A METHOD TO FORECAST THE CONCENTRATION OF SALT IN WATER DRAINED OFF DEEP OPEN-CUT MINES

P. Nillert, VEB Geothermie Neubrandenburg
J. Tesch, VEB Hydrogeologie Nordhausen
GDR

ABSTRACT

A model-aided forecasting of measures affecting the groundwater balance in connection with mine drainage assumes particular importance in cases where the water contains a certain percentage of salt and is difficult to discharge without causing damage. Extensive hydrogeological explorations, tests, special gravimetric investigations, laboratory and isotope investigations have to be conducted before a hydrogeological model can be set up as a basis of simulations to be made for forecasting purposes. Highly complicated and intricate groundwater-flow and migration models can be broken down into detail models and then be studied, with certain schematization principles and adequate initial and marginal conditions observed. Afterwards, these detail model and their results are transformed into reduced block models and combined to form a block model system that enables investigations into alternatives and optimizations to be conducted within certain limits.

1. INTRODUCTION

The GDR is forced to open up deep open-cut mines in the current long-term planning period, because brown coal is its main energy source and the most important fuel for its power industry, another reason being the brown coal's regional distribution and the depths at which the seams are located. The GDR is a densely populated country, open cuts are often located near urban conglomerations, water resources are put to maximum use and some of the open-cut mines are under mutual effect. All of these facts give rise to specific problems which call for a general, economical solution. The need to drain off rather salty water is a factor complicating the opening up of deep open-cut mines.

2. PROBLEM IN HAND

The present study considers a case where, in order to secure the supply of power and make transport economical, a deep open-cut mine was to be opened up in an area

- which is characterized by a high rate of water-resource utilization, including
  - supply of water to major cities,
  - supply of water for industrial use,
  - supply of water to agriculture for irrigation and other purposes;

- which is sensitive to pollution control, including problems such as
  - the need to drain off highly mineralized water from the mine with as little damage as possible and with a view to observing river pollutant concentration limits,
  - a possible affection of crops in agriculture and forestry as a consequence of groundwater lowerings,
  - possible restrictions restrictions regarding the layout of the external spoil heaps;

- which, in its adjacent areas, is still unaffected by drainage due to open-cut mining;

- whose open-cut-mine boundary is tangent to a major river (about 25 m^3/s).

The host of problems arising from this situation had to be recognized at an early stage and adequately solved, with all those affected being included in the decision-making process. The resultant priority problems, which had to be approached in their complexity, included the following ones:

- The need to control the continuous non-stationary drainage process with groundwater lowerings down to 140m beneath the surface plus the need to constantly monitor mine waters at different locations and times, because their quality varies due to their differing origins;

- The loss of several big catchments of groundwater, with the geohydrodynamic effect on existing catchments to be identified as accurately as possible in order that relief measures may be taken or suitable mine water be transferred in time;

- The existence of salty groundwater in the area to be lowered and the danger of salty-water intrusions as a result of high differences in pressure in the drainage area, and the discharge of the minor-quality drainage water;

- The need to provide alternatives to water supply facilities which can no longer be used in full or in part. These solutions had to be economical and to consider an optimum use of the open-cut waters;

- The need to develop and design the technology for the drainage systems in the region concerned.

A model-aided forecasting of the changes in the water balance and the inevitable drainage measures as derived from the above tasks and problems is thus of special importance when it comes to making the fundamental economic decision in advance of the opening-up of the open-cut mine.

3. METHODOLOGY

The entire effort was a two-step operation:

- In the initial stage, exploratory work and measurements were conducted to identify the present state of the system as accurately as possible (geology, dynamics, salt distribution and potential sources), including a determination of the systems parameters characteristic of the flow processes.

- Then, forecasting investigations were conducted using models which simulated the dynamic changes to be expected on the basis of the parameters found and analyzed possible salt migration processes. In particular, the following questions were posed:

  + What is the percentage, in the drained-off water, of the different waters originating from different groundwater-bearing beds?

  + What is the percentage of waters from different water-bearing beds over time?

  + What are the effects of erosion, exarations or tectonically caused disturbances regarding salty-water rise accompanying a hydrodynamic relief?

  + What will be the quality of the drained-off water regarding its salt content?

4. HYDROGEOLOGICAL SITUATION IN THE AREA UNDER INVESTIGATION

The area under the hydrogeological investigation was about 700 km^2, with the shape and the size of the depression funnel viewed as being a function of the mining depths, the rate of advance and the overall configuration of the future open-cut mine. About 200 hydrogeological exploratory holes between 20 and 400m deep were made to get an understanding of the entire set of hydrogeological problems involved, with the results of the various stages of brown coal exploration included in the considerations. This was accompanied by pumping tests carried out in the various water-bearing beds of the area under review for the most varied purposes (including the determination of such parameters as geohydraulic aquifier parameters applying to the entire area, the quantification of silting-up parameters, and the identification of condition parameters). In addition, a geophysical logging was conducted for a direct and an indirect parameter determination.

Aside from the exploratory drilling, extensive special-type geophysical measurements were taken, including measurements using the seismic reflection and gravimetric methods to identify the structure and the facies of the complicated pre-Tertiary underground of the area concerned (determination of the boundaries of an anhydrite eminence and identification of the vertical range of Tertiary and pre-Tertiary strata strata series).

Horizontal and vertical groundwater observation networks were set up to determine the hydrodynamic conditions in the area as a basis for geohydrological computations of groundwater reserves and forecasts of the trend in the groundwater dynamics. The networks were used to obtain an aquifier-related picture of the flow conditions. The data obtained were then used to identify intra-aquifier relationships. Sandy and cohesive, organogenically enriched deposition series were mapped by distribution and thickness by means of special-type geoelectric and radiometric investigations of the bottom of flowing and stagnant waters in the area affected by the open-cut mine to be developed. Together with a great number of research institutions, data obtained was assessed as a basis for the extensive quantity-quality model investigations which had to be conducted.

The pre-Tertiary underground of the area concerned consists of Upper Cretaceous marlstones and, in the place where a Hercynian trend fault zone is tangent to the future open-cut mine, it is made up of Triassic and Jurassic limestone, marlstone and mudstone. A NW-to-SE lathshaped block structure is a striking feature together with salt structures in the southern part of the future open-cut mine at depths of more than 1,000m. Today's structural characteristics of the pre-Tertiary surface are assumed to be attributable mainly to the tectonic movements of the laramic phase at the turn from the Cretaceous to the Tertiary and the helokinesis which accompanied it or was activated by it.

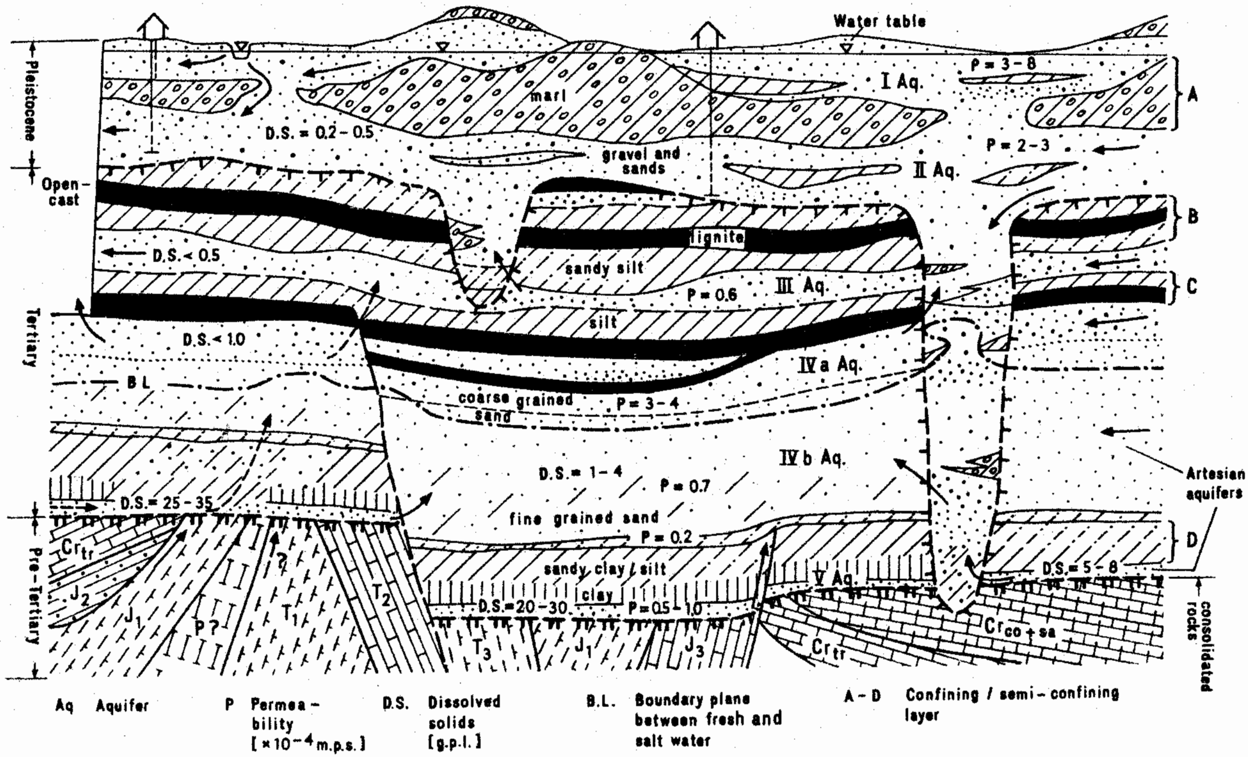
No clear stratigraphic and tectogenetic understanding has so far been obtained of the position of a massive anhydrite which was found to be located in a limited area at a depth of only 160m. It is underlain by a thick sequence of mineral salt and fault-bounded on all sides. It cannot be ruled out that it was halokinetically squeezed off from its root.

In the area concerned, the pre-Tertiary surface features throws of up to 80m reflecting a multi-phase differentiated reactivation of individual faults in a system of trough faults and horsts, which is about 3 to 5km wide. In addition, the salt pillow structures which date back to the turn from the Cretaceous to the Tertiary and are now found in the northern and southern parts of the area underwent a halokinetic development which resulted in the formation of a Tertiary depression taking the form of an intermediate salt pillow depression.

Five major groundwater-bearing beds were found to exist in the Quaternary and Tertiary strata series, each of which having a characteristic permeability behaviour (see Fig. 1).

Hydraulic connections of differing intensities were found to exist between the groundwater storeys. These connections are due to Pleistocene erosional channels (down to 200m), some of which date back to the pre-Tertiary. They are also due to exaration zones, locally heavy dislocations of glacigenous and/or geotectonic origin and to a permeability of the boulder

Figure 1: Schematic cross-section through the structure of the future lignite opencast with recent hydrodynamic and chemical situation



clay which is facially conditioned and becomes active this way. As a result, groundwater-bearing beds 1 through 4 were assigned to a uniform communication system which is operative over a large area. Various types of hydrogeological windows act as pressure compensation zones and may constitute potential pathways through which mineralized deep water may rise. Possible obstructions to communication depend upon the local facial character of the channel casts. Each of the five groundwater storeys was assigned its own groundwater dynamics. Except for the uncovered Quaternary water-bearing bed (1, in part 1 and 2), all other beds contain confined water, whereas at the centre of the depression (after conversion of all measured piezometric levels to a uniform density level) there is artesian water in the 4th and 5th groundwater storeys. Still the question remains unanswered where, to which extent and to which degree of mineralization, the existing fault system may force waters mineralized in the pre-Tertiary to rise into the overlying 5th groundwater-bearing bed or may be prompted to rise as a result of open-cut drainage.

An extensive and thorough interpretation of data of more than 1,000 water analyses and a large number of loggings conducted to determine the degree of mineralization enabled us to determine, in cooperation with various research institutes (which, among other things, conducted analyses using tritium, 14 C, deuterium, helium and U^{234}/U^{238}), the mineralization characterizing the individual groundwater storeys. The salt content was between 20 and 30 mg/kg in the 5th bed in the pre-Tertiary fault system, whereas it was an average 5 g/kg in the marginal zones. Analyses of water from the pre-Tertiary series of the Cenomanian and the Lias at depths between 250 and 450m at the margin of the area under review (that is, outside of the above-mentioned fault zone) found an average degree of mineralization of about 20 g/kg, ranging from 22 to 35 g/kg. The 4th groundwater storey is situated above the fifth storey, separated from the latter by Oligocene Rupelian layers which are 30 to 40m thick and impound the water. In the fourth storey, scattered increased-mineralization anomalies were found (about 5g/kg) reflecting the effect of tectonically exposed areas at geomorphologic depth, which resulted in structural disturbances of the Rupelian layers. In addition, there is, aside from hydrogeological windows originating from glacidynamic effects, a facies variation of the Rupelian causing the water-retaining effect to be lowered.

All of the above findings were used in the modelling and simulation of hydrogeological phenomena and processes so that the hydrodynamic processes caused by the mining activity could be forecast on a scientific basis. In particular, this included the need to forecast the probable salt content of the mine water as exactly as possible, because the discharge capacity of the receiving water was limited by the quality constraints imposed by existing and future plant supplying drinking water and water for industrial use. Accordingly, forecasting the amount and the quality of the open-cut-mine water to be drained became the ascending basis for decisions regarding the feasibility, cost and profitability of the open-cut mine that was to be opened up.

5. MODEL STUDY

It was not possible to adopt an integrated approach to the problem using, for example, a 3-D quantity-quality model, because

- a simulator which would have met the resultant requirements was unavailable;
- the data available allowed no such complicated modelling to be made.

Therefore, it was necessary to draw up a methodology for all the model studies and forecasts as early as in the exploratory stage. The methodology categorized all modelling into three stages featuring the following characteristics:

Stage 1: Basic and methodological model study; identification of analogy for certain partial problems; evaluation of the literature; operational updating; organizing the sequence of operations.

Stage 2: Detail investigations using various simulators and data processing; operational modifications as a result of detail findings.

Stage 3: Summirizing evaluation of detail-model findings using derived, reduced models; examination of alternatives and solution optimization by means of project-specific derived simulation model; recording of results; conclusions.

The major problems arising in stage 1 can be describing by posing the following questions:

a) What are the major targets of the modelling and evaluation operations and what is the data collection strategy to meet the formulated ends?

b) Which of the variables, interrelationships and partial aspects are instrumental to obtaining the desired results; which ones can be sidelined or defy interpretation?

c) What methods and simulators can be used to obtain the detailed information outlined under (b)? What are the basic and phenomenological investigations to be carried out to determine the effect of variables whose action is poorly understood so far?

d) Are the simulators as named under (c) available? Is the available computer capacity sufficient? Can maintenance personnel be contacted in case of problems or failures (software/hardware)? What operations can be performed by third parties on a contractual basis? Does the updated methodology allow deadlines and quality requirements to be met or does the plan need revision regarding input and results?

The three-stage methodology as outlined above constituted only a framework for the work to be carried out, with the operations accomplished determining the scope and type of the work to be done subsequently. A certain degree of flexibility regarding planning and organization is needed if such extensive and complex work is to be done successfully. Stage 2 constituted the model study proper. It was conducted using two sets of models - flow models and migration models which rested on a unified pattern. The overall task was broken down into detail tasks which were studied using detail models. In the process, initial and marginal conditions and the principles of schematization had to be harmonized for all detail models in order to retain their cohesion and allow detail-model findings to be processed by means of derived reduced block models.

In the case under review, finite-difference models were used to study flow problems. Regional groundwater dynamics, recent local peculiarities and open-cut drainage factors characterized by renewing, static and bank-filtered inflow, were studied by means of a regional, horizontal-plane model. A breakdown of the catchment area into inflow sectors, bearing in mind the deviating mineralization in the 4th groundwater-bearing bed, further categorized the open-cut waters. Several vertical-plane flow models simulated a number of typical geological intersections of the area under review and the open-cut mine. In this way, information was obtained regarding the distribution of the open-cut inflows over the individual groundwater-bearing beds, the maximum amount of bank filtrate originating from a near river, the amount of water flowing through the hydrogeological windows from one groundwater-bearing bed to another and the time it takes the mineral waters from the Rupelian exarations to flow to the open-cut mine.

Other model tests included those of the intensity of possible leakage of mineral waters from the pre-Tertiary or the Rupelian basic sands through exaration and erosion holes to the Rupelian layers in the fourth groundwater-bearing bed.

Finite-element models (FEM) were used to look into the details of salt migration. A number of vertical-plane models were conducted to investigate the following phenomena:

- The rise of salty water through the windows in the Rupelian layers and the process of migration up to the edge of the open-cut mine;
- Functions of salty-water concentration at the drainage wells as a function of operating time, exaration-to-mine distance, spring concentration and geological conditions;
- Description of the delayed release of salty water from the highly mineralized micaceous sands into the poorly mineralized quartz sands in the 4th groundwater-bearing bed and the resultant concentration over time.

Vertical rotation symmetric FEMs were used to conduct special-type migration studies of the dynamics of the geogenically conditioned salty-water intrusion at the wells, the protection of waterworks wells from contamination and a selective pumping of salty water.

All the studies so far described are suited to solve detail problems, obtain specific simulation results and identify the phenomenological properties of the flow and migration processes involved. At present, it is impossible to comprehensively analyze the problem using a single system-describing structural model involving deterministically distributed parameters. However, the reduction of all above-mentioned detail models and their input data and findings to derived block models in stage 3 was crowned with practical success. Simple and usable transformation functions were used for the purpose. As a result, the very complex system-describing detail models used in stage 2 were transformed into simple block models (or black-box models) and combined to form a comprehensive simulation model which was programmed within a very short time and allowed to conduct investigations in terms of water balance, drainage and hydrochemical problems associated with the opening-up of the open-cut mine. The forecasting period is up to 30 years, with input parameters being variable within the limits set by the detail models. All results are put out in the form of tables and diagrams as time-dependent functions (up to 57 per alternative), including the amount of water to be pumped out, the salty-water percentage, the bank-filtrate percentage, groundwater lowerings of regional or local importance, salt load from exarations, salt load from 4th-groundwater-bed water, the concentration of pumped-out water at various drainage sections in normal and selective drainage conditions.

A favourable, a probable and an unfavourable alternative was simulated and evaluated as a basis for decisions. All decisive variables were varied, considering the reliability and representativeness of the results of hydrogeological studies. A compressed compilation of results, part of which were transformed into rough approximation values by means of time-averaging, constituted the basis for the assessment and planning of the entire project. It should be noted that comprehensive stage-3 evaluation is feasible and, in fact, was efficiently conducted using personal computers, while the complicated stage-2 simulations required the use of high-performance personal computers or bigger computer machinery.

One of the advantages of the described methodology is that the stage-2 detail problems can be solved more or less simultaneously. Snags encountered regarding certain details can be overcome relatively independent of other problems whose solution is hardly affected. In addition, certain model investigations can start even before the end of the entire hydrogeological exploration, provided that the data required for a certain detail model is available.

It is an essential feature of the simulation and forecasting method described above that it allows complex hydrogeological or hydrotechnical processes to be studied and optimized solutions to be found using comparisons of alternatives. One such process is the drainage of a deep opne-out mine containing mineralized waters for which no uniform deterministic model can be established. All factors considered to be of importance were included in the study.