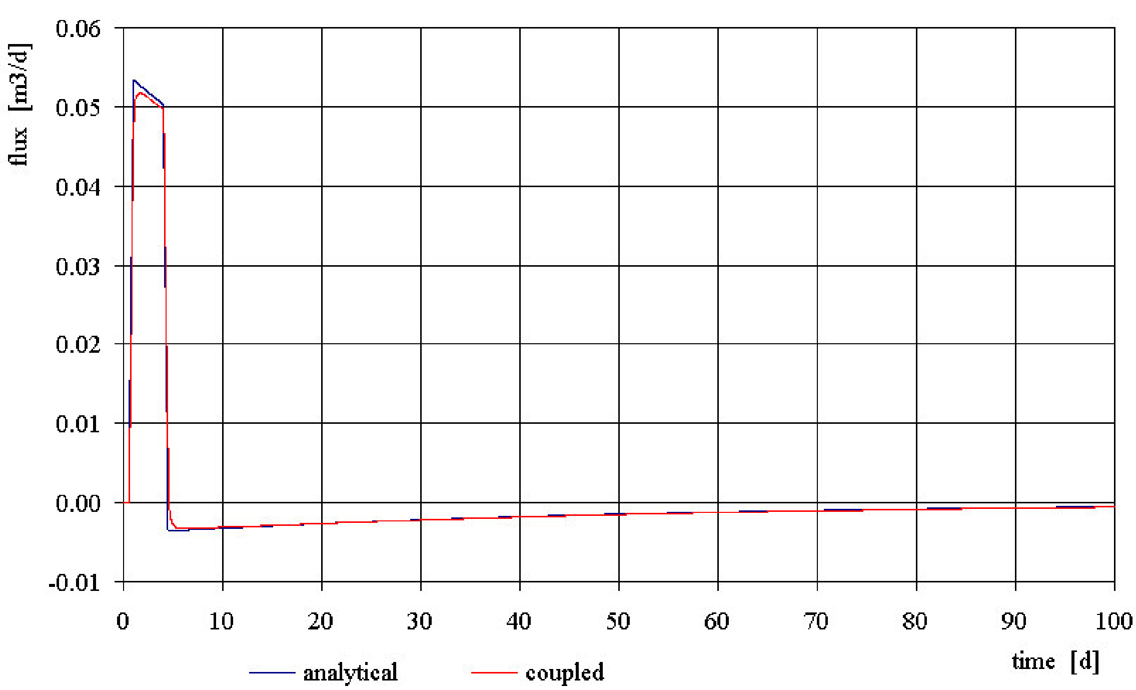

Fig. 13 Analytical and coupled model fluxes between the aquifer and the lake.

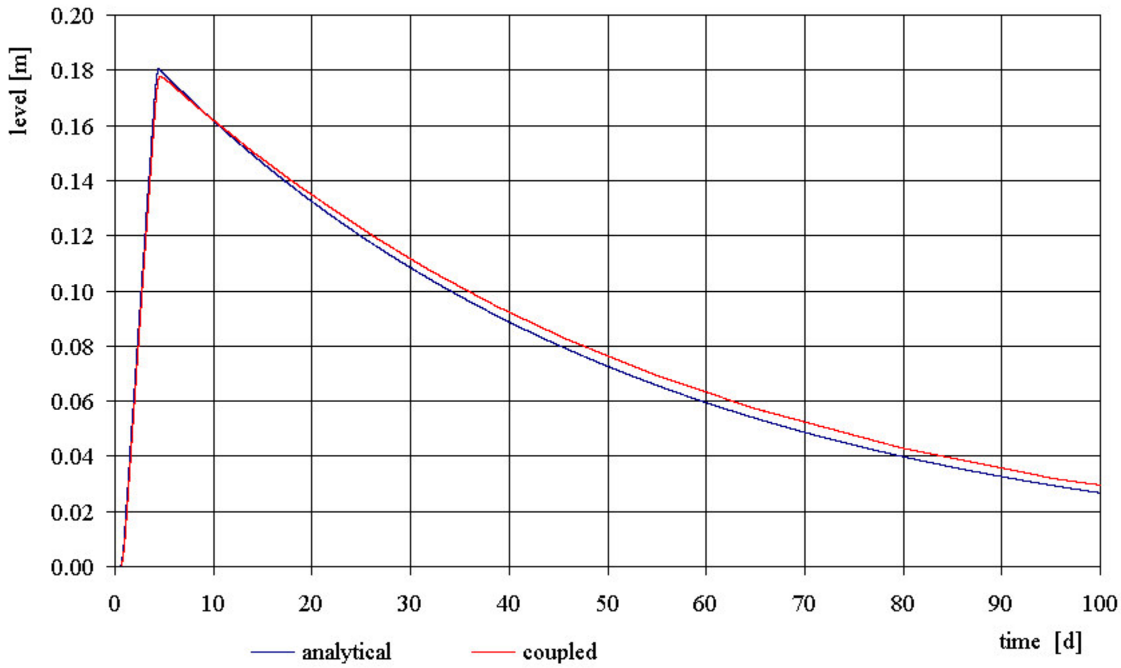

Fig. 14 Analytical and coupled model water levels in the lake.

The coupling module generated logical results for all test models. The fluxes between the coupled Duflow and MicroFem models, the water levels and the hydraulic heads were calculated correctly.

APPLICATIONS

Examples

Compared to individual model results, coupled model calculations with Duflow and MicroFem have a surplus value in all situations with a significant mutual influence between the surface-water and the groundwater system. Under such circumstances it is difficult to choose the boundary conditions for each system.

A practical application of such conditions can be found, for example, in an unconfined groundwater system with streams that run partially or occasionally dry. Also when streams have to be diverted, deepened or widened, a Duflow model with only the RAModule might be inadequate to calculate the expected discharge rates and the hydraulic dimensions of the stream. The effects of stream regulations on the nearby groundwater levels and the interaction between both systems are better simulated with a coupled model.

In situations where one tries to control the water table depth with surface-water inflow or in case a complex drainage system has to be modelled in much detail, a coupled model approach may be favourable compared with the standard way of modelling groundwater.

A coupled regional model

A coupled model is built of a surface-water infiltration system around a well field for water-supply in the eastern part of the Netherlands. The infiltrating watercourses are recharged by a nearby stream to reduce the depth and the radius of the cone of depression and to compensate the negative effects on the environment. In Fig. 15 the layout of the infiltration system, and the location of the production and observation wells are presented.

The watercourses in this region may drain, infiltrate and run dry depending on the season and the availability of discharge from upstream areas. All tricky situations in which a coupling module can get stuck are present in this area. Preliminary tests with simple boundary conditions showed that the coupled model produces the expected heads and fluxes for this complex system, both in time and in place. Further investigations will include the real boundary conditions, as obtained from measured water table levels and river flow.

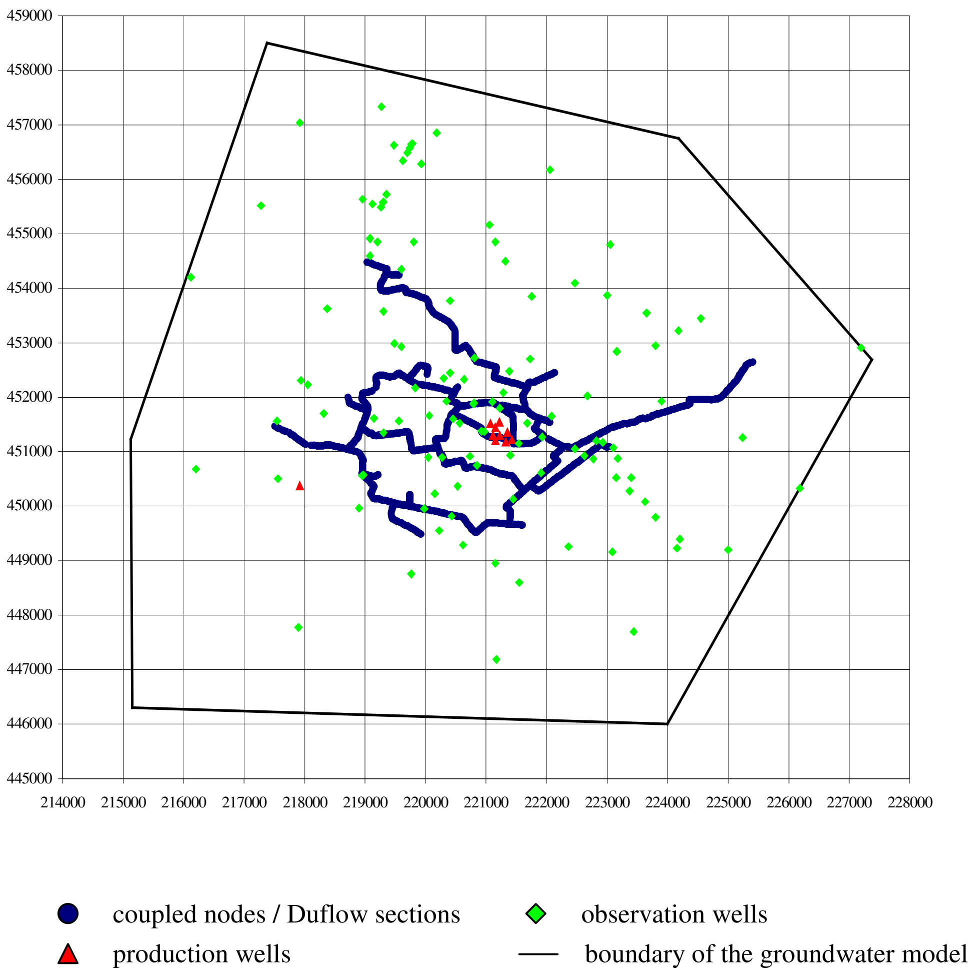

Fig. 15 Regional groundwater model with a surface-water infiltration system (coordinates in metres).

Execution time

The iterative linking of models is always a computer time consuming procedure and the present coupling module is no exception. The time required for a coupled run of a regional MicroFem model and a complex system of watercourses is hours rather than minutes. Because the time interval in which the results are brought in equilibrium with each other, the accuracy and the maximum number of iterations per time interval are all free to choose, the user has some control on the accuracy of the results and the associated execution time.

CONCLUSIONS

Compared to individual surface-water and groundwater flow models, coupled models have a surplus value in all situations where flow systems have a significant mutual interaction.

The presented method couples the model codes Duflow and MicroFem. It uses the river-type top boundary condition in MicroFem. One or more MicroFem nodes can be coupled with each Duflow section. The coupling module interpolates for each coupled MicroFem node the bottom level and the dimensions of the cross-section of the coupled Duflow section.

The modelled period is usually divided up into several time intervals. In each time interval the coupling module brings the results of both models in equilibrium with each other. The length of the intervals as well as the Duflow and MicroFem time steps within an interval can be chosen freely. For each time interval and for each coupled MicroFem node the fluxes between the surface-water system and the groundwater system are calculated by MicroFem and taken by Duflow as a boundary condition for the corresponding coupled section. For the same time interval the water levels and wet areas are calculated by Duflow and used as a river-type top boundary condition in MicroFem.

Within a coupled model watercourses may run dry temporarily, a limit can be set to the infiltration rate and the drainage of sub-catchments can be directed to the main watercourses in Duflow.

The coupling software was verified with simple models and analytical solutions. A coupled regional model was built of a water-supply well field with a complex surface-water infiltration system. It produced proper results for the tested boundary conditions.

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