WATER RESOURCES MODELING FOR DECISION SUPPORT IN OPEN-PIT LIGNITE MINING AREAS

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ABSTRACT

Open-pit lignite mining is one of the most severe impacts on water resources systems. The Lusatian lignite region in the Eastern part of Germany is an example for the dimension and complexity of problems. The economical situation in the region has changed drastically over the last decades. Lignite mining has started already in the 18th century. After the first world war lignite became an important source for energy and chemical production in Germany. From the sixties onwards, in the former GDR (East-Germany) lignite mining increased further, up to about 200 Mio. t/year and 1200 Mio. m^3/year mine drainage water. As a consequence the water resources systems, i.e. the river basin of Spree river has been severe affected. After the German unification lignite mining again has changed, now it is strongly reduced. And this causes new problems with regard to the groundwater table rise because of mine closure and inadequate surface water flow in the river Spree.

The complexity of problems can only be understood with the help of mathematical models. Such models are used e.g. for the design of mine water drainage systems, for environmental impact studies and for long-term water resources planning.

Based on an introduction to the water problems in the Lusatian lignite region the author will present different types of models, which have been developed and/or used for the Lusatian lignite mining region. Such models include groundwater flow and transport models (FEFLOW), long-term water resources planning models (GRM) and decision-support models (DSS MINE).

The applicability of such models, their advantages, disadvantages, and their role in practical planning and decision making will be discussed.

THE LUSATIAN LIGNITE MINING AREA

Due to the specific geological history of lignite (brown coal) lignite seams are commonly embedded in Quarternary aquifers. It is necessary to dewater mines by pumping groundwater throughout, and prior to, the whole mine operation period. In loose rocks the surrounding aquifers have also to be drained in order to maintain the geochemical stability of the slopes and the bottom of the open-pit mines.

In the Lusatian district lignite mining began as early as in the 18-th century. In Figure 1 the development of mined lignite, overburden and mine drainage over the last seventy years is illustrated.

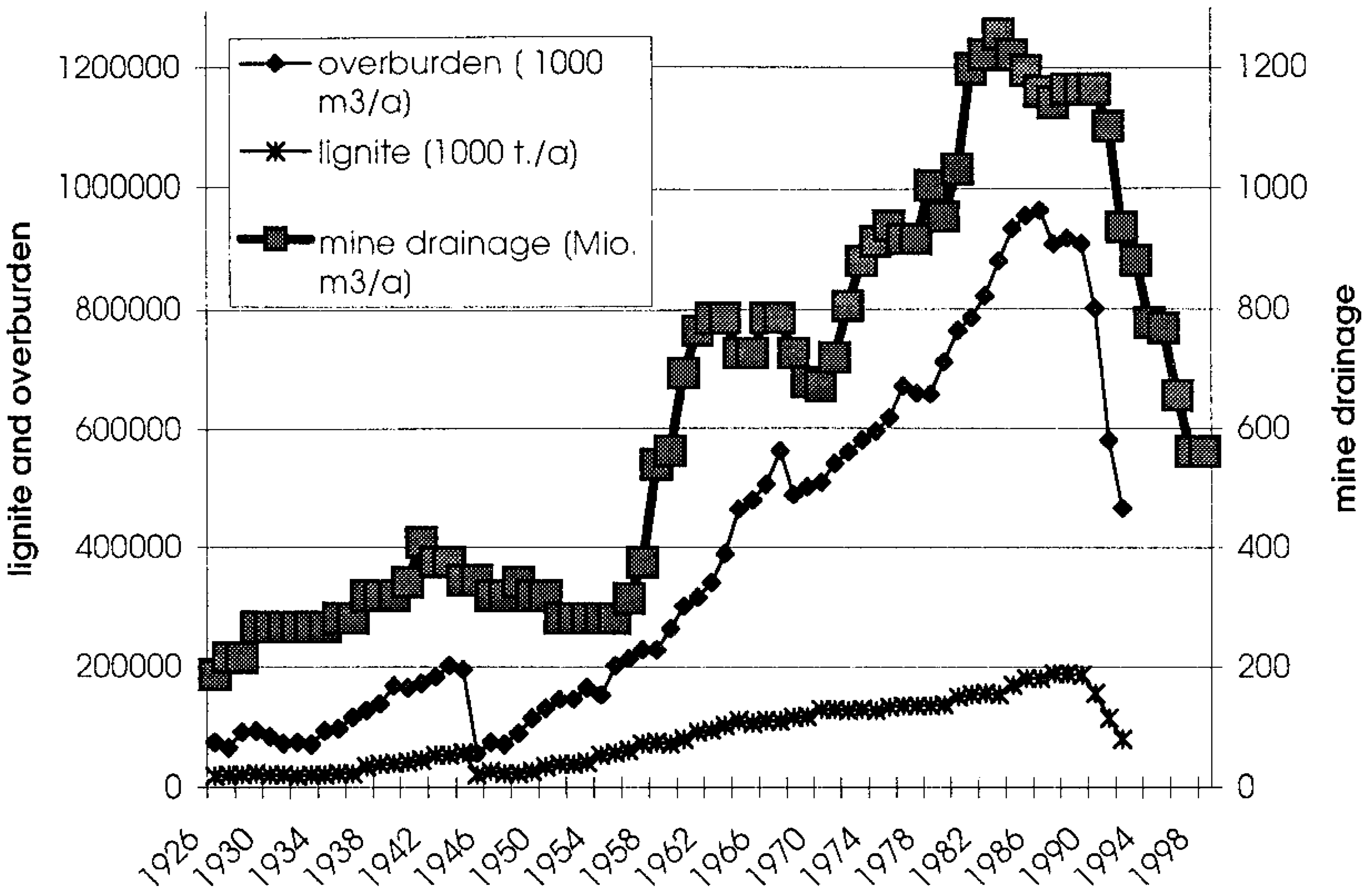

Figure 1: Development of lignite mining in the Lusatian lignite mining district (DORNIER 1993)

The development of mine drainage in particular shows clearly the different stages. The steady increase in mining until 1989 is interrupted only by the second world war and during a period in the sixties. At this time a change in the energy policy from lignite to oil and gas was planned in the former GDR. The oil crisis ended this trend and mining increased further from about 1970. In 1989 approx. 183 millon tons lignite were produced. For that purpose about 1200 million m^3/year had to be pumped out for mine drainage. With the German reunification in 1990 the economic importance of lignite dropped dramatically. In 1995 only approx. 70 million tons were produced, DVWK (1997).

The environmental impacts and also the economic consequences of open-pit lignite mining are extensive. In sandy aquifers in particular, the mine drainage leads to the formation of large cone-shaped groundwater depressions. As a result small rivers fall dry or large ones lose part of their runoff due to the infiltration of water from them into the depression zone. Water supply and agricultural production also suffers from the lowering of the groundwater table. E.g., wells for water supply have to be replaced.

Ecological conditions are drastically disturbed by lowering the groundwater level. Wetland and park landscapes are in great danger with the lowering of the groundwater table, surface water ecosystems suffer from water depletion and pollution.

Additionally, water quality is affected by mine drainage due to the oxidation of ferrous minerals (e.g. pyrite) in the dewatered underground layers. 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 acidic. The same effect occurs during the groundwater rise after the mines are closed.

Finally serious contamination risks for groundwater are incurred by disposal of liquid and solid wastes in the mining region. These wastes along with military waste disposals (a typical problem in former East Germany) may be washed out especially with rising groundwater tables.

The main river in the Lusatian region is the Spree, flowing through an important wetland, the Spreewald (UNESCO biosphere reserve) and finally through Berlin, the old and new German capital. The water supply of Berlin strongly depends on the river Spree (mainly bankfiltration). And the runoff of the Spree depends to a large extent on the flow augmentation due to mine drainage, as Table 1 illustrates.

Table 1: Mean annual runoff of river Spree, Cottbus

Period	MQ [m^3/s]	MNQ_{mon} [m^3/s]
1901 - 1935	12,4	
1921 - 1959 (limited mining)	14,5	7,2
1960 - 1989 (extensive mining)	19,0	11,7

MQ: annual mean flow; MNQ: annual mean of monthly low water

In case of a sudden drop of mine drainage due to the large cone-shaped depression the river Spree would practically dry out. The total volume of water deficit amounts to approx. 10.000 million m^3. It would need about 20 years to compensate this deficit, using the total runoff of the Spree, which is impossible. Consequently, strategies have to be found to get a sustainable development - at least for the remediation period.

MODELS FOR DECISION-SUPPORT IN MINING REGIONS

Lignite mining with large scale groundwater depletion results in one of the greatest impacts on the water resources system. Consequently, mathematical modeling or more general decision support systems became import tools for planning, design and impact studies in mining regions. The term "Decision Support System" is used here in a broad sense, as a tool for supporting decision making. In Table 2 an overview on typical tools is given.

One has to distinguish between predictive models (simulation models) and normative tools. Whereas the first allow the prediction of future systems development for a predefined scenario of mining operation, the latter enable the user to find rational (optimal) scenarios, taking into account certain objective functions as cost, environmental impacts etc. Normative tools are usually coupled with simulation models. In practice simulation models are better understood and accepted. One of the reasons may be the degree of simplification required for normative models. With increasing computer power, this problem almost has disappeared.

Table 2: Water resources modeling and decision support in mining regions

Tool	Application examples	Character	Practical importance and application
Modeling and simulation	Modeling of groundwater flow and mass transport Modeling of surface water flow and balances	predictive	high, used for drainage design, mining operation and planning high, used for water resources planning and management
Optimization	Estimation of optimal technical / planning solution	normative	small, only selected technical problems
Multi-criteria analysis	Estimation of pareto-optimal technical / planning solution	normative	small, only selected problems
Knowledge based systems	Parameter estimates; evaluation of consequences	descriptive; guessing	small, perhaps increasing
Decision support systems	Combination of tools above	descriptive predictive, normative	increasing importance

The water management problems in the Lusatian region have been discussed in the chapter above. The author of this paper has contributed to different aspects of decision support in this region, firstly with groundwater modeling for the design of mine drainage systems in the seventies, secondly with the development of a prototype decision-support system for the mining region in the eighties, and finally with different water management modeling during the last years. Some of the experience gathered will be reported in the remaining text. Future developments are discussed.

DECISION-SUPPORT FOR THE LUSATIAN LIGNITE MINING REGION

Groundwater modeling

With the increase of lignite mining in the seventies and the corresponding increase of mine drainage required the effective design of the mine drainage system (well galleries) became important. Appropriate groundwater flow models had to be developed, considering the specifics of the hydrogeological setting (multi-layer aquifer system) as well as the typical boundary conditions, e.g. KADEN et al. 1976. Such models are classic simulation models, i.e. they are used to predict the groundwater development in space and time depending on the given technological assumptions. Effective technical solutions and management strategies have to be found by trial and error within a scenario analysis. The model TAFEGA, KADEN et al. 1976 e.g. was used for many years for successfully designing the drainage systems in the Lusatian lignite region - and it is still used for preliminary studies. This model was a 1 1/2-D model. It considered the groundwater flow along streamlines in an multi-layer aquifer system. In the eighties mine water problems also became more and more regional problems. Consequently 2D/3D groundwater models had to be used. And with the development of 2D/3D-models mass transport problems became of interest. The model system GEOFIM (BOTH et. al., 1990, SAMES, 1995) a model system had been developed with special consideration of 3D mine water problems. With GEOFIM regional groundwater models have also have been implemented for the Lusatian region by the mining company, which are still in use.

One of the most advanced models for coupled 3D groundwater flow and mass transport is the model system FEFLOW (DIERSCH, 1993, 1996).

FEFLOW is an interactive, graphics-based groundwater modeling system for 2D (horizontal, vertical or axisymmetric) and fully 3D, fluid-density coupled or uncoupled, transient flow and chemical species transport in subsurface water resources. It represents an efficient simulation tool, e.g. in order to

- describe the spatial and temporal distribution of contaminants,
- estimate the duration and traveltimes of a pollution in aquifers,
- plan and design remediation strategies and interception techniques
- assist in designing alternatives and effective monitoring schemes.

FEFLOW is an interactive, fully graphics-oriented and menu-driven, hierarchically structured software system based on the finite element method. It contains graphical editors and mesh generators for the geometric design and discretization of possibly complex study areas as well as of the problem attribute specifications, more general computational techniques to solve a wide class of subsurface flow and mass transport problems characterized by flexibility and robustness, and a lot of additional graphical tools to manage the entire solution process and model data. The complexity of FEFLOW models possible is illustrated in Figure 2, which is especially important for multi-layer mine water problems.

The definition of the initial and boundary conditions can be relatively general so that formulations on arbitrary geometries with different types are possible. Accordingly, it also allows the handling of mixed conditions (e.g., surface water interactions or pumping/injection well functions) as well as specific mass flux-occupied boundaries (e.g. leaching of substances or diffuse intake of chemicals from landfills etc.).

FEFLOW is modular and built with an open architecture concept as a basic design guide. Thus, while being an operational system at any time, modifications and extensions can easily be made at low cost, keeping the simulator open for eventual modifications as experience grows. The FEFLOW system is coupled with the geographical information system ARC/INFO.

In the Lusatian lignite mining region FEFLOW has been used for instance to analyse the water flow between remaining pits (former mines, used as water reservoirs) and the surrounding groundwater aquifer (KADEN et al. 1995). For that purpose the FEFLOW feature of modeling of free surfaces with a moving grid method was important.

Groundwater models are well accepted and widely used tools for mine water problems in the Lusatian district. In general, there are no groundwater related decisions made without groundwater modeling. But, optimal scenarios have to selected by trial and error. That is why there have been attempts already from the eighties onwards to use normative models, i.e. decision support systems.

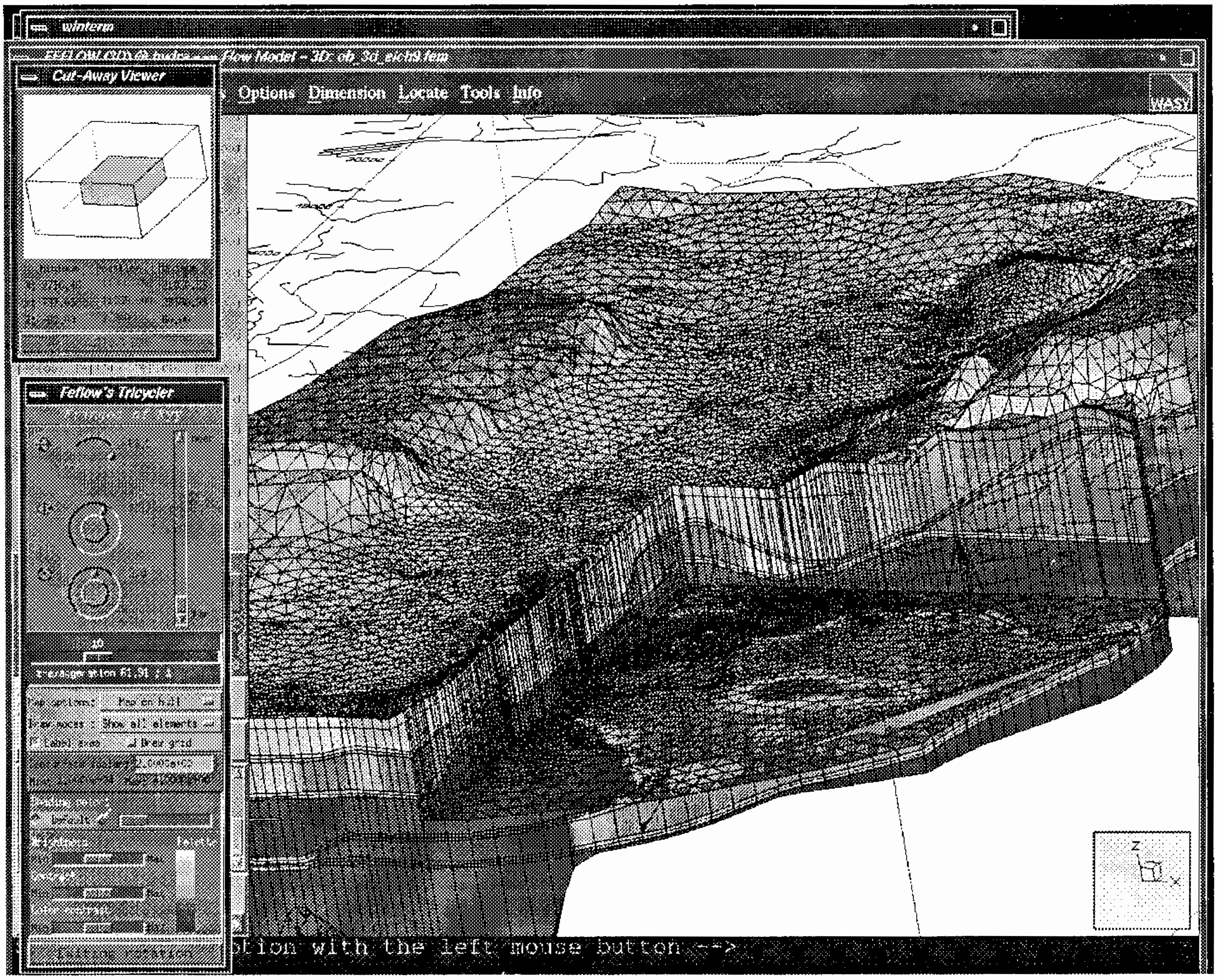

Figure 2: FEFLOW-3D: model for a multi-layer aquifer system

Decision-support system DSS MINE

The DSS MINE was developed at the International Institute for Applied Systems Analysis (IIASA) in co-operation with different institutes in the former GDR (ORLOVSKY, KADEN & VAN WALSUM, 1986). The general objective was to support the development of rational long-term water policies which could reduce impacts of mine drainage on the natural water resources system as well as the environment, and on the socio-economic development in the region. In Figure 3 an impact diagram is given, illustrating the considered processes and users.

As the figure illustrates in this case not only groundwater but also the surface water system had to be taken into the account in terms of water quality and water quantity.

The dynamic system (time horizon of 50 years) was modeled using a hierarchical approach. The model hierarchy depends on the step-size and on the available mathematical models. In the given case a two-level model system has been developed consisting of a first level **Planning Model** and a second level **Management Model.**

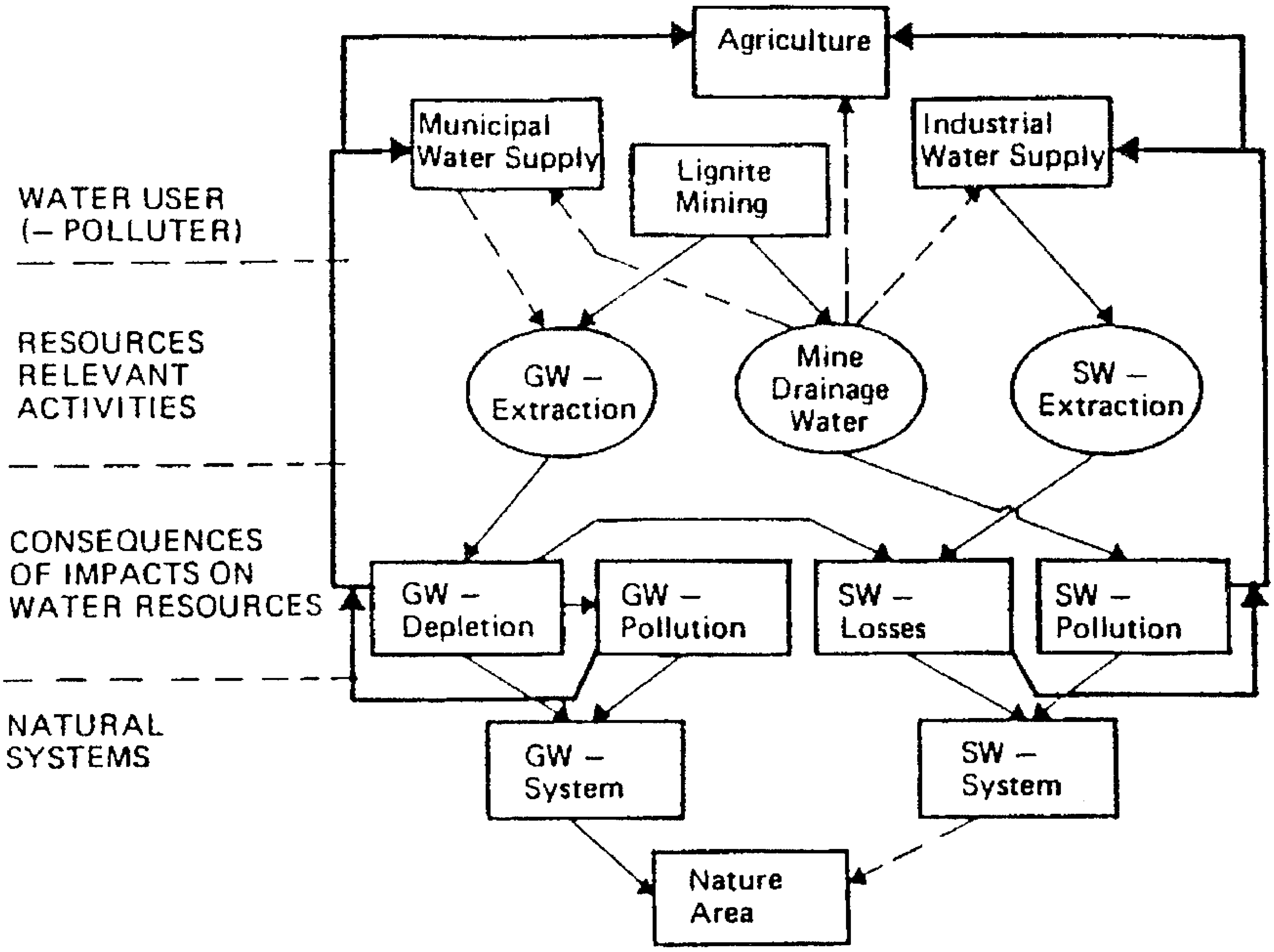

Figure 3: Impact diagram for open-pit lignite mining

The Planning Model was designed for screening of principal management/technological decisions by means of a dynamic multi-criteria analysis for a relatively small number of planning periods, representing a characteristic time step for such decisions (varying from yearly periods to longer time periods). With the Planning Model rational strategies of long-term development are selected in the course of multi-criteria analysis considering a number of **criteria (objectives)** which can be chosen from a set of **indicators**, e.g. cost of water supply, cost of mine drainage, satisfaction of water demand, and environmental requirements. In Figure 4 the basic structure of the planning model is depicted.

The planning model considers principal management/technological decisions for estimated input values (expectation values). The feasibility for estimated decisions is checked only in the mean for the planning periods by the help of the constraints and bounds. Problems arise if the principal decisions are superimposed by managerial decisions for shorter time intervals, depending on the current, at times, random systems development (e.g. stochastic character of precipitation).

For that purpose the second level Management Model is used. By the help of Monte Carlo simulation the feasibility of strategies is verified and the strategies are statistically evaluated. The model realizes the following steps:

1. Stochastic simulation of uncertain hydrological and socio-economic inputs, i.e. inflow and water demand.
2. Simulation of monthly systems development based on stochastic inputs and management rules considering the strategies estimated with the planning model.
3. Statistical analysis of selected decisions, state variables, descriptive variables and indicators for probabilistic assessment of the management strategy.

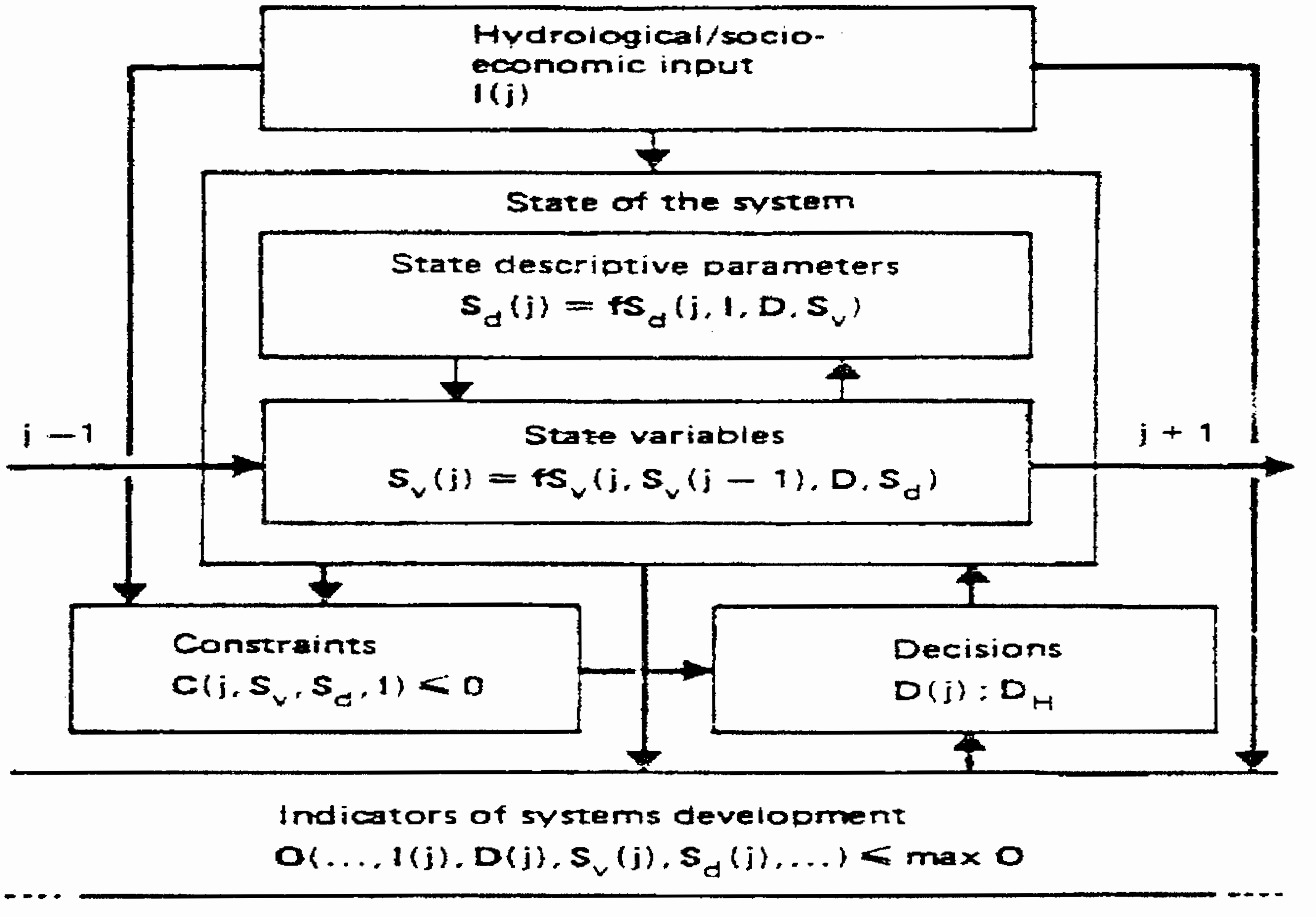

Figure 4: Block schema of the planning model, DSS MINE

For details about that model see e.g. ORLOVSKY, KADEN & VAN WALSUM (1986) but also the proceedings of the IMWA-congress Granada.

What happened to the DSS MINE developed at IIASA with simplified, partly distorted data (because of security requirements of the GRD officials) after the end of the IIASA project?

In the years 1986-1988 the DSS MINE was adapted to more realistic conditions in the Lusatian lignite district, KADEN et al. (1989). With the regional water authorities responsible the permanent use of the model system was prepared, but not continued. In 1988 the economical crisis of the GDR accelerated and resulted later in a political disaster. Consequently there was decreasing interest in long term strategies. Decisions were made on a operational basis. That is why there is no real proof, whether the system could have been used successfully in practice. What had not been considered in the model was of course that drastic economic change in 1990. But, the model might be used to analyze the consequences of these changes.

After the German reunification 1990 there have been attempts to continue the work with the DSS MINE, unfortunately without success. To use a tool as the DSS MINE reasonable and well-defined scenarios of technical and socio-economic development are required. These presumption could of course not been satisfied in the transition period. The general problem of such types of models is - the more complex the models become, and the more they assume an interregional and intersectional character, the more difficult it will be to find a client, KADEN et. al., 1989.

Modeling for long-term water resources planning

In 1992 under the control of the German Federal Environmental Agency (Umweltbundesamt) a project was started to develop strategies for the remediation of the lignite mining region (not only from the point of view of water management), DORNIER (1993). The WASY institute was asked to contribute with water management studies with special regard to the surface water system. The model used was a model of the type of the management model within the DSS MINE - a long-term simulation model, but for the whole Spree river basin. The Lusatian lignite district is a major part of it. This model, called GRMDYN Spree, has become perfected during the last years in co-operation and under contract of the water authorities of Saxonia and Brandenburg. One of the major improvements is the detailed consideration of the flooding process of remaining pits. In Figure 5 a detail of the model structure is shown. The model considers 26 hydrological subbasins, 58 balance profiles, 180 water user, 7 reservoirs and 24 specific control elements as water transfer to user regions, flooding of remaining pits.

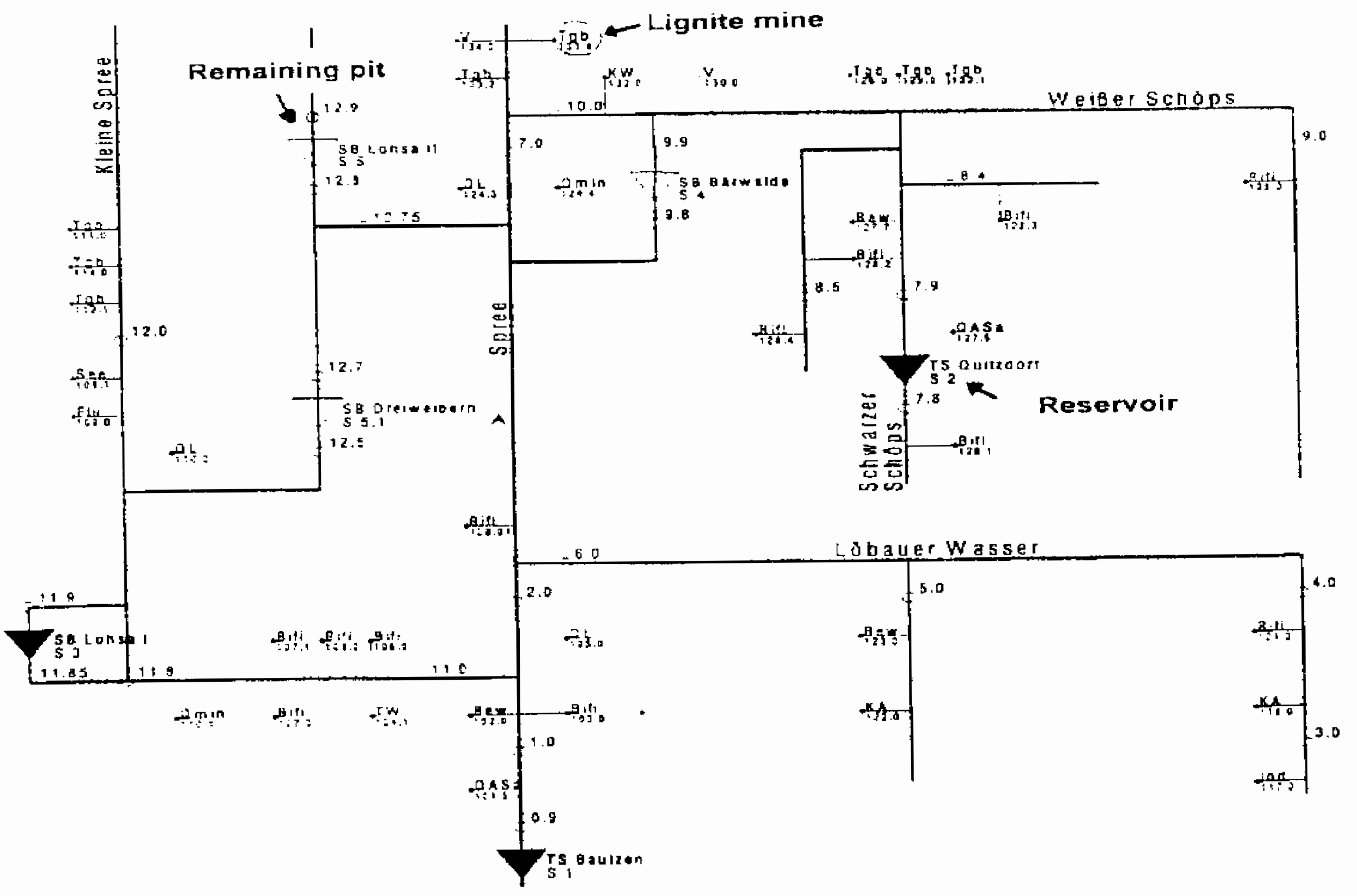

Figure 5: Detail of the modell structure GRMDYN Spree

In Figure 6 the results of two different scenarios are compared - the extreme scenario of closing down the mines as soon as possible, and a more realistic scenario of reduced continuation of mining. It shows the probability to satisfy a given water demand of different users or to guarantee a minimum runoff of the Spree, KADEN & SCHRAMM (1993).

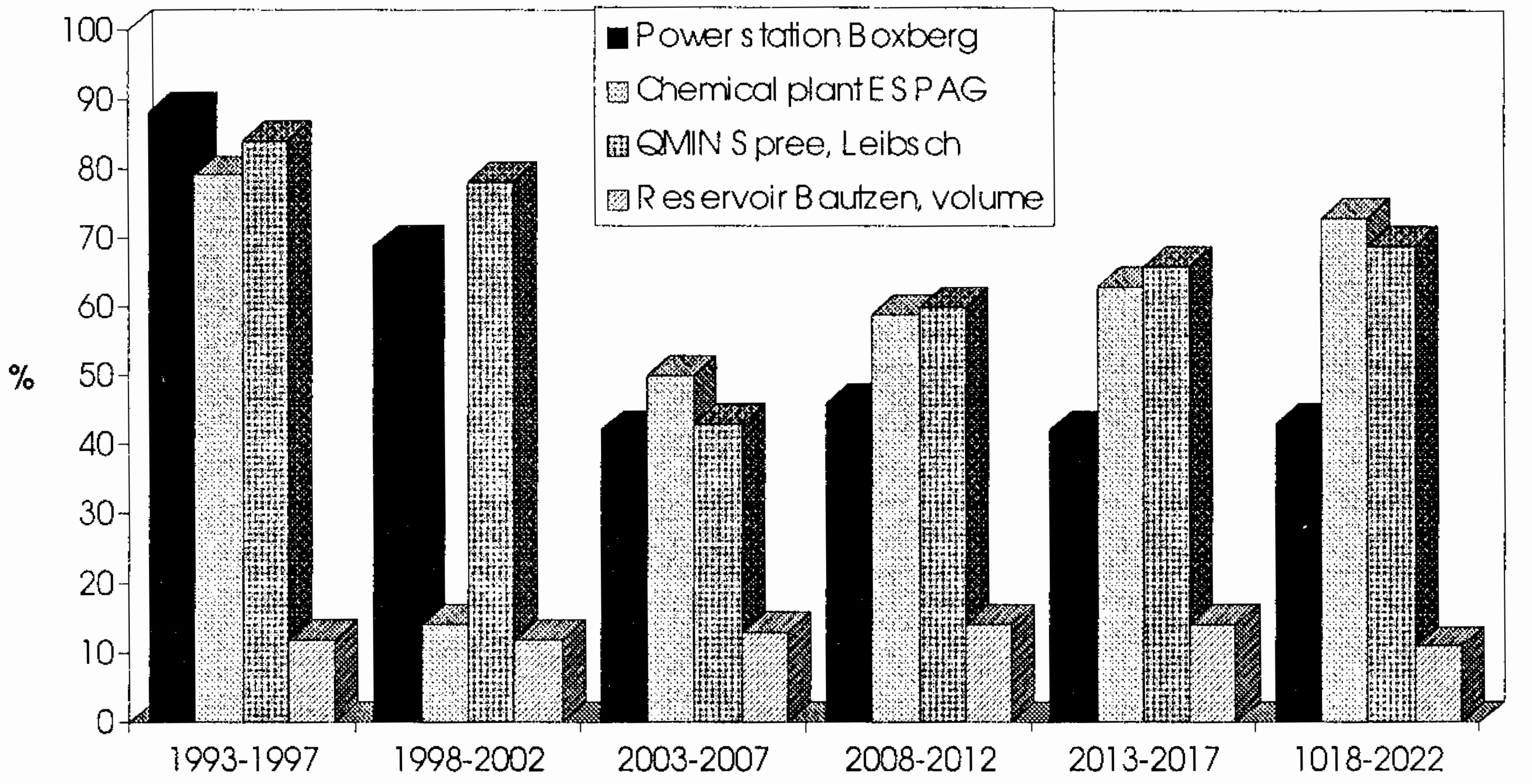

Figure 6: Water management scenarios for the Spree river basin; probability to satisfy water demand for time periods

SUMMARY AND OUTLOOK

Mathematical models are important tools to support drainage design, operation of mine drainage systems, water resources planning and management - in other words, decision support systems. Models as FEFLOW, GEOFIM or GRMDYN have found a high degree of practical acceptance. Managerial and planning decisions are made both, by the mining company and by the water authorities based upon such simulation models. But, to find rational (optimal) scenarios trial-and error-based methods of scenario analysis are used. „High-end" decision support systems as the DSS MINE did not find real practical acceptance. Obviously there is a gap between the complex structure of such systems and decision making in practice. There are many interrelated problems to be solved, but in most cases problems are studied by a certain interested group, from a certain point of view.

Until now, water resources modeling in the mining region was mainly directed towards water quantity. But, with special regard to the well-known weathering processes in dewatered aquifers resulting in acidification, simulation models for water quality become more important. Such processes had been considered already in the above described DSS MINE. Now a project is in preparation, to couple the long-term-planning model with water quality. Such a tool would enable the user to predict water quality in the water system depending on different management strategies and to evaluate the results statistically. And this would support urgent strategic decisions about the remediation of the Lusatian mine district after abandoning more than two third of the previously operating lignite mines .

References

1. BOTH, J., KADEN, S., NILLERT, P. and SAMES, D. (1990): The program system GEOFIM for the digital simulation of subsurface water movement and transport. In: Groundwater Monitoring and Management, Proceedings of the Dresden Symposium, March 1987, IAHS Publ. no, 173, 1990, pp. 203 - 211.
2. DIERSCH, H.-J.G. (1993): Computational aspects in developing an interactive 3D groundwater transport simulator using FEM and GIS. Paper presented at the International Conference on Groundwater Quality Management (GQM 93), Tallinn, Estonia, Sept. 1993 (IAHS-Proceedings in preparation).
3. DIERSCH H.-J.G. et al. (1994): The simulation system FEFLOW, User manual. WASY Ltd., Berlin.
4. DORNIER (1993): Ökologischer Sanierungs- und Entwicklungsplan Niederlausitz. FE-Vorhaben 10104057/02 des Umweltbundesamtes, Berlin, (Ecological recreation and development plan Lower Lusatia; research report).
5. DVWK (1997): Wasserwirtschaftlich-ökologische Forderungen an den Braunkohlenabbau. Merkblatt des Deutschen Verbandes für Wasserwirtschaft und Kulturbau, Entwurf, 1997, Bonn.
6. KADEN, S., HÄNEL, U. und SEIDEL, Karl-Heiz (1976): Digitale Berechnung der Entwässerungswirkung von Tagebaufeld- und -randgalerien (Digital computation of mine-drainage with well galeries). NEUE BERGBAUTECHNIK, Leipzig, 6, Juni 1976, S. 418 - 423.
7. KADEN, S., BECKER, A. and GNAUCK, A. (1989): Decision-support systems for water management. In: Closing the Gap Between Theory and Practice; Proceedings of the Baltimore Symposium, May 1989, IAHS publ. no. 180, pp. 11-21.
8. KADEN, S., MICHELS, I. and SCHRAMM, M. (1995): Stochastische Modellierung der Wasserbewirtschaftung in den Einzugsgebieten von Spree und Schwarzer Elster. In: 4. Dresdner Grundwasserforschungstage, 24./25. 10.1995. Proceedings, Teil 2, S. 23 - 37, Herausgeber: DGFZ e.V.
9. ORLOVSKI, S., KADEN, S. and VAN WALSUM, P. (1986): Decision support systems for the analysis of regional water policies. Final Report. IIASA, Laxenburg, WP-86-33.
10. SAMES, D. (1995): PCGEOFIM, "Programsystem for Computation Geofiltration and Geomigration, Version 6.01". IBGW Ingeniuerbüro für Grundwasser GmbH, Leipzig.