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Decision Support System Mine -The Management Model

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PREFACE

The *Regional Water Policies* project of IIASA was focused on intensively developed regions where both groundwater and surface water resources are integrating elements of the environment. The research was directed towards the development of methods and models to support the resolution of conflicts within such socio-economic environmental systems. For that reason Decision Support Systems have been developed and implemented for important test areas.

The complex problems of such regional policy analysis are not tractable in one model using any of existing computational methods. That is why a heuristic two-level model approach has been applied. Simplified first-level models together with interactive procedures for multi-criteria analysis are used for screening analysis of rational long-term policies. The more comprehensive second-level models serve for the verification and specification of the results of screening analysis. They are used to check the managerial feasibility of estimated strategies.

One of our case studies deals with open-pit lignite mining areas. The developed Decision Support System MINE has been implemented for a test region in the Lusatian Lignite District of the GDR. The paper describes the approaches for the second-level models (Management Model) of that DSS. This research has been done within the framework of a collaborative agreement between IIASA and the Institute for Water Management in Berlin. This paper is the final report for the third (last) stage of collaboration.

Sergei Orlovski
Project Leader
Regional Water Policies Project

ABSTRACT

The Decision Support System MINE has been developed for the analysis of regional water policies in open-pit lignite mining areas. It is based on a two-level model approach. The first-level *planning model* is used for the estimation of rational strategies of long-term development applying dynamic multi-criteria analysis. Therefor simplified submodels are used for a rough time discretization (yearly time steps and larger). The second-level *management model* considers managerial/operational aspects for shorter time steps (monthly and yearly) employing more comprehensive submodels. It is a classic simulation model. For selected submodels stochastic simulation (Monte Carlo method) is used in order to consider random inputs (e.g. hydrological inflow and water demand). This model serves for the verification of strategies obtained in the planning model, for the verification of simplified submodels used in the first-level model, and for the specification of strategies.

Starting with the description of the position of the management model within the DSS MINE the structure of the management model is given. The used submodels for surface water/groundwater interaction and water quality are described. In the Appendix computer subroutines of some submodels are given being suitable for a more general application.

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DECISION SUPPORT SYSTEM MINE - THE MANAGEMENT MODEL

S. Kaden[1], I. Michels[2] and K. Tiemer[2]

1. Introduction

1.1. Background and Objectives for the DSS MINE

Regions with open-pit lignite mining are characterized by complex and grave interactions in the socio-economic environmental system with special regard to groundwater and surface water resources. To illustrate this for the German Democratic Republic as the country with the greatest lignite production (about one third of the world production):

1. The annual output of lignite amounts to more then 300 mill. tons/annum. Thereby it is necessary to pump out more then 1.7 bill. m^3/annum water for dewatering the open-pit mines. This amounts to about 20% of the stable runoff of the whole country.
2. The dewatering results in regional cone shaped groundwater depressions and consequently in extensive changes of the hydrological regime and of the conditions for water resources use and management, also in down-stream river basins.
   - Infiltration losses of surface water caused by mine dewatering reduce the water supply for down-stream water users and increase the groundwater pumpage necessary for dewatering of the lignite mines.
   - significant alterations of natural groundwater recharge are caused by the extensive changes of geographical and ecological conditions in open-pit mining areas. For example, the natural groundwater recharge of a typical agricultural area is changing under the climatic conditions of the GDR from about 200 mm/yr. up to 400 mm/yr., Kaden et al. 1985c.

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- The rate of water pumped from the mining area into the surface water system amounts to about 30-50 % of the total river discharge (70% under low flow conditions).

3. In lignite mining areas the groundwater quality and consequently the quality of mine drainage water, as well as the water quality in remaining pits is strongly affected by the oxidation of ferrous minerals (e.g. pyrite) in the subsoil. 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. In the post-mining period the same effect occurs by the raising of groundwater table and the leaching of acid products.

From the mentioned processes caused by open-pit lignite mining originate significant conflicts between different interest groups. Figure 1 illustrates the most important interdependencies between water users and the water resources subsystems in an impact diagram.

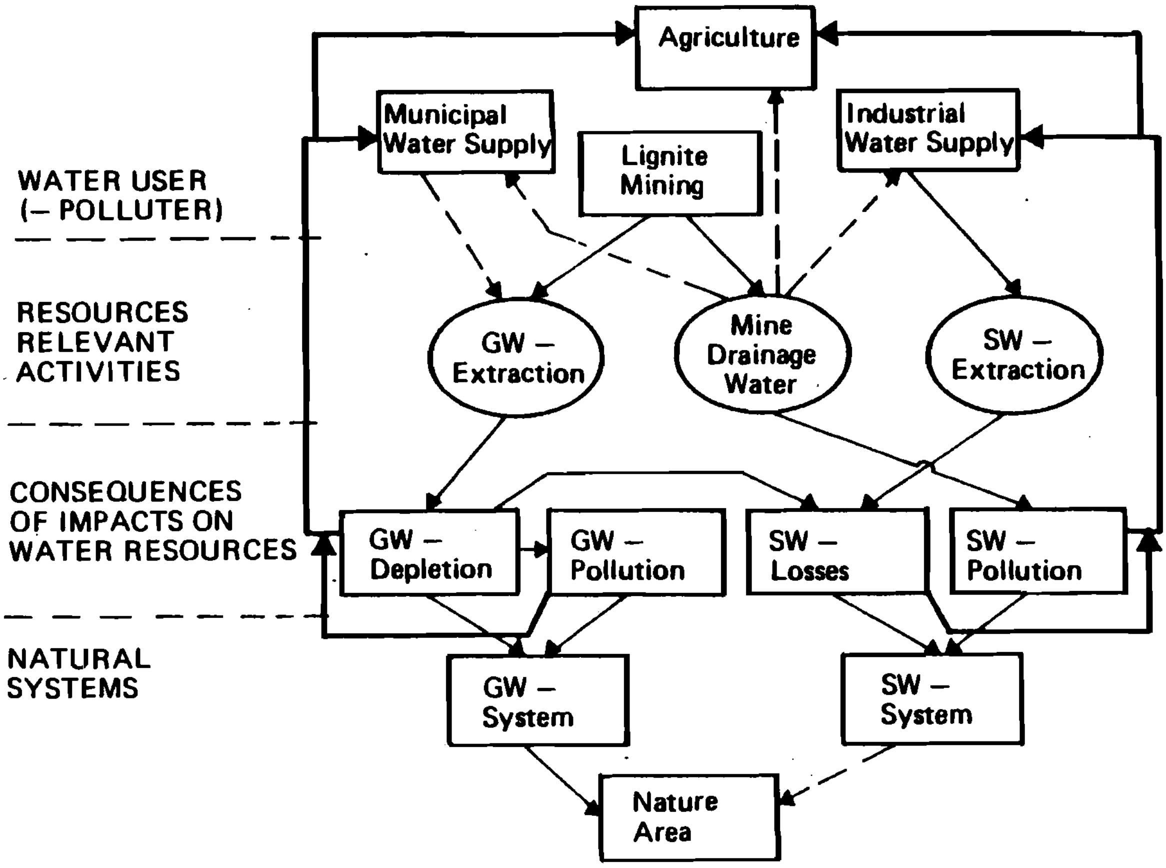

Figure 1: Water resources impact diagram for lignite mining regions

Due to the complexity of the socio-economic environmental processes in mining areas, the design of regional water policies and water use technologies as well as mine drainage can only done properly based on appropriate mathematical models. From a critical analysis of the state-of-the-art of modeling in lignite mining areas it has been concluded, that above all methods and models are required to support the analysis and implementation of *rational long-term regional water policies* in open-pit lignite mining areas, to achieve a proper balance between economic welfare and the state of the environment, Kaden et al. 1985b.

Towards that goal the research of the Regional Water Policies project of IIASA, in collaboration with research institutes in the GDR, and in Poland, in the period 1984-1985 was directed. One of its major products is the **Decision Support System MINE**, see Kaden et al. 1985a, 1985c, Kaden 1986.

1.2. General Structure of the DSS MINE

The analysis of regional water policies in mining regions is a problem of dynamic multi-criteria choice. It is embedded in a complicated policy making process. An advanced system of decision aids is needed which allows:

- to consider the controversy among different water users and interest groups,
- to include multiple criteria some of which can not be evaluated quantitatively,
- to take into the account the uncertainty and the stochastic character of the system inputs as well as the limited possibilities to analyze all the decisive natural and socio-economic processes and impacts,
- to offer a set of decision alternatives, demonstrating the necessary trade-offs between different water users and interest groups.

At present no mathematical methods are available or practical applicable considering all these problems in one single model. E.g. this holds true for any nonlinear stochastic multi-criteria analysis. *Only hierarchical model systems can satisfy all requirements.*

In general, dynamic problems of regional water management are approached by time-discrete dynamic systems models. The step-size and the available mathematical methods are the structural factors of the necessary model hierarchy. Frequently already a two-level model hierarchy satisfies most requirements. For the DSS MINE such a two-level system has been realized, combining a first-level *Planning Model* with a second-level *Management Model.*

The first-level **Planning Model** realizes a dynamic multi-criteria analysis for a relatively small number of *planning periods* , $j=1,\ldots,J$ as the time step for principal management/technological decisions. The time step depends on the variability in time of relevant processes, on the required criteria and their reliability, and on the frequency of decisions. As a compromise between accuracy and both, data preparation and computational effort, for the DSS MINE variable time steps are used, starting with one year and increasing with time up to 15 years. This has been done taking into account the uncertainties in predicting model inputs and the required accuracy of model results, decreasing with time.

The planning model serves for the estimation of rational strategies of long-term systems development. These strategies are selected by multi-criteria analysis considering a number of *criteria*. The criteria have to be chosen from a given set of *indicators*, e.g. cost of water supply, cost of mine drainage, satisfaction of water demand and environmental requirements. These indicators are assumed to be integral values over the whole planning horizon.

In Figure 2 a block scheme of the planning model is given. According to the Figure the systems state is characterized by *state variables* depending on previous systems state and by *state descriptive parameters*. The latter are auxiliary parameters with respect to the multi-criteria analysis but although results of that analysis being of interest for the model user. The state variables are treated as control variables (decisions) in the multi-criteria analysis.

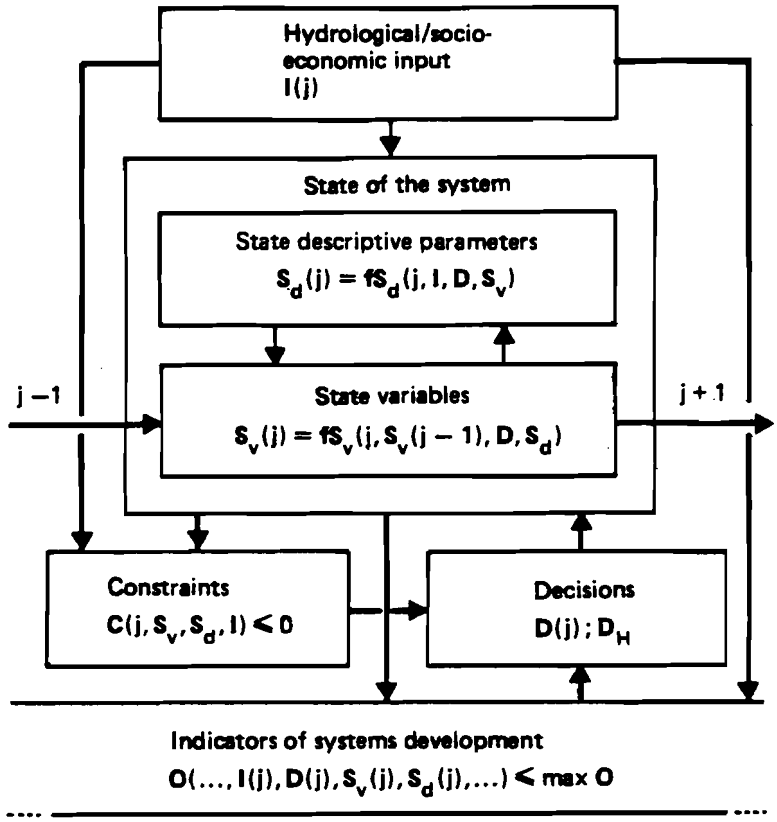

Figure 2: Block schema of the planning model

With the purpose of a unified model being independent on the chosen criteria all indicators are bounded and treated as constraints. Based on that the following multi-criteria problem for a subset $O_l \; l \in L_0$ of the indicators $\mathbf{O}(O_l, \, , l=1,\dots,L)$ is defined:

$$O_l = \mathit{Minimum}\ ! \; l \in L_0 \tag{1.1}$$

subject to inequality constraints

$$\mathbf{O} \le \max \mathbf{O} \tag{1.2}$$

$$\mathbf{C}_{in}(j) \le 0 \;,\; j=1,\dots,J$$

equality constraints

$$\mathbf{C}_{eq}(j) = 0 \;,\; j=1,\dots,J \tag{1.3}$$

$$\mathbf{S}_v(j) - \mathbf{fS}_v(j) = 0 \;,\; j=1,\dots,J$$

bounds

$$\min \mathbf{D}(j) \le \mathbf{D}(j) \le \max \mathbf{D}(j) \;,\; j=1,\dots,J \tag{1.4}$$

$$\min \mathbf{D}_H \le \mathbf{D}_H \le \max \mathbf{D}_H$$

The planning model as a first-level screening model is based on a series of more or less strong simplifications in order to obtain a manageable system being suitable for multi-criteria analysis. The major simplifications are:

- the discretization of the planning horizon into a small number of planning periods; all model data, e.g. decisions, state variables are assumed to be constant within the planning period,
- the neglection of uncertainties in model inputs,
- the application of simplified environmental submodels based on comprehensive models,
- the neglection of relevant environmental subprocesses as the interaction between groundwater and surface water depending on the surface water table.

That is why a second-level **Management Model** for the simulation of systems behavior for a larger number of smaller *management periods* (monthly and yearly time steps) is applied. It is used to analyze managerial decisions by the help of stochastic simulation and to verify results obtained with the planning model.

In the given paper the Management Model will be described in detail. This research has been carried out in the framework of the collaborative agreement between IIASA and the Institute for Water Management in Berlin, GDR.

1.3. The GDR Test Area

The DSS MINE has been developed with special regard to a test region in the German Democratic Republic. It is an about 500 km^2 large area in the Lusatian Lignite District. A detailed description is given in Kaden et al., 1985a. We consider a planning horizon of 50 years, divided into 10 planning periods. In Figure 3 a scheme of the test region is depicted, illustrating the essential *decisions* on systems development.

The following *decisions* are taken into the account (the indices are explained in Figure 3):

$\mathbf{q}_{\alpha,\beta}$	-	flux from α to β
$\mathbf{cq}_{\alpha}$	-	supply of lime hydrate for water treatment
$\mathbf{\Delta tm}_d$	-	duration of mine drainage mine D before starting its operation
$\mathbf{maxh}_p$	-	maximum water level in the remaining pit

The systems state is characterized by the following parameters *):

$\mathbf{h}_p$	-	water table in the remaining pit
$\mathbf{c}_p(l)$	-	concentration of component l in the remaining pit $l=1 \rightarrow Fe^{2+}$, $l=2 \rightarrow H^+$
$\mathbf{v}_p$	-	storage volume in the remaining pit.
qg_{α}	-	groundwater flow to α
$qi_{\alpha,\beta}$	-	infiltration balance segment $\Delta s_{\alpha,\beta}$
h_{α}	-	representative groundwater table
$cg_{\alpha}(l)$	-	concentration of component l in the flow to α
$c_{\alpha}(l)$	-	concentration of component l in drainage water after treatment
qs_{α}, hs_{α}	-	flux/ water table at balance profile bp_{α}
$cs_{\alpha}(l)$	-	concentration of component l in the flux through balance profile bp_{α}
$q_{i,s}$	-	quantity of industrial waste water
$c_{i,s}(l)$	-	concentration of component l in the industrial waste water.

*) Parameters typed bold are state variables of the planning model.

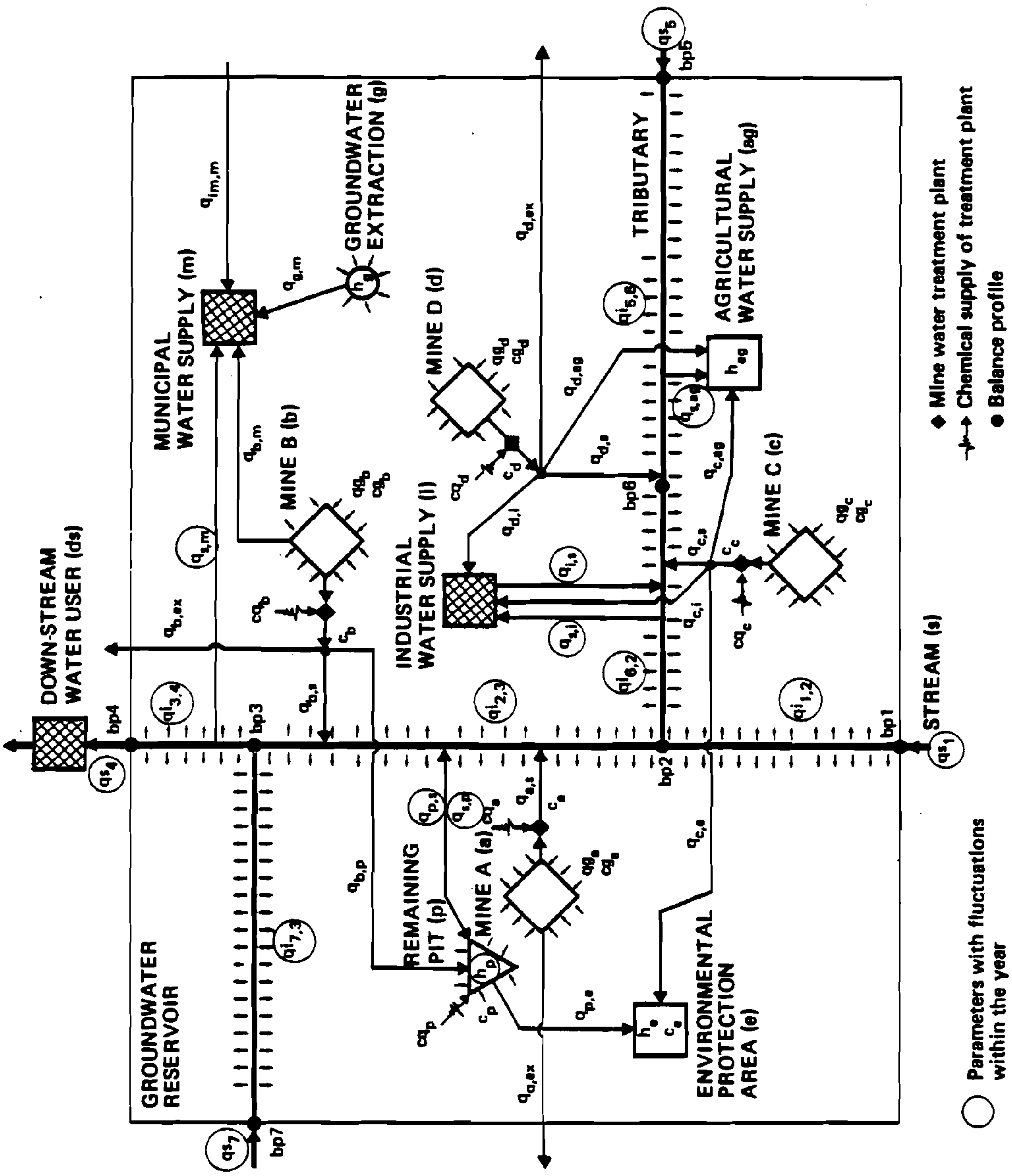

Figure 3: Detailed scheme of the test region

We consider a planning horizon of 50 years, divided into 10 planning periods. The long-term development is above all determined by the mine drainage. This is a continuous process without relevant medium- and short-term (within the year) variations. Therefor it is assumed that all decisions and systems descriptive values related to mine drainage are sufficiently described by mean values over planning periods (or linear interpolated between planning periods).

The systems variability within the years results from the hydrological inflow into the region and the fluctuating water demand. In this case the related decisions, state variables and systems descriptive values depend on managerial aspects to be considered on a monthly basis within the management model. In the Figure 3 those parameters being of interest for the management model are special signed.

2. Stochastic Simulation of Management Strategies

2.1. Basics

According to the first simplifications the planning model considers principal management/technological decisions for estimated input values (expectation values). The feasibility of the estimated decisions is checked only in the mean for planning periods (by the help of constraints $C_{in}(j)$, $C_{eq}(j)$ and bounds, compare Eq. (1.2)-(1.4)).

Problems arise if the principal decisions are superimposed by managerial decisions for shorter time intervals, depending on the actual partly random systems development. This is especially typical for water demand/supply. Both, the models for the actual water demand, and for the available water resources have to consider autocorrelated and random components. The water demand has to be satisfied according to its variations between and within years. It is not sufficient to satisfy the water demand in the mean over planning periods. E.g. water for supplementary irrigation is needed in the vegetation period but not even distributed over the year.

Consider the water users l, $l=1,\ldots,L$ with the water demand dem_l and the water supply sup_l. For the planning model the following criteria is used:

$$\sqrt{\sum_{j=1}^{J}\left[dem_l(j) - sup_l(j)\right]^2} = Minimum\ !\ ,\ l=1,\ldots,L \tag{2.1}$$

Result of the multi-criteria analysis is some rational supply strategy $[\,sup_l(j),\ j=1,\ldots,J,\ l=1,\ldots,L\,]$. This strategy has to be transformed by an appropriate ***management rule*** into the actual water supply strategy for all month k in the years i, $i=1,\ldots,I$: $[\,sup_l^*(i,k),\ i=1,\ldots,I\ ,\ k=1,\ldots,12\,]$.

The common criteria for the satisfaction of water demand for long-term water management and planning is as follows:

$$prob\left\{\ dem_l^*(i,k) - sup_l^*(i,k) \le 0\ \right\} \ge pdem_l\ ! \tag{2.2}$$

with i - year, k - month.

Now it has to be checked whether the strategy obtained based on criteria (2.1) satisfies criteria (2.2). And this is the first task of the second-level management model. By the help of stochastic simulation based on the Monte Carlo method the ***feasibility of strategies is verified*** and the strategies are statistically evaluated.

The model realizes the following steps:

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

The statistical reliability of results depends on the number of realizations of the Monte Carlo simulations and the degree of influence of stochastic inputs. In most cases 100 realizations should be sufficient. Nevertheless the numerical effort is high. For the 50-years planning horizon in this case the simulation has to be done for 60000 month.

This aspect has to be considered in the model for stochastic simulation as it is illustrated in Figure 4.

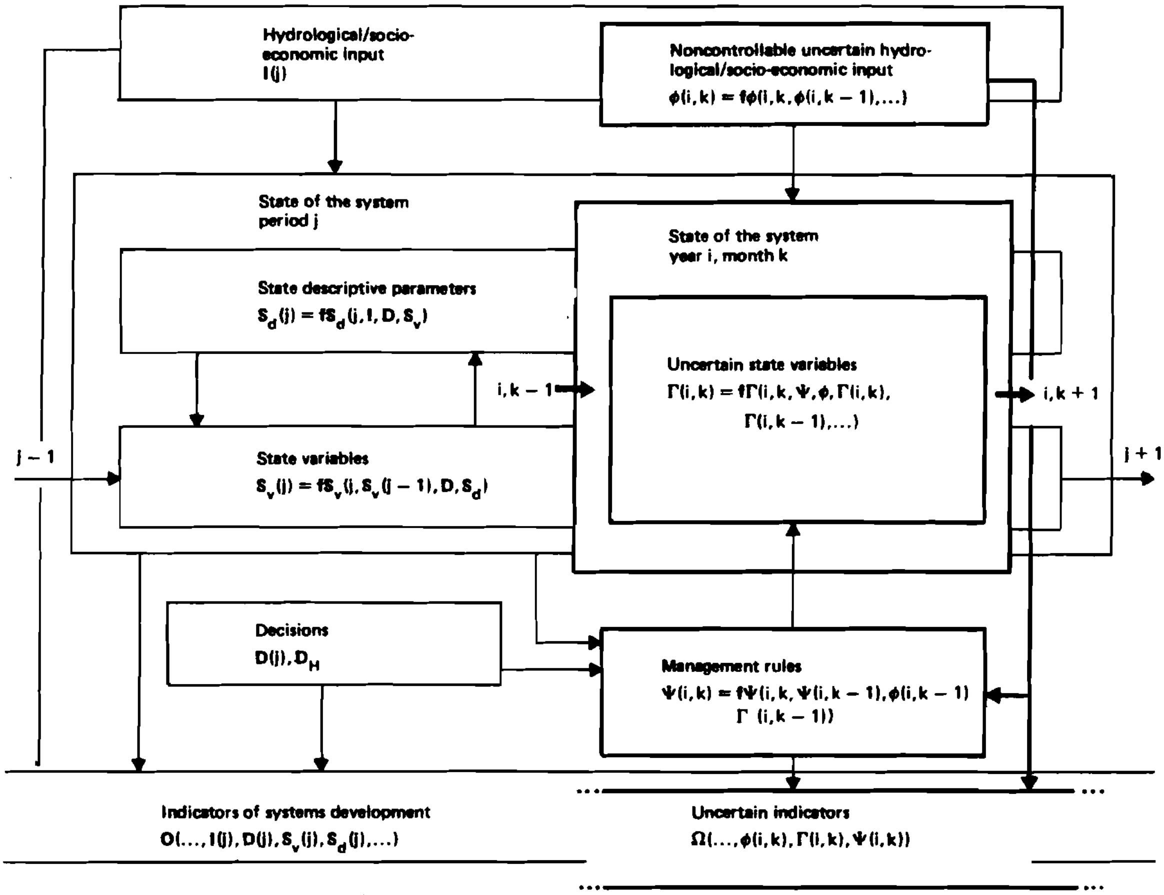

Figure 4: Block scheme of the management model
part 1 - stochastic simulation of management strategies

Only those decisions $\Psi(i,k)$ and submodels are included in the Monte Carlo simulation strongly depending on the stochastic inputs $\Phi(i,k)$. For the remaining decisions, inputs and submodels the results of the planning model are used as mean values for planning periods. Based on the results of the planning model (decisions) a ***management rule***

$$\Psi(i,k) = f\Psi(i,k,\Psi(i,k-1),\Phi(i,k-1),\Gamma(i,k-1)) \quad (2.3)$$

is defined for the estimation of the ***managerial decisions*** $\Psi(i,k)$. Based on these decisions and the uncertain inputs $\Phi(i,k)$ the state variables $\Gamma(i,k)$ are estimated (for the management model is no need to distinguish between state variables and state descriptive parameters):

$$\Gamma(i,k) = f\Gamma(i,k,\Psi(i,k),\Phi(i,k),\Gamma(i,k),\Gamma(i,k-1),\ldots) \quad (2.4)$$

Again, only those state variables are considered strongly depending on uncertain inputs and managerial decisions.

In Figure 5 a simplified scheme of the test region is given illustrating the decisions, inputs and state variables being considered in the stochastic simulation (compare Figure 3). In compewrison to Figure 3 a few additional balance points have been introduced.

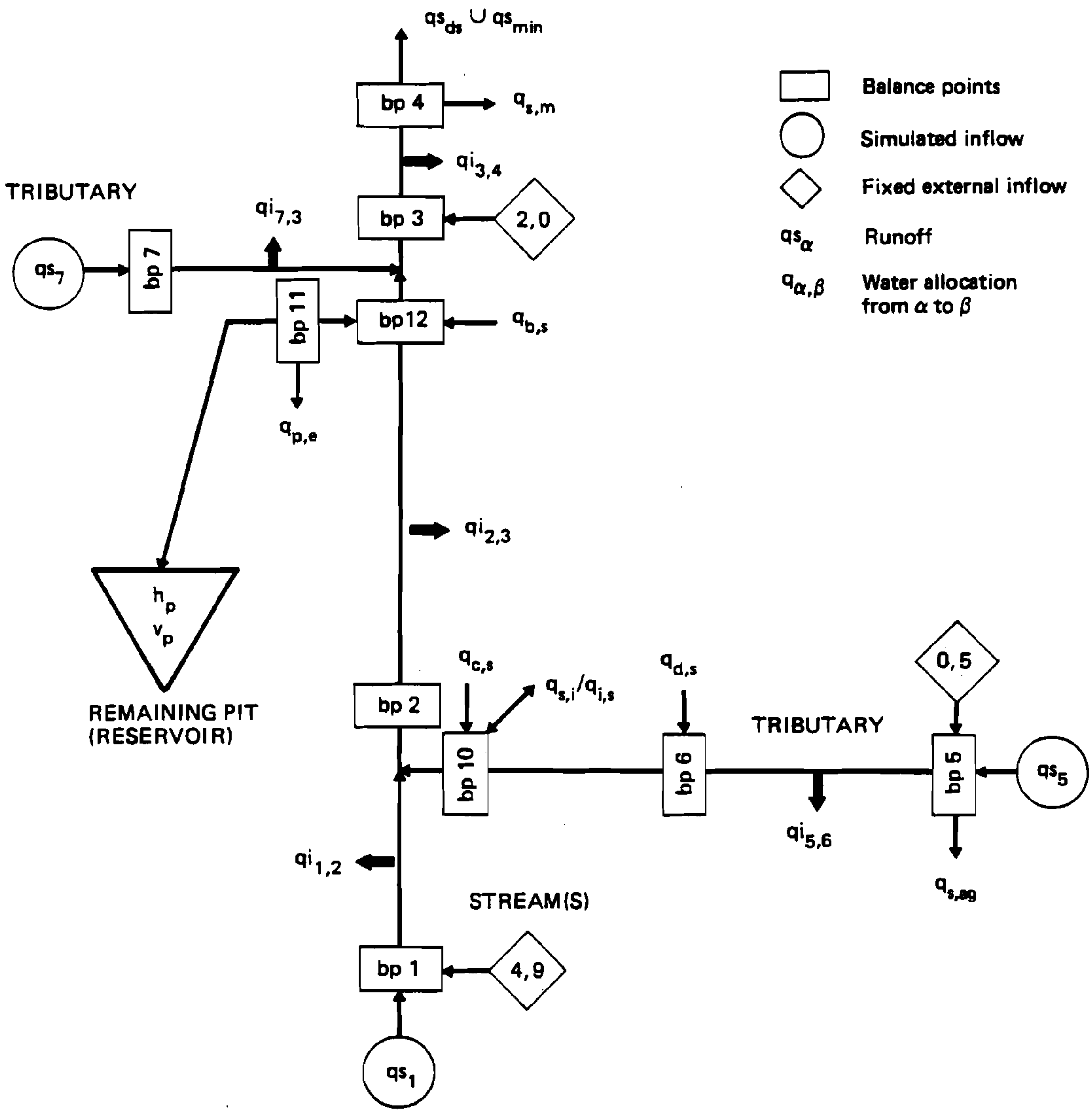

Figure 5: Simplified scheme of the test region for stochastic simulation

The major simplifications are:

- all mining activities are assumed to be constant during planning periods. Short term variations in mine drainage and mine drainage water allocation are neglected.

- water quality processes are neglected; It is assumed that water quality processes are damped and violations of water quality requirements are less significant as the dissatisfaction of water demand in terms of water quantity. Water quality alterations are above all caused by mine drainage, and that is taken as constant during planning periods.
- groundwater flow variations during planning periods are neglected due to the damped groundwater flow processes.

That means all monthly varying water requirements have to be satisfied from the stream.

2.2. Stochastic simulation of input data

2.2.1. Hydrological inflow

The inflow into the region is assumed to be a natural hydrological process. A comprehensive analysis of several long duration time series of runoff has shown, that natural runoff under the climatic conditions of the GDR and with monthly time steps posses the following properties, see Schramm 1975:

- it is nonstationary and cyclic with the period one year,
- its monthly one-dimensional distribution function can sufficiently well be approximated by a transformed normal distribution function, e.g. a three-parametric log-normal distribution

$$X = F(Q) = \frac{ln(Q - q_0) - \bar{q}}{\sigma} \tag{2.5}$$

with

Q	-	mean monthly runoff
X	-	transformed N(0,1)-distributed runoff
$q_0, \bar{q}, \sigma$	-	parameters of the distribution function

- the process has Markovian character.

Starting with the transformation F of the runoff and estimates of the auto- and cross-correlation a multi-dimensional runoff process is simulated. General purpose programs for this simulation:

- program SIKO for time series analysis including parameter estimation
- program SIMO for runoff generation

are explained and listed in Kaden et al., 1985c.

For the test area the three inflows qs_1, qs_5, qs_7 have to be simulated. This can not be done directly because the balance points $bp1$, $bp5$, $bp7$ are not identically with river gauges.

In the test area four river gauges are located close to these balance points. The above mentioned assumptions have been proven for the runoff $\bar{q} = (q_1, q_2, q_3, q_4)^T$ through the gauges (30-years time series of observation). Based on that the parameters of three-parametric log-normal distributions have been estimated.

For the N(0,1) transformed runoff in the month k the following simulation model holds:

$$\bar{q}_N(k) = A(k) \cdot \bar{q}_N(k-1) + B(k) \cdot \bar{q}_N(k) + \bar{\sigma}(k) \cdot \bar{\varepsilon} \tag{2.6}$$

$$\text{for } k = 1, \cdots, 12$$

with

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

The actual runoffs are estimated by the retransformation

$$\bar{q}(k) = \bar{q}_0(k) + e^{\bar{s}(k)\cdot\bar{q}_N(k) + \overline{qm}(k)} \quad \text{for } k = 1, \cdots, 12 \tag{2.7}$$

with

$\bar{q}_0, \bar{s}, \overline{qm}$ - parameters of LN-3 distribution.

The inflows qs_1, qs_5, qs_7 are weighted sums of the simulated runoffs, taking into the account the actual catchment areas.

$$qs_1 = 1.014\cdot q(1) + 2.00\cdot q(2) - 0.50$$
$$qs_5 = 1.321\cdot q(3) + 5.58\cdot q(4) \tag{2.8}$$
$$qs_7 = 0.20\cdot q(1) + 0.50$$

Besides the simulated inflows in the surface water system a few fixed inflows have to be taken into account (compare Figure 5 and surface water balances in Kaden et al., 1985a). Those are either small tributaries, waste or mine water allocations not being explicitely considered in the model system. Detailed informations on fluctuations of those inflows are not available. Therefore they are correlated to the simulated inflow of the respectiv stream or tributary, compare the balance model in Appendix 3.

2.2.2. Water demand

For the monthly water demand of any water user the following general stochastic model may be used:

$$dem(i,k) = (trend(i,k) + osci(k) + auto(i,k))\cdot rand \quad [m^3/sec] \tag{2.9}$$

with

trend(i,k)	-	deterministic trend
osci(k)	-	deterministic oscillation component depending on typical seasonal behaviour of water users
auto(i,k)	-	autocorrelated component
rand	-	random component (noise)

In the GDR test region the following water user have to be considered (compare Figure 3): municipal water supply (m), industrial water supply (i), agricultural water supply (ag), downstream water user (ds), environmental protection area (e).

The agricultural water demand and the demand for environmental protection depend on the actual water tables in these regions. The models are given in Kaden et al., 1985a. Random components are neglected.

The model for the ***municipal water demand*** has been developed according to Eq. (2.9). The trend is described as a linear model, the autocorrelated component as a first order model. The oscillation component is approximated by a Fourier-series, see Kaden et al. 1985a.

$$dem_m(i,k) = \Big[\min[\,(2826. + 309.\cdot(i+k/12))\,,\,25000.\,] + \\ + 0.726\cdot dem_m(i,k-1) + \tag{2.10}$$

$$-816.\cdot\sin(\frac{\pi}{6}k) - 481.\cdot\cos(\frac{\pi}{6}k) +$$

$$\left. + 592.\cdot\sin(\frac{\pi}{6}(k-1)) + 349.\cdot\cos(\frac{\pi}{6}(k-1))\right]\cdot rand$$

The industrial water demand is assumed to be constant. Seasonal oscillation components are negligible. We consider only a random component.

$$dem_i(i,k) = 4.0\cdot rand \quad [m^3/sec] \tag{2.11}$$

The water demand of downstream users is slightly increasing in time. For the time being seasonal components are neglected.

$$dem_{ds}(i,k) = \left[8.0 + 0.1\cdot i \right]\cdot rand \quad [m^3/sec] \tag{2.12}$$

Besides the water demand for downstream users a minimum flow has to be guaranteed with respect to environmental aspects.

$$dem_{ds,min} = 8.0 \quad [m^3/sec] \tag{2.13}$$

For the *random* component the following model is used:

$$rand = (1. - fac\cdot\varepsilon) \tag{2.14}$$

ε is a N(0,1)-distributed random number, fac a scaling coefficient (for numerical tests $fac = 0.4$ has been used).

In order to realize a negative correlation between the water demand and the hydrological inflow (usually low inflow means drought and consequently high water demand), for the random number ε the number used for the stochastic inflow generation is taken.

2.3. Management rules

The management rules for managerial decisions have to be defined in order to satisfy the monthly varying water demand of the above mentioned water users as good as possible. In case of water deficits the users are ranked with respect to their socio-economic importance. The remaining pit can be used as a reservoir to minimize deficits.

2.3.1. Balancing of water users

For the management model we are only interested in the water requirements to the stream and the remaining pit. Keeping in mind that the other supply components (mine drainage water and groundwater) are assumed to be constant during a planning period the following balance equation holds:

$$dq_{s,u}(j,i,k) = dem_u(j,i,k) - \sum_{l=1}^{L} q_{l,u}(j) \tag{2.15}$$

with

$dem_u(j,i,k)$ - total demand of user u, planning period j, year i, month k

$q_{l,u}(j)$ - supply component from source l to user u, planning period j

$dq_{s,u}(j,i,k)$ - demand of user u for water allocation from the stream (or the remaining pit), in month k, year i, planning period j.

Based on this equation and on Figure 5 the balance equations for each user can be given (downstream requirements can only be satisfied by the stream):

$$dq_{s,m}(j,i,k) = dem_m(j,i,k) - \mathbf{q}_{b,m}(j) - \mathbf{q}_{g,m}(j) - \mathbf{q}_{im,n}(j) \qquad (2.16)$$

$$dq_{s,i}(j,i,k) = dem_i(j,i,k) - \mathbf{q}_{c,i}(j) - \mathbf{q}_{d,i}(j) \qquad (2.17)$$

$$dq_{s,ag}(j,i,k) = dem_{ag}(j,i,k) - \mathbf{q}_{c,ag}(j) - \mathbf{q}_{d,ag}(j) \qquad (2.18)$$

$$dq_{p,e}(j,i,k) = dem_e(j,i,k) - \mathbf{q}_{c,e}(j). \qquad (2.19)$$

Thus, the supply requirements to the stream and the remaining pit are defined. The extend to which these requirements are satisfied is used as a criterion to determine in how far the long-term strategy estimated with the planning model can be implemented under concrete conditions with monthly or seasonal fluctuations of discharge (inflow) and demand.

In case the requirements can not be met in a given month the following lexicographic ordering (ranking) is considered:

Highest priority:	Municipal water supply
	Minimum downstream flow
	Industrial water supply
	Down-stream water supply
	Agricultural water supply
Lowest priority:	Water supply for environmental protection.

A more detailed lexicographic ordering might be introduced splitting the users into subusers as it is usually be done in long-term water management models, see Kozerski 1981.

2.3.2. Remaining pit management

In the test region a remaining pit originating after abandoning mine A in the planning period j_a=7 can be used as a reservoir for water supply and flow augmentation.

In order to use the remaining pit as a reservoir it is necessary to fill it up to the lower storage limit. Both, the filling and the actual management of the pit are characterized by extensive exchange relations between surface water (the reservoir) and the surrounding groundwater (aquifer).

Due to these exchange relations the control of the filling process and the management of the remaining pit had to be included as decisions into the planning model because of conflicting interests between various water users and the mining authority. The water users are interested in an early usage of the remaining pit as a reservoir; that means a fast artificial filling of the pit. This, however, contradicts to the interests of the mining authority. An accelerated rise of the water level in the remaining pit causes a considerable increase in cost of mine drainage in neighboured mines. Very illustrative examples for that are given by Peukert et al., 1985.

Depending on the preferences of model users the planning model will generate some compromise solution for the remaining pit filling and management in terms of mean values for planning periods.

The obtained long-term strategy has to be transformed into an adequate monthly management rule, both, for the filling, and for the management.

Filling phase

During the filling process the remaining pit can be considered as a common water user. The demand equals to the estimated allocation from the stream to the pit during the planning periods.

$$dq_{s,p}(j,i,k) = \mathbf{q}_{s,p}(j) \qquad (2.20)$$

Instead of the constant values the monthly demand could be interpolated between values for planning periods. In the given case the "user" remaining pit is ranked between the agriculture and the environmental protection area.

The management rule is the same as for any user. The possible allocation is compared with the water demand. If the possible allocation is larger then the demand the demand is satisfied, otherwise a deficit occurs (and is recorded for statistical evaluation). This rule is a "pessimistic" one, because any deficit can not be compensated later. This means for the remaining pit, that the filling goal can not be satisfied.

In difference to common water users for the remaining pit deficits can be compensated, because a surplus of allocation can be realized (if it is available). In this case the allocation is not controlled by the water demand according to Eq. (2.20) but by the water level.

Define $\mathbf{h}_p(i,k)$ the water level in the remaining pit estimated in the planning model (the monthly values are obtained by linear interpolation between the solutions for planning periods). The monthly allocation to the remaining pit is aimed towards the realization of this water level. Therefor the required amount of inflow $dq^*_{s,p}(i,k)$ has to be estimated in order to increase the water level in the remaining pit from the actual value $h^*_p(i,k-1)$ in month $k-1$ to the goal $\mathbf{h}_p(i,k)$. Now the remaining pit is considered as a user with the demand $dq^*_{s,p}(i,k)$.

In Figure 6 the different outcome of the given management rules is illustrated. Both alternatives can be checked with the simulation model.

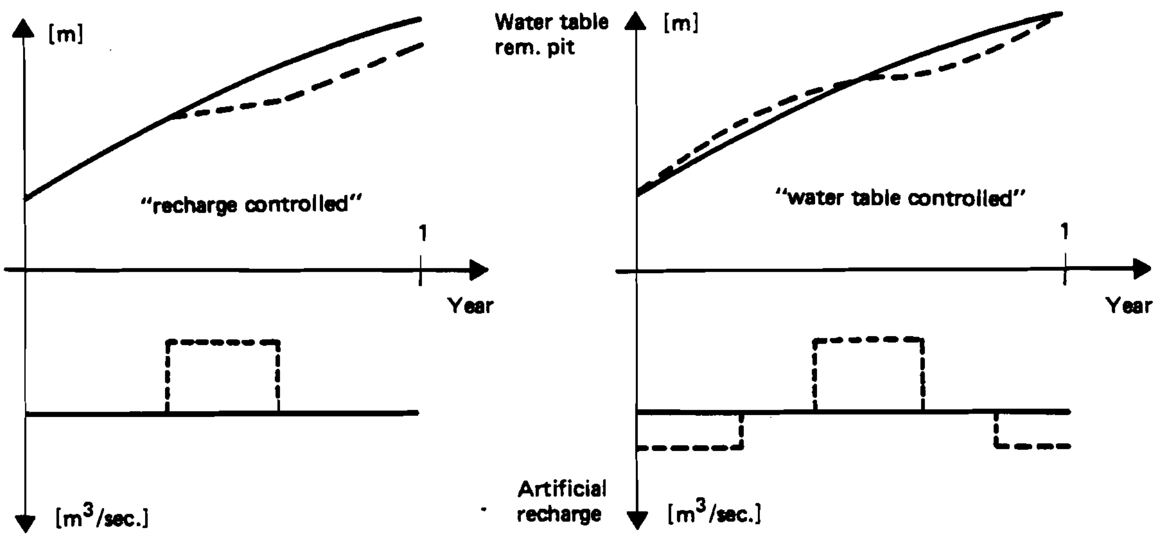

Figure 6: Management rules for the filling phase of the remaining pit

Management phase

If the water level in the remaining pit has reached the lower storage limit the pit can be managed as a reservoir. There is a large amount of concepts and models for reservoir management available, both, for flood protection, and for leveling of water deficits. In the given study directed towards rational long-term strategies the use of the storage for flood protection is less important. For long-term management modeling, periods of low flow conditions are considered as the significant events. As a first alternative the following simple management rule is implemented:

In case of downstream water deficits the reservoir is used for flow augmentation in order to level up the deficit. Any surplus of runoff in the stream is used for filling up the remaining pit to the upper storage limit. Consequently, it is a strategy of maximum storage parsimony on the one hand and of possibly full compensating of deficits on the other one.

But, there is a significant difference to common storages. Due to the low groundwater table around the remaining pit caused by mine drainage in neighboured mines the reservoir permanently loses water to the ground. The loss increases with increasing water level in the remaining pit. That means, high water levels are less economically not only because of lost discharge to the pit, but although because of increased pumpage for mine drainage in neighbouring mines. In the time being management rules should be studied taking this into the account. Obviously a compromise between the reliability of satisfaction of water demand and the storage volume (the water level) has to be found.

2.4. Simulation of systems development

2.4.1. Remaining pit submodel

The submodel of the remaining pit has to describe the essential interrelations between the surface water in the pit and the surrounding groundwater in the filling phase as well as in the management phase. That is why the common balance equation for reservoir management in its usual form

$$\Delta S = P + Z - E - R \tag{2.21}$$

with

- ΔS - change of storage volume
- P - precipitation
- Z - inflow
- E - evapotranspiration
- R - outflow

can not be used here. The equation has to be extended by a term that takes into the account the infiltration into the groundwater or the flux of groundwater into the reservoir. This is illustrated in Figure 7. It demonstrates the effect of different management strategies during one year on the state of the reservoir at the end of the year.

The deviations depend on the difference between the state variables ***water level remaining pit*** **and** ***water table in the aquifer***. Consequently the dynamics of the groundwater system have to be considered in addition to the dynamics of the storage. This was done by computing management alternatives by means of a complex comprehensive groundwater flow model and by deducing a reduced grey-box model. The methodology is described in detail by Kaden et al., 1985c. The result of model reduction are models for yearly and for monthly time steps. The monthly model has been developed in such a way that it provides the same results at the end of one year as the yearly model if the inflow is constant during the year.

The monthly model needed for the management model has the following form:

$$\begin{aligned} h_p(i,k) &= h_p^0(i,k) + a_1 \cdot \tilde{h}_p(i,k-1) + a_2 \cdot \tilde{h}_p(i,k-2) + \\ &\quad + b_0 \cdot q_p(i,k) + b_1 \cdot q_p(i,k-1) \end{aligned} \tag{2.22}$$

$$v_p(i,k) = fv_p(\, h_p(i,k)\,) \;,\quad \tilde{h}_p(i,k) = h_p(i,k) - h_p^0(i,k)$$

$$q_p(i,k) = q_{p,s}(i,k) + q_{s,p}(i,k)$$

with

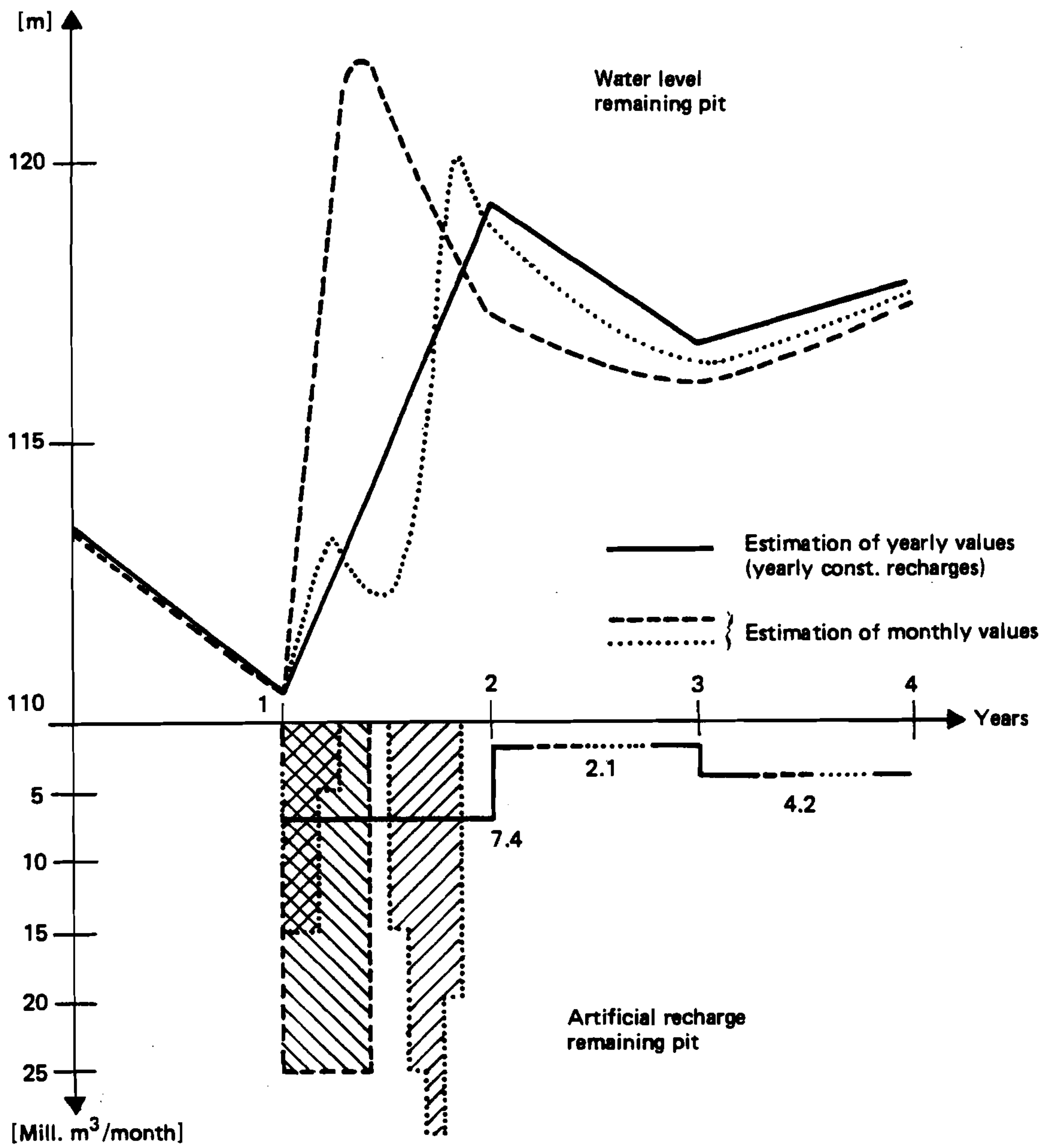

Figure 7: Impact of different management strategies on the water level in the remaining pit

$h_p(i,k)$	-	water level in the remaining pit $[m]$, at the end of month k in the year i
$h_p^0(i,k)$	-	water level in the remaining pit under natural conditions (q_p =0), at the end of month k, year i
$q_p(i,k)$	-	flux between stream and remaining pit $[m^3/sec]$, month i, year k
a_1, a_2, b_0, b_1	-	parameters.

Precipitation and evaporation are considered in the water table under natural conditions. Their alteration during month and due to different surface of the pit in case of accelerated filling are negligible.

This model is used in realizing the management rules given in Section 2.3.2. During the filling phase the model above is applied from month to month with the given inflow. For the management phase the remaining pit computation has to be divided into two parts.

In the first step the total usable storage volume is imaginary added to the natural discharge in the stream and considered to be available for downstream or other users. In order to consider the exchange processes between groundwater and remaining pit the following algorithm has to be used, compare Eq. (2.22):

$$q_{p,s}^{pot}(i,k) = \min\left\{\frac{h_p^{min} - c}{b_0}\ ,\ q_{p,s}^{max}\right\} \tag{2.23}$$

$$c = h_p^0(i,k) + a_1 \cdot \tilde{h}_p(i,k-1) + a_2 \cdot \tilde{h}_p(i,k-2) + b_1 \cdot q_p(i,k-1) \tag{2.24}$$

with

$q_{p,s}^{pot}(i,k)$ - potential maximum discharge $[m^3/sec]$, month i, year k

h_p^{min} - lower storage limit $[m]$

$q_{p,s}^{max}$ - maximum allocation capacity $[m^3/sec]$.

After balancing off all users in the system the final reservoir state is computed in terms of the actual required discharge to the stream and the water level at the end of the studied month. This is based on the minmum of the free discharge (not used) $qs_{min}(i,k)$ of all balance points.

If $qs_{min}(i,k) > q_{p,s}^{pot}(i,k)$ there is a surplus of surface water $dq_{s,p}(i,k) = qs_{min}(i,k) - q_{p,s}^{pot}(i,k)$ to be allocated to the stream. For the potential maximum allocation to the pit holds, analogously to Eq. (2.24)

$$q_{s,p}^{pot}(i,k) = \min\left\{\frac{h_p^{max} - c}{b_0}\ ,\ q_{s,p}^{max}\right\} \tag{2.25}$$

with

$q_{s,p}^{pot}(i,k)$ - potential maximum inflow $[m^3/sec]$, month i, year k

h_p^{max} - upper storage limit $[m]$

$q_{s,p}^{max}$ - maximum allocation capacity $[m^3/sec]$

Using Eq. (2.24) and (2.25) we obtain:

$$q_{s,p}(i,k) = \begin{cases} dq_{s,p}(i,k) & \text{for } dq_{s,p}(i,k) < q_{s,p}^{pot}(i,k) \\ q_{s,p}^{pot}(i,k) & \text{for } dq_{s,p}(i,k) \geq q_{s,p}^{pot}(i,k) \end{cases} \tag{2.26}$$

If $qs_{min}(i,k) \leq q_{p,s}^{pot}(i,k)$ there is a deficit of surface water. For the discharge to the stream holds:

$$q_{p,s}(i,k) = q_{p,s}^{pot}(i,k) - qs_{min}(i,k) \tag{2.27}$$

With Eq. (2.22) the final water level in the remaining pit at the end of month k is estimated.

In Appendix A the computer program for this submodel is given.

2.4.2. Infiltration submodel

The major part of common long-term water management modeling is the balancing of water users according to their local distribution and lexicographic ranking in order to meet their water demand. The ranking is considered by the help of a respective temporal sequence of balancing.

This approach causes difficulties if the ranking sequence does not coincide with the local distribution (upstream user before downstream user) and if the satisfaction of the requirements of lower-priority upstream users effect the supply of downstream users with higher priority. And this happens if the stream is characterized by discharge dependent infiltration losses (or base flow!).

In the mining test region water level alterations in the stream cause significant changes in the infiltration and consequently in the discharge between various balance profiles. This process and ways for modeling have been discussed in detail by Kaden et al., 1985a, 1985c. For each balance segment (compare Figure 3) black-box models of the following structure have been developed:

$$\begin{aligned} \Delta qi(i,k) &= a_1 \cdot \Delta qi(i,k-1) + a_2 \cdot \Delta qi(i,k-2) + \\ &+ b_0 \cdot u(i,k) + b_1 \cdot u(i,k-1) + b_2 \cdot u(i,k-2) \\ u(i,k) &= h_s(i,k) - \bar{h}_s(i) \end{aligned} \tag{2.28}$$

with

$\Delta qi\,(i,k)$ - infiltration between stream and groundwater due to water level changes in the stream $[m^3/sec]$

$h_s(i,k)$ - actual water level in the stream over bottom (mean value for the balance segment) $[m]$, year i, month k

$\bar{h}_s(i)$ - average water level in the stream over bottom (mean value for the balance segment) $[m]$, year i (mean value of the respective planning period).

The impulse $u_{\alpha,\beta}(i,k)$ for a balance segment $[\alpha,\beta]$ results from the actual discharge at the respective stream profile. Since this profile might change between upstream and downstream balance point for the effective impulse a weighted mean is used. The weighting factor is γ, $0 \le \gamma \le 1$, usually $\gamma = 0.5$.

$$u_{\alpha,\beta}(i,k) = \gamma \cdot u_\alpha(i,k) + (1-\gamma) \cdot u_\beta(i,k) \tag{2.29}$$

With Eq. (2.29) a feed-back between infiltration and changes in discharge is realized. The infiltration for the balance segment effects the upstream balance profile as a consequence of water level changes. Additionally external inflows/outflows within the balance segment have to be considered for the infiltration calculation. For the impulse at the downstream profile holds:

$$u_\beta(i,k) = fh_{s,\beta}\left[qs_\alpha(i,k) - (\overline{qi}_{\alpha,\beta}(i) + \Delta qi_{\alpha,\beta}(i,k) + dq_\beta(i,k))\right] - \bar{h}_s(i) \tag{2.30}$$

with

$qs_\alpha(i,k)$ - discharge at the upstream balance profile, year i, month k

$qi_{\alpha,\beta}(i)$ - infiltration for the balance segment at mean water level, year i

$dq_\beta(i,k)$ - external inflow/outflow at the downstream balance profile, year i, month k

$fh_{s,\beta}$ - water level key function for the downstream profile.

The actual discharge at the downstream profile β can be estimated iteratively applying Eq. (2.28) - (2.30). The above mentioned difficulty in balancing under consideration of infiltration becomes now obvious.

In Appendix 2 the computer code for the infiltration submodel of the management model is given.

2.4.3. Balance submodel

The management rules, the submodels for input simulation, and the above given submodels for the remaining pit and the infiltration have to be combined for balancing the surface water resources.

Due to the discharge dependent infiltration the balancing of the entire system is only possible by iterative computation. The infiltration in all balance segments has to be estimated before balancing of all water users. However, through the term $dq(i,k)$ in Eq. (2.30) the infiltration depends on the user balancing.

The following algorithm has been developed assuming that in the majority of realizations the requirements of all users can be satisfied. It consists of two separate balance computations:

1. balancing of the surface water system upstream-downstream for a given actual water demand of all users, considering the infiltration,
2. balancing of water users according to their lexicographical ranking.

The computation starts with procedure 1 for the given water demand. If the water demand is fully satisfied, all parameters have been exactly estimated and an iteration is redundant.

If the water demand is not satisfied, in procedure 2 the available resources are distributed between the users according to their priority. After that in procedure 1 the system is balanced considering the reduced water demand from procedure 2. This computation is continued iteratively until the discharges for all balance profiles do not change during iteration (within a given accuracy).

In Appendix 3 the computer code of the subroutine balance of the management model is given.

2.5. Monte Carlo simulation and statistical evaluation

The major problem related to the Monte Carlo simulation is its high computational effort depending on the number of realizations NREL. Frequently fixed numbers of realizations (e.g. NREL=100) are selected. In this case NREL usually will be overdimensioned in order to ensure a certain statistical evidence and the numerical effort will be higher as necessary.

Principally, the number of realizations depends on the required statistical evidence of the results. If this evidence is checked in the course of the computation, the simulation can be stopped as soon as possible. For the DSS MINE such a test has been realized in the following simple form:

Every 10 realizations the mean values for selected parameters $\bar{x}$ (decisions and state parameters for each planning period) are compared. If the deviation is smaller then ε with respect to the mean value of the planning model $\bar{x}_p$ the simulation is stopped.

$$| \bar{x}(irel+10) - \bar{x}(irel) | < \varepsilon \cdot | \bar{x}_p | \; ! \qquad (2.31)$$

According to that the number of realizations is controlled by the factor ε to be fixed by the user (e.g. 0.05).

In Figure 8 a simplified flow chart of the subroutine controlling the Monte Carlo simulation is depicted.

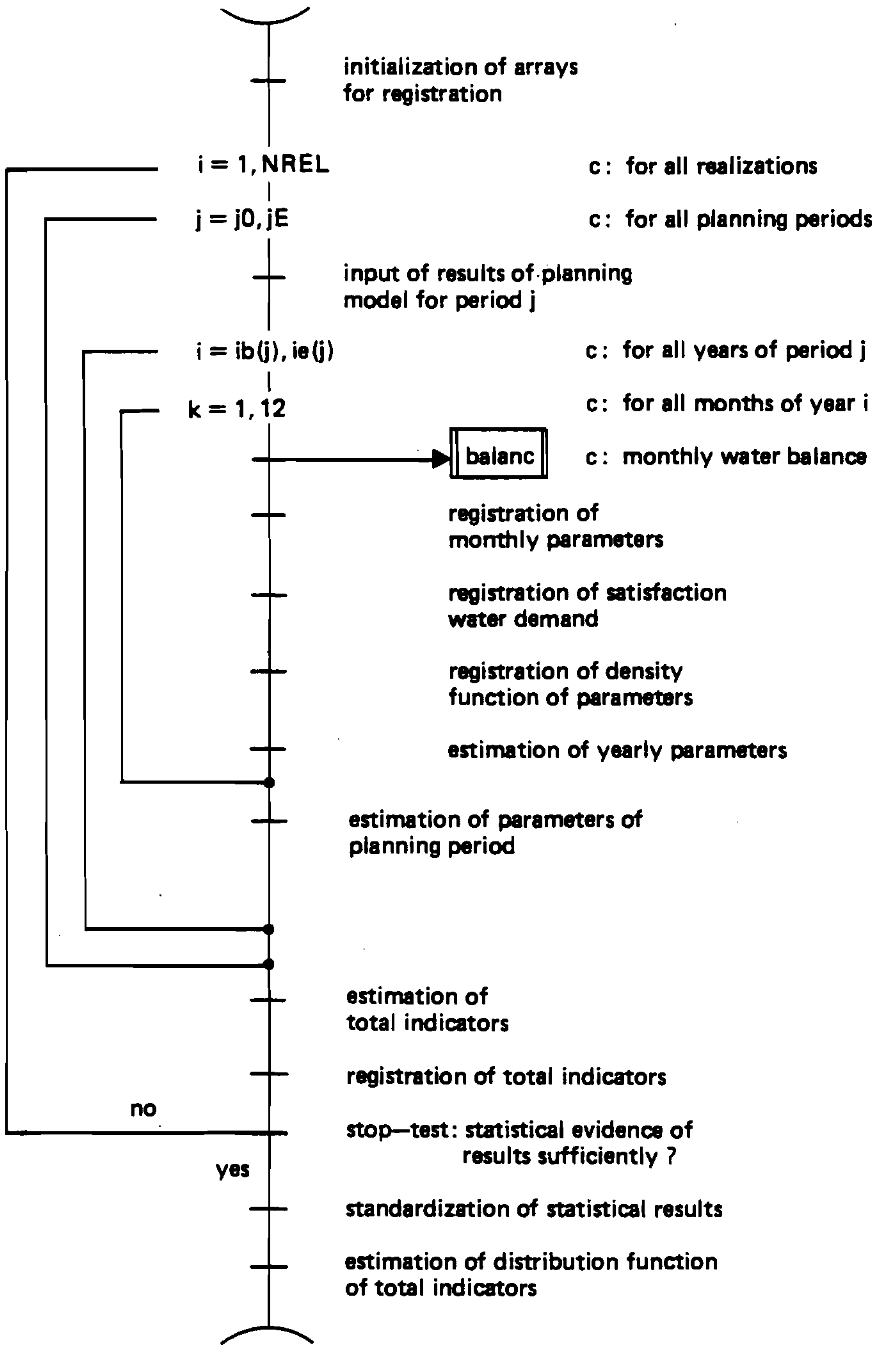

Figure 8: Flow chart of Monte Carlo simulation

An important methodological problem is the registration and statistical evaluation. The following types of registration are common:

- distribution functions of reliabilities of the occurrence of defined events, e.g. the satisfaction of water demand,
- distribution functions of selected parameters, e.g. the total cost of mine drainage,
- density functions of selected parameters, e.g. water allocation.

These continuous functions can only be registered empirically in a discrete form for defined classes. Define $(sclass\,(l\,), l=1,\ldots,KL)$ the scaling factor of the classes, for convenience the same for all functions (e.g. 0. - 0.5 - 0.7 - 0.8 - 0.9 - 0.95).

The registration depends on the definition of the reference value. It is advantageous to use a reference value being known in advance. In this case the statistical events have not to be stored and the empirical functions can be estimated during the simulation. This is necessary especially then if a large number of parameters is to be registered, e.g. for the GDR test area 21 parameters for 10 planning periods and 12 month. (I.e. for 100 realizations 252000 values.)

For the DSS MINE the following empirical probabilistic functions are estimated:

Satisfaction of water demand

$$P_S\left(\left(\frac{sup}{dem}\right)^0\right) = Prob\ \left\{ \frac{sup}{dem} > \left(\frac{sup}{dem}\right)^0 \right\} \tag{2.32}$$

with dem - water demand, sup - water supply.

This function is estimated for all month in all planning periods. In this case we use probabilities as the reference values for registration and sup is normalized by dem, consequently the discrete function values can be estimated during stochastic simulation.

Indicators of systems development

$$P_I(\,ind^0\,) = Prob\ \{\,ind\ < ind^0\,\} \tag{2.33}$$

All events have to be stored. The empirical distribution function is estimated at the end of simulation. The probability is scaled with $sclass$, see above.

Parameters of systems development

For decisions, state parameters and state variables a density function is estimated.

$$P_P(\,par^0\,) = Prob\ \{\,par^0 \le par\ < par^0 + \Delta par\ \} \tag{2.34}$$

The function is estimated for all planning periods and all month. As the reference value we use the known result of the planning model (mean value for each period).

In Figure 9 the above defined probabilistic functions and their scaling are illustrated.

2.6. Numerical tests

Basis of the numerical test was a typical result of the planning model obtained for a multi-criteria analysis for the criteria:

$dev-m$ - deviation water demand/supply municipality
$dev-i$ - deviation water demand/supply industry
$cost-mi$ - total mine drainage cost
$cost-m$ - cost municipal water supply
$cost-i$ - cost industrial water supply.

For each criteria the utopia-point has been selected as reference point. These results have been used as initial values for the management model.

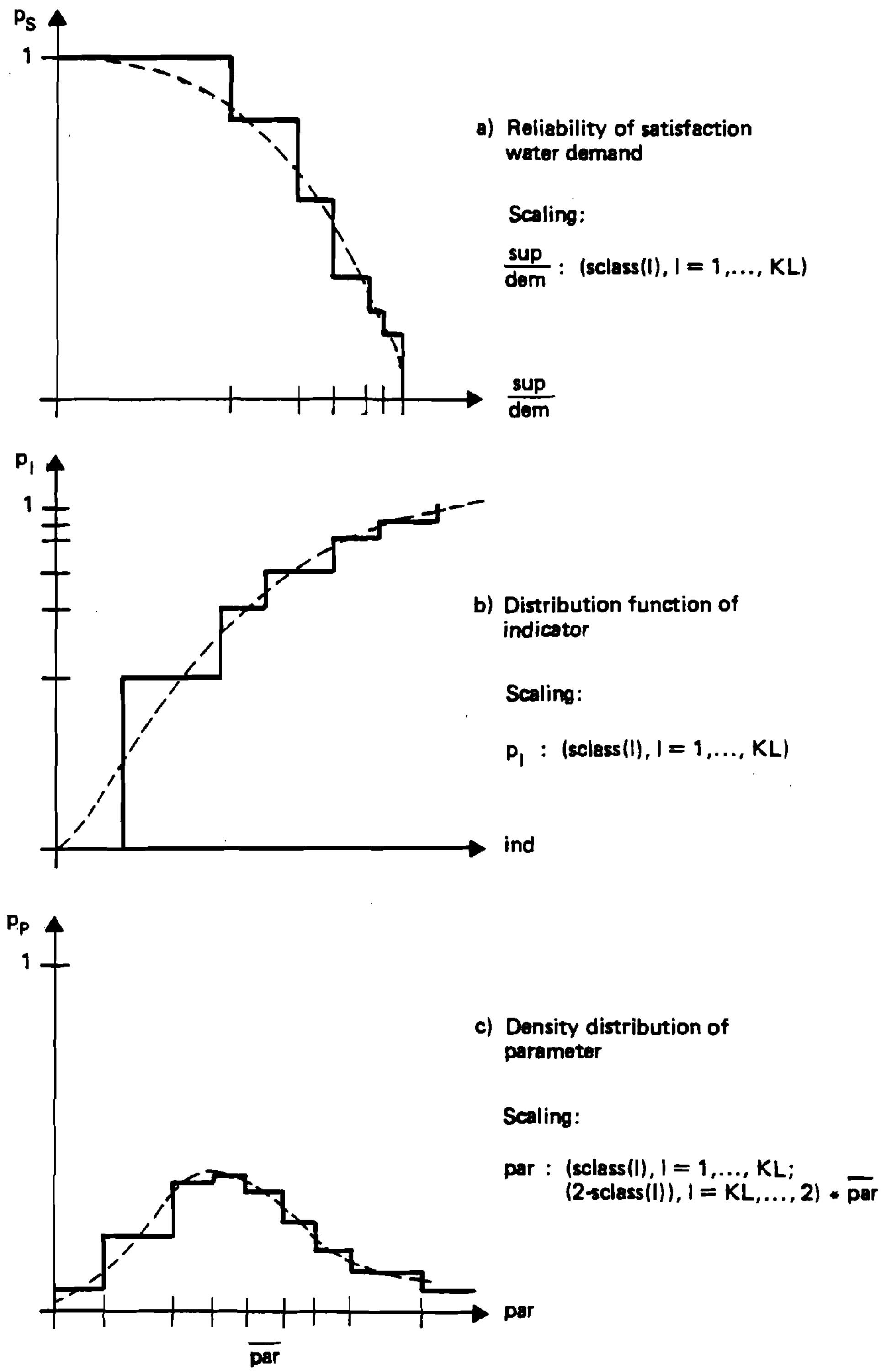

Figure 9: Statistical evaluation

The simulation has been performed with 60 realizations. Therefor about 6 Min. CPU-time at the VAX 11/780 was consumed. A detailed evaluation of the numerical results can not be given in this paper. This has to be done by the experts of the water authority responsible for the test region. In the following some aspects will be discussed.

A fundamental methodological problem is the consistency between the rough planning model and the management model. This can be checked easily comparing the results of the planning model with the related results of the management model (average value for planning periods or for the planning horizon of all realizations of Monte Carlo simulation). In Table 1 for some parameters and indicators the results are compared. The significant differences for the costs of agricultural water supply are caused by increased use of surface water during the summer period within the management model, and this is much more expensive than the mine water used in planning models.

Table 1: Comparison between planning model and management model

planning m.		management model					
indicator	solution	mean	value	95%	90%	80%	70%
1 dev-m	0.02	0.	0.	0.	0.	0.	0.
2 dev-i	0.00	0.05	0.08	0.07	0.06	0.06	0.06
3 dev-ag	0.02	-0.02	0.09	0.06	0.03	0.02	-0.01
4 dev-e	0.03	0.01	0.01	0.01	0.01	0.01	0.01
5 dev-ds	-8.42	0.01	0.02	0.02	0.02	0.01	0.01
14 cost-m	28.12	30.01	30.16	30.14	30.08	30.05	30.00
15 cost-i	1304.37	1265.83	1275.09	1274.20	1270.99	1268.36	1265.42
16 cost-ag	7.40	45.87	63.77	60.04	53.69	51.78	44.26

According to this table the consistency between the models is ensured with an accuracy being sufficiently for practical decision making. Consequently the practical realization of an estimated rational long-term strategy (planning model) will be close to this strategy, i.e. close to the Pareto-optimal solution.

The next problem to be answered with the management model is the proof that a long-term strategy proposed by the planning model is practically feasible. In this context feasibility means that the monthly water demand of the water users is satisfied with a certain reliability. In Table 2 the result for one period with respect to industrial water supply is depicted.

Table 2: Reliability of satisfaction of industrial water demand, period 4.

month	1	2	3	4	5	6	7	8	9	10	11	12
avdem	4.00	4.01	3.99	3.98	4.00	3.94	4.10	3.96	4.07	3.99	4.03	3.98
> 95%	85.8	90.8	87.5	85.8	78.3	67.5	48.3	58.3	50.0	68.3	72.5	82.5
> 90%	86.7	91.7	88.3	86.7	81.7	70.8	54.2	64.2	51.7	72.5	76.7	85.8
> 80%	92.5	93.3	94.2	92.5	85.0	75.8	58.3	70.8	60.8	77.5	81.7	90.8
> 70%	94.2	96.7	98.3	96.7	91.7	80.0	67.5	80.0	72.5	89.2	90.8	93.3
> 50%	100.0	100.0	100.0	100.0	96.7	96.7	86.7	92.5	90.0	100.0	100.0	99.2

It is up to the experts in the region to decide whether these reliabilities are acceptable or not. If not, there are two ways to get better results:

- to run the planning model again with changed reference points; in the example above for the industry higher mean water demand would have to be required,
- to change the management rule in order to increase the rank of a certain user.

The second alternative is more difficult because it necessitates changes in the algorithm, presently only to be done by specialists. In the future the management rules might be included in form of input data (with an interactive data input).

3. Deterministic Simulation of Long-term Policies

The stochastic simulation within the management model is used to proof the feasibility of policies with respect to water supply considering stochastic inputs. For practical reasons only those decisions and submodels have been included in this monthly simulation strongly depending on those inputs. The applied submodels have been developed based on comprehensive models. Numerical tests have shown that these submodels reflect the processes under consideration sufficiently accurately for monthly time steps (the minimum time step of interest). For the remaining decisions, submodels, and inputs the mean results of the planning model have been used.

It has to be checked whether the simplifications included in the planning model but also in the management model for stochastic simulation do not affect significantly the results in terms of the estimated long-term policies. The only way therefore is a deterministic simulation based on more comprehensive submodels and smaller time steps. Besides the verification of the results of the planning model this deterministic simulation can be used to get more detailed results (in time as well as in space) and to verify the feasibility of long term management strategies e.g. with respect to mine water treatment. According to that we understand as the second task of the management model a *verification and specification of the results of the planning model.*

In principle any comprehensive submodel might be used for that task, e.g. even a comprehensive groundwater flow model with distributed parameters as it is available for the test region. But this would require a high effort in adapting the submodels to the needs of the management model with respect to input and output data. The resulting model would be time consuming and consequently far from being interactively.

The deterministic simulation of long-term policies within the management model has to consider shorter time steps as the planning model. Submodels are needed being adaquate to these time steps and to the relevant processes with respect to long-term policies. These submodels have to be simpler as the basic comprehensive models (as far as such models are available), but they might be more comprehensive as the submodels used in the planning model.

Available basic comprehensive models can be used both, for the development of simplified submodels, and for the verification of these submodels. We assume that this will be done only for principal considerations, not within the regular interactive application of the DSS MINE. Consequently we do not need an on-line interface between the different model levels. In this case common comprehensive models are used for simulation based on input data obtained from the planning model. Because this is a classical modeling task it needs no further discussion here.

For the deterministic simulation of long-term policies within the management model (part 2) we propose the following approach:

- discretization into yearly time steps,
- the yearly decisions needed to simulate the yearly systems behaviour are obtained from the results of the planning model (mean values for planning periods) by linear interpolation,

- for all relevant subprocesses adaquate submodels are used considering yearly time steps.

In Figure 10 the block structure of this part of the management model is given.

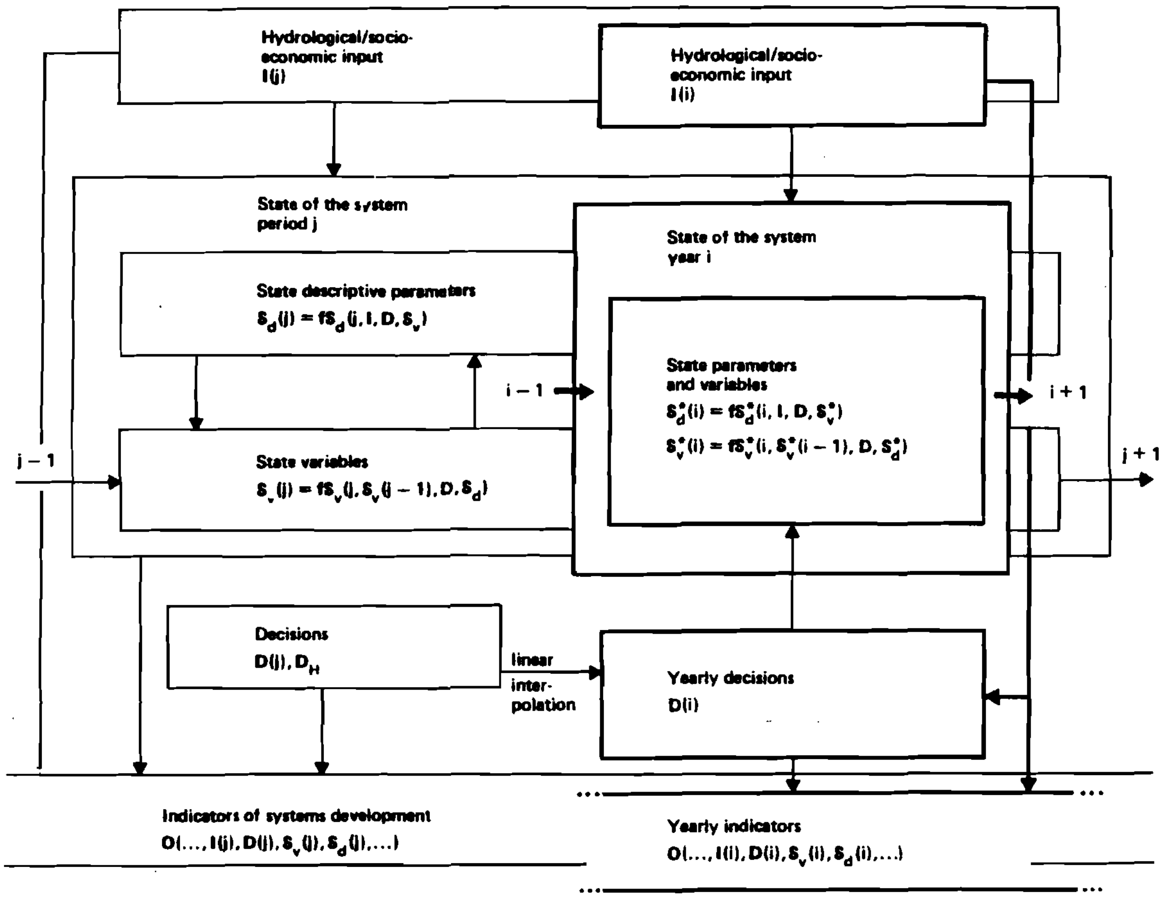

Figure 10: Block scheme of the management model
part 2 - deterministic simulation of long-term policies

The adequate submodels being developed are described in Kaden et al. 1985a,b (remaining pit management, mine drainage) and Luckner et al. 1985 (groundwater and surface water quality, mine water treatment).

This part of the management model will be finalized at the Institute for Water Management, Berlin, during the phase of implementation of the DSS MINE.

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Appendix 1

SUBROUTINE REMPIT - remaining pit submodel of the management model

```
      subroutine rempit(i,k,ilo,vpit,dqp,new,hpmin,hpmax,hp)
c
c ***  management remaining pit
c
c ***  i         - year
c ***  k         - month
c ***  ilo       - number of calls of rempit during actual month
c                  1        --> first call for management phase
c                  2        --> final call for management phase
c                  3        --> call for filling phase
c ***  vpit      - storage volume remaining pit
c ***  dqp       - storage usage (inflow -> + ; outflow -> -)
c ***  new       - .false.--> iteration
c                  .true. --> new month
c ***  hpmin     - min. water table rem.pit for management
c ***  hpmax     - max. water table rem.pit for management
c ***  hp        - act. water table rem.pit
c
      implicit real*8 (a-h,o-z)
      logical      new
      dimension    a(2),b(2),hps(2),v(8),h(8),ti(35),hagain(35)
      save         hp0,dqp0,c,a,b,h,ti,hagain,hps,dqp1,ijahr,v,h
      data         a/1.747939,-0.751772/
      data         b/3.97425e-3,-3.110242e-3/
      data         h/68.,70.,80.,90.,100.,110.,118.,127.5/
      data         v/0.,17.6,105.6,193.6,281.6,369.6,440.0,523.6/
      data         hps/2*0.0/
      data         ti/0.,12.,24.,36.,48.,60.,72.,84.,96.,
     *                108.,120.,132.,144.,156.,168.,180.,192.,204.,
     *                216.,228.,240.,252.,264.,276.,288.,300.,312.,
     *                324.,336.,348.,360.,372.,384.,396.,408./
      data hagain /82.,86.1,89.7,92.1,94.4,96.3,97.8,99.1
     *             ,100.1,100.9,101.6,102.1,102.6,102.9,103.2,103.5
     *             ,103.7,103.8,104.0,104.1,104.2,104.2,104.3,104.3
     *             ,104.4,104.4,104.5,104.5,7*104.6/
c
c ***  a,b       - coefficients of recursive equation
c ***  v,h       - interpolation nodes of
c                  water table - storage volume function
c ***  hps       - history of water table
c ***  dqp1      - history of inflow/outflow
c ***  dqp0      - necessary inflow to obtain max. water table
c ***  hagain,   - interpolation nodes for natural recharge
c      ti
c

c ***  transformation of discharge m3/sec -> Mill. m3/year
      dqp=dqp*31.5
      ijahr=i-17
```

```
1       goto (10,100,200),ilo

c ***   first storage calculation
c       (complete discharge of available capacity)
10      hp=pol(8,v,h,vpit)

        if(new .eq. .false.) goto 20
c ***   iteration

c ***   new month
        xmon=(ijahr-1)*12+k
        hps(2)=hps(1)
        if(xmon.gt.1.) hps(1)=hp-hp0
        dqp1=dqp
        hp0=pol(35,ti,hagain,xmon)

20      dqp=0.0
        c=hp0+a(1)*hps(1)+a(2)*hps(2)+b(2)*dqp1
        dqp0=(hpmax-c)/b(1)
        if(c.le.hpmin) hp=c
        if(c.le.hpmin) return
        dqp=(hpmin-c)/b(1)
        dqp=-dqp/31.5
        return

c ***   final storage calculation
100     if(dqp.gt.dqp0) dqp=dqp0

c ***   storage calculation for given inflow
200     hp=c+b(1)*dqp
        vpit=pol(8,h,v,hp)
        dqp=dqp/31.5

        return
        end
c
        function pol(k,x,y,xs)
c
c ***   function for linear interpolation between interpolation nodes
c
        implicit real*8 (a-h,o-z)
        dimension x(k),y(k)
        if(k.eq.1) goto 2
        x0=xs
        if(x0-x(1).lt.0.0) x0=x(1)
        do 1 i=1,k
        xt=abs(x(i)-x0)
        if(xt.le.1.e-9) goto 3
        if(x(i).gt.x0)  goto 4
1       continue
2       pol=y(k)
        return
3       pol=y(i)
        return
4       pol=(y(i)-y(i-1))*(x0-x(i-1))/(x(i)-x(i-1))+y(i-1)

        return
        end
```

Appendix 2

SUBROUTINE INFI - **infiltration submodel of the management model**

```
      subroutine infi (iubp,idbp,hskju,hskjd,qijud,
     *                                 qsu,qd,qil,new)
c
c ***   monthly infiltration for river sections
c
c ***   iubp     - index of up-stream balance profile
c ***   idbp     - index of down-stream balance profile
c ***   hskju    - mean water table profil iubp [m above bottom]
c ***   hskjd    - mean water table profil idbp [m above bottom]
c ***   qijud    - infiltration for mean water table between
c                  profile iubp and idbp for period j [m3/sec.]
c ***   qsu      - flux up-stream balance profile [m3/sec.]
c ***   qd       - inflow/outflow down-stream balance profile [m3/sec.]
c ***   qil      - total infiltration [m3/sec.]
c ***   new      - .true.  -> next month
c ***              .false. -> iteration
      real*8  hskju,hskjd,qijud,qsu,qd,qil
      logical new
c ***   a1,a2,b0,
c       b1,b2,c0            - coefficients of recursive equation
c ***   alpha               - weighting factor
c ***   qsu1,qsu2,uk1,uk2
c                           - history for recursive equation
      dimension a1(7),a2(7),b0(7),b1(7),b2(7),c0(7)
      dimension qsu1(7),qsu2(7),uk1(7),uk2(7),u(7),dqikl(7)
      data  a1 /1.0933,1.0504,1.1167,0.0,1.1414,1.1819,1.1947/
      data  a2 /-0.1910,-0.1622,-0.2035,0.0,-0.2136,-0.2431,-0.2563/
      data  b0 /0.646,0.244,0.129,0.0,0.177,0.306,0.601/
      data  b1 /-0.8943,-0.3393,-0.1871,0.0,-0.2360,-0.4077,-0.827/
      data  b2 / 0.2549,0.0978,0.0593,0.0,0.0606,0.1058,0.2332/
      data  c0 /0.07,0.16,0.09,0.0,0.0,0.0,0.0/
      data  alpha/0.5/
      save qsu1,qsu2,uk1,uk2,u,dqikl
      data qsu1,qsu2,uk1,uk2 /28*0.0/
      if(.not.new) goto 20
c ***   iteration
c
c ***   next month
      qsu2(iubp)=qsu1(iubp)
      qsu1(iubp)=dqikl(iubp)-c0(iubp)*u(iubp)
      uk2(iubp)=uk1(iubp)
      uk1(iubp)=u(iubp)
c
20    qsl=qsu+qd-qijud
      qsln=qsl
      hsk=fhs(iubp,qsu)
      uk=alpha*(hsk-hskju)
30    qsla=qsln
      hsl=fhs(idbp,qsla)
      ul=hsl-hskjd
```

```
      u(iubp)=(uk+(1-alpha)*ul)/100.0
      dqikl(iubp)=a1(iubp)*qsu1(iubp)+a2(iubp)*qsu2(iubp)
     *            +(b0(iubp)+c0(iubp))*u(iubp)+b1(iubp)*uk1(iubp)
     *            +b2(iubp)*uk2(iubp)
      qsln=qsl-dqikl(iubp)
      if(abs(qsla-qsln).gt.0.01) goto 30
c ***   internal iteration
c
      qil=dqikl(iubp)+qijud
      return
      end
c
c *********************************************************************
c
      function fhs(ibp,qsk)
c
c ***   water level key-function
c
c ***   ibp      - index of balance profile
c ***   qsk      - flux through balance profile
c
c ***   k1,k2,k3          - coefficients of key-curves

      real  k1(7),k2(7),k3(7)
      data  k1 /-8.6621,-7.3409,-3.07,-14.419,-8.6874,-3.25,-8.6621/
      data  k2 /2.1305,1.99712,1.3811,3.1104,2.2545,1.2453,2.1305/
      data  k3 /40.5,0.31,140.9,-70.0,24.5,97.0,40.5/

      fhs=exp((alog(qsk)-k1(ibp))/k2(ibp))+k3(ibp)

      return
      end
```

Appendix 3

SUBROUTINE BALANC - balanc submodel of the management model

```
      subroutine balanc(j,ja,i,k,dq,aq)
c
c ***  monthly water balance
c
c ***  j        - planning period
c ***  ja       - last period for mine a, next period rem.pit operates
c ***  i,k      - year, month
c ***  dq       - demand for water allocation
c ***  aq       - actual water allocation
c
c ***  common for planning model
c
c ***  descriptors
c
      common /svalue/qga,qgb1,qgb2,qgc,qgd,
     *               qi12,qi23,qi34,qi73,qi62,qi56,
     *               hag,hg,he,
     *               cgaf,cgb1f,cgb2f,cgcf,cgdf,cgpf,
     *               cgah,cgb1h,cgb2h,cgch,cgdh,cgph,
     *               caf,cbf,ccf,cdf,
     *               cah,cbh,cch,cdh,
     *               qs5,qs6,qs1,qs2,qs7,qs3,qs4,
     *               qqis,cisf,cish,
     *               cs5f,cs6f,cs1f,cs2f,cs7f,cs3f,cs4f,
     *               cs5h,cs6h,cs1h,cs2h,cs7h,cs3h,cs4h,
     *               qgp,dqp
      common /hsvalu/hs5,hs6,hs1,hs2,hs7,hs3,hs4
c
c ***  ihs      - coordination between order of qs/hs and bal.profiles
c
      common /ihsva/ ihs(NPBP)
c
c ***  decisions in planning periods
c
      common /decper/qqas,qqaex,
     *               qqps,qqpe,
     *               qqbm,qqbex,qqbs,qqbp,
     *               qqci,qqcag,qqcs,qqce,
     *               qqdi,qqdex,qqds,qqdag,
     *               qqsm,qqsi,qqsag,qqsp,qqgm,qqimm,
     *               cqa,cqb,cqc,cqd,cqp
c
c ***  decisions in planning horizon
c
      common /dechor/dtmd,hpmax
c
c ***  state variables
c
      common /stva/  hp,cpf,cph,vpe
c
c ***  state variables of previous period
c
      common /stvam1/hpm1,cpfm1,cphm1,vpem1
```

```
c
c
c ***   common for water balance in management model
c
c ***   qact    - actual flow through balance profile
c ***   qprot   - protected flow
c ***   next    - indicies of next down-stream balance profile
c ***   qiter   - actual flow through balance profile, previous iterat.
c
c ***   NBP     - number of balance profiles in the management model
        parameter (NBP  = 15)
        real*8  qact,qprot,qiter
        common /balan/qact(NBP),qprot(NBP),qiter(NBP),next(NBP)
c
c ***   common for management model to save intermediate data
c
c ***   monthly values
        common /valuek/qs1k,qs2k,qs3k,qs4k,qs5k,qs6k,qs7k,
     *               qi12k,qi23k,qi34k,qi56k,qi73k,
     *               qsagk,qsik,qsmk,qpek,qpsk,qspk,
     *               hpk,vpk
        common /demank/demom,demoi,demoag,demoe,demods,demdsm

c ***   yearly values
        common /valuei/qs1i,qs2i,qs3i,qs4i,qs5i,qs6i,qs7i,
     *               qi12i,qi23i,qi34i,qi56i,qi73i,
     *               qsagi,qsii,qsmi,qpei,qpsi,qspi,
     *               hpi,vpi

c ***   values for period
        common /valuej/qs1j,qs2j,qs3j,qs4j,qs5j,qs6j,qs7j,
     *               qi12j,qi23j,qi34j,qi56j,qi73j,
     *               qsagj,qsij,qsmj,qpej,qpsj,qspj,
     *               hpj,vpj
        common /indicj/devm,devi,devag,deve,devds,envds,enve,envp,
     *               com,coi,coag,coe,cop
c
        dimension dq(NMQ),aq(NMQ)
        logical new

c ***   inflow balance profiles 1,5,7
        call inflow(k,qs1k,qs5k,qs7k)

c ***   min.water table rem.pit fot management
        hpmin=110.0

c ***   correlation coefficients for unspecified inflow
        coef1=qs1k/qs1
        coef5=qs5k/qs5
        coef7=qs7k/qs7

c ***   demand for water allocation
        call demmon(j,i,k)
```

```
c ***   estimation of demand for water allocation from the stream
c       and the remaining pit
c ***   actual water allocation = water demand

        dqsag=demoag-qqcag-qqdag
        if(dqsag .lt. 0.) dqsag=0.
        dq(1)=dqsag
        qsaqk=dqsag
        dqsi =demoi-qqci-qqdi
        if(dqsi .lt. 0.) dqsi=0.
        dq(2)=dqsi
        qsik=dqsi
        dqsm =demom-qqbm-qqgm-qqimm
        if(dqsm .lt. 0.) dqsm=0.
        dq(3)=dqsm
        qsmk=dqsm
        dqmin=demdsm
        dq(4)=dqmin
        qmink=dqmin
        dqsds=demods-demdsm
        dq(5)=dqsds
        qsdsk=dqsds
        dqpe=demoe-qqce
        if(dqpe .lt. 0.) dqpe=0.
        dq(6)=dqpe
        qpek=dqpe
        dqps=0.
        dq(7)=dqps
        qpsk=dqps
        dqsp=pqsp
        dq(8)=dqsp
        qspk=dqsp

        hpact=hpold
        new=.true.

c ***   next month

10      continue
c ***   entry for iteration

        do 20 l=1,NBP
                qprot(l)=0.
                qact (l)=0.
20      continue

c ***   balance segment 5,6
        call chq(qs5k,5,0)
        qsu=qs5k-qsagk
        qd =qqds+0.5*coef5
        call infi(5,6,hs5,hs6,qi56,qsu,qd,qi56k,new)
        call chq(-qi56k,6,0)
        call chq(qd,6,0)

c ***   balance segment 6,2
        qsu=qsu+qd-qi56k
        qd =qs1k+qqcs-qsik+.3*(qsik+qqci+qqdi)+4.9*coef1
```

```
        call infi(6,2,hs6,hs2,qi62,qsu,qd,qi62k,new)
        call chq(-qi62k,10,0)
        call chq(qqcs+.3*(qqci+qqdi),10,0)

c ***   balance segment 1,2
        qd =qsu+qd-qs1k-qi62k
        call chq(qs1k,1,0)
        call infi(1,2,hs1,hs2,qi12,qs1k,qd,qi12k,new)
        call chq(4.9*coef1-qi12k,2,0)

c ***   balance segment 2,3
        qsu=qd+qs1k-qi12k

        if (j .le. ja) goto 30

c ***   remaining pit
        ilo=1
        vpit=vpit+qqbp*2.627

        call rempit(i,k,ilo,vpit,qpsk,new,hpmin,hpmax,hpact)
        dqpa=qpsk
        call chq(qpsk,11,0)

30      qd =qs7k+qpsk-qspk+qqbs+qqas
        call infi(2,3,hs2,hs3,qi23,qsu,qd,qi23k,new)
        call chq(-qi23k,12,0)
        call chq(qqas+qqbs,12,0)

c ***   storage release for lowest volume
        if (j .gt. ja) call chq(qpsk,12,0)

c ***   balance segment 7,3
        call chq(qs7k,7,0)
        qd=qsu+qd-qs7k-qi23k
        call infi(7,3,hs7,hs3,qi73,qs7k,qd,qi73k,new)
        call chq(-qi73k,3,0)

c ***   balance profile 3,4
        qsu=qs7k+qd-qi73k
        qd =-qsmk
        call infi(3,4,hs3,hs4,qi34,qsu,qd,qi34k,new)
        call chq(-qi34k,4,0)

c ***   balance q-s,m
        if (dqsm .gt. qact(4)) qsmk=qact(4)
        call chq(-qsmk,4,0)

c ***   balance q-s,ds for minimum flow
        if (dqmin .gt. qact(4)) qmink=qact(4)
        qprot(4)=qmink

c ***   balance q-s,i
        if (dqsi .lt. 0.01) goto 45
        v =0.7*dqsi
        hv=hmin(10,0)
        if (dqsi .lt. qact(10) .and. v .lt. hv) goto 40
```

```
      wv=hv/v
      we=qact(10)/dqsi
      if (wv .lt. we) we=wv
      qsik=we*dqsi
      v =we*v
40    call chq(-v,10,0)
      qprot(10)=qsik-v

c *** balance q-s,ds for down-stream user
45    if (dqsds .gt. qact(4)-qprot(4)) qsdsk=qact(4)-qprot(4)
      qact(4)=qact(4)-qsdsk
c *** balance q-s,ag
      hv=hmin(5,0)
      if (dqsag .gt. hv) qsagk=hv
      call chq(-qsagk,5,0)

      if (j .le. ja) goto 60

      if (hpact .gt. hpmin) goto 50
c *** storage management

c *** filling of reservoir according planning model
      hv=hmin(12,0)
      if (dqsp .gt. hv) qspk=hv
      call chq(-qspk,11,0)
      ilo=3
      call rempit(i,k,ilo,vpit,qspk,new,hpmin,hpmax,hpact)
      goto 60

c *** balance q-p,e
50    hv=hmin(12,0)
      if (dqpe .gt. hv) qpek=hv
      call chq(-qpek,11,0)

c *** balance q-p,s/s,p
      hv=hmin(12,0)
      dqp=hv-dqp
      ilo=2
      call rempit(i,k,ilo,vpit,dqp,new,hpmin,hpmax,hpact)
      hv=dqpa+dqp
      call chq(-hv,11,0)
      if (dqp .lt. 0.) then
              qaps=-dqp
              qspk=0.
      else
              qspk=dqp
              qpsk=0.
      endif

c ***
60    aq(1)=qsagk
      aq(2)=qsik
      aq(3)=qsmk
      aq(4)=qmink
```

```
      aq(5)=qsdsk
      aq(6)=qpek
      aq(7)=qpsk
      aq(8)=qspk

      if (new) goto 80

c *** test for iterative estimation of infiltration

      do 70 l=1,NBP
              if (abs(qact(l)-qiter(l)) .lt. 0.01) goto 70
              goto 100
70    continue
      goto 120

c *** end of iteration

80    if (j .gt. ja) goto 100
c *** if remaining pit is available at least one iteration

c *** comparison between actual allocation and demand
c *** allocation remaining pit is not considered!

      do 90 l=1,NMQ-2
              if (abs(aq(l)-dq(l)) .gt. 0.01) goto 100
90    continue
      goto 120

c *** preparation of next iteration
100   do 110 l=1,NBP
              qiter(l)=qact(l)
110   continue
      new=.false.
      goto 10

120   hpold=hpact

      qs2k=qact(2)
      qs3k=qact(3)
      qs4k=qact(4)
      qs6k=qact(6)

      return
      end
c
c ********************************************************************
c
      subroutine chq(dq,k1,k2)
c
c *** balancing of all down-stream balance profiles
c
c *** k1      - balance profile under consideration
c *** k2      - last profil under consideration
c *** dq      - inflow/outflow at profile k1,added to k1 and all
c ***           down-stream profiles
c
      parameter (NBP  = 15)
      real*8  qact,qprot,qiter
      common /balan/qact(NBP),qprot(NBP),qiter(NBP),next(NBP)
c
```

```
      if(abs(dq).lt..001) return
      k=k1
      if(k2) 10,20,30
10    ke=-k2
      goto 40
20    ke=-999
      goto 40
30    ke=next(k2)
40    if(k.eq.ke) return
      if(k.lt.1 .or. k.gt.NBP) write(*,999) k1,k2,k
999   format(' error in next, k1,k2,k',3i5)
      qact(k)=qact(k)+dq
      k=next(k)
      goto 40
      end
c
c ****************************************************************
c
      function hmin(k1,k2)
c
c ***   estimation of available flow
c
c ***   k1      - balance profile under consideration
c ***   k2      - last balance profile under consideration
c
      parameter (NBP  = 15)
      real*8  qact,qprot,qiter
      common /balan/qact(NBP),qprot(NBP),qiter(NBP),next(NBP)
c
      hmin=1000000.
      k=k1
      if(k2) 10,20,30
10    ke=-k2
      goto 40
20    ke=-999
      goto 40
30    ke=next(k2)
40    if(k.eq.ke) return
      h=qact(k)-qprot(k)
      if(h.lt..00001) goto 50
      if(h.lt.hmin) hmin=h
      k=next(k)
      goto 40
50    hmin=0.

      return
      end
```