THREE LARGE SCALE GROUNDWATER MODELS AT THE LOWER RHINE – COUPLING AND DATA MANAGEMENT

BERNHARD BECKER[1], FELIX NOTERMANNS[1] AND JÜRGEN KÖNGETER[2]

[1] Research Engineer, Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Germany
[2] Professor, Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Germany
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Abstract

Three finite element groundwater models were developed to forecast the impact of draining measures from open pit mining in the Lower Rhine Brown Coal Mining Area on the groundwater balance. Different scenarios of resource management shall be simulated and evaluated. One major attitude is the evaluation of measures to protect wetlands, which are endangered by the mining drainage. The groundwater models represent the geological units of "Erftscholle", "Rurscholle", and "Venloer Scholle". In total, the three models cover an area of about 3070 square kilometers and take into account seven, eight, or nine aquifers, respectively, and their separating aquitards.

We introduce the models and show the challenges of large scale modeling: besides the multiple boundary conditions, drainage wells, infiltrations, and public and industrial withdrawal result in a large amount of different transient sources and sinks. Additionally, the modeling of the open pit mining process requires a transient behaviour of soil parameters.

The complex groundwater exchange rates between the three units used to be calculated in an iterative process of boundary condition adjustment. To improve modeling results and to avoid the time-consuming process of generating boundary conditions, the groundwater interchange now is realized by numerical coupling of the three models: finite beam elements are inserted between the boundary nodes and replace the exchange boundary conditions. Thus, the coupled models now are treated as one model. From the model coupling also further information about the interaction of the geological units are expected. We describe the coupling concept and show how the numerical coupling improves the model results.

The coupling induces various new data management tasks. Aspects of model handling and data management are presented: The combined usage of advanced visualisation tools, geographic information systems (GIS) and databases allows an efficient handling, updating and checking of the large amount of model input and output data.

Correspondence:
Bernhard Becker, Tel.: +49 241 80-25266, E-Mail: b.becker@iww.rwth-aachen.de

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1. Introduction

The open pit mines of the Lower Rhine Brown Coal Mining Area cover an operational area of 92.985 km^2. Mining depth is between 100 and 350 m (DEBRIV – Bundesverband Braunkohle, 2002). Figure 1 shows the three geological units (blocks) "Erftscholle", "Rurscholle" and "Venloer Scholle". Each unit contains one of the opencast pit mines "Inden", "Hambach", and "Garzweiler".

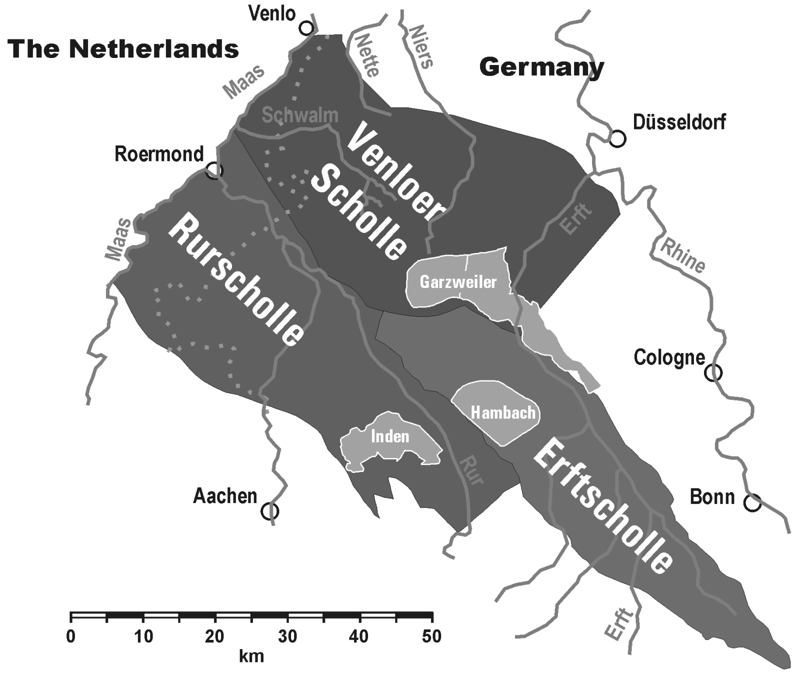

Figure 1. Overview of the modeling area with the geological units and open pit mines

The mining work requires the removal of groundwater from the deposit. To estimate the impact of draining on the groundwater level, three large scale transient finite element groundwater models for the "Erftscholle", the "Rurscholle" and the "Venloer Scholle" have been developed. In total, they cover a modeling area of 3070 km^2. With the three models questions about

- the impact of draining on the water balance,
- the effectivity of measures to protect wetlands,
- the time period to flood the relict lakes,
- the water level during the process of relict lake flooding,
- the balanced state, and the time of its achievement

can be answered.

In the groundwater model "Erftscholle", which covers an area of 820 km^2, eight aquifer layers and seven aquitards, which separate the aquifer layers, are implemented; "Venloer Scholle" covers 1040 km^2 and comprises seven aquifers and six aquitards, in the model "Rurscholle" (1210 km^2) nine aquifers and eight aquitards are included. The upper aquifers consist of gravel, the lower aquifers consist of sand, while the aquitards are clay or brown coal beds.

2. Numerical background

The basic equation for the model software FESSIM (RWTH, 2005) is the partial differential equation for transient flow through a saturated porous medium (equation 1, see Freeze & Cherry (1979)), which is spatially discretised by the finite element method (see Pelka, 1988).

$$S_\mathrm{S}\frac{\partial h}{\partial t} - \frac{\partial}{\partial x_i}\left(k_{ij}\frac{\partial h}{\partial x_j}\right) - q_\mathrm{QS}(t) = 0, \quad i,j = x,y,z \tag{1}$$

In this equation, h is the unknown waterlevel at the cartesian coordinate x_i at the time t, S_S describes the storage coefficient, k is the hydraulic conductivity, and q_QS is the source-and-sink-term. For aquifers, the equation is simplified to two-dimensional horizontal flow, while in aquitards only one-dimensional flow in vertical direction is assumed. Aquifer layers consist of a mesh of finite triangle elements, finite bar elements join the nodes of two aquifers and display the aquitards. The time discretisation is based on the Crank-Nicholson-scheme.

3. Coupling of the groundwater models

3.1. **Modeling block interaction.** Over the geological faults which separate the three blocks "Erftscholle", "Rurscholle" and "Venloer Scholle" groundwater interchange takes place. These faults are modeled with Dirichlet- and Neumann-boundary conditions. To reach consistency, the three interacting models are to be adjusted. E. g.: if in two models a Dirichlet boundary condition is set for one shared boundary point, the soil parameters have to be adjusted until both models yield the same amount of boundary flow at this point. This adjustment used to be done in an iterative process (Köngeter et al., 1998) and became necessary after every update of one model. To avoid the time consuming adjustment procedure, the three models were coupled numerically. Additionally, by modeling the flow paths at the separating geological faults shared by the sub-models, more knowledge about the interchange processes and interchange amounts shall be derived.

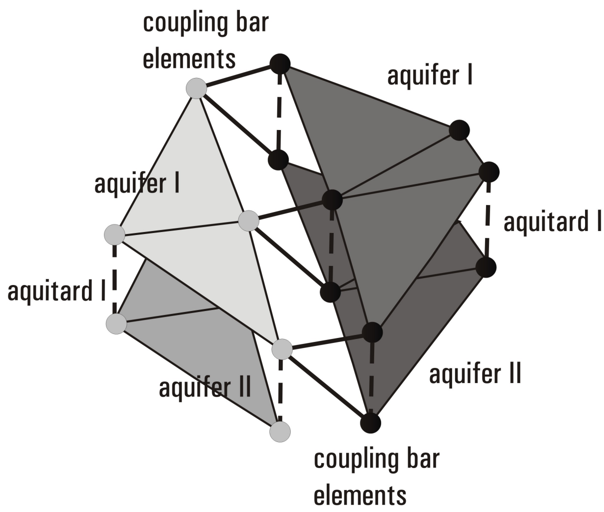

Figure 2. Meshes of two models coupled by finite bar elements.

The final model contains the meshes and the whole data basis of the three sub-models. The finite element meshes of two models are linked with finite bar elements. These idealized bar elements allow one-dimensional flow. Figure 2 shows a sample section of the meshes from two

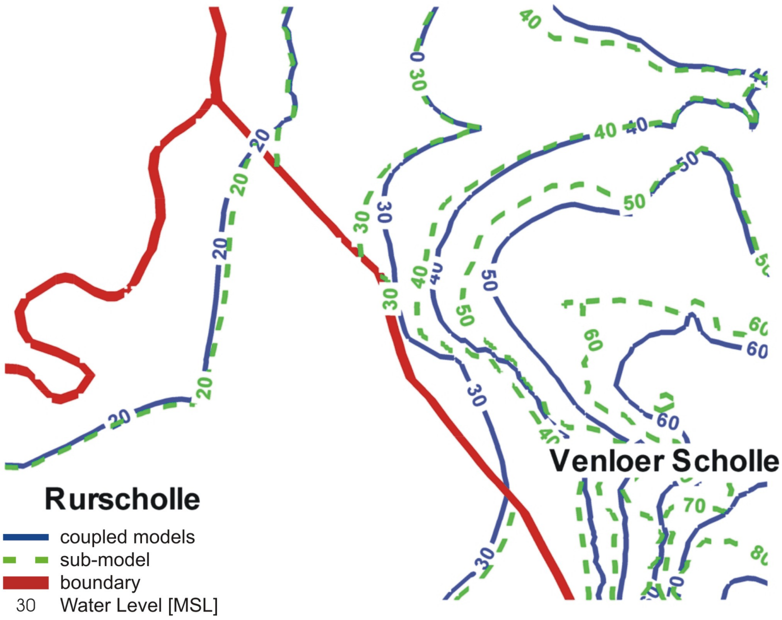

FIGURE 3. Isolines of the top aquifer water level: simulation results of the coupled model and the sub-models

models, each model has two aquifers (triangle elements) and one aquitard (vertical bar elements). In this case the top aquifer of the left model is joined with the top and the bottom aquifer of the right model. The coupled model is computed simultaneously, which ensures consistency in interchange flow. After coupling the three sub-models “Erftscholle”, “Rurscholle” and “Venloer Scholle” a multi-aquifer mesh with 124,512 nodes, 241,548 triangle elements (aquifers) and 109,421 bar elements (aquitards) results.

Interchange paths between the three geological units are defined by a steering committee including the contracting authority, members of environmental protection offices, geological state offices, water management companies, and the mining company.

The calibration of the new coupled model is done manually and focusses on the coupling bar elements which also contains the redefinition of interchange paths. New information about the interchange processes at the separating geological faults is implemented into the coupled model. This complicates the calibration process, because the interchange paths of the coupled model do not match those previously implemented into the sub-models as boundary conditions. Another problem are small differences in interchange amounts between the sub-models which remained from the iterative boundary condition adjustment. Additionally, the three models have different states of maintenance, respectively.

3.2. **Results.** Figure 3 shows the north-western part of the modeling area where the geological units “Rurscholle” and “Venloer Scholle” meet. The top aquifer of “Rurscholle” and “Venloer Scholle” is connected completely hydraulically. The isolines illustrate the computed waterlevel of the top aquifer. The green lines are the combined results of the two sub-models “Rurscholle” and “Venloer Scholle”. Although the boundary conditions were adjusted, the isolines still have interruptions at the shared boundary. The blue lines display the result of the coupled model, indicating that a continuous progression of isolines across the block boundary was achieved.

Modeling the separating geological faults with bar elements turns to be an appropriate way especially for areas with more complex interchange paths. In the vicinity of the city Niederzier (located near the mine "Hambach"), for example, 16 different aquifer connections are considered to be possible. The way the major interchange takes place is derived by adjusting the hydraulic conductivity of the coupling bar elements within the calibration.

4. Data management

4.1. **Introduction.** More than thousand drainage wells remove the groundwater from the open pit mine Hambach ("Erftscholle"), the well filters of most drainage wells are located in more than one aquifer. In the block unit of "Venloer Scholle" there are about 280 infiltration wells to protect wetlands in the catchment area of the rivers Schwalm and Nette. Groundwater withdrawal for public or industrial demand is to be considered at more than 1,500 points. The groundwater recharge is set transiently and the mining progress makes the change of soil parameters during simulation time necessary, because the mining dump has different properties to the undisturbed material. About 60 rivers and streams are modeled with the Cauchy boundary condition type. The large number of different objects makes the coupled model of "Erftscholle", "Rurscholle" and "Venloer Scholle" very complex, although the number of finite elements and mesh nodes is comparatively small. Time variation curves for the large number of objects are to be implemented, aligned or reimplemented, if new data is available. This requires a flexible data management system, because the raw data structure may differ for each group of objects. For the described model the data is administrated by application of a geographical information system (GIS) in combination with relational databases and SQL-functions (SQL: structured query language). In the next sections, aspects of preprocessing the raw data to model input data and postprocessing are described, which are completely separated from computation.

4.2. **Preprocessing.** As example for a preprocessing task the update of the model with new data for the withdrawal wells is described. It contains the following work steps:

- check of data for completeness and duplicates
- identification of relevant wells
- junction of the wells to spatial discretisation
- alignment of the withdrawal curves to the time discretisation
- verification of the new model input data

The raw data specifies the x-y-location of every withdrawal well, information about well filters and the withdrawal curves over time. Storing the data in a relational database allows to identify incomplete datasets and duplicates quickly with the grouping and sorting functions. Those wells, which are located in the modeling area, are identified with the adequate GIS-function. Additional criteria for relevant wells, for example a minimum average withdrawal amount, are applied via SQL queries. The GIS also provides functions to join the withdrawal wells to the adjacent mesh nodes (spatial discretisation). The work load for merging the transient curves to the time discretisation depends on the raw data structure. Sometimes small additional computer programs are necessary, especially to generate the different management scenarios. Because the large scale model has a coarse mesh, multiple well withdrawal curves are to be added up to one node withdrawal curve with SQL-functions.

Model input data is one eminent source of errors in the modeling process (Forkel, 2004). To minimize the error rates from model input data, it becomes very important to verify that the raw data is implemented correctly. Therefore, the work step results are permanently compared with the raw data. Counting, sorting, summarizing and visualising the data can be done very easily within the database, which assures a good verification quality.

Due to the model's space and time discretisation, on the way from raw data to model input data some details get lost. The way the data is preprocessed depends on the modeler's interpretation. Standard commercial software products are used to facilitate the frequent data exchange between the modeler, the data provider and the contracting authority to obtain transparency of the modeling process.

4.3. **Postprocessing.** Simulation results are presented as waterlevel isolines as shown in figure 3. They can be obtained from the software output by a finite element visualisation software. For further analysis the software output is transferred to a database. The postprocessing tools are customized permanently on the respective demand. For example, to calibrate the model, computed isolines are compared with reference isolines in the GIS. With the aid of database functions, measured hydrographic curves from observation points and the corresponding model output values are combined in diagrams. To balance the water flow over one special part of the block separating geological faults, queries were programmed to add up the flow through the coupling bar elements to be compared with estimated numbers.

5. Summary and Outlook

From the three finite element groundwater models for the hydrogeological blocks "Erftscholle", "Rurscholle" and "Venloer Scholle" a new model was created by coupling the three submodels numerically. The main intention was to avoid the time consuming process of adjusting boundary conditions at shared model boundaries.

During its lifetime the new coupled model has to be updated with new data continually. The large modeling area contains multiple objects to be considered in the model. To transform the raw data into model input data, database functions and a GIS are used. This allows to flexibly handle a large amount of data with different data structures and simplifies to verify that the raw data is preprocessed correctly. The database-GIS-combination is also used for special postprocessing tasks, for example for calibration work.

At present, the coupled model is calibrated. After completing the calibration, the model will be used to simulate different management strategies for the Lower Rhine Brown Coal Mining Area.

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