ANALYSIS OF REGIONAL WATER POLICIES IN OPEN-CAST MINING AREAS - A CONCEPTION

S. Kaden

October 1983
WP-83-92

IIASA
International Institute
for Applied Systems Analysis

ANALYSIS OF REGIONAL WATER POLICIES IN OPEN-CAST MINING AREAS - A CONCEPTION

S. Kaden

October 1983
WP-83-92

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
2361 Laxenburg, Austria

PREFACE

The Impacts of Human Activities on Environmental Systems (IMP) Project is concerned with the analysis of interacting socio-economic and environmental systems. The methodological research is based on national studies of environmental and resource policies carried out in several NMO countries in collaboration with IIASA. The main focus of these studies are large-scaled (time and/or space) groundwater depletion and protection problems.

One of these studies is the Analysis of Regional Water Policies in Open-Cast Mining Areas undertaken in collaboration with the Institute for Water management, Berlin and the Technical University, Dresden, GDR. Open-cast lignite mining is one of the conspicuous examples for complex interactions in socio-economic and environmental systems with special regard to groundwater degradation. These problems concern especially countries in middle and eastern Europe, in particulr the GDR, FRG, CSSR, Poland, etc.

This paper outlines the conception for this study. Based on the description of the problem, the proposed methodological approach and the working plan are drafted. The paper should be useful for the initiation of in-house collaboration as well as the establishment of collaborating activities with NMO cuntries, dealing with groundwater depletion problems in open-cast mining areas.

Janusz Kindler
Leader
Impacts of Human Activities on Environmental Systems Project

ACKNOWLEDGEMENTS

I am indebted to a number of persons in preparing this paper. First, I would like to express my gratitude to Rafael Bras and Janusz Kindler, who provided many useful comments. Secondly, I wish to thank Manfred Grauer and Sergei Orlovsky for the useful and stimulating discussions.

ABSTRACT

In the GDR more than two-thirds of the total output of primary energy is based on lignite extracted exclusively by strip-mining. Mining results in significant environmental and resource use conflicts between different users in such regions. This paper describes the concept of a study on the analysis of Regional Water Policies in Open-Cast Mining Areas in collaboration with institutes in the GDR. The study is directed at the development and implementation of methods and models for analyzing the use of water resources and environmental problems in open-cast mining areas.

The study is one of a network of national studies concerned with environmental and resource policies carried out in several National Member Organization (NMO) countries within the IIASA Program "Institutions and Environmental Policies." Based on the problem definition the research topics are characterized, a few methodological approaches outlined and the working plan presented.

CONTENTS

ANALYSIS OF REGIONAL WATER POLICIES IN OPEN-CAST MINING AREAS - A CONCEPTION

S. Kaden

1. Introduction

Within the Institutions and Environmental Policies Program at IIASA, a project which deals with the design of resource and environmental policies is planned. The motivation for this project is the growing socio-economic development in many regions of the world, which creates severe and complex environmental and resource use conflicts.

The project will focus on concepts, procedures, and methods in the area of resource and environmental policy design. The research will concentrate on generic issues that dominate virtually all problems in environmental and natural resource policy design and also characterize groundwater management and protection problems. First, these problems always involve controversy among interest groups. Second, it is difficult or impossible to select a single criterion for appraising alternative courses of action which is fully acceptable to all participants. Beyond that, not all objectives concerning human health and fundamental environmental equilibria can be translated into monetary values. Third, uncertainty and imprecision due to limited understanding, data basis and predictive capabilities are common.

The main objective of this project is the development of relatively simple policy-oriented methods and computerized procedures that can assist in addressing the above-mentioned generic issues--in other words, the development of policy-oriented decision support models with special regard to groundwater management and protection strategies and policies. The project team is working with, and attempting to synthesize experience from, a network of national studies concerned with environmental and resource policies carried out in several National Member Organization (NMO) countries. One of these studies is the Analysis of Regional Water Policies in Open-Cast Mining Areas undertaken in collaboration with institutes in the GDR. The study is directed at the development and implementation of methods and models for analyzing the use of water resources and environmental problems in open-cast mining areas. Conflicts caused by open-cast lignite mining in middle and eastern Europe, essentially in the GDR, USSR, FRG, CSSR, and Poland, are one of the conspicuous examples for interactions in socio-economic environmental systems with special regard to ground- and surface water.

The profound theoretical and practical experience of the Research Group for Open-Cast Mine Dewatering of the Institute of Lignite Mining and the Dresden Technical University, TUD, and of the Institute for Water Management, IfW, in the domain of modeling mine impacts on water resources systems forms a good basis for the study (see, for instance, Luckner et al., 1982; Peukert et al., 1982; Kaden, 1982; Zwirnmann, 1980). The most important parts of the study will be the development and integration of different simplified submodels of the complicated subprocesses that form a part of a policy-oriented decision support system and the study of the interactions in the socio-economic environmental system. Following this, a conception of the study is given based on discussions with colleagues from

IIASA and collaborating institutes in the GDR.

2. Problem Definition

In the GDR, more than two-thirds of the total output of primary energy is based on lignite extracted exclusively by strip mining. The annual output of lignite amounts to more than 250 million tons/annum. Thereby it is necessary to pump out 1.5 milliard m^3/annum water for the dewatering of the open-cast mines. For 1990, an output of about 300 million tons/annum is planned; the rate of mine water pumping is estimated at about 2 milliard m^3/annum. The stable runoff of the GDR runs to 9 milliard m^3/annum. That means that the amount of mine water is about 20% of the stable runoff (see, for instance, Luckner et al., 1982). Hence in the mining area itself the water resources system is mainly determined by the lignite mining (a fact which is not only typical for the GDR conditions).

The impact of mining upon water resources creates significant environmental and resources use conflicts between different users in such regions. The most important interest groups are mining, municipalities, industry, in many cases located downstream, and agriculture. The activities of each of these interest groups modify more or less the water resources system, as well as the conditions for resources use by other groups. Figure 1 gives a general view of the interdependencies of the water users and water resources subsystems in mining areas. Recreation and environmental protection also represent conflicting users.

Under the typical hydrogeological conditions in lignite mining areas, mine dewatering becomes a significant cost and energy factor. The amount of water to be pumped exceeds ten to one hundred times the output of coal! That means a considerable part of the energy produced by lignite is used for dewatering the mine itself. Since the mines are about 40 to 60 meters deep (sporadic 100 meters or more, but not in the GDR), in the high-permeable glacial aquifers large regional cone-shaped groundwater depressions are formed. One of the consequences is that

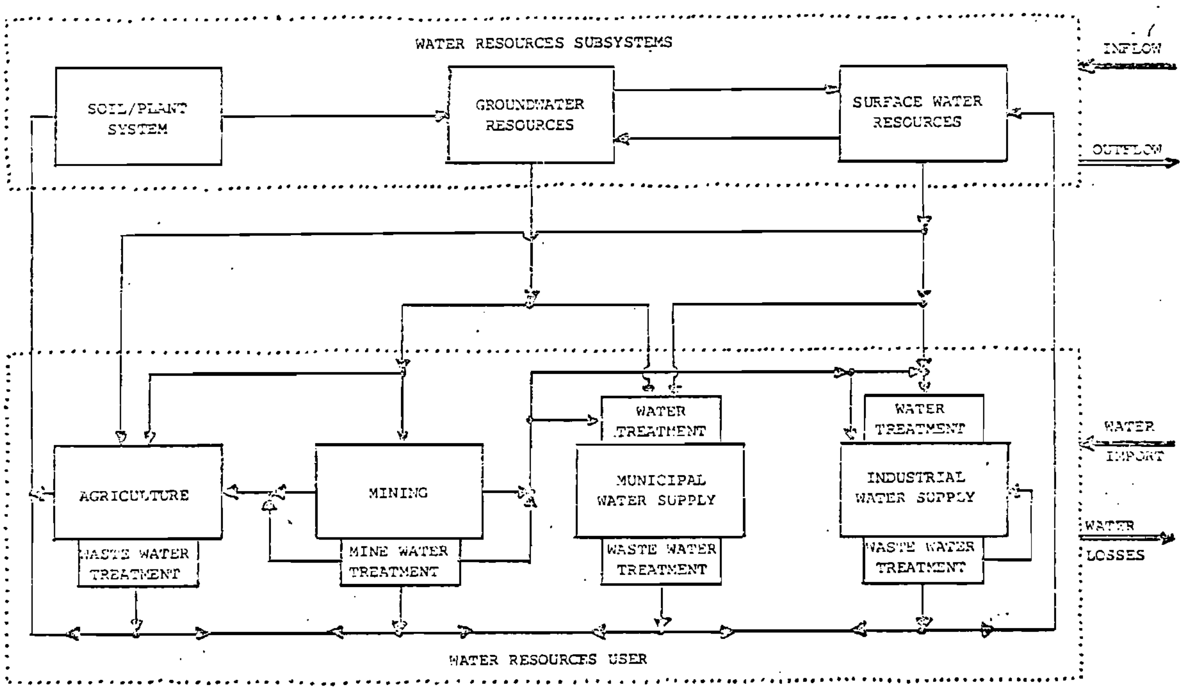


Figure 1. Interdependencies between water resources users and water resources subsystems in mining areas.

the wells for municipal water are becoming dry. Hence the objective "satisfying drinking water supply in a certain quality and quantity" conflicts with the mining objective "lowering the groundwater table in given areas and time". Management/technological alternatives are, for instance, the limitation of groundwater depression areas with the help of side walls, switch to alternative water supply sources (e.g. surface water, water transfer from other regions, re-use of mine water, etc.).

There are also water quality problems caused by mining. Mine drainage water characteristically contains both high suspended and dissolved solids, particularly iron and sulphate ions resulting from the oxidation of ferrous sulphides in the host rocks. Chloride concentrations may also be high because of connate water trapped within the sedimentary rocks. Commonly, the conspicuous quality problems are connected with mine edges. For example, in the Lusatia area in the GDR, sulphate-concentrations up to 700 mg/l have been estimated in the drainage water of mine edges (Starke, 1980). Polluted mine water may affect downstream water yields significantly.

Each of the interest groups can be characterized by its objectives, technological and/or management alternatives, and impacts on the water resources system. Table 1 gives an overview of these characteristics for the major interdependent interest groups in mining areas, that means, mining, municipal and industrial water supply, and agriculture. The remaining interest groups, like downstream water users, and environmental protection have not been introduced because they do not impact the water resources system in the mining region itself. But it is necessary to consider their objectives--satisfying water levels and water quality (surface- and groundwater) constraints for environmental protection, and satisfying water demand of downstream users.

Minimizing costs is one of the important objectives of all interest groups. Therefore, controlling prices, besides legislative measures, becomes one of the most effective regulating means. A good example is the use of mine drainage water for drinking water supply. The costs of such utilization of this water are often relatively low. They amount, for example, only to about 0.10 M/m^3 in the Lusatia area, where about 400,000 m^3/day is produced. In contrast, the equivalent costs of the utilization of surface water in that area runs up to 1.50 M/m^3. Since the beginning of 1981 a new regulation promotes the utilization of mine drainage water for the drinking water supply in the GDR. The producer of drinking water gets 0.70 M/m^3 from the distributor and the distributor gets 0.90 M/m^3 from the consumer. This is an economic incentive for the lignite open-cast mines to produce drinking water (Luckner et al., 1982).

Table 1. Characteristics of interest groups in mining areas.

	OBJECTIVES		Technological/management alternatives	Impacts on water resources subsystems		
	General	Water management		Soil/plant systems	Groundwater resources	Surface water resources
MINING	maximizing coal production with minimized costs	- mining drainage for given time, depth and areas - minimizing costs for mine drainage and mine water treatment - minimizing energy consumption for mine drainage	- mine drainage technology (little or big wells, side walls) - technologies considering acidification and chloride coning - optimal filling technology of remaining pits - river sealing	- changed soil conditions in recultivated areas (edges)	- regional lowering of water table due to withdrawal - regional raising of water table in coal-extract areas - infiltration of surface water - changed hydrogeological/hydrochemical conditions in dewatered areas and edges - pollution due to mining	- discharge of mine drainage water - infiltration in groundwater subsystems - (discharge of mine waste water)
MUNICIPAL WATER SUPPLY		- satisfying water demand relative quantity and quality - minimizing costs for water production and treatment - (minimizing costs for sewage treatment)	- use of alternative sources for water supply (groundwater, mine drainage water, water import) - reservoirs		- local lowering of water table due to withdrawal	- withdrawal of surface water - discharge of treated sewage
INDUSTRIAL WATER SUPPLY	maximizing industrial production with minimized costs	- satisfying water demand relative quantity and quality for given technologies - minimizing costs for water production and treatment - minimizing costs for waste water treatment and allocation - minimizing losses due to reduced water supply	- use of alternative sources for water supply (surface water, mine drainage water, treated waste water) - reservoirs - water reduced technologies - wastewater treatment with extraction of secondary raw materials		- point pollution by hazardous wastes	- withdrawal of surface water - discharge of wastewater (more or less treated)
AGRICULTURE	maximizing agricultural production with minimized costs	- satisfying optimal conditions for plant growth (soil moisture and nutrients) - minimizing costs for irrigation and fertilizing - minimizing costs for sewage disposal, allocation, treatment	- use of alternative sources for irrigation (groundwater, surface water, wastewater, mine drainage water) - reservoirs - optimal irrigation and fertilizing control	- changed soil moisture and nutrient content due to irrigation and fertilizing	- local to regional lowering of groundwater table due to withdrawal for irrigation - nonpoint pollution due to leaching of fertilizers, etc. - point pollution due to sewage disposals	- withdrawal of surface water for irrigation - discharge of treated sewage

Table 1 elucidates for the main interest groups the manyfold impacts of technological/management alternatives to be considered.

Beyond that, interdependencies between water resources subsystems determine the system behavior. The interdependencies between the subsystems are illustrated in Figure 2 and Table 2.

Table 2. Characteristics of water resources subsystems in mining areas.

impacts ↗ on of	groundwater subareas	river section	remaining pit	lake/ reservoir	processes in the subsystem	process/status variables*
groundwater subareas	groundwater flow	(infiltration of gw.)	infiltration of gw.	(infiltration of gw.)	gw. storing, quality variation	gw. table, storage volume, inflow/outflow
river section	infiltration of gw.	inflow	X	outflow	quality variation (water storing)	inflow/outflow water level
remaining pit	infiltration of gw.	X	X	X	water storing, quality variation	inflow/outflow storage volume
lake/ reservoir	(infiltration of gw.)	inflow	X	X	water storing, quality variation	inflow/outflow storage volume
soil/plant subarea	percolation	X	X	X	soil water storing, quality variation	soil moisture content, perculation rate

*quantity and quality

Looking at the table, it becomes obvious that the groundwater flow is the medium integrating the whole system. Due to the depth of groundwater the soil/plant subsystem has more effect on the groundwater system than vice-versa, and it can be assumed to be nearly independent.

In general, the water resources and environmental problems in mining areas include long-term planning (management) and short-term control aspects. They are embedded in a hierarchical policy-making process with interdependent policy makers (see Figure 3). For short-term control problems the policy makers as well

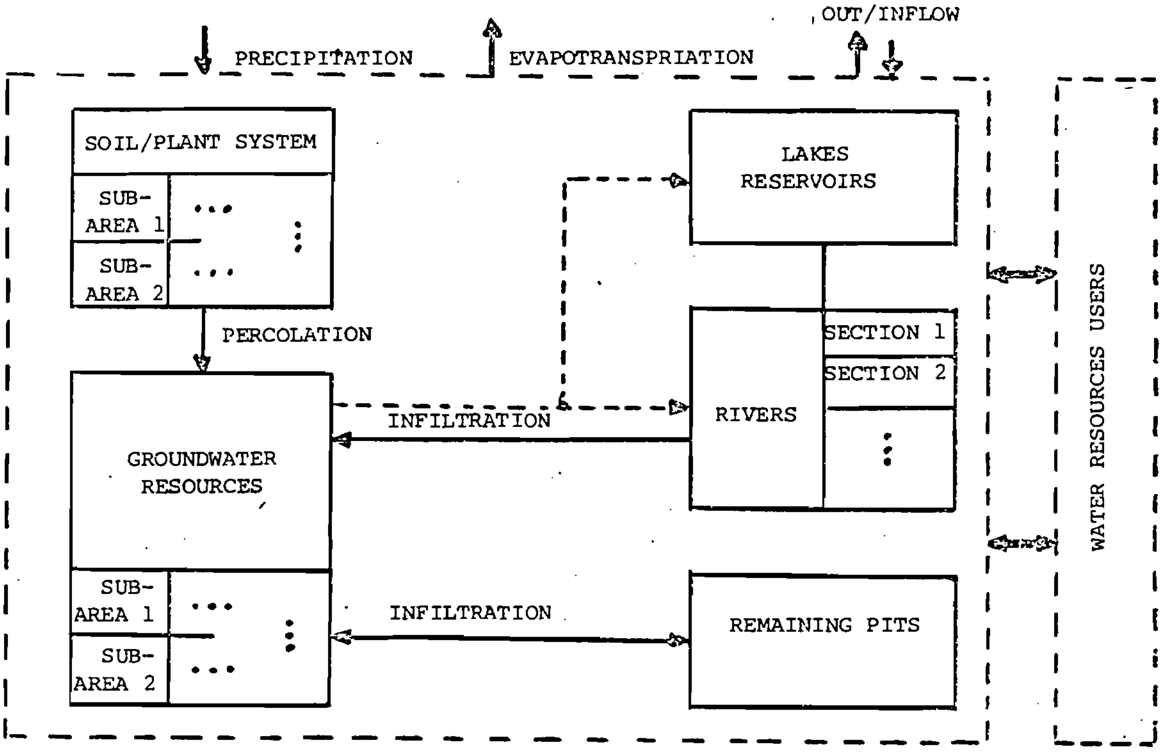


Figure 2. Interdependencies between water resources subsystems in mining areas.

as the environmental subsystems can be assumed to be independent. Based on the different time characteristics of the water resources subsystems, above all the significant retardation in the system due to the groundwater flow, these problems usually are solved separately for the different water resources subsystems (considering other subsystems as constraints).

The *long-term planning* pinpoints the general targets and thereby sets up the margins for short-term activities. It becomes the crucial task due to the significant interdependencies in the socio-economic environmental system and policy-making process.

The planning horizon amounts to about 30-50 years. The time interval to be adopted for analysis may vary from month to year, considering the processes under

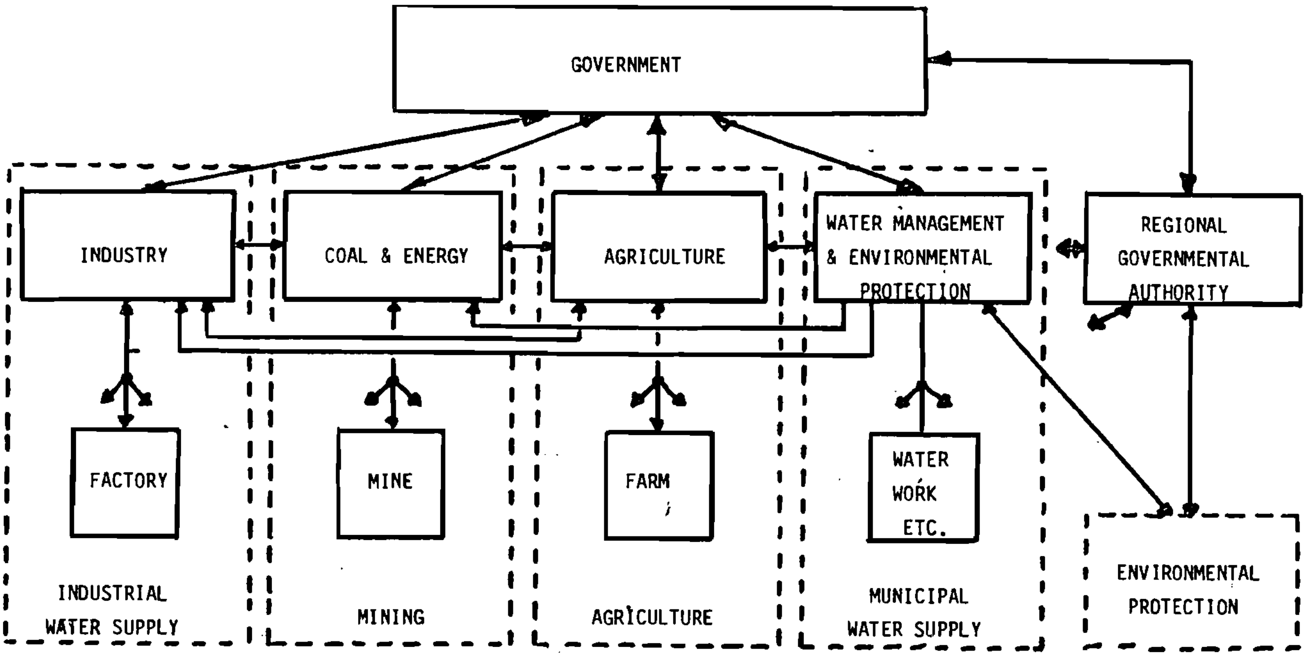


Figure 3. Schematic policy making system in mining areas.

consideration. The area affected by open-cast lignite mines accounts to some 10,000 km^2. For the purpose of this study, a test subregion has to be selected with typical geographical, hydrological, and hydrogeological conditions as well as conflicting impacts. Probably an area of about 1000 km^2 has to be chosen.

The above described interdependencies between water resources users and water resources subsystems, creating manifold conflicts, elucidate the importance of effective management alternatives and means of regulating the interactions within the socio-economic-environmental system. Mathematical, computerized models are a necessary and useful tool--models which fit in the policy-making process.

3. Obstacles to be Avoided for Effective Policy-Modeling

> "We have the feeling that some model builders look
> like cyclists pedalling along elegantly and powerful
> in a chainless bike." (DeDonnea, 1978)

Resources use and environmental problems initiated extensive research effort in many countries using elaborate mathematical models and computer techniques. Yet the impact of all these efforts has not been very satisfactory in the sense that the majority of the mathematical models elaborated have not found their effective application for the analysis of real systems as an integrated part in policy-making processes (see, for example, Greenberger et at., 1976). What are the main obstacles to the effective use of models within the policy-making process?

First, much of the modeling and analytical effort is more or less sharply divided between the following two lines:

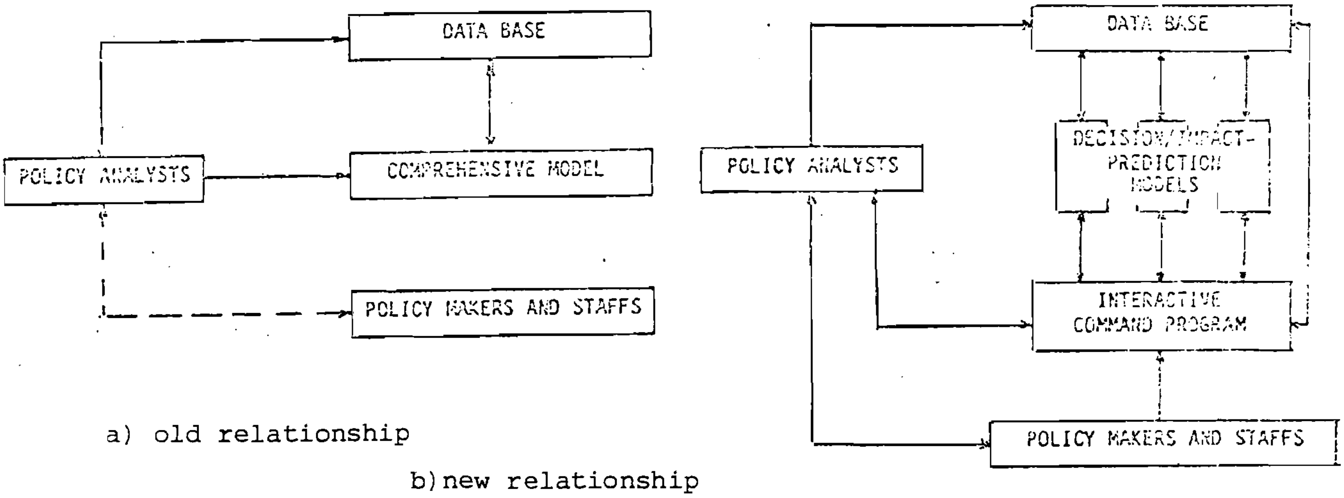
- modeling and analyzing various environmental systems, and
- modeling and analyzing economic development (economic modeling on various scales).

What has not sufficiently been emphasized in these studies is probably the key role of the interactions between the socio-economic development and the environmental processes. The great majority of environmental modeling systems analyze the impacts of resources use, or more general, of socio-economic development, but do not consider socio-economic consequences of these impacts. This part belongs to the job of the decision-makers and staff. On the other hand, economic models in many cases neglect environmental consequences due to socio-economic activities and often thereby neglect the interlacing of certain parts of the socio-economic development through environmental systems (for instance, the water resources system in mining areas, see Section 2).

Second, in the last two decades of policy modeling, there was a tendency to move from the development of simple to much more complex and comprehensive simulation and optimization models. Kindler and Loucks (1983) described the increasing difficulties using such models. The difficulties relate to their sometimes mysterious contents from the users' point of view, to the incompatability between available time and budget and the collection and verification of the data required, to the differences between generated solutions and the solutions preferred by the policy-makers. "Their greatest shortcoming, it is generally acknowledged, stems from the fact that they, the models and the analysts, do not fit very well into the decision making process." In many cases the real challenge and need is not for developing bigger, better, more sophisticated models, but rather with sitting down and developing very simple-minded procedures (Eisel, 1981). More attention has to be devoted to the investigation of models in the policy-making process, for instance, such as those shown in Figure 4.

Third, normative models directly aimed at helping in the policy-making process to choose "optimal" or "satisfactory" actions from among several alternatives necessitate a judicious choice of optimization criteria. Often the optimization criteria incorporated into models are not relevant enough and do not meet legitimate preferences. Above all, it has to be emphasized, that economic efficiency is only one of several criteria. Some of the environmental effects can hardly be translated into monetary values; perhaps models may never be able to do this convincingly. "Economists should abandon efforts to develop more or less heroic methods for putting monetary values on intangibles. Intangibles should be accounted for in multicriteria analysis" (DeDonnea, 1978).

Fourth, in most of the cases, the existence and quality of the relevant data are not adequate to the complicated sophisticated models. The lack of model-adequate data is a well-known but frequently neglected fact. Many models are built upon



a) old relationship

b) new relationship

Figure 4. Relationships among policy-makers, policy analysts, their models and their data (source: Kindler and Loucks, 1983).

incomplete or untrustworthy data. Consequently, untrustworthy results discredit models with the policy-makers. Similar problems grow out of uncertainty and imprecision due to limited understanding and predictive capabilities of the processes going on. Typical examples are most of the ecological processes but the same applies to uncertainties on the side of the socio-economic development (economic and/or technological uncertainty).

Fifth, policy modeling requires an adequate institutional framework. The use of models in the policy-making process must be favored by the institutional framework, otherwise the models might never be used. A model which has not been ordered by the agency which has the decision-making power in the relevant area has only a slight chance of being used by this agency. Moreover, if the responsibilities are spread over several agencies, a model will fit if the more or less conflicting goals of these agencies are reflected (for more details, see De Donnea, 1978).

Finding ways to avoid these obstacles is a challenging task for the planned study.

4. Research Topics

The choice of a suitable test area determines both the theoretical and the practical value of the study. Therefore, the following suppositions will be considered:

- the test area has to reflect the real policy-making process in mining regions through a statement of typical preferences and objectives as well as decision alternatives.
- the dimension of the test area has to be restricted to minimize the data preparation and computing.
- typical environmental subprocesses in mining areas such as the conjunction of grondwater and surface water flow or processes forming the water quality have to be integrated.

In the appendix an appropriate test area is schematically outlined.

Based on the rough problem definition in section 2, the *first research topic* of the study will be a detailed analysis of the socio-economic environmental process in the test area.

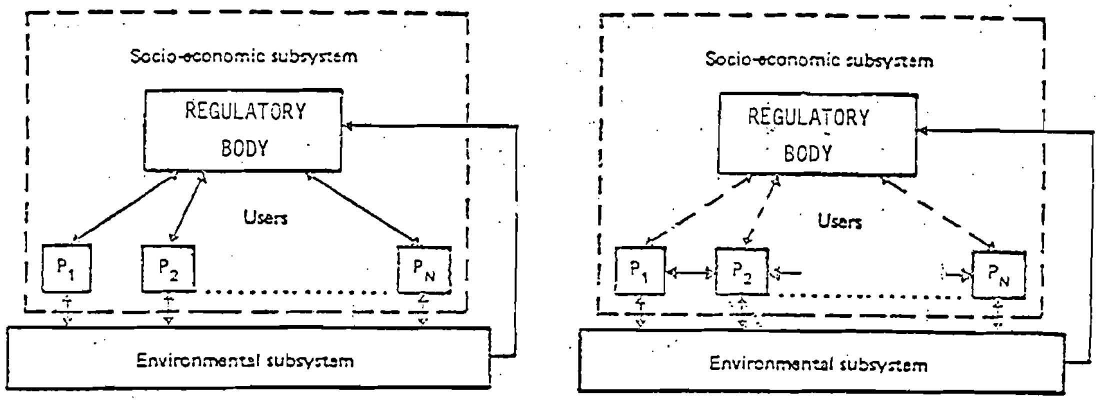
As the *second research topic*, suitable submodels for these processes have to be developed. On the one hand the submodels should be simple enough for their integration in a complex policy-oriented model and on the other hand reflect the reality sufficiently accurately for policy-making. Particular difficulties will originate from the differing spatial dimensions and varying time behavior of the environmental submodels. In section 4.1 the development of the water resources submodels is outlined. Submodels for the socio-economic processes can be developed probably relatively simply. Difficulties will arise out of the qualification of the models with real data.

The *third research topic* is the choice and development of the mathematical and computing framework for systems analysis, aiming at a policy-oriented interactive decision support model. A first approach is characterized in section 4.2, based on experiences with long-term water management models. Above all this topic determines the applicability of the model system in the policy-making process. The obstacles, described in section 3 have to be taken into account. The crucial point lies in the interactive character of the model system.

The *fourth research topic* will be the development of an approach for the integration of the decision support model in the policy making process. Considering the complicated hierarchical structure of the policy-making process in mining regions, it becomes obvious that only a simplified structure of this process can be taken as a basis for the study. A sensible compromise would be a two-level system as shown in Figure 5.

For a two-level system with a regulating body and different independent users or interest groups as shown in Figure 5a, a suitable two-state decomposition approach has been proposed by Orlowski (see Hughes et al., 1983). The feasibility of this approach for the mining problems will be studied. Additional approaches which stress the interdependencies of the interest groups have to be developed (Figure 5b).

The *final (fifth) research topic* will be the use of methods and models developed for policy design in the test area.



a) independent users

b) interdependent users

Figure 5. Two level policy-making systems.

4.1. Water Resources Submodels

The water resources system will be modeled as a system of interlinked submodels. Many highly valued methods for the separate modeling of water resources subsystems exist. These models are mostly not well suited for linking. The submodels would be best suited for normative modeling if they could be described as a set of algebraic equations depending on the decision variables. In the literature some examples of this approach are known (see for example, Haimes and Kindler, 1981, Yaron and Tapiero, 1980).

For the water resources system in mining areas we can separate three main subsystems (see Figure 3):

- the soil/plant system

- the groundwater resources
- the surface water resources

Submodels have to be developed describing both the water quality and essential water quality processes.

4.1.1. Water Quantity Submodels

Following Figure 2, the only function of the *soil/plant system* is the transformation of diffuse water inputs (precipitation, irrigation) into percolation and finally into groundwater recharge. This is based on the assumption that dealing with grondwater tables lowered below the threshold of capillary rise, further changes of groundwater resources do not affect the soil/plant system. Another assumption can be made that considering the hydrological and hydrogeological properties of mining areas as well as their usually flat topography surface runoff is very small compared to percolation and thus can be neglected. Consequently, if we ignore crop production, the submodel of the soil/plant system can be replaced by, and limited to, a model of groundwater recharge.

Considering the objective of the study directed towards long-term planning, and further the significant groundwater lowering, obviously short-term (within-the-year and from year to year) changes of groundwater recharge can be neglected. For the determination of long-term mean values of groundwater recharge in the GDR the program RASTER has been developed (Enderlein et al., 1980). Based on long-term mean values of precipitation and potential evapotranspiration, the real evapotranspiration is estimated using the Bagrov- approximation (Dyck, 1978). The following parameters are considered in the approximation, the main form of land utilization, the soil type, the type of agricultural land use and the agricultural yield classes. The groundwater recharge itself results from the balance of precipitation minus real evapotranspiration. Long-term changes of land use and soil types due to mining activities imply changes in groundwater recharge. Based on the program RASTER simplified relationships between the groundwater recharge and the above mentioned factors can be estimated and integrated as the submodel "Groundwater Recharge" in the complex model system.

In looking for the appropriate submodels for ground- and surface water, it is reasonable to concentrate on models which are already used for management or policy-making purposes.

Up until the present, water resources modeling was more or less sharply divided into groundwater and surface water modeling. The development reflects the different methodological approaches of the surface water hydrology and the hydrogeology or geohydrology. The main reasons for these differences are the different time behaviors and the different influence of the precipitation as a stochastic input. For *groundwater management*, sophisticated models based on finite difference or finite elements methods are often developed. Hierarchical systems of such models allow the simulation of the future systems behavior. Management alternatives have to be considered exogenously. These types of models found great popularity in many countries for long-term planning and short-term control of open-pit mine dewatering (see for example, Weeks, 1982). In the GDR for instance, a powerful regional model has been developed for Eastern Lusatia. Typical model results - groundwater tables and groundwater withdrawal - are shown in Figure 6 for a planning period till the year 2000 (Peukert et al., 1982).

The great data requirements and the complicated processes simulated by such models do not easily allow for their direct integration in decision-oriented analytic packages.

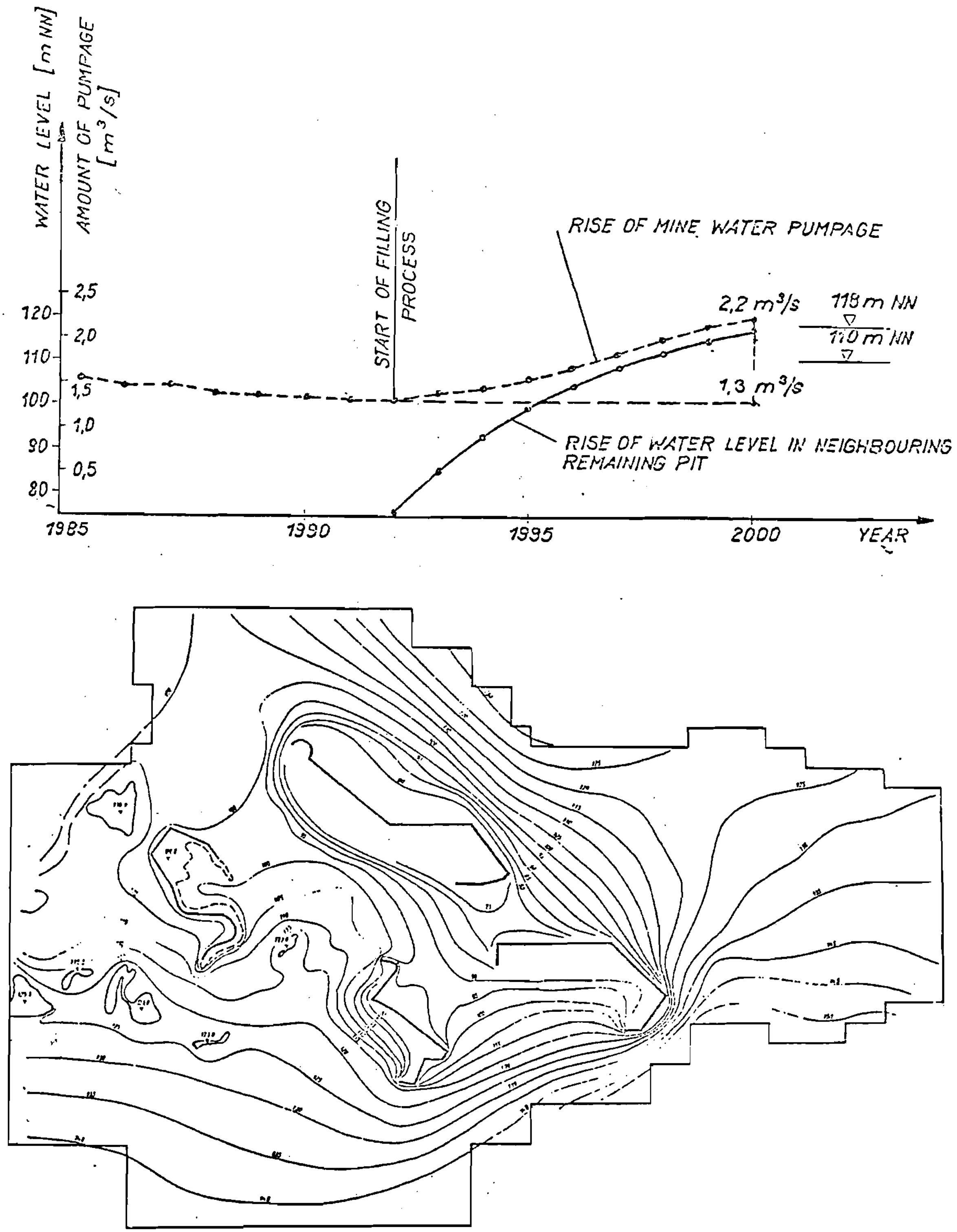


Figure 7. Simulation results of a regional mine-drainage model (source: Peukert et al., 1982).

For *surface water management*, models combining stochastic (streamflow, etc.) and deterministic inputs (water use) are used (usually on a monthly basis). In order to simulate the behavior of a river basin, the system under analysis is commonly represented by means of a network of nodes (structural or nonstructural components of the river basin system) and arcs (natural or man-made connections of the river system, linking the nodes) (see for example Figure 7).

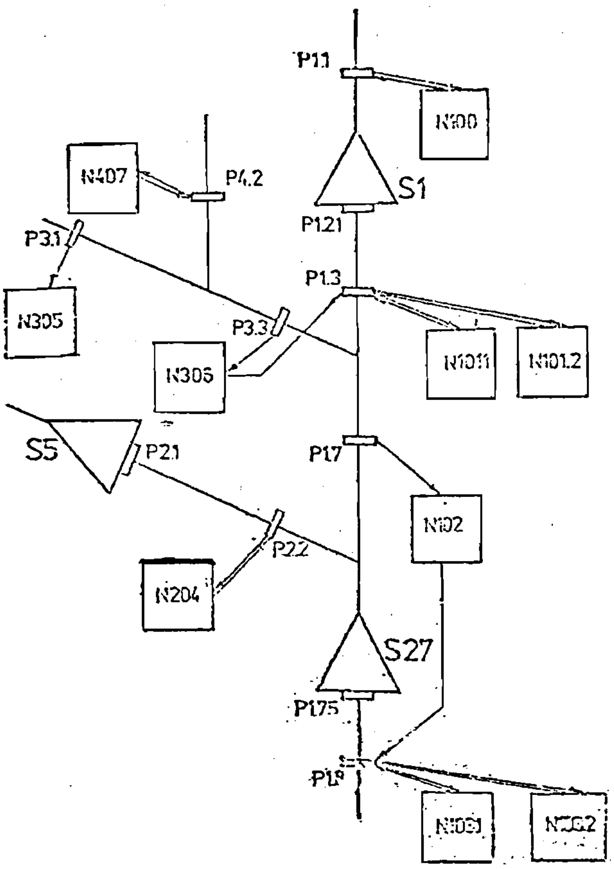


Figure 7. Schematic view of a river basin with balance-profiles (P), users (N) and reservoirs (source: Kozerski, 1981).

Such generalized planning models have been developed in many countries (Strzepek, 1981 - MITSIM2; Kozerski, 1981 - GRM; etc) in most cases dealing with water quantity only. Management alternatives have to be introduced exogenously. The basic structure of these models - algebraic equations of water balances for balance profiles - fits the requirements of the model system prepared herein.

Summarizing the discussion, the main difficulties in the development of the water resources submodels are related to the simplification of the groundwater subsystem and the interlinking of the ground- and surface water submodels. The best solution would be the integration of the groundwater subsystem with the surface water balance models mentioned above.

Figure 8 gives an overview of the typical groundwater-surfacewater flow problems in mining areas which have to be taken into account. The main difficulties with these problems are:

- nonlinearity caused by the high amplitude of changes in the groundwater table,
- the hydrogeological conditions change in time due to the mining (edges, remaining pits), and
- the flow between surface water and groundwater is a function of the water table changes in time between the limiting values of baseflow and free infiltration.

Commonly, the original 3-dimensional groundwater flow problems are simplified into multi-layer flow problems, with the assumptions made that in the aquifers, only horizontal flow takes place, and in the aquitards, only vertical flow takes place. Based on these assumptions further simplifications are needed.

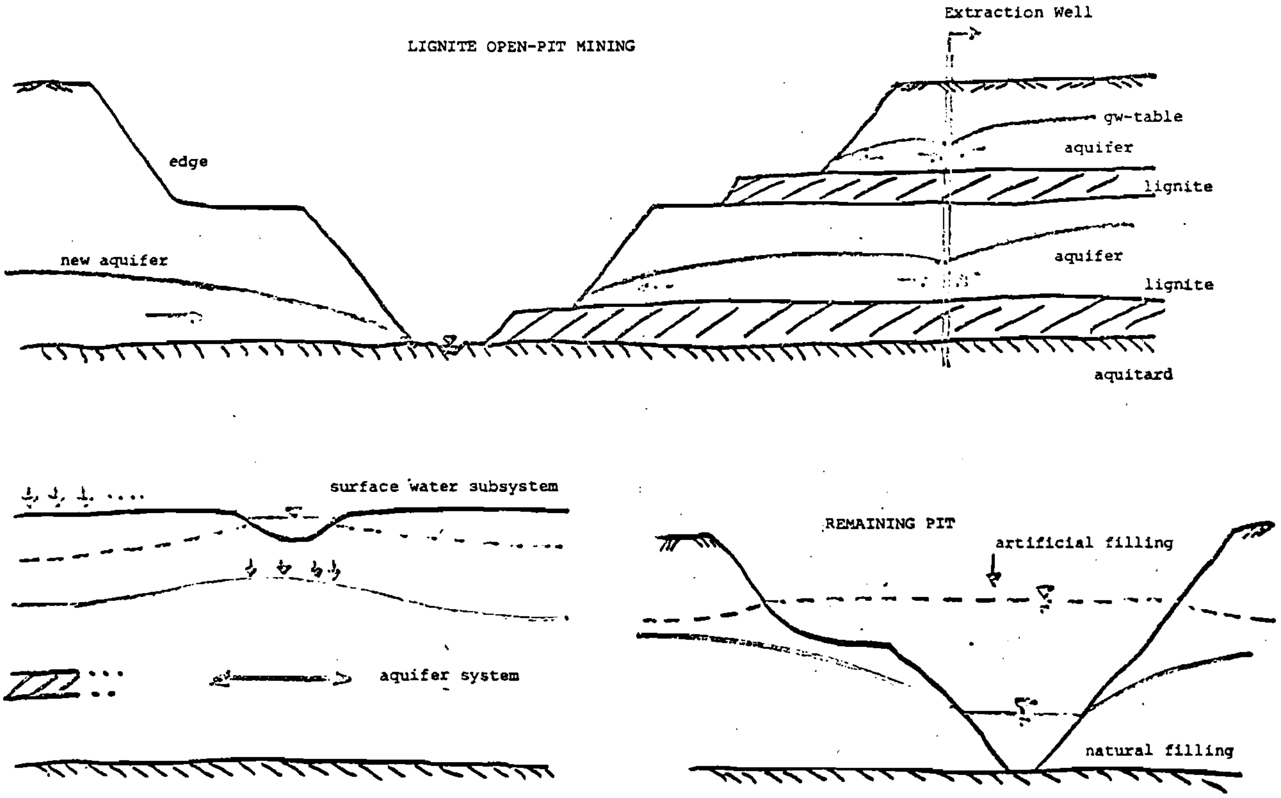


Figure 8. Typical flow problems in mining areas.

4.1.1.1. Simplification of Groundwater Models Based on the Mathematics of Linear Systems

In the last decade, modeling for groundwater management, with special regard to the conjunctive use of surface and groundwater, has been increasingly based on the mathematics of linear systems. Linear systems can be characterized by one function, the unit impulse kernel (or Green's Function). The response of this system to any input can be predicted by the convolution equation.

$$q(t)=\int_{o}^{b} k(t-\tau)r(\tau)d\tau. \tag{1}$$

with

q = response to the system

k = impulse kernel function

r = excitation pattern

t = time

Using a step kernel function K, the above equation can be rewritten in the form

$$q(t)=K(t)\cdot r(0^+)+\int_0^t K(t-\tau)\frac{\partial r(\tau)}{\partial \tau}d\tau. \tag{2}$$

For practical solutions, instead of the continuous description of the convolution equation, a discrete description will be used considering the unit pulse

$$q(n)=\sum_{\nu=1}^{n}\delta(n-\nu+1)r(\nu). \tag{3}$$

with

n, ν = discrete times

$$\delta(n)=\int_0^1 k(n-\tau)d\tau = \text{discrete pulse kernels} \tag{4}$$

$r(\nu)$ = constant input for the interval $(\nu-1,\nu)$.

In the case of m different inputs, we obtain

$$q(n)=\sum_{i=1}^{m}\sum_{\nu=1}^{n}\delta_i(n-\nu+1)\cdot r_i(\nu). \tag{5}$$

Two similar directions are most important - the above discrete kernel approach (for instance, Morel-Seytoux, 1978) and the algebraic technological functions (for instance, Maddock, 1972, Haimes et al., 1977). In the GDR, the latter method is used to develop simple models for the short-term control of groundwater extraction for municipal water supply (for instance, Luckner et al., 1979). Generally, the discrete kernels have to be obtained numerically. For the numerical generation of the discrete kernels, more or less complicated flow models (finite difference of finite elements models) are used.

In these methods the systems behavior is described by algebraic equations of the sought after system responses on the system impacts or influences only. Such a model is best suited for its integration in management models. The need of sophisticated flow models for their numerical generation is unfavorable. If the linearization for the mining problem is not possible, the implementation of non-linear algebraic technological functions or discrete kernels should be provided. Maddock 1974, developed such functions for the drawdown in unconfined aquifers due to pumping. The resulting functions are nonlinear polynomical relationships between pumping and drawdown. In general, based on the pertubation theory, it is possible to transform the nonlinear flow problem into a set of linear problems. For each of the linear problems the theory of linear mathematics can be used as described above. First test calculations indicate that two linear problems will be a sufficient approximation of the nonlinear problem.

4.1.1.2. Groundwater Balance Models

The development of balance models for groundwater subareas, and the coupling of these balance models as a system of linear or nonlinear reservoirs is another promising approach. In general, groundwater balance equations are used in the following form:

$$Q_{in}^{t} - Q_{out}^{t} = A \cdot S \cdot \frac{dh}{dt} \approx A \cdot S \frac{h^{t} - h^{t-\Delta t}}{\Delta t}. \tag{6}$$

with

Q_{in}^{t} = inflow in the balance area $[\frac{m^3}{s}]$

Q_{out}^{t} = outflow out of the balance area $[\frac{m^3}{s}]$

A = area $[m^2]$

S = storage coefficient [-]

h = peizometric head $[m]$

t = time $[s]$

Introducing the DARCY-Equation, Eq.(6) will be transformed in the typical groundwater flow equation in terms of h. This equation hardly can be coupled with surface flow balance equations in terms of Q.

Tiemer, 1983 developed a balance model for a groundwater storage in the GDR based on the storage volume

$$V_s^t = C \cdot V^{t-\Delt t} + Q_{in}^{\Delta t} - Q_{out}^{\Delta t} \,. \tag{7}$$

with

V_S = storage volume

C = coefficient characterizing storage losses

Such submodels are best suited for an integration in long-term management models. Difficulties arise with the estimation of the factor C, or more general, with the flow between subareas if coupled subareas have to be taken into account. For their determination, in case more sophisticated groundwater models are available, such models can be used. Otherwise rough balance models in terms of h (Eq.(6)) or estimates based on analogous situations have to be employed.

A new effective method is also the BIEM (Boundary Integral Equation Method), see for example Lafe et al., 1981. This method allows the estimation of the boundary flux or boundary piezometric head of subareas without determining the head distribution in the subarea.

4.1.2. Water Quality Submodels

In comparison with the above-mentioned quantity problems, the difficulties of developing water quality submodels for their integration in management models is tremendous. The hydrogeochemical and biological processes forming the quality of *groundwater recharge* and *groundwater* itself in mining areas, such as the weathering of pyrith and marcasite, are partly unknown, and due to the inhomogeneity of the porous medium, are full of uncertainties (a problem of data availability). It is obvious that the research work for the mathematical description of these quality processes is still in an early stage. The state-of-the-art of this research especially for mining problems is characterized among others by Luckner and Hummel, 1982.

For the solution of groundwater quality problems efficient models are available mostly based on Finite-Difference-, Finite-Element-Methods, the Methods of Characteristics and the Random-Walk-Method. An international overview is given by Bachmat et al., 1980. The state-of-the-art in the GDR is characterized by Kaden, 1982.

Analogous to the water quality models the integration of such sophisticated models in decision models is unrealistic, especially for the complicated water quality processes in mining areas. Only a few publications are known about the integrated groundwater/surface water management for irrigation and water pollution control (see for example, Haimes and Kindler, 1981, Yaron and Tapiero, 1980).

For the groundwater quality submodel in the study proposed herewith, only simplified block-models (conceptual block models based on simple transport models or black-box models) or quality-balances can be used. The modeling of the surface water quality probably can be reduced on simplified balance-models considering sources and sinks.

The discussion above emphasizes the important role of simplified models. Consequently, the verification of such models becomes the key role of their practicability. Due to the lack of data, and the restricted knowledge of some processes, only a verification by means of more sophisticated models is useful. Test areas should be chosen considering this aspect.

4.2. Decision Support Model

The following general goals should be considered:

- The model must integrate the essential interactions between as well as within the socio-economic subsystem (water users) and the environmental subsystem (water resources system).
- The model must fit in the policy-making process, that means it has to reflect the goals and policy-making reality of the policy-makers in mining areas.
- The model should be based on methods which have proved to have been successful and with extensive practical application in the policy-making process.

Consequently, it is reasonable that common surface water supply models which are based on the stochastic simulation of inputs (streamflow) and the deterministic simulation of water usage, (considering the preferences of certain users) will form the basis for the proposed model. Such models found extensive practical application in the GDR for long-term water planning purposes (see for example, Kozerski, 1981). These models combine stochastic inputs with deterministic simulation using the Monte-Carlo-Method. This method allows one to deal with the streamflows as a multidimensional, nonstationary, standardized-normal distributed Markovian process, which has been established as a well-suited flow model (Dyck, 1976).

Figure 9 characterizes the practical application of the long-term planning models. Management/technological alternatives have to be included exogenously.

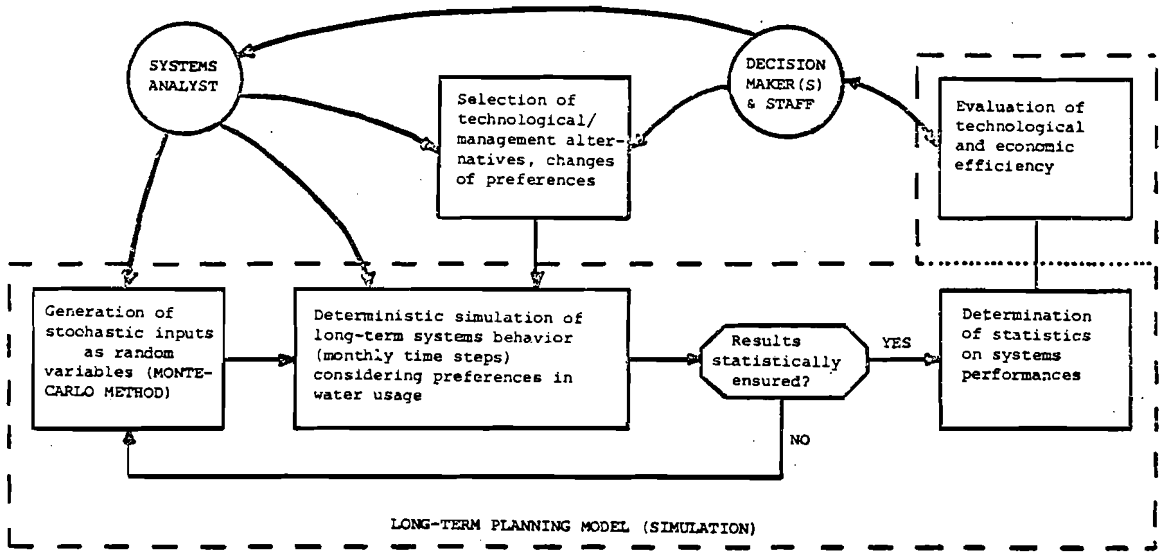


Figure 9. Typical long-term water management approach

The decision-makers and their staff perform the analysis by evaluating the economic and technical efficiency, and by selecting alternatives, occasionally through changes of preferences. In this sense, the approach is a simple form of scenario analysis. Without conflicting interest groups (and consequently decision-makers) this is a helpful tool. In the case of multiple objectives or decision-makers, the manual selection of optimal scenarios is very difficult, often impossible. The water resources use and environmental problems in mining areas is an example of this.

The further development of this approach towards a decision model for the socio-economic-environmental processes in mining areas necessitates:

- the integration of submodels for all water resources subsystems (see section 4.1), and
- the integration in, or combination with, normative models for a partial automatized choice of scenarios or selection of technological/management alternatives.

For the scenario analysis methods of multiobjective analysis will be used. The main difficulties in implementing these methods evolve from the dynamic and at the same time stochastic systems behavior. To avoid these difficulties a two level model system is provided for:

- a time-discrete multiobjective model for planning periods (one to five years) aggregating long-term decisions and objectives,
- a simulation model for the monthly systems behavior in the planning period using stochastic input simulation and deterministic allocation of water resources between users (with given preferences).

Figure 10 characterizes in a simplified way the application of this approach. Based on an exogenous selection of fundamental technological management alternatives by the decision maker(s) and staff (DM), the choice of scenarios for the planning period can be done with the help of an appropriate time-discrete multiobjective model used interactively with the DM. For an estimation of the parameters of the multiobjective model and the verification of its results, the simulation model with stochastic inputs capturing monthly system behavior will be used.

For the model system characterized in Figure 10 an effective multiobjective model is needed. Summarizing the discussions in the previous sections, in general, this model should:

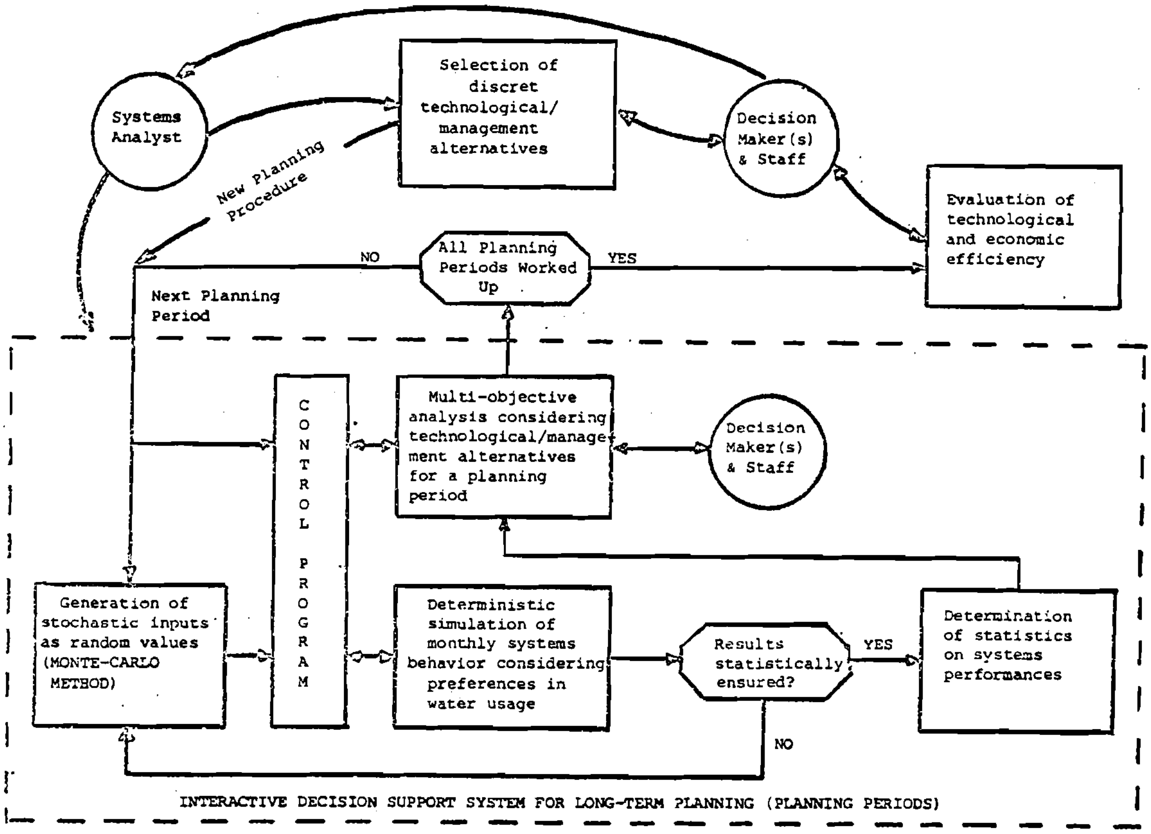


Figure 10. Decomposition approach for long term planning of water resources use and environmental problems.

- consider discrete and continuous decisions. The technological alternatives lead to discrete decisions, due to the finite number of options (for example, mine drainage technology). Otherwise, management alternatives, such as the allocation of water resources between certain users, are continuous.
- the model should allow linear as well as nonlinear objectives and constraints.
- it should allow random variables, both in objectives and in constraints.

With regard to the state-of-the-art of multiple-criteria optimization theory and the computing facilities, a simplification of the problem is indispensable. In the appendix, one of the possible mathematical models for the multiobjective analysis of a test area is outlined.

The literature on appropriate methods for multicriteria analysis is manifold (for example, Cohon, 1978, and Goicoechea et al., 1982). A few applications for socio-economic environmental problems in mining areas are known. Extensive work has been done in the Mining Research Institute in Budapest (see for example, Bogardi et al., 1977 and 1980) for karstic water conditions (without surface water and water quality impacts). Goicoechea et al, 1982 describe an equal approach for land reclamation. after coal strip-mining activities. There is now place to discuss all these powerful methods and their practical applications. A relatively new method which will most probably be used in this study has been developed at IIASA - the reference point approach (see Wierzbicki, 1983). Based on this method, an interactive multicriteria programming package (linear and nonlinear) for decision support, DIDASS, has been developed (see Lewandowski et al., 1982, Grauer, 1983) and implemented for some technical and economic practical problems (see for example, Grauer et al, 1982). This method is founded on the idea of satisficing decision making. Based on aspiration levels, and in dynamic cases reference trajectories, efficient responses will be computed. The best-suited solution (considering the preferences of the decision-maker or some decision-makers) can be obtained by correcting the aspiration levels in an interactive procedure.

5. Conclusions and Working Plan

The paper outlines the conception for a collaborative study on the Analysis of Regional Water Policies in Open-Cast Mining Areas. Due to the complexity of the socio-economic environmental problems and the manifold different methodological tools which are needed for their solution the research team has to deal with and to integrate different branches of knowledge. Within IIASA's Institutions and Environmental Polcies Program, inhouse collaboration above all with the SDS-Program, and collaboration with institutes in the GDR are fundamental suppositions for successful work.

Although the practical importance of the planned study is obvious, it is worth mentioning also some of its methodological advantages:

- the study is aimed at the development of an interactive decision support model for a complex socio-economic environmental system which is suited for its integration in the real policy-making process.
- the model will integrate the groundwater flow in mining areas as a highly nonlinear submodel, appropriate simplified models will be developed.
- the model will combine classical water supply models based on stochastic flow simulation with normative decision support models.
- the model will be used to study the interactions and regulatory means in a socio-economic environmental system.
- the study will be a contribution to the further development of groundwater protection strategies (Kaden, 1983).

Table 3 represents a rough schedule of work to be refined after consultation with collaborators.

Table 3. Conception of a Working Plan.

Research Topics	Institution		Time
	Responsible	Collaborative	
1. Analysis of the decisive socio-economic and environmental problems in lignite-mine regions	IFW/TUD	IIASA	7-10/83
o formulation of broad goals and specific objectives of the study			
o choice of technological/management alternatives → identification of decision variables			
o choice and detailed description of test areas			
2. Development of submodels for environmental/socioeconomic subsytems			9/83-3/84
o surface/groundwater quantity	IFW	IIASA,TUD	
o groundwater quality	TUD	IIASA,IFW	
o surface water quality	IFW		
o mining submodels	TUD		
o water management submodels	IFW		
3. Choice and development of the mathematical framework for multiobjective analysis			
o scientific foundation of the two-level model approach	IIASA	IFW, TU	9/83-12/83
o implementation of DIDASS for the aggregated model	IIASA		9/83-2/84
o development of the simulation model for monthly systems behavior	IFW	TU, IIASA	9/83-2/84
o development of a control program linking both the models, considering an interactive, policy-oriented use	IIASA		1/84-5/84
4. Approach for the integration of the decision support model in the policy making process	IIASA	TFW	9/83-3/84
5. Experimental use of the models for policy design in the test areas	IIASA/IFW		1/84-12/84
o data gathering	IFW/TUD		1/84-5/84
6. Preparation of the research report			1-3/85

REFERENCES

Bachmat, Y., Bredehoeft, J.B., et al. 1980. Groundwater Management, the use of numerical models. Washington: American Geophysical Union, Water Resources Monograph 5.

Bogardi, Z., Z. Kesseru, A. Schmieder, and F. Szidarovszky. 1977. Multiobjective Approach for Trading-Off the Mining Natural Resources with Environmental Considerations. Systems Analysis Seminar on Complex Utilization of Natural Resources, Sopron 1977, 36pp.

Bogardi, Z. et al. 1980. Systems Models for Mining under Water Hazard. In: IFAC Mining, Mineral and Metal Processing, Montreal, Canada 1980, pp. 145-153.

Cohon, J.L. 1978. Multiobjective Programming and Planning. New York: Academic Press.

DeDonnea, F.-X. 1978. The role and limits of normative models in water resources policy and management. In: Water Resources and Land-Use Planning, edited by P. Laconte and Y.Y. Haimes. The Hague: Martinus Nijhoff Publishers.

Dyck, S. 1976. Angewandte Hydrologie, Teil 1 (Applied Hydrology Part 1). VEB Verlag fuer Bauwesen, Berlin.

Dyck, S. 1978. Angewandte Hydrologie, Teil 2 (Applied Hydrology Part 2). VEB Verlag fuer Bauwesen, Berlin.

Eisel, L.M. 1981. Uncertainty. The water resources decision-making dilemma. In: Risk/Benefit Analysis in Water Resources Planning and Management. New York: Plenum Press.

Enderlein, R., G. Glugla, and A. Eyrich. 1980. Estimation of Water Balance Components in Watersheds by Generalizing Point Measurement of Physiographic and Climatologic Factors. Contribution to the IHP Symposium on "The Inflence of Men on the Hydrologic Regime." Helsinki, 1980.

Goicoechea, A., D.R. Hansen, and L. Duckstein. 1982. Multiobjective Decision Analysis with Engineering and Business Applications. New York: John Wiley & Sons.

Grauer, M., A. Lewandowski, and L. Schrattenholzer. 1982. The generation of efficient energy supply strategies using multicriteria optimization. Pages 683-687 in: Cybernetics and Systems Research, edited by R. Trappel. North-Holland Publishing Company.

Grauer, M. 1983. A Dynamic Interactive Decision Analysis and Support System (DIDASS), User's Guide. WP-83-60. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Greenberger, M., M.A. Crenson, and B.L. Cressey. 1976. Models in the Policy Process. New York: Russell Sage Foundation.

Habegger, L.J., L.J. Hoover, and N.V. Vorontsov. 1980. A Framework for Integrating Regional Environmental Goals into Coal Production and Utilization Strategies. CP-80-5. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Haimes, Y.Y., and Y.C. Dreizen. 1977. Management of groundwater and surface water via decomposition. Water Resources Research 13(1):69-77.

Haimes, Y.Y., and J. Kindler, eds. 1981. Water and related land resources systems.

IFAC Symposium, Cleveland, Ohio, May 28-31, 1980. Oxford: Pergamon Press.

Hughes, T.C., S. Orlovsky, and R. Narayanan. 1983. Salinity Management by Use of Low Quality Water. WP-83-18. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Kaden, S. 1982. EDV-gestützte Grundwasserbewirtschaftung in der DDR (Computerized Groundwater Management in the GDR). Ph.D. dissertation, (Dr.sc.techn.) Technical University, Dresden (in German).

Kaden, S. 1983. Position of Groundwater Resources in Resource and Environmental Policy Design. Contribution to the ECE Seminar on Groundwater Protection Strategies and Practices, Athens, Greece, October.

Kindler, J., and D.P. Loucks. 1983. Interactive approaches for exploring water resource management alternatives. Pages 3-13 in: Optimal Utilization of Water Resources. Proceedings of the Symposium, Varna, Bulgaria, May 26-28, Part II.

Kozerski, D. 1981. Rechenprogrammsystem GRM als verallgemeinertes Langfristbewirtschaftungsmodell (Computer program systems as a generalized long-term management model). Wasserwirtschaft/Wassertechnik Berlin (31)11:390-394 and (31)12:415-419 (in German).

Lafe, O.E., Liggett, J.A., and P.L.-F. Liu. 1981. BIEM Solutions to Combinations of Leaky, Layered, Confined, Unconfined, Nonisotropic Aquifers. Water Resources Research 17(5): 1431-1444.

Lewandowski, A., and M. Grauer. 1982. The Reference Point Optimization Approach -- Methods of Efficient Implementation. WP-82-26. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Luckner, L., Tiemer, K., Kaden, S., and W. Nestler. 1979. Rechnergestuetzte Bewirtschaftung der Grundwasserressourcen in der DDR (Computer-added Management of Groundwater resources in the GDR).

Wasserwirtschaft/Wassertechnik, Berlin 29(3): S.82-86.

Luckner, L., and J. Hummel. 1982. Modelling and Prediction of the Quality of Mine Drainage Water used for the Drinking Water Supply in the GDR. First International Mine Water Congress, Budapest, Hungary.

Maddock, T. III. 1972. Algebraic Technological Function from a Simulation Model. Water Resources Research 8(1): 129-134.

Maddock, T. III. 1974. Nonlnear Technological Functions for Aquifers Whose Transmissivities Vary with Drawdown. Water Resources Research 10(1): 877-881.

Morel-Seytoux, H.J. 1978. Development of a Stream-Aquifer Model Suited for Management. Fort Collins: Colorado State University, Water Resources Research Institute.

Peukert, D., H. Reissner, and W. Kunze. 1982. Application of a Continuously Working Model for the Prognosis of a Regional Groundwater Situation Caused by Open-Cast Mine Dewatering Measures. First International Mine Water Congress, Budapest, Hungary.

Starke, W. 1980. Nutzung von Grubenwasser der Braunkohlentagebaue zur Trinkwasserverzorgung (Utilization of lignite-mine drainage water for municipal water supply). Wasserwirtschaft/Wassertechnik, Berlin, Vol.30, No. 11, pp 386-388.

Tiemer, K. 1983. Beitrag zur Entwicklung praxisadäquate Modell für die Grundwasserbewirtschaftung (Contribution to the Development of Praxis-adequate Models for Groundwater Management). Ph.D. dissertation, Technical University, Dresden (in German).

Weeks, J.B. 1982. Simulated oil-shale mine dewatering using a confined multiquifer model, Piceance basin, Colorado, U.S.A. In: Groundwater Models, Vol. I, UNESCO Studies and Reports in Hydrology 34, pp. 151-165.

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

Yaron, D., and C.S. Tapiero, eds. 1980. Operations Research in Agriculture and Water Resources. Proceedings of the Oragawa International Conference, Jerusalem, November 25-29, 1979. North-Holland Publishing Company.

Zwirnmann, K.-H. 1980. Modeling strip mining impacts on groundwater resources for use in coal development planning. Pages 81-96 in: Szczyrk Conference Papers, Part II. Coal: Issues for the Eighties, edited by N. Vorontsov. CP-80-24. Laxenburg, Austria: International Institute for Applied Systems Analysis.

APPENDIX: Schematic description of the test area "Deep Open-Pit Mine"

Under the typical hydrogeological conditions in the GDR with highly mineralized groundwater already to a depth of about 100 m., deep open-pit mines create significant water management and environmental problems due to the drainage of highly mineralized groundwater (NaCl, etc.).

The test region is characterized by a deep open-pit mine, located near a river. The main impacts on the water resources system are focussed by:

- regional lowering of groundwater table which essentially affects the riverflow (infiltration losses) as well as a groundwater-waterworks in this region.
- highly mineralized mine drainage water which is needed for river flow augmentation but affects the downstream water use.

Possible technological alternatives are for instance:

- water import for water supply, and for flow augmentation
- water export for highly mineralized water
- selective mine drainage
- treatment of highly mineralized water.

Figure 11 characterizes the test areas schematicaly with the interest group deep open mining drinking water supply (user 1), downstream user (user 2), and environment. A rough description of the model follows.

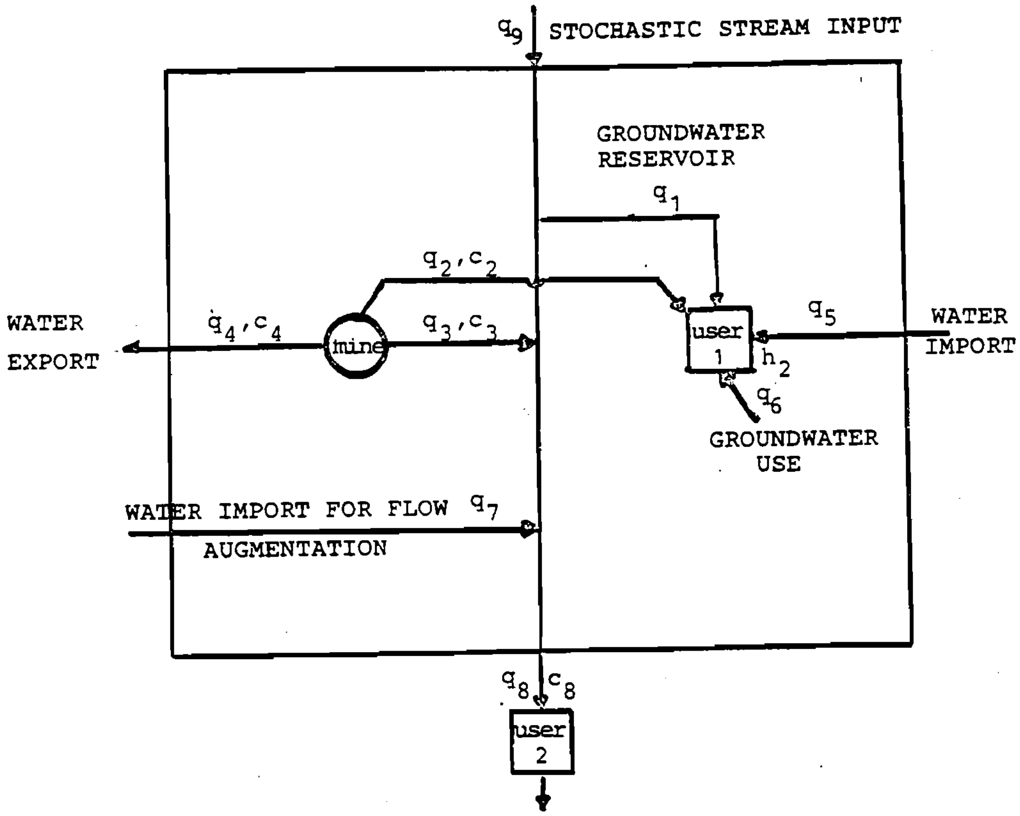


Figure 11. Schematic Test Area.

TECHNOLOGICAL/MANAGEMENT ALTERNATIVES - DECISION VARIABLES

q_1^{t*} - surface water for user 1 [m^3 over time unit]

q_2^t - mine drainage for user 1

---

*)t - time-dependent decision variable

q_3^t - outflow of mine drainage water into stream

q_4^t - export of mine drainage water

q_5^t - water import for user 1

q_6^t - groundwater use for user 1

q_7^t - water import for flow augmentation (user 2)

T - available time for prepartion of technological alternatives

STATE VARIABLES

The state of the system is described in terms of the flux, mineralization (groundwater and surface water) and groundwater tables. Changes in the stream water table can be neglected.

A few of these state variables are necessary for the description of the objective functions, that means:

q_8^t - stream output of user 2

c_2^t - mineralization of mine drainage water for user 1 $[\frac{mg}{l}]$

c_3^t - mineralization of mine drainage outflow into the stream

c_4^t - mineralization of mine drainage water export

c_8^t - mineralization of stream output for user 2

h_1^t - characteristic groundwater table around the mine $[m]$

h_2^t - characteristic groundwater table around the wells for groundwater use (user 1)

A further set of set variables is necessary for the determination of decision variables and constraints. This set depends on the mathematical model of the groundwater-surface-water system. Let us state that the stream is divided into sections and the groundwater reservoir into subareas, as shown in Figure 12.

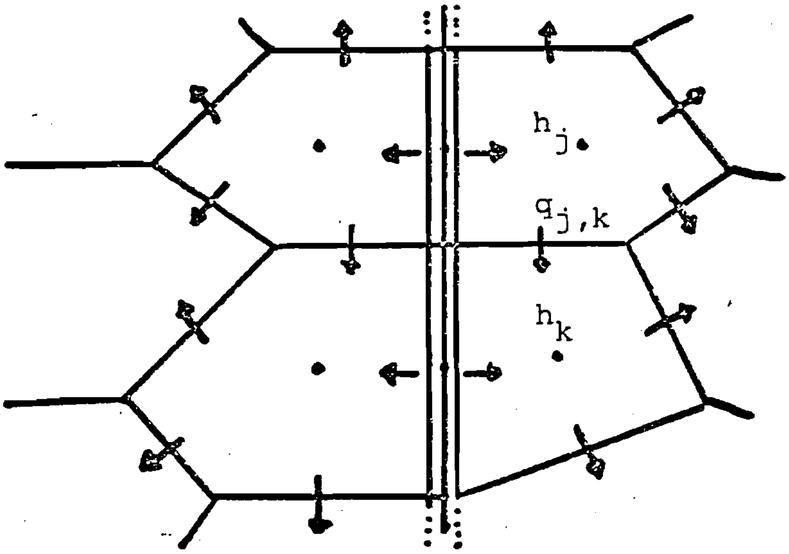


Figure 12. Schematic representation of the water resource system

Additional state variables are

qs_i^t - infiltration/exfiltration of the stream in the segment i

$q^t_{j,k}$ - flux between groundwater subareas j - k

h_j - characteristic groundwater table of subarea j.

OBJECTIVE FUNCTIONS

Minimizing costs for mine drainage

$$\rho^t_1 = f^t_1(q_{2,} q_{3,} q_{4,} c_{2,} c_{3,} c_{4,} h_{1)} \rightarrow \text{Min.} \tag{8}$$

Minimizing deviations between the groundwater table in the mine itself and a given drainage aim

$$\rho^t_2 = h^t_{mine} - h^t_1 \rightarrow \text{Min.} \tag{9}$$

Minimizing costs for water supply for user 1

$$\rho^t_3 = f^t_3(q_{1,} q_{2,} q_{5,} q_{6,} c_{2,} h_{2,} T) \rightarrow \text{Min.} \tag{10}$$

Minimizing deviation between water supply and demand for user 1

$$\rho^t_4 = q^t_{demand\ 1} - (q_1 + q_2 + q_5 + q_{6)} \rightarrow \text{Min.} \tag{11}$$

Minimizing costs for downstream waster use

$$\rho^t_5 = f^t_5(q_{7,} q_{8,} c_{8,} T) \rightarrow \text{Min.} \tag{12}$$

Minimizing deviation between water supply and demand for downstream water use

$$\rho^t_6 = q^t_{demand\ 2} - q_8 \rightarrow \text{Min.} \tag{13}$$

Minimizing mineralization of surface water by mine drainage water with respect to environmental protection objectives

$$\rho_7^t = c_8^t \rightarrow \text{Min.} \tag{14}$$

CONSTRAINTS

The constraints are mainly determined by a set of equations, describing the state of the system. Such equations are:

- the flux balance for stream sections
- the balance equations for groundwater subareas

$$\sum_k q_{j,k}^t = A_j \cdot S_j \frac{(h_j^{t+\Delta t} - h_j^t)}{\Delta t} \tag{15}$$

with

A_j - area of subarea j

S_j - storage coefficient of subarea j

Δt - time interval

- equations estimating mineralization, probably nonlinear influence functions

Additional constraints are connected with treatment facilities of water users, for instance

$C_2 \leq C_{\max}$ (maximum mineralization tobe efficiently treated). (16)

with restrictions of technological alternatives such as the water import, etc.