Large-scale groundwater flow and transport modelling: methodology and application to the Meuse Basin, Belgium

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Abstract To meet the requirements of the EU Water Framework Directive, an integrated water management project named PIRENE was initiated by the Walloon Region of Belgium. A partner of this project, the Hydrogeology Group of the University of Liège, is in charge of the development of a physically based transient groundwater flow and transport model for the Walloon part of the Meuse Basin (approximately 17 000 km²). To face the problems associated with this large-scale model, a general approach has been developed that combines a hydrogeological database and GIS systems to manage data. Techniques of spatial discretization have been applied that optimize the number of unknowns. For modelling groundwater flow and transport on a large scale, a new numerical approach called the Hybrid Finite Element Mixing Cell (HFEMC) has been implemented in the 3-D simulator SUFT3D.

Key words database; flow; GIS; groundwater; HFEMC; large-scale modelling; Meuse Basin, Belgium; transport

INTRODUCTION

Water management at the basin scale represents a key issue to insure good water quality for different uses and a sustainable quantity production. The Water Framework Directive 2000/60/EC of the European Council requires an integrated water management by “hydrological district” that can be for the sake of simplicity assimilated here to the hydrological basin. In each basin, water bodies, considered as management units, have to be delineated, characterized, managed, protected against further degradation, and if possible, restored. To meet these requirements, the Government of the Walloon Region (Belgium) initiated, in 2000, the PIRENE project to develop a tool for integrated water quantity/quality modelling in the region. Part of this project, the Hydrogeology Group, has developed a physically based, transient groundwater flow and transport model for the Walloon part of the Meuse Basin (Fig. 1).

Classical groundwater flow and transport modelling techniques are not adapted on such a large scale. Large data sets such as geological maps, piezometric level maps, hydrogeological parameters (hydraulic conductivity, specific yield, porosity), etc., have to be managed to build, calibrate, and validate the model. Actually, the degree of characterization could hardly provide enough parameter values to define or sufficiently constrain the model. Moreover, no measurement on a large scale is available. For transport simulation, as mean values introduce artificial dispersion that could be
greater that natural dispersion, the traditional advection–dispersion equation could not be ideal to simulate the transport processes. Finally, classical numerical techniques are CPU consuming and prone to instabilities such as spatial or time oscillations. To face these issues, a new general methodology including data management, spatial discretization and numerical development is developed (Fig. 2).

Fig. 1 Location of the modelled basin.

Fig. 2 Scheme of data management.
GENERAL METHODOLOGY

Data management and model preprocessing

Large amounts of data are required for large-scale groundwater flow and transport modelling when adopting a spatially distributed and physically consistent approach. Geological data such as maps, borehole data and logs, data from geophysical survey have to be used in an optimal way to create the spatial discretization. Parameters such as values of hydraulic conductivity, specific yield, and porosity of the different distinguished hydrological units are needed to constrain the calibration of the model. Historical values of piezometric levels and concentrations are needed for calibration and validation procedures. These data have been collected and introduced in a hydrogeological database (HYGES) coupled with a GIS system (ArcGIS®) (Radu et al., 2001). Based on queries and GIS pre-processing, data are transferred into the pre- and post-processor package Groundwater Modelling System (GMS®). A conceptual model was developed that consists in different layers of information built independently of any numerical and discretization choices. This information is transferred in a further step to the mesh used for the computation. This procedure allows new data to be easily introduced and processed. After computation, visualization of results can be performed using GMS, ArcGIS, or any other visualization tools for calibration, output production.

SPATIAL ISSUES

Division of the modelled area

The geology of the studied area shows a high degree of heterogeneity: Primary folded terrigene rocks (phyllite, quartzite, shale) are mainly found in the southern part of the basin, Primary folded and fractured limestone, sandstone and shale are found in the central zone and unfolded Secondary and Tertiary chalk, limestone, sandstone and sand in the northern and the southern parts of the basin. Such a geology generates drastically different hydrogeological conditions: less permeable formations, porous, fissured and karstic media, perched, unconfined and confined aquifers. Moreover, the degree of hydrogeological characterization can vary strongly from one part of the basin to another. Some sub-basins were investigated by previous studies involving shallow geophysical prospecting, boreholes, piezometric surveys, pumping tests, tracer tests, water balance. In other parts of the basin, even water balance studies at the catchment scale are lacking and general groundwater flow direction are unknown. To face this reality, two basic principles have been adopted. First, hydrogeologically independent sub-basins can be modelled independently. The Meuse Basin is accordingly subdivided in 14 hydrogeologically independent areas for which submodels are developed. Each submodel could be modelled independently of the others. Secondly, different ways of modelling are considered as a function of the investigation degree and data availability. Each submodel is thus further divided into subdomains, as a function of the local hydrogeological characteristics and the degree of hydrogeological
characterization. Exchange of water fluxes is made possible and simulated between these subdomains.

Spatial discretization

The discretization process consists of transforming a continuous space into a finite number of points for which a solution of the problem is computed (piezometric heads and concentration for groundwater flow and transport problem, respectively). In traditional local scale groundwater models, most of the elements having an influence on groundwater (geology, faults, wells, galleries, rivers) are taken into account in the discretization. At the scale of the River Meuse basin, the major constraint lies in optimizing the number of unknowns. To reach this goal, only large scale factors of heterogeneity are taken into account.

NUMERICAL DEVELOPMENT

Development of a mesh division module and a river module

A 3-D finite element-based spatial discretization is adopted for each submodel. The possible exchange of water between the subdomains is modelled by internal boundary conditions of three types. If the piezometric level can be considered as continuous between two subsequent subdomains, a Dirichlet boundary condition is prescribed. If the piezometric level cannot be considered as continuous, the two subdomains must exchange a water flux that is based on the piezometric level difference, and a Fourier boundary condition is prescribed. If there is no exchange of water, a no-flow boundary is prescribed. Numerically, the second and the third internal boundary condition require the unknowns on the boundary to be duplicated. So, in practice, the nodes of the arc representing the limit between these subdomains have to be doubled (Fig. 3). For this operation, a mesh division module has been developed. Using polygons for representing the subdomains, it is allowed: (a) to define the type of internal boundary condition between subdomains; (b) to divide the original mesh into submeshes by doubling the boundary nodes; and (c) to renumber the elements and the nodes for obtaining a continuous numbering in each submesh. Subdomains and internal boundary conditions can also be useful to represent two aquifers separated by a thin, less permeable layer (aquitard). Each aquifer becomes a subdomain and the exchange of water through the thin less permeable layer is represented by the Fourier internal boundary condition.

In hydrogeological models, rivers are often introduced through the use of Fourier boundary condition (i.e. the exchanged water flux is a function of the difference of water level in the river and the aquifer). At such a large scale, it is impossible to take the river network into account explicitly in the 3-D discretization process. To perform the mapping between the river network and the 3-D mesh, a river module has been developed to compute the length of the river segment crossing the upper face of each element $e_i$ and a conductance coefficient $\alpha_i$ allowing computing the water flux between the aquifer and the river.
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Fig. 3 Division of a global mesh into submeshes.

\[ Q_i = \alpha_i \left( h_{riv,i} - h_{aq,i} \right) = \frac{KL_l}{e} \left( h_{riv,i} - h_{aq,i} \right) \]

where \( Q_i \) is the water flux exchanged between the river and the aquifer through element \( e_i \) (\( \text{m}^3 \text{s}^{-1} \)), \( K \) the hydraulic conductivities of the river sediment (\( \text{m s}^{-1} \)), \( L_l \) the length of the river segment in element \( e_i \) (m), \( l \) the width of the river (m), \( e \) the thickness of the river sediment (m), \( h_{riv,i} \) the mean river water level in the element \( e_i \) (m), \( h_{aq,i} \) the groundwater level in the element \( e_i \) (m).

Adapted version of the SUFT3D code: Hybrid Finite Element Mixing Cell (HFEMC) method

The SUFT3D (Saturated Unsaturated Flow Transport 3D) is a Control Volume Finite Element (CVFE) based code developed by the Hydrogeology Group (Carabin et al., 1999; Brouyère, 2001). For the purpose of the PIRENE project, the code has been translated in Fortran 90, using dynamic allocation and progressive object-oriented coding (new Fortran derived-types such as subdomain, elements). The code has been organized in a way that allows parallel processing of the submodels and subdomains. For large-scale modelling purposes, a new flexible and modular method, the Hybrid Finite Element Mixing Cell (HFEMC) method, has been implemented. In each
Table 1 Solutions implemented in the code and restrictions of use.

<table>
<thead>
<tr>
<th>FLOW</th>
<th>TRANSPORT</th>
<th>Distributed Mixing Model</th>
<th>Advection–dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Linear Reservoir</td>
<td>OK</td>
<td>Not possible</td>
<td>Not possible</td>
</tr>
<tr>
<td>Distributed Linear Reservoir</td>
<td>OK</td>
<td>OK</td>
<td>Not possible</td>
</tr>
<tr>
<td>Flow in porous media</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>

Subdomain, different mathematical and numerical solutions of the groundwater flow and transport equation can be selected in function of the actual degree of knowledge of the hydrogeological conditions. Basic approaches such as (linear reservoir, distributed reservoir, mixing cells) can be used where the hydrogeological knowledge is limited. On the other hand, when it is possible, classical detailed and physically consistent solution based on the Darcy’s law and the advection–dispersion equation can be applied. The choice of a simplified solution for simulating the groundwater flow conditions implies to choose also a simplified method for solving the transport problem (Table 1).

EXAMPLE

Presently, the global Meuse model is under finalization. Results for the Geer sub-basin can be presented at this stage of the study. The Geer sub-basin (350 km²) is located in the north of Liège and was previously studied in details (Brouyère et al., 2003). Regarding geological and hydrogeological conditions, it can be considered as independent from the other parts of the Meuse Basin: according to the methodology described here above, it has been considered as a submodel. The aquifer consists mainly in chalk that can be divided in two formations separated by a thin layer of hardened-chalk. Such a system can be modelled by two interacting subdomains (Fig. 4). First results for groundwater flow computation using the physically consistent flow equation show relatively good results in terms of computed piezometric levels (Fig. 5).

![Fig. 4 Schematic cross-section in the Geer catchments and conceptual model. (where Q is the water flux exchange through the hard-chalk (m³ s⁻¹), K the hydraulic conductivity of the hard chalk (m s⁻¹), S the surface of the hard-chalk (m²), l the thickness of the hard-chalk layer (m) and ∆h the difference of x-water level between the two chalky layers (m)).](image-url)
CONCLUSIONS

A new methodology is proposed for large-scale groundwater flow and transport modelling. This methodology includes data management with GIS and a hydrogeological data base, a process of spatial discretization based on domain dividing into submodels and subdomains. For computation, a new modular and flexible HFEMC method has been implemented in the SUFT3D code. First results obtained for a small catchment seem to be promising but the methodology must still be tested on more complex example involving different hydrogeological conditions. The methodology developed allows to consider large basins in the modeling procedures. It is thus useful for providing regional results and trends to decision makers, for example in relation with the impact of climate change or changes in agricultural practices.

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REFERENCES