The Versatile Soil Moisture Budget (VB4) model is found to realistically capture the long-term moisture variation observed in the soil surrounding the various trees studied.

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3D flow and transport groundwater modelling including river interactions

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Abstract

In the framework of the SALMON project (Sea Air Land Modelling Operational Network) supported by the IBM International Foundation at the University of Liège (Belgium), three existing models (ocean, river and groundwater) are to be connected adequately in order to form one single model. This model should be able to describe all water and contaminant fluxes in a whole system at regional scale including marine, river, groundwater and atmospheric inputs. In practice, the connection of the different models is done through a specific interface, called ' Junction'.

In the SUFT3D groundwater model, the interactions with the river are based on the Fourier boundary conditions. In the presence of 'wet docks', supplementary equations based on flow and solute mass balance have to be added in the 3D groundwater model in order to compute the appropriate water and solute mass fluxes which are exchanged with the 'wet dock' in connection with the 1D river model.

As each model has its own time and space discretizations, the junction must organize the data exchanges, including various time and space interpolations schemes. The particular role of the junction between the groundwater and the river models is tested on an actual site located in the river Meuse valley (Belgium) where two production wells are stressing the groundwater–river interactions in the alluvial aquifer. The test results show the impact of these interactions on the computed groundwater quantity and quality.

1 Introduction

In the groundwater modelling, the interactions with the other parts of the water cycle (atmospher, river and ocean) are usually taken into account with prescribed external input/output boundary fluxes. This is often considered as convenient in most of the studied cases when the exchanges can be estimated. However, an accurate assessment of these exchanges is certainly not easy, particularly when previsional simulations are concerned. In the SALMON project (Sea Air Land Modelling Operational Network) designed to describe water and contaminant fluxes in a whole system (including marine, river, groundwater and atmospheric inputs) at regional scale, the groundwater model is connected to other models (river and ocean models) by a « junction ». This junction is designed to manage the data exchange between models, using various time and space interpolations schemes. The boundary conditions are not estimated beforehand but deduced from the results of the other models. More details on the conceptual organisation of the data exchanges via the junction can be found in Dassargues *et al.*[1]. These developments are introduced taking advantage of clustered RS/6000 machines - an IBM SP2 parallel computer - and using the PVM (Parallel Virtual Machine) software for the data exchange management between the tasks running on the different processors.

Only the interactions with the river model are considered in this paper with an application on an actual pumping site in the river Meuse valley.

2 Interactions with the river

2.1 Theoretical background in groundwater modelling

The classical way to represent the interaction with a river in the groundwater modelling is to adopt one of the two following flow boundary conditions :

1) a Dirichlet boundary condition (boundary condition of the first kind) ; the total head values (H_g) are prescribed equal to the elevation of the water level in the river (H_r) :

$$H_g = H_r \tag{1}$$

2) a Fourier boundary condition (boundary condition of the third kind) ; the exchanged fluxes (q) between the river and the aquifer are computed depending on the difference existing between the piezometric head in the aquifer and the water level in the river :

$$q = \frac{K_r}{e_r} \cdot \left(H_g - H_r\right) \tag{2}$$

where K_r and e_r are respectively the hydraulic conductivity [L/T] and the thickness [L] of the river bottom.

The choice of the boundary condition is usually guided by the characteristics of the contact existing between the aquifer and the river. Bear & Verruijt [2] suggest the use of the Fourier boundary condition whenever the porous medium flow domain is in contact with a body of open water through a relatively thin semipervious layer. If this layer does not exist between the two domains, a Dirichlet condition is suitable. The Fourier condition can be used on the whole length of the water courses (McDonald & Harbaugh [3], Nawalany [4]) even if an actual low permeable layer is not present in some places of the interface with the aquifer. Moreover the nature of this last boundary condition allows to simulate the situations where the water level in the aquifer can fall below the river bottom. In this case, H_g is automatically replaced by the level of the river bottom (l_{rb}) in eqn (2) in order to calculate the seepage from the stream.

2.2 Developments for the SALMON project

2.2.1 Connection with the River Model : the junction

In the SALMON project, the exchanges between the GroundWater Model (GWM) and the River Model (RM) are estimated by the Fourier boundary condition. The exchanged fluxes are directly obtained by eqn (2) and the resulting contaminants mass fluxes (q_c) are easily deduced if adsorption or degradation processes and chemical reactions are neglected in the streambed :

$$q_c = \begin{cases} qC_r & \text{if } q < 0 \\ qC_g & \text{if } q > 0 \end{cases} \tag{3}$$

The data exchanges are organized at each time step. The computed water levels and solute contaminants concentrations are sent to the Junction by both models (GWM and RM). After possible spatial and time interpolations, the junction sends back to each model the calculated water fluxes and the resulting contaminants mass fluxes using eqns (2) and (3).

The Fourier boundary condition has been implemented in the groundwater finite element code SUFT3D (Saturated Unsaturated Flow and Transport in 3D) in order to be able to prescribe the fluxes on boundary edges as well as on boundary element sides. By this way, rivers with very different width can be considered and consequently the modelled RM-GWM interface can be 1D or 2D.

2.2.2 Integration of wet docks for the Groundwater Model

Usually, small zones of quasi-stagnant surface waters are neglected by river models. In the present case, a wet dock cannot be modelled in the 1D River Model. Even if its influence is negligible for the dynamic and the transport of solutes in the river, it is not the same for the exchanges with groundwater. So it has to be taken into account in the GWM.

In order to apply the Fourier boundary condition on the GWM-wet dock interface, the water level and the concentration of the considered solutes have to be known in the wet dock. Since it is in connection with the river, the values calculated by the RM can be used under some simplifying assumptions. The water level in the wet dock is assumed equal to the water level in the river at the entrance of the dock. The water flow rate exchanged between the wet dock and the river during the time Δt can be estimated by the following equation (based on the water balance and assuming the above-mentioned hypothesis):

$$Q_{d\to r} = Q_{g\to d} - \frac{\Delta h_r}{\Delta t} \cdot S_d = Q_{g\to d} - \frac{h_r^{t+\Delta t} - h_r^t}{\Delta t} \cdot S_d \tag{4}$$

with $Q_{d\to r}$: the water flow rate going from the wet dock to the river,

$Q_{g\to d}$: the water flow rate going from the aquifer to the wet dock,

S_d : the surface of the wet dock,

h_r^t : the water level in the river at the entrance of the wet dock.

The last term of the right-hand side is the flow rate coming from the basin to the river due to the time variations of the water level in the river.

For the transport modelling, the concentrations of the studied solutes in the wet dock cannot be chosen equal to the concentrations in the river. Indeed the period of the river contamination can be very brief inducing a negligible intrusion of contaminant into the wet dock. On the other hand, if the contamination of the river lasts longer, the wet dock plays the role of a « buffer zone ». Moreover, this role is also true when the pollution comes from the groundwater into the wet dock.

Some additional assumptions are considered for each contaminant :

- an uniform concentration (C_d) is supposed everywhere in the wet dock,
- no degradation, neither chemical reaction occur in the wet dock.

The solute mass balance in the wet dock gives the following equation :

$$\frac{D}{Dt}\int_V C_d dV = \int_S \sum_i q^i_{in(g\to d)} C^i_{in} dS - \int_S \sum_j q^j_{out(d\to g)} C_d dS + \begin{cases} -Q_{d\to r} C_d & \text{if } Q_{d\to r} \geq 0 \\ -Q_{d\to r} C_r & \text{if } Q_{d\to r} < 0 \end{cases} + \text{mixing effect} \tag{5}$$

with C^i_{in} : the concentration ([M/L³]) in the groundwater at the node i

$q^i_{in(g\to d)}$: the water flux going from the aquifer to the dock at the node i

$q^j_{out(d\to g)}$: the water flux going from the dock to the aquifer at the node j

C_r : the concentration in the river at the entrance of the wet dock

The last term (mixing effect) is added to take into account the dispersion due to turbulences in the connection zone between the river and the wet dock. So, when no water flux exists between the river and the wet dock, a mass flux can exist if the concentrations are different on both sides. This term can be estimated by an expression of the following type :

$\alpha(C_r - C_d)$ where α is a coefficient of mixing [1/T].

3 Application on an actual site

3.1 Description of the site

The site is situated on the right bank of the river Meuse at Dinant in Belgium (figure 1). There are two pumping wells located very near from the river and a wet dock. A mean groundwater flow-rate of 1500 m³/d is pumped out from the gravel aquifer. This pumping stresses the groundwater-river interactions in the alluvial plain. A layer of loose gravel sediments (about 10 m thick) forms the main aquifer. The geology of the underlying bed-rock is composed of Devonian and Carboniferous sandstones, limestones and shales. The bed-rock cannot be considered as an impervious basis for the gravel aquifer and so it is taken into account in the 3D groundwater modelling.

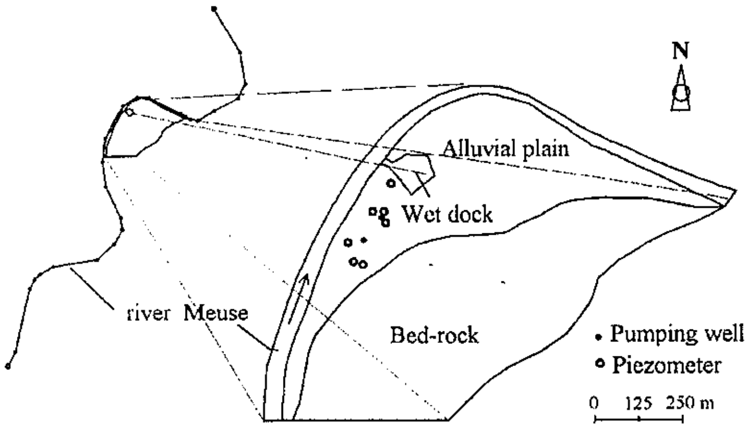

Figure 1: Modelled domain

3.2 Tests results

Several tests have been carried out to check the efficiency of the junction. In figure 2, the flow results are shown for a time period of 30 days. The global exchanged flux is mainly negative (river→ aquifer) due to the effect of pumping. Moreover the extracting rates increase after the 16th day (from 0.0062 to 0.0122 m³/s). For the transport modelling, two different tests have been carried out with a passive solute tracer :

- case 1 : the tracer is injected at the top of the aquifer near the river in the southern part of the GWM domain and in the north of the wet dock.
- case 2 : the tracer is injected in the river (about 1 km upstream from the GWM domain).

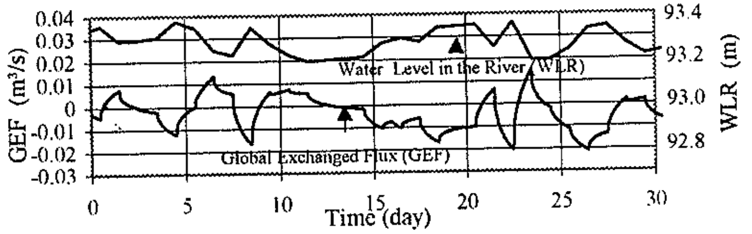

Figure 2 : The calculated global exchanged flux between the RM and GWM and the water level in the RM during a test period long of 30 days

The figure 3 shows the transport results in the case 1. The exchanged solute mass fluxes increase in time (the tracer goes progressively into the river) and vary with the exchanged water fluxes coming into the river near the injection zones (low WLR on figure 2). The concentrations in the river and in the wet dock fluctuate differently with the groundwater inflow. In the river, the tracer is diluted in the 45 m³/s river flow rate whereas, in the wet dock (containing approximatively 43000 m³ of water), the tracer is accumulated and then released in the river or the aquifer.

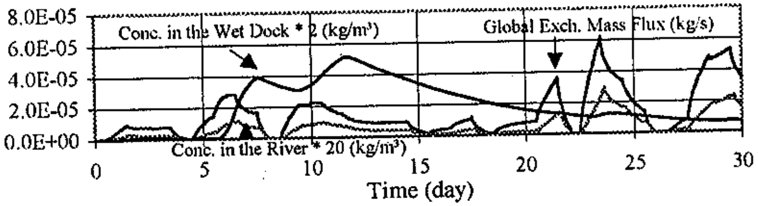

Figure 3 : Case 1: Evolutions of the concentrations in the wet dock and in the river and of the global exchanged solute mass flux.

The transport results of the case 2 (continuous injection in the river) are shown in the figure 4. Since the concentration in the river is relatively constant, the concentration in the wet dock equilibrates with this after a certain time (about 15 days). The tracer comes into the groundwater from the river and the wet dock and it converge towards the pumping wells. In the aquifer, the concentrations become slowly equal to these of the river.

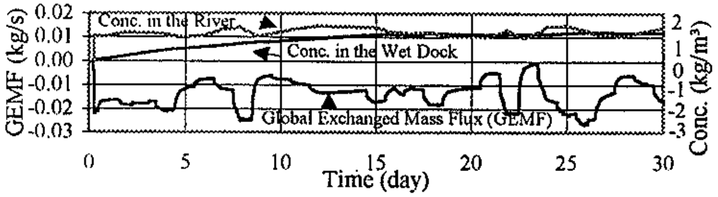

Figure 4 : Case 2: Evolutions of the concentrations in the wet dock and in the river and of the global exchanged solute mass flux.

4 Conclusion

The difficulty to take into account the interactions with a river, when the variations in water level or in the solute concentration are unknown in the river, is resolved here by a parallel run of the GWM and the RM. The exchanged water and solute mass fluxes through the contact interface are calculated by a junction on basis of the received results from each model at each time step. These calculations are made using a Fourier boundary conditions. The tests show the importance of these interactions on the computed groundwater quantity and quality in an alluvial aquifer where important pumping is made.

The junction river-aquifer is now ready to be integrated in a more general application of the SALMON project.

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