Application of a numerical model to facilitate mine water management in large coal fields in Germany

Michael Eckart[1], Holger Kories[1], Rudolf Rengers[2] & Werner Unland[1]

[1]DMT – Deutsche Montan Technologie GmbH, Am Technologiepark 1, 45307 Essen, Germany, michael.eckart@dmt.de, holger.kories@dmt.de, werner.unland@dmt.de
[2]DSK – Deutsche Steinkohle AG, Shamrockring 1, 44623 Herne, Germany, rudolf.rengers@deutsche-steinkohle.de

Abstract

The Ruhr district and Saarland coal fields of Germany are due for significant changes in mine water management. The size of the areas affected and the complicated nature of the subject make it necessary to select a systematic numerical approach to represent the status quo, to develop alternative scenarios and to predict their respective consequences. A “box model” has been employed as the numerical tool of choice and has been further developed to cope with the features of extensively exploited large coal fields. The box model concept is presented and its further developments are described, including:

– increase of flexibility in 3D-structures
– variable connection of boxes
– introduction of turbulent and laminar flow functions and time-dependent conductance between boxes
– the combination of the box model with standard close to surface aquifer models
– the combination of the box model with a multi-component mass-transport-model.

The present status of applying the box model in the Saarland and Ruhr coal districts is provided. It is concluded that the box model has become a well suited forecast instrument to prepare alternative scenarios for economic and environmental decisions on mine water management.

1 Introduction

The Deutsche Steinkohle AG (DSK) operates underground coal mines in the Ruhr district and in the Saarland (Fig. 1). Since the 1960s the operation has been scaled down for economic reasons and subject to controversial political and socio-ecologic discussions. As a consequence, a number of mines had to be shut down and further mines will be forced into closure (depending on what will politically be defined as the “national energy reserve”). In contrast to this development mine water management is continued for practically all mines, closed or still active, due to specific hydrogeologic reasons and also due to former merger of coal mines resulting in numerous hydraulic connections between mine fields.

In the Ruhr coal mine district the underground mines developed from coal outcrops in the south and followed the general coal seam dipping down to more than 1,300 m towards the north where the Carboniferous strata are overlain by considerable overburden. Mines located south of the small river Emscher have all been closed. A number of shafts, however, are still kept open to facilitate operation of several underground pumping stations. The system of mine water pumping stations allows removal of mine water from moderate depths before it otherwise could penetrate into the deeper active mining area further north. Annually, an average total of about 95 million m^3 of mine water is pumped in the Ruhr mine district. With the decreasing number of active coal mines the increasing cost burden requires an ongoing optimization of the mine water management system.

In the Saarland coal mine district the economic development is comparable, while the geological and hydrogeological conditions differ. As an additional constraint, the Saarland coal mines at the south and southwest are more or less intensely connected with French coal mines of the Lorraine coal basin, where the last mine ceased production in April 2004. At present, about 23 million m^3 of mine water are pumped annually from the Saarland mines. Mine water management at the Saarland mines is known to be significantly affected should mine dewatering at the French side be shut down.

For both German coal mine districts significant changes in mine water management are anticipated and plans have to be prepared to allow management decisions between various alternatives. The size of the areas affected and the complicated nature of the subject make it necessary to select a systematic numerical approach to represent the status quo, to implement alternative scenarios and to predict their respective consequences. Alternatives for partial and complete flooding of mine systems have been considered using a numerical model to predict the impact and measures necessary to protect adjoining mine fields. The so called “box model” originally applied for simulation of groundwater rebound at underground uranium mines [Gatzweiler et al. 1997] was further developed to cope with the features of extensively exploited large coal fields. The principle nature of the box model had been presented at the IMWA 2000 meeting [Eckart and Unland 2000].

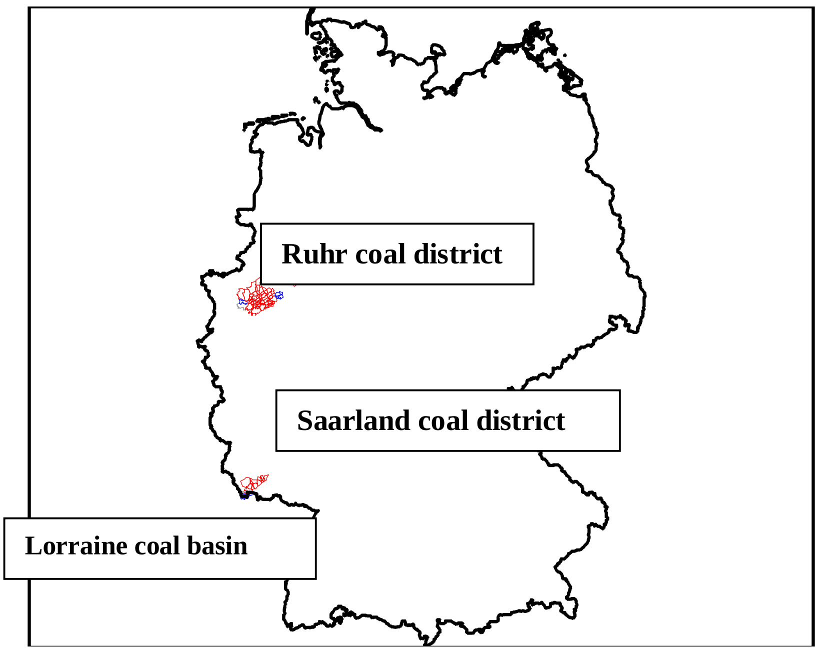

Fig. 1. Location map of coal districts

The concept of the box model is summarized in the following section. Further developments to match special requirements of large coal fields are described subsequently. The present and future applications in mine water management of DSK are discussed in the final sections of this paper.

2 Box model concept

Numerical models are applied in DSK mine water management where pure assessment by experience or comparison with similar events does not suffice. Well accepted models do exist for water management problems, e.g. seepage, surface run-off, groundwater flow and contaminant transport. Finite element and finite difference models are available for flow in porous and fractured media. However, these type of models encounter some numerical problems when mine cavities and hydraulic "short cuts" in form of drifts, shafts, goafs have to be considered. Generally, a tremendous "ballast" of numerous nodal points is needed to approximate a complicate geometry (Fig. 2). The available hydrogeological information from the mining activities relate mostly to a single mine unit (some square kilometers) or a level of an underground mine. Detailed data referring to a dense grid of data points are the exception.

Practical experience shows that the pressure (or hydraulic head) differences within a large coal mine field are close to zero in the horizontal direction. Hence, there is no good hydraulic reason to create a balance-unit smaller than a single mine unit. Additional elements would not increase the information about the hydraulic system. On the other hand, in the vertical direction the consideration of several levels is very important. Consequently, an appropriate numerical model has to consider a system of fairly large balance cells or compartments, the so called boxes. A box is assigned all important information and components of the mine field in the hydrogeological sense: storage volume, recharge, discharge and also information on mine-water-quality: pH, Eh, temperature, concentrations, stored contaminants, typical minerals etc..

A single box is not only a fictive balance unit, it is a picture of a real mine field and needs real geographic data: X-, Y – coordinates, bottom and top elevations.

The description of the flow process has to consider both geological hydraulic connections (porous aquifers) as well as hydraulic short cuts (roadways, drifts, shafts, faults, fractures etc.). The hydraulic connection between boxes is a very general parameter, which can be calculated from the permeability or the transmissivity under consideration of the geometry of the special water bearing unit. All detailed information can be expressed using a single transfer function, here called conductance, which is the functional key (complex) parameter for all hydraulic connections:

$$C = k_f \cdot A / s \qquad (1)$$

$$C = T \cdot M / s \qquad (2)$$

C = conductance [m²/s]
k_f = permeability [m/s]
s = distance between boxes or relevant distance for the special resistance to flow [m]
M = thickness of layer [m]
A = area through which water flows [m²] and
T = Transmissivity [m²/s].

The calculation of C, directly by division of flux and potential difference between mine fields, is very practicable when one is unable to describe the detailed geometry of hydraulic connections.

This conceptual approach of boxes and connections is easily understood and can be handled by mine personnel without any sophisticated qualification in computer handling and without any long term training. The geometries of boxes and hydraulic relevant structures are taken from regular mine survey maps or directly from digitized mine data using standard CAD and data handling software.

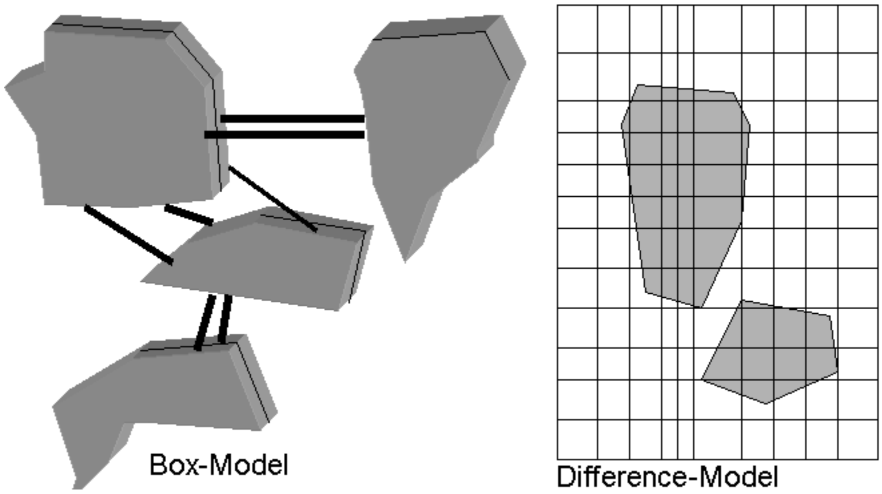

Fig. 2. Structure of Box- and Finite-Difference-Model

3 Further developments of the box model

The development of the box model for large underground coal fields was conducted with support from the North-Rhine Westphalia mine supervisory board and funds of the North-Rhine Westphalia ministry of economics and energy during the period from 2001 to 2003. Altogether, the last 4 years of application at the extensive DSK mine fields have caused considerable further developments and refinements to the box model, making it the tool of choice for any future planning and permitting process with reference to mine water management. The most important additional features since the first presentation at IMWA [Eckart and Unland 2000] are:

- increase of flexibility in 3D-structures (flexible number of boxes per slice)
- variable connection of boxes independently of model slice
- introduction of turbulent and laminar flow functions and time-dependent conductance between boxes
- the combination of the box model with standard close to surface aquifer models
- the combination of the box model with a multi-component mass-transport-model.

These features are briefly described below.

3.1 Flexibility of 3D-structures

As part of the development a user-friendly pre-processor has been created to handle the input of box geometries and hydraulically-relevant structures. In theory, the boxes can adopt any coherent form which can be circumvented by a ring polygon. In practice, the boxes are represented by a fairly irregular planar shape and regular vertical spacings. However, spacings are allowed to vary which is in particular very helpful when mining activities concentrated on some deeper levels or boxes at higher elevations are represented by overburden only. Hence, the contour spacings of boxes in the vertical direction and the number of boxes in the horizontal direction can vary. With the support of a CAD system and a suitable software package implementation of additional boxes is simple. Where required, modern CAD systems also help to overcome the discrepancies between finite element/finite difference grids and the box model concept by making the boxes very small. In the plan view shown in Fig. 3 the box model (thick black contours) is able to adopt the geometry of a FE grid (thin contours).

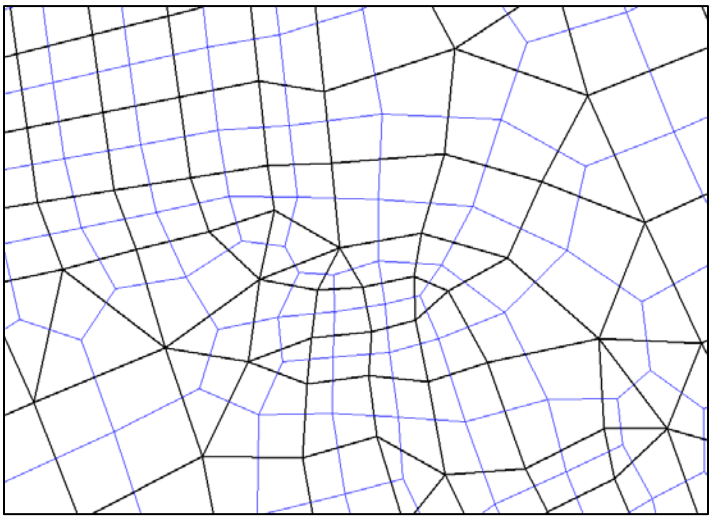

Fig. 3. Structure of a refined box model (thick lines) reflecting a FE grid (thin lines)

3.2 Connection of boxes

The water levels in flooded mine systems show considerable variations depending on the type and nature of their connection with other saturated parts of the underground. The simplest structure is a roadway excavated in stable country rock which defines very well decanting points between mine fields. Other features are observed in practice and some supposed decanting points proved to be not effective when water levels increased.

Connections between boxes are created by drawing a line between boxes, assigning the necessary coordinates and elevations and a value for the corresponding conductance. Boxes which are no direct neighbours can thus be connected.

All data, including the date the conductance value corresponds to, are stored within the box model. Even complicate connections consisting of drill holes, goaf or sections of collapsed drifts can be integrated (symbolically shown in Fig. 4).

To cope with the real world the conductance value for any connection has to be treated as a variable depending on flow rates and time. At a number of instances the hydraulic connections left between mine fields are through pipes or open drill holes where friction losses may become dominant. The numerical solutions for the box model include an algorithm for turbulent flow. Other connections between boxes proved to be time dependent due to ongoing settlements or clogging of former flow paths. This is a typical feature for extensive coal mine fields and a logarithmic equation has been developed varying conductance with time (Fig. 5).

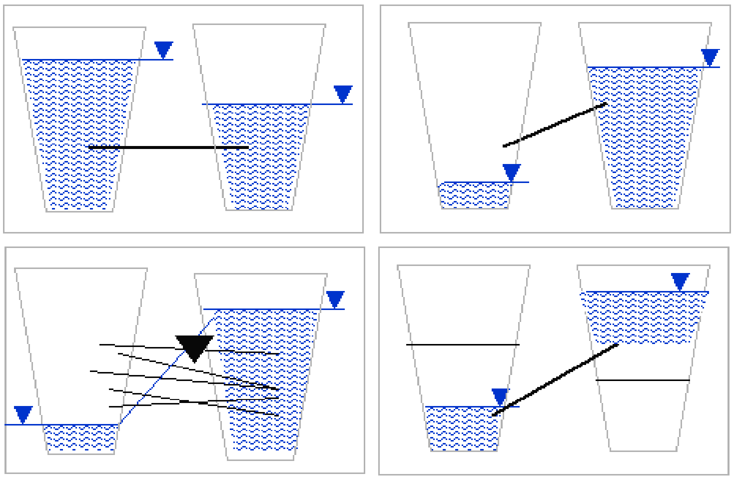

Fig. 4. Various types of connections between boxes

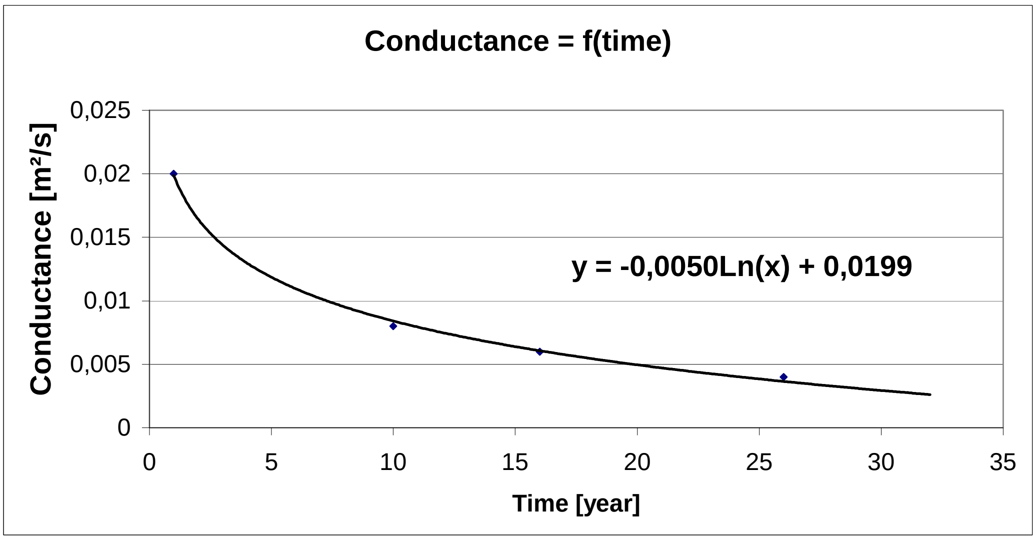

Fig. 5. Variation of conductance with time resulting from the calibration process for the Ruhr box model

3.3 Combination of the box model with a standard groundwater model

One of DMT's objectives is the development of a numerical tool to combine the box model with a standard FE-model for an aquifer close to surface. The combined numerical models allow simulation of the mine water situation as well as the groundwater situation regarding the mutual influence of these two dynamic systems. As described in section 3.1 and Fig. 3, the contours of a box can assume a variety of geometries, hence, a box can be defined by contours of any polygon shape and then it is possible to numerically treat this element like any other following the volume balance method. This way both types of models follow one concept and solutions can be obtained using a combined equation system.

A first set of trial runs was made using groundwater models completed by DMT in combination with the box model structure. The subsequent Figure 6 displays the superposition of a standard FE-groundwater model above a typical box model structure.

Following this concept, the uppermost layer represents a continuous aquifer system and contains considerably more elements than the two lower ones. A suitable pre-processor has been developed in order to automatically generate the geometric coupling using the contours of the underlying boxes as the starting point. The FE-model is based on parameters which are defined by the element's area and the nodal points of the FE-grid. Furthermore, the balance of volume flow is not strictly tied into volumes exchanged between single element areas but rather the result of integrating over the total area.

In the event the standard groundwater model is based on a finite difference approach, the solution is simplified since there is a common numerical solution for balancing the volume flow between elements. All parameters and variables are represented by the centre of each element and the volumes calculated flow across the element contours.

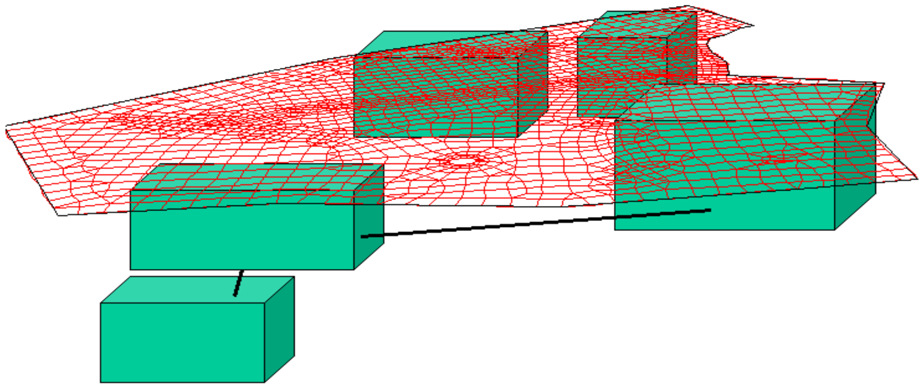

Fig. 6. Combination of box model with a FE groundwater model

3.4 Combination of the box model with a multi-component reactive model

For any meaningful planning and prognosis the mine water quality is to be taken into consideration. Therefore, the box model has been further developed to integrate a multi-component reactive transport model. Chemical reactions in the liquid phase do occur and make it impossible to simulate the transport of chemical components separately. To model the real world it is necessary to describe the transport in parallel for each box, at the same time interval. As a minimum the following components are required:

Kations: Ca, Fe, Mg, Na, K, Mn, Ra, Ba, Sr, Al, B

Anions: SO_4, CO_3, Cl, NO_3

(all in mg/L) and a balance concentration for the redox-state (OPV).

When quantifying these components it is possible to calculate the chemical equilibrium and to acquire such important information like the distribution of species, the Eh- and the pH-value. A numerical program similar to PHREEQE [Parkhurst et al. 1980] has been developed and directly integrated in the box model (An earlier approach to couple PHREEQC directly with the box model code as an external program resulted in intolerably slow execution rates).

The integration of the chemical reaction mechanisms yields totally different results from what would have been obtained by transport modeling and application of simple mixing formulas with sorption. A fairly drastic example is the mixing of water at one of the deep mines in the Ruhr district: incoming flow from the north contains high salt concentrations (Ba-concentrations > 2 mg/L) and meets incoming flow from the southern direction (low salt but relatively high sulphate concentration > 200 mg/L). The dominant reaction when mixing these waters (after 300 days in the following figure) is the precipitation of barite which actually has been observed (Fig. 7).

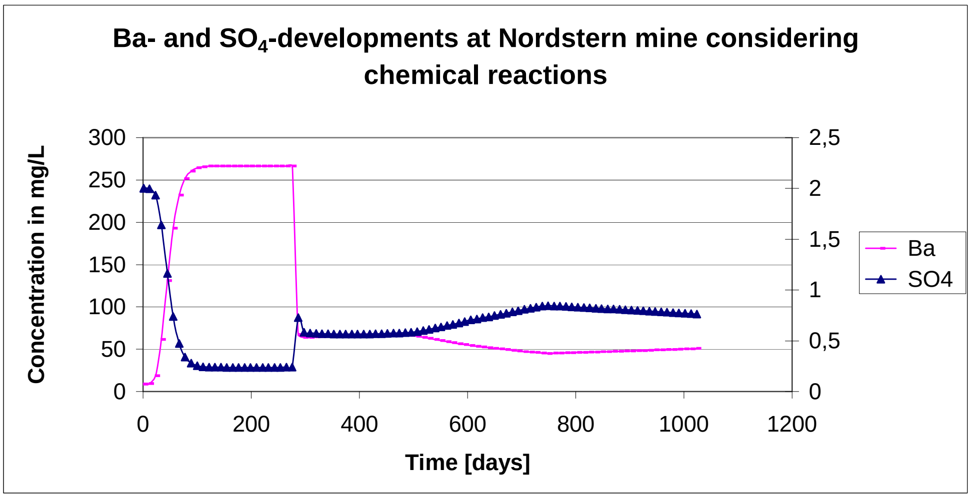

Fig. 7. Integration of chemical reactions in the box model: calculated development of SO_4 and Ba concentrations with precipitation at the Nordstern mine water pumping station

An excellent opportunity to calibrate the chemical reaction model derived from numerous chemical analysis data obtained when partially flooding a mine in the Ruhr coal district. The flushing process resulted in a typical sharp increase and subsequent exponential decline as shown for actual sulphate concentrations during a 4-year period in Fig. 8. It took about 4 to 5 exchanges of the pore volume until the sulphate concentration assumed again the previous mine water concentration of about 210 mg/L. In order to reflect this pattern in the numerical calculations a storage concept involving an active and a passive porosity was applied. “Active porosity” is understood as that storage volume where flow passes through directly (e.g. roadways, drifts, shafts) causing the initial sharp increase in concentration. “Passive porosity” is understood as the stagnant storage volume which is coupled by diffusion with the active porosity. Easily soluble components like iron, chloride and sulphate require storage within the passive porosity at fairly high concentration levels in order to fit the values observed at the pumping discharge. For components with limited solubility, e.g. gypsum, an additional solid phase can be taken into account which can be reactivated when concentration levels of the liquid phase drop below the solubility product. Fig. 8 shows the best fit of concentrations of sulphate calculated vs. those observed using this concept.

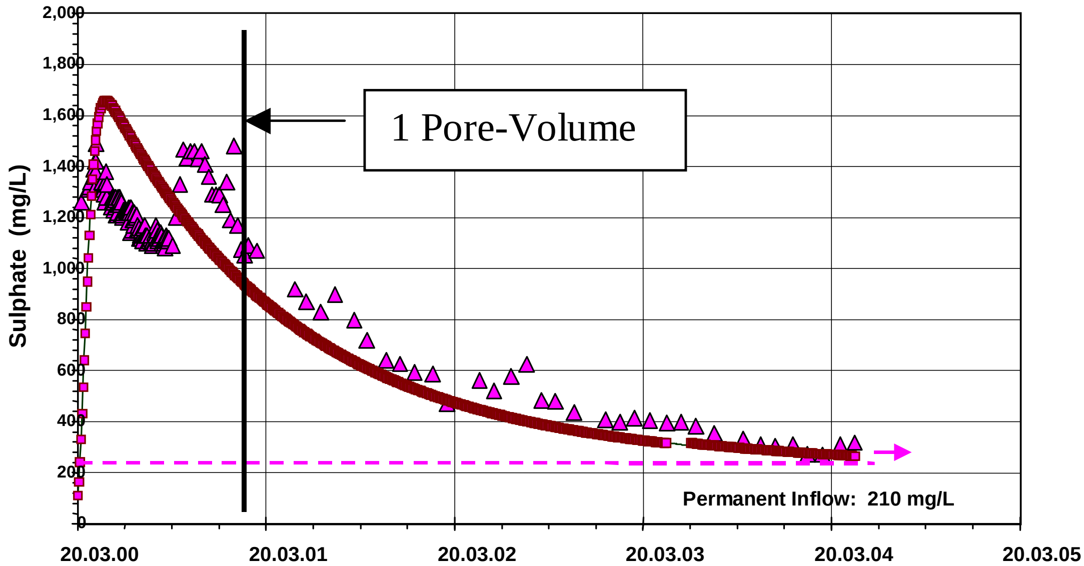

Fig. 8. Model fit for sulphate concentrations calculated (squares) vs. measured (triangles) using the concept of active and passive porosity on chemical reactions

4 Further application of the box model

The box model has been applied in a number of practical day to day problems as well as an indispensable planning tool for the mine water management at large coal fields. Some examples of ongoing activities are described in the following.

4.1 The Saarland box model

In the year 2003 a task force team of DSK and DMT started to set up the first box model for the entire Saarland coal district. With concrete plans to start the flooding activities on the French side of the coal basin the strategy was changed/forced to model the interaction between the mine fields in France and Germany. The mines are interconnected in a way that at the final stage of flooding a substantial part of the mine water would discharge at a low point (Gustav shaft) on the German mine field Warndt. Following questions are being addressed while preparing this paper and will be solved by means of an expanded Saarland box model including boxes for the French mine fields (Fig. 9):

- Which quantity of flow will finally discharge in Germany?
- How effective are the hydraulic short cuts in the old mine system? Several scenarios will be calculated and the box model will be adjusted in accordance with the actual monitoring data obtained during the initial stage of flooding. The impact could be a higher than expected final water level on the French side.
- What mine water quality can be expect at the Gustav shaft?
- How can the pressure difference be reduced at an underground dam protecting the ongoing mine operations on the German side? The present plans are to flood concurrently from both sides of the dam to the effect that at no time the pressure difference exceeds 30 bar. For this scenario additional water from the river Saar needs to be introduced at the north side of the dam (Box Luisenthal Fig. 10) to partially balance the rise in mine water levels at the south side (Box Warndt/Geislautern Fig. 10).

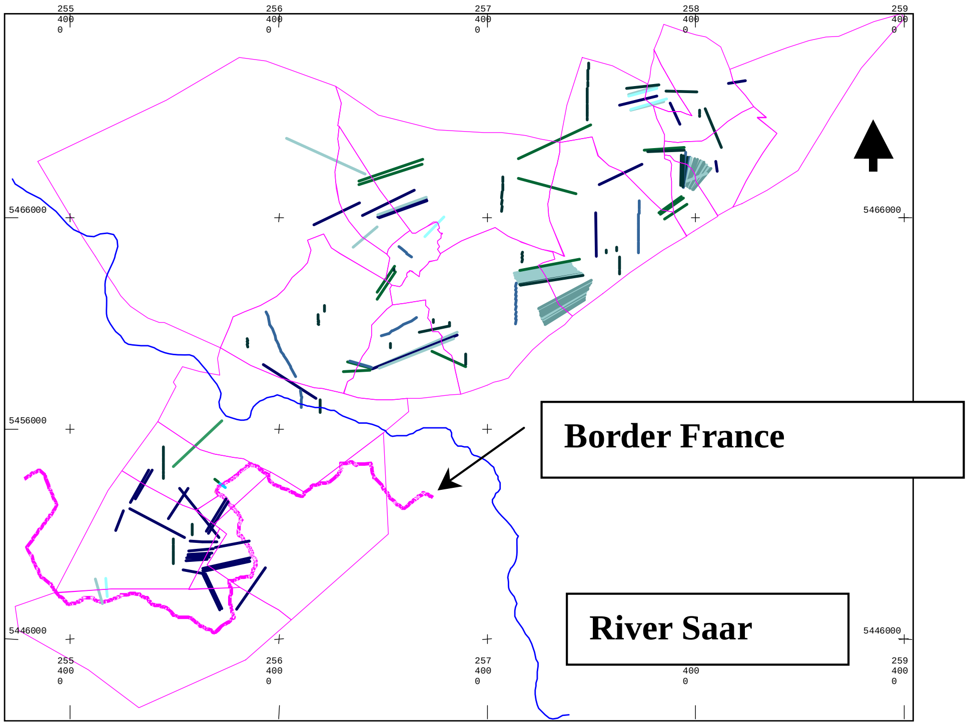

Fig. 9. Layout of the extended Saarland box model with digitized connections

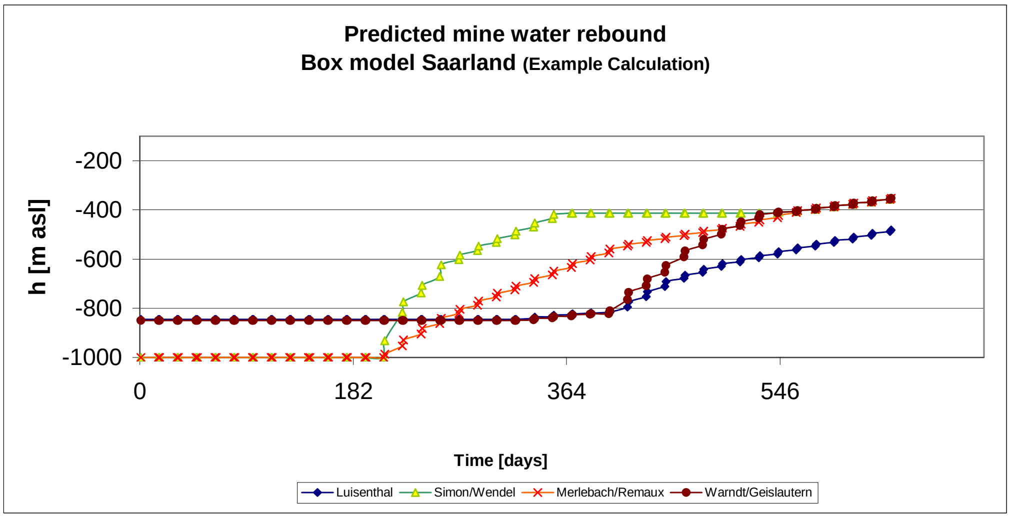

Fig. 10. Scenario of reducing the pressure difference on an underground dam by flooding with water of the river Saar

4.2 Mine water management in the Ruhr coal district

As described in section 1, the actual mine water management takes care that water in the closed mines of the south is kept down by pumping to facilitate operation further north. A box model has been developed to assist in optimizing the pumping operation in the central part of the Ruhr coal mine district which is represented by the abandoned Emscher-Mulde mine field and a central pumping station (former mine Zollverein).

The box model applied is a joint effort between DSK and DMT and after its calibration it can now be used to calculate various scenarios for future mine management. Considerable effort had to be invested in the determination of the residual void volume left underground. One important feature to approach the residual void volume and its spatial arrangement was the availability of a complete coal resource model (Fig. 11) in combination with coal production records available also from many old mines.

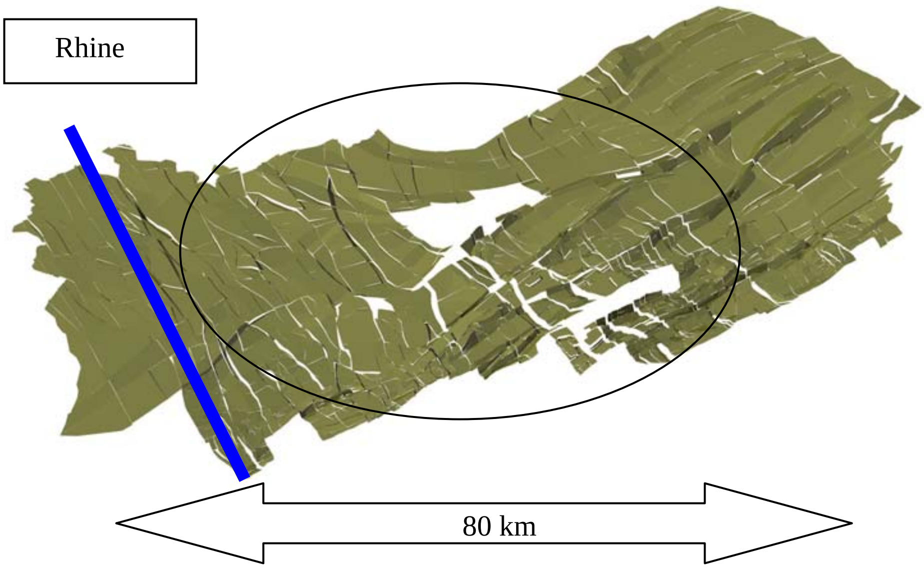

Fig. 11. Distribution of coal seam “Sonnenschein” within the Ruhr box model area (circled)

5 Conclusions

The box model has become an indispensable tool for planning of mine water management at the large coal fields in Germany. The progress made in recent years now allow the box model to be coupled with standard close to surface groundwater models and to combine it with a geochemical reaction model. The box model has become a well suited forecast instrument to prepare alternative scenarios for economic and environmental decisions on mine water management.

References

Eckart M., Unland W. (2000). Numerical Model for water management at complicated underground workings, 7th International Mine Water Association Congress, Ustron, Poland, Sept. 2000, 536-543

Gatzweiler, R., Hähne, R., Eckart, M., Meyer, J., and Snagowski, S. (1997). Prognosis of the flooding of uranium mining sites in east Germany with the help of numerical box-modeling, 6th Intern

Parkhurst, D.L. Thorstenson, D.C. Plummer, L.N. (1980). PHREEQE - a computer program for geochemical calculations; US Geological Survey Water-Resources Investigations 80-96, 216 p.