# Working Paper

## WATER POLICIES: REGIONS WITH OPEN-PIT LIGNITE MINING (INTRODUCTION TO THE IIASA STUDY)

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January 1985
WP-85-4

International Institute for Applied Systems Analysis
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# PREFACE

The "Regional Water Policies" project of IIASA focuses on economically developed regions where both groundwater and surface water are integrating elements of the environment. In these regions the multiplicity and the complex nature of the relations between water users and water subsystems pose problems to authorities that are responsible for guiding the regional development. The objective of the project is the elaboration of analytical methods and procedures that can assist the design and implementation of policies aimed at providing for the rational use of water and related resources, taking into account economic, environmental and institutional aspects.

In the course of the research, the project team is drawing from case studies when attempting to generalize and/or point out the dissimilarities between analysis procedures for regions with differing environmental and socioeconomic settings. Within the project, the first order differentiation between these settings has been made according to the dominating economic activity, reflecting that from a systems analytical point of view this will provide the most interesting type of material for a synthesizing analysis of the case studies.

This differentiation is reflected in the ongoing studies based on "experimental" regions. One of them is the Southern Peel region in the Netherlands, where agriculture is the dominating activity. Another region in the GDR is a typical open-cast mining area. This paper is concerned with the second study and the research on this study is a collaborative effort of the IIASA project team and of the Institute for Water Management, Berlin, the Institute for Lignite Mining Grossräschen, and the Dresden University of Technology, GDR. It is not a final report, rather it should be viewed as an outline of the approaches and models that are under implementation.

S. Orlovski
Project Leader
Regional Water Policies Project

# ABSTRACT

There is an apparent need for the analysis of long-term regional water policies to reconcile conflicting interests in regions with open-pit lignite mining. The most important interest groups in such regions are mining, municipal and industrial water supply, agriculture as well as the "environment". A scientifically sound and practically simple policy-oriented system of methods and computerized procedures has to be developed.

To develop such a system is part of the research work in the Regional Water Policies project carried out at the International Institute for Applied Systems Analysis (IIASA) in collaboration with research institutes in the German Democratic Republic, Poland, and in other countries as well. A test area that includes typical water-related elements of mining regions and significant conflicts and interest groups has been chosen.

The first stage in the analysis is oriented towards developing a scenario generating system as a tool to choose "good" policies from the regional point of view. Therefore a policy-oriented interactive decision support model system is under development, considering the dynamic, nonlinear and uncertain systems behaviour. It combines a model for multi-criteria analysis in planning periods with a simulation model for monthly systems behaviour. The paper outlines the methodological approach, describes the test region in the GDR, and the submodels for the test region.

# Content

# WATER POLICIES: REGIONS WITH OPEN-PIT LIGNITE MINING (INTRODUCTION TO THE IIASA STUDY)

S. Kaden[1], J. Hummel[2], L. Luckner[3], D. Peukert[2] and K. Tiemer[4]

## 1. Introduction

The Regional Water Policies project focuses on intensively developed regions where both groundwater and surface water are integrating elements of the environment. Regions with open-pit lignite mining are one of the conspicuous examples of complex interactions in socio-economic and environmental systems with special regard to groundwater. These problems concern especially countries in Central and Eastern Europe, in particular the GDR, FRG, CSSR, Poland, etc.

The GDR is the country with the greatest lignite production (almost one-third of the world production). More than 70% of the total output of primary energy is based on lignite extracted exclusively by open-pit mining. The annual output of lignite amounts to more than 250 million tons/annum. 300 million tons/annum are planned for 1985. Thereby, it is necessary to pump out 1.7 billion $m^3$/annum water for dewatering of the open-pit mines. For 1990, a coal output of about 300 million tons/annum is planned; the rate of mine water pumping is estimated at about 2 billion $m^3$/annum. This means that the amount of mine water is about 20% of the stable runoff of the whole country (Luckner et al., 1982). Consequently, the impact of mining upon water resources creates significant environmental and resource use conflicts between different users in such regions. The most important interest groups are mining, municipalities, industry, in many cases located downstream, and agriculture. Recreation and

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environmental protection are conflicting interests too. The conflicts will be demonstrated by some examples:

Since the mines are about 40 to 80 meters deep (sporadically 100m or more) in sandy aquifers large regional cone-shaped groundwater depressions are formed. These cones of depression are one of the main impacts on the environment in mining regions, resulting in water resources use conflicts.

The goal of the *mining industry* to satisfy the geostability of the open cast mines by lowering the groundwater table conflicts with the goals:

- to satisfy water demand in a certain quality and quantity for *municipal, industrial and agricultural* water supply
- to satisfy optimal soil-moisture conditions for plant growth by the help of capillary rise, irrigation and drainage.
- and to satisfy optimal ecological conditions for a worthy natural human environment.

The satisfaction of the municipal, industrial and agricultural water demand is a difficult problem in mining regions, because wells for groundwater extraction of water works fall often dry due to the groundwater depletion, little rivers fall dry or larger ones lose a part of their runoff by infiltration into the cone of depression. For the agricultural crop production difficulties arise from the lowering of the groundwater surface. In general, the moisture supply of the plants cannot be satisfied by capillary rise. To satisfy a stable crop production supplementary irrigation becomes necessary that means higher costs and a higher agricultural water demand in comparison with natural conditions.

Besides the mentioned water quantity problems in the mining areas significant water quality problems occur (Luckner and Hummel, 1982):

In lignite mining regions the groundwater quality and consequently the quality of mine drainage water is frequently strongly affected by the oxidation of ferrous minerals (e.g. pyrite) in the dewatered ground. In the cone of depression the overburden is aerated. With the natural groundwater recharge the oxidation products are flushed out, and the percolated water becomes very acid. Consequently the acidity of the groundwater increases. The same effect occurs during the groundwater rise after the closing of mines. Especially the acidity of groundwater in spoils is very high, if the geological formations have a low neutralisation capacity. In the GDR sulphate concentration in the groundwater of spoils greater than 700 mg/l have been estimated (Starke, 1980).

In mining areas many industrial activities, especially disposals of liquid and solid wastes are connected with serious contamination risks for groundwater and mine drainage water. Typical contaminants are heavy metals, organics (phenols etc.) and others. In such regions it is very difficult or even practically impossible to protect drinking water resources by protection zones.

Another risk is related to salt water intrusion or salt water upconing. In several lignite deposits in the GDR salt water is situated not deep below the lignite seams. Hence, pumpage causes the risk of salt water upconing. High salt content of mine drainage water causes many difficulties in water treatment technology. The discharge of the polluted mine water into streams may effect down-stream water yields significantly.

Another problem caused by mine drainage is the land subsidence resulting from groundwater lowering (Luckner 1983). In the post-mining time, when the groundwater table rises up to its former elevation, its depth under the soil surface might be less than in the pre-mining time, sometimes artificial drainage systems are necessary to protect municipalities and factories in such post-mining areas. Also, agricultural land and forest have to be drained in such districts frequently.

Last not least the ecological equilibrium is often disturbed by lowering the groundwater level. Especially old areas or park landscapes are in great danger when the groundwater table falls down.

The above-mentioned examples illustrate the significant conflicts between different interest groups caused by the impact of open-pit lignite mining on water resources. The activities of each of the interest groups modify more or less the water resources system and at the same time the conditions for resources use by other groups. It is also important that these activities might lead to a deterioration of the natural environment.

Due to the complexity of the socio-economic environmental processes in mining areas, the design of water management strategies and water use technologies as well as mine drainage can only be done properly based on appropriate mathematical models. For short-term control and medium-term water management as well as the design of drainage systems (local problem) qualified methods and models exist (Kaden and Luckner, 1984). Thereby, the complex interdependencies of the system are partly neglected. However, there is an apparent need for the development of methods and models supporting the *analysis and implementation* of long-term regional water policies, to reconcile the conflicting interests in open-pit lignite mining areas, to achieve a proper balance between economic welfare and the state of the environment.

This study is carried out in collaboration with research institutes in the GDR:

- Institute for Water Management, Berlin
- Institute for Lignite Mining, Grossräschen
- Dresden University of Technology, Water Sciences Division

and in Poland:

- Institute of Environmental Engineering, Technical University of Warsaw
- Institute of Automated Control, Technical University of Warsaw

Figure 1.1 gives an overview on the collaboration network.

The study is based on a test region in the GDR.

The paper consists of 3 major sections. In Section 2 an outline of the conceptual and methodological approach is given. After schematizing the policy-making process in mining regions our approach to the development of a *Decision Support Model System* is described. This model system is based on a *Planning Model* for multicriteria analysis and on a *Management Model* for stochastic systems simulation. An overview on the methods for the development of appropriate environmental and socio-economic submodels is given. Finally some aspects of the design of interactive software are discussed.

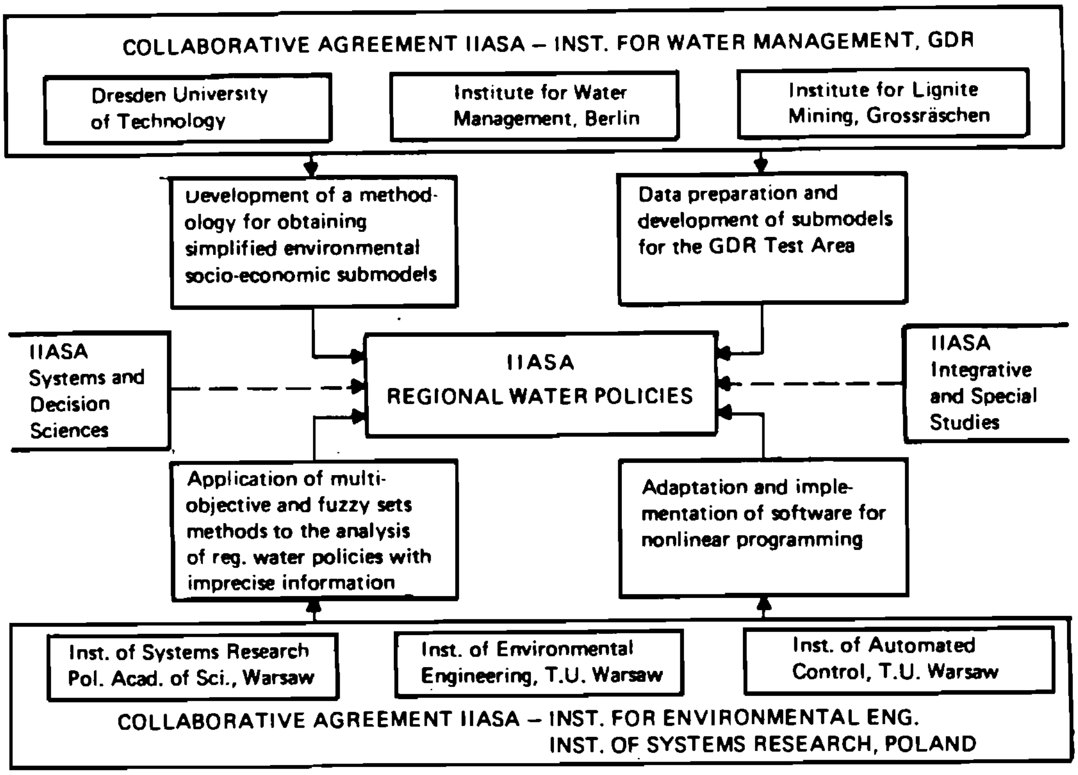


**Figure** 1.1: Collaboration network

In Section 3 the GDR Test Area is elucidated, Section 4 describes the mathematical model for this region.

The authors would like to acknowledge the contributions of scientists of the collaborating institutes, the methodological support of the project leader Dr. Sergei Orlovski, IIASA and the contributions of Dr. Kurt Fedra, IIASA in conceptualizing and preparation of the interactive software.

## 2. Methodological Approach

### 2.1. Hierarchical Policy Making Structure and Decomposition Analytical Approach

Within the Regional Water Policies project at IIASA, the regional systems under study are viewed to consist of two major subsystems—the environmental subsystem and the socio-economic subsystem (see Orlovski et al. 1984). Between and within both subsystems manifold interrelationships occur. Socio-economic activities result in strains on the environment, in our case in the depletion and pollution of water resources. On the other hand, the deterioration of the environmental subsystem leads to restrictions in its use as natural resources for the socio-economic development.

It is out of the scope and the possibilities of the study to consider all the complexity of the hierarchical policy making process related to regional water policies in mining areas. This policy making process includes in a centrally planned economic system as in the GDR all decision levels from the government (Central Planning Authority, different ministries), regional authorities (District Planning Authority, Regional Water Authority, etc.) up to the lowest level (mines, farms, municipal water supply agencies etc.) interacting directly with the water resources system. In the mining regions these interactions depend on the mining and mine drainage technology, on the demands and sources for water supply of different water users, on the agricultural land use practice and technologies, on the waste-disposal and waste water treatment technology and allocation etc. Orlovski et al. (1984) pointed out that, "The major fact is that in regional systems these local interactions are often focused on local goals and are not coordinated with each other." Undoubtedly, this is true to a certain extent although for centrally planned economic systems.

The upper level elements of the socio-economic system have preferences based on a national or regional point of view, above others related to the social welfare. Characteristic aspects are both, a high national income, and the preservation of the environment as an important social component. The upper level elements of the socio-economic system generally do not directly control the interactions of the lowest level users with the environment, but the have principal regulation power for influencing their behaviour using legislative, economic and/or other types of policies or mechanisms. Typical policies include imposing constraints on water usage and allocation of waste water (based on the water law of the GDR), various economic measures including investment, pricing, taxing, subsidizing and others.

Figure 2.1 gives a rough overview on the complex hierarchical structure of the socio-economic system under study.

Typical for a socio-economic system is its division in upper elements, representing national and regional perspectives, and lower elements — the water users. Obvsiously, a two-level representation of the system becomes a realistic assumption. Our analysis is based on the schematized policy-making system shown in Figure 2.2.

We assume a two-level system with a Central Planning Authority and Regional Authorities for mining, municipal and industrial water supply, agriculture and environmental protection. A "regional authority" represents both, the global interest of a sector of economy, and its regional interest. The Central Planning Authority represents global economic and social preferences.

For the long-term development of open-pit lignite mining areas two principle problems have to be solved:

1. *To find "good" long-term strategies oriented towards achieving a proper balance between both national and regional economic needs, regional social needs and the regional preservation of the environment.*

2. *To find and realize controlling policies in order to direct the regional development according to the estimated "good" long-term strategies.*

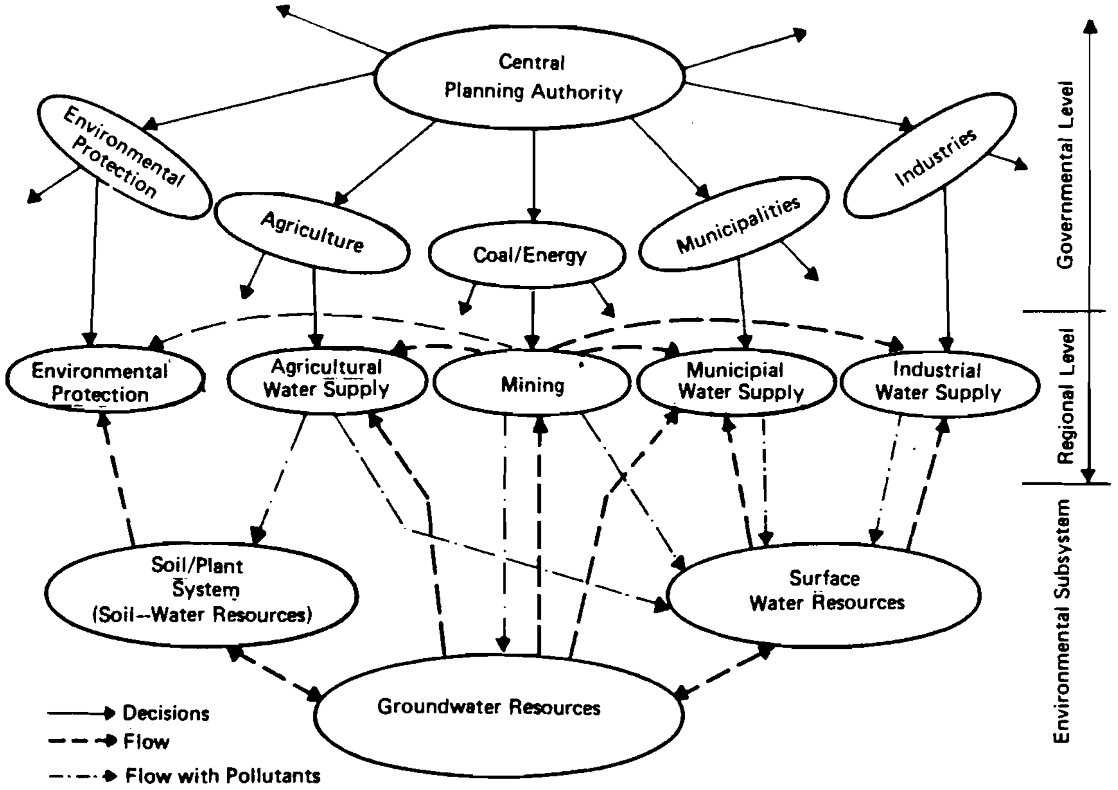


**Figure 2.1:** Schematic environmental/socio-economic system in open-pit lignite mining areas.

According to these problems our research is based on a two-stage decomposition approach, proposed by Orlovski et al. 1984, based on the concepts of hierarchical gaming. The first stage of the analysis is directed towards generating rational scenarios of the long-term regional development based on preferences of the Central Planning Authority. Behavioural aspects of the lower-level water users are considered only in terms of general regional socio-economic preferences of the corresponding economic sector.

Based on more detailed considerations of behavioural aspects, in the second stage of analysis feasible regulation policies will be studied in order to direct the behaviour of water users and consequently the regional development along the reference scenarios obtained at the first stage.

The fundamental tool for both stages of analysis is an appropriate model system suitable for analysing long-term regional water policies. From the systems analytical point of view such an analysis might be seen as a problem of dynamic multi-criteria, multiple-decision maker choice taking into account the fuzziness pertaining to human behaviour, uncertainties and imprecisions resulting from limited understanding of the complex processes under study and the lack of data. According to our discussion above, this choice is embedded in a complicated policy making process and it is based on "hard" criteria as costs,

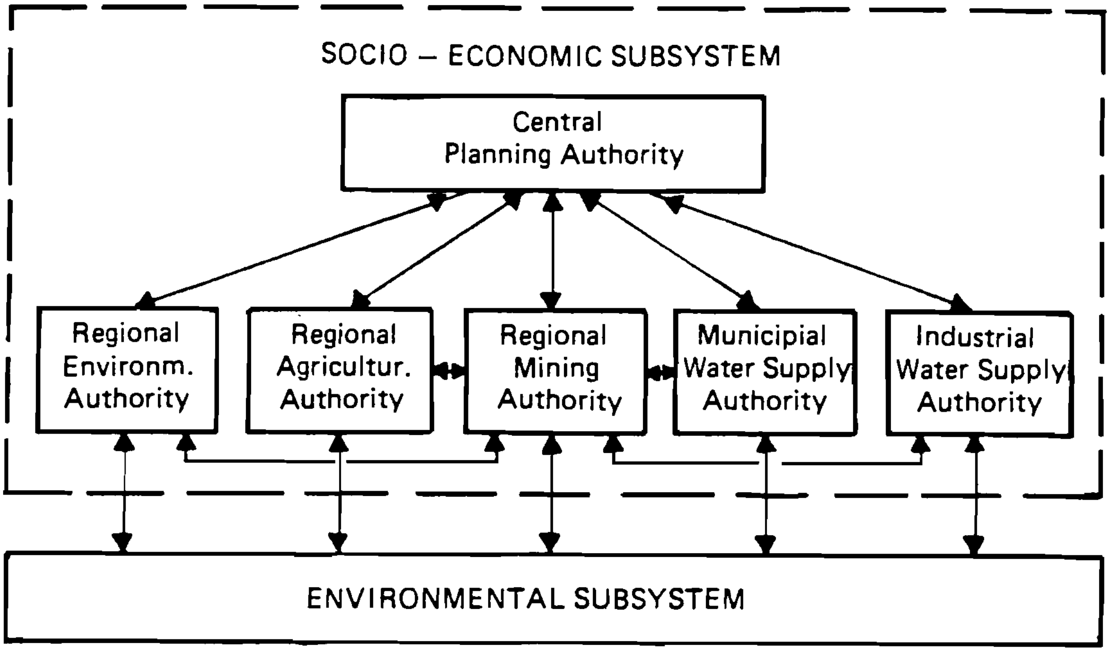


**Figure 2.2:** Schematized policy-making process.

water supply etc., as well as on "soft" social and political criteria, e.g. the quality of life in the region. We are not able to develop a model system considering all the complexity of the policy making reality, anticipating the decisions of the policy makers. However, we can support the policy maker in analysing appropriate decisions by the help of a *Decision Support Model System*. Such a DSMS should reflect the policy making process and the goals of the conflicting interest groups and integrate the essential interactions between as well as within the environmental subsystem and the socio-economic subsystem. In the following the methodological approach for such a DSMS and its realization for the GDR Test Area will be described.

## 2.2. Methods for Scenario Analysis

In general, dynamic problems of the studied type are approached by time-discrete dynamic systems models. The step size depends on the variability in time of the processes to be considered, on the required criteria and their reliability, and on the frequency of decisions (control actions) effecting the systems development. Taking into account the policy-making reality related to long-term regional water management and planning two different step-sizes discretizing the *planning horizon* T (of about 50 years) are of major interest:

- the ***planning periods*** $\Delta T_j, j = 1, \ldots, J$ $(T = \sum_{j=1}^{J} \Delta T_j)$ as the time step for principal management/technological decisions, (e.g. water allocation from mines, water treatment, drainage technology)

- the *management periods* of one month for management decisions within the year related to short-term criteria as the satisfaction of monthly water demand (the classical criteria for long-term water resources planning).

The discretization of the planning horizon into a restricted number of planning periods enables principally to apply optimization techniques for multi-criteria analysis. Small time steps (for instance, $\Delta T_j$ = 1 year) for the planning periods are favourable from the point of view of the evidence and accuracy of model results. Otherwise the number of planning periods should be minimized with respect to the available methods for multi-criteria analysis, computational facilities, and budget as well as time for analysis. As a compromise our DSMS is based on variable planning periods, starting with one year and increasing with time. Taking into account the uncertainties of long-term predictions of model inputs (water demand, decisions on investment, etc.) and the required accuracy, decreasing with time, this approach is quite reasonable as illustrated in Figure 2.3.

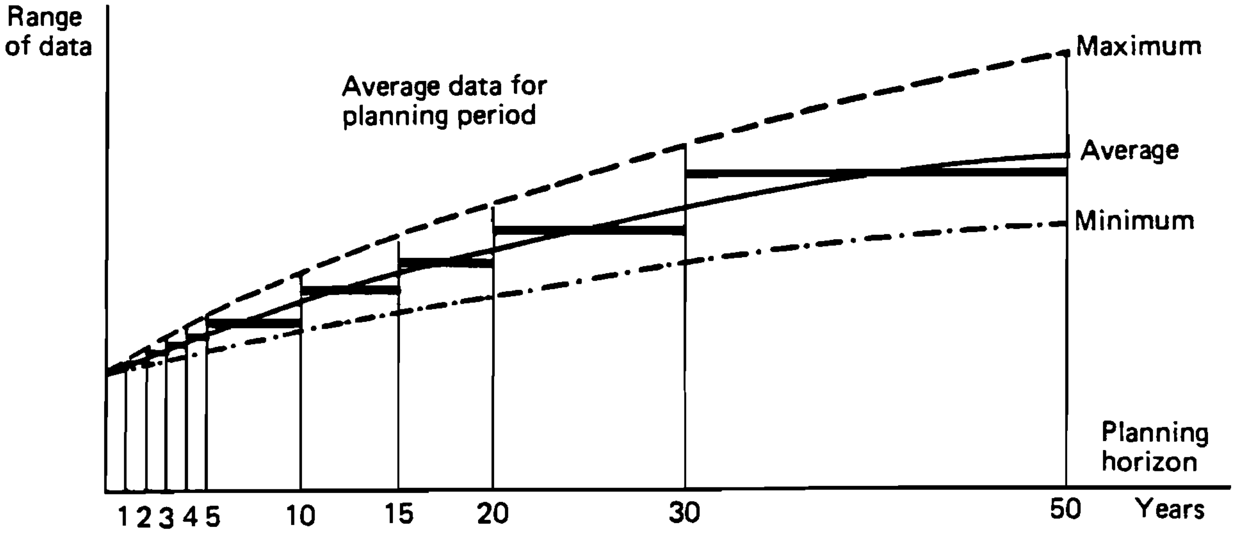


**Figure 2.3**: Relationship between planning periods and expected range of model data (input and output).

For monthly time steps (600 for a planning horizon of 50 years) the application of any optimization technique becomes unrealistic. To study monthly systems behavior systems simulation is the only applicable tool. Furthermore this simulation opens an easy way to consider stochastic inputs (hydrological data, water demand etc.) applying the Monte-Carlo-Method for stochastic simulation.

Based on these assumptions we develop a heuristic two-level model system (Kaden 1983), consisting of

- *planning model* for dynamic multi-criteria analysis for all planning periods in the planning horizon

- *management model* for the stochastic simulation of monthly systems behaviour in the planning horizon.

In Figure 2.4 the general structure of the DSMS is depicted.

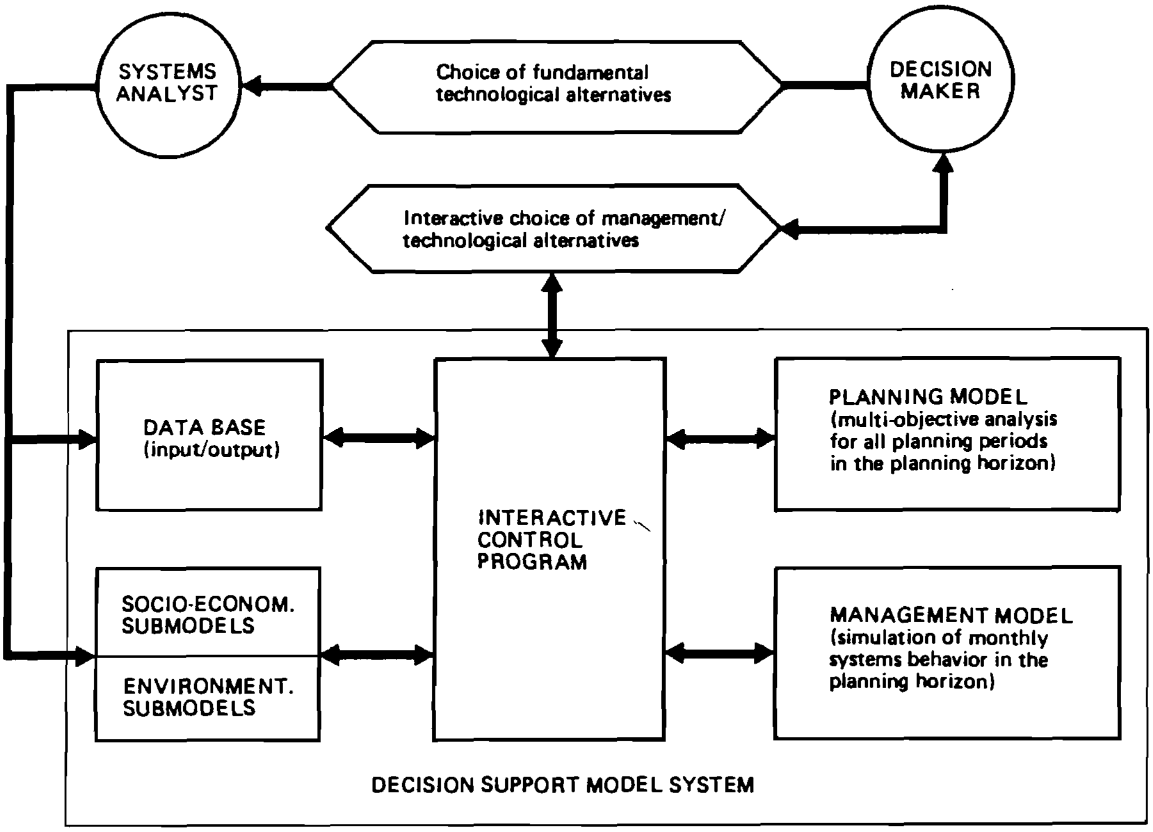


**Figure 2.4**: Structure of the Decision support model system.

As the figure illustrates, the choice of fundamental technological alternatives (e.g. decisions on the construction of a treatment plant, of a pipeline, the dimension of pipes, etc.) are supposed to be fixed exogenously and might be considered as different scenarios. For the time being the DSMS analyses continuous management/technological decisions for planning periods only.

To characterize the model system we use in the following capital Roman letters for the planning model (deterministic inputs and outputs) and capital Greek letters for the management model (partly random inputs and outputs). The letter $\mathbf{f}$ defines a vector function. Generally all values/parameters under consideration represent mean values for the given time step. In the following the models are compared.

| **PLANNING MODEL**<br>$(j=1,\ldots,J)$ | **MANAGEMENT MODEL**<br>$(m=1,\ldots,M)$ |
|---|---|

SYSTEMS INPUT

*Hydrological input* (noncontrolable input as precipitation, stream flow, evapotranspiration)

| | |
|---|---|
| $\mathbf{I}_{hy}(j)$ | $\Phi_{hy}(m)$ |

*Socio-economic input* (noncontrolable input as water demand, investment, prices etc.)

| | |
|---|---|
| $\mathbf{I}_{se}(j)$ | $\Phi_{se}(m)$ |

DECISIONS ON SYSTEMS DEVELOPMENT

*Control variables* for planning periods (water allocation, etc.)

| | |
|---|---|
| $\mathbf{D}(j)$ | $\Psi(m)$ |
| with bounds<br>$\min\mathbf{D}(j) \leq \mathbf{D}(j) \leq \max\mathbf{D}(j)$ | with the deterministic rule<br>$\Psi(m) = \mathbf{f}\Psi(m, \Gamma_d(m-1), \Psi(m-1), \Gamma_v(m), \Gamma_v(m-1), \ldots)$ |

*Total control variables* for the planning horizon

| | |
|---|---|
| $\mathbf{DT}$ | not considered |
| with bounds<br>$\min\mathbf{DT} \leq \mathbf{DT} \leq \max\mathbf{DT}$ | |

DESCRIPTORS OF SYSTEMS DEVELOPMENT

*Systems descriptive values* (auxiliary parameters characterizing the systems behaviour in the planning period; not explicitely depending on previous planning periods, e.g. surface water flow)

| | |
|---|---|
| $\mathbf{S}_d(j)$ | $\Gamma_d(m)$ |

with the *systems descriptive functions*

| | |
|---|---|
| $\mathbf{S}_d(j)=\mathbf{fS}_d(j, \mathbf{D}(j), \mathbf{S}_v(j), \mathbf{I}_{hy}(j))$ | $\Gamma_d(m)=\mathbf{f}\Gamma_d(m, \Psi(m), \Gamma_d(m), \Phi_{hy}(m))$ |

*State variables* (dynamic parameters depending explicitely on the previous planning periods, e.g. water table in the remaining pit)

| | |
|---|---|
| $\mathbf{S}_v(j)$ | $\Gamma_v(m)$ |

with the *state transition functions*

| | |
|---|---|
| $\mathbf{S}_v(j+1)=\mathbf{fS}_v(j, \mathbf{D}(j), \mathbf{S}_d(j), \mathbf{S}_v(j), \mathbf{S}_v(j-1), \ldots)$ | $\Gamma_v(m+1)=\mathbf{f}\Gamma_v(m, \Psi(m), \Gamma_d(m), \Gamma_v(m), \Gamma_v(m-1), \ldots)$ |

CRITERIA (OUTCOME) OF SYSTEMS DEVELOPMENT

*Criteria for planning periods* (e.g. deviation water supply-demand)

| | |
|---|---|
| $\mathbf{O}(j) => Min.!$ | $\bar{\Omega}(j)$ |

with the *criteria functions*

| | |
|---|---|
| $\mathbf{O}(j) = \mathbf{fO}(j, \mathbf{D}(j), \mathbf{S}_d(j),$<br>$\mathbf{S}_v(j), \mathbf{I}_{se}(j))$<br>and bounds<br>$\min\mathbf{O}(j) \leq \mathbf{O}(j) \leq \max\mathbf{O}(j)$ | $\bar{\Omega}(j) = \mathbf{f}\bar{\Omega}(\ldots, \Omega(m), \cdots)_{m \varepsilon j}$<br>$\Omega(m) = \mathbf{f}\Omega(m, \Psi(m), \Gamma_d(m),$<br>$\Gamma_v(m), \Phi_{hy}(m), \Phi_{se}(m))$ |

*Total criteria for the planning horizon*

| | |
|---|---|
| $\mathbf{OT} => Min.$ | $\Omega\mathbf{T}$ |

with the *total criteria function*

| | |
|---|---|
| $\mathbf{OT} = \mathbf{fOT}(\mathbf{O}(1), \ldots, \mathbf{O}(J))$<br>and bounds<br>$\min\mathbf{OT} \leq \mathbf{OT} \leq \max\mathbf{OT}$ | $\Omega\mathbf{T} = \mathbf{f}\Omega\mathbf{T}(\Omega(1), \ldots, \Omega(J))$ |

CONSTRAINTS ON SYSTEMS DEVELOPMENT

| | |
|---|---|
| $\mathbf{C}(j) = \mathbf{fC}(j, \mathbf{D}(j), Spj,$<br>$(S_v(j), \mathbf{I}_{se}(j)) \geq 0$ | not considered |

For the planning model a nonlinear multi-criteria programming system has been developed, using the reference point approach (Wierzbicki, 1983). The method is based on the idea of "satisficing". Starting from aspiration levels of decision makers for the indicators of systems development (reference points or reference trajectories) efficient responses are generated (Pareto points "closest" to the reference points). The best-suited solution (considering the preferences of the decision maker) can be obtained by correcting the aspiration levels in an interactive procedure. The principle use of the method is illustrated in Figure 2.5 for two objectives. A detailed description of the method and its application for the GDR Test Area will be given in a forthcoming paper. The program system is based on the nonlinear multi-criteria programming package DIDASS/N (Grauer and Kaden, 1984) coupled with the nonlinear programming system MSPN, developed at the Institute of Automated Control, Technical University Warsaw by Kreglewski et al.

In the case of many criteria the reference point procedure and the comparability of solutions might become complicated for the decision making. For this reason the DSMS renders the interactive determination of criteria to be minimized, for the remaining criteria their bounds are considered. As a second method we are planning to apply an interactive procedure for multi-criteria analysis, developed by Kindler et al. 1980 for water resources allocation problems.

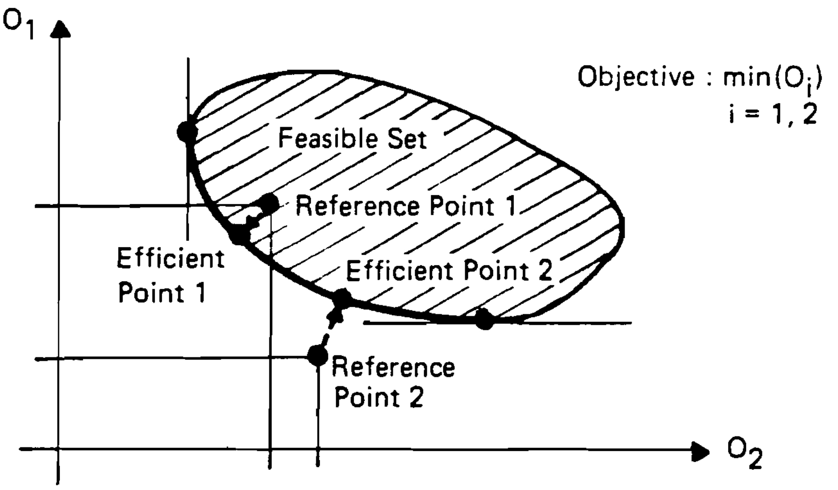


**Figure 2.5**: Illustration of the reference point approach

The planning model of the DSMS is applied first, resulting in an efficient solution for planning periods. The determined control variables $D(j)$ are used to estimate the parameters of the deterministic rule $\Psi(m)$ for the management model. Based on that, the ***management model*** serves as a stochastic simulation model, simulating monthly systems behaviour. The Monte-Carlo-Method is used to generate random inputs $(\Gamma_{hy}, \Gamma_{se})$. From this simulation we obtain empirical distribution functions or frequency distributions for systems behaviour. For instance, the common criteria for monthly water supply in long-term planning models is

$$Prob(demand(m) < supply(m)) \geq p \qquad (2.1)$$

The management model is used to estimate the empirical probability with which a given monthly demand is satisfied — an important criteria in water management.

The most favourable case in running both models would be, if the deviations between the results are negligible and the decision maker is satisfied with the results. Otherwise the planning model has to be used again with changed aspiration levels. To ensure consistency between the planning model and the management model as far as possible we require for the systems input:

$$I_{hy|se}(j) = \sum_{m \in j} E[\Phi_{hy|se}(m)] \qquad (2.2)$$

with $E[]$ - expectation value.

The deterministic rule estimating the control variables in the simulation model should satisfy the following condition:

$$| E[\Psi(j)] - D(j)| \leq \varepsilon \qquad (2.3)$$

with

$$\overline{\Psi}(j) = f\,\overline{\Psi}(\ldots,\Psi(m)\,,\,\ldots\,,\,)_{m \epsilon j} \tag{2.4}$$

The smaller the $\varepsilon$ is chosen, the better is the consistency that is required between the models.

For the practical case, it has to be proved whether the interrelationship between the management and the planning model might be completely mathematically formalized or heuristic interactive procedures are favourable.

### 2.3. Development of Environmental and Socio-Economic Submodels

The submodels for the complex model system under development have to be characterized by two major features. On the one hand, they should be simple enough mathematically (even as simple as possible) to be integrated in a complex model system suitable for an interactive use. On the other hand, they have to reflect the important socio-economic and environmental processes with an accuracy required for making appropriate decisions based on the model system. Obviously, these features may be contradictory and a compromise should be found. Depending on the state-of-the-art of modeling of a given process, the availability of comprehensive models and data, different methods for the development of submodels have to be used. In the following only an overview will be given. For details see the forthcoming collaborative papers.

*Groundwater Flow Submodels*

For a part of the Lusatian Lignite District (about 1300 km$^2$) in the last years a comprehensive groundwater flow model has been developed. The GDR Test Area considered here is located in this district. The model, described by Peukert et al. (1982) was used for prognostic simulation of the groundwater regime for a planning horizon of 25 years. In the meantime this model was improved and extended for a planning horizon of 50 years acording to the needs of the present case study. The following boundary-conditions have been considered in the model:

- temporal and spatial development of all open-pit mine dewatering measures
- operation of all existing as well as planned remaining pits
- operation of all waterworks considering their planned capacity increase
- operation of irrigation systems for agriculture
- infiltration/exfiltration of rivers and ponds
- natural groundwater recharge depending on the mining activties.

For the groundwater flow model the program HOREGO, developed at the Dresden University of Technology and implemented at an EC 1055 main frame computer was used. This program is based on the mathematical model of the non-steady horizontal plane groundwater flow with nonlinear parameters of transmissivity. The discretization of the flow field is done by orthogonal finite elements, considering an optimal adaptation of the model to the internal and external boundary conditions.

For the test region the interactions between mine dewatering, remaining pit utilization, surface water/groundwater flow, etc. have been investigated by the help of the comprehensive groundwater flow model. Based on these investigations submodels have been developed describing the interrelationships between the state of the groundwater system and selected decisions (control variables).

In developing these submodels (systems descriptive or state transition functions) the main difficulties result from the nonlinearity of groundwater flow (strong changes of transmissivities in time). To overcome this problem, we proceed in the following way. The comprehensive flow model is first used to simulate an average expected systems development $\bar{S}(j)$[1] for mean expected values of inputs and decisions $\bar{I}(j)$, $\bar{D}(j)$, considering the nonlinearity of flow in the entire region. As a result we get expectation values for the groundwater tables, groundwater pumpage, etc. as functions in time.

The actual inputs $I(j)$ and decisions $D(j)$ are assumed to be close to the expected values:

$$D(j) - \bar{D}(j) = \Delta D(j) \ll \bar{D}(j) \,;\, I(j) - \bar{I}(j) = \Delta I(j) \ll \bar{I}(j) \qquad (2.5)$$

Now the comprehensive model is used to estimate the consequences of $\Delta I$, $\Delta D$, (e.g. changes of the filling process in a remaining pit or in the timing of the dewatering process at one of the mines) on the systems development, assuming linearity. Consequently, the effects $\Delta S_l^D$, $\Delta S_l^I$ (e.g. changes in the development of groundwater tables in the water pumpage from neighbouring mines, in the infiltration of river sections) of each input $\Delta D_l$ or $\Delta I_l$ can be studied separately and the superposition principle is applicable.

$$S(j) = \bar{S}(j) + \sum_l (\Delta S_l^D(j, \Delta D_l(j))) + \sum_l (\Delta S_l^I(j, \Delta I_l(j))) \qquad (2.6)$$

The function $\Delta S_l$ might be nonlinear. For small $\Delta D(j)$ and $\Delta I(j)$ the error due to the nonlinearity should be small. The comprehensive model is used to check this assumption.

Figures 2.6 and 2.7 demonstrate some simulation results for the development of submodels (compare Sections 3 and 4). In Figure 2.6 the development of groundwater lowering and rebound in an agricultural area and in an environmental protection area is depicted. Figure 2.7 shows the infiltration behaviour at selected river sections.

*Groundwater-Surface Water Interaction*

Models used in groundwater/surface water management may be divided into two types regarding their mathematical structure:

- box models (input-output models)
- system descriptive models (state models)

---

[1] The index $j$ indicates a planning period, the bar indicates an expectation value.

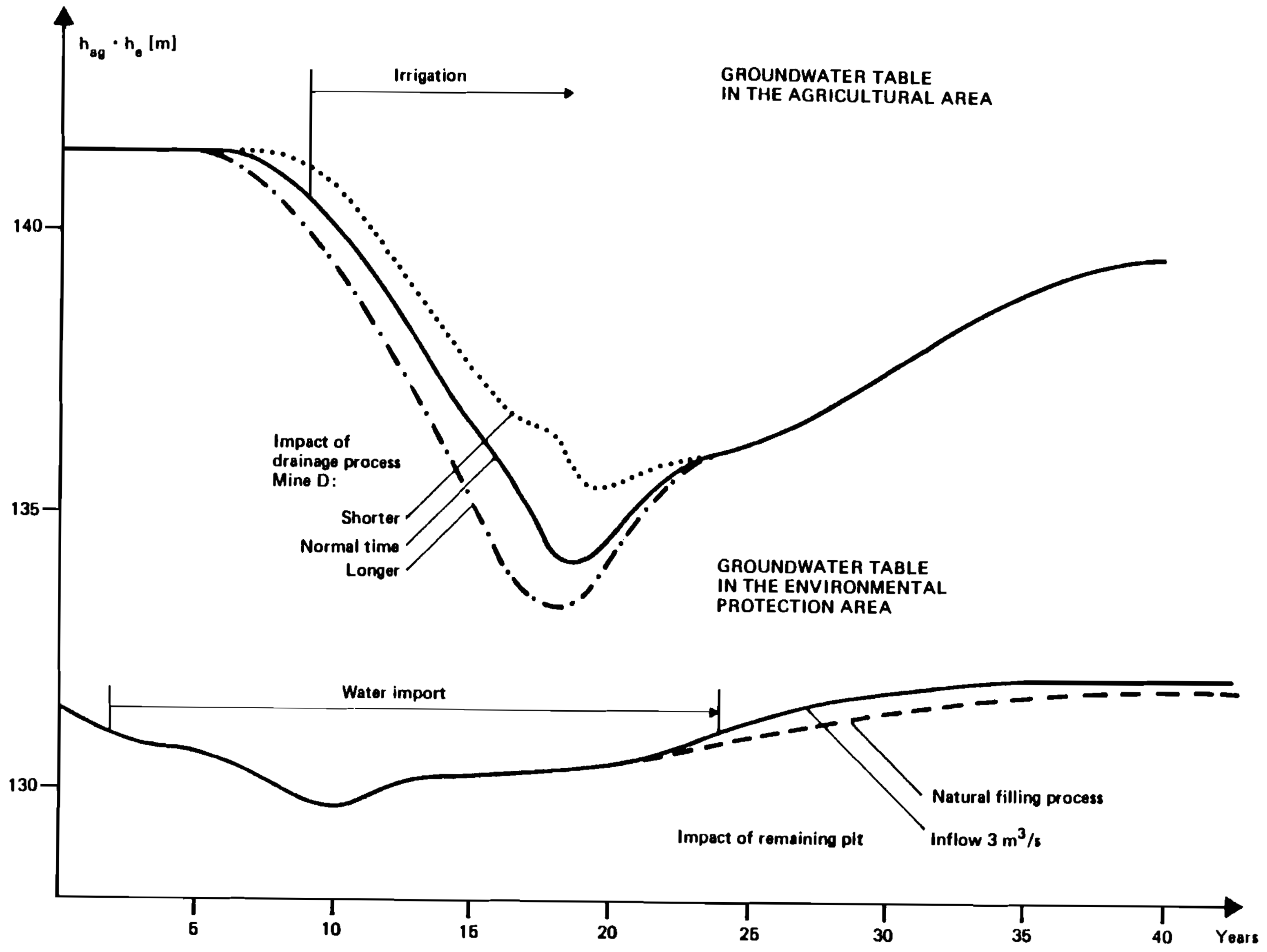


**Figure 2.6:** Influence functions for the groundwater table in the agricultural and the environmental protection area.

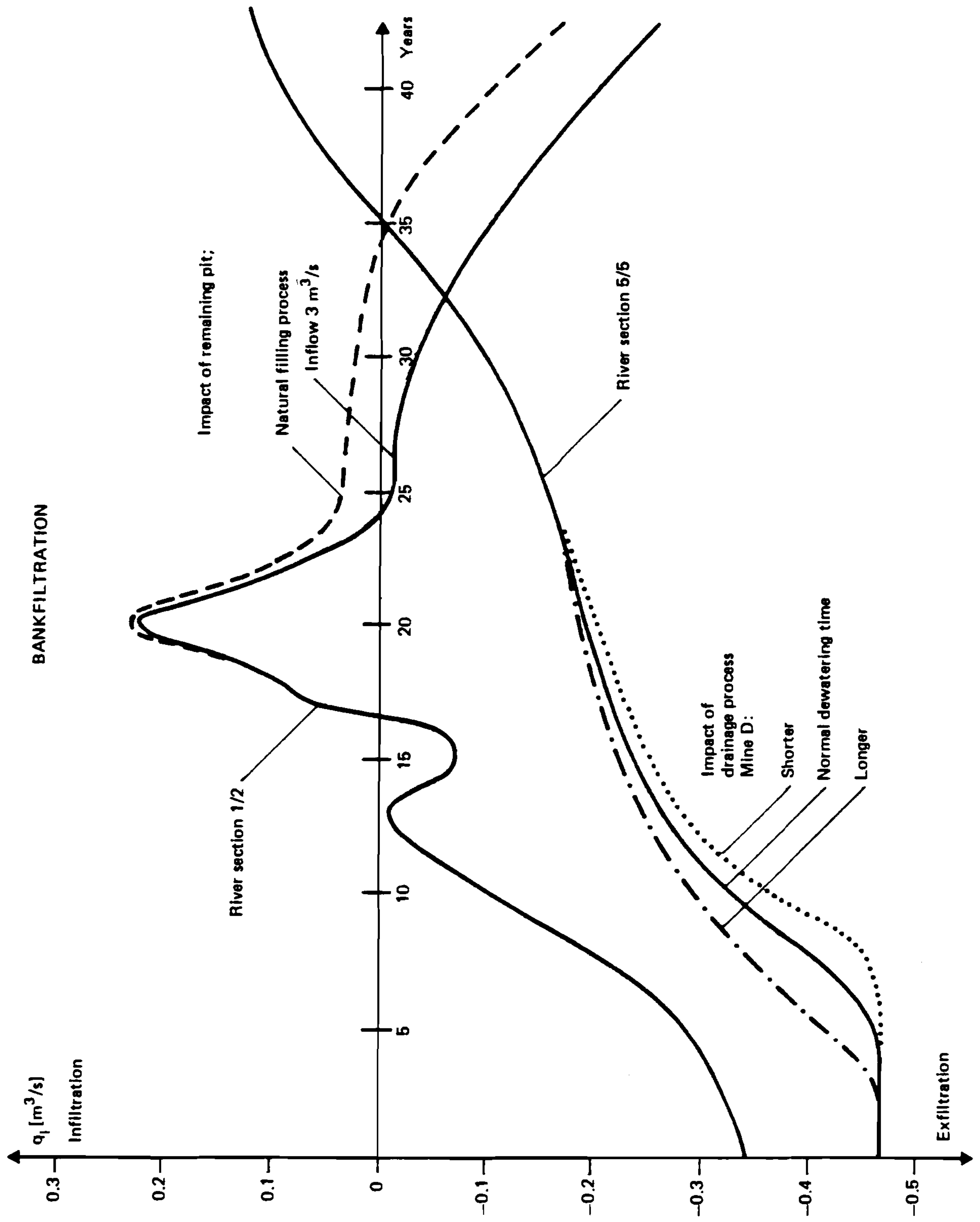


**Figure 2.7:** Influence functions for the bank-filtration

Only box-models may be called reduced models. With regard to the transition functions these models may be deterministic or stochastic. In the field of groundwater management deterministic box-models are dominant.

Another aspect is the way of obtaining the transition function. In the case of *conceptual box models* the transition function is derived from special analytical solutions of the system descriptive model. Therefore, the parameters of this type of models allow for a clear physical interpretation. Such models have the advantage that they might be derived for regions even if no comprehensive model is available.

A physical interpretation is not possible for *black-box-models*. The parameters of their transition functions are obtained by adapting empirical or theoretical formulas to observation data or calculations using comprehensive models. This difference between conceptual and black-box-models is important for the methodology of model reduction. Figure 2.8 shows the main steps for model reduction.

For the test region the regional groundwater flow model presented by Peukert et al. 1982 gives an excellent base for the development of reduced submodels for groundwater-surface water interaction. In the following two typical examples of submodels are discussed using different ways of model reduction.

Submodel of the remaining pit management:

The process of the remaining pit management is a highly non-linear subprocess of the decision problem due to the infiltration from the pit into the aquifer. The derivation of an adequate submodel was based on a large number of calculations with the comprehensive groundwater flow model. As the dominant input the difference between the inflow into and the discharge from the remaining pit reservoir was varied over an interval being realistic from the hydrological point of view. Based on the calculated data a black-box model in terms of a difference equation considering a history of 2 years was found to be the best suited model. Simultaneously a conceptual box-model of the remaining pit management was derived.

Submodel of River sections:

For modeling the influences of water level variations on the infiltration and exfiltration processes the regional groundwater flow was used for a relatively small number of variants. The results demonstrated that the exchange processes between groundwater and surface water may be characterized as local processes neglecting the external boundary conditions of the groundwater flow field. Therefore, it is possible to derive a conceptual box-model describing the transition functions for all interesting stream sections in a discrete form (monthly values). To simplify the analytical functions again a difference equation was found to be suitable.

### *Water quality*

The most important water quality impact in lignite mining regions is the discharge of acid ferruginous mine water into rivers. The main problem is the choice of the necessary purification degree for mine water treatment plants, taking into account the self-purification in rivers and remaining pits, as well as the water quality demand of downstream users. Standards are fixed by governmental water authorities and controlled at the intake points. Exceeding those standards results in legal fines.

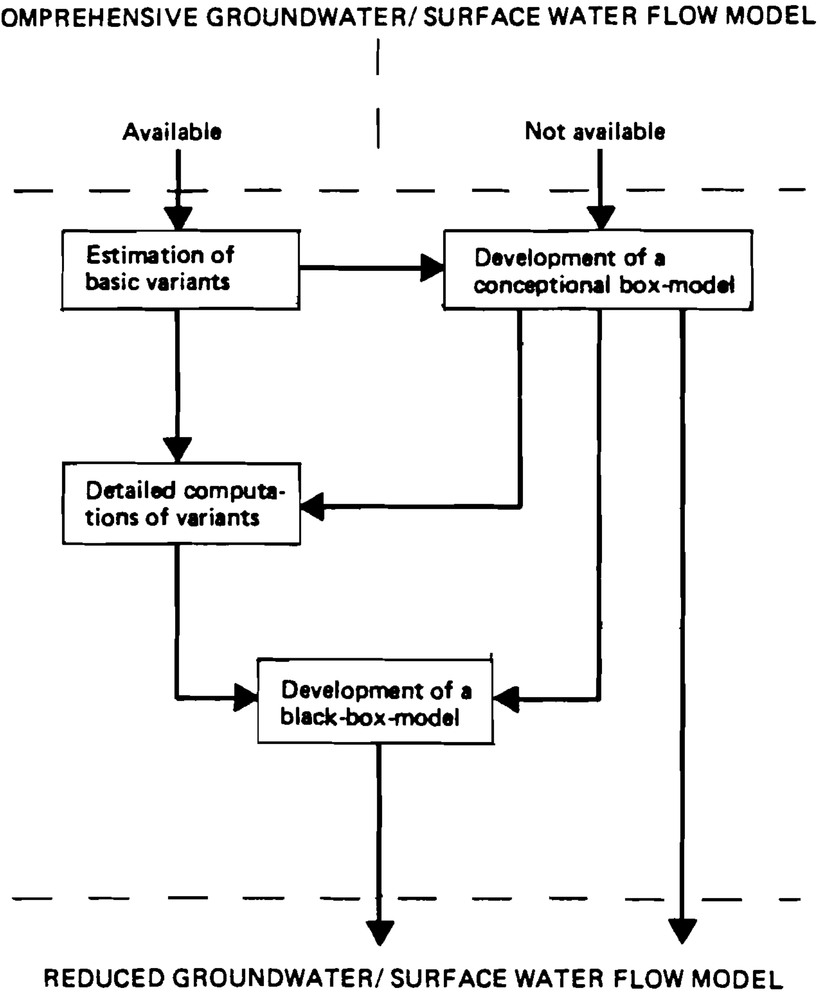


**Figure 2.8**: Working steps for model reduction

The major chemical reactions that occur in the formation and treatment of acid ferruginous mine water, are schematically represented in Figure 2.9.

The parameters will be influenced in the mine water treatment plant by added lime hydrate. The remaining iron(II) in the treated water will be oxidized by air in the river, respectively in the remaining pit, hydrolized and precipitated according to the kinetic of reactions and residence times. The kinetic of all these reactions is among other things essentially depending on the pH-value.

The model of the substance exchange, transport and storage processes is a system descriptive migration model for 4 coupled components. These components are (see Figure 2.9):

- in the underground: $FeS_2$, $Fe^{2+}$, $O_2$, $H^+$
- in the mine water treatment plant: $Ca(OH)_2$, $H^+$, $CO_2$, $Fe^{2+}$

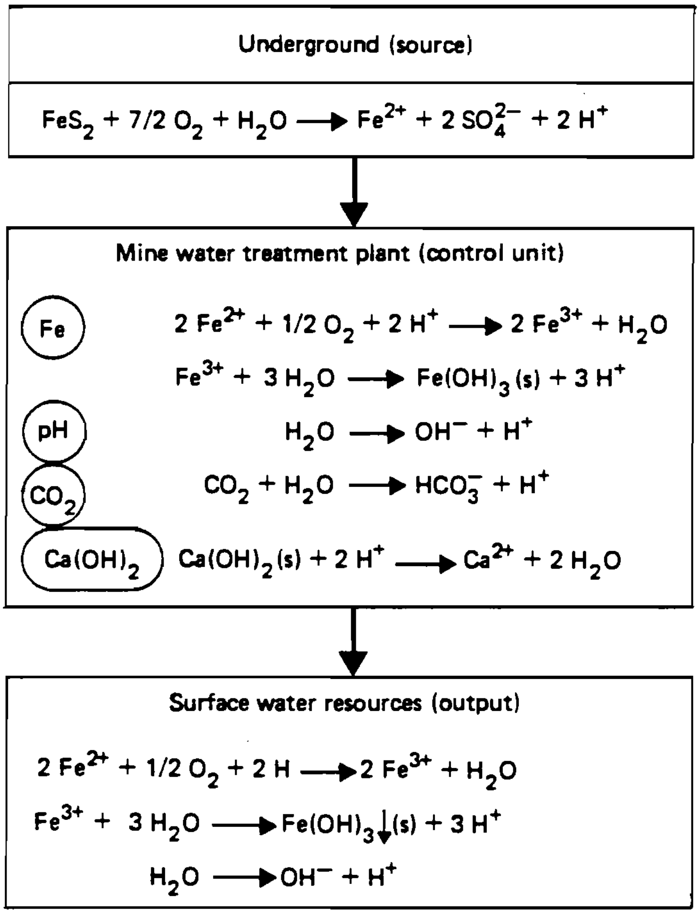


**Figure 2.9**: Important reactions of the weathering of ferrous-disulphide caused by lignite mine dewatering.

- in the surface waters: $Fe^+$, $O_2$, $H^+$

In our case the sulphide will be neglected because it is not essentially influenced by the mentioned processes.

The coupling of models is done according to the decisive component of the reactions. That is, oxygen in the underground and in the surface water resources, lime hydrate in the mine water treatment plant. The reactions in the mine water treatment plant and in the surface water resources are formulated in reduced conceptional models (balance models). The neglect of storage and transport terms in the planning model is reasonable because the residence time is essentially shorter than the planning period ($\geq$ 1 year). Only in the remaining pit storage has to be considered. In the management model (monthly time steps) the changes in storage and the kinetics of the reactions has to be taken into account. For the description of the kinetic reactions a first order law of velocity is formulated. The structure model for coupling the substances in mine water treatment plants shows Fgure 2.10. By adding lime hydrate the concentrations of pH-value, $Fe^{2+}$ and $CO_2$ are influenced.

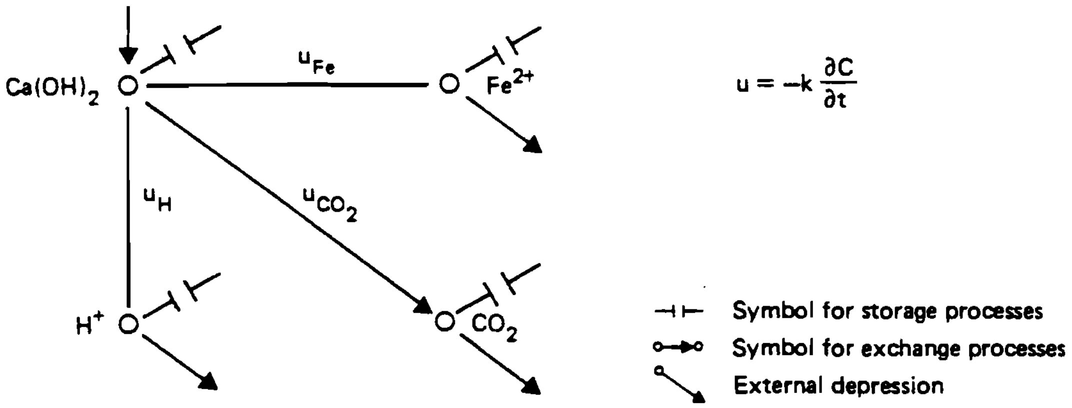


**Figure 2.10**: Structure model for the reactions in a mine water treatment plant

## 2.4. Design of an Interactive Decision Support Model System

In the last years the revolutionary development in electronic data processing has opened completely new possibilities for model applications in the practical decision making for large-scale, long-term planning. It is well-known that models for such purposes in the past did not find a wide application and impact in real policy analysis. As the main causes of that we see the following points:

- Modeler tried to *solve* long-term planning problems, *anticipating decisions* of the decision makers, neglecting subjective criteria in the decision making process.
- Generally models developed had to be used by specialists (systems analysts), the decision makers did interact with the model only through those specialists.
- Models frequently did not answer questions asked directly by the decision makers.

"The question, thus, is not whether to model, but how, and, most importantly, how to interface models with our more traditional ways of planning and decision making" (Fedra and Loucks 1984). Obviously models or model systems do not replace real-world planning and decision making but should be designed to support them. To be accepted and used by the decision makers such Decision Support Model System must fit in the decision making reality (compatibility with common planning and decision making practice), and it has to be user-friendly, reliable, robust and credible.

The development of an interactive decision support model system for the analysis of regional water policies in open-pit lignite mining areas is oriented towards those goals. With the methodological approach described in Section 2.2 the policy making reality is reflected sufficiently, as we believe. The model system focuses on the necessary decisions and common criteria for long-term water management. The underlying time discretization corresponds to the common planning practice.

Based on the reference point approach for multi-criteria analysis coupled with a stochastic simulation the model system is methodologically suitable for an interactive use. In addition the model handling and data management has to be designed interactively and user-friendly. We consider the following aspects in the model system:

- hierarchical data base (input and output data) with a robust screen oriented data display and editing system
- style and language of model use according to the planning and decision making reality
- use of computer colour graphics for visual display of computational results.

The use of the hierarchical data base is menu-driven. Each data base level characterizes a menu and the user can either move downwards according to the menu or upwards to the previous level, or return to one of the models. In Figure 2.11 an overview on the structure of the data base is given.

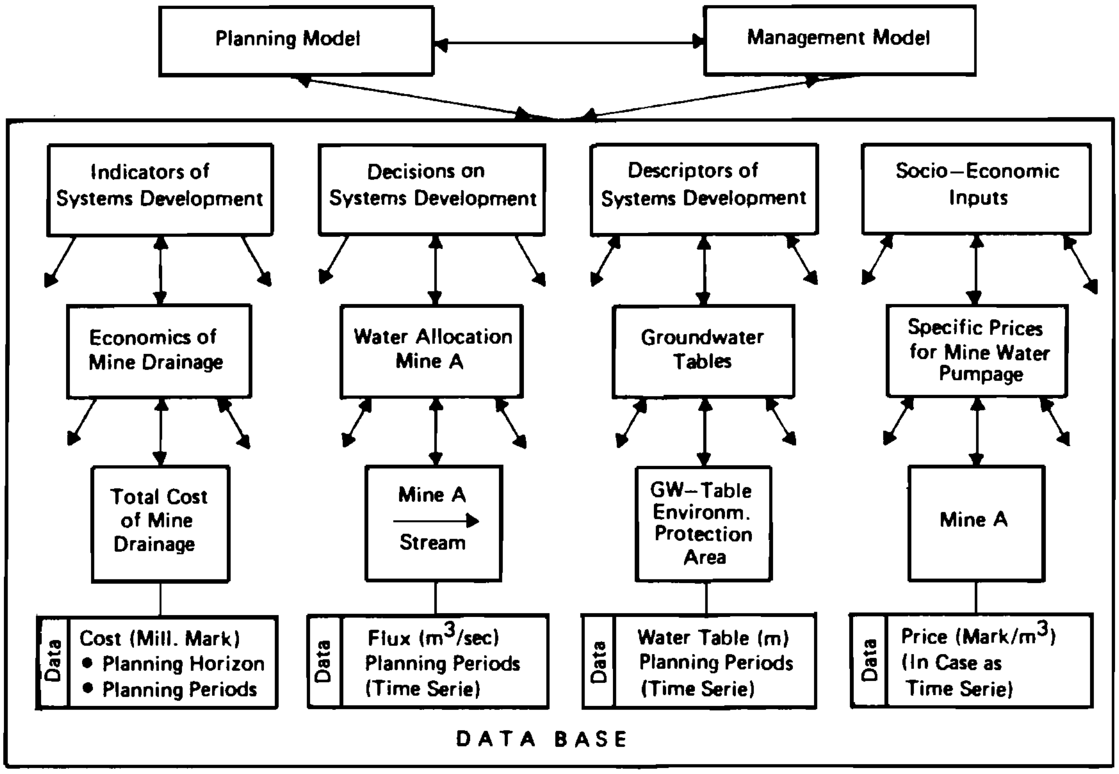


**Figure 2.11**: Hierarchical structure of the data base

For the data editing simple screen editor has been developed. Data checks realize the graceful recovery from failures. For the menu description we use as far as possible linguistic elements according to the practical language, as indicated in Figure 2.11 (the text within the boxes is similar to the given menus).

For the visual display of model results a flow chart representation of the Test Area is used on a colour monitor. The flow chart is similar to Figure 4.1. The water quantity (flow) is characterized by the thickness of lines, and the water quality by the colour. These graphical symbols correspond to given ranges of data which might be defined as linguistic variables (water quality—excellent, fair, bad, very bad). To compare the criteria of different scenarios bar charts may be used.

## 3. The GDR Test Area

### *Environmental Setting*

The test area is located in the Lusatian Lignite District in the lowlands of the south-eastern part of the GDR. Its area amounts to approximately 500 km$^2$. In Figure 3.1 an overview is given.

The quarternary aquifer system of the test area can be schematized in three aquifers (the first being unconfined), separated by aquitards (lignite). In Figure 3.2 the hydrological situation is depicted.

The boundary of the test area is not identical to the subsurface catchment area. Groundwater inflow, outflow respectively have to be considered. The region is crossed by a stream and some tributaries. The groundwater and surface water resources are closely interrelated (baseflow into surface waters under natural conditions, infiltration (percolation) of surface water into the aquifer in the course of groundwater lowering due to mine drainage). The inflows into the region from the stream and the tributaries are natural ones depending on the hydro-meteorological situation in the upstream catchment areas. Consequently, the actual inflows are random values.

From the point of view of geohydrochemistry, in the first and second aquifer the processes of weathering of ferrous-disulphide minerals are most important. In the underground ferrous-disulphide will be oxidized by oxygen in the air. At the same time originate iron(II)-, sulphate-ions and protons. The acidity increases in the groundwater. The reaction products will be flushed out with the percolated water from aerated zones and transported by the rise of groundwater. Especially high is the iron and acid concentration in the percolated water in spoils. Furthermore, the groundwater is characterized by increased concentrations of $CO_2$ resulting from biochemical degradation processes. The discharge of acid ferruginous minewater into the stream or remaining pit is the decisive quality impact caused by mining.

The deepest third aquifer frequently contains highly mineralized groundwater (natrium chloride, etc.). Processes of salt-water upconing have to be considered (this will be done in further research).

### *Human Activities and Their Impacts*

The regional development is primarily determined by 4 open-pit lignite mines:

| | |
|---|---|
| MINE A | going out of operation within the planning horizon; the REMAINING PIT will be used as a water reservoir |

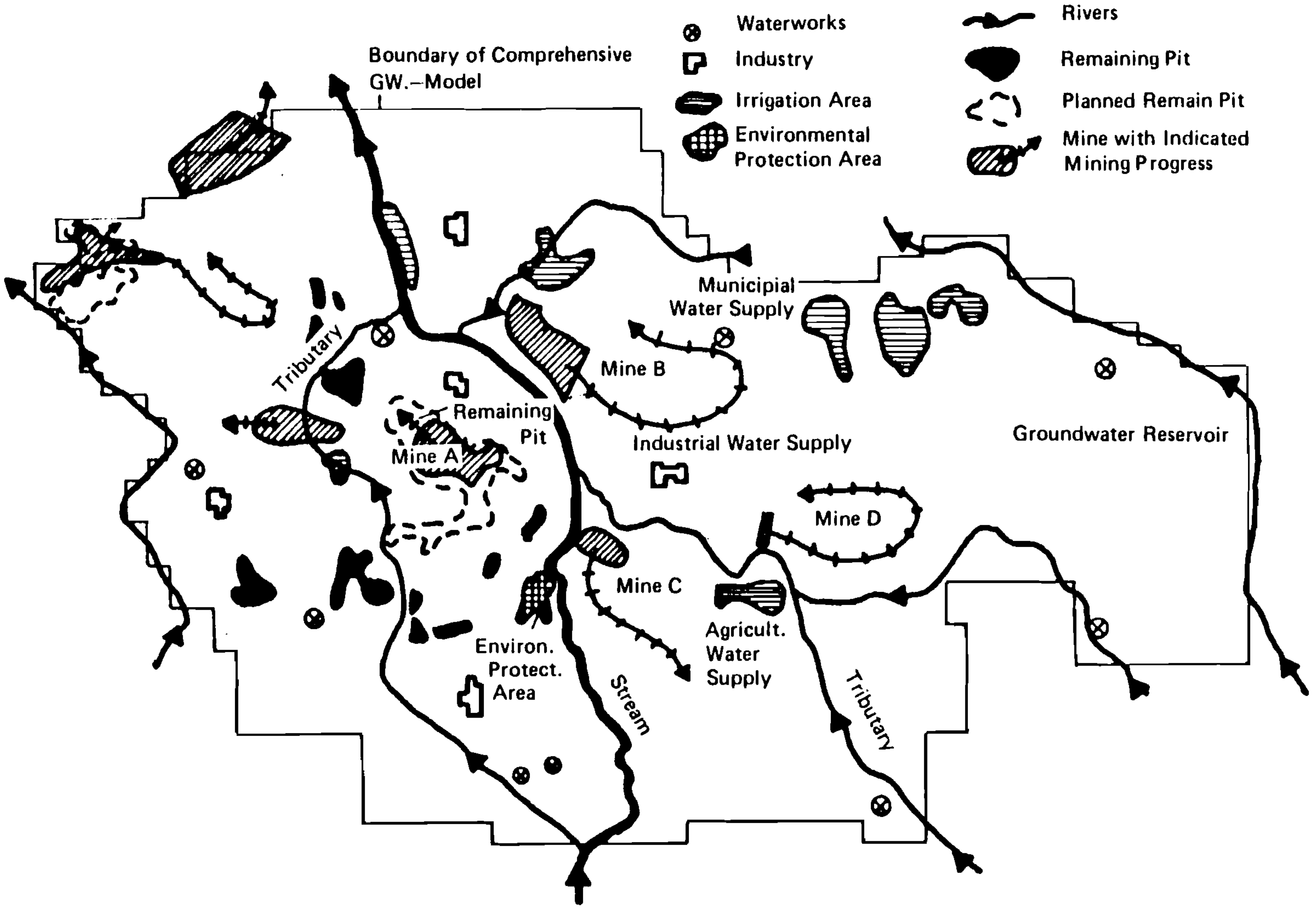


Figure 3.1: GDR test area

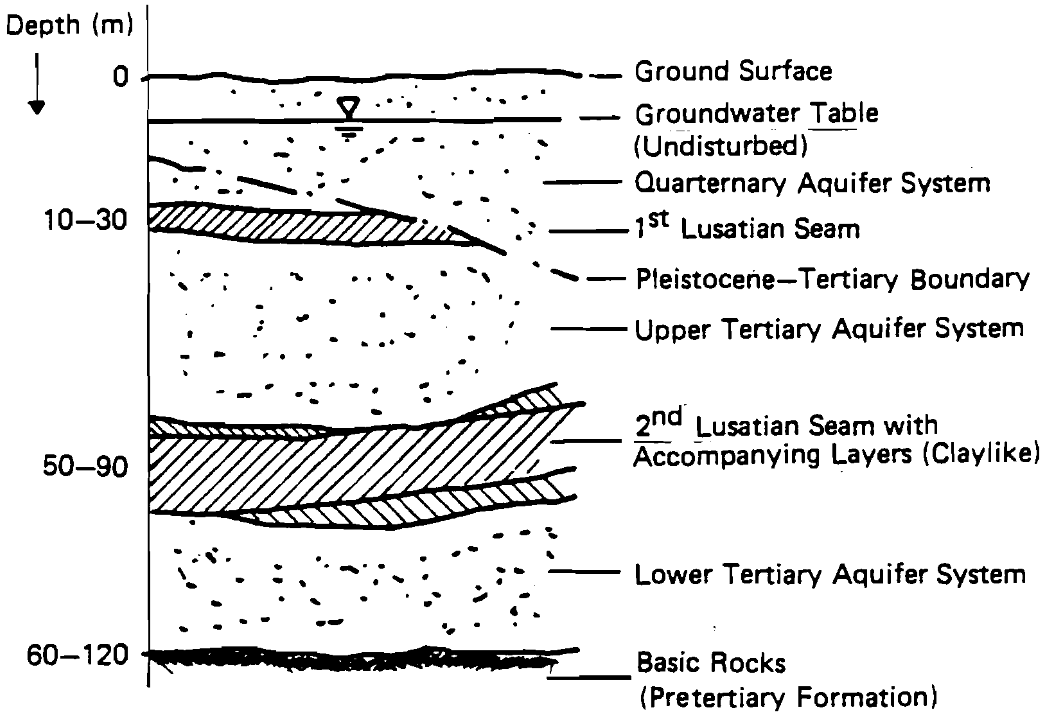


**Figure 3.2:** Hydrological schematization

| | |
|---|---|
| MINE B | operating within the whole planning horizon; one selected drainage well gallery has been especially designed for municipal water supply |
| MINE C | operating within the whole planning horizon |
| MINE D | opening within the planning horizon. |

The mine drainage is done by extraction wells surrounding the mines (border well galleries) and within the mine-field (field well galleries). Different mine drainage technologies as the use of side walls will not be considered. The dates of mining (closing mine A, opening mine D), as well as the mining capacities are supposed to be fixed. Consequently, the groundwater tables within the mines during the operation time are fixed. The amount of mine water to be pumped can be only controlled by the timing of mine drainage activities and by the filling process of the remaining pit. For the test region we will consider as decisions the time of opening the mine drainage for mine D and the filling of the remaining pit as well as its management. In Figure 3.3. the expected amount of mine water to be pumped is depicted for a predrainage period of 3 years for mine D and an artificial filling of the remaining pit with water at the rate of 3 $m^3/s$.

The mine drainage resulting in a large cone-shaped groundwater depression effects primarily:

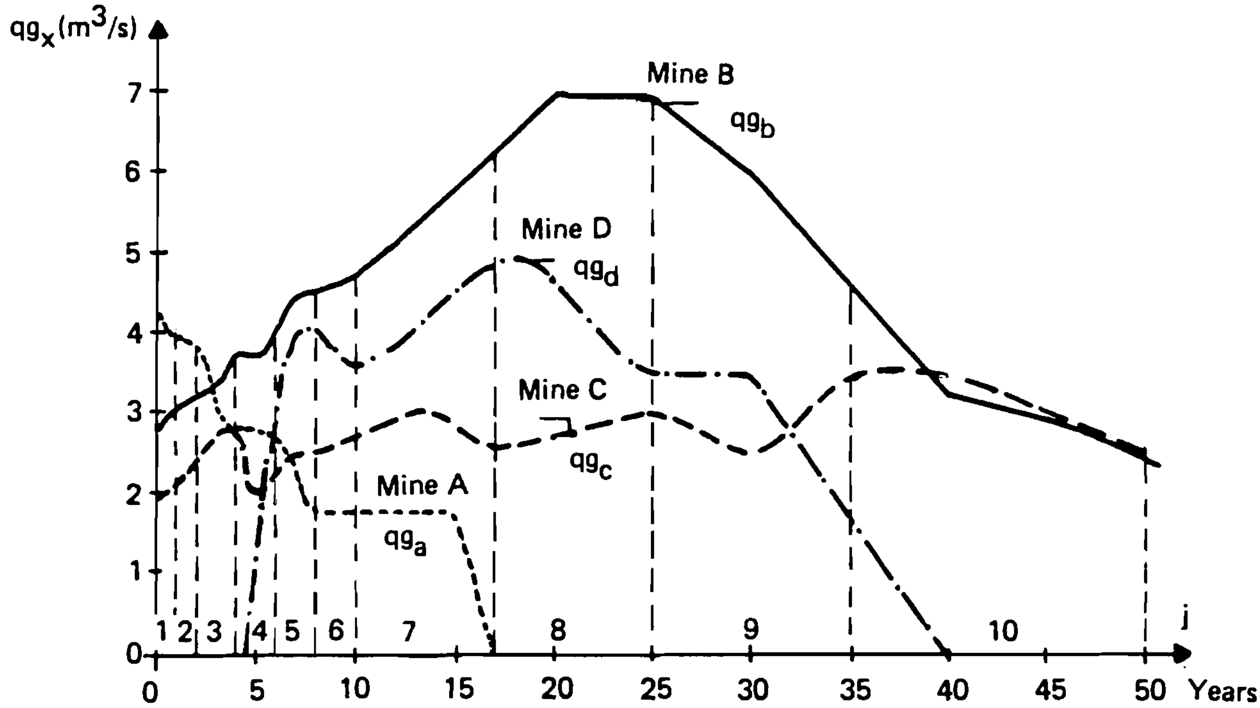


**Figure 3.3**: Expected mine water drainage

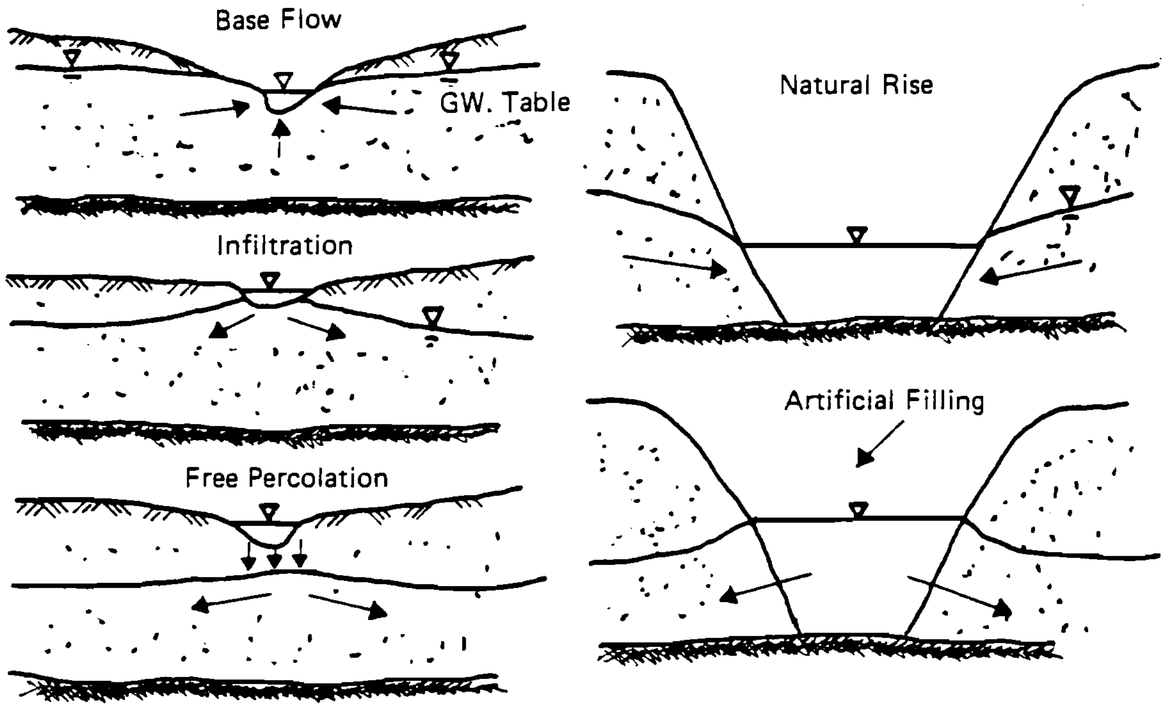
1. *Groundwater Extraction for Municipal Water Supply*. The capacity of extraction wells depends on the groundwater table near the wells. A well can only operate if the groundwater table is above the well screen. To satisfy the municipal water demand additional more costly sources have to be used. Principle alternatives are surface water (with complicated and expensive water treatment), water import from other regions (high cost for water allocation), and above all mine water (MINE B) from especially designed mine drainage galleries.

2. *Agricultural Water Supply*. The agricultural crop production as an important economic sector also in mining regions is above others a function of the moisture in the rootzone. In case of shallow groundwater tables, a substantial part of the moisture required for crop growth is supplied by capillary rise from the aquifer to the rootzone. With decreasing groundwater tables the capillary rise decreases and supplementary irrigation becomes necessary (sometimes additional to already implemented irrigation).

The water demand for supplementary irrigation might be satisfied by both, surface water, and mine drainage water (MINEs C and D).

3. *Environmental Protection Area*. The survival of valuable flora depends on stable groundwater tables and groundwater quality within a small range. Based on the assumption that the mining activities are fixed the groundwater regime in the environmental protection area can only be controlled by artificial groundwater recharge. Taking into account the insufficient water quality in the stream as sources for the recharge mine drainage water (MINE C) and water from the REMAINING PIT might only be used.

4. *Infiltration Between the Stream/Tributaries and the Groundwater Reservoir.* This interrelationship is illustrated in Figure 3.4a. Depending on the groundwater and the surface water table we have to deal with baseflow to the stream or infiltration from the stream into the aquifer.



a) Stream–Aquifer

b) Remaining Pit–Aquifer

**Figure** 3.4: Infiltration between surface water and groundwater.

Increased infiltration losses may affect both, DOWN-STREAM WATER YIELDS and the INDUSTRIAL WATER SUPPLY in the region. The possibility of mine drainage water use for industrial water supply has to be considered.

5. *Filling Process of the Remaining Pit.* The interrelationship between groundwater table and water table in the remaining pit is depicted in Figure 3.4b. The remaining pit will be used as a reservoir to control the surface water flow for down-stream water users. Therefore, a technologically substantiated minimum water table has to be reached. Consequently, from the water management point of view the artificial filling of the remaining pit with surface water or mine drainage water becomes favourable to fasten the filling process. Otherwise, high water tables in the remaining pit increase the amount of mine water drainage (and cost) for MINE B.

6. *Quality of the Water in the Groundwater Reservoir and the Remaining Pit.* (The most important chemical processes has been characterized above).

The mine drainage water is either allocated to different water users (including water export) or discharged into surface water resources. To satisfy quality constraints, quality requirements of surface water users respectively, it has to be treated in special MINE WATER TREATMENT PLANTS. The necessary purification degree depends on the quality of the mine drainage water, the quality requirements of users and on the self-purification in surface water resources. The purification degree in the treatment plant is above all controlled by the adding of lime hydrate. By adding lime hydrate into the remaining pit a certain purification affect may also be expected there.

All mining activities cause mainly long-term changes in the system. Medium-term variations (within the year) of mining activities are negligible. For the surface water flow medium-term variations (monthly) have to be considered, caused by random changes in hydro-meteorological conditions. Partly correlated to these conditions, the water demand of water users is also characterized by monthly variations. The monthly time step is typical for long-term water management and planning. Short-term variations (daily) are negligible for problems of the studied type in flat regions as the mining regions are.

## 4. Mathematical Model for the GDR Test-Area

### 4.1. Introduction

We consider a planning horizon of 50 years, divided into 10 planning periods. In Table 4.1 the time discretization is depicted.

**Table 4.1:** Time discretization of the model for the GDR Test-Area

| j | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Planning period | 1981 | 1982 | 1983 -1984 | 1985 -1986 | 1987 -1988 | 1989 -1990 | 1991 -1997 | 1998 -2005 | 2006 -2015 | 2016 -2030 |
| $\Delta T_j$ [years] | 1 | 1 | 2 | 2 | 2 | 2 | 7 | 8 | 10 | 15 |
| $i_B$ | 1 | 2 | 3 | 5 | 7 | 9 | 11 | 18 | 26 | 36 |
| $i_E$ | 1 | 2 | 4 | 6 | 8 | 10 | 17 | 25 | 35 | 50 |

$i_B$ - first year per period; $i_E$ - last year per period.

In Figure 4.1 a scheme of the test region is given, depicting the essential *decisions* on the systems development and *descriptors* of the systems development. In this scheme only those elements are included which are supposed to be affected by decisions. For instance, we neglect here a few tributaries (compare Figure 3.1).

We consider the following *decisions* on systems development (the used indices are given in Figure 4.1).

*Decisions*

$\mathbf{q}_{\alpha,\beta}$ - flux from $\alpha$ to $\beta$ (water allocation)
$\alpha = (a|b|c|d|s|g|p|im|i)$
$\beta = (s|m|i|ag|ex|p|e)$
$\mathbf{cq}_{\alpha}$ - supply of lime hydrate for water treatment
$\alpha = (a|b|c|d|p)$
$\mathbf{\Delta tm}_d$ - duration of mine drainage mine D before starting its operation
$\mathbf{maxh}_p$ - maximum water level in the remaining pit

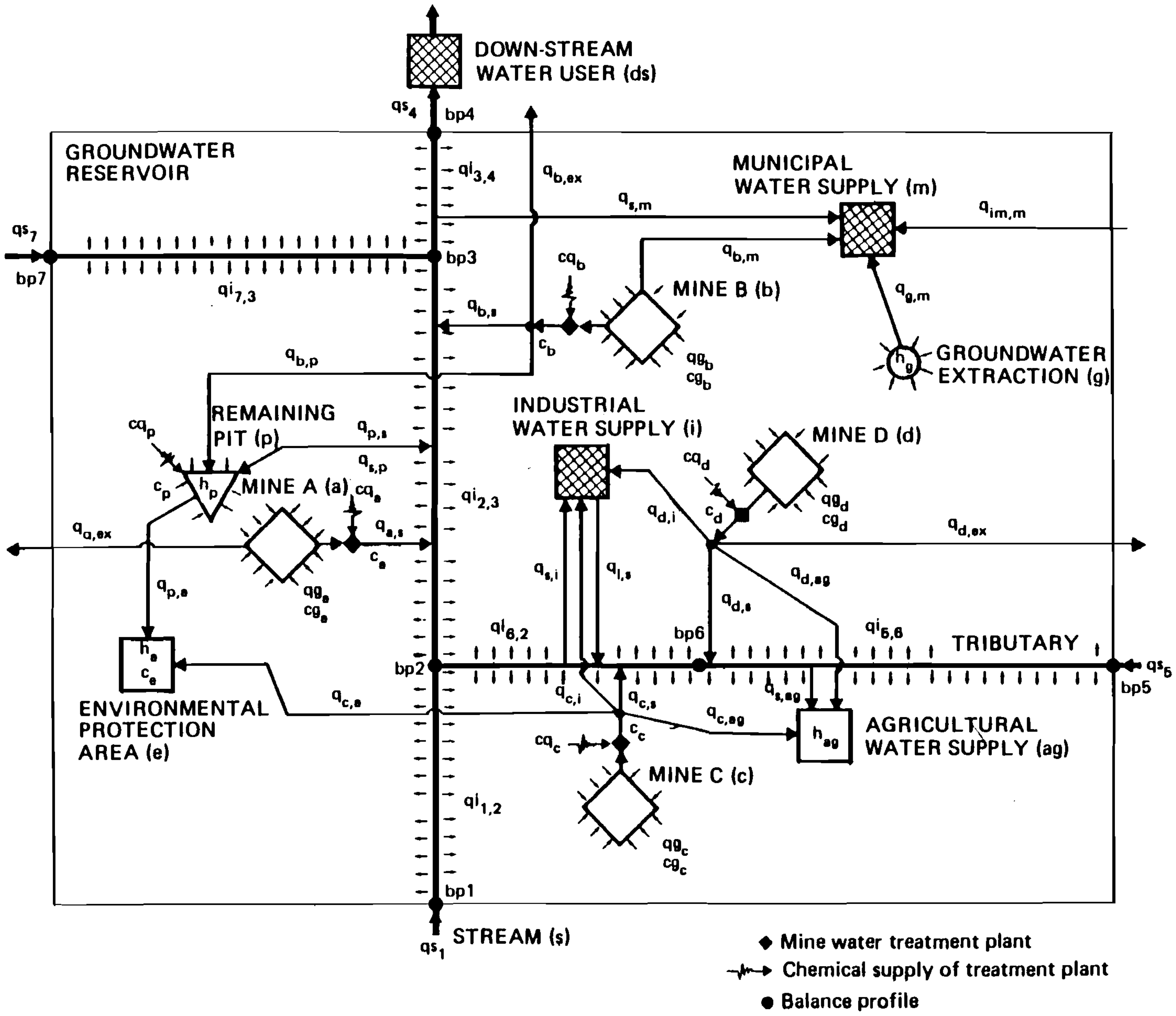


Figure 4.1: Detailed scheme of the test region.

The present model considers only continuous decision variables. Discrete decision on investment, for instance, to construct a treatment plant, an allocation pipe have to be done in a preparatory stage. In the long-term planning model bounds for the decision variables are considered, reflecting these investment decisions, e.g. the maximum flow through a pipeline according to its diameter. The used bounds are given in Appendix 2.

As *descriptors* of the systems development we have to take into account:

*Descriptors*

$qg_\alpha$ - groundwater flow to $\alpha$
$\alpha = (a|b1|b2|c|d|p)$
$qi_{\alpha,\beta}$ - infiltration balance segment $\Delta s_{\alpha,\beta}$
$h_\alpha$ - representative groundwater table
$\alpha = (ag|g|e)$
$cg_\alpha(l)$ - concentration of component $l$
$l=1 \rightarrow Fe^{2+}$, $l=2 \rightarrow H^+$
in the flow to $\alpha$
$\alpha = (a|b1|b2|c|d|p)$
$c_\alpha(l)$ - concentration of component $l$
in drainage water after treatment
$qs_\alpha, hs_\alpha$ - flux, respectively surface water
table at the balance profile $bp_\alpha$.
$cs_\alpha(l)$ - concentration of component $l$ in the
flux through balance profile $bp_\alpha$
$q_{i,s}$ - quantity of industrial waste water
$c_{i,s}(l)$ - concentration of component $l$ in the industrial waste water
$h_p$ - water table in the remaining pit
$c_p(l)$ - concentration of component $l$ in the remaining pit
$v_p$ - storage volume in the remaining pit

A detailed description of the abbreviations is given in Appendix 1.

To characterize the time dependency we use three different indices:

$j$ - characterizing the planning period $(j = 1, \cdots ,10)$
$i$ - characterizing the year $(i = 1, \cdots ,50)$
$k$ - month within one year $(k = 1, \cdots ,12)$

We use the following notation of time dependency of a value $x$:
$x(j)$ - mean value of $x$ for period $j$
$x(i)$ - mean value of $x$ for year $i$
$x(i,k)$ - mean value of $x$ for year $i$, month $k$.

Mine drainage of mine A is terminated in the planning period $j_a = 7$, after this period the remaining pit has to be considered. The mine drainage of mine D can start in period $j_d = 3$.

In the following the submodels for the long-term planning model and the management model are described, without giving the detailed background for their development. This will be done in a series of collaborative papers.

### 4.2. Indicators of Systems Development

We consider three types of indicators

- *deviation between water demand and supply* measured in $m^3/s$ as the mean value for a given time unit
- *environmental quality* for typical water quality parameters ($Fe^{2+}$, $H^+$) measured in $g/m^3$ as the mean value for a given time unit
- *economic characteristics* of regulating activities

#### 4.2.1. Water Demand-Water Supply Deviation

From the point of view of water management the satisfaction of the water demand of different users in the region is the most important indicator.

The minimum time unit for long-term planning studies in water management usually is one month. For the mean monthly water demand in the month *k* of the year *i* the following stochastic model is used principally:

$$dem(i,k) = trend\ (i,k) + oszi(k) + auto\ (i,k) + random \quad [m^3/sec] \qquad (4.1)$$

with:

| | | |
|---|---|---|
| $trend\,(i)$ | - | trend function (basically a deterministic function with a stochastic component) |
| $oszi(k)$ | - | deterministic oscillation component depending on typical seasonal behaviour of water users |
| $auto\ (i,k)$ | - | autocorrelated component |
| $random$ | - | random component (noise) |

In Figure 4.2 these components are illustrated.

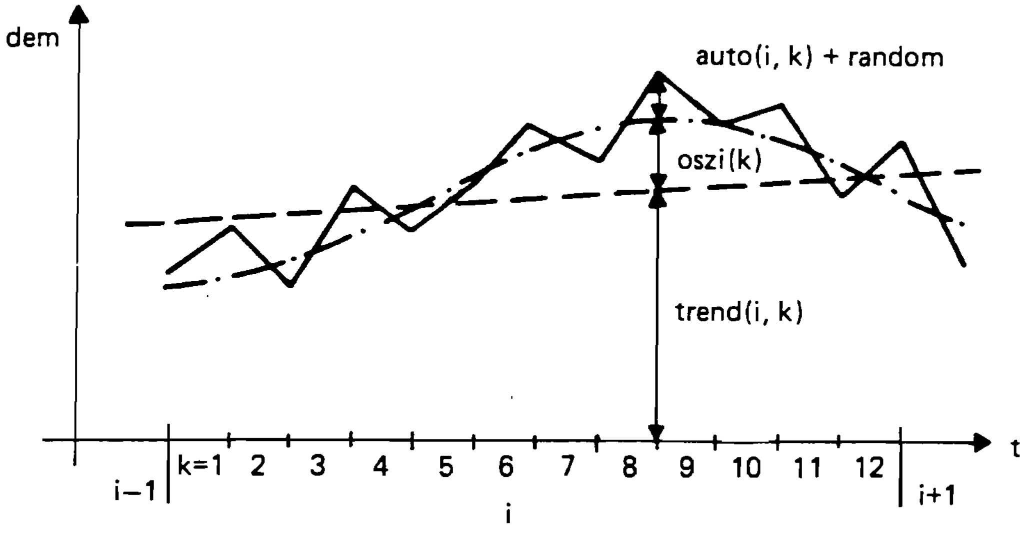


**Figure 4.2**: Characteristics of monthly water demand.

A detailed description of the modeling of water demand based on such *signal models* and their parameter estimation is given by Nestler et al. 1982.

Depending on the type of water user different models have to be built. In the following the models for the test area are given:

*Muncipal Water Demand*

$$dem_m(i,k) = trend_m(i,k) + oszi_m(k) + auto_m(i,k) \tag{4.2}$$

As a first assumption we consider a linear trend with an upper bound:

$$trend_m(i,k) = \min\{a_0 + a_1 \cdot (i + \frac{k}{12}), maxdem_m\} \tag{4.2a}$$

The oscillation component is approximated by a simple Fourier-series:

$$oszi_m(k) = a_2 \cdot \sin(\frac{\pi}{6}k) + a_3 \cdot \cos(\frac{\pi}{6}k) \tag{4.2b}$$

The autocorrelated component is described as a first-order model:

$$auto_m(i,k) = a_4 + a_5 \cdot \Delta dem_m(i,k-1) \quad .$$

With

$$\Delta dem_m(i,k-1) = dem_m(i,k-1) - trend_m(i,k-1) - oszi_m(k-1)$$

we get:

$$auto_m(i,k) = a_6 + a_7 \cdot dem_m(i,k-1) + a_8 \cdot (trend_m(i,k-1) + oszi_m(k-1)) \tag{4.2c}$$

For the *municpal water supply* in the test region the following function has been adopted:

$$\begin{aligned} dem_m(i,k) = {} & min[2826. + 309. \cdot (i+\frac{k}{12}), 25000.] \cdot (1. + \varepsilon) \\ & + 0.726 \cdot dem_m(i,k-1) - 816. \cdot sin(\frac{\pi}{6}k) - 481. \cdot cos(\frac{\pi}{6}k) \\ & + 592. \cdot sin(\frac{\pi}{6}(k-1)) + 349. \cdot cos(\frac{\pi}{6}(k-1)) \\ & + \varepsilon \quad [m^3/sec.] \end{aligned} \tag{4.3}$$

$$\text{index } i = 1 \mathrel{\hat{=}} \text{year 1981}$$

The random component $\varepsilon$ is assumed to be normal distributed with the standard deviation $\sigma = 0.67$.

For the long-term planning model we consider only the deterministic trend. We get the mean water demand for a planning period $j$ as

$$dem_m(j) = \frac{1}{2}(\hat{dem}_m(ib(j)) + \hat{dem}_m(ie(j)) \quad [m^3/sec.] \tag{4.4}$$

with $\hat{dem}_m(i) = 10240. + 1125. \cdot i$

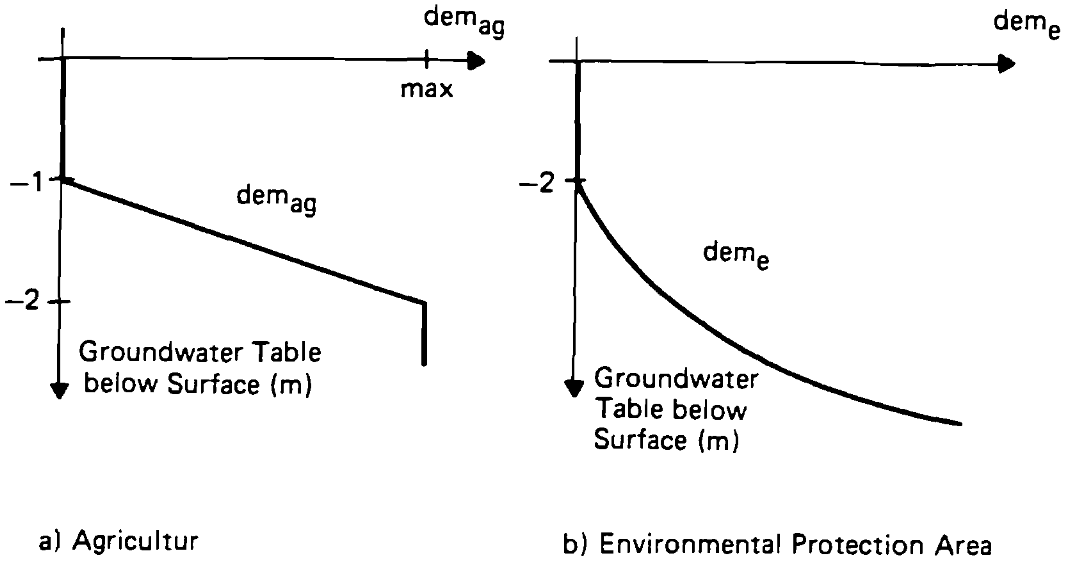
*Agricultural Water Supply*

In the test area we take into account agricultural water demand for irrigation only. This demand depends primarily on the groundwater tables in the agricultural area and on the actual precipitation. We take the following simplifying assumptions:

If the groundwater table is above one meter below the surface, the water demand by plants is satisfied by precipitation and capillary rise.

If the groundwater table is lower than 2 m below the surface, capillary rise is neglected.

The demand for supplementary irrigation consequently depends on the groundwater table. We use a simplified linear function (see Figure 4.3a).



a) Agricultur

b) Environmental Protection Area

**Figure 4.3**: Water demand depending on groundwater tables

For an arable land of 10 km$^2$ with a maximum supplementary irrigation rate of 200 mm/year and the surface level 141.5 m we obtain:

$$dem_{ag}(j) = \begin{cases} 0 & \text{for } h_{ag}(j) \geq 140.5 \\ 89.92-0.64 \cdot h_{ag}(j) & [m^3/sec.] \\ 0.64 \; m^3/sec & \text{for } h_{ag}(j) \leq 139.5 \end{cases} \tag{4.5}$$

This respresents the deterministic trend component of agricultural water demand. For the oscillation component we simply assume that the irrigation takes place in the vegetation period with a constant rate.

$$dem_{ag}(i,k) = \begin{cases} 0 & \text{for } k = 1,2,3,10,11,12 \\ 1/6\ dem_{ag}(j) & \text{for } k = 4, \ldots, 9 \end{cases} \tag{4.6}$$

The use of more sophisticated models is possible, for instance, the consideration of autocorrelated or random components.

*Water Demand of Down-Stream Water Users*

For the down-stream water use we might consider a model similar to that for the water demand for municipal water supply (Eq. (4.2)-(4.2c)). The quantification of such a model would be rather complicated because of the fact that the down-stream water demand represents a sum of manifold different water yields. As a first simple assumption we consider a constant demand for down-stream water use, that means a minimum outflow from the region has to be guaranteed.

$$dem_{ds}(i,k) = dem_{ds}(j) = 8\ m^3/s \tag{4.7}$$

*Industrial Water Demand*

Based on the assumptions of a constant industrial water demand in the yearly average (no extension of production as well as no change in specific water demand) and of annual random oscillation we obtain:

$$dem_i(j) = 4.0\ m^3/s \tag{4.8a}$$

$$dem_i(i,k) = 4.0 + \varepsilon \tag{4.8b}$$

$dem_i(i,k)$ is assumed to be normal distributed with a standard deviation $\sigma = 0.15$.

*Water Demand for Environmental Protection*

As mentioned above, the groundwater table in the environmental protection area is controlled by artificial groundwater recharge. We consider for the water demand a nonlinear function depending on the groundwater table (see Figure 4.3b). The nonlinearity reflects the increasing infiltration losses with decreasing groundwater tables. The following function is used

$$dem_e(j) = 0.075 \cdot (h_e(j) - 132.0)^2 \tag{4.9}$$

Changes in the water demand within planning periods are neglected.

Based on these demand functions we use the following indicators for the mean *deviation between water demand and supply* in planning periods:

*Municipal water supply*

$$dev_m(j) = |dem_m(j) - (q_{g,m}(j) + q_{b,m}(j) + q_{im,m}(j) + q_{s,m}(j))| \tag{4.10a}$$

Total criteria:

$$sdev_m = \sqrt{\sum_{j=1}^{J} (dev_m(j) \cdot \gamma(j))^2} \tag{4.10b}$$

For the weighting factor we consider the number of years per period

$$\gamma(j) = (i_E(j) - i_B(j) + 1)/i_E(J) \tag{4.11}$$

(compare Table 4.1).

*Industrial water supply*

$$dev_i(j) = |dem_i(j) - (q_{s,i}(j) + q_{c,i}(j) + q_{d,i}(j))| \tag{4.12a}$$

Total criteria:

$$sdev_i = \sqrt{\sum_{j=1}^{J} (dev_i(j) \cdot \gamma(j))^2} \tag{4.12b}$$

*Agricultural water supply*

$$dev_{ag}(j) = |dem_{ag}(j) - (q_{s,ag}(j) + q_{c,ag}(j) + q_{d,ag}(j))| \tag{4.13a}$$

Total criteria:

$$sdev_{ag} = \sqrt{\sum_{j=1}^{J} (dev_{ag}(j) \cdot \gamma(j))^2} \tag{4.13b}$$

*Water supply for down-stream water use*

$$dev_{ds}(j) = dem_{ds}(j) - qs_4(j)^{*)} \tag{4.14a}$$

Total criteria:

$$sdev_{ds} = \sum_{j=1}^{J} dev_{ds}(j) \tag{4.14b}$$

*Water supply for environmental protection area*

$$dev_e(j) = |dem_e(j) - (q_{c,e}(j) + q_{p,e}(j))| \tag{4.15a}$$

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*) The outflow from the region cannot be restricted to the water demand of down-stream users, $dev_{ds}$ can be negative.

Total criteria:

$$sdev_e = \sqrt{\sum_{j=1}^{J} (dev_e(j) \cdot \gamma(j))^2} \tag{4.15b}$$

For the monthly deviation between water demand and supply in the management model we use the following indicator, with *'pdem'* being a given probability:

*Municipal water supply*

$$dev_m(i,k) = dem_m(i,k) - (q_{g,m}(i,k) \pm q_{b,m}(i,k) + q_{im,m}(i,k) + q_{s,m}(i,k)) \tag{4.16a}$$

$$prob\ \{dev_m(i,k) \le 0\} \ge pdem_m = 0.95 \tag{4.16b}$$

*Industrial water supply*

$$dev_i(i,k) = dem_i(i,k) - (q_{s,i}(i,k) + q_{c,i}(i,k) + q_{d,i}(i,k)) \tag{4.17a}$$

$$prob\ \{dev_i(i,k) \le 0\} \ge pdem_i = 0.90 \tag{4.17b}$$

*Agricultural water supply*

$$dev_{ag}(i,k) = dem_{ag}(i,k) - (q_{s,ag}(i,k) + q_{c,ag}(i,k) + q_{d,ag}(i,k)) \tag{4.18a}$$

$$prob\ \{dev_{ag}(i,k) \le 0\} \ge pdem_{ag} = 0.80 \tag{4.18b}$$

*Down-stream water yield*

$$dev_{ds}(i,k) = dem_{ds}(i,k) - qs_4(i,k) \tag{4.19a}$$

$$prob\ \{dev_{ds}(i,k) \le 0\} \ge pdem_{ds} = 0.90 \tag{4.19b}$$

### 4.2.2. Environmental Quality

The state of the environment in the mining region is above all characterized by the water quality in the stream (outflow from the region), in the remaining pit, and in the environmental protection area. As substantiated above, for the test region the decisive water quality parameters are the $Fe^{2+}$ and $H^+$ concentrations.

We assume that optimal value for these parameters are specified. We define the environmental criteria in terms of the deviation from these optimal values in the mean for planning periods.

$$env_\alpha(j) = \frac{1}{2} \sum_{l=1}^{2} \frac{c_\alpha(l,j) - optc_\alpha(l)}{optc_\alpha(l)} \tag{4.20}$$

with $\alpha =$
$p$ – remaining pit
$ds$ – down–stream
$e$ – environmental protection area

$c_\alpha(l,j)$ – concentration of ion $l$ for *period* $j$

$l = 1 - Fe^{2+}$ $[g/m^3]$

$l = 2 - H^+$ $[g/m^3]$

$optc_\alpha(l)$ – optimal concentration of ion $l$

*Total criteria*

$$senv_\alpha = \sum_{j=1}^{J} env_\alpha(j) \cdot \gamma(j) \tag{4.21}$$

For the water quality of the artificial recharge in the environmental production area holds

$$c_e(l,j) = \frac{c_c(l,j) \cdot q_{c,e}(j) + c_p(l,j) \cdot q_{p,e}(j)}{q_{c,e}(j) + q_{p,e}(j)} \tag{4.22}$$

For the present stage of the study short-term variations in water quality are neglected.

### 4.2.3. Economic Indicators

Our principle economic indicators refer to the economics of mine drainage, economics of water supply and of environmental protection. To characterize the economical efficiency we use a complex index of expenses $E$. It includes

- the capital investment for technical installations such as drainage wells, pumps, pipelines and water treatment plants, $I$ defines the amortization;

- the maintenance and operational cost of technical installations $M$;
- benefits $B$ from water allocation for water user. These benefits are fixed by governmental laws. For instance, the mining industry gains for produced drinking water 0.70 Mark/m$^3$ if the water has drinking water quality, and 0.16 Mark/m$^3$ if the water needs additional treatment.

All prices used below are based on the price-level of the year 1980. In the socialist economy of the GDR prices are adapted yearly in accordance with the general economic development. This is considered by a yearly price index $\delta_d = 1.05$.

Characterizing economical indicators an important question is their evaluation and comparability in time. Generally, in case of investments for nonprofitable activities (in our case, for example, mine drainage, water treatment, etc.) the respective economic sector is interested to postpone these investments as far as possible. In the mean time the capital saved may be used for other, perhaps, more profitable activities. To model this behaviour we consider an "accumulation factor" $\delta_a = 1.065$. Expenses in later time periods get a lower weight than those in early periods.

Based on this we define the following economical indicator to be minimized

$$E = \sum_i \left[ I(i) + (M(i) + B(i)) \cdot \delta_d^i \right] \cdot \delta_a^{-i} \qquad (4.23)$$

For technical installations we assume fixed capacity and size.

The *amortization of water allocation installations* depends above all on the diameter and length of pipes. We use the following function (including the amortization for pumps) considering a service life of 20 years:

$$\alpha_{x,y} = (260.0 + 0.036 \cdot D^{1.559}) \cdot 1.1 \cdot L/20 \cdot 10^{-6} \ \text{[Mill.Mark/year]} \qquad (4.23a)$$

with D - Diameter of the pipe in [mm] and
L - Length of the pipe in [m] between "$x$" and "$y$".

For the *amortization of mine water treatment plants* holds:

$$\alpha_{t,x} = 0.18 \cdot Q_c \quad \text{[Mill.Mark/year]} \qquad (4.23b)$$

with $Q_c$ - projected capacity of the treatment plant x in [m$^3$/sec.].

Expenses for *maintenance* are defined as follows:

*Water treatment plants* (municipal and industrial water supply)

$$(\beta_{t,x} + \gamma_x \cdot c_x) \cdot q_x \cdot 31.5 \quad \text{[Mill.Mark/year]} \qquad (4.24)$$

with $\beta_{t,x}$ - specific expenses for maintenance depending on water quantity [Mark/m$^3$]
$\gamma_x$ - specific expenses for maintenance depending on load of pollutant [Mark/g]
$c_x$ - concentration of $Fe^{2+}$ [g/m$^3$]
$q_x$ - flow through treatment plant [m$^3$/sec]

*Mine water treatment plants*

$$(\beta_{t,x} + \gamma_t \cdot \mathbf{cq}_x) \cdot q_x \cdot 31.5 \quad [\text{Mill.Mark/ year}] \qquad (4.25)$$

with $\beta_{t,x}$ - see above
$\gamma_t$ - specific expenses for lime hydrate [Mark/g]
$\mathbf{cq}_x$ - supply with lime hydrate [g/m$^3$]
$q_x$ - see above

The parameters for these submodels are summarized in Appendix 3, Table 1 and 2.

The amortization and maintenance of mine water of drainage wells are considered in the specific expenses for mine water pumpage.

*Mine water pumpage*

$$\beta_{w,x} \cdot q_x \cdot 31.5 \quad [\text{Mill.Mark/ year}] \qquad (4.26)$$

with $\beta_{w,x}$ - specific expenses for mine water pumpage [Mark/m$^3$]
$q_x$ - flow [m$^3$/sec.]

The specific expenses for mine water pumpage are given in Appendix 3, Table 3.

The following specific benefits (expenses) for water allocation, discharge respectively, are considered.

$\beta_i$ - specific benefit (expenses) for water allocation from mines for industrial water supply = 0.16 $Mark / m^3$
$\beta_m$ - specific benefit (expenses) for water allocation from mines for municipal water supply
= 0.16 $Mark / m^3$ (not drinking water quality)
= 0.70 $Mark / m^3$ (drinking water quality)
$\beta_{ag}$ - specific benefit (expenses) for water allocation from mines for agricultural water supply = 0.00 $Mark / m^3$
$\beta_e$ - specific benefit (expenses) for water allocation to the environmental protection area = 0.02 $Mark / m^3$
$\beta_s$ - specific expenses for surface water use for industrial water supply = 0.12 $Mark / m^3$
$\beta_{uw}$ - specific expenses for industrial waste water allocation into the stream = 0.02 $Mark / m^3$

The expenses for mine water allocation into the stream depend on the water quality. We consider following simplified expression:

$$\gamma_s(c_x) \cdot c_x \cdot q_x \cdot 31.5 \quad [\text{Mill.Mark/ m}^3] \qquad (4.27)$$

with $\gamma_s$ = $0.00002 \cdot c_x - 0.001$ [Mark/g]
$c_x$ - concentration of $Fe^{2+}$ [g/$m^3$]
$q_x$ - flow [m$^3$/ sec.]

The economical indicators are considered for planning periods. To simplify the model description we define weighting factors

$$\delta_1(j) = \frac{1}{i_E(j) - i_B(j) + 1} \cdot \sum_{i=i_B(j)}^{i_E(j)} \delta_a(i)^{-i} \qquad (4.28a)$$

$$\delta_2(j) = \frac{1}{i_E(j)-i_B(j)+1} \cdot \sum_{i=i_B(j)}^{i_E(j)} \delta_d^i \qquad (4.28b)$$

In Table 4.2 the weighting factors for the planning periods are given:

**Table 4.2**: Weighting factor for economical indicators

| j | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\delta_1(j)$ | 0.939 | 0.882 | 0.803 | 0.708 | 0.624 | 0.550 | 0.417 | 0.261 | 0.149 | 0.069 |
| $\delta_2(j)$ | 1.05 | 1.103 | 1.187 | 1.308 | 1.442 | 1.590 | 1.989 | 2.873 | 4.472 | 8.332 |

Based on the above assumptions, the detailed economic indicator functions may be defined. Although we use the abbreviation "cost" in terms of Mill.Mark per time unit, the economic indicators are not the economical expenses themselves but their evaluations.

*Economics of mine drainage for the planning periods [Mill.Mark]*

**Mine A**

$$\begin{aligned} cost_a(j) = \delta_1(j) \cdot (a_{t,a} + a_{a,ex} + \\ + [\beta_{w,a} \cdot qg_a(j) + (\beta_{a,ex} - \beta_{i)}\mathbf{q}_{a,ex}(j) + \\ + (\beta_{t,a} + f\gamma_s(c_a(1,j)) \cdot c_a(1,j) + \gamma_t \mathbf{cq}_a(j)) \cdot \mathbf{q}_{a,s}(j)] \cdot \delta_2(j)31.5) \cdot \Delta T_j \end{aligned} \qquad (4.29)$$

**Mine B**

We assume that expenses for water allocation to the remaining pit are paid by the water agency. Expenses for water allocation to the municipal water supply are considered in the price of water pumpage.

$$\begin{aligned} cost_b(j) = \delta_1(j) \cdot (\alpha_{t,b} + \alpha_{b,ex} + \\ + [\beta_{w,b1} \cdot qg_{b1}(j) + (\beta_{b,ex} - \beta_i) \cdot \mathbf{q}_{b,ex}(j) + \\ + (\beta_{w,b2} + \beta_{t,b} + \gamma_t \cdot \mathbf{cq}_b(j)) \cdot qg_{b2}(j) \\ - \beta_m \cdot \mathbf{q}_{b,m}(j) + f\gamma_s(c_b(1,j) \cdot \mathbf{q}_{b,s}(j)] \cdot \delta_2(j) \cdot 31.5) \cdot \Delta T_j \end{aligned} \qquad (4.30)$$

**Mine C**

We assume that expenses for water allocation to the industry are paid by the industry:

$$\begin{aligned} cost_c(j) = \delta_1(j) \cdot (\alpha_{t,c} + \alpha_{c,e} + \alpha_{c,ag} + \\ + [(\beta_{c,ag} - \beta_{ag}) \cdot \mathbf{q}_{c,ag}(j) + (\beta_{c,e} - \beta_e)\mathbf{q}_{c,e}(j) + \\ + (\beta_{w,c} + \beta_{t,c} + \gamma_t \cdot \mathbf{cq}_c(j)) \cdot qg_c(j) \\ - \beta_i \cdot \mathbf{q}_{c,i}(j) + f\gamma_s(c_c(1,j)) \cdot c_c(1,j) \cdot \mathbf{q}_{c,s}(j)] \cdot 31.5 \cdot \delta_2(j)) \cdot \Delta T_j \end{aligned} \qquad (4.31)$$

**Mine D**

We assume that expenses for water allocation to the industry are paid by the industry:

$$\begin{gathered} cost_d(j) = \delta(j) \cdot (\alpha_{t,d} + \alpha_{d,ex} + \alpha_{d,ag} + \\ + [(\beta_{d,ag} - \beta_{ag}) \cdot \mathbf{q}_{d,ag}(j) + (\beta_{d,ex} - \beta_i)\mathbf{q}_{d,ex}(j) + \\ + (\beta_{w,d} + \beta_{t,d} + \gamma_t \cdot \mathbf{cq}_d(j)) \cdot qg_d(j) \\ - \beta_i \cdot \mathbf{q}_{d,i}(j) + f\,\gamma_s(c_d(1,j) \cdot \mathbf{q}_{d,s}(j))]\,\delta_2(j) \cdot 31.5) \cdot \Delta T_j \end{gathered} \tag{4.32}$$

*Economics of mine drainage for the planning horizon* [*Mill.Mark*]

$$scost_x = \sum_{j=1}^{J} cost_x(j)\ ,\ x = (a \mid b \mid c \mid d) \tag{4.33}$$

Total costs for mine drainage:

$$scost_{mine} = scost_a + scost_b + scost + scost_d \tag{4.34}$$

*Economics of water supply in planning periods* [*Mill.Mark*]

**Municipal water supply**

$$\begin{gathered} cost_m(j) = \delta_1(j) \cdot (\alpha_{s,m} + \alpha_{t,m} + \alpha_{im,m} + \\ + [(\beta_{w,g} + \beta_{t,m}) \cdot \mathbf{q}_{g,m}(j) + (\beta_m + \beta_{t,m})\mathbf{q}_{b,m}(j) + \\ + (\beta_{s,m} + \beta_{t,m} + \gamma_m \cdot cs_3(1,j) \cdot \mathbf{q}_{s,m}(j) \\ + (\beta_{im,m} + \beta_m) \cdot \mathbf{q}_{im,m}(j)] \cdot 31.5 \cdot \delta_2(j)) \cdot \Delta T_j \end{gathered} \tag{4.35}$$

**Industrial water supply**

$$\begin{gathered} cost_i(j) = \delta_1(j) \cdot (\alpha_{s,i} + \alpha_{t,i} + \alpha_{i,s} + \alpha_{c,i} + \alpha_{d,i} + \\ + [(\beta_{c,i} + \beta_{t,i} + \beta_i + \gamma_i \cdot c_c(1,j)) \cdot \mathbf{q}_{c,i}(j) + \\ + (\beta_{d,i} + \beta_{t,i} + \beta_i + \gamma_i \cdot c_d(1,j)) \cdot \mathbf{q}_{d,i}(j) + \\ + (\beta_{s,i} + \beta_s + \beta_{t,i} + \gamma_i \cdot cs_2(1,j)) \cdot \mathbf{q}_{s,i}(j) \\ + (\beta_{i,s} + \beta_{ww} + \beta_{t,w}) \cdot \mathbf{q}_{i,s}(j)] \cdot 31.5 \cdot \delta_2(j)) \cdot \Delta T_j \end{gathered} \tag{4.36}$$

**Agricultural water supply**

$$\begin{gathered} cost_{ag}(j) = \delta_1(j) \cdot (\alpha_{s,ag} + \\ + [(\beta_{s,ag} + \beta_s) \cdot \mathbf{q}_{s,ag}(j) + \beta_{ag}(\mathbf{q}_{c,ag}(j) + \mathbf{q}_{d,ag}(j))] \cdot 31.5 \cdot \delta_2(j)) \cdot \Delta T_j \end{gathered} \tag{4.37}$$

*Economics of water supply for the planning horizon* [*Mill.Mark*]

$$scost_x = \sum_{j=1}^{J} cost_x(j)\ \ x = (m \mid i \mid ag) \tag{4.38}$$

*Economics of environmental protection and control of remaining pit for planning periods [Mill.Mark].*

**Remaining pit**

$$cost_p(j) = \delta_1(j) \cdot (\alpha_{s,p} + \alpha_{p,s} + \alpha_{b,p} + \\ + [\beta_{s,p} \cdot \mathbf{q}_{s,p}(j) + \beta_{p,s} \cdot \mathbf{q}_{p,s}(j) + \beta_{b,p} \cdot \mathbf{q}_{b,p}(j) \\ - \beta_e \cdot \mathbf{q}_{p,e}(j) + \gamma_t \cdot \mathbf{cq}_p(j)] \cdot 31.5 \cdot \delta_2(j)) \cdot \Delta T_j \tag{4.39}$$

**Environmental protection**

$$cost_e(j) = \delta_1(j) \cdot (\alpha_{p,e} + \\ + [(\beta_{p,e} + \beta_e) \cdot \mathbf{q}_{p,e}(j) + \beta_e \cdot \mathbf{q}_{c,e}(j)] \cdot 31.5 \cdot \delta_2(j)) \cdot \Delta T_j \tag{4.40}$$

*Economics of environmental protection/control of the remaining pit for the planning horizon [Mill.Mark]*

$$scost_x = \sum_{j=1}^{J} cost_x(j) \quad x = (e \mid p) \tag{4.41}$$

The used economical functions are of a simplified, preliminary character. It is presumed to specify these functions in the future based on detailed economical analysis. Nevertheless, we assume that these functions capture the economical processes sufficient accurately for the present study.

## 4.3. Descriptors of Systems Development

### 4.3.1. System Descriptive Functions

*Groundwater Flow into Mines*

Based on the methodology described in Section 2.3 the following submodels for the mean groundwater flow in planning periods into the mines has been developed (for the parameters see Appendix 3, Table 4.)

**Mine A**

$$qg_a(j) = a_1(j)^* \tag{4.42a}$$

**Mine B**

$$qg_{b1}(j) = a_1(j) \tag{4.42b1}$$

$$qg_{b2}(j) = a_1(j) + a_2(j) \cdot \mathbf{h}_p(j) \tag{4.42b2}$$

**Mine C**

$$qg_c(j) = a_1(j) \tag{4.42c}$$

**Mine D**

$$qg_d(j) = a_1(j) + a_2(j) \cdot \mathbf{\Delta tm}_d + a_3(j) \cdot \mathbf{\Delta tm}_d^2 \qquad (4.42d)$$

For the first stage of our study we assume that the groundwater flow to mines A, C and $B_1$ (special well galleries for municipal water supply) is not affected by control actions. The mine drainage B depends linear on the water table in the remaining pit. For the mine drainage mine D we consider a quadratic dependency on the timing of mine drainage. The interpolation function is based on computations with the sophisticated groundwater flow model for the values $\mathbf{\Delta tm}_d = -2$ years, 0,+2 years.

For the management model we have to consider the changes in mine drainage mine B due to the monthly changes of the water table of the remaining pit $\mathbf{h}_p$.

A linear time discrete boxmodel has been developed. For the additional groundwater flow $\Delta qg_b$ into mine B due to the remaining pit control the following model holds (yearly mean values):

$$\begin{aligned} \Delta qg_b(i) = {} & a_1 \cdot \Delta qg_b(i-1) + a_2 \cdot \Delta qg_b(i-2) \\ & + a_3 \cdot \tilde{q}(i) + a_4 \cdot \tilde{q}(i-1) + a_5 \cdot \tilde{q}(i-2) \end{aligned} \qquad (4.43)$$

$$\tilde{q}(i) = qg_p(i) - qg_p^o(i) \quad [m^3/sec] \qquad (4.43a)$$

with $qg_p(i)$ - actual groundwater flow into the remaining pit (see Equation 4.49a)

$qg_p^o(i)$ - groundwater flow into the remaining pit in the case of its natural rise (see Appendix 3, Table 5)

$a_1 = 0.6541$ , $a_2 = -0.0042$
$a_3 = -1.64 \cdot 10^{-4}$ $a_4 = -7.65 \cdot 10^4$ $a_5 = 2.6775.10^{-4}$

The actual groundwater flow into mine B is

$$qg_{b2}(i) = qg_{b2}^o(j) + \Delta qg_b(i) \qquad (4.43b)$$

with $qg_{b2}^o(j)$ - groundwater flow into Mine B
in the case of natural rise of the remaining pit

The reference values $qg_p^o$ , $qg_{b2}^o$ are given in Appendix 3 Table 5.

*Bankfiltration for stream segments*

For the long-term planning the submodels for the bankfiltration for stream segments have been developed according to the methodology in Section 2. In these models we neglected changes in the water table in the stream segments resulting from fluctuations in the inflow. Obviously, this is a reasonable

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*)$a_1(j), a_2(j)$, etc. mean that the value for period $j$ is given as a constant, the values are different for each expression.

assumption for mean values for yearly and even longer time periods. The model parameters are given in Appendix 3, Table 6.

**Segment $\Delta s_{1,2}$**

$$qi_{1,2}(j) = a_1(j) + a_2(j) \cdot \mathbf{h}_p(j) \tag{4.44a}$$

**Segment $\Delta s_{2,3}$**

$$qi_{2,3}(j) = a_1(j) + a_2(j) \cdot \mathbf{h}_p(j) \tag{4.44b}$$

**Segment $\Delta s_{3,4}$**

$$qi_{3,4}(j) = a_1(j) \tag{4.44c}$$

**Segment $\Delta s_{6,2}$**

$$qi_{6,2}(j) = a_1(j) + a_2(j) \cdot \Delta\mathbf{tm}_d + a_3(j) \cdot \Delta\mathbf{tm}_d^2 \tag{4.44d}$$

**Segment $\Delta s_{5,6}$**

$$qi_{5,6}(j) = a_1(j) + a_2(j) \cdot \Delta\mathbf{tm}_d + a_3(j) \cdot \Delta\mathbf{tm}_d^2 \tag{4.44e}$$

**Segment $\Delta s_{7,3}$**

$$qi_{7,3}(j) = a_1(j) \tag{4.44f}$$

For the management model the impact of surface water table (inflow) fluctuations has to be considered. Based on the methodology outlined in Section 2 the following model has been developed for the infiltration in the balance segment $\alpha,\beta$ :

$$qi_{\alpha,\beta}(i,k) = qi_{\alpha,\beta}(j) + \Delta qi_{\alpha,\beta}(i,k) \tag{4.45}$$

$\Delta qi_{\alpha,\beta}(i,k)$ is the infiltration resulting from changes in surface water tables during month $k$ of the year $i$, $qi_{\alpha,\beta}(j)$ is the mean infiltration for the corresponding planning period. Based on the convolution integral we obtain for $\Delta qi_{\alpha,\beta}$

$$\begin{aligned}\Delta qi_{\alpha,\beta}(i,k) &= a_1 \cdot \Delta qi_{\alpha,\beta}(i,k-1) + a_2 \cdot \Delta qi_{\alpha,\beta}(i,k-2) \\ &+ (b_0 + c_0) \cdot u_{\alpha,\beta}(i,k) + b_1 \cdot u_{\alpha,\beta}(i,k-1) + b_2 \cdot u_{\alpha,\beta}(i,k-2)\end{aligned} \tag{4.46}$$

with $u(i,k) = hs(i,k) - hs(j)$
$hs$ – surface water table.

In Appendix 3, Table 7 the coefficients are given for all stream segments under consideration. For the surface water table key functions of the type

$$hs = fhs(qs) = exp((ln\ qs - k1)/k2) + k3 \tag{4.47}$$

with $hs$ - surface water table (over bottom)
$qs$ - flow
$k\,1,2,3$ - parameters

have been estimated. The parameters are given in Appendix 3, Table 8.

For the step $u_{\alpha,\beta}(i,k)$ in a balance segment $\alpha,\beta$ a weighted mean between the steps in the inflow profile $\alpha$ and the outflow profile $\beta$ has to be used.

$$u_{\alpha,\beta}(i,k) = \gamma \cdot u_{\alpha}(i,k) + (1-\gamma) \cdot u_{\beta}(i,k) \tag{4.48a}$$

$$u_{\alpha}(i,k) = fhs_{\alpha}(qs_{\alpha}(i,k)) - hs_{\alpha}(j) \tag{4.48b}$$

$$u_{\beta}(i,k) = fhs_{\beta}(qs_{\alpha}(i,k) - qi_{\alpha,\beta}(j) - \Delta qi_{\alpha,\beta}(i,k)) - hs_{\beta}(j) \tag{4.48c}$$

We use as a first assumption $\gamma = 1/2$. This model has to be run iteratively.

### *Infiltration from the groundwater into the remaining pit*

From the water balance we get for the planning period (compare Section 4.4.2)

$$\begin{aligned} qg_p(j) = (&-v_p(i_b(j)-1) + v_p(i_e(j))) \cdot 0.0317 - \\ &-(\mathbf{q}_{b,p}(j) + \mathbf{q}_{s,p}(j) - \mathbf{q}_{p,s}(j) - \mathbf{q}_{p,e}(j)) \end{aligned} \tag{4.49a}$$

and for the year

$$\begin{aligned} qg_p(i) = &(v_p(i) - v_p(i-1)) \cdot 0.0317 \\ &-(\mathbf{q}_{b,p}(i) + \mathbf{q}_{s,p}(i) - \mathbf{q}_{p,s}(i) - \mathbf{q}_{p,e}(i)) \end{aligned} \tag{4.49b}$$

Monthly fluctuations of the infiltration will be neglected.

### *Groundwater Tables*

We consider only long-term changes in groundwater tables for planning periods. Annual changes in groundwater tables will be neglected. Based on the methodology described in Section 2 we obtained the following submodels for representative groundwater tables (for the model parameters see Appendix 3, Table 9).

### **Groundwater table in the agricultural area**

$$h_{ag}(j) = a_1(j) + a_2(j) \cdot \Delta \mathbf{tm}_d + a_3(j) \cdot \Delta \mathbf{tm}_d^2 \tag{4.50a}$$

**Groundwater table near the groundwater extraction wells**

$$h_g(j) = a_1(j) + a_2(j) \cdot \Delta\mathbf{tm}_d + a_3(j) \cdot \Delta\mathbf{tm}_d^2 \qquad (4.50b)$$

**Groundwater table in the environmental protection area**

$$h_e(j) = a_1(j) + a_2(j) \cdot \mathbf{h}_p(j) \qquad (4.50c)$$

*Surface Water Inflow*

The inflow into the region $(qs_1, qs_5, qs_7)$ as a noncontrollable hydrological input is modelled as a multidimensional, nonstationary, logarithmic normal distributed Markovian process. Define $\overline{qs} = (qs_1, qs_5, qs_7)^T$ as the vector of unknown inflow and $\overline{qs}_N$ the corresponding vector of N(0,1) distributed inflows. Both vectors are correlated by a logarithmic normal distribution with 3 parameters $(q\bar{0}, \bar{s}, \overline{qm})$:

$$\overline{qs}(j) = q\bar{0}(j) + \exp[\bar{s}(j) \cdot \overline{qs}_N(j) + \overline{qm}(j)] \qquad (4.51a)$$

$$\text{for } j = 1,2, \cdots ,12$$

For the inflow in the month $j$ the following simulation model holds

$$\overline{qs}_N(j) = A(j) \cdot \overline{qs}_N(j-1) + B(j) \cdot \overline{qs}_N(j) + \bar{\sigma}(j) \cdot \bar{\varepsilon} \qquad (4.51b)$$

$$\text{for } j = 1,2, \cdots ,12$$

with $A(j)$, $B(j)$ - matrices of regression coefficients,
$\bar{\sigma}(j)$ - vector of residual standard distribution,
$\bar{\varepsilon}$ - N(0,1)-distributed random vector.

The parameters of the distribution functions and the regression coefficients have been estimated based on a 30-years series of observation data.

For the planning model we use the long-term mean values $qs_1(j) = 4.71\ m^3/s$, $qs_5(j) = 3.13\ m^3/s$, $qs_7(j) = 0.98\ m^3/s$.

*Surface water balances*

For the surface water balances in the stream and its tributaries in monthly or greater time units the storage capacity is negligible in comparison to the flow. The following balance equations hold:

**Balance profile bp6:**

$$qi_{5,6} + \mathbf{q}_{s,ag} - \mathbf{q}_{d,s} + qs_6(j) = 0.5 + qs_5 \qquad (4.52a)$$

**Balance profile bp2:**

$$qi_{1,2} + qi_{6,2} + \mathbf{q}_{s,i} - \mathbf{q}_{c,s} - \mathbf{q}_{i,s} + qs_2 = 4.9 + qs_1 + qs_6 \qquad (4.52b)$$

**Balance profile bp3:**

$$qi_{7,3} + qi_{2,3} + \mathfrak{q}_{s,p}(j) - \mathfrak{q}_{p,s} + \mathfrak{q}_{a,s} - \mathfrak{q}_{b,s} + qs_3 = 7.2 + qs_2 + qs_7 \tag{4.52c}$$

**Balance profile bp4:**

$$qi_{3,4} + \mathfrak{q}_{s,m} + qs_4 = 2.0 + qs_3 \tag{4.52d}$$

*Groundwater quality*

The representative water quality parameters are the iron concentration $Fe^{2+}$ and the hydrogen concentration $H^+$. For the forecast of these values no sophisticated groundwater quality model was available. Based on samples a linear trend of the groundwater quality and its deviations $\sigma_r$ have been estimated for the planning periods. The values are given in Appendix 3, Table 10 (for the $H^+$ concentration in terms of the pH value).

For the stochastic simulation in the management model we generate the actual concentrations with a random generator for the given mean values and rest deviations. In case for the deviation $\sigma_r$ a linear trend might be considered.

*Quality of surface water inflow*

Due to the lack of more detailed information we start with constant quality parameters.

$$\begin{array}{rl@{\qquad}rl} & cs_1(1,j) = 2\,g/m^3 & & cs_1(2,j) = 6.5 \\ Fe^{2+}: & cs_5(1,j) = 1\,g/m^3 & pH: & cs_5(2,j) = 6.8 \\ & cs_7(1,j) = 5\,g/m^3 & & cs_7(2,j) = 6.2 \end{array} \tag{4.53}$$

*Quality balance for stream sections*

For the water quality in the stream its self-purification capacity is important. We consider a stream section $\alpha,\beta$ of the length $\Delta s_{\alpha,\beta}$ as a "black-box". The decomposition rate in the stream for the concentration of $Fe^{2+}$-ions $C_{Fe}$ has been estimated as

$$R = k' \cdot \frac{C_{Fe}}{C_H^2} = 4.1 \cdot 10^{-18} \cdot \frac{C_{Fe}}{C_H^2} \tag{4.54a}$$

with $C_H$-hydrogen concentration.

Hence we obtain

$$-v \cdot \frac{\partial C_{Fe}}{\partial x} = R \;, \quad C_{Fe}(x=0) = C_{Fe,a} \tag{4.54b}$$

with $v$ - flow velocity
$x$ - coordinate
$C_{Fe,a}$ - $Fe^{2+}$ - concentration of inflow

Solving this problem we obtain for $x = \Delta s$ the $Fe^{2+}$-concentration of the outflow of the stream section $C_{Fe,\beta}$ as

$$C_{Fe,\beta} = C_{Fe,\alpha} \cdot \exp\left(-\frac{k' \cdot \Delta s_{\alpha,\beta}}{v_{\alpha,\beta} \cdot C_H^2}\right) \tag{4.54c}$$

For the flow velocity $v_{\alpha,\beta}$ we consider an average constant value and for the $H^+$ - concentration $C_H$ the concentration of the inflow $C_{H,\alpha}$ to avoid an iteration procedure. With the common terminology of our model we get

$$cs_\beta^\alpha(1) = cs_\alpha(1) \cdot \exp\left(\frac{\tilde{k}}{cs_\alpha(2)^2}\right) \tag{4.54d}$$

with

$$\tilde{k} = -\frac{k' \cdot \Delta s_{\alpha,\beta}}{v_{\alpha,\beta}} \tag{4.54e}$$

For the $H^+$-concentration of the outflow $C_{H,\beta}$ holds

$$C_{H,\beta} = C_{H,\alpha} + 3.58 \cdot 10^{-5} \cdot (C_{Fe,\alpha} - C_{Fe,\beta}) \quad , \tag{4.54f}$$

respectively

$$cs_\beta^\alpha(2) = cs_\alpha(2) + 3.58 \cdot 10^{-5}(cs_\alpha(1) - cs_\beta(1)) \tag{4.54g}$$

With the estimated selfpurification model (4.54d, g) we can describe the principle balance equations for the stream segments ($l$ = 1,2)

**Balance profile bp6:**

$$cs_6(l) = \frac{cs_6^5(l) \cdot qs_5 + c_d \cdot \mathbf{q}_{d,s}}{qs_6} \tag{4.55a}$$

**Balance profile bp2:**

$$cs_2(l) = \frac{cs_2^1(l) \cdot qs_1 + cs_2^6(l) \cdot qs_6 - cs_6(l) \cdot \mathbf{q}_{s,i} + c_c(l) \cdot \mathbf{q}_{c,s} + ci_s(l) \cdot \mathbf{q}_{i,s}}{qs_2} \tag{4.55b}$$

**Balance profile bp3:**

$$cs_3(l) = \frac{cs_3^2(l) \cdot qs_2 + cs_3^7(l) \cdot qs_7 + c_a(l) \cdot \mathbf{q}_{a,s} + c_b(l) \cdot \mathbf{q}_{b,s} + c_p(l) \cdot \mathbf{q}_{p,s} - cs_2(l) \cdot \mathbf{q}_{s,p}}{qs_3} \tag{4.55c}$$

**Balance profile bp4:**

$$cs_4(l) = \frac{cs_4^3(l)\cdot qs_3 - cs_3(l)\cdot \mathbf{q}_{s,m}}{qs_4} \tag{4.55d}$$

*Industrial waste water*

For the given industry in the test region, 70% of the water supply is consumed, only 30% is discharged as waste water back into the stream.

*Amount of industrial waste water*

$$q_{i,s} = 0.3\cdot(\mathbf{q}_{s,i} + \mathbf{q}_{d,i} + \mathbf{q}_{c,i}) \tag{4.56}$$

The water quality model of the industrial waste water is based on the assumption that the $Fe^{2+}$ and $H^+$ load in the water is not changed in the course of industrial water use. Consequently we obtain

*Quality parameter of industrial waste water* ($l = 1,2$)

$$ci_s(l) = (cs_6(l)\cdot \mathbf{q}_{s,i} + c_c(l)\cdot \mathbf{q}_{c,i} + c_d(l)\cdot \mathbf{q}_{d,i}) / q_{i,s} \tag{4.57}$$

*Mine water treatment*

For the purification capacity of the mine water treatment plants as a first approach the following model has been developed:

$$C_{Fe}^{o} = C_{Fe} - 0.698\cdot C_{LH} \tag{4.58a}$$

$$C_{Fe}^{t} = \begin{cases} 0 & \text{for} \quad C_{Fe}^{o} \le \vartheta \\ C_{Fe}^{o} & \text{for} \quad C_{Fe}^{o} > \vartheta \end{cases} \tag{4.58b}$$

$$C_H^t = \begin{cases} C_H & \text{for} \quad C_{Fe}^{o} > 0 \\ C_H - 0.025\cdot C_{LH} + 0.0358\cdot(C_{Fe} - C_{Fe}^{t}) & \text{for} \quad C_{Fe}^{o} \le 0 \end{cases} \tag{4.58c}$$

$$10^{-8.5} \le C_H^t \le 10^{-6.5}$$

with $C_{Fe}$ - $Fe^{2+}$-concentration of inflow into treatment plant ($g/m^3$)

$C_H$ - $H^+$-concentration of inflow ($g/m^3$)

$C_{Fe}^t$ - $Fe^{2+}$-concentration of outflow from treatment plant ($g/m^3$)

$C_H^t$ - $H^+$-concentration of outflow ($g/m^3$)

$C_{LH}$ - added lime hydrate ($g/m^3$)

This model is used for the management model. For the planning model the unsteadiness of the model cannot be considered. Therefore, we use the following smooth model (in terms of the common model parameter)

$$c_\alpha^{o} = cg_\alpha(1,j) - 0.698 \cdot cq_\alpha(j) \tag{4.58d}$$

$$\gamma = \frac{1}{\pi} \cdot arctan(1000 \cdot c_\alpha^{o}) \tag{4.58e}$$

$$c_\alpha(1,j) = c_\alpha^{o} \cdot (\gamma + 1/2) \tag{4.58f}$$

$$c_\alpha(2,j) = cg_\alpha(2,j) + (0.025 \cdot cq_\alpha(j) - 0.0358 \cdot (cg_\alpha(1,j) - c_\alpha(1,j)) \cdot (1/2 - \gamma) \quad \text{for} \quad \alpha = a \,|\, b \,|\, c \,|\, d \tag{4.58g}$$

### 4.3.2. State Transition Functions

The dynamics of the water resources system in the test region strongly depends on the control of the remaining pit. This holds for the water quantity as well as the water quality.

*Water table in the remaining pit*

Based on the methodology outlined in Section 2.3, a linear time discrete box model has been developed for the water table in the remaining pit at the end of one year ($ip$ - year of flooding the remaining pit).

$$h_p(ip) = -0.0421 \cdot \Delta h_p(ip) + 0.0156 \cdot \Delta h_p(ip)^2 + 86.1 \tag{4.59a}$$

$$h_p(ip+1) = 0.0102 \cdot \Delta h_p(ip+1) + 1.2458 \cdot h_p(ip) - 17.5949 \tag{4.59b}$$

for $i = ip + 2, \ldots, i_E(J)$:

$$\begin{aligned} h_p(i) = h_p^0(i) &+ 1.278 \cdot (h_p(i-1) - h_p^0(i-1)) - 0.378 \cdot (h_p(i-2) \\ &- h_p^0(i-2)) + 0.655 \cdot \Delta h_p(i) - 0.42 \cdot \Delta h_p(i-1) + 0.024 \cdot \Delta h_p(i-2) \end{aligned} \tag{4.59c}$$

with

$ip$ - year of opening the remaining pit

$\Delta h_p(i)$ - hypothetic water table difference due to change of storage volume in the year $i$, neglecting infiltration

$h_p^0(i)$ - water table in the remaining pit in the case of its natural rise (see Appendix 3, Table 5)

To estimate the hypothetic water table difference $\Delta h_p$ we need the filling function of the remaining pit

$$h_p = fh_p(v_p) \ ; \ v_p = fv_p(h_p)$$

with $v_p$ - storage volume in the remaining pit [Mill.m$^3$].

In Table 4.3 the filling function is given in tabulated form. For the model we use piecewise linear interpolation.

**Table 4.3**: Filling function of the remaining pit

| $h_p[m]$ | 68.0 | 70.0 | 80.0 | 90.0 | 100.0 | 110.0 | 118.0 |
|---|---|---|---|---|---|---|---|
| $v_p[Mill.m^3]$ | 0.0 | 1.4 | 3.7 | 10.0 | 28.0 | 70.0 | 129.0 |

Using these functions we obtain

$$\Delta h_p(i) = fh_p(v_p(i-1) + \Delta q_p(i)) - h_p(i-1) \tag{4.60}$$

with

$$v_p(i-1) = fv_p(h_p(i-1)) \tag{4.60a}$$

$$\Delta q_p(i) = (\mathbf{q}_{b,p}(i) + \mathbf{q}_{s,p}(i) - \mathbf{q}_{p,s}(i) - \mathbf{q}_{p,e}(i)) \cdot 31.5 \quad [Mill.m^3/\,year] \tag{4.60b}$$

Based on Eq. (4.57) we obtain the mean water table in the remaining pit for the planning period to

$$\mathbf{h}_p(j) = \frac{1}{i_E(j) - i_B(j) + 2} \sum_{i=i_B(j)-1}^{i_E(j)} h_p(i) \tag{4.61}$$

$$h_p(ip-1) = h_p^0(ip-1)$$

For the monthly water table in the remaining pit we obtain

$$h_p(i,k) = h_p(i-1) + \frac{k}{12}(\hat{h}_p - h_p(i-1)) \tag{4.62a}$$

with

$$\begin{aligned} \hat{h}_p &= h_p^0(i) + 1.278 \cdot (h_p(i-1) - h_p^0(i-1)) \\ &\quad - 0.378 \cdot (h_p(i-2) - h_p^0(i-2)) \\ &\quad + 0.655 \cdot \frac{12}{k} \Delta h_p(i,k) - 0.424 \cdot \Delta h_p(i-1) + 0.024 \cdot \Delta h_p(i-2)) \end{aligned} \tag{4.62b}$$

$$\Delta h_p(i,k) = fh_p(v_p(i-1) + \sum_{n=1}^{k} \Delta q_p(i,n)) - h_p(i-1) \tag{4.62c}$$

*Water quality in the remaining pit*

The water quality in the remaining pit depends on storage, decomposition, inflow and outflow, as well as on the adding of lime hydrate. The following principle model has been developed

$$0 = \frac{d(C_{Fe} \cdot v_p)}{dt} + 4.1 \cdot 10^{-18} \frac{C_{Fe}}{C_H^2} \cdot v_p - \sum q_i^{in} \cdot C_{Fe,i}^{in} - \sum q_i^{out}\, C_{Fe} - 0.022 \cdot C_{LH} \tag{4.63a}$$

$$0 = \frac{d(C_H \cdot v_p)}{dt} - 3.58 \cdot 10^{-5} \cdot \frac{d(C_{Fe} \cdot v_p)}{dt} - \sum q_i^{in} \cdot C_{H,i}^{in} + \sum q_i^{out} \cdot C_H \tag{4.63b}$$

with

$v_p$ - volume of remaining pit [Mill.m$^3$]

$C_{Fe}$ - $Fe^{2+}$ - concentration [g/m$^3$]

$C_H$ - $H^+$ - concentration [g/m$^3$]

$q_i$ - infow/outflow [m$^3$/sec.]

$C_{Fe,i}$ - $Fe^{2+}$ - concentration of inflow/outflow

$C_{H,i}$ - $H^+$ - concentration of inflow/outflow

$C_{LH}$ - added lime hydrate [1000kg/year]

If we assume a linear change of the storage volume in time and consider a given $H^+$ concentration $C_H$, Eq. (4.63a) and Eq. (4.63b) can be solved analytically and we obtain for the planning period $j$ in terms of the common model parameters for $l = 1,2$.

$$c_p(l,j) = a_1(l) + (c_p(l,j-1) - a_1(l)) \cdot \exp(-\frac{a_2(l) \cdot 2}{v_p(j-1) + v_p(j)} \cdot \Delta T_j) \tag{4.64}$$

with

$$a_2(1) = \frac{v_p(j) - v_p(j-1)}{\Delta T_j} + \frac{4.1 \cdot 10^{-18}}{c_p(2,j-1)^2} \cdot \frac{v_p(j) - v_p(j-1)}{2} + q_{p,e}(j) + q_{p,s}(j) \tag{4.64a}$$

$$a_1(1) = (q_{s,p}(j) \cdot cs_3(1,j) + q_{b,p}(j) \cdot c_b(1,j) + q_{g,p}(j) \cdot cg_p(1,j) + 0.022 \cdot cq_p(j)) / a_2(1) \tag{4.64b}$$

$$a_2(2) = \frac{v_p(j)-v_p(j-1)}{\Delta T_j} + \mathbf{q}_{p,e}(j) + \mathbf{q}_{p,s}(j) \qquad (4.64c)$$

$$\begin{aligned} a_1(2) = (q_{s,p}(j) \cdot cs_3(2,j) + \mathbf{q}_{b,p}(j) \cdot c_b(2,j) + \mathbf{q}_{g,p}(j) \cdot cg_p(2,j) \\ + 3.58 \cdot 10^{-5} \cdot \frac{c_p(1,j-1) \cdot v_p(j-1) - c_p(1,j) \cdot v_p(j)}{\Delta T_j}) / a_2(2) \end{aligned} \qquad (4.64d)$$

For the management model the same model is used for yearly time-steps. Monthly variations of the water quality will be neglected.

## 4.4. Constraints on Systems Development

For the planning model we have to consider a set of constraints characterizing the water balance for mines (equality constraints) and bounding the decisions. In the management model these constraints enter into decision rules. The estimation of these rules will be done in the next stage of research.

*Water balance equations for mines*

**Mine A**

$$wb_a(j) = qg_a(j) - \mathbf{q}_{a,s}(j) - \mathbf{q}_{a,ex}(j) = 0 \ , \ \text{for } j \le j_a \qquad (4.65a)$$

**Mine B**

$$\begin{aligned} wb_b(j) = qg_{b1}(j) + qg_{b2}(j) - \mathbf{q}_{b,m}(j) - \mathbf{q}_{b,s}(j) \\ - \mathbf{q}_{b,ex}(j) - \mathbf{q}_{b,p}(j) = 0 \end{aligned} \qquad (4.65b)$$

**Mine C**

$$wb_c(j) = qg_c(j) - \mathbf{q}_{c,s}(j) - \mathbf{q}_{c,i}(j) - \mathbf{q}_{c,ag}(j) - \mathbf{q}_{c,e}(j) = 0 \qquad (4.65c)$$

**Mine D**

$$\begin{aligned} wb_d(j) = qg_d(j) - \mathbf{q}_{d,s}(j) - \mathbf{q}_{d,i}(j) - \mathbf{q}_{d,ag}(j) \\ - \mathbf{q}_{d,ex}(j) = 0 \ , \ \text{for } j \ge j_d \end{aligned} \qquad (4.65d)$$

*Possible groundwater extraction*

We assume a fixed construction of the wells for groundwater extraction. Groundwater extraction only then is possible, if the groundwater table is above the well screen. Define with $uh_w$ and $lh_w$ the upper and lower bounds of the height of the screen in all wells. Assuming a linear distribution of the number of wells within these bounds we get the following constraint:

$$pq_{g,m}(j) = - \frac{uq_g}{uh_w - lh_w} \cdot (h_g(j) - lh_w) + \mathbf{q}_{g,m}(j) \le 0 \qquad (4.66)$$

with $uq_g$ - maximum well capacity (all wells operate)

With $uh_w = 110.8m$ , $lh_w = 103.5m$ and $uq_g = 0.25m^3/sec$ we obtain

$$pq_{g,m}(j) = -0.034 \cdot h_g(j) + \mathbf{q}_{g,m}(j) + 3.54 \leq 0 \qquad (4.67)$$

*Constraint for water table in the remaining pit*

$$hpma(j) = -\mathbf{maxh}_p + \mathbf{h}_p(j) \leq 0 \quad \text{for} \quad j > ja \qquad (4.68)$$

*Constraints on water use from the remaining pit*

Water from the remaining pit can be used for flow augmentation and supply of the environmental protection area, if the water table in the pit is greater than $minh_p (= 110.0m)$.

$$pq_{p,\alpha}(j) = -(\mathbf{h}_p(j) - \mathrm{min}h_p) \cdot \mathbf{q}_{p,\alpha}(j) \leq 0 \quad \text{for} \quad j \geq j_a \quad \alpha = s \,|\, e \qquad (4.69)$$

*Constraints on water use because of the water quality* $(l = 1,2)$

**Municipal water supply**

$$pq_{b,m}(l,j) = -(uc_m(l) - cg_{b1}(l,j)) \cdot \mathbf{q}_{b,m}(j) \leq 0 \qquad (4.70a)$$

**Industrial water supply**

$$pq_{\alpha,i}(l,j) = -(uc_i(l) - c_\alpha(l,j)) \cdot \mathbf{q}_{\alpha,i}(j) \leq 0 \quad \alpha = c \,|\, d \qquad (4.70b)$$

**Agricultural water supply**

$$pq_{\alpha,ag}(l,j) = -(uc_{ag}(l) - c_\alpha(l,j)) \cdot \mathbf{q}_{\alpha,ag}(j) \leq 0 \quad \alpha = c \,|\, d \qquad (4.70c)$$

**Environmental protection**

$$pq_{\alpha,e}(l,j) = -(uc_e(l) - c_\alpha(l,j)) \cdot q_{\alpha,e}(j) \leq 0 \quad \alpha = c \,|\, p \qquad (4.70d)$$

**Water export**

$$pq_{\alpha,ex}(l,j) = -(uc_{ex}(l) - c_\alpha(l,j)) \cdot \mathbf{q}_{\alpha,ex}(j) \leq 0 \quad \alpha = a \,|\, b \,|\, d \qquad (4.70e)$$

*Constrants on the quality of discharged water*

The quality of mine water after treatment should not be worse than the standard permits for water discharge into streams.

$$pc_\alpha(1,j) = -(uc_s - c_\alpha(1,j)) \leq 0 \quad \alpha = a \,|\, b \,|\, c \,|\, d \qquad (4.71a)$$

$$pc_\alpha(2,j) = (uc_s - c_\alpha(2,j)) \leq 0 \quad \alpha = a \,|\, b \,|\, c \,|\, d \qquad (4.71b)$$

In Table 4.4 the upper bounds for the concentrations are summarized.

**Table 4.4**: Upper bounds for water quality

| | l | $uc_m(l)$ | $uc_i(l)$ | $uc_{ag}(l)$ | $uc_e(l)$ | $uc_{ex}(l)$ | $uc_s(l)$ |
|---|---|---|---|---|---|---|---|
| $Fe^{2+}[g/m^3]$ | 1 | 10 | 5 | 20 | 20 | 10 | 2 |
| pH | 2 | 6 | 6 | - | - | - | 7 |

## 5. Concluding Remarks

This paper outlines a conceptual and methodological approach for the analysis of regional water policies in open-pit lignite mining areas, focusing at a test area in the GDR.

Based on this approach a Decision Support Model System is under development. This system is designed for scenario generation of "good" long-term policies providing a balanced socio-economic development and evolution of natural ecosystems. The main features of our DSMS are conceptualized to be its interactive use by decision makers based on a structured decision oriented data input and output and the integration of colour graphics for decision-oriented data output. Future research is oriented towards the following directions:

- Development of an approach towards for nonlinear multi-criteria analysis with fuzzy parameters (constraints and objective functions); this work aims at the use of linguistic elements in the process of scenario generation according to the decision making reality.
- Integration of methods for integer programming to consider investments as decision variables in the system.
- Policy analysis based on the DSMS using methods of operational gaming to study the effectiveness of economic and legislative policies for a "good" long-term development.

## REFERENCES

Fedra, K., Loucks, D.P. 1984. Interactive Comparative Technology for Policy Modeling. Paper submitted to Water Resources Research.

Grauer, M., Kaden, St. 1984. A nonlinear dynamic interactive decision analysis and support system (DIDASS/N), Users Guide. IIASA, WP-84-23.

Kaden, St. 1983. Analysis of regional water policies in open-pit mining areas - a multicriteria approach. In: A. Wierzbicki and M. Grauer (Ed.), Interactive Decision Analysis and Interpretative Computer Intelligence, Springer-Verlag, pp. 218-226.

Kaden, St., Luckner, L. 1984. Groundwater management in open-pit lignite mining areas. International Symposium on Groundwater Resources Utilization, Montreal, Canada, May 21-23, 1984.

Kindler, J. Zielinski, P., de Marc, L. 1980. An interactive procedure for multiobjective analysis of water resources allocation. IIASA, WP-80-85.

Luckner, L. 1983. Groundwater and Geotechnical Problems. International Journal of Mine Water, Vol. 2, No. 1, March 1983, pp. 31-40.

Luckner L., Hummel, J. 1982. Modelling and predictions of the quality of mine drainage water used for the drinking water supply in the GDR. 1st International Mine Water Congress of the IMWA, Budapest, Proc. D, p. 25-36.

Nestler, W., Luckner, L., Hummel, J. 1982. Die Nutzung von Signalmodellen zur Wasserbedarfsprognose als Basis einer effektiven Steuerung von Wasserversorgungsprovision, WWT, Berlin, 32(1982), 12, pp. 414-418.

Orlovsky, S.A., van Walsum, P.E.V. 1984. Water Policies: Regions with Intense Agriculture (Introduction to the IIASA study). IIASA, WP-84-40, p. 54.

Peukert, D., Reisner, H., Kunze, W. 1982. Application of a continuously operating model for forecasting a regional groundwater flow situation caused by open-cast mine dewatering measures. 1st International Mine Water Congress of the IMWA, Budapest, Proc. A, pp. 209-225.

Starke, W. 1980. Nutzung von Grubenwasser der Braunkohlentagebaue zur Trinkwasserversorgung, Wasserwirtschaft/Wassertechnik, Berlin, Vol. 30, No. 11, pp. 386-388.

Wierzbicki, A.P. 1983. A Mathematical Basis for Satisficing Decision Making. Mathematical Modeling USA 3:391-405 (Report IIASA RR-83-7).

## APPENDIX 1

*Abbreviations of the Mathematical Model*

### DECISIONS *D* ON SYSTEMS DEVELOPMENT

*Water allocation mine A / remaining pit* $[m^3/sec.]$

$\mathbf{q}_{a,s}$ - flux from mine A into stream, for $t \leq t_a$
$\mathbf{q}_{p,s}$ - flux from remaining pit into stream, for $t > t_a$
$\mathbf{q}_{p,e}$ - flux from remaining pit into environm. protection area, for $t > t_a$
$\mathbf{q}_{a,ex}$ - flux from mine A out of the region (export), for $t \leq t_a$

*Water allocation mine B* $[m^3/sec.]$

$\mathbf{q}_{b,m}$ - flux from mine B to municipal water supply
$\mathbf{q}_{b,ex}$ - flux from mine B out of the region (export)
$\mathbf{q}_{b,s}$ - flux from mine B into stream
$\mathbf{q}_{b,p}$ - flux from mine B into remaining pit, for $t > t_a$

*Water allocation mine C* $[m^3/sec.]$

$\mathbf{q}_{c,i}$ - flux from mine C to industrial water supply
$\mathbf{q}_{c,ag}$ - flux from mine C for irrigation
$\mathbf{q}_{c,s}$ - flux from mine C into stream
$\mathbf{q}_{c,e}$ - flux from mine C into environm. protection area

*Water allocation mine D* $[m^3/sec.]$, for $t \geq t_d$

$\mathbf{q}_{d,i}$ - flux from mine D to industrial water supply
$\mathbf{q}_{d,ex}$ - flux from mine D out of the region (export)
$\mathbf{q}_{d,s}$ - flux from mine D into stream
$\mathbf{q}_{d,ag}$ - flux from mine D for irrigation

*Surface water use* $[m^3/sec.]$

$\mathbf{q}_{s,m}$ - flux from stream to municipal water supply
$\mathbf{q}_{s,i}$ - flux from stream to industrial water supply
$\mathbf{q}_{s,ag}$ - flux from stream for irrigation
$\mathbf{q}_{s,p}$ - flux from stream into remaining pit

*Groundwater use, water import* $[m^3/sec.]$

$\mathbf{q}_{g,m}$ - groundwater use for municipal water supply
$\mathbf{q}_{im,m}$ - water import for municipal water supply

*Quality control : supply with lime hydrate* $[g/m^3]$

$\mathbf{cq}_a$ - *lime supply for mine water treatment plant mine A, for* $t \leq t_a$
$\mathbf{cq}_b$ - *lime supply for mine water treatment plant mine B*
$\mathbf{cq}_c$ - *lime supply for mine water treatment plant mine C*
$\mathbf{cq}_d$ - *lime supply for mine water treatment plant mine D*

$\mathbf{cq}_p$ - *lime supply for remaining pit* $[1000\ kg\ /\ year]$, *for* $t > t_a$

*Mine drainage timing* $[years]$

$\Delta\mathbf{tm}_d$ - duration of mine drainage mine D before opening the mining

*Water level in the remaining pit* $[m]$

$\mathbf{maxh}_p$ - maximum water level

## DESCRIPTORS OF SYSTEMS DEVELOPMET

*Systems Descriptive Values* $S_d$

*Groundwater flow* $[m^3/\ sec.]$

$qg_a$ - groundwater flow to mine A
$qg_{b1}$ - groundwater flow to mine B, suitable for municip. water supply
$qg_{b2}$ - groundwater flow to mine B, not suitable for mun. water supply
$qg_c$ - groundwater flow to mine C
$qg_d$ - groundwater flow to mine D
$qg_p$ - groundwater flow into remaining pit

*Infiltration from surface water for stream segments* $[m^3/\ sec.]$

$qi_{1,2}$ - infiltration segment $\Delta s_{1,2}$
$qi_{5,6}$ - infiltration segment $\Delta s_{5,6}$
$qi_{6,2}$ - infiltration segment $\Delta s_{6,2}$
$qi_{2,3}$ - infiltration segment $\Delta s_{2,3}$
$qi_{7,3}$ - infiltration segment $\Delta s_{7,3}$
$qi_{3,4}$ - infiltration segment $\Delta s_{3,4}$

*Groundwater tables* $[m]$

$h_{ag}$ - groundwater table in the agricultural area
$h_g$ - groundwater table near wells for groundwater use
$h_e$ - groundwater table in environm. protection area

*Groundwater quality* $[g\ /\ m^3]$

$cg_a(l)$ *) - water quality of drainage water mine A
$cg_{b1}(l)$ - water quality of drainage water $qg_{b1}$ mine B
$cg_{b2}(l)$ - water quality of drainage water $qg_{b2}$ mine B
$cg_c(l)$ - water quality of drainage water mine C
$cg_d(l)$ - water quality of drainage water mine D
$cg_p(l)$ - water quality of groundwater water into remaining pit

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*) The index $l$ represents the qualiy parameter under consideration:

*Quality of treated mine water* $[g / m^3]$

$c_a(l)$ - water quality mine A
$c_b(l)$ - water quality mine B
$c_c(l)$ - water quality mine C
$c_d(l)$ - water quality mine D

*Infiltration from surface water for stream segments* $[m^3/ sec.]$

$qi_{1,2}$ - infiltration segment $\Delta s_{1,2}$
$qi_{5,6}$ - infiltration segment $\Delta s_{5,6}$
$qi_{6,2}$ - infiltration segment $\Delta s_{6,2}$
$qi_{2,3}$ - infiltration segment $\Delta s_{2,3}$
$qi_{7,3}$ - infiltration segment $\Delta s_{7,3}$
$qi_{3,4}$ - infiltration segment $\Delta s_{3,4}$

*Surface water flow* $[m^3/ sec.]$

$qs_1$ - surface water flow balance profile bp1
$qs_2$ - surface water flow balance profile bp2
$qs_3$ - surface water flow balance profile bp3
$qs_4$ - surface water flow balance profile bp4
$qs_5$ - surface water flow balance profile bp5
$qs_6$ - surface water flow balance profile bp6
$qs_7$ - surface water flow balance profile bp7

*Industrial waste water*

$q_{i,s}$ - waste water from industrial water use into stream
$cis(l)$ - water quality of industrial waste water

*Surface water quality* $[g / m^3]$

$cs_1(l)$ - water quality balance profile bp1
$cs_2(l)$ - water quality balance profile bp2
$cs_3(l)$ - water quality balance profile bp3
$cs_4(l)$ - water quality balance profile bp4
$cs_5(l)$ - water quality balance profile bp5
$cs_6(l)$ - water quality balance profile bp6
$cs_7(l)$ - water quality balance profile bp7

*Surface water tables* $[m]$

$hs_1$ - surface water table balance profile bp1
$hs_2$ - surface water table balance profile bp2
$hs_3$ - surface water table balance profile bp3
$hs_4$ - surface water table balance profile bp4
$hs_5$ - surface water table balance profile bp5

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$l = 1$ $Fe^{2+}$ - concentration $[g/m^3]$
$l = 2$ $H^+$ - concentration $[g/m^3]$

$hs_6$ - surface water table balance profile bp6
$hs_7$ - surface water table balance profile bp7

*State transition variables* $S_v$

*Remaining pit*

$\mathbf{h}_p$ - water table in the remaining pit $[m]$
$cp(l)$ - water quality in the remaining pit $[g/m^3]$
$vp$ - storage volume in the remaining pit at the end of one time unit [Mill.$m^3$]

## APPENDIX 2

## UPPER BOUNDS FOR DECISIONS

*Water allocation of mines*

| j | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $u\,q_{a,s}$ | 4.1 | 3.9 | 3.3 | 2.8 | 2.2 | 1.8 | 1.5 | 0 | 0 | 0 |
| $u\,q_{a,ex}$ | 1.8 | 1.7 | 1.2 | 1.4 | 1.4 | 1.6 | 1.5 | 0 | 0 | 0 |
| $u\,q_{b,s}$ | 3.0 | 3.2 | 3.4 | 3.5 | 3.9 | 4.1 | 5.0 | 6.4 | 5.4 | 3.0 |
| $u\,q_{b,p}$ | 1.2 | 1.3 | 1.5 | 1.6 | 1.9 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 |
| $u\,q_{b,m}$ | 0 | 0 | 0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| $u\,q_{b,ex}$ | 1.2 | 1.3 | 1.5 | 1.6 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| $u\,q_{c,s}$ | 2.1 | 2.3 | 2.7 | 2.3 | 2.5 | 2.6 | 2.8 | 2.8 | 2.9 | 3.2 |
| $u\,q_{c,i}$ | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| $u\,q_{c,ag}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| $u\,q_{c,e}$ | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.1 | 0.05 |
| $u\,q_{d,s}$ | 0 | 0 | 0 | 1.1 | 3.8 | 3.9 | 4.3 | 4.3 | 3.1 | 0.3 |
| $u\,q_{d,i}$ | 0 | 0 | 0 | 1.1 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 0.3 |
| $u\,q_{d,ex}$ | 0 | 0 | 0 | 0.5 | 1.9 | 1.9 | 2.0 | 2.0 | 1.5 | 0 |
| $u\,q_{d,ag}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

*Water allocation from surface water/groundwater*

| j | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $u\,\mathbf{q}_{p,s}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 1.0 | 1.5 |
| $u\,\mathbf{q}_{p,e}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.3 | 0.5 |
| $u\,\mathbf{q}_{s,m}$ | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| $u\,\mathbf{q}_{s,i}$ | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| $u\,\mathbf{q}_{s,ag}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| $u\,\mathbf{q}_{s,p}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4.0 | 4.0 | 4.0 |
| $u\,\mathbf{q}_{g,m}$ | 0.2 | 0.2 | 0.2 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| $u\,\mathbf{q}_{im,m}$ | 0 | 0 | 0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

*Water quality control*

$$u\,\mathbf{cq}_a = u\,\mathbf{cq}_b = u\,\mathbf{cq}_c = u\,\mathbf{cq}_d = 300\ g/m^3$$

$$u\,\mathbf{cq}_p = 500 * 1000\ kg/year$$

*timing of mine drainage*

$$-2.0\ years \leq \Delta\mathbf{tm}_d \leq +2.0\ years$$

*Maximum water table in the remaining pit*

$$113.0\ m \leq \underline{\mathbf{maxh}_p} \leq 118.0\ m$$

## APPENDIX 3

## MODEL DATA

**Table** 1: Cost coefficients for water allocation installations

| Allocation | | L[m] | D[mm] | $\alpha$ [Mill.Mark/ year] | | $\beta$ [Mark/ $m^3$] | |
|---|---|---|---|---|---|---|---|
| from | to | | | | | | |
| Mine A | Export | 10000 | 1000 | $\alpha_{a,ex}$ | 1.320 | $\beta_{a,ex}$ | 0.05 |
| Mine B | Export | 10000 | 1500 | $\alpha_{b,ex}$ | 2.380 | $\beta_{b,ex}$ | 0.05 |
| | Remaining pit | 3000 | 1500 | $\alpha_{b,p}$ | 0.713 | $\beta_{b,p}$ | 0.02 |
| Mine C | Agriculture | 10000 | 300 | $\alpha_{c,ag}$ | 0.316 | $\beta_{c,ag}$ | 0.03 |
| | Environmental protection | 8000 | 300 | $\alpha_{c,e}$ | 0.253 | $\beta_{c,i}$ | 0.03 |
| | Industry | 2000 | 1500 | $\alpha_{c,i}$ | 0.475 | $\beta_{c,i}$ | 0.02 |
| Mine D | Agriculture | 6000 | 300 | $\alpha_{d,ag}$ | 0.190 | $\beta_{d,ag}$ | 0.02 |
| | Export | 16000 | 1500 | $\alpha_{d,ex}$ | 3.803 | $\beta_{d,ex}$ | 0.07 |
| | Industry | 5000 | 1500 | $\alpha_{d,i}$ | 1.188 | $\beta_{d,i}$ | 0.03 |
| Import | Municipality | 20000 | 600 | $\alpha_{im,m}$ | 1.327 | $\beta_{im,m}$ | 0.05 |
| Stream | Municipality | 20000 | 600 | $\alpha_{s,m}$ | 1.327 | $\beta_{s,m}$ | 0.05 |
| | Industry | 1500 | 1500 | $\alpha_{s,i}$ | 0.357 | $\beta_{s,i}$ | 0.01 |
| | Agriculture | 2000 | 300 | $\alpha_{s,ag}$ | 0.063 | $\beta_{s,ag}$ | 0.01 |
| | Remaining pit | 3000 | 2000 | $\alpha_{s,p}$ | 1.102 | $\beta_{s,p}$ | 0.02 |
| Industry | Stream | 1500 | 1000 | $\alpha_{i,s}$ | 0.197 | $\beta_{i,s}$ | 0.01 |
| Remaining pit | Stream | 3000 | 1000 | $\alpha_{p,s}$ | 0.395 | $\beta_{p,s}$ | 0.01 |
| | Environmental protection | 6000 | 600 | $\alpha_{p,e}$ | 0.398 | $\beta_{p,e}$ | 0.02 |

**Table 2**: Cost coefficients for water treatment plants

| Treatment plant | Qc [m$^3$/sec] | $\alpha$[Mill.Mark/ year] | | $\beta$[Mark/m$^3$] | | $\gamma$[Mark/g] | |
|---|---|---|---|---|---|---|---|
| Mine A | 3.0 | $\alpha_{t,a}$ | 0.540 | $\beta_{t,a}$ | 0.015 | $\gamma_t$ | $6.10^{-5}$ |
| Mine B | 5.5 | $\alpha_{t,b}$ | 0.990 | $\beta_{t,b}$ | 0.017 | | |
| Mine C | 3.0 | $\alpha_{t,c}$ | 0.540 | $\beta_{t,c}$ | 0.016 | | |
| Mine D | 4.0 | $\alpha_{t,d}$ | 0.720 | $\beta_{t,d}$ | 0.017 | | |
| Municipal water supply | 0.2 | $\alpha_{t,m}$ | 0.200 | $\beta_{t,m}$ | 0.05 | $\gamma_m$ | 0.01 |
| Industrial water supply | 3.0 | $\alpha_{t,i}$ | 1.500 | $\beta_{t,i}$ | 0.05 | $\gamma_i$ | 0.004 |
| Industrial waste water | - | - | - | $\beta_{t,w}$ | 0.20 | | |

**Table 3**: Specific cost for water pumpage [Mark/m$^3$]

| Mine A | Mine B | | Mine C | Mine D | Groundwater |
|---|---|---|---|---|---|
| | 1 | 2 | | | |
| $\beta_{w,a}$ | $\beta_{w,b1}$ | $\beta_{w,b2}$ | $\beta_{w,c}$ | $\beta_{w,d}$ | $\beta_{w,g}$ |
| 0.24 | 0.35 | 0.28 | 0.28 | 0.30 | 0.10 |

**Table 4**: Parameter for submodels "Groundwater flow into mines

| Mine | parameter | j=1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | $a_1(j)$ | 4.10 | 3.90 | 3.25 | 2.78 | 2.23 | 1.75 | 1.51 | 0 | 0 | 0 |
| B $B_1$ | $a_1(j)$ | 0 | 0 | 0 | 0.25 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| $B_2$ | $a_1(j)$ | 2.95 | 3.15 | 3.40 | 3.50 | 3.88 | 4.10 | 4.98 | 6.23 | 5.11 | 2.61 |
| | $a_2(j)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0012 | 0.0027 | 0.0028 |
| C | $a_1(j)$ | 2.05 | 2.25 | 2.70 | 2.28 | 2.45 | 2.60 | 2.82 | 2.78 | 2.86 | 3.18 |
| D | $a_1(j)$ | 0 | 0 | 0 | 1.13 | 3.80 | 3.85 | 4.25 | 4.25 | 3.09 | 0.29 |
| | $a_2(j)$ | 0 | 0 | -.183 | -.700 | -.412 | -.175 | -.225 | -.063 | -.128 | -.023 |
| | $a_3(j)$ | 0 | 0 | 0.092 | 0.068 | -.131 | -.013 | -.013 | 0.019 | 0.011 | 0.003 |

**Table 5:** Reference values (natural rise of remaining pit) for management model

| i | | | | | | | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| $qg_{b2}^0(i)$ | | | | | | | 6.7 | 6.6 | 6.5 | 6.4 |
| $qg_p^0(i)$ | | | | | | | 0. | -2.57 | -2.26 | -4.08 |
| $h_p^0(i)$ | | | | | | | 82.0 | 86.1 | 89.7 | 92.1 |
| i | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| $qg_{b2}^0(i)$ | 6.3 | 6.2 | 6.1 | 6.0 | 5.9 | 5.8 | 5.7 | 5.6 | 5.5 | 5.40 |
| $qg_p^0(i)$ | -4.08 | -3.41 | -2.75 | -2.33 | -1.9 | -3.36 | -2.91 | -2.31 | -1.89 | -1.51 |
| $h_p^0(i)$ | 94.4 | 96.3 | 97.8 | 99.1 | 100.1 | 100.9 | 101.6 | 102.1 | 102.6 | 102.9 |
| i | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
| $qg_{b2}^0(i)$ | 5.3 | 5.1 | 4.8 | 4.6 | 4.4 | 4.2 | 4.0 | 3.8 | 3.6 | 3.3 |
| $qg_p^0(i)$ | -1.26 | -1.05 | -0.8 | -0.71 | -0.55 | -0.46 | -0.38 | -0.29 | -0.25 | -0.21 |
| $h_p^0(i)$ | 103.2 | 103.5 | 103.7 | 103.8 | 104.0 | 104.1 | 104.2 | 104.2 | 104.3 | 104.3 |
| i | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
| $qg_{b2}^0(i)$ | 3.0 | 2.7 | 2.4 | 2.2 | 2.2 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| $qg_p^0(i)$ | -0.17 | -0.13 | -0.08 | -0.08 | -0.04 | -0.04 | 0 | 0 | 0 | 0 |
| $h_p^0(i)$ | 104.4 | 104.4 | 104.5 | 104.5 | 104.6 | 104.6 | 104.6 | 104.6 | 104.6 | 104.6 |

**Table 6:** Parameters for submodels "Bankfiltration"

| Segment | Parameter | j=1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Delta s_{1,2}$ | $a_1(j)$ | -0.34 | -0.33 | -0.32 | -0.28 | -0.23 | -0.15 | -0.04 | 0.27 | 0.73 | 6.49 |
| | $a_2(j)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -.0016 | -.0065 | -.057 |
| $\Delta s_{2,3}$ | $a_1(j)$ | 0.80 | 0.80 | 0.81 | 0.84 | 0.88 | 0.90 | 0.90 | 2.01 | 4.27 | 15.0 |
| | $a_2(j)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -.013 | -.035 | -.129 |
| $\Delta s_{3,4}$ | $a_1(j)$ | -0.09 | -0.08 | -0.07 | -0.06- | -0.0 | -0.0055 | -0.04 | -0.04 | -0.06 | +0.11 |
| $\Delta s_{6,2}$ | $a_1(j)$ | 0.55 | 0.55 | 0.56 | 0.61 | 0.68 | 0.69 | 0.69 | 0.69 | 0.68 | 0.33 |
| | $a_2(j)$ | 0 | 0 | 0 | -.018 | -.013 | 0 | 0 | 0 | 0 | 0 |
| | $a_3(j)$ | 0 | 0 | 0 | -.004 | -.004 | 0 | 0 | 0 | 0 | 0 |
| $\Delta s_{5,6}$ | $a_1(j)$ | -0.47 | -0.47 | -0.46 | -0.46 | -0.43 | -0.36 | -0.26 | -0.19 | -0.09 | -0.09 |
| | $a_2(j)$ | 0 | 0 | 0 | -.015 | -.025 | -0.025 | -0.01 | 0 | 0 | 0 |
| | $a_3(j)$ | 0 | 0 | 0 | 0.005 | 0.005 | 0 | 0 | 0 | 0 | 0 |
| $\Delta s_{7,3}$ | $a_1(j)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 7**: Parameter for the infiltration submodel

| Balance Segment | $a_1$ | $a_2$ | $b_0$ | $b_1$ | $b_2$ | $c_0$ |
|---|---|---|---|---|---|---|
| 1,2 | 1.0933 | -0.1910 | 0.6460 | -0.8943 | 0.2549 | 0.07 |
| 2,3 | 1.0504 | -0.1622 | 0.2440 | -0.3393 | 0.0978 | 0.16 |
| 3,4 | 1.1167 | -0.2035 | 0.1290 | -0.1871 | 0.0593 | 0.09 |
| 6,2 | 1.1414 | -0.2136 | 0.1770 | -0.2360 | 0.0606 | 0.0 |
| 5,6 | 1.1819 | -0.2431 | 0.3060 | -0.4077 | 0.1058 | 0.0 |
| 7,3 | 1.1947 | -0.2563 | 0.6010 | -0.8270 | 0.2332 | 0.0 |

**Table 8**: Key function for surface water table

| Balance profile | K1 | K2 | K3 | restriction |
|---|---|---|---|---|
| bp1=bp7 | -8.6621 | 2.1305 | 40.5 | |
| bp2 | -5.5372 | 1.7040 | 0.4 | $0<qs_2\leq 10.35\ m^3/s$ |
| | -4.0515 | 1.4111 | 9.5 | $qs_2>10.35\ m^3/s$ |
| bp3 | -3.1125 | 1.3897 | 140.7 | |
| bp4 | -14.4190 | 3.1104 | -70.0 | |
| bp5 | -8.6874 | 2.2545 | 24.5 | |
| bp6 | -3.2500 | 1.2453 | 97.0 | |

**Table 9**: Parameter for submodels groundwater table

| Groundwater table | Parameter | j=1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $h_{ag}$ | $a_1(j)$ | 141.5 | 141.5 | 141.5 | 141.5 | 141.3 | 140.7 | 137.8 | 135.1 | 137.5 | 139.5 |
| | $a_2(j)$ | 0 | 0 | 0 | 0 | 0.125 | 0.325 | 0.55 | 0.3 | 0 | 0 |
| | $a_3(j)$ | 0 | 0 | 0 | 0 | -.038 | -.038 | -.050 | -.075 | 0 | 0 |
| $h_g$ | $a_1(j)$ | 118.9 | 118.1 | 117.8 | 115.0 | 111.0 | 106.3 | 93.1 | 0 | 0 | 0 |
| | $a_2(j)$ | 0 | 0 | 0 | 0.125 | 0.350 | 0.425 | 0.10 | 0 | 0 | 0 |
| | $a_3(j)$ | 0 | 0 | 0 | -.038 | 0.025 | 0.213 | 0.050 | 0 | 0 | 0 |
| $h_s$ | $a_1(j)$ | 131.4 | 131.2 | 130.9 | 130.7 | 130.3 | 129.8 | 130.1 | 130.6 | 127.0 | 132.0 |
| | $a_2(j)$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.04 | 0 |

**Table 10**: Groundwater quality

| | Parameter | j=1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | $\sigma_r$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $cg_a(j)$ | $Fe^{2+}$ | 38.6 | 41.5 | 45.8 | 51.7 | 57.2 | 62.9 | 75.8 | - | - | - | 10.0 |
| | pH | 6.03 | 6.01 | 5.97 | 5.92 | 5.87 | 5.82 | 5.71 | - | - | - | 0.25 |
| $cg_{b1}(j)$ | $Fe^{2+}$ | 0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 0 |
| | pH | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 0 | |
| $cg_{b2}(j)$ | $Fe^{2+}$ | 17.0 | 17.8 | 19.0 | 20.7 | 22.3 | 23.9 | 27.6 | 33.7 | 41.1 | 51.3 | 6.0 |
| | pH | 6.11 | 6.1 | 6.08 | 6.05 | 6.02 | 5.99 | 5.93 | 5.82 | 5.69 | 5.51 | 0.16 |
| $cg_c(j)$ | $Fe^{2+}$ | 16.6 | 17.2 | 18.0 | 19.1 | 20.3 | 21.4 | 23.9 | 28.2 | 33.3 | 40.3 | 5.0 |
| | pH | 5.84 | 5.82 | 5.80 | 5.78 | 5.75 | 5.72 | 5.67 | 5.57 | 5.45 | 5.28 | 0.23 |
| $cg_d(j)$ | $Fe^{2+}$ | - | - | 11.6 | 12.5 | 13.5 | 14.5 | 16.0 | 20.3 | 24.6 | 30.7 | 6.5 |
| | pH | 6.03 | 6.02 | 6.0 | 5.97 | 5.94 | 5.91 | 5.85 | 5.74 | 5.61 | 5.43 | 0.21 |
| $cg_p(j)$ | $Fe^{2+}$ | - | - | - | - | - | - | - | 70.0 | 80.0 | 90.0 | - |
| | pH | | | | | | | | 5.5 | 5.25 | 5.0 | - |

$Fe^{2+}$ [g/m$^3$], pH [-]