Specific demands and solutions regarding the FEFLOW large scale groundwater model "Erftscholle, Rurscholle and Venloer Scholle"

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ABSTRACT: Since 1984, the brown coal mining in the Rhenish Area (Germany) is accompanied by large scale groundwater modeling on behalf of the North-Rhine Westfalia State Agency for Nature, Environment and Consumer Protection (LANUV NRW). The intention for the model development was to assess the impact of mine drainage on the ground water balance. The modeling area covers the hydrogeological units "Erftscholle", "Rurscholle", and "Venloer Scholle" and extends to an area of about 3070 square kilometers with seven to nine aquifers and the separating aquitards in-between. The model is based on the groundwater flow simulation system FESSIM (Pelka, 1988), which solves the groundwater flow equation with the finite element method in 2 ½ spatial dimensions.
To reach compliance to other groundwater models maintained by the funding authority and with respect to future requirements, the FESSIM-model has been transferred to the FEFLOW groundwater simulation program. It was possible to take the mesh geometry from the FESSIM model directly to FEFLOW and enlarge it to three dimensions. However, because FESSIM has been developed for the purpose of large scale modeling with respect to open pit mine operation, some features offered by FESSIM are not available in FEFLOW or handled in a different way. Examples for such model objects and how they can be represented in FEFLOW are shown in this article.

INTRODUCTION

In the year 2006, 176.3 million tons of brown coal were mined in Germany, which gives brown coal a 42.5 % share in Germany's primary energy production (DEBRIV, 2007). In the Rhenish Area, which is located within the city-triangle of Aken, Dusseldorf and Cologne, the lignite open pit mines cover an operational area of about 90 km². The mining depth is between 40 and 350 m. Lignite is mined here with the bucket wheel excavator technology involving combinations of excavators, belt conveyor system and spreaders.
The basic prerequisite for the operation of opencast mines is the provision of stable slopes and load bearing working levels for the mining equipment. Ensuring such conditions, it is necessary to drain the water-bearing layers located over the coal (dewatering). For this purpose, wells are built to lower the groundwater level. Well galleries surrounding the working area catch the inflowing water from outside the borders of the operational area, while wells within the mine precede the working area in order to dry the beds. In the deep aquifers, wells are installed to reduce the hydraulic pressure on the working levels.
In view of the hydrogeological features, it is not possible to restrict the impact of the mine drainage on the operational area of the open pit mine. This makes several counter measures necessary, for example the stabilization of the groundwater level with infiltration wells in order to protect wetlands of ecological importance (DEBRIV, 1999). The brown coal extraction causes a mass deficit. Thus, usually the remaining relict pits are filled with water. In order to accelerate the relict lake filling and in order to assure stable slopes of the relict pits, the natural inflow is augmented with additional water. In the end, pit lakes become biotopes and local recreation areas (Forkel and Rinaldi, 2008).
To assess the impact of the drainage and to answer questions concerning the relict lake filling, three numerical large scale groundwater models representing the hydrogeological units (blocks) "Erftscholle" (Erft Terrain), "Rurscholle" (Rur Terrain), and "Venloer Scholle" (Venlo Terrain) in the lower Rhine region have been developed and maintained since 1984 till today on behalf of North-Rhine Westfalia State Agency for Nature, Environment and Consumer Protection (LANUV NRW). The models were used to evaluate different operational options by comparison of predictive results for different scenarios (Hüsener, 2008). The last major model update was the unification of the three groundwater models to the "ERV model" (Becker et al., 2008). This coupled site-specific model covers an area of about 3070 square kilometers and comprises between seven up to nine aquifers with aquitards in-

between. Figure 1 gives an overview of the modelling area divided into the three sub-models for each hydrogeological unit. The model area covers parts of the Niederrheinische Bucht, each sub-model contains one of the open pit mines Garzweiler, Hambach and Inden.

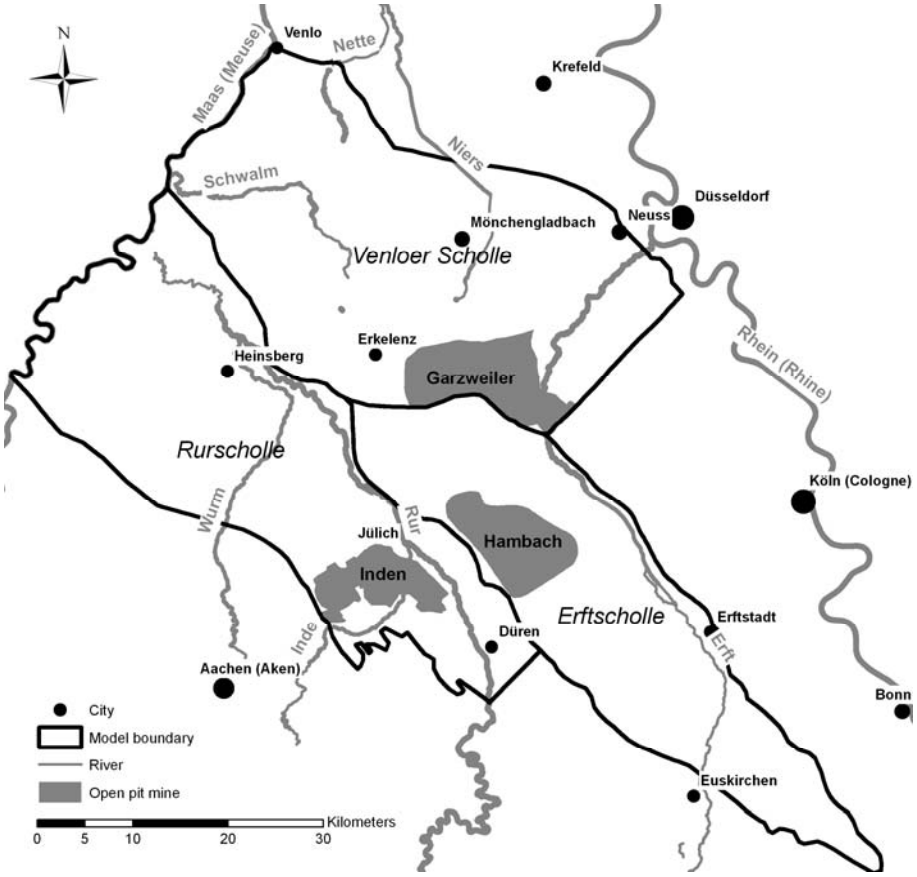

Figure 1: Modeling Area given by the hydrogeological units "Erftscholle", "Rurscholle" and "Venloer Scholle"; location of rivers, cities and open pit mines (after Becker et al., 2008)

While in the past the modelling work has been carried out by the RWTH Aachen University Institute of Hydraulic Engineering and Water Resources Management (IWW) as contractor, in future, the LANUV will take over the model and work with it. Because of the already existing experience with FEFLOW and the high quality support, in order to reach compliance to other groundwater models maintained by the funding authority and with respect to future requirements, for example mesh refinements, the groundwater simulation program FEFLOW has been chosen as generic model by LANUV. FESSIM has been designed for the particular task of mine operations. Some specific model objects offered by FESSIM are not available in FEFLOW. The Mesh transfer and examples for special model objects and how they can be treated in FEFLOW are described in the following section.

MODEL TRANSFER FROM FESSIM TO FEFLOW

Mesh transfer

The generic model (or computer code) FESSIM (Becker et al., 2007; Pelka, 1988) solves the equation of transient flow in porous media with a coupled two-dimesional/one-dimensional finite element scheme following Pinder and Frind (1972). For the aquifers, it is assumed that the flow within the aquifers is horizontal, thus it is modelled with two-dimensional triangle elements. One-dimensional finite elements model the vertical interchange between aquifers (see e. g. Bachmann et al., 2007) and between the hydrogeological units over the block boundaries (Becker et al., 2008). FEFLOW solves the flow equations with the finite element method, too, but in three dimensions. Figure 2 compares the two modelling approaches. For the model transfer, two-dimensional triangle elements had to be changed to three-dimensional elements, vertical oriented one-dimensional beam-elements became three-dimensional triangle elements as well.

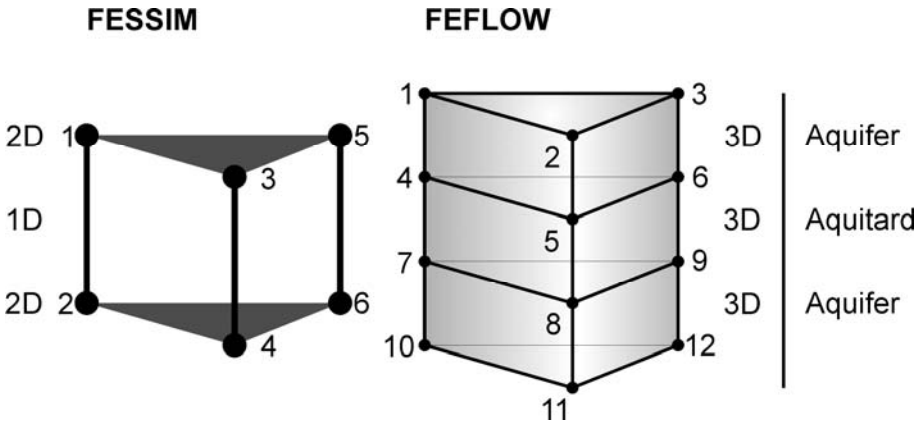

Figure 2: Example for a finite-element mesh structure from FESSIM and FEFLOW to model multilevel aquifer systems with number of dimensions and node numbers

The FESSIM mesh has been generated with the Triangle mesh generator (University of California at Berkeley, 2007). This mesh generator complies with FEFLOW, so the FESSIM mesh could be transferred by extracting the mesh from the first model aquifer and renumbering the nodes. The mesh was formatted according to the FEFLOW input data file structure (*.fem), imported into FEFLOW and enlarged to three dimensions with 17 layers via the FEFLOW graphical user interface. Node elevations and hydrogeological element parameters then were assigned according to the FESSIM model. In the FESSIM model, beam elements form the flow paths between the block boundaries and model the water interchange (Becker et al., 2008; Becker et al., 2006). In the FEFLOW model, the block interchange is represented by fracture elements (see Diersch, 2005). Table 1 summarizes the properties of the FESSIM and the FEFLOW model. While the FESSIM model has different numbers of model aquifers and model aquitards for each block within the modeling area, layers of the FEFLOW model without any physical representation in reality were assigned with idealized geometry information and thickness (“dummy-layers”). The new FEFLOW model and the FESSIM model have identical modelling areas and comprise the same aquifers and aquitards. A detailed description of the model transfer is given by Köngeter et al. (2007).

Table 1: model properties of the FESSIM model and the FEFLOW model. “e” indicates the model part covering the Erft terrain, “r” the Rur terrain and “v” the Venlo terrain.

model property	FESSIM model	FEFLOW model
number of nodes	124 512	281 862
number of triangle elements	241 548 (two-dimensional)	516 953 (three-dimensional)
beam elements for aquitards	108853	0
elements representing block interchange (beam or fracture elements)	515	515
model aquifers	8 (e), 9 (r), 7 (v)	9
model aquitards	7 (e), 8 (r), 6 (v)	8

Model objects

Introduction

Model objects represent a process or a device in the real world having influence on the groundwater hydrology, for example groundwater recharge (process) or a drainage well (device) withdrawing water from the ground. Most model objects are implemented into the groundwater model with boundary conditions. Because of the large number of model objects within the large scale model, the administration and the update of model data is a major challenge of large-scale groundwater modelling. For the FESSIM model, a data management system has been developed (Becker et al., 2006) which is based on MS Access and can be easily connected to the geographic information system ESRI ArcInfo. Because one important model output are in- or outflow amounts summarized for object groups for each block (balancing), this data management system has been adapted for the FEFLOW model, too. The connection between FEFLOW and the model database is realized with VisualBasic scripts and interface manager modules (IFM-modules). The IFM-modules write FEFLOW simulation results into tables to be imported easily into the model database.

The groundwater flow simulation program FESSIM has been developed for the purpose of large scale modeling with respect to open pit mine operation. Hence, special pit mine operation features are not available in FEFLOW or handled in a different way. The different treatment of specific model objects are discussed in the following paragraphs.

Rivers and streams

The interchange of an aquifer with a surface water body is often described by using a leakage boundary condition given by the two following equations (see e. g. Forkel, 2004, Diersch, 2005):

$$Q = c \cdot A \cdot \Delta h \quad (1)$$

$$\Delta h = h_R - h_G \quad (2)$$

$$c = k_F / d \quad (3)$$

Q denotes the flow from or to the river, c is the transfer parameter (FEFLOW) or leakage parameter (FESSIM) defined as the ratio from the conductivity k_F and the thickness d of a sediment layer, which separates the aquifer and the river. Usually, for inflow and for outflow, the leakage parameter is different due to riverbed colmation (Brunke and Gonser, 1997, Diersch, 2005). Δh is the head difference between river stage h_R and groundwater level h_G.

For the FESSIM model, the Leakage-Parameter and the contact area are defined by the user. In FEFLOW only the transfer parameter is a model parameter, while the contact area A is calculated from the mesh geometry. In a three-dimensional model, nodes with a transfer boundary condition are treated as vertices of a contact area polygon (Kernbach, 2007). This can be very helpful in small models, where a river or a stream dominates the groundwater flow (see e. g. Jansen, 2009), but for the large scale groundwater model described in this article, rivers and streams are modeled as line objects formed by a chain of nodes within the first slice. The calculation of contact areas from neighbored nodes often leads to undesired results: contact areas are overestimated in the vicinity of stream branches (Figure 3)and for solitaire nodes with a transfer boundary condition a contact area of zero value does not give any exchange quantity.

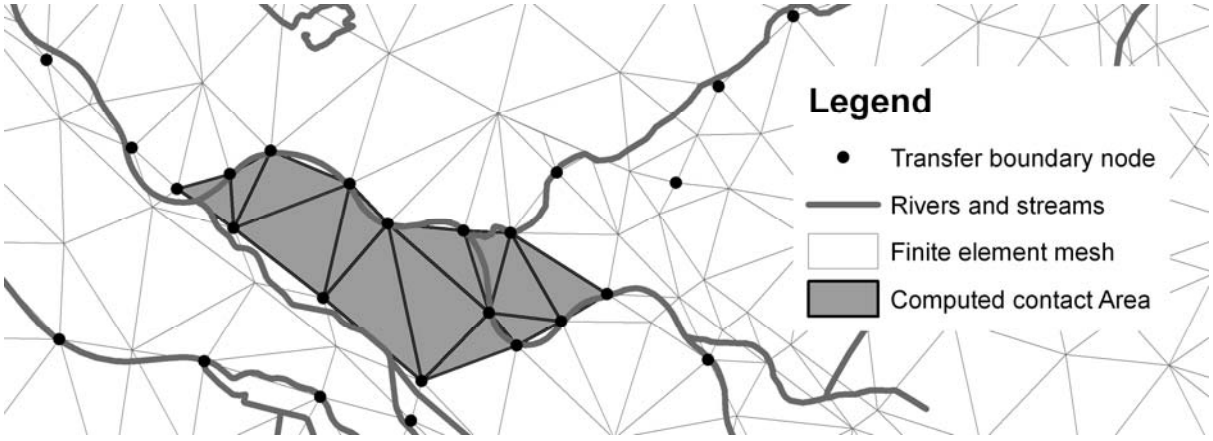

Figure 3: Transfer boundary nodes for rivers and streams and node connections for the FEFLOW contact area A calculation

To overcome this problem, the leakage boundary condition module leakGRM (Schüttrumpf and Becker, 2008) has been developed. The user defines node-based contact areas and leakage parameters in a table-structured text file. The general problem of implementing a leakage boundary condition into a groundwater flow program is, that the groundwater level h_G is initially unknown. FESSIM estimates the groundwater level from previous results and adjusts it within an iteration loop over the overall mass balance, while FEFLOW integrates the unknown groundwater level into the equation system. The latter method avoids time-consuming iterations, but, in case of flow direction change, the wrong transfer parameter c may be chosen (Nowack, 2007). The leakGRM module uses the first method, because at the moment, there is no IFM-function available which allows to modify the contact area related to a boundary condition node.

The exchange quantity with the river is calculated from the boundary condition value h_R and the previous result of h_G as first guess with equations 1 and 2 and implemented as source or sink (well boundary condition). With the resulting groundwater head, the quantity is calculated again and is again implemented as well boundary condition. This procedure is repeated until the change of quantity reaches a predefined error criterion. The leakage quantities and iteration steps can be printed into a text file to be checked by the user. The module leakGRM was tested by using a small three dimensional test model. The test-model consists of three slices, 128 triangle elements and 135 nodes. Figure 4 shows the resulting isolines of the calculated hydraulic heads and the position of the nodes assigned with a leakage boundary condition. Around the leakage nodes, the increase of the hydraulic head caused by the leakage boundary condition can be clearly observed. Without the leakGRM model, only the nodes 28, 29 and 25 who form vertices of a transfer area would cause a transfer rate.

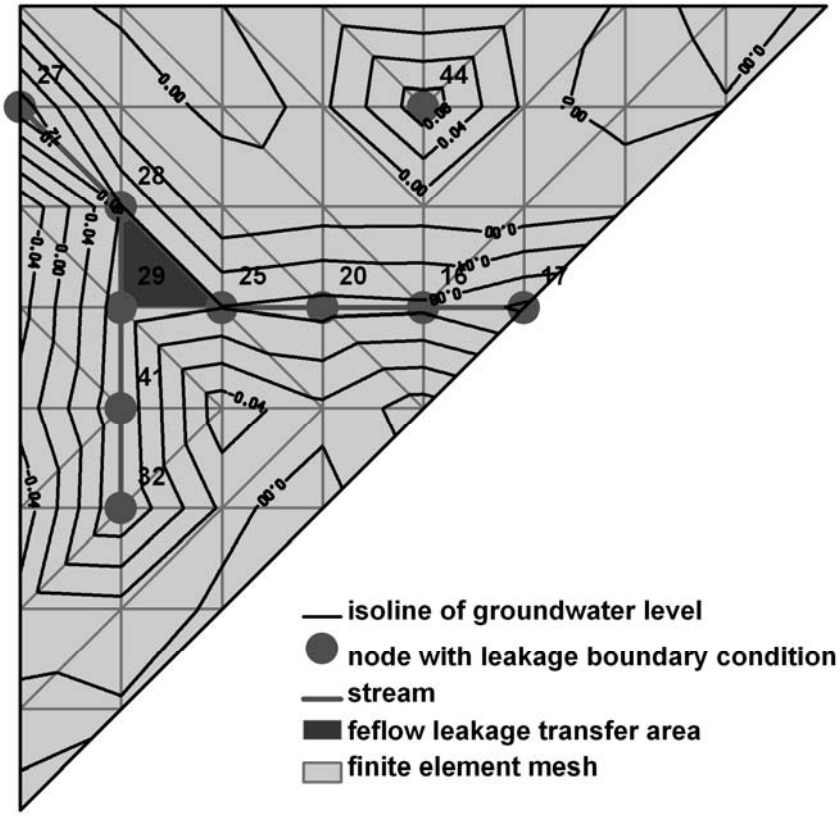

Figure 4: Test model with leakage nodes and computational results with the leakGRM module, presented as isolines of the hydraulic heads

Mine drainage wells and relict lake filling

Due to model-historical reasons, in each of the FESSIM-sub-models, the mine drainage used to be modeled with different types of boundary conditions:

- Erft terrain model: head boundary conditions
- Venloer terrain model: leakage boundary conditions
- Rur terrain model: source/sink type boundary conditions (Bachmann et al., 2007)

Each approach has its advantage or drawback (Romunde, 1995), the choice of a boundary condition type depends on the available data and the questions to be answered with the model (Klauder et al., 2008). During the transfer process, the opportunity has been taken to unify the approaches of modeling mine drainage for the entire modeling area. Hence, the modeling of the mine drainage is now realized by well boundary conditions. In case of nodes with boundary condition values different to a flow quantity, the simulation results of the FESSIM model were taken.

Another interesting model object group are the relict lake fillings. The first question is the required water amount. However, to stabilize the bank, surrounding well gallerys are installed around the relict lake. The well gallery withdraws water to make sure, that the hydraulic gradient is always directed

towards the bank and not towards the lake. Thus, a second question is, how much water has to be withdrawn from the bank in order to obtain a hydraulic gradient directed towards the bank. In FESSIM a modelling technique is implemented, to realize slope stabilisation during pit lake filling. For now FEFLOW does not provide such an approach, but the leakGRM module should be updated to ensure a hydraulic gradient from the pit lake towards the embankment.

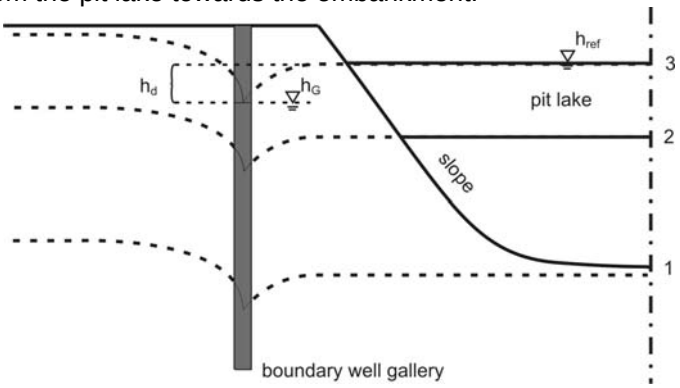

Figure 5: Boundary well gallery for pit lake slope stabilization. Around the pit lake, the groundwater level is fixed 10 m below the water level in the pit lake.

The modelling task is to let the lake water level follow the given hydrograph of relict lake water stage and at the same time to keep the groundwater level at the lake bank below the lake water level.
For the pit lake filling itself, the standard leakage boundary formulations given by equations 1, 2 and 3 can be used, where the leakage coefficient c becomes a parameter controlling the filling amount. The boundary condition value is given by the lake water level hydrograph. Nodes where boundary conditions to fill the pit lake are applied are called pit lake filling nodes. To model lake-like flow behaviour, the finite elements located within the pit lake get a hydraulic conductivity of k = 1m/s. Like FEFLOW, the generic model FESSIM allows to set transient material parameters. For the bank well gallery nodes, FESSIM provides a modified third order leakage boundary condition. Different to equation 1, the head difference depends on the water level of a reference node h_{ref} (equation 4). This value is initially unknown. h_{d} is a fixed head difference between the water level of a reference node h_{ref} and the lowered water level h_{G}. This water level difference ensures slope stability.

$$\mathrm{h_d = h_{ref} - h_G \geq 10\,m} \qquad (4)$$

For this value, $h_{\mathrm{d}} = 10$ m is set to fix the water level at the lake bank ten meters below the water level in the lake. This ensures a hydraulic gradient towards the embankment. Unknown values are h_{ref} and h_{G} (Figure 5). As first guess, these values are taken from the last computed time step and then it are adjusted within the iteration loop. Nodes with this kind of boundary condition are called bank gallery nodes. The withdrawal of gallery nodes is calculated with equation 2. For the Hambach open pit mine, the pit lake filling nodes, the bank gallery nodes and the reference nodes for the bank gallery nodes are shown in Figure 6. FEFLOW does not provide a boundary condition of this type. As a workaround for now, modelling results from the FESSIM model are implemented as well boundary conditions. Considering the relict lake filling taking place after the end of mine operations, for the present work step of calibration this workaround is satisfactory, but for future development it is planned to update the leakGRM module with an option for reference node.

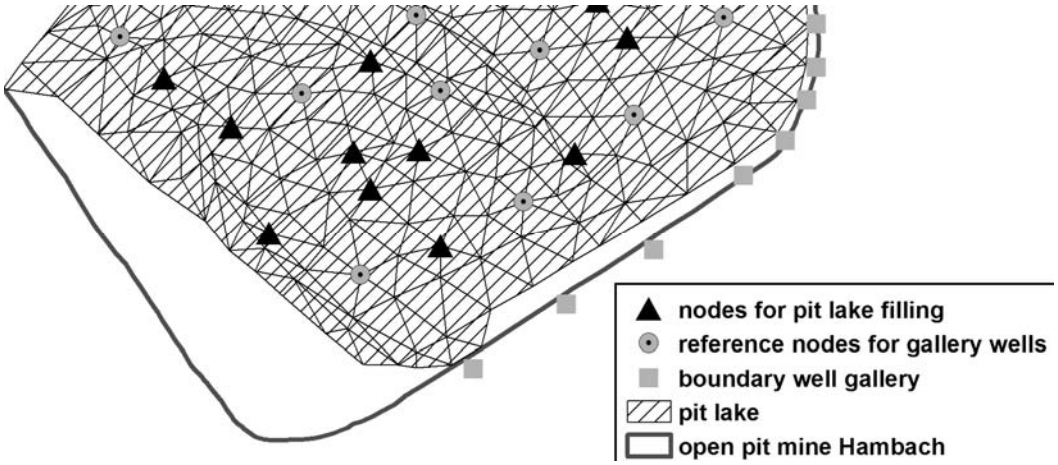

Figure 6: Boundary condition nodes for pit lake filling, boundary well gallery nodes, reference nodes, Hambach open pit mine operational area and pit lake elements

SUMMARY, CONCLUSION AND OUTLOOK

The FESSIM groundwater model, developed by the IWW, was transferred to the groundwater simulation program FEFLOW in order to reach compliance to other groundwater models maintained by the funding authority and in order to address of future requirements.
Because of the complexity and the large number of model objects in this groundwater model, the well-proven data management system based on GIS and databases was adapted to the new FEFLOW model.

The FESSIM model has been developed for the particular task of mine operations. Hence, some features offered by FESSIM are not available in FEFLOW. However, FEFLOW provides generally more features; e. g. flow and transport processes can be computed for unsaturated and variably saturated media based on the Richards flow equation. Furthermore, with the IFM it is possible to implement custom code for special model features. One example is the leakGRM module, which has been developed in order to model the interchange between a river and the groundwater body in a large scale groundwater model. Rivers and streams can now be modeled as line objects formed by a chain of nodes now. Considering the relict lake filling, it is planned to update the leakGRM module with an option for reference node.

The transfer to FEFLOW is a major change in the modelling concept. Thus, the model “Erftscholle, Rurscholle and Venloer Scholle” has to be calibrated again. Because the model parameters from the FESSIM model are expected to form a good initial basis for the calibration, within in the first calibration phase, the focus is on the parameters coming from the transfer from 2 ½ dimensions to the fully three-dimensional approach. New parameters are given by the hydraulic conductivities of the aquifers in vertical direction and the hydraulic conductivities of the aquitards in the horizontal layer.

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