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GROUNDWATER FLOW SUBMODEL FOR THE ANALYSIS OF REGIONAL WATER POLICIES IN OPEN-PIT LIGNITE MINING AREAS

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ABSTRACT

The paper outlines the approach to groundwater flow submodels for the analysis of regional water policies in a test region in the German Democratic Republic located in the Lusatian Lignite District.

An introductory methodological overview on the use of comprehensive groundwater flow simulation models in lignite mining is given. For the test region the interactions between mine dewatering, remaining pit utilization, surface water/groundwater flow, etc. have been investigated by the help of such a groundwater flow model described in brief.

Based on these investigations submodels have been developed analysing the interrelationships between the state of the groundwater system and selected decisions on mine dewatering and water resources management. The methodological approach is described and illustrated with practical examples.

INTRODUCTION

Generally in lignite mining areas groundwater resources are the integrating element of the regional water resources system being effected by open-pit mining. Any model system for policy analysis of the economic water resources system in such areas has to be based on appropriated state functions for groundwater flow, so-called groundwater flow submodels. These functions should be simple enough for their integration in complex policy-oriented model systems and besides this they should reflect the reality for policy making sufficiently accurately.

The paper outlines the approach for the development of groundwater flow submodels for a Decision Support Model System for the analysis of regional water policies in a test region in the German Democratic Republic being located in the Lusatian Lignite District (compare Kaden et al. (1985 a,b)). For the determination of the groundwater flow process in this region with its numerous impacts varying in time and space a comprehensive groundwater flow simulation model has to be used. By means of such a model it is possible to investigate the influence of various impacts on the groundwater flow. It will be demonstrated how the comprehensive flow model was used for the estimation of reduced, simplified groundwater flow models.

GROUNDWATER FLOW SIMULATION MODELS

Methodological Overview

The development of mathematical models as a tool for the simulation of both prognostic, and epignostic states of groundwater systems due to human impacts has been forced for mining problems for two reasons.

First, construction and operation of mine drainage systems are highly expensive and their operation determines the safety of the mining. For their design groundwater flow models have been developed taking into account the complicated hydrogeological stratification, as well as the time-dependent mine drainage operation.

Second, as demonstrated by Kaden et al. (1985a), the mining causes manifold impacts on the socio-economic and water resources system in the mining regions. Due to mine drainage and mining, groundwater quantity and quality processes are changed drastically.

In the GDR, in the past decade a system of highly sophisticated conceptual models for groundwater management has been elaborated ,see Kaden and Luckner (1984); Kaden (1984). For modeling of groundwater quantity a set of models is available based on finite difference and finite elements methods. These models are formulated for the system descriptive mathematical model of saturated flow in porous media with distributed parameters. Generally, multi-layer horizontal plane flow models are used. Such models are available both for orthogonal (HOREGO) and for triangular finite elements grids (HOREG, HY75). They are especially designed for mining problems by consideration of mining specific boundary conditions.

Simulation models of environmental processes as groundwater flow form only an image of the reality with a certain accuracy. The accuracy of simulation results depends on the abstractions needed for model structuring and on the completeness and quality of input data. The lack of knowledge of processes and data in preliminary steps of analysis or in general requires the step by step improvement of the models and their data. For groundwater systems with their strong damping and phase shifting between impact on the system and observable system response this can well be done by comparing simulation results with real systems responses. Based on that in the GDR the methodology of Continuously Working Models has been developed organising information processing according to cybernetic principles, Peukert (1979), Peukert et al. (1982).

As a so-called Continuously Working Model (CWM) we understand a methodology and a model system for monitoring and controlling of long-term industrial and (or) economic impacts on groundwater resources. Generally the model system consists of two main parts:

- a specific data bank for information storing, and
- a simulation model for information processing.

By means of simulation models the influence of feasible control measures can be simulated before their implementation in practice. The sequence of data acquisition, data processing and simulation includes the feedback of information being active either already during the simulation run or in the phase of implementation. In such a way, the simulation is guaranteed to be based on the latest available data situation. In principle, the CWM is in opertion parallel in time, but discontinuously with the running original mining process. The steps of its operation depend on size and importance of the model.

Usually a hierarchical system of models is needed to meet different requirements in the spatial and temporal resolution. It is not possible to simulate both the regional groundwater flow process and the operation of single dewatering wells inclusive the frequency of submersible motor pumps during the whole dewatering time.

For groundwater management in lignite mining areas a 3-level hierarchy has proven to be suitable, as shown in Figure 1. Generally, this hierarchical system is structured in

- regional models (3rd level),
- open-pit mine models (2nd level), and
- operational models (1st level).

Regional models are mainly used for medium and long-term predictions for regional planning, water management and mining, open-pit mine models for medium-term predictions for planning and design of mine drainage measures and in some cases for water management, and operational models for short-term predictions for operational control of especially important parts of mine drainage systems.

These models are embedded in the hierarchical process of policy making, but it has to be pointed out that continuously working models cannot be called *decision models*. They are purely environmental models for the simulation of certain states. Management/technological alternatives have to be fixed exogenously for the simulation models. In the case of multiple objectives and decision makers that we have to deal with concerning the mining regions, the manual selection of efficient scenarios is very difficult and time as well as money consuming, or even impossible, Kaden and Luckner (1984). This problem can only be solved by means of a complex Decision Support Model System, Kaden et al. (1985a,b).

Such a Decision Support Model System for the analysis of long-term regional water policies in mining areas can be interpreted as a 4th level above the hierarchy of continuously working models (Figure 1). It will be applied for decision making of central and regional planning authorities. The lower level models are used for more detailed and specific investigations.

Groundwater Flow Model for the GDR Test Area

The test area has been characterized by Kaden et. al. (1985a,b), therefore, only some additional remarks will be given.

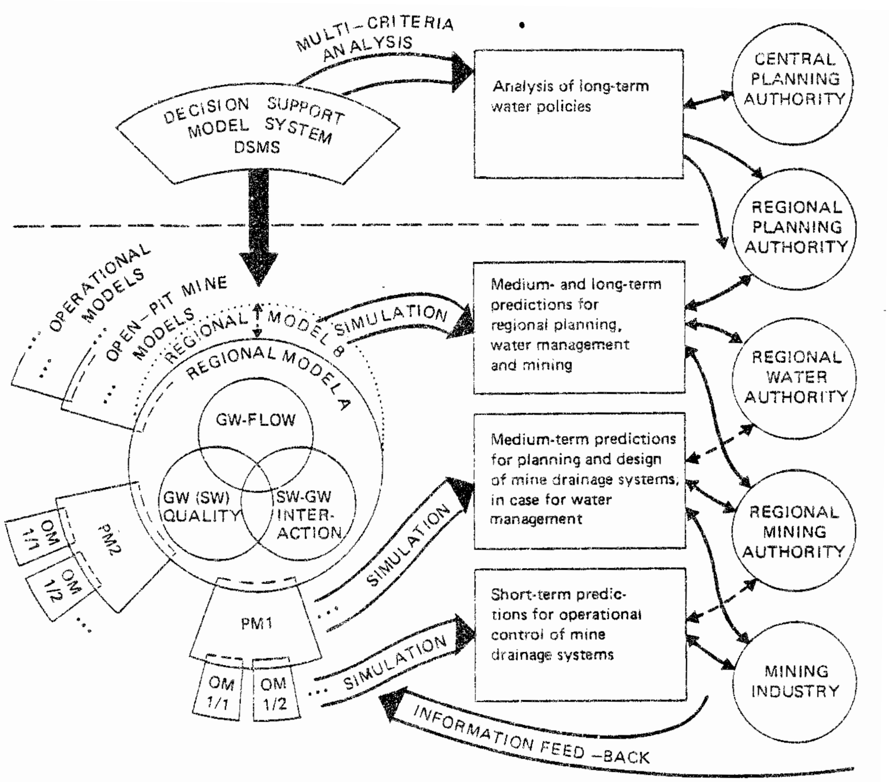


Figure 1: Hierarchy of continuously working models

The selected test area is located in the south-east of the German Democratic Republic in the Lusatian Lignite District, the most important and eldest lignite mining centre of our country. Since the middle of the 19th century open-pit lignite mines are in operation there.

Due to the dewatering measures of these mines the groundwater flow is strongly influenced. At present about 30 mines are in operation, numerous of these in immediate vicinity of each other. The cone-shaped groundwater depressions caused by the dewatering measures of these mines superimpose each other. The state of superposition is permanently changing in space and time due to the progress of mining. It results in some large cone-shaped groundwater depressions with extensions of more than 200 km^2. Consequently, municipal and industrial water supply plants as well as agricultural and forest areas are influenced and the water balance equilibrium between rivers or ponds and groundwater is changing.

After closing lignite mining in some mines, combined with the abandoning of dewatering measures the regional groundwater lowering process is additionally superimposed by groundwater rebound. This groundwater rebound process will be forced by newly formed remaining pits, frequently used as water reservoirs and for flood regulation by water management authorities.

The rise of the water table in the remaining pits up to the planned final water levels affects the amount of water pumpage of dewatering wells operating in the vicinity of these remaining pits. However, due to the rise of groundwater table often the negative effects caused by open-pit mine dewatering measures are compensated for several interest groups.

Other problems are related to changes of the catchment areas of aquifers and also rivers due to the dewatering measures, strongly affecting the run-off balance in mining regions.

In the test region the most important impacts on the groundwater flow system in mining areas are considered, Kaden et al. (1985b). In order to analyse the consequences of these impacts on groundwater flow it was necessary to use a comprehensive regional groundwater flow model.

The test region is a part of a mining area, for which a regional comprehensive continuously working model is already existent. This model is in operation in its third stage of improvement and complementation. For the simulation the two-dimensional non-steady model HOREGO, Gutt (1984), was chosen. The discretization of the flow field is done by a grid of orthogonal finite elements. These elements have been arranged in such a way that a minimum number of elements leads to an optimal adaptation of the internal and external boundary conditions. The finite elements grid for the regional continuously working model consists of about 1000 elements with an area between 1 and 4 km^2, Peukert et al. (1982). The model was calibrated for a period of 8 years. The groundwater flow process in the test region was well-known for this period due to sufficient measurements of the groundwater table and of water pumpage in the individual open-pit mines.

The calibration of the groundwater flow model was done by trial-and-error. Especially the transmissivity of the aquifer system and boundary conditions of the model have been varied. The calibration was stopped when a sufficient degree of concordance was obtained between measured values and simulated results in groundwater table and mine water pumpage.

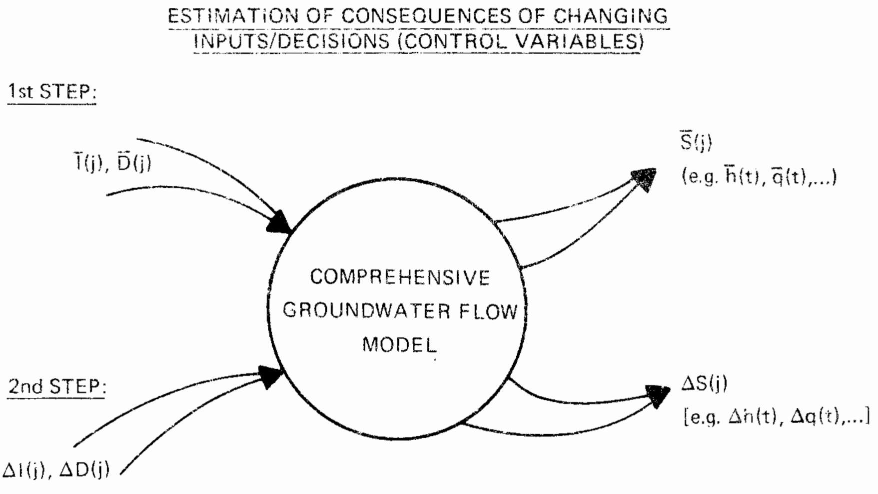
It is evident, the best done calibration cannot prevent from a decreasing reliability of simulation results with increasing time horizons for prediction because of uncertainties and inaccuracies of model data. For this reason continuously working models are calibrated again in later periods.

DEVELOPMENT OF REDUCED GROUNDWATER FLOW MODELS

It is out of question that a comprehensive flow model of the type described cannot be used as a submodel for groundwater flow in a complex Decision Support Model System. Simplified, reduced, groundwater flow models have to be developed for this purpose.

Such models are required for the estimation of interactions between mine dewatering, remaining pit utilization, surface water-groundwater flow, etc. They have to describe the interrelationships between the state of the groundwater system and selected decisions (control variables) affecting the system.

In developing these submodels (system-descriptive or state-transition functions) the main difficulties result from the nonlinearity of groundwater flow, especially from the strong changes of transmissivities in time. To overcome this problem, the following approach, as illustrated in Figure 2, may be used.



3rd STEP:

Superposition: $S(j) = \bar{S}(j) + \Sigma\,\Delta S(j, \Delta I(j)) + \Sigma\,\Delta S(j, \Delta D(j))$

$[\text{e.g. } h_{ag}(j) = \bar{h}_{ag}(j) + \Delta h_{ag}(j, \Delta tm_d(j)) + \Delta h_{ag}(j, \Delta h_p(j))]$

Figure 2: Development of groundwater flow submodels

In a first step the comprehensive groundwater flow model is applied for the simulation of an average systems behaviour $\bar{S}$ in each planning period j, caused by mean expected inputs $\bar{I}$ and decisions $\bar{D}$, considering the nonlinearity of the groundwater flow in the entire region. As a result we obtain expectation values for groundwater tables $\bar{h}(t)$, groundwater pumpages $\bar{q}(t)$ etc. as functions in time. We assumed the actual inputs I and decisions D to be close to the mean expected values $\bar{I}$ and $\bar{D}$.

In a second step the comprehensive groundwater flow model is used for the estimation of the consequences on the systems development ΔS, caused by changes of inputs ΔI or decisions ΔD.

We studied separately the consequences of:

- changes in the filling process of the remaining pit
- changes of the predewatering process in one of the mines

on the development of:
- the groundwater tables Δh_{ag} in an agricultural area
- the groundwater table Δh_e in an environmental protection area
- the groundwater table Δh_m in the immediate vicinity of wells for municipal water supply
- on the amount of groundwater pumpage Δq_m in some mines

- the bank filtration Δq_s for river sections.

By means of superposition of the average systems behaviour $\bar{S}$ and the independently studied consequences ΔS we get in a third step a usable model of the systems behaviour S, assuming that the error due to the nonlinearity would be small. This may be checked by the comprehensive groundwater flow model, too.

For the test area the simulation over the whole planning horizon of 50 years (divided in 10 planning periods) was carried out in 10 steps of 5 years. The simulation results (e.g. groundwater tables at the grid nodes, mine water pumpage, infiltration rates at nodes representing river sections, water table in the remaining pit) have been printed at the end of each year.

We had to realize about 35 simulation runs with a total CPU-time of about 35 hours of a middle-size main frame computer, similar to the IBM 370.

In the Figures 3-5 some selected simulation results for the development of submodels and for the estimation of the consequences of changes of some inputs and decisions (control variables) by use of the existing comprehensive regional groundwater flow model are demonstrated, see also Kaden et al. (1985a,b), especially Figure 1 in Kaden et al. (1985b).

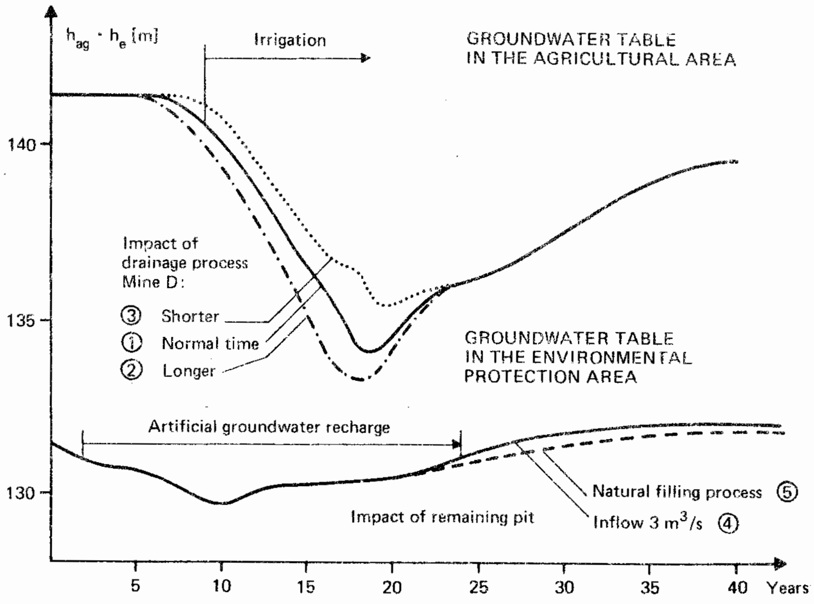


Figure 3: Influence functions for groundwater tables

In the upper part of Figure 3 the development of the groundwater table in an agricultural area is shown. We see that in general the groundwater table is lowering with the movements of mines closer to the agricultural area. The main influence results from mine D in this case. The process of groundwater rebound in this area is postponed due to the drainage measures of mine B. This can be recognized in the curve after the 25th year. At this time mine D is already far away from the agricultural area, but the dewatering systems of mine B are still operating and the groundwater rebound process is delayed.

Curve 1 shows the development of the groundwater table at normal predewatering conditions in mine D, that means 3 years in advance. Curve 2 holds if the start of the dewatering measures is two years earlier and curve 3 if this start is two years later. The coincidence of all three lines after the simulation year 25 elucidates once again the decreasing influence of mine D at the groundwater table in this area.

In the lower part of this figure the development of the groundwater table in an environmental protection area is shown influenced by the filling process in the neighbouring remaining pit. At the beginning the groundwater table development is influenced by the dewatering measures of the mines C and A. In the year 10 of simulation mine C is located in the closest distance from the environmental protection area. At the same time the dewatering measures of mine A are getting out of operation. The groundwater rebound in this region begins. In the 17th year of investigation starts the filling process in the newly formed remaining pit situated in the area of the former mine A. Curve 4 shows the development of the groundwater table if the remaining pit will be filled with water from the river (100 Mill. $m^3/a \approx 3\ m^3/s$)and curve 5 shows this development if the remaining pit will be filled only by inflow of natural groundwater. The impact of the filling process of the remaining pit on the development of the groundwater table in the environmental protection are strongly dampened because the distance is about 6 km.

In the lower part of Figure 3 the time period is marked for which an artificial groundwater recharge is necessary in the influenced area in order to prevent changes in the environmental protection area.

In the upper part of the Figure 4, the development of the exfiltration/infiltration behaviour of a river section is shown influenced by the filling process of the remaining pit. The exfiltration in this section is decreasing to about the 13th simulation year due to the dewatering measures of the neighbouring mines A and B. Because of closed dewatering of mine A near the year 10 a short-term increasing of the exfiltration rate can be recognized. In the year 15, the influence of mine B becomes significant resulting in infiltration in this river section. From the 20th year the influence of the filling process in the remaining pit is obviously superimposed by the slowly reduced influence of mine B.

In the lower part of this figure the development of the exfiltration/infiltration behaviour of another river section is shown influenced by the changing dewatering process of mine D.

In Figure 5 the development of a simplified model for the groundwater pumpage in mine D shall be demonstrated. As mentioned above, three functions are shown, curve 1 for common dewatering time, curve 2 2 years later ($\Delta tm_d = +2$) and curve 3 2 years earlier ($\Delta tm_d = -2$).

We recognize that the consequences of maximum values of water pumpage, caused by drastic changes of dewatering measures are dampened more or less depending on the size of the cone-shaped groundwater depression. It is evident that a longer predewatering time causes a larger cone-shaped groundwater depression than a shorter

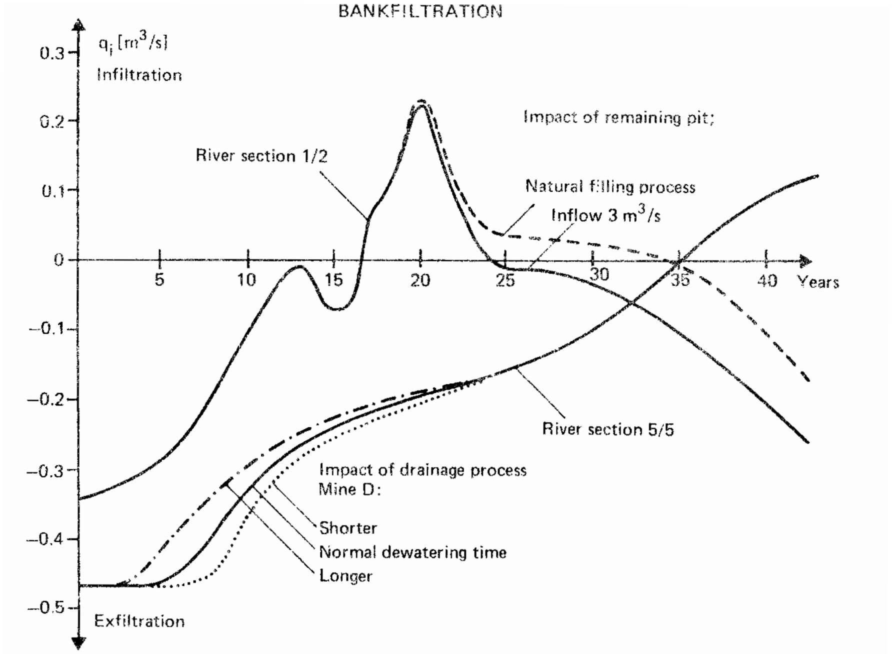


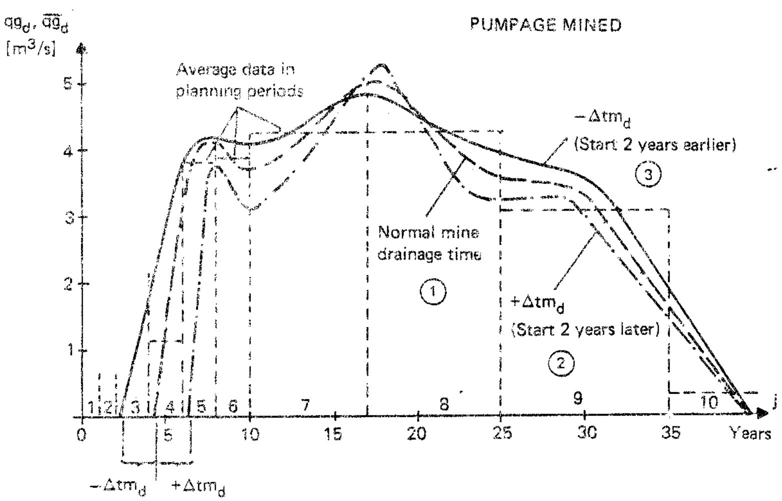
Figure 4: Influence functions for bank filtration

predewatering time and therefore the dampening is more or less strong.

In the lower part of this figure an analytic function is given, characterizing the development of water pumpage in mine D sufficiently accurately. The coefficients α_1 to α_3 can be taken from the table for each planning period j.

Altogether the following submodels (state function) were derived from the comprehensive groundwater flow model, using the same methodology:

- groundwater pumpage of all mines,
- raising process of the water level in the remaining pit,
- development of the groundwater level in an agricultural area,
- development of the groundwater level in an environmental protection area,
- development of the groundwater level in the vicinity of wells for municipal water supply,



$$qg_d(j) = a_1(j) + a_2(j) * \Delta tm_d + a_3(j) * \Delta tm_d^2$$

j	1	2	3	4	5	6	7	8	9	10
a_1	–	–	–	1.13	3.80	3.85	4.25	4.25	3.09	0.29
a_2	–	–	–.183	–.700	–.412	–.175	–.225	–.063	–.128	–.023
a_3	–	–	.092	.068	–.131	–.013	–.013	–.019	–.011	–.003

BOUNDS. – 2 YEARS $\leq \Delta tm_d \leq$ +2 YEARS

Figure 5: Submodel for groundwater pumpage

- development of infiltration/exfiltration behaviour for all river sections.

The proposed methodology should be generally applicable. Nevertheless, results of modeling based on such strongly simplified models should be verified using comprehensive flow models.

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