WORKING PAPER

DECISION SUPPORT SYSTEMS FOR
THE ANALYSIS OF REGIONAL WATER POLICIES:
Final Report of the Collaborative IIASA
"Regional Water Policies" Project
(1984-85)

Editors:
S. Orlovski
S. Kaden
P. van Walsum

July 1986
WP-86-33

IIASA
International Institute
for Applied Systems Analysis

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OF THE AUTHOR

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PREFACE

When a scientist or a research team identify their field as physics, chemistry or other natural science this is not only sufficiently well understood but also suggests an idea of possible products of their work. But identifying one's field as the systems analysis frequently causes confusion, because nowadays this term is often used to cover many diverse occupations with this diversity growing. Clearly, it is hardly possible to give a precise definition to what systems analysis is, which is also true for many other disciplines, but certain features which are inherent to this discipline from our viewpoint can be drawn. We can refer to *Mathematical Problems of the Systems Analysis* by N.N. Moiseev, "Nauka, Moscow, 1981 (in Russian), where these features are drawn with remarkable precision.

Any study in the field of the systems analysis is of interdisciplinary character in that it tends to use knowledge and data generated by various disciplines. It requires unification and coordination of information generated by concrete studies in, say, economics, sociology, agricultural sciences, hydrology, civil engineering, etc. Success of a systems analytic study rests largely on the possibilities of information processing and application of mathematical methods that emerged with the development of computers and offered a language of a high degree of universality. By using this language as a framework for thinking and describing complex real systems the practitioner can often analyze difficult problems in a fruitful manner.

There is a great deal of similarity between natural sciences and the systems analysis. When physicists undertake a study of a certain system or a phenomenon a great deal of their time and effort is invested into designing sometimes very complex installations for performing the necessary analytical experiments. Such an installation is always a synthesis of many existing devices and recognized principles brought together to form a qualitatively new tool serving a given purpose. Clearly, it is more the creative talent of the physicists than formal procedures that plays a decisive role in this process.

The arsenal of devices and principles used by systems analysts includes varieties of formal and informal methods as well as logic of reasoning and data processing based on common sense, on formal mathematical methods, and on the use of computers. And in any systems analytic study as in experimental natural sciences, it is always important to find a good synthesis of these formal and informal tools and ***to design*** a computerized system as a qualitatively new tool for the analysis of concrete problems pertinent to a concrete real system under study. And if such a system is designed as a tool to assist decision making focused at resolving these problems we call it a ***decision support system***. To our understanding this ***problem of synthesis or design*** is the focal point of the systems analysis.

The process of design can never be formulated and reduced to solving one or even a sequence of formally stated mathematical problems. Contradictory requirements, lack of knowledge and many uncertainties involved in this process always urge analysts (or rather designers) to use informal considerations, heuristic procedures, and also computational experiments. And in every concrete case it does not suffice to know existing recipes. A study of a real system is always unique and a great role in it is played not only by a cultural and scientific background of the analysts, but also by their creative talent.

A systems analytic study is always focused on concrete problems. A great role is played here by a general mathematical background of the analysts. They should be able not only to understand clearly the contents of these problems, but also to formulate them in the form that is analyzable using mathematical, computational, and other means at their disposal.

Because as has been argued earlier this process of design necessarily involves informal steps, its final product – a computerized decision support system designed as well as results emerging from its use can never be formally proved to be the best possible. The major justification for their "goodness" is the satisfactory quality and usefulness of information they provide for practitioners. Therefore, any systems analytic study is always experimental and is always applied. (In this respect the term applied systems analysis is probably redundant.)

It is the above understanding of the contents and products of the systems analysis that underlined the activities of the IIASA project "Regional Water Policies". This report and the two decision support systems it describes are products of the collaborative work conducted during the 2 year period of 1984/85 by groups of scientists at IIASA and from research institutes in different countries. Two regions which provided the experimental bases for this work influenced also its organizational structure. One of these regions is an agricultural region of Southern Peel in the Netherlands, the other is an open-pit lignite mining region of Lusatia in the German Democratic Republic.

The research team of the IIASA project "Regional Water Policies" was the core of this collaborative work. This team not only coordinated this work but also essentially developed the methodological basis, structural design of the decision support systems, analytical procedures, and also implemented them on the IIASA VAX 11/780 computer.

But the successful work of this team would have been impossible without the direct participation in this work of the other two research groups in the GDR and in the Netherlands. The group in the GDR includes:

- D. Lauterbach, K. Tiemer, B. König, I. Michels, and M. Schramm from the Institute for Water Management, Berlin;
- L. Luckner from Dresden University of Technology;
- D. Peukert and J. Hummel from the Institute for Lignite Mining, Grossräschen.

The group in the Netherlands includes scientists from the Institute for Land and Water Management Research in Wageningen: J. Drent, J. van Bakel, E. Querner, P.E. Rijtema, J. Berghuijs-van Dijk, R. Kemmers, L.J. Locht, J. Vreke, R.A. Feddes, J. Reinds, J. Steenvorden, and K. Wit.

To say that these groups provided support for the IIASA project will not fully reflect their decisive contributions to the project, which included not only the necessary data and the basic models for the respective regional studies, but also their active participation in shaping the research strategy.

Scientists from other institutes made important contributions to our work: T. Kreglewski from the Institute of Automatic Control of the Technical University of Warsaw, J. Kindler and his colleagues from the Institute of Environmental Engineering of the same University, J. Kacprzyk and A. Ziolkowski from the Institute of Systems Research of the Polish Academy of Sciences, Warsaw, V.Y. Lebedev and A.N. Lotov from the Computing Center of the USSR Academy of Sciences, Moscow. A number of participants of the Young Summer Scientists Programme contributed to our research: J. Jiranek from the Technical University of Prague, J. Kettunen and O. Varis from Helsinki University of Technology, and I.-M. Andreasson from Stockholm School of Economics. Other scientists from different countries were in permanent contact with the project and contributed useful ideal and criticism in personal discussions as well as during a number of fruitful meetings and workshops held by the project.

To all these organisations and people we express our deep gratitude.

Finally, we should remark here that this Report although finalizing the IIASA collaborative project does not end the studies that it describes. Initiated by this project, further research in this direction is being continued in the respective institutes both in the GDR and the Netherlands to make the decision support systems developed reflecting more closely practical needs in specific regions.

S.A. Orlovski
Project Leader
Regional Water Policies

INTRODUCTION

Intense socio-economic development in many regions of the world puts increasing pressure on the environment both by depleting natural resources and by polluting them causing actual and potential hazards to the population and to natural ecosystems. In many regions a substantial part of these impacts takes place through regional natural water systems. Together with being a resource that is vital for socio-economic development and for the evolution of natural ecosystems, the regional water system is a basic medium through which local human interventions penetrate to and are "felt" in other parts of the region and also frequently beyond its boundaries. The research outlined in this Report focuses on economically developed regions of this type where both groundwater and surface water are integrating elements of the environment. Figure I.1 gives a convenient schematic representation of the types of regions considered in this report. The arcs in this diagram indicate the links or interactions that play the most important part in this type of regions. In other words we consider regions where the major impacts occur on and/or through water systems.

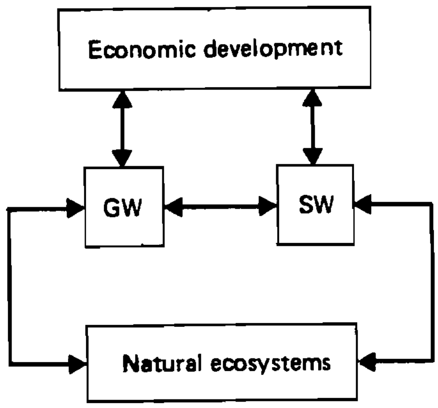

Figure I.1: Schematic representation of the region

Two concrete regions of this type in the Netherlands and in the German Democratic Republic form an experimental basis for our work.

One of these test regions – the Southern Peel region of the Netherlands – is predominantly agricultural. The intense agriculture in this region creates already existing and anticipated in future significant problems with the deteriorating quantity and quality of groundwater and surface water resources. Some measures should be introduced in this region to redirect may be through structural changes its future development towards more sustainable coevolution with the environment.

In the other test region of Lusatia in the GDR the major environmental impacts are associated with the open-pit lignite mining activities that cause major changes in groundwater and surface water regimes. But differently to the Southern Peel region the development of the mines and of the accompanying industry is predetermined by national political and economic concerns. Therefore, long-term water policies are to be considered here which can reduce impacts of mine drainage on the natural water resources systems as well as on the socio-economic development in the region. More detailed characterizations of these regions are presented respectively in Parts 2 and 3 of this Report.

In the two regions considered by this study the multiplicity and the complex nature of relations between water users and natural water systems on the one hand, and between water systems and natural ecosystems, on the other, pose problems to authorities that are concerned with and are responsible for guiding the regional development. The complexity of these problems and also vast amounts of information to be considered and processed for the analysis of these problems motivate the development of computer based means that can be used for the analysis of alternative paths of regional development.

Examples of various existing and anticipated concerns and problems typical to such regions are frequently quoted in the literature. Many models of individual processes like groundwater flow and quality processes, crop growth processes related to water and nutrients supply, etc., are described together with examples of their application to specific problems.

On the other hand, reports on studies encompassing the multiaspected regional framework and based on the use of systems of such models are much less numerous. Of those we can mention a study of alternatives for the agricultural uses of groundwater resources in the San Joaquin Valley in California, USA, described in *Hydrologic-Economic Model of the San Joaquin Valley*, 1982. We should, of course, mention the multivolume report on a major study "Policy Analysis for the Water Management of the Netherlands (PAWN) in *Policy Analysis of Water Management for the Netherlands*, Vol. I–XX, The Rand Corporation, 1983. This study involved 125 man-years of effort and considered all sectors of the Dutch economy based on the utilization of water resources.

A detailed analysis of water policies has been done for the Rheinish Lignite Mining District, FRG. It was directed towards the development of a conceptual plan for water management schemes considering the impact of mine dewatering on the environment and on water supply, B. Boehm, Conceptual plan for water management schemes in the northern part of the Rheinish Lignite Mining District. In: *Groundwater in Water Resources Planning*, Symposium, Koblenz, August–September 1983, Proceedings Vol. II, pp. 571–580.

Compared to the PAWN study in particular, the studies described in this Report are of much lower scale and effort. They also differ from the above mentioned studies in their focus on the development of efficient and convenient in their use decision support tools rather than on the elaboration of policy recommendations. We believe in the crucial importance of the direct participation of the policy makers in various stages of analysis because each of these stages may involve aspects of subjectivity and uncertainty unresolvable on a purely formal basis.

Such a tool in the form of a flexible computerized decision support system should be able to assist the user to handle various types of information, obtain answers to multiple questions pertinent to regional concerns and be convenient in its use. Designing two such systems for the two concrete prototype regions was the focus of the project's work, and this report describes the underlying logic of this design and also the systems designed themselves. It also provides guidelines for using the systems developed in the context of the concrete regions considered.

A systems analytic study starts with a necessarily vague description of a real system and the scope of problems of concern. Its final product is a computer implemented decision support system designed (and tested) as a tool for the analysis of alternative solutions to those problems. Therefore, designing such a system should involve translation of the initial vague description into a more logically structured and mathematically formal one allowing for its computer implementation. This translation would necessarily omit many irrelevant (and sometimes relevant) aspects of the real system and problems, but at the same time it would allow to more clearly reveal the structure of the major regional issues, and therefore, allow for their more concentrated systematic analysis.

This Report describes subsequent stages of this type of a translation process. It consists of three major Parts. Part 1 outlines a general logic used in designing decision support systems for the test regions. It describes general methodological aspects, steps of the design process, and also the underlying analytical framework. The process of design is viewed in this Part as based on gradual concretization of the initial description of the region and problems of concern into a compressed formalization implementable in the form of computer software. One aspect of the methodology is the use of auxiliary simplified models of the basic natural interrelationships and processes involved. Some principles and procedures for the development of such models are also indicated in Part 1.

Parts 2 and 3 are directly related to the test regions of the project: the agricultural region of Southern Peel in the Netherlands, and the open-pit mining region of Lusatia in the GDR. These regions and their problems related to water resources are represented there to more detail. Structures of the respective decision support systems are also described there together with illustrative examples of their applications.

The Report is supplemented with a number of publications giving more detailed coverage of important aspects of both studies. These publications are used as references in the Report.

PART 1

LOGIC OF DESIGN

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in collaboration with

Y. Nakamori

PART 1. LOGIC AND ASPECTS OF DESIGN

1.1 Introduction

This Report focuses on the design of decision support systems as tools for the analysis of a regional water policies in two concrete regions.

A region means a certain territory. And boundaries of a region as an object of study can be chosen using different formal and informal principles and considerations. In more physically oriented studies a region as an object of study may be "cut off" from the surrounding territories along some physical boundaries, for instance, boundaries of a river basin catchment area, boundaries of a closed aquifer, etc. In studies focused more on policy analysis aspects, it is sometimes more convenient to consider certain administrative boundaries. A region may also be defined basing on many informal historical, organisational, political and other considerations. Very frequently the availability of data plays a significant role.

The available knowledge about any region is vast and much of it lies beyond the scope of a concrete study. Using this diverse knowledge quite different "portraits" of the region can be drawn depending on the purpose of the study. Figuratively speaking we can look at the region at different angles and have its different images. All these images are, of course, true in their own sense, but what we need is a "portrait" that is suitable and convenient for our concrete problem-oriented study, containing at the same time as little irrelevant details as possible. Having such a "portrait" that may have a form of a verbal description, diagrams, etc., we can proceed with formalizing further a structure of the decision support system to be designed.

This structure and its constituent mathematical models and computational procedures may be very different depending on their planned utilization. Therefore, besides the above-mentioned portrait of the region we should have a more or less clearly pictured logic (concept) of the analysis to be performed using the system designed. This concept of the analysis in turn, should be based on the scope of problems in the real region considered because every step of such analysis is in fact obtaining answers to questions pertinent to regional problems.

Such portraying of the region together with the proposed logic of analysis will form a skeleton, to be gradually enriched with more "fleshy" mathematical models and concrete analytical as well as computational procedures.

The following sections illustrate the above points using our test regions as examples.

1.2 Portraying the Region

1.2.1 Impact diagram (Physical system)

Given a concrete region of the type illustrated in Figure I.1 and having in mind regional environmental and other concerns the following questions should first of all be clarified:

- what economic sectors in the region make the most significant impacts on regional water systems and through them on other parts of the environment,
- what are activities of these sectors that make the greatest impacts,
- how or rather through what natural processes do these impacts take place,
- what parts of natural systems are affected by these impacts, and what are negative feedbacks of these impacts on the economic sectors themselves as well as on the quality of life in the region.

The answers to all these questions can conveniently be depicted in the form of an ***impact diagram***, that is in fact the first more or less formal representation (model) of the region under study.

For illustration we briefly outline impact diagrams of the two test regions of this study. More detailed descriptions are presented in the respective Parts 2 and 3 of this Report.

Agricultural region of Southern Peel, Netherlands. The agriculture in this region is considered as the dominant economic sector both in its economic value and also in its environmental impacts. The impacts of agriculture on the natural water system may, of course, vary from region to region. They depend on the climate of the region, on its hydrogeological characteristics, on the degree and the orientation of its agroeconomic development, and many other factors. But the following two aspects of these impacts pertaining to the Southern Peel region are virtually common to most types of agricultural regions.

The first aspect is that agriculture uses water as the resource needed to sustain its development. This causes depletion of groundwater and surface water resources and negatively affects the availability and quality of water for natural ecosystems as well as for other regional economic activities.

The second aspect of agricultural impacts on the regional environment is that agriculture is a major source of contamination of surface water and/or groundwater systems owing to the application of animal wastes, artificial fertilizers, pesticides and insecticides. Fractions of these substances are either washed out into rivers, lakes and other reservoirs, and/or are leached into groundwater. Through these systems contaminants reach other sometimes distant parts of the region, where they can negatively affect the quality of water used for drinking and for other purposes and also harm natural ecosystems. These impacts are of major concern in the Southern Peel region.

Apparently, the natural processes responsible for the "transfer" of the agricultural impacts throughout the region depend to a great extent on the structure of the regional water system, and in particular, on the relative influence of its surface water and groundwater parts.

Besides agriculture, public water supply should also be considered as the major economic sector of the Southern Peel region primarily due to the concerns in the region about possible deterioration of quality of drinking groundwater due to the agricultural impacts.

Figure 1.2.1 illustrates the resultant impact diagram that "portrayed" the physical part of the Southern Peel region and formed the basis for the subsequent design of the decision support system.

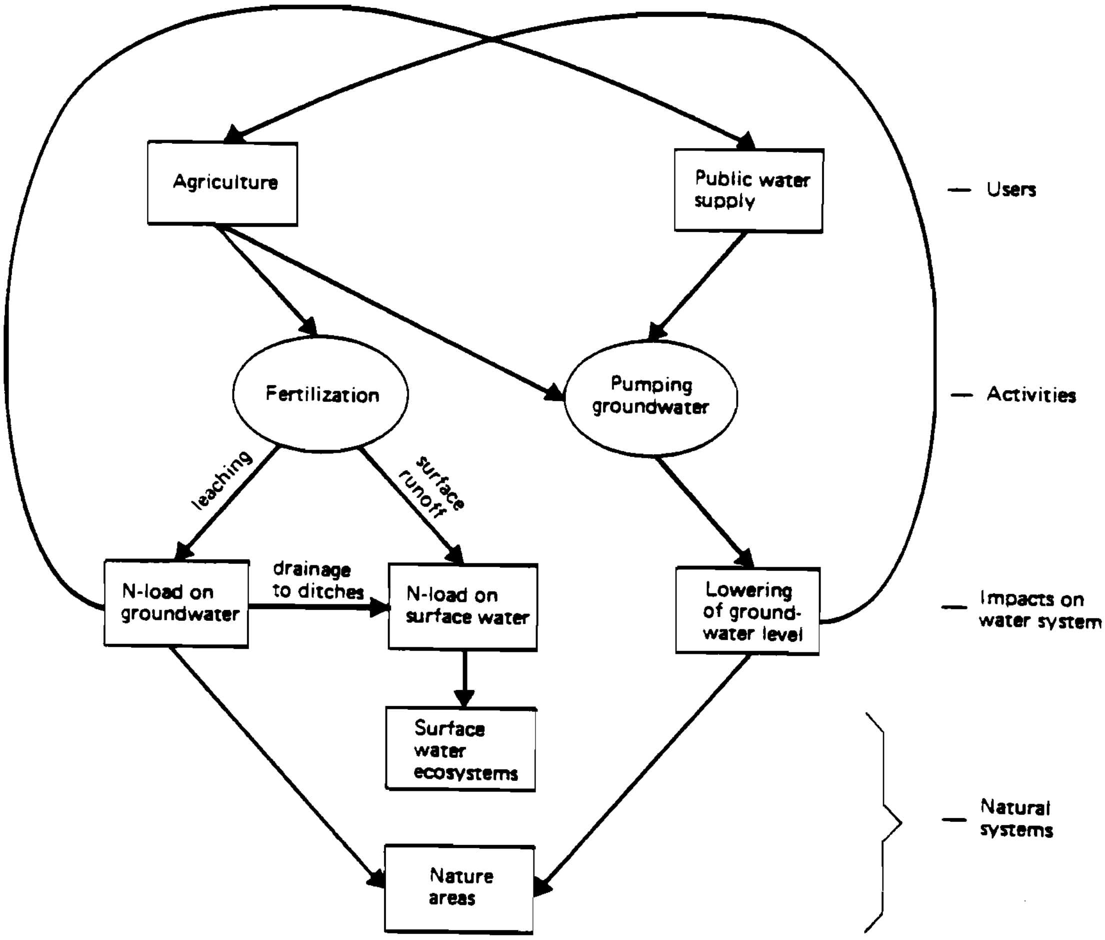

Figure 1.2.1: Impact diagram for Southern Peel region

Open-pit lignite mining region of Lusatia, GDR. Open-pit lignite mining is the dominant economic sector in this region as in all lignite mining regions in the GDR due to the importance of lignite as the basis for energy production. Major impacts of lignite mining on the environment are caused by the necessity to pump huge volumes of water for mine drainage.

This dewatering results in the formation of regional groundwater depressions and consequently in extensive changes in regional hydrological regimes as well as in conditions for water resources use and management in the region and frequently beyond its boundaries. In regional river basins losses of surface water due to the increased infiltration caused by mine dewatering reduce the water availability for downstream water users and necessitates increased groundwater pumpage for dewatering of the lignite mines. Significant alterations of natural groundwater recharge are caused by the extensive changes of the landscape and ecological conditions in open-pit mining areas.

Significant lowering of groundwater tables in the region cause deficiencies in the moisture supply to agricultural crops (and other vegetation) through capillary rise, and also causes difficulties with water supply from wells.

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

In lignite mining areas the groundwater quality and consequently the quality of mine drainage water as well as the water quality in remaining pits are 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 highly acidic. Consequently, the acidity of the groundwater increases. In the post-mining period the same effect is caused by the raising of groundwater table and the leaching of acid products.

Besides mining, industrial and municipal water supply as well as agriculture should be considered as major water users significantly affected by the mine drainage. The impact diagram depicting these interrelationships is shown in Figure 1.2.2.

An impact diagram portrays mostly physical aspects relevant to the scope of regional concerns motivating the study. And as we remember these concerns were focused on measures to be taken to reduce the existing and anticipated environmental and economic impacts in the region. These measures were meant to cause changes in the existing, anticipated, or planned agricultural, mining, and other regional economic practices. But then the question arises ***who makes what changes and why***? To analyse this question we should look into the socio-economic structure of the regional system.

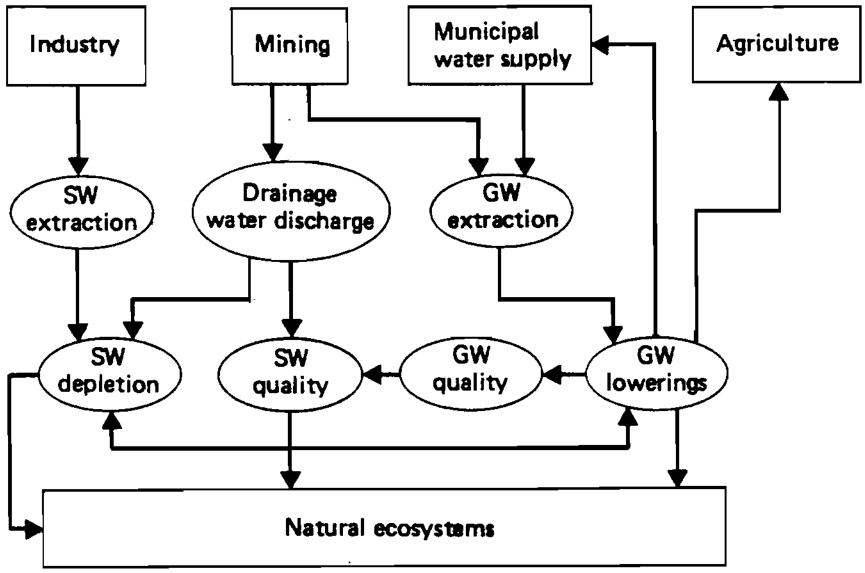

Figure 1.2.2: Impact diagram for the open-pit mining region of Lusatia, GDR

1.2.2 Hierarchy of regional decision makers

The basic elements of the regional socio-economic structure are interdependent decision makers: farmers, various regional and governmental agencies, ministries or their departments, etc. All these decision makers have different preferences and possibilities for action and they interact with each other in a complex way. The knowledge about this system is important for designing a decision support system. As with the physical part of our regional system this knowledge may be vast and multiaspected and we should try to omit unnecessary details and find a concentrated and simplified representation of the regional socio-economic system that is more focused on the scope of problems of our concern.

It is also important at this stage to identify our "client", or, a decision making unit of this structure for which we are designing our decision support system. Different decision makers may have different perspective views on the regional development and therefore face quite different problems. Consequently, decision support systems for them may have different structures (or designed to answer different types of questions). A decision support system for a farmer or for managers of an industrial enterprise may be different from a system for a regional water commission, or for a governmental agency.

One important aspect of the socio-economic part probably of any economically developed region is its inherently *hierarchical structure*. This hierarchy exists due to different types of decisions considered by different decision makers in the region, and it is possible to consider in this hierarchy two major classes of decision makers that we refer to as *upper-* and *lower level decision makers*. This classification is, of course, relative in character, and, to a certain degree depends on a concrete socio-economic system considered, and in particular, on the choice of a decision making unit to be considered as our "client".

The upper level decision-makers may include various types of regional (and/or national) governmental agencies (organisations) whose preferences and responsibilities presumably more closely reflect the integral regional economic and environmental perspectives. The upper level decision makers themselves may be interlinked in a complex hierarchical structure. But common to all of them is that usually they do not directly control all choices of decisions by the lower level decision makers, but may have varying degrees of regulation power (depending on the particular region) for influencing these choices indirectly using economic, legislative, and other types of policies. The feasibility of various regulation policies depends of course on the political and socio-economic system.

For the Southern Peel region in the Netherlands, for example, as the upper level decision makers we should consider the Regional Water Board (a department of the provincial government), departments of some ministries of the central government involved in regional water management such as ministries of public works, of agriculture and fisheries, of welfare, health and cultural affairs, of housing, physical planning and environment. Policies that may be considered as decisions of these agencies may include such measures as regulating extractions of groundwater, fixing prices for water, imposing taxes on the application (and/or production) of manure, etc.

For the open-pit mining region of Lusatia, a part of the centrally planned economy of the GDR, the upper level decision maker considered is a form of a Central Planning Authority. In choosing its decisions this Authority reflects preferences of the respective ministries, national preferences, and also overall regional environmental concerns. Its policies may include fixing prices for water, subsidizing water supply, introducing penalizing measures for polluting water systems, fixing standards for water quality, and others.

The lower level decision makers (or users of the environment) are assumed to interact directly with the environment. These interactions depend upon production and other technologies (or, generally, the environment use technologies) implemented by these users, and they apply them according to their preferences. For an agricultural region like the test-region of Southern Peel in the Netherlands, as an example, the lower level decision makers may include individual farmers and public water supply companies. Their decisions mostly concern choices of land use practices, irrigation and water supply, the use of animal wastes and chemical fertilizers, etc. For a region with large scale open-pit mining like the test region of Lusatia, in the GDR, the lower level decision makers may include regional boards of mining enterprises, of industrial plants, of public water supply agencies, cooperative farmers. Their decisions concern choices of technologies of mine drainage, of managing remaining pits, various alternatives and schedules of water supply, waste water treatment, etc.

The important fact here is that decisions of these lower level elements are primarily focused on their specific goals, and often are not coordinated with each other and do not fully (if at all) reflect integral regional environmental and economic concerns, as long as this coordination and reflection are not ensured by policies of the upper level decision making elements.

This hierarchy of the lower and upper level decision makers is reflected also by a specific sequence of their decision making. The upper level elements choose their decisions (policies) and inform the lower level elements about them. The latter respond by making their own decisions. This two-step sequence can of course be iteratively repeated, for instance, when regional or governmental agencies try to make adaptive changes in their regulations.

Clearly, the hierarchy of decision making elements and decision processes in a region is far more complex, and no formal description can encompass all its aspects. What we need at this stage is a representation of this system that is simple enough for further analysis, and yet reflects its most essential hierarchical aspects.

Having this in mind, we use in the contexts of our two test regions a simple two-level hierarchical representation of a regional socio-economic (decision making) structure, illustrated in Figure 1.2.3.

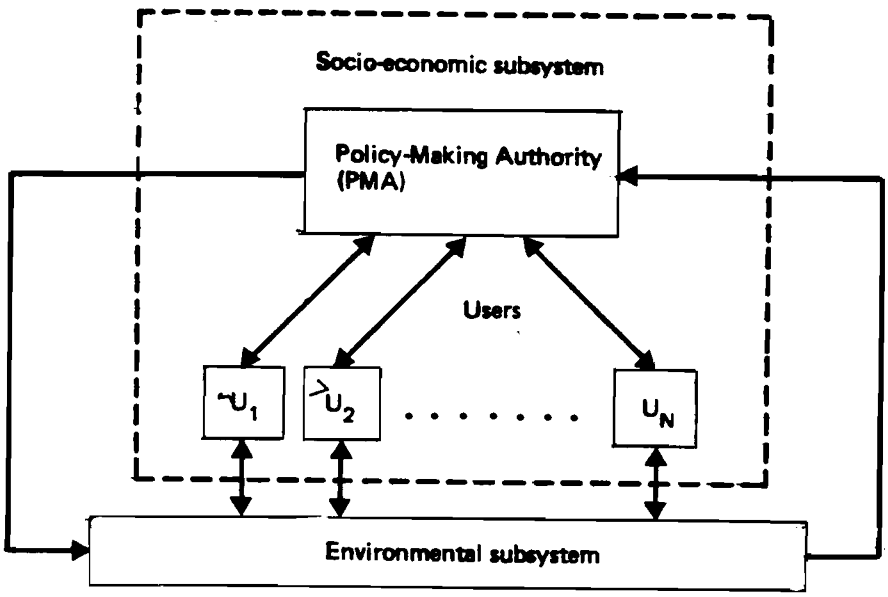

Figure 1.2.3: Two-level hierarchy of regional decision makers

According to this scheme we consider only one upper level decision maker that we refer to as the Policy Making Authority (PMA). Clearly, by the PMA we understand not a single agency but rather a surrogate for a number of agencies at national and/or regional level which (1) have an interest and responsibility in the development of the region in question and (2) have regulatory power that can influence this development. Of course, these agencies do not have the same objectives, therefore, the single PMA concept is an obvious first approximation. But this approximation can be a useful starting point for further research in this direction using more comprehensive institutional models and analytical procedures.

Having thus formalized the structure of the regional decision making we can proceed with outlining a more concrete (and therefore, necessarily also formalized) scheme of decision making in this structure. Rather than trying to capture the most general case, we use a simple illustrative scheme.

Let us consider a system similar to that in Figure 1.2.3 but with only two lower-level decision makers DM1 and DM2 (see Figure 1.2.4).

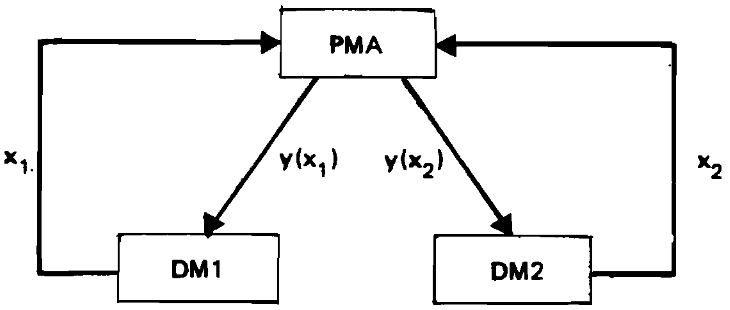

Figure 1.2.4: Illustrative diagram of decision making process

We denote by x_1, x_2 variable choices by DM1 and DM2 respectively and by y we denote choices of the PMA. Values of x_1 and x_2 for example, may have the meaning of amounts of water for irrigation, associated with the uses of certain production technologies. Values of y may have the meaning of prices on water fixed by the PMA.

We assume for simplicity in this example that the objective of the PMA is to obtain higher possible values of some function $F(x_1,x_2,y)$ which may be meant to reflect varying quality of the regional environment. We also assume that the sequence of decision making is fixed as follows: first the PMA makes its choice of a value of y (fixes price) and informs about this choice DM1 and DM2. In turn, DM1 and DM2 knowing the value of y respond with their own choices of x_1 and x_2 respectively. This scheme can be made more adequate to many real cases if we assume that the PMA can choose and communicate to DM1 and DM2 polices of the type $y(x)$, or, in other words, it can make its choices conditioned by choices of DM1 and DM2. Using the above interpretation of y (price) a policy $y(x)$ can mean, for instance, progressive pricing depending on the actual amounts of water used by lower level decision makers. Other interpretations are of course possible.

With the policy $y(x)$ chosen by the PMA our decision makers DM1 and DM2 will have to pay respective amounts $y(x_1) \cdot x_1$ and $y(x_2) \cdot x_2$ for their choices of x_1 and x_2. The problem faced by the PMA is to determine an appropriate policy $y(x)$ that would result in higher possible (satisfactory) values of function F introduced earlier. But values of this function depend also on choices by DM1 and DM2. Therefore, to be able to choose rationally a policy $y(x)$ the PMA should use whatever knowledge it has (or can obtain) about possible responses of DM1 and DM2 to choices of policies $y(x)$. Clearly, the better this knowledge the better prediction of responses of DM1, DM2 can be made resulting in a choice of a more efficient policy $y(x)$ by the PMA.

Sure enough, in situations even a little bit more realistic that the above example the goals of the PMA are far more complex than just obtaining higher possible values of a single function, and the analysis in such cases becomes more involved.

An accurate formalization and analysis of even this simplified structure requires explicit consideration of preferences and actions (responses) of all the decision makers involved. Examples of this type of formalization and of their analyses based on concepts of the hierarchical game theory can be found in Germeyer 1976*; Ereshko and Vatel 1977. This theory gives a clear understanding of the nature of various types of regulation policies and respective decision processes and is very helpful in structuring the analysis of socio-economic systems.

Two important aspects of the decision making procedure illustrated by the above example should be underlined here. First, analyses of situations with a number of decision makers may be different depending on from which decision maker's viewpoint the analysis is performed. In the above example

*)The basic concepts and methods of the hierarchical game theory were developed by the group led by the late Professor Y.B. Germeyer at the Computing Center of the USSR Academy of Sciences. Unfortunately, no descriptions of these concepts and methods exist in the English scientific literature. An English translation of the book by Germeyer "Games with nonantagonistic interests" is planned for publication in 1986 by Reidel.

we reasoned from the viewpoint of the PMA since it represented the regional concerns which are the focus of our study.

Second, in making choices of policies the PMA has to consider possible responses of the lower level decision makers. Because of the obvious impossibility to formalize precisely these responses always involving a human element, choices of the PMA have always to be based on more or less adequate hypotheses about these responses and are therefore of subjective nature. In other words, no "objectively optimal" policies can be found in socio-economic systems.

Having in mind the above two aspects, in designing the decision support systems we picture the analysis to be performed using these systems from the viewpoint of the upper level regional decision maker PMA, and understand the PMA as a major future user of the decision support system systems under design. Since preferences of neither PMA, nor lower level decision makers can be modeled precisely, no rational regional policies can be found automatically without the participation of the PMA in this process. Therefore, the system designed should be not an automatic solver substituting the PMA, but rather an interactive decision support giving the PMA opportunity to effectively participate in the process of analysis itself.

1.2.3 Schematic of regional problems

Having already chosen schematized representations of the "physical" and socio-economic parts of a region we can now make a further step in our design process and picture more precisely an overall problem to be studied using the decision support system that we have in mind.

At any stage of its development a regional system can be represented by values of various characteristics of different nature. The specification of these characteristics is determined, of course, by the goals of the study and is to a certain extent already indicated by the impact diagram and by the hierarchical representation of interrelationships between the regional decision makers accepted earlier.

Since the projected use of the decision support system by the PMA includes the analysis of alternatives of future development of the region in time it is convenient to view the regional system as a dynamic control system, and classify for this purpose the characteristics representing the region into the following three categories exemplified in Section 1.4.1:

- *control variables*: related to those aspects of the regional development that can be changed directly by the decision makers when necessary.

- *uncontrolled parameters*: related to those aspects or characteristics that change in time but cannot be controlled by the regional decision makers and are "chosen" by nature, or determined by exogenous factors.

- *state variables*: related to those regional aspects which undergo changes resulting from changes in controlled variables and uncontrolled parameters.

A collection (vector) of values of state variables related to a certain time can be referred to as the state of the regional system at that time, and we can understand any pattern of the regional development as a sequence of changing states in time and refer to such sequences as trajectories of the regional development.

Different policies chosen by PMA (and subsequent decisions by the lower level decision makers) may lead to different regional trajectories. Speaking about rational policies we have in mind that the PMA has certain preferences with regard to these trajectories which enable the PMA to compare them with each other. These preferences are based on multiple economic, environmental, social, and political concerns and can never be fully formalized even by the PMA itself. On the other hand, some more apparent quantitative aspects of these preferences can be included into the decision support systems designed to assist the PMA in the process of analysis. This can conveniently be done by introducing ***indicators*** quantifying relevant economic and environmental aspects of a regional trajectory (performance).

To be able to use these indicators for comparing the "goodness" of various policies for the PMA we should have provisions in our system for projecting trajectories of future regional development invoked by different optional policies. And this in turn can be based on mathematically formalized relationships between uncontrolled parameters, as well as control and state variables chosen to characterize regional development in time. In other words, we shall need in our system interlinked mathematical descriptions (models) of various relevant processes indicated in the impact diagram. As has been said earlier, some formalized hypotheses about possible responses of the lower level regional decision makers should also be included.

Using such formal descriptions we could in principle formulate mathematically relevant hierarchical dynamic control problems and incorporate procedures for their analysis into our decision support system. But if we take into account the complexity of the interlinked natural processes, the difficulties of formalizing preferences of the PMA and of projecting responses of lower level decision makers and also multiple uncertainties related to quantification of uncontrolled parameters then it becomes clear that such straightforward formalization of the overall problem would be untractable using practically implementable analytical and computational methods.

To obviate these difficulties we look at the overall analysis as decomposed into two stages. This decomposition is described in the next section.

1.3 Scheme of Analysis: Two-Stage Decomposition

To summarize the above description we can visualize the type of an integral problem faced by the PMA as follows: to find policies which through complex dynamic interrelationships between natural processes and responses of the lower level decision makers would induce satisfactory (from the viewpoint of the PMA) trajectories of the regional development originating from the present state of the region.

By the decomposition of this problem we mean its analysis in two subsequent stages: stage one - ***scenario analysis***, stage two - ***policy analysis***.

At the first stage, the analysis aims at determining a trajectory (scenario of future regional development) that appears satisfactory to the PMA in its economic, environmental and other aspects. No behavioural aspects (responses) of the lower level decision makers are explicitly considered at this stage, and in the course of this analysis the PMA can to a certain extent "play" freely with the control variables many of which in the context of the overall problem are controlled by the lower level decision makers. As a result of this analysis the PMA determines a potentially rational trajectory of future regional development that is based on trade-off's among goals of economic sectors, regional interest groups and is satisfactory environmentally, economically, and in other aspects of interest to the PMA. A more detailed description of the problems and methods involved is given in subsequent sections.

After having determined a satisfactory trajectory the *second stage* of analysis (by, or on behalf of, the PMA) is concerned with the search for those feasible regulation policies that influence the behaviour of the lower level decision makers and by doing that can direct the development of the region along or close to the trajectory determined at the first stage.

Since the first stage of the analysis is performed without explicitly considering feasible polices, the trajectory of the regional development obtained at the first stage may be practically unattainable. In other words, the result of the second stage analysis may be that no one of the feasible policies of the PMA may provide for the realization of this trajectory. In such cases, the analysis will have to come back to the first stage to search for another probably "less ideal" trajectory that is attainable using some of the feasible policy devices. (Moreover, feasible policies may differ from each other by the public reaction to their implementation). Recognizing this factor, environmentally and/or economically less effective trajectories may have to be considered that may be achieved using those "more popular" regulation policies. Schematically, this decomposition analytical procedure is illustrated in Figure 1.3.1.

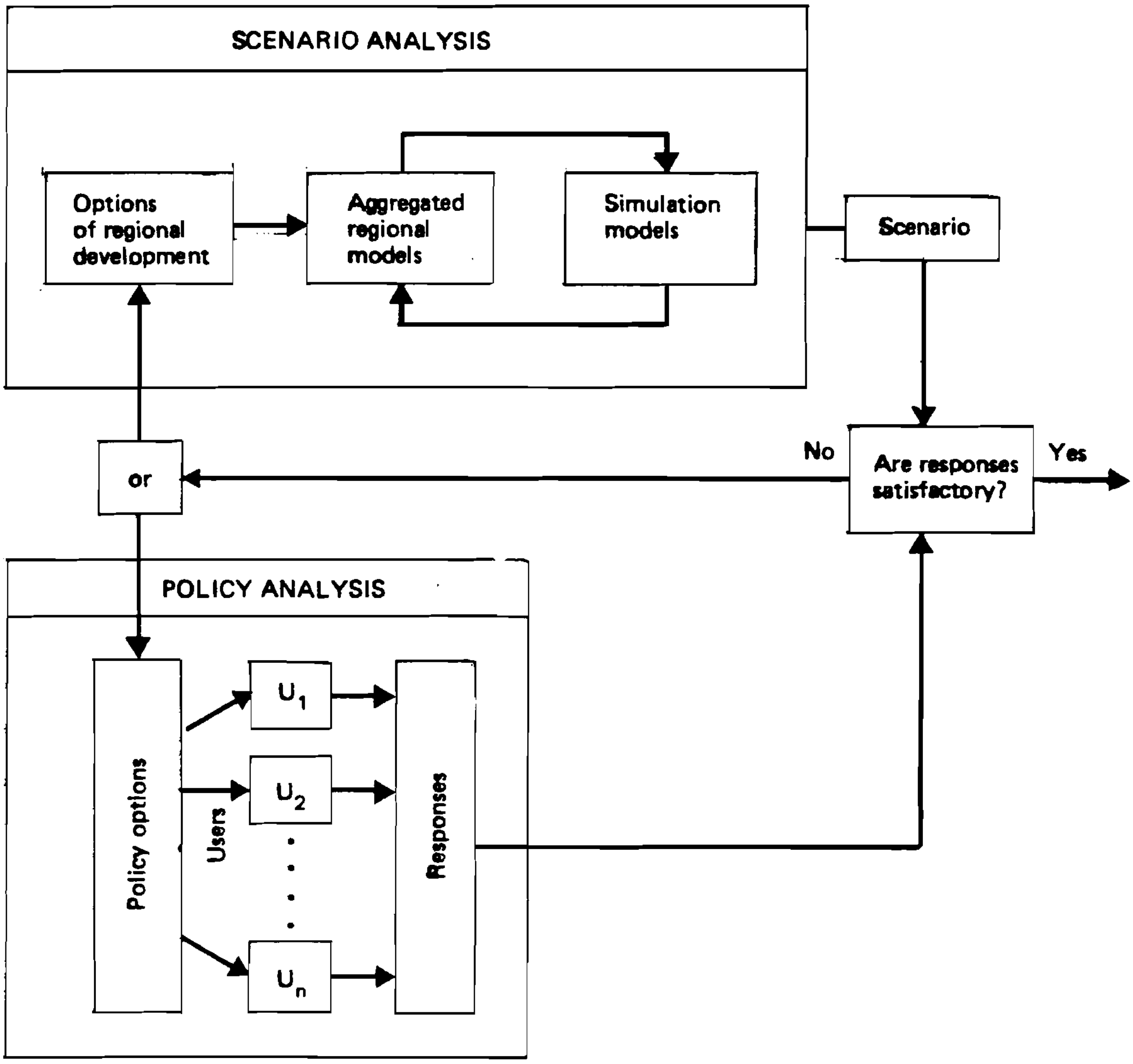

Figure 1.3.1: Schematic of two-stage decomposition

1.4 Scenario Analysis

The structure of a system for scenario analysis should reflect our vision of the scope of problems to be addressed by this analysis. To choose this structure we should first accept a certain formal representation of these problems and then try to find the means for their analysis using practically implementable mathematical models and corresponding computational algorithms. This section indicates major steps of such a process.

The framework outlined in this section underlines the designs of the scenario generation systems for the two studies described in this report. These studies although related to different regions have many common methodological, modeling and analytical aspects, and we outline these aspects here leaving the description of more concrete details to Parts 2 and 3.

1.4.1 Generic integral formulation

In this section we outline a general integral formulation of the problem addressed by the scenario analysis. Besides representing the underlying logic this formulation is used further as a guidance in the elaboration of concrete models and analytical procedures implemented in our decision support systems.

Scenario analysis is based on formalized descriptions (models) of various natural and economic aspects and processes in the system. These processes may have different characteristic times which should be taken into consideration in the structure of analysis. Of course, natural processes, in particular, evolve continuously, but having in mind computational necessities we have to accept their description in a discrete form. The choice of time intervals for such a description depends on a number of considerations such as the nature of the processes themselves, the required degree of detailization of the analysis, models available, computational possibilities, and others. An important consideration are frequences of different types of decisions typical for the region. Basing on similar considerations, we also need to assume a certain spatial discretization of the processes considered.

We consider two types of decisions in our formulation:

- relatively frequent (short-term) operational (or managerial) decisions used to adapt regional performance to changes in weather conditions, in water demands, in market prices, and other exogenous factors;
- less frequent (long-term) planning decisions related to certain structural and major technological changes in the region.

These two types of decisions are exemplified below. In accordance with these two types of decisions we number by τ minimal characteristic time intervals related to operational decisions (days, decades, months), and by t – characteristic time intervals related to economic and technological planning decisions in the region (years or longer periods). We denote by M the number of intervals τ in an interval t.

Following the dynamic description of the regional processes indicated in Section 1.2.3 we introduce the following vectors related to time intervals τ and t and with components related to different discretized parts of the region:

s^τ – *vector of values of state variables* such as:

- groundwater tables,
- soil moisture,
- actual evapotranspiration,
- surface water flows,
- concentrations of pollutants in groundwater and surface water,
- economic characteristics of relevance,

u^τ – *vector of values of operational control variables*, such as

- irrigation rates (sprinkler, subirrigation) from groundwater and surface water for various crops,
- application of different types of fertilizers to different crops
- municipal, industrial and other water supply,
- yields of water from reservoirs,

x^t – *vector of planning control variables*, such as

- areas of land-use technologies,
- intensities of other technologies,
- various types of irrigation, manure storage and other capacities,
- surface water supply capacities,
- capacities of water treatment plants,
- mine drainage water allocation.

ξ^{τ} – *vector of uncontrollable parameters*, such as

- precipitation,
- ambient temperature,
- inflows of water into rivers,
- water demands.

The relationships between these variables and parameters reflecting various economic and natural aspects and processes in the real system can be schematized in the following form:

$$s^{\tau} = B(s^{\tau-1}, u^{\tau}, \xi^{\tau}, x^{t}) \text{ , } \tau = 1,2 \text{ , } \ldots \text{ ,} \tag{1.4.1}$$

It is assumed that for the purpose of our analysis these relationships based on τ as the minimum time interval represent sufficiently detailed descriptions of economic and natural aspects and processes. For reasons that will become clear later on, we refer to them as simulation models. A number of approaches to their development are outlined in Section 1.8 of this Report, and the simulation models used for the respective studies are described in Parts 2 and 3 as well as in accompanying papers.

Time-varying operational decisions u^{τ}, planning decisions x^{t} and uncontrollable parameters ξ^{τ} would through relationships (1.4.1) generate trajectories $\{s^{\tau}, \tau = 1,2 \text{ },\ldots\}$ originating from a given initial (present) state s^{0}.

Since our analyses are to be based on the use of computational algorithms we cannot deal with trajectories of infinite duration (and it is hardly possible that a user of our system would wish to consider such trajectories). Therefore, in our subsequent formulations we use notation T for the number of time intervals t in the time horizon considered (which does not imply that we will always use an *a priori* fixed value of T.

Following our discussion in Section 1.2.3 we can introduce indicators reflecting concerns of the PMA and providing for quantitative (partial) comparisons of various trajectories with each other. Depending on the problems of concern in a region such indicators may reflect:

economic and technological aspects, such as incomes of the regional producers in different years, total costs involved in changes of allocation of production in the region, costs of mine drainage and water supply, satisfaction of water demands, investments into pollution abatement measures, and others.

Environmental aspects, such as

- groundwater tables in various parts of the region,
- quality (concentrations of contaminants) of groundwater in various parts of the region,
- quality of surface water in various parts of the region.

Different indicators may be used for the evaluation of trajectories on different temporary scales. For instance, groundwater tables may be of interest every month, the net income of the regional agricultural producers may be evaluated on a yearly basis, investments may be evaluated over a longer period of regional development, etc. Leaving these details for more concrete descriptions in the subsequent parts of this Report we will denote such indicators by

$$\varphi_i(s^\tau, u^\tau, \xi^\tau, x^t \mid \tau = 1,2, \ldots, M \cdot T;$$

$$t = 1,2 \cdots T;\ \tau \geq (t-1) \cdot M),\ i = 1, \ldots, n \quad .$$

Without a loss of generality we can assume that higher values of all these indicators are more preferable to the PMA.

In this formalization we should also take into account that not all values of control variables can be considered as feasible. For instance, we must have in mind that total area of land allocated to crops cannot exceed the area of arable land in the region, that water balances in various parts of the region cannot be violated, etc.

This type of considerations can be reflected using systems of appropriate *constraints* of the form ($\bar{\psi}$ - vector function):

$$\bar{\psi}(s^\tau, u^\tau, \xi^\tau, x^t) \leq \bar{0};\ \tau = 1,2, \ldots, M \cdot T;\ t = 1,2, \ldots, T; \qquad (1.4.2)$$

$$\tau \geq (t-1) \cdot M$$

and in the analysis of alternative decisions we should see to it that these constraints are not violated.

To complete this formulation we should concretize the following *informational assumptions* concerning uncontrollable uncertain parameters ξ^τ, and also the different time-scales of the planning control variables x^t and the operational control variables u^τ. For the types of problems considered in our studies we assume that choices of planning decisions x^t are based only on whatever knowledge we have at the time of analysis about future (and the past) values of parameters ξ^τ, whereas choices of the actual values of operational controls u^τ can be made operationally basing on concrete realizations of values of ξ^τ in the future. This last point means that at the time of analysis we have the opportunity to consider as choices not fixed values of u^τ, but operational rules $u(s^{\tau-1}, \xi^\tau, x^t)$ according to which these values can be adaptively determined at subsequent times in future when actual values of ξ^τ become known (observed).

Now we are in a position to offer the following formal picture of the generic mathematical problem of the scenario analysis stage:

Problem I

given a system of state equations (simulation models):

$$s^\tau = B(s^{\tau-1}, u^\tau, \xi^\tau, x^t), \quad \tau = 1,2, \ldots, M \cdot T;$$

$$t = 1,2, \ldots, T; \quad \tau \geq (t-1) \cdot M$$

and the constraints:

$$\bar{\psi}(s^\tau, u^\tau, \xi^\tau x^t) \leq \bar{0}, \quad \tau = 1,2, \ldots, M \cdot T; \quad t = 1,2, \ldots, T; \quad \tau \geq (t-1) \cdot M$$

determine feasible values of planning control variables x^t and operating rules for values of operational control variables u^τ,
such that the corresponding trajectory generated through the state equations is characterized by satisfactory (higher possible) values of the indicators

$$\varphi_i(s^\tau, u^\tau, \xi^\tau, x^t \mid \tau = 1,2, \ldots, M \cdot T; t = 1,2, \ldots, T;$$

$$\tau \geq (t-1) \cdot M)\ ,\ i = 1\ , \ldots ,\ n \quad .$$

In fact, two versions of this generic formulation underlie the two studies of this project. In the study related to the open-pit mining region of Lusatia, GDR the time horizon T is considered as *a priori* fixed basing on exogenous technological and economic aspects of the development of the region. In the study related to the agricultural region of the Southern Peel, Netherlands, the time horizon is a variable considered as one of the indicators of trajectories and its smaller values are preferred. These aspects are considered to more detail in the respective Parts of this Report.

The formalization of the generic Problem I outlined is a more or less concentrated integral description of what we have in mind for the scenario analysis, but it is not tractable using existing computational methods. Its state equations based on relatively short time intervals τ contain an overwhelming number of variables and the relationships involved are very complex. The problem is also methodologically and computationally complicated by the presence of uncontrollable parameters with future values unknown, as well as by the necessity to make rational choices of the values of control variables comparing multiple indicators. Of course, there always exists the possibility of selecting satisfactory controls by trial-and-error simulation techniques, but the computational efforts required will almost certainly be enormous.

To make the necessary computational effort reasonable we apply in our studies a heuristic approach that has long become a common practice in systems analytic design. This approach is outlined in the next section.

1.4.2 Two-level decomposition of scenario analysis

Guided by the above generic formulation of Problem I we implement in our scenario generating systems the following analytical procedure that includes two major iterative parts and is based on a hierarchy of models of different complexity. Using the simulation models (represented by state equations in Problem I) we formulate their simplified prototypes that involve as major elements only planning control variables x^t and appropriate aggregates η^t of uncontrollable parameters ξ^τ. We use systems of such simplified models together with interactive (semi-automatic) procedures of multiobjective analysis for preliminary relatively fast *screening* of feasible planning decisions in order to determine those sequences of them which in some sense deserve more detailed further evaluation. Accordingly, we call these simplified models *screening models*.

The more detailed evaluation of the planning decisions x^t is the second part of the procedure and is performed using the simulation models which describe the processes involved on finer temporary and spatial scales (state equations in Problem I, Section 1.4.1). Besides the values of planning decision variables obtained in screening analysis, these models are "fed" with sequences of values ξ^τ of uncontrollable parameters taken from their past observations and/or statistically generated. The required disaggregated values u^τ of operational or managerial control variables are generated in the process of simulation using appropriately (heuristically) fixed operating rules, e.g. of the form $u^\tau = u(s^{\tau-1}, \xi^\tau, x^t)$. Trajectories emerging through this simulation process are evaluated in terms of the quantitative indicators introduced in Section 1.4.1 (Problem I). Such evaluations obtained for varieties of sequences of (exogenous) uncontrollable parameters ξ^τ provide the necessary statistical evidence about the acceptability of the corresponding sequences $x^1, \ldots, x^T$ of the planning control variables.

In cases when these evaluations indicate that the planning control decisions tested are not satisfactory the analysis can be repeated starting from its first screening part and taking into consideration the results of the simulation runs.

Schematically this procedure is illustrated in Figure 1.4.1.

As we said before, the first part of this procedure that we refer to as *screening analysis* is based on the use of simplified models of the processes in the systems under study. The major of these are those of groundwater flow and of interactions between groundwater and surface water systems, as well as of crop growth, and other processes. Because in this framework we use the results of the simulation runs as *the final analytical evidence*, the aim of the first part of this procedure is to determine values of the planning control variables having higher possible

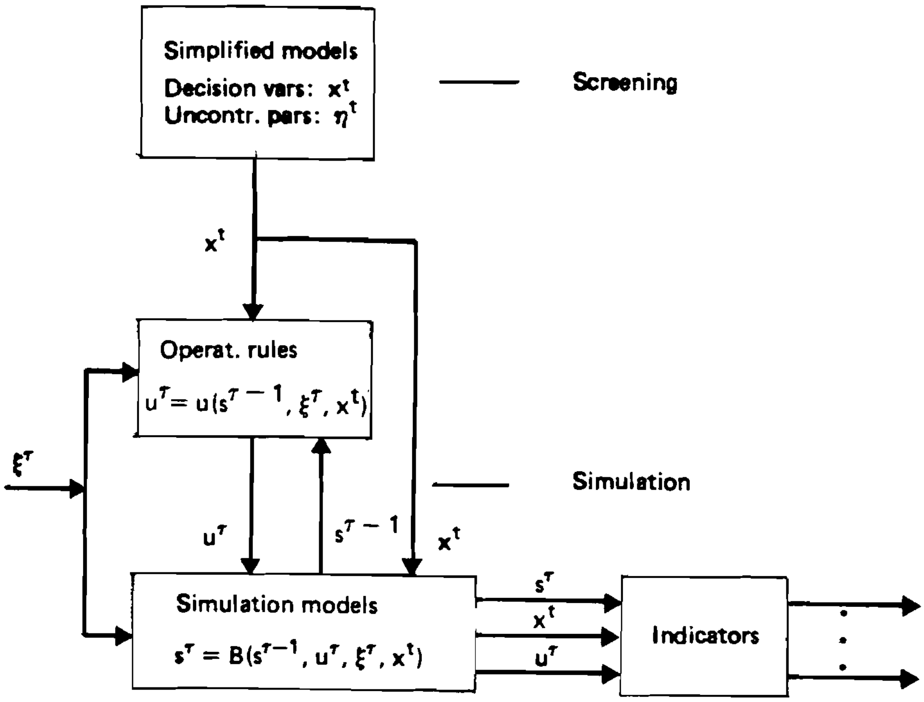

Figure 1.4.1: Schematic of scenario analysis

chances of producing satisfactory results in these simulation runs. In this respect, the way of obtaining simplified versions of the basic models plays an important role and deserves separate discussion. But to maintain the continuity of our presentation we postpone discussion of the corresponding simplification methods and computational procedures used in our two studies until Section 1.8 and focus here on the basic aspects of the screening analysis.

1.5 Screening of Planning Decisions

1.5.1 Generic formulation

The generic problem underlying the screening analysis and based on the use of simplified models can be formulated in the following form of multiobjective mathematical programming:

Problem II:

$$\Phi(x^1, \ldots, x^T ; \eta^1, \ldots, \eta^T) \rightarrow \underset{x^1, \ldots, x^T}{\textbf{satis}^*} \tag{1.5.1}$$

$$\Psi(x^1, \ldots, x^T ; \eta^1, \ldots, \eta^T) \leq \bar{0} \tag{1.5.2}$$

where

- x^t, $t = 1, \ldots, T$ – vectors of planning control variables for respective time intervals,
- η^t, $t = 1, \ldots, T$ – aggregated uncontrollable parameters,
- $\Phi(\cdots)$ – vector-function of indicators corresponding to indicators in Problem I
- $\Psi(\cdots)$ – vector function of equations and inequalities representing simplified relationships between the variables and parameters (simplified screening models obtained from the basic models) and also requirements which should be satisfied by feasible vectors x^t, $t = 1, \ldots, T$.

The above generic formulation underlies the screening analysis in both our studies and its respective concretizations are discussed in Parts 2 and 3 of this Report. In the following we indicate major aspects of the analysis of this type of problems which are common to both of them.

1.5.2 Uncertain parameters and deterministic formulation

The first aspect of importance in Problem II is the presence in relationships involved of the exogenous uncertain parameters η^t which are not controlled by the PMA and the future values of which are not known at the time of the analysis. The only information available about them is based on past observations of their values and or on experts judgements, and this information is not sufficient for the unambiguous evaluation of the indicators Φ as well as of the feasibility of choices of controls according to constraints (1.5.2). In such cases a reformulation of Problem II is required that would resolve this ambiguity.

*) Here and thereafter we use symbol "**satis**" rather than the commonly used "**max**" in order to underline that a solution to this problem is one satisfying the PMA.

In many studies sequences of uncertain parameters, are modeled as stochastic vectors or processes having in mind subsequent use of probabilistic methods for the analysis itself as well as for the interpretation of the results. Two major obstacles often stand in the way of such an approach. First, a justifiable application of a probabilistic formulation in such cases is strongly based on the specification of probability distributions for the sequences of parameters modeled as stochastic vectors or processes. In turn, this specification or hypotheses about the necessary probability distributions should be adequately supported by the statistical evidence requiring sufficiently great amounts of observations of these parameters. But the amount of observations is rarely sufficient to justify the use of elaborated constructs of the probability theory.

Second, even if there is enough statistical observational evidence justifying the application of stochastic optimization algorithms for multiobjective analysis the efficiency (speed, in particular) of analysis would often be intolerably low due to the slowness of the existing stochastic algorithms.

Having in mind the above considerations we base our screening analysis on the use of heuristic procedures which, however, can methodologically be supported by viewing our Problem II through the following informal reformulation.

The indicators Φ and constraint functions Ψ in Problem II depend on uncontrollable parameters η^t, the future values of which are assumed to be not known at the moment of choosing controls x^t. Therefore, even for fixed values of x^t we can know not exact values of these functions but only sets of their possible values corresponding to possible future values of parameters η^t. Let us think about these possible values of vectors η^t as realizations of the respective random vector.

Then we can speak about corresponding probabilities of occurrence of values of vector functions Φ and Ψ. If we introduce threshold values Φ_0 of function Φ then we can think in terms of the following probability

$$P_I(x^1, \ldots, x^T, \Phi^0) = \text{Prob}\,\{\Phi(x^1, \ldots, x^T; \eta^1, \ldots, \eta^T) \geq \Phi_0\}$$

or, in other words, the probability that the values of the indicators considered are not lower than the threshold values. This probability of course depends on the values of controls x^t and on the chosen threshold values of the values of indicators themselves.

We can also think in terms of the following probability

$$P_c(x^1, \ldots, x^T) = \mathrm{Prob}\,\{\Psi(x^1, \ldots, x^T; \eta^1, \ldots, \eta^T) \leq \bar{\bar{0}}\}$$

or the probability that the controls $x^1, \ldots, x^T$ are feasible.

Now we can choose some acceptable minimum values of the above probabilities as p_I and p_c respectively and reformulate Problem II into the form:

Problem III

$$[\Phi_0^1, \ldots, \Phi_0^n] \rightarrow \underset{x^1,\ldots,x^T}{\mathbf{satis}}$$

$$P_I(x^1, \ldots, x^T; \Phi_0^1, \ldots, \Phi_0^n) \geq p_I \tag{1.5.3}$$

$$P_c(x^1, \ldots, x^T) \geq p_c \tag{1.5.4}$$

Suppose sequence $x_0^1, \ldots, x_0^T$ is a solution to this problem, and $\Phi_0^{1P}, \ldots, \Phi_0^{nP}$ are the corresponding threshold values of the indicators. Then we can conclude:

1. *Feasibility*: $x_0^1, \ldots, x_0^T$ are feasible with probability not lower than p_c,
2. *Guarantee*: with probability not lower than p_I sequence of planning decisions $x_0^1, \ldots, x_0^T$ guarantees obtaining values of indicators not lower than the respective threshold values $\Phi_0^{1P}, \ldots, \Phi_0^{nP}$,
3. *Satisfaction*: the combination of the threshold values for the indicators considered satisfies the PMA.

An essential point in this formulation is that the choices of planning decisions $x^1, \ldots, x^T$ under conditions of uncertainty are based on compromises not directly among the values of the indicators Φ but among their lower estimates Φ_0 obtainable to a prespecified reliability degree. Clearly, choices of $x^1, \ldots, x^T$ in the above formulation depend on values of probabilities p_I and p_c. The higher these values, i.e., the higher the required degrees of reliability (guarantee) the lower the threshold values of the indicators which can be guaranteed. In this sense probabilities p_I and p_c can also be considered as indicating the quality of choices together with components of the threshold vector Φ_0 in the context of Problem III.

In principle, had we known probability distribution functions for parameters η^t, we could have approached solving Problem III as a deterministic problem of multiobjective choice, since in such a case constraints (1.5.3), (1.5.4) would have been unambiguously specified. But then the forms of these constraints would have been too complex and the algorithmic effort required would have been unjustifiably high taking into account the preliminary nature of the screening analysis.

Having this in mind and also that the screening analysis should be relatively fast we apply a much simpler approach based on the concept of an equivalent deterministic formulation of Problem III. In this approach we take into account that usually in a practice oriented study we do not have enough observations of values of uncertain parameters η^t for constructing their probability distributions. We accept instead that we have a finite number N of possible sequences of values $\eta^1, \ldots, \eta^T$. These sequences may include those observed in the past and also sequences which might have been added to make the collection a sufficiently good representation of possible future realizations of uncontrolled parameters. We denote this finite collection of sequences by E.

Then, rather than dealing with probability distributions as in Problem III, we think "finitely" in terms of p-feasible alternatives defined as follows. A sequence of planning decisions $x^1, \ldots, x^T$ is p-feasible, if the system of inequalities

$$\Phi(x^1, \ldots, x^T; \eta^1, \ldots, \eta^T) \geq \Phi_0$$

$$\Psi(x^1, \ldots, x^T; \eta^1, \ldots, \eta^T) \leq \bar{\bar{0}}$$

holds for at least $N \times p$ sequences $\eta^1, \ldots, \eta^T$ from set E. For an example, 0.8-feasible sequence $x^1, \ldots, x^T$ satisfies the above inequalities for at least 80% of the total number N of sequences $\eta^1, \ldots, \eta^T$ of the set E.

Using this concept we reformulate Problem III as follows:

Problem IV

Given a finite set E of N future possible sequences of values of $\eta^1, \ldots, \eta^T$ find a p-feasible sequence (p with fixed) of planning decisions $x^1, \ldots, x^T$ such that

$$\Phi_0 = (\Phi_0^1, \ldots, \Phi_0^n \longrightarrow \underset{x^1, \ldots, x^T}{\textbf{satis}}$$

and

$$\Phi(x^1, \ldots, x^T; \eta^1, \ldots, \eta^T) \geq \Phi_0 \tag{1.5.5}$$

$$\Psi(x^1, \ldots, x^T; \eta^1, \ldots, \eta^T) \leq \bar{0} \tag{1.5.6}$$

$$(\eta^1, \ldots, \eta^T) \in E$$

As we remember relationships in the form of functions Φ and Ψ were obtained by aggregate simplification of the basic models, and sequences of values $\eta^1, \ldots, \eta^T$ also represent corresponding aggregates of the original uncontrollable parameters ξ^τ. This correspondence should be such that p-feasible planning decisions $x^1, \ldots, x^T$ chosen by solving a problem of the type IV have good chances to pass simulation tests and produce trajectories with satisfactory values of indicators attainable in a percentage of simulation runs close to p.

One of the simplest means of determining solutions to Problem IV is to use its deterministic equivalent formulation based on the appropriately chosen fixed values of parameters $\eta^1, \ldots, \eta^T$. The applicability of such an approach depends on the following reasoning that we illustrate using the following simple example.

Suppose we have inequality of the form

$$\psi(x, \nu^1, \ldots, \nu^m) \geq b \tag{1.5.7}$$

where $x \in X$ is a vector of decision variables and $\nu = (\nu^1, \ldots, \nu^m)$ are uncontrollable uncertain parameters. We also have a finite set E of N possible values of vector ν.

Let us assume that for any $x \in X$ function ψ is monotone with respect to each of ν^i , $i = 1, ..., m$. Without any loss of generality we can assume that ψ is nondecreasing with respect to each of ν^i (if this is not the case for some ν^i we can consider $-\nu^i$ as the corresponding parameter). Then as is easily seen, any $x \in X$ satisfying the inequality

$$\psi(x, \nu_0^1, \ldots, \nu_0^m) \geq b \tag{1.5.8}$$

for some fixed values $\nu_0^1, \ldots, \nu_0^m$ of the parameters satisfies inequality (1.5.7) also for any vector of parameters $\nu = (\nu^1, \ldots, \nu^m) \in E$ such that

$$\nu^1 \geq \nu_0^1, \ldots, \nu^m \geq \nu_0^m \quad .$$

Having this property of function ψ and choosing appropriately values $\nu_0^1, \ldots, \nu_0^m$ (not necessarily one of the vectors from set E) we can assure that any $x \in X$ satisfying (1.5.8) is p-feasible in the above sense, or, in other words, satisfies (1.5.7) for at least $N \times P$ vectors ν from E. To ensure this it is sufficient that $\nu_0^1, \ldots, \nu_0^m$ are such that inequalities

$$\nu^1 \geq \nu_0^1, \ldots, \nu^m \geq \nu_0^m$$

hold for at least $N \times P$ vectors $\nu = (\nu^1, \ldots, \nu^m)$ from set E.

Applying this approach to Problem IV we obtain the following (deterministic) formulation:

Problem V

$$\Phi_0^1, \ldots, \Phi_0^n \rightarrow \underset{x^1, \ldots, x^T}{\textbf{satis}}$$

$$\Phi(x^1, \ldots, x^T; \eta_0^1, \ldots, \eta_0^T) \geq \Phi^0$$

$$\Phi(x^1, \ldots, x^T; \eta_0^1, \ldots, \eta_0^T) \leq \bar{0}$$

where $\eta_0^1, \ldots, \eta_0^T$ is a fixed sequence chosen basing on properties of functions Φ and Ψ as well as considering desired reliability degrees.

Commonly depending on the complexity of functions Φ, Ψ choices of fixed values of the uncertain parameters for Problem V involve a high degree of informal reasoning based on two conflicting considerations: a degree of reliability of the values of Φ_0 obtained and these values themselves. By choosing the most unfavourable values of parameters for Problem V we end up with a solution that would guarantee to a very high degree of reliability (for all possible sequences of parameters from set E) obtaining not very satisfactory values $\Phi_0^1, \ldots, \Phi_0^n$ of the indicators. In the other extreme, by choosing unjustifiably favourable values of parameters for Problem V we will obtain a solution $x^1, \ldots, x^T$ that would "promise" very good values of $\Phi_0^1, \ldots, \Phi_0^n$ but with a very low degree of reliability (only for a small number of sequences from set E). Finding a compromise between these two extremes is always problem specific and requires a certain degree of computational experimenting.

1.5.3 Multiobjective choice

The second important aspect of the screening analysis is the multiobjective nature of the underlying choice problems. Regional preferences of the PMA are only partly characterized in the above generic and deterministic formulations in terms of a number of indicators (components of vector function φ in Problem II; components of the threshold vector φ_0 in Problem V) reflecting as has been mentioned in Section 1.4.1 qualitatively different economic, technological, and environmental aspects of these preferences. Alternative decisions that are good economically may at the same time be unacceptable environmentally, and vice versa. In such situations the concept of optimal or best alternatives loses its meaning and choices have to be made on the basis of compromises among all the different indicators considered.

The basic mathematical concept in multiobjective analysis is a so-called effective or Pareto optimal alternative, i.e. an alternative that cannot be improved in values of any of the indicators without worsening the value of at least one other indicator. In a well mathematically defined multiobjective problem effective alternatives are the only natural candidates for a rational choice, because for any noneffective alternative there is a better effective one. For this reason all formal approaches to multiobjective choice are based on computational algorithms enabling to arrive at an effective alternative. But the intrinsic feature of a multiobjective problem is that there are numerous and formally noncomparable with each other effective alternatives. The final choice of one of them can be made only by an analyst or an expert participating in the analysis. And any procedure of multiobjective analysis is completed not using any formal "stop rule" as in single objective optimization, but when the analyst is satisfied with some alternative identified in the course of the analysis.

For this reason most procedures for multiobjective analysis are designed to speed up this process of search by incorporating provisions for interactively controlling the direction of this search. The role of mathematical methods and computational procedures in such situations is to assist the PMA in selecting alternative planning decisions which may lead to satisfactory compromises among the indicators of different nature.

The field of multiobjective analysis is extensively developed and many procedures as well as their software implementations are described in the literature (see, for instance, G. Fandel and J. Spronk 1985). One of the most natural and common types of approaches to this is to give the analyst possibilities to specify desired combinations of values of the indicators and then try to determine an alternative that either achieves values of the indicators possibly closer to those specified or better values. Approaches of this type are used in both studies described in this Report.

In the approach to the screening analysis for open-pit mining regions minimum requirements are specified for some indicators and values for the rest are specified as desirable reference values. The underlying computational algorithm determines an effective alternative that satisfies the requirements for the first group of indicators and achieves closer possible or better values of indicators of the second group basing on the specified combination of their reference values. A more detailed description of the application of this approach for the test region of Lusatia is presented in Part 3 of this report.

In many cases of practical implementations of multiobjective analysis the indicators explicitly formulated may not represent all the indicators considered by the decision maker. In such cases an alternative that is not effective with respect to the indicators explicitly included may well be effective with respect to these indicators plus some other indicators not explicitly included into the problem formulation but of significance to the decision maker. This means that an approach limited to the generation of effective alternatives may not be sufficient in determining satisfactory choices. Taking into account that algorithms for the determination of effective alternatives are often quite complex, the additional computational effort associated with their application in the above cases may not be well justified (see, for example, Zionts 1985). Basing on this consideration simpler procedures are often used that generate reasonably good but not necessarily effective alternatives achieving desired values of the indicators considered.

The procedure implemented for the Southern Peel test region belongs to this latter class. It gives the analyst possibilities to determine alternatives satisfying specified minimum requirements for the values of all indicators or an alternative providing for the optimal value of one of the indicators with satisfied minimum requirements for the rest. (The latter types of alternatives are commonly referred to as semiefficient.) A more detailed outline of this procedure is given in Part 2 of this Report.

1.6 Simulation of Screened Scenarios

As we outlined earlier in this Report, screening analysis as the first level of scenario analysis is based on the use of considerably simplified models and computational algorithms for multiobjective analysis. In screening analysis we determine values of planning decisions corresponding to relatively long (aggregated) periods of time and do not explicitly consider the performance of the system within these periods. As a result a vector of planning decisions determined can only be considered as a preliminary choice and requires further more detailed verification.

One purpose of such a verification is to demonstrate that compatible operating rules for determining values of operational or managerial decisions (see Section 1.4.1) exist which together with the planning decisions determined would provide for satisfactory trajectories of regional development. Another purpose is to verify that these operational and planning decisions perform satisfactorily in a sufficient variety of possible scenarios of future precipitations, temperatures, and other uncontrolled factors.

Such verification is performed by means of simulation runs with models having higher degrees of detailization corresponding to operational decisions. These models that we refer to as simulation or second level models are described in the respective Parts 2 and 3 of this report as well as in papers supplementing it.

Such second level models are used to compute regional characteristics of interest to PMA with a time step corresponding to the time step of operational decisions considered in the analysis. For the open-pit mining test regions operational decisions are concerned with monthly amounts of water supplied to the users to satisfy their demands. For the agricultural test region they are weekly amounts of irrigation water applied to various crops.

As represented by state equations in the formulation of Problem I (Section 1.4.1) a simulation model performs computations sequentially from one time step to the next. At each time step τ the model is supplied with respective values of planning decision variables x^t, operational decision variables u^τ, and uncontrolled parameters ξ^τ. On the basis of these inputs plus the computational results from the previous time step the model computes values of various factors related to this time step such as for example groundwater tables in different parts of the region, soil moisture and evapotranspiration related to crops, amounts of water exchanged between surface water and groundwater systems, concentrations of pollutants in surface water and groundwater, and many others.

As we mentioned earlier (see Section 1.4.1) we use *a priori* fixed forms of operating rules for computing actual values of operational decisions for each time step. These forms are chosen to reflect actual rules used in the regions considered. For example, the forms of operating irrigation rules for the Southern Peel region are chosen to reflect rotational schemes of seven days per technology. According to these rules the actual amount of irrigation water supplied to the soil depends on the relative moisture content in the soil, on the production level of a technology, and also on capacities of sprinkling equipment installed for the given vegetation period. The latter are determined by the corresponding components of the vector of planning decisions chosen at the screening stage, and are used as parameters.

Operating rules for satisfying water demands of various users in the test region of Lusatia are chosen to reflect existing priorities in water allocation among these users expressed as their lexicographic ordering. The water demands of the users may vary depending also on various unknown factors and are therefore uncertain. Total amounts of water for the allocation among the users are parameters of the respective operating rules and are determined as values of the respective planning variables in the screening analysis.

More details about the operating rules used in simulation runs for the test regions can be found in the respective parts of this Report.

Values of vectors of uncontrolled parameters ξ^{τ} (weekly or monthly precipitation, temperature, other factors) are used in simulation runs as representatives of future possible realisations of these factors. In the study based on the Southern Peel region in which the duration of the simulation period is one year the simulation is based on the use of available past weekly observations of the uncertain factors considered (past weather years). If the collection of such past observations considered is not rich enough to represent possible future outcomes of uncontrolled parameters, then additional "synthetic" realizations are generated basing on the available data, and using Monte-Carlo computational techniques. This latter approach is applied in our study based on the test region of Lusatia.

As a result of simulation runs we obtain for one vector of planning decisions a number of possible regional trajectories each corresponding to one of "future realizations" of the vector of uncontrolled parameters from the collection of such realizations observed in the past or generated. These simulated trajectories represent possible paths of regional development that may occur with a given fixed vector of values of planning decisions, and with the chosen operating rules for operational decisions. Such a collection of regional trajectories provides the PMA with the necessary more detailed evidence with regard to the alternative of planning decisions considered.

1.7 Implementational Aspects of Scenario Analysis

As we repeatedly stress in this Report, a decision support system should not be an automatic problem solver, but a flexible tool designed to assist the PMA in the analysis of regional problems. Therefore, the form of implementation of this system is one of the important aspects of its design. The use of this tool by the PMA may be viewed as a dialogue between the PMA and the decision support system in the course of which the PMA sequentially poses various questions to the system and obtains information guiding him to further questions and eventually to a choice of a satisfactory solution.

To facilitate such interactive process a decision support system should have appropriate features. It should be simple in operation and therefore usable by experts without preliminary special training in computer application and without extensive studying the structure of the system. It should also be relatively fast in its responses to questions posed by the user. A slow system with delayed responses makes it difficult for the user to keep concentrated on the analysis, and the efficiency of the analysis suffers. The system should also be capable of responding to a wider possible scope of potential questions relevant to the problem area of its design. It is clearly impossible to foresee in the process of design all future questions that might arise even for the PMA himself. Therefore, it can be useful to have in the system provisions for incorporating in it responses to new types of questions that emerge in the course of analysis.

An obviously essential feature of a decision support system is its ability to present adequate information in a convenient and easily understandable form. Probably, the best way of achieving this is to use both alphanumeric and image representations of information in the course of analysis. The image representation mobilizes the excellent human capability of comparing and memorizing images, and the numeric representation provides more precise data when necessary.

These features are realized in the decision support systems described in this Report. The simplicity of their operation and user friendliness is facilitated by equipping them with menu driven interactive software systems. The self-explanatory menus are organized in a hierarchical manner, and position of the user in this hierarchy is always indicated on the alpha numerical screen. For easy user access and interpretation of results these interactive systems are equipped with computer colour graphics that provide the display of data on the coloured screen, for example, in the form of maps, flow schemes, bar and pie charts.

The screening analysis for the test region of Southern Peel is based on the use of an efficient and user-friendly cross-compiler GEMINI developed by V.Y. Lebedev (1985) at the Computing Center of the USSR Academy of Sciences coupled with the linear programming software package MINOS developed by B.A. Murtagh and M.A. Saunders (1977) at Stanford University. The cross compiler accepts the description of problems underlying the screening analysis in the form very close to usual mathematical description. This gives the opportunity of easily changing the structure of the problem (forms of constraints and objective function) when it is necessary to widen the scope of questions answerable by the scenario analysis. The interactive menu driven data display and management system of this decision support system allow for interactive multiaspected comparison of optional scenarios (trajectories) pregenerated using the above combination GEMINI–MINOS as well as display and analysis of data generated in subsequent simulation runs using second level models. A more detailed description of this interactive system is given in Part 2 of this Report.

In addition to such display and analysis of data the decision support system for the test region of Lusatia enables the user also to conduct and control the screening analysis. The user of the system can interactively specify lower and/or upper bounds for some of the indicators as well as reference values of the other indicators. The resultant nonlinear multiobjective programming problems are solved by the minimization of a scalarizing function using a nonlinear programming algorithm developed by T. Kreglewski 1985. More details about this system are presented in Part 3 of this Report and also in the papers supplementing it.

1.8 Development of Simplified Models

1.8.1 Introduction

As we discussed earlier in this Report, the basic part of a decision support system designed to assist the analysis of regional resource problems is a system of computerized mathematical models representing processes and interrelationships in the region relevant to the goals of such an analysis. For our studies, water quantity and quality processes in and between the water resources subsystems "soilwater", "groundwater" and "surface water" are the most important.

Substantial and successful research in hydrology and hydrogeology during the last decades has resulted in a deeper understanding of these processes. On the basis of experimental as well as theoretical research considering basic natural laws and relationships detailed mathematical descriptions (models) of these individual processes were developed. Some of these models served to further improve and concentrate scientific understanding of the dynamics of these processes. Motivated by the increasing pressure on water resources due to the socio-economic development on the one hand, and the development in computer data processing on the other, powerful computer models of these processes have been designed, implemented and applied. Their application was focused on water management and engineering problems, e.g. reservoir management, design of groundwater wells, irrigation schemes, etc.

The common feature of these models is that they tend to capture many aspects of the processes modeled and therefore have a great degree of detailization. In many cases this tendency is in contradiction with the availability of the necessary information and data. For convenience we shall refer to these types of models as *comprehensive models* (sometimes they are called *deterministic models*). In most cases these models are restricted to quantitative or qualitative aspects in one of the water resources subsystems.

As we have already mentioned, the relatively recent growth of awareness about long-term economic impacts on water systems and the environment on a regional scale necessities the consideration of many processes of this type in their interlinked integrity. And the model representation of this integrity in the framework of a workable decision support system puts limitations on the degree of sophistication of its constituent submodels. Not only these models should be representative of the processes studied but their response time, or in other words, the computational effort required should be small enough to allow for their interactive use. The latter requirement prevents from the straightforward use of comprehensive models developed for various specific tasks in a integral framework of decision support systems of the types considered in this report. On the other hand, these models are adequate representations of the processes under consideration and are based on the scientific knowledge accumulated as well as on vast amounts of data collected. Therefore, often they can be used as a basis for the development of relatively simple models which can be incorporated in a system of models for policy analysis on a regional scale.

As is inherent to the systems analysis the development of problem oriented simplified models of processes is always based on combinations of formal and informal considerations. Various theoretical and heuristic approaches have been suggested in different fields. It is not our intention to give a structured overview of these usable approaches. Rather, we outline here those approaches that we used in designing decision support systems for our two test regions. Figure 1.8.1 gives an overview of these approaches.

By a simplified model we understand a set of mathematical relationships between variables in the form suitable for their computer implementation within the structure of the computerized decision support system under design. The variables quantify different aspects of processes considered and they are chosen out of various considerations such as the suitable degree of aggregation in space and time, desired degree of accuracy and of complexity of the model, available computational possibilities, links of the given model with other models of the system, and others. The choice of variables is largely specific to the real process considered as well as to the

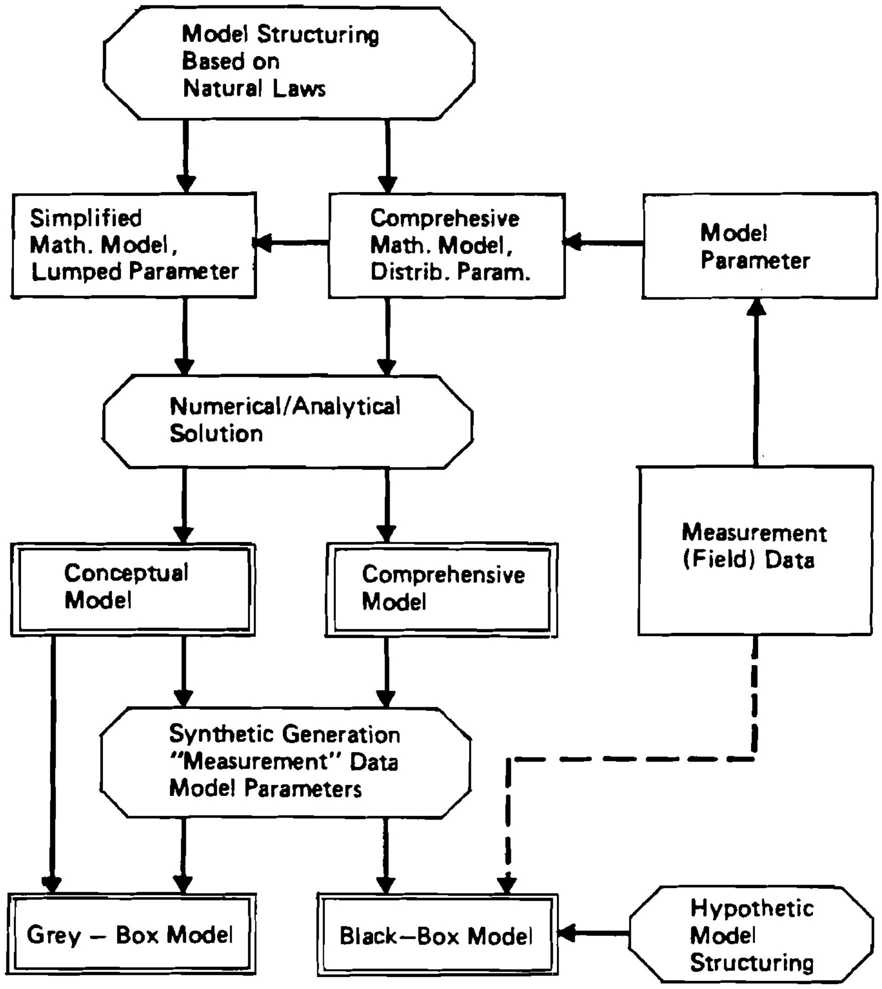

Figure 1.8.1: Methods for developing simplified models

goals of analysis and no formal recipes exist applicable to every particular case.

As is common, we shall refer to the form of the relationships constituting a model as the structure of the model. And we shall use the term parameters to refer to those quantitative characteristics by which models of the same structure can differ from each other. In developing a simplified model the interrelationship between the model structure and the availability of data has to be considered. In principle, there are two sources for obtaining data for model quantification. The logical way is the use of field measurements and laboratory tests. Unfortunately, in many cases for the above processes the amount and character of data available do not fit well to the requirements of simplified modeling. This, above all, holds true for the "hidden" processes in the subsoil and in aquifers. If a comprehensive computerized model of the studied process is available, this model can be used for synthetic data generation. In this case it is assumed that the model is a sufficiently accurate representative of the process. Based on that with the comprehensive model a more or less detailed observation programme is simulated with low cost and in a short time. For most of the submodels developed in the framework of our studies such synthetic data generation has been utilized.

In developing a simplified model of a process the structure of the model can be chosen on the basis of natural laws and relationships applicable to the variables chosen. Such simplified models are commonly referred to as *conceptual models*. Opposite to the comprehensive models based on similar laws and relationships for conceptual models simple arrangements of a relatively small number of components are used. Frequently these components represent in a simplified way one process element in the system modeled. Another approach to developing a conceptual model is the simplification of a corresponding comprehensive model, e.g. by introducing a smaller number of variables aggregated in space and time as well as by lumping their parameters.

A very common approach to developing simplified models are input-output models, or, as they are frequently referred to *black-box models*. This approach is used in cases when natural laws and other relationships between the variables are either not known *a priori* or are too complex for their use in formulating the structure of the model. Therefore, the structure of the model is chosen more or less arbitrarily. The model parameters are quantified basing on data obtained from simulations with comprehensive models of the process considered and/or using field data if available.

In a certain sense conceptual and black-box models represent two extremes of a continuous spectrum of possible model structures, and various degrees of combinations of these two types are used in practice. One indication to this are various types of "grey-box" models that increasingly appear in literature. The association of a simplified model to one of these categories depends partly on the subjective views of the modeler and his background. In hydrology/hydrogeology the term "grey-box" is frequently used for models with a conceptual model structure (based on some natural laws and relationships) but including parameters that do not have a "natural" interpretation, and often cannot be obtained directly from field/laboratory data. In Section 3.4.2.3 an example is given of this type of a model for remaining pit management. More generally, grey-box models are sometimes described as combining human mental models with black-box models. For the development of such models interactive computer model systems are best suited. In the course of such interactive process an expert can iteratively use his knowledge of some aspects of the real system or process modeled for modifying the structure of the model.

In the following we outline major approaches to the development of simplified models used for our studies focusing on their general aspects. The application of these approaches to certain subprocesses is reflected within the framework of the corresponding studies in Parts 2 and 3.

1.8.2 Conceptual models

As we said before the structure of a conceptual model is based on natural laws and known relationships applicable to the description of a process in terms of the chosen variables. The means of developing conceptual models depend on the specific nature of these laws, relationships and the chosen model structure. In the following some major aspects usually considered in developing a conceptual model will be discussed.

Model structuring

The model structure should be reasonably applicable to the variables chosen to quantify aspects of the process of interest. Two possibilities for model structuring are common. First, to use a comprehensive mathematical model of the process studied and to simplify it by means of aggregating its variables in space and time. This way is most preferable because it makes the simplifications more or less obvious. An example of such an approach applied to water quality models is described in Section 3.3.3, see also Luckner et al. 1985. The second possibility is based on the formulation and combination of natural laws and relationships describing process of interest. In this case, one tries to formulate these laws and relationships according to the required simplifications as mentioned above. Typical examples are the conceptual models of groundwater–surface water interaction described in Section 3.3.2 and in Kaden et al. 1985. Sometimes experiments with comprehensive computer models are helpful to verify certain hypotheses underlying the structure of a simplified model, see Section 3.3.2.

Since we consider models designed for computer computations, and therefore discrete, or aggregated, there may be a contradiction between the degree of discretization (aggregation of variables) and the scale of certain physical and other principles used. For example, in describing the dynamics of water flows mass balance relationships representing the law of conservation of mass can be applied to variables of virtually any degree of aggregation. On the other hand, the application of the law of conservation of momentum represented by difference equations of the second order requires more careful consideration of the aggregation of variables. Of course, we can apply this type of relationships even for variables of a very high degree of aggregation, but then physical or other interpretation of parameters in such relationships loses partly its meaning and the model itself should be looked at as a grey-box model. One example of a grey-box model for the remaining pit management can be found in Section 3.4.2.3.

Parameter quantification

The second aspect in the development of a conceptual model is the quantification of its parameters. If the model is truly conceptual, or, in other words, if there is no drastic contradiction between the degree of aggregation of its variables and the nature of the physical and other laws underlying its structure, then the model parameters having a physical meaning can often be quantified using known physical/chemical/other constants and coefficients. The latter are in turn based on field observations in studies of the process considered and are in a certain sense of a universal application. In this sense if a model is truly conceptual it is easily adaptable to describing similar processes in other studies. If the model parameters are highly aggregated and there is a lack of field data for quantifying these parameters experiments with a comprehensive model can be used for generating synthetic data in order to quantify (or verify) these parameters.

Mathematical description and computer implementation

The mathematical description of a conceptual model can have different forms: explicit functional relationships between the variables considered, implicit functional relationships, finite difference equations, differential equations and others. In the case of differential equations these equations can be solved by known analytical and numerical methods. For submodels describing interrelationships between surface and groundwater the Laplace transformation can be a useful method. This well-known method has been used, e.g. in the past for constructing analytical solutions in the well hydraulics. In our case for the complicated models either no analytical inverse Laplace transformation could be found or its use requires too high computable effort. Therefore, a numerical *Laplace* transformation is used. In Section 3.3.2 models based on this approach are described, see also Kaden et al. 1985. In any case the necessary mathematical preparation depends on the model structure and on the planned model use. Sometimes explicit functional relationships are required. In other cases the models form constraints in optimization problems, i.e. implicit functional relationships are sufficient. Finally the models have to be implemented on the computer considering the requirements of the complex model system they have been designed for. Examples of conceptual models used in our studies can be found in Section 3.3.2, Kaden et al. 1985, and Luckner et al. 1985.

1.8.3 Black-box models

As we said before the structure of a black-box model is chosen more or less arbitrarily and is not based on known physical or other laws and principles. These types of models are used in cases when physical relationships for the variables chosen are too complex for their use in the analysis, or, when such laws and principles are not applicable to these variables.

The basic presumption for constructing black-box models is the availability of input–output data with respect to the studied process and chosen variables. If enough data are available the development of a black-box model usually starts with the statistical analysis of these data. Based on that appropriate models are constructed.

The most simple type of statistical models are linear regression models. In our mining study this approach has been used for modeling the trend of groundwater quality in the mining area, see Section 3.1, Figure 3.1.3. More complicated are the multi-dimensional Marcovian models applied for the simulation of the discharge in streams. In Section 3.5.1.2 an overview is given.

In our studies in most cases the amount and character of field data were not sufficient for their direct use in constructing black-box models. If comprehensive models are available they can be used for the synthetic generation of input–output data. The advantage is that such simulation experiments can be designed with special regard to the chosen structure of the black-box models, sometimes even resulting in the direct estimation of their parameters (impulse response function). For this reason with regard to dynamic water processes the following types of black-box models are of particular interest:

- models based on recursive difference equations,
- models based on the convolution integral representing dynamic linear systems,
- parameter-free models and models based on local approximations.

Recursive difference equations

In the studies described in this Report, this form of black box models are used to represent dynamic groundwater flow and groundwater–surface water interaction processes.

As a simple example we can consider a system characterized by a state variable $y(t)$ and by an input variable $w(t)$. This example is typical for instance for modeling water tables in a groundwater reservoir influenced by inflows and outflows of water. The input variable $w(t)$ is usually discretized in the following way:

$$w(t) = w_i \quad \text{for} \quad (i-1) \cdot \Delta t \leq t \leq i \cdot \Delta t \quad ,$$

where Δt is the length of the discrete time-interval considered.

Using this time discretization the corresponding values $y_k = (k \cdot \Delta t)$ of the state variable $y(t)$ are obtained through the following recursive equations representing the structure of the model:

$$y_k = \sum_{i=1}^{m} a_i \, y_{k-i} + \sum_{i=0}^{n} b_i w_{k-i} \quad .$$

Values of parameters m , n related to the "memory" of the process considered are chosen in the course of adapting the model to data available. For example, in our studies related to groundwater, groundwater–surface water flow $m = 2$ and $n = 1$ appeared to be practically significant (Kaden et al. 1985). This is quite reasonable because the resultant equation

$$y_k = a_1 y_{k-1} + a_2 y_{k-2} + b_0 w_k + b_1 w_{k-1} \tag{1.8.1}$$

is an analogue of a second order linear differential equation and this is the mathematical model of a linear storage or of a confined groundwater flow in a homogeneous aquifer.

Coefficients a_i and b_i in this structure are chosen to obtain a "best fit" (i.e. in the sense of the least squares metric) between the collection of data for y_k, w_k available and the corresponding collection of values obtained using the given model. As has been noted the data for y_k, w_k may be obtained from field measurements. More frequently they have to be synthetically generated in simulation runs using other more detailed models of the same process. Sometimes it is useful to consider aadditionally to Eq. (1.8.1) some special systems properties, i.e. the realization of a stationary value for constant inputs. This results in additional conditions for the coefficients and the resulting systems of equations to be solved approximately using common methods.

Black-box models of this type are used in the decision support system for the test region of Lusatia (see Section 3.5.1) to represent processes of water exchange between a remaining pit and the surrounding aquifer as well as surface water–groundwater infiltration processes (see also Kaden et al. 1985).

Local approximations of comprehensive models

In some cases certain stages of analysis require simplified representations of a process only in a small range of variations of the variables. A useful approach then may consist in formulating for each time interval considered a separate simplified approximation of an existing comprehensive model in a vicinity of values of the variables of interest. A typical example (see Section 3.4.2) is the development of a simplified model to describe variations of groundwater tables at certain points due to variations in pumping rates at other points. This approach is practically justified if the number of variables considered is small enough.

Suppose that vectors S_j, D and I are chosen to represent respectively values of state variables corresponding to a time step j considered, control variables, and uncontrolled parameters of the simplified model. Then at the first step of this approach vectors $\bar{D}$ and $\bar{I}$ are chosen to represent in a certain sense average or basic values of the respective variables. In cases of dynamic processes simplified models can be formulated separately for each time interval considered. If, for example, vector I represents uncontrolled inputs like precipitation then depending on the logic of the analysis vector $\bar{I}$ can be chosen as an average precipitation observed or precipitation having higher probability of occurrence to make the results of analysis in a certain sense more reliable. For each time period j vectors $\bar{I}$ and $\bar{D}$ chosen (or more often their disaggregates) are fed into the comprehensive model and the results of this simulation run are used to compute corresponding basic state vector $\bar{S}_j$ for a given time step j.

Then the simplified model is formulated as follows:

$$S_j(D) = \bar{S}_j + \Delta S_j(D - \bar{D})$$

With a sufficiently simple form of function $\Delta S_j(\cdot)$ its parameters are evaluated using results of simulation runs with the comprehensive model for vectors D not too far deviating from the "basic" vector $\bar{D}$.

This approach to modeling was used for developing screening models in both studies described in this Report (see Sections 2.5.4, 3.4.2).

Convolution integrals representing dynamic linear systems

Since the development of the Unit-Hydrograph method by Sherman 1932 linear systems models underwent fast development and found extensive applications in hydrology. Description of input–output relationships of linear, time invariant systems based on the instantaneous Unit-Hydrograph (IUH) is the most commonly used approach in hydrology. Originally, it has been developed for predicting surface runoff resulting from rainfall events. The first applications of this approach to groundwater systems are due to Edelman 1947 who modeled groundwater flow into a unit length of a channel. To illustrate this approach let us consider a system, e.g. a groundwater reservoir with the following properties:

– the system is linear, i.e. the response of the system (groundwater flow or groundwater table) is proportional to the input (infiltration or groundwater extraction by wells);

– the system is time invariant, i.e. the systems response to a certain input does not depend on the point of time of its occurrence.

As is well known, the properties of the system assumed allow for the use of the so-called superposition principle according to which we can describe the response of the system $Q(t)$ to input $I(t)$ in the form of the following convolution integral

$$O(t) = \int_0^t k(t-\tau)I(\tau)d\tau$$

where $k(\cdot)$ is a so-called impulse response function of the system. This approach is illustrated in Figure 1.8.2.

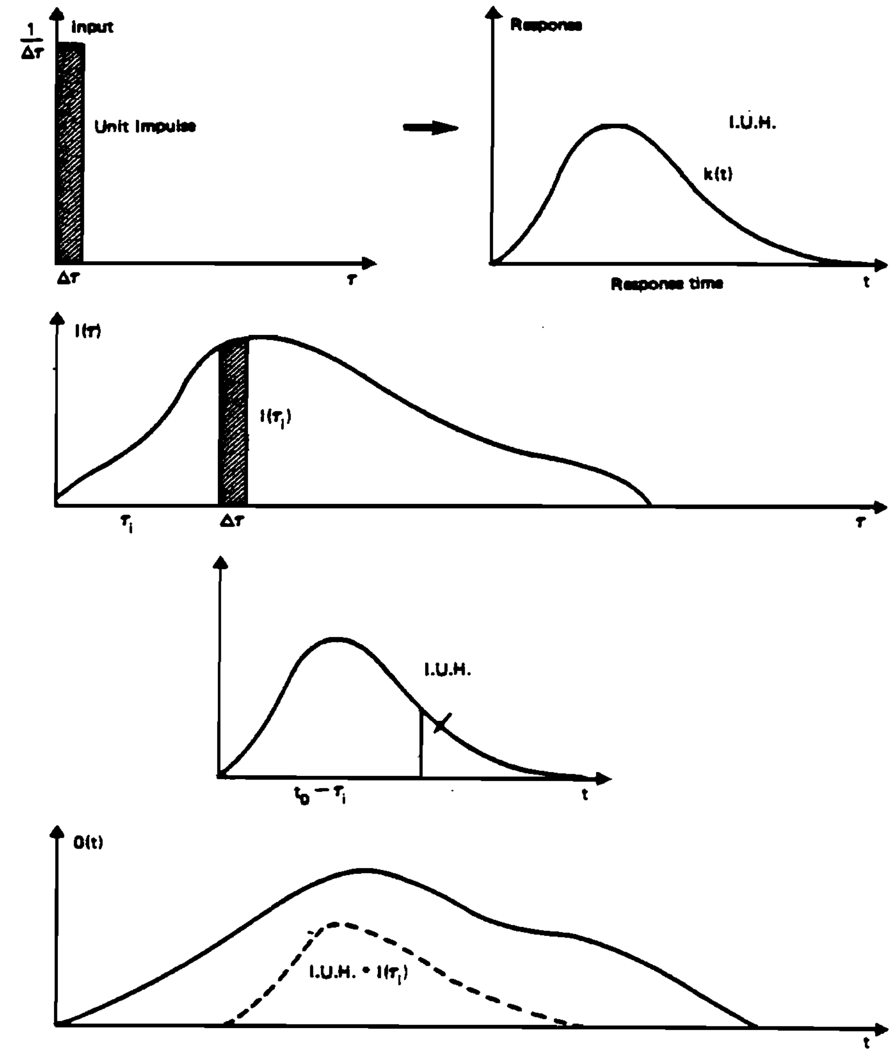

Figure 1.8.2: Impulse response approach

Superposition over space variables can similarly be used for more complex systems. We can extend the approach to describe the response of the system to a number of inputs $i = 1, \dots, N$:

$$O(t) = \sum_{i=1}^{N} \int_0^t k_i(t-\tau) \cdot I_i(\tau) d\tau$$

For computational purposes time-discrete representations of this principle are used in the following form:

$$O(T) = \sum_{i=1}^{N} \sum_{\tau=1}^{T} [\delta_i(T-\tau+1) \cdot I_i(\tau)]$$

with

T , τ - discrete time parameters,

$\delta_i(T) = \int_0^1 k_i(T-\tau)d\tau$ - discretized impulse response functions,

$I_i(\tau)$ - discretized input function.

The necessary values of the discrete impulse response functions are evaluated in most cases using data obtained in specially designed simulation runs with more detailed comprehensive models. If appropriate observation data have been recorded, characterizing the systems response on one or a set of systems inputs, these data may be used to estimate the model parameters. A typical example is the base flow-infiltration relationship. Then the well known methods of least squares, Fourier coefficients, Laguerre coefficients, etc. may be used for this evaluation. In modeling groundwater flow processes instead of the impulse response the step response function is used frequently.

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).

In our studies the above discretization approach was used to develop a black-box model of the surface water–groundwater infiltration processes (mining test region, see Section 3.5.1.) as well as for developing simple groundwater flow models (agricultural test region, see Section 2.5.4). In the second case the above approach was used in an even more simplified form – the so-called *influence matrices*. It is based on a lumped time step

ΔT (e.g. vegetation period).

$$O(\Delta T, l) = \sum_{i=1}^{N} \delta_i(\Delta T, l) \cdot I_i(\Delta T)$$

with l - index of output component, e.g. groundwater table at a certain location

$M = [\delta_i(\Delta T, l)] i = 1, \ldots, N;\ l = 1, \ldots, L$ is the influence matrix.

The basic assumption of the above approaches is the linearity of the mathematical model. However, for groundwater flow processes in unconfined aquifers with significant drawdown, as is typical for lignite mining areas, this assumption is not adequate. In such cases nonlinear algebraic technological functions or discrete kernels could be implemented. Maddock 1974 developed such functions for drawdowns in unconfined aquifers due to pumping. The resulting functions are nonlinear polynomial relationships between pumping and drawdown. But the numerical effort of such approach is quite substantial and the resulting models are relatively complicated.

1.8.4 Interactive system for developing simplified models (IMSS)

The development of black-box models is based on the use of observed and/or simulated values of the variables together with statistical techniques for the evaluation of parameters of the model. But often experts developing the model may have additional knowledge with regard to interdependencies between the variables. This knowledge interpreted as a "mental" model of the system considered can be used to make the model a more adequate representation of the given process or system. On the other hand, this knowledge is often of subjective nature and cannot be fully formalized. Therefore, the use of this knowledge in developing a desired model necessitates the direct participation of experts in the modeling process itself. This in turn necessitates the development of computer-aided modeling systems that facilitate such participation.

The development of one computerized system of this type originated by a group of Japanese scientists led by Y. Sawaragi was continued at IIASA by Y. Nakamori in the framework of studies described in this Report. A relatively detailed description of this system is presented in Nakamori et al.

1985. An example of application of this system for the development of simplified models involving groundwater and cropped soil systems is described in Van Walsum and Nakamori 1985. Here we give its brief outline.

Suppose that the following variables are used for describing a real system:

$$s = \{x_i, i = 1, \ldots, n\}$$

Then two types of inputs are considered in the modeling process using the IMSS:

– measurement or simulated data for these variables,

– cause–effect matrix $A = \|a_{ij}\|$ defined as follows:

$$a_{ij} = \begin{cases} 1 & \text{if } x_i \text{ influences } x_j \\ 0 & \text{otherwise.} \end{cases}$$

While the measurement data are given *a priori* and fixed, the initial cause–effect matrix A may be changed in the course of the modeling process. In fact, by changing this matrix interactively the modeler inputs his knowledge into the modeling process. The process of modeling using IMSS includes three interdependent stages as shown in Figure 1.8.3.

The *first stage* is designed for the preparation and statistical analysis of the measurement data, possible introduction of different types of nonlinear transformations of variables for simplifying the model. Initial version of the cause–effect matrix A is also formed basing on the information from the modeler as to which variables do not affect which.

The *second stage* is designed for determining a compromise between a structure of the model based on statistical analysis of the measurement data and the modeler's knowledge about dependencies between variables. Based on the measurement data and the initial version of the cause–effect relation represented by matrix A a model is constructed using one of the options of the regression methods available in the system. The model constructed is linear in variables transformed at the first stage, but, of course, depending on these transformations it may be nonlinear in the original variables.

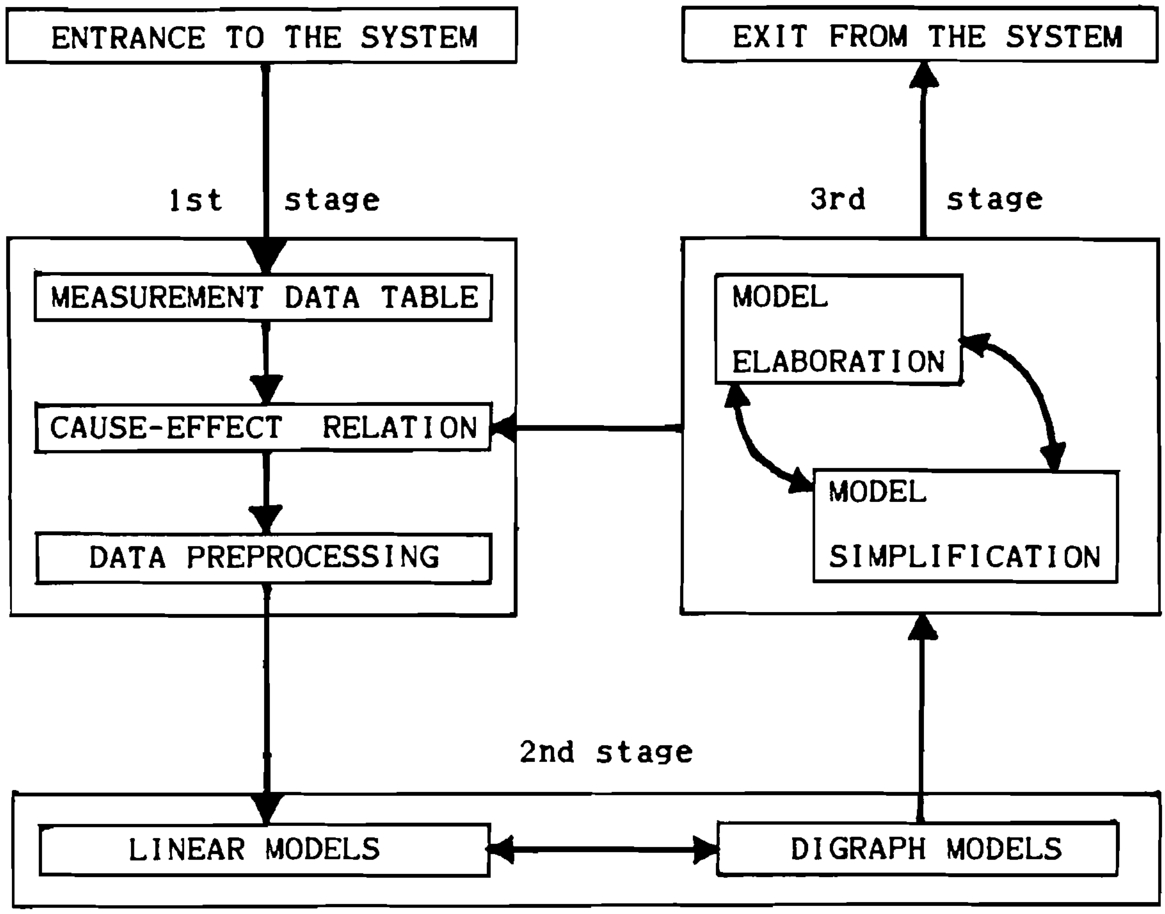

Figure 1.8.3: Stages of modeling process

After this various forms of graphs of interrelationships between the variables of this version of the model may be presented to the modeler (the original graph, its transitive closure, skeleton) and one can interactively introduce modifications into this graph and repeat the procedure. There is no formal stop rule, and this iterative procedure can continue until the structure of the model appears satisfactory to the modeler.

The *third stage* is related to model simplification and final evaluation of its parameters. The simplification of the model is based on the graph–theoretic analysis of equivalences between variables. The final elaboration of the model is based on the application of a suitable regression techniques, including hypotheses testing for estimated coefficients as well as the examination of explanatory and predictive potential of the model.

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PART 2

DECISION SUPPORT SYSTEM FOR REGIONS WITH INTENSE AGRICULTURE

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PART 2. DECISION SUPPORT SYSTEM FOR REGIONS WITH INTENSE AGRICULTURE

In this Part, we focus on the development of the decision support system for the agricultural test region of Southern Peel in the Netherlands. Following the framework suggested in Part 1 we start with general information about the regional economy and the environment paying particular attention to its water resources. Then after presenting an overview of the structure of the decision support system, we outline models of major processes relevant to our study, models that are used for simulation at the second level of scenario analysis. Some of these models were used as a basis for the formulation of corresponding relatively simplified models for the screening analysis. We describe these latter models in subsequent sections together with assumptions used in their formulation. Then using somewhat generalized form of these models and relationships we outline the logic of the screening analysis and also indicate methods used in this analysis.

After outlining the linkage between the screening and simulation levels of scenario analysis, we give more details about computer implementation of the decision support system and illustrate an interactive session with the system. Finally, in Section 2.8 we discuss aspects of policy analysis and suggest some formulations that can be used to assist this analysis. More details about various aspects reflected in this Part can be found in papers supplementing this Report.

2.1 General Information About the Test Region of Southern Peel in the Netherlands

Introduction

Precipitation, groundwater and surface water are important life strings for natural ecosystems, for cultivated plants, for population at large, and industries. As a result of socio economic developments waste land has been put under the plough for feed supply. With this the water management in rural areas has been attuned to the demand of agriculture and horticulture.

During the last decades in the Netherlands the food production per ha has increased. Firstly because of the improvement of the discharge of drainage water and of the improvement of the possibilities of additional water supply in dry periods (surface and ground water). Secondly, because of better stocks, increasing mechanization, combating of plant diseases, specialisation, and the development of factory farming.

Natural ecosystems are developed throughout the ages with climate, quantity and quality of groundwater and surface water as guiding factors. The remaining nature areas in the Netherlands often derive their special value from a high groundwater level or from a specific water quality. The already mentioned economic development puts an increasing pressure on the environment by consuming natural resources, by lowering ground water levels, and by discharging pollutants.

Population and industry ask for water of good quality. Therefore, groundwater is used preferably. The groundwater withdrawn is mainly infiltrated precipitation surplus. To maintain constant and safe quality of the groundwater it is important to protect the water resource areas against contaminants.

During a long time natural ecosystems and the socio-economic activities could endure more or less undisturbed side by side. The growing economic developments over the last decades and the increased awareness of the necessity of preservation of natural resources have led to situations that activities of the different water users have started to interfere with each other.

Location

The Southern Peel is a relatively flat and sandy area situated in the delta of the rivers Rhine and Meuse (black area in Figure 2.1.1). Its area is about 30,000 ha, the altitude varies between 17 and 35 m above sea level.

The shadowed part on Figure 2.1.1 is the part of the Netherlands above mean high-tide sea level, the rest is lower, up to 6 m below mean sea level. In the lower part most of the soils are clayey or peaty. The higher parts are mostly sandy areas.

Geohydrology and hydrology

The Netherlands has humid climate with mean yearly precipitation of about 700 mm, and the mean actual evapotranspiration about 450 mm during the growing season.

The test area has a shallow groundwater table, mostly between 1 and 2 m below ground level. This means that a substantial part of the moisture required for crop growth can be supplied by the capillary rise. The other natural sources of moisture are soil storage and precipitation. In dry periods water is also supplied by sprinkling irrigation or subirrigation. Water for sprinkling is pumped from the groundwater or from the surface water supply system.

The surface water system in the Southern Peel consists of some larger canals and a network of ditches and brooks with a varying density (see Figure 2.1.2).

Water levels in ditches and brooks are controlled by weirs. At present surface water is partly imported from outside of the region. The capacity for importing surface water is 3 m^3 per sec. Generally, in autumn and winter the weirs are lowered to lower the groundwater table to provide for acceptable circumstances for harvesting and tillage. In spring the weirs are usually raised to raise the water level in drainage ditches to reduce the outflow of groundwater.

The groundwater flow is partly dependent on the hydrological properties of different geological formations. Hydraulic conductivity and the thickness of layers play an important role. A major feature of the regional hydrogeology is the presence of a fault that divides the area into a Western part "Slenk" and an Eastern part "Horst". Figure 2.1.3 shows a schematic representation of the different geological formations and the main faults.

The Slenk has a deep hydrological basis at 300 - 350 m below ground level. In the Horst the basis is at 8 - 36 m. The formations in the block-diagram (Figure 2.1.3) are divided into aquifers and aquitards.

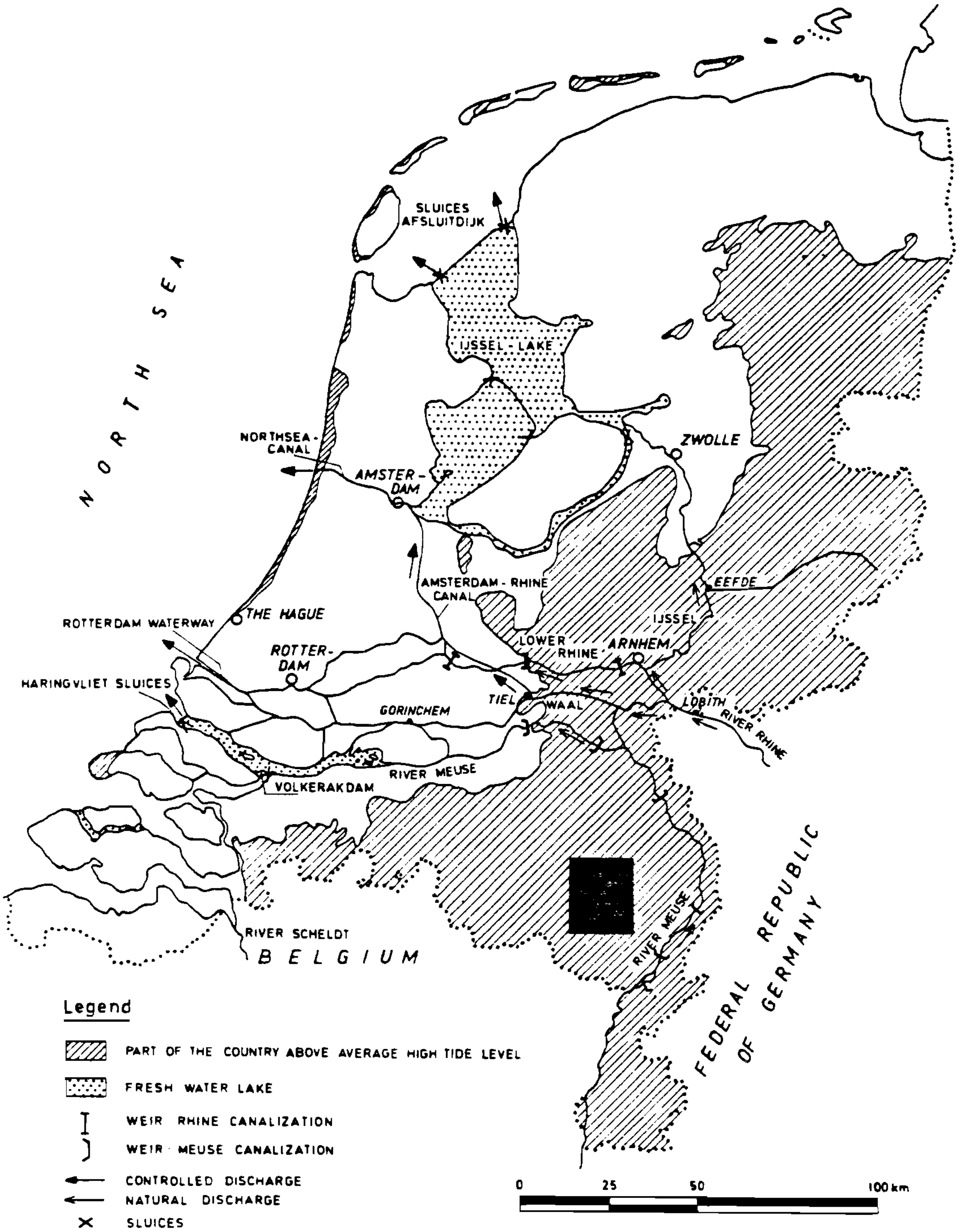


Figure 2.1.1: Location of the Southern Peel study region on the map of the Netherlands, including principal elements of the water system (Pulles 1982)

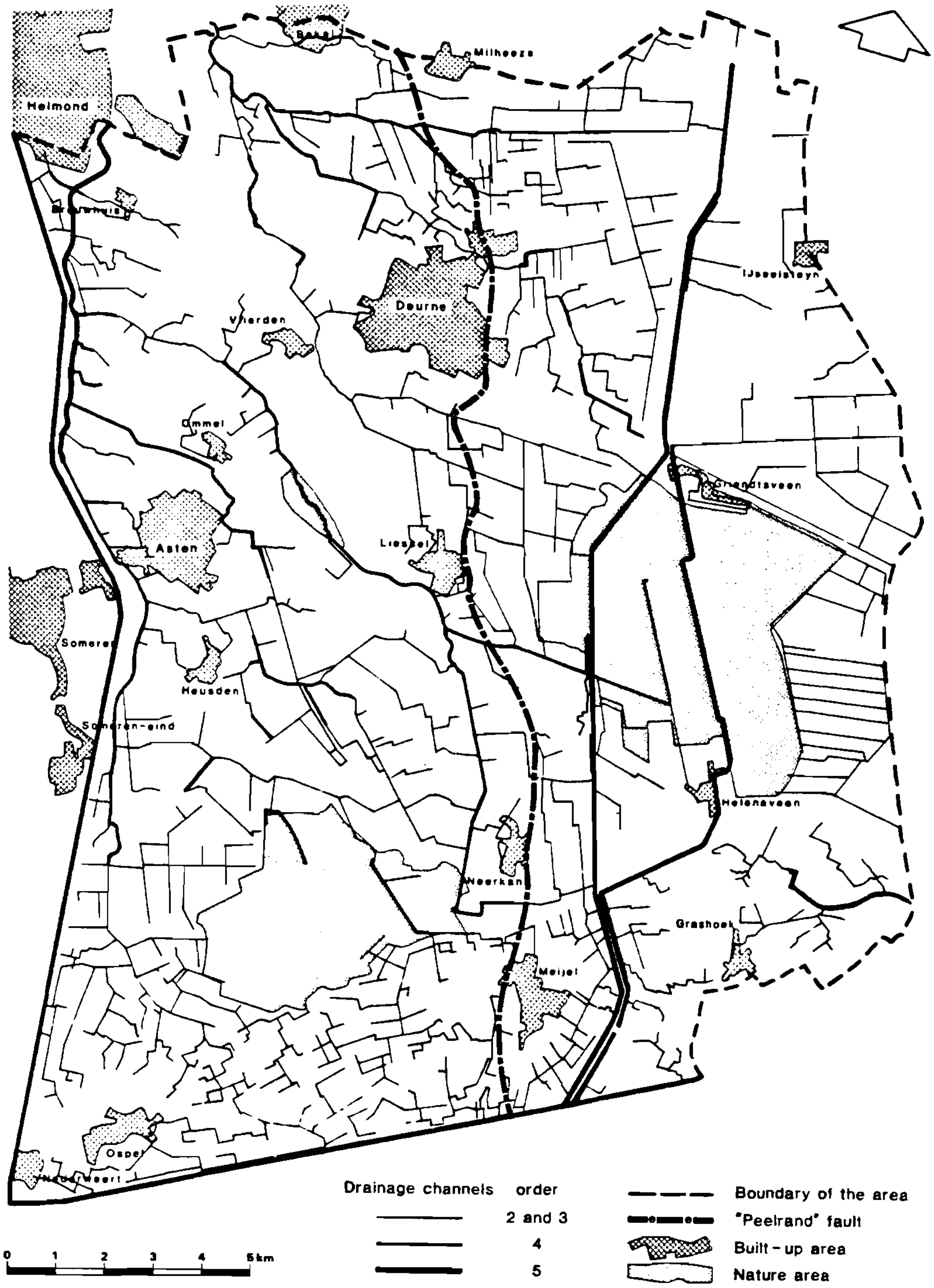


Figure 2.1.2: Surface water system of the Southern Peel

In the Slenk three important aquifers with a high conductivity (1,3 and 5) can be distinguished. These aquifers consist of coarse and sometimes gravel-bearing sand. The groundwater flow is mainly horizontal. These aquifers are separated from each other by formations with a high hydrological resistance. These aquitards consist of peat, clay and loamy sands with different thicknesses. The groundwater flow here is mainly vertical. In the southern part the second aquitard is not always present. In the Horst there is only one aquifer with a mean thickness of about 10 m.

The phreatic aquifer in both areas consists of fine sand; in the Slenk with a thickness between 15 and 20 m and in the Horst between 5 and 10 m (Van Rees Vellinga and Broertjes, 1984).

The hydrological conductivity of different aquifers has been derived from the available geohydrological records as well as from supplementary borings and pumping tests in the region. The resulting kD-values(T) for the first aquifer are given in Figure 2.1.4 (Van Rees Vellinga and Broertjes, 1984).

The drainage of precipitation surplus in undulating areas takes place in several drainage levels. Therefore the surface water system has been divided into 5 categories. The tertiairy system consists of shallow ditches, the secondary of brooks and larger canals (see Figure 2.1.2).

For testing the kD-values and for information about the vertical resistance of the aquitards, groundwater and surface water balances were calculated basing on field data of 1982 and 1983. Important terms in the water balances used were:

- supply and drainage of surface water(measured data)
- discharge of purification plants and industries(measured data)
- net groundwater flow in aquifers across the boundaries of subregions (calculated from hydraulic head gradients and kD-values),
- ground water withdrawals for public and industrial water supply (monitored data),

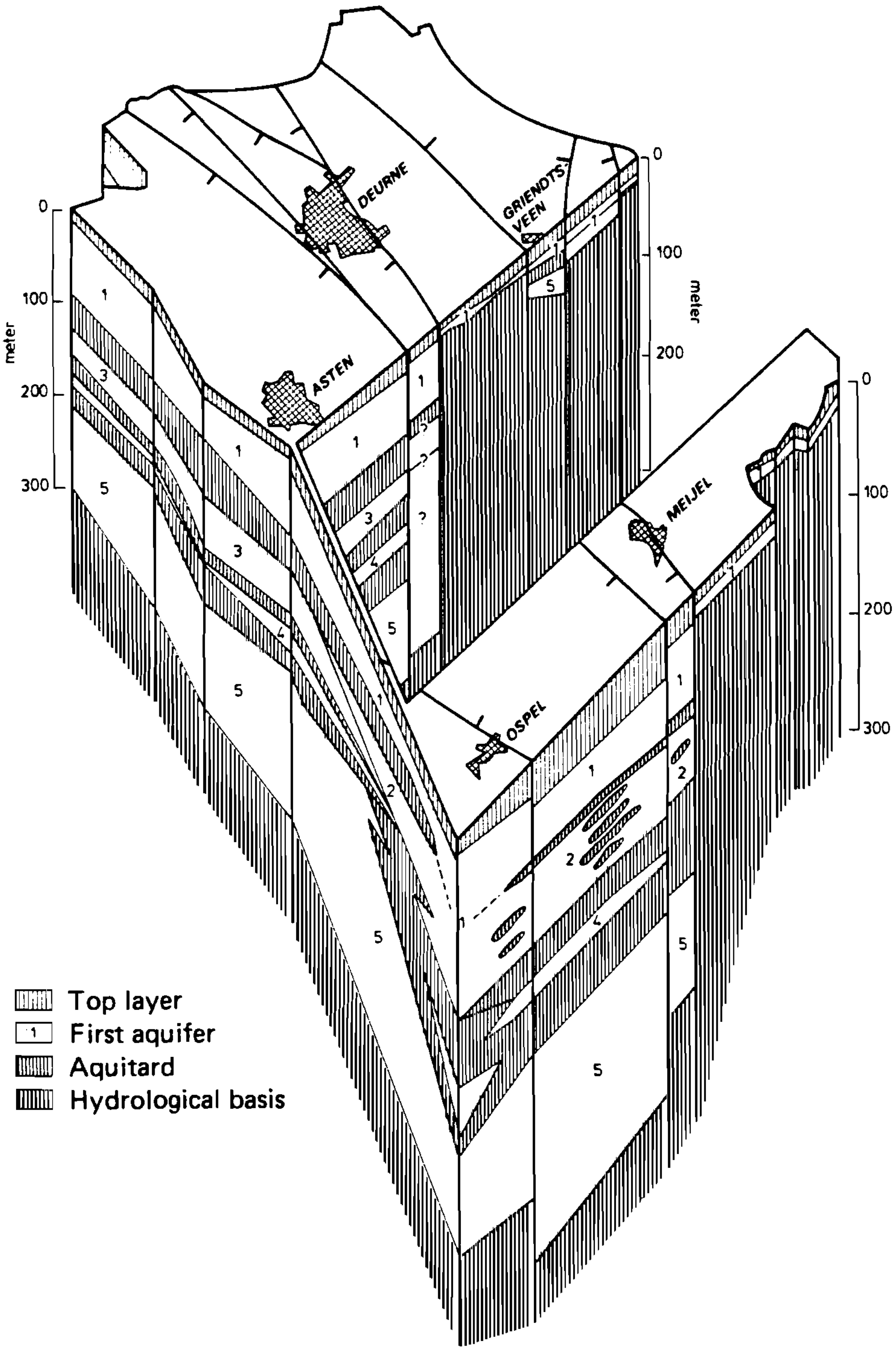


Figure 2.1.3: Schematic representation of the subsurface situation in the Southern Peel region.

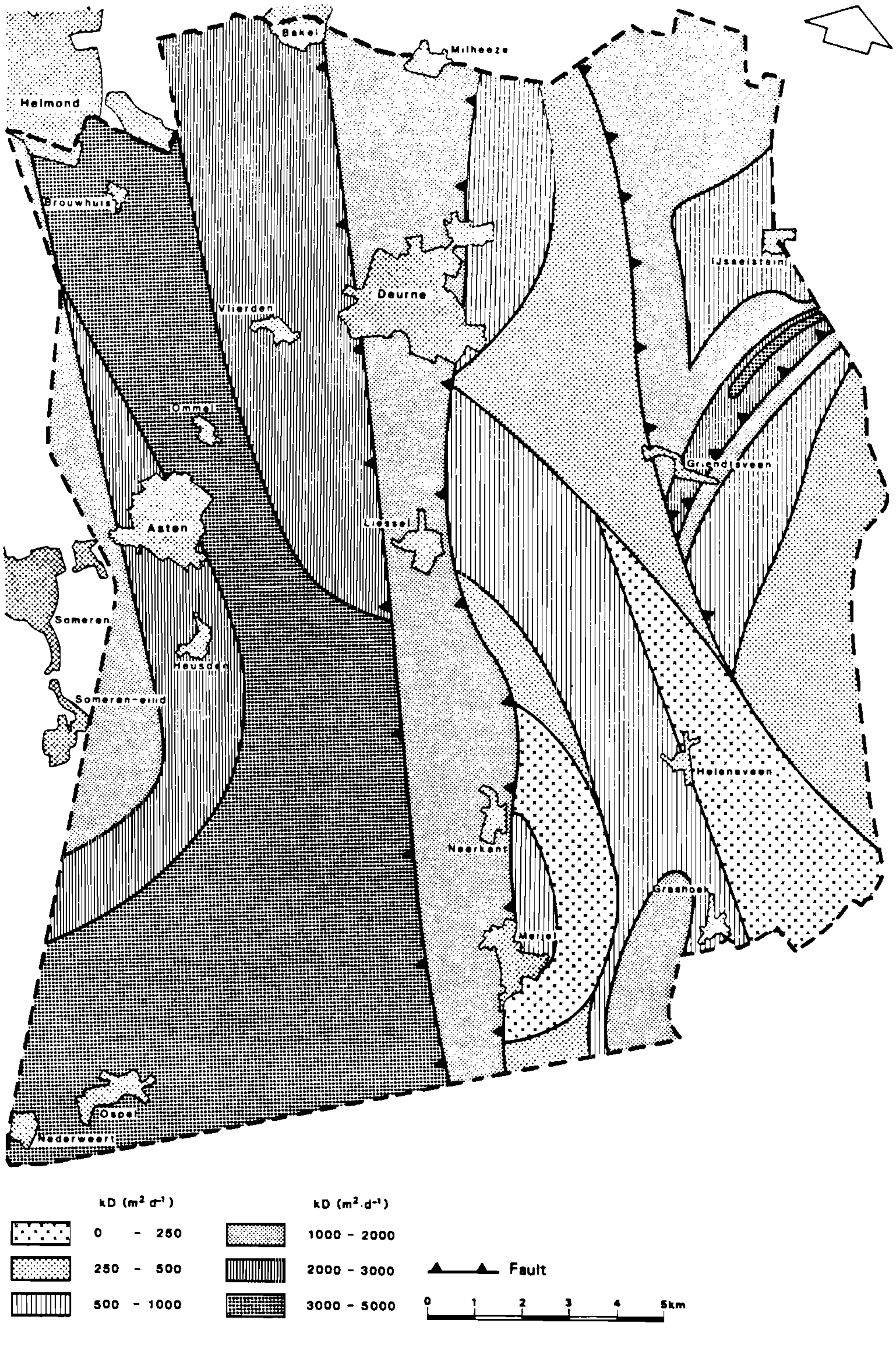


Figure 2.1.4: Map of the transmissivity (kD-values) of the first aquifer of the Southern Peel region.

- precipitation (monitored data).

The actual evapotranspiration is calculated as a residual term in the water balance equation. For these calculations the geohydrological system in the Slenk has been further simplified into one phreatic aquifer and two deep aquifers separated by an aquitard (Wit, 1985). Similar simplification is used in the hydrological models, described in Section 2.3.1 (Figure 2.1.1).

The results of the water balance calculations show that 93 % of the precipitation surplus is drained by the surface water system and 7 % by the groundwater system. For the whole region the net drainage through the second aquifer can be neglected. Considering some more specific subregions in the southern Slenk, however, it appears that the second aquifer is really important for the drainage. Dependent on local circumstances 15–100 mm of water level per year is drained to this aquifer. In more northern subregions this percolated water flows back to the first aquifer and is drained ultimately via the surface water system. It can be concluded from this phenomenon that the deep aquitard has locally a lower vertical resistance than that determined by earlier research.

In some small areas the first kD-values have been adjusted. Near the Peelrand fault the groundwater flux across the fault is very small and can be neglected, this fact in combination with a high hydraulic gradient indicates a lower kD-value. This means that the drainage of precipitation surplus across the fault takes place more than 95 % by surface water (Wit, 1985)

Surface water and ground water quality

The agricultural development in the study region is illustrated in Table 2.1.4 in this section. Changes in intensities of soil use and the fast development of factory farming have led to an over-production of manure compared with applicable quantities to different kinds of crops.

The production of nitrogen (N) and phosphorus (P) from animal slurries and the consumption of mineral fertilizers are compared in Table 2.1.1 with crop needs for the year 1980.

A relatively small part of the mineral excess is transported to regions with a low production of animal slurries. This has led to situations where excessive amounts of slurry are applied to agricultural land, especially soils with silage maize.

Table 2.1.1: Production in animal slurries, consumption of mineral fertilizers, crop need and excess minerals for nitrogen and phosphorus on agricultural land for the year 1980 in the Southern Peel.

	N (kg/ha/yr)	P (kg/ha/yr)
animal slurries	525	178
mineral fertilizer	225	18
Total input	750	196
crop use	320	26
excess minerals	430	170

The impacts on surface water quality in the watershed Diepenloop are shown in Table 2.1.2.

During the last 10 years the total-N and total-P concentrations have increased respectively by more than 80% and 45%. During the same period there was an increase in the production of animal slurry and in the consumption of mineral fertilizers amounted to 60% for N and 80% for P in total. The P-concentration in the surface water in other agricultural subregions is in the range between 0.4 and 1.0 g/m^3, which corresponds to an annual discharge of roughly 1.5 respectively 3.0 kg P per ha of agriculture land. Inputs from households are small and can be neglected. Diffuse agricultural sources are responsible for most of the discharged P. Surface runoff from agricultural soils is the most important transport mechanism. Surface runoff from fields where slurry has recently been spread contains particularly high concentrations of P and N. However, the total amount of discharged P is only 1 - 2 % of the calculated excess (Table 2.1.1). The explanation is that in sandy soils the P surplus is bound by Fe and Al. In the near future, gradually increasing amounts of P will reach surface waters via the groundwater system as the P-binding capacity of the soils is being exhausted by the high slurry dressing.

The N concentration in the surface waters in other agricultural regions is roughly of the same order as that for the watershed Diepenloop (Table 2.1.2).

Table 2.1.2: Concentration of nitrogen and phosphorus in the surface waters of the watershed Diepenloop in the periods 1971-1974 and 1981-1982 (g/m^3).

	1971-1974	1981-1982
nitrate-N	2.0	4.6
ammonium-N	1.5	2.6
organic-N	1.5	2.0
total-N	5.0	9.2
total-P	0.5	0.7

The nitrogen concentration is influenced by many factors of which the most important are: fertilization level, soil type, type of crop, hydrological situation, and land use distribution. A preliminary analysis of the results for the Southern Peel region indicates that the concentrations of nitrate and total N are closely related with the percentage of the soil used for agricultural production (Figure 2.1.5).

The variation in the soil use between the watersheds is small. Roughly one-third of the agricultural area is in use for arable crops and two-thirds is in grass. The input of nitrate to surface water occcurs via the groundwater system. In the upper parts of the groundwater system the nitrate concentrations range between 0 and 200 g/m^3.

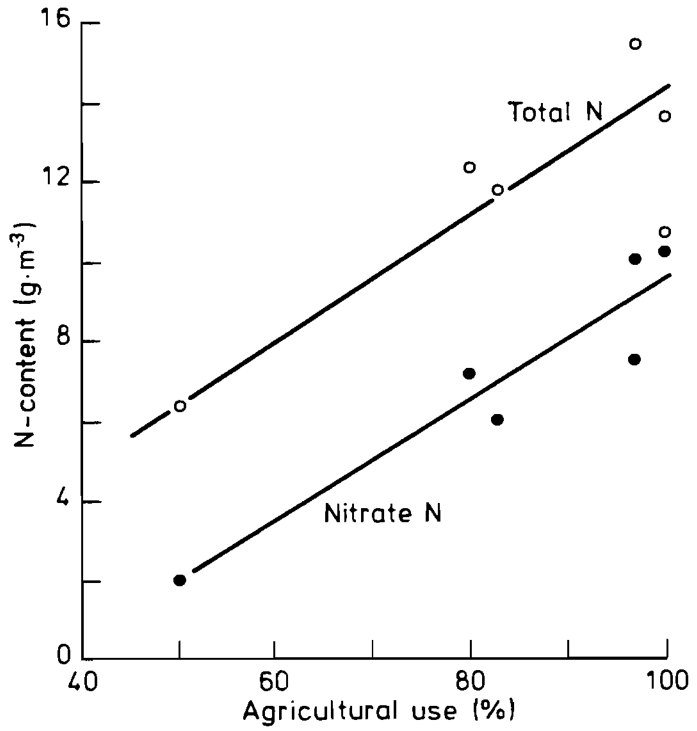


Figure 2.1.5: Relation between percentage of soil in agricultural use and concentration of nitrate and total N in the surface waters of 6 watersheds in the Southern Peel area in the period October 1981–May 1982.

At depths greater than about 5 meters nitrates completely disappear. Laboratory experiments with soil columns indicate that the denitrification in the groundwater plays an important role. Besides the denitrification the hydrological circumstances may also be a reason for a relatively undeep penetration of nitrates. Because of health aspects the European Community has stipulated that 11.3 g nitrate-N per m^3 is the highest level acceptable in drinking water wells. The water withdrawn from the deeper aquifers is percolated precipitation surplus. Because of the already high nitrate contents in the upper phreatic aquifer the drinking water companies are concerned about the future rise of nitrate content in their wells in the long run. A good example of what may occur is given in Figure 2.1.6. The figures indicated are related to wells outside of the Southern Peel region but with comparable soil use circumstances. In two wells the nitrate content has grown to alarming levels. The year indicated with the name of the pumping station gives the moment of starting with pumping (Werkgroep nitraat, 1985).

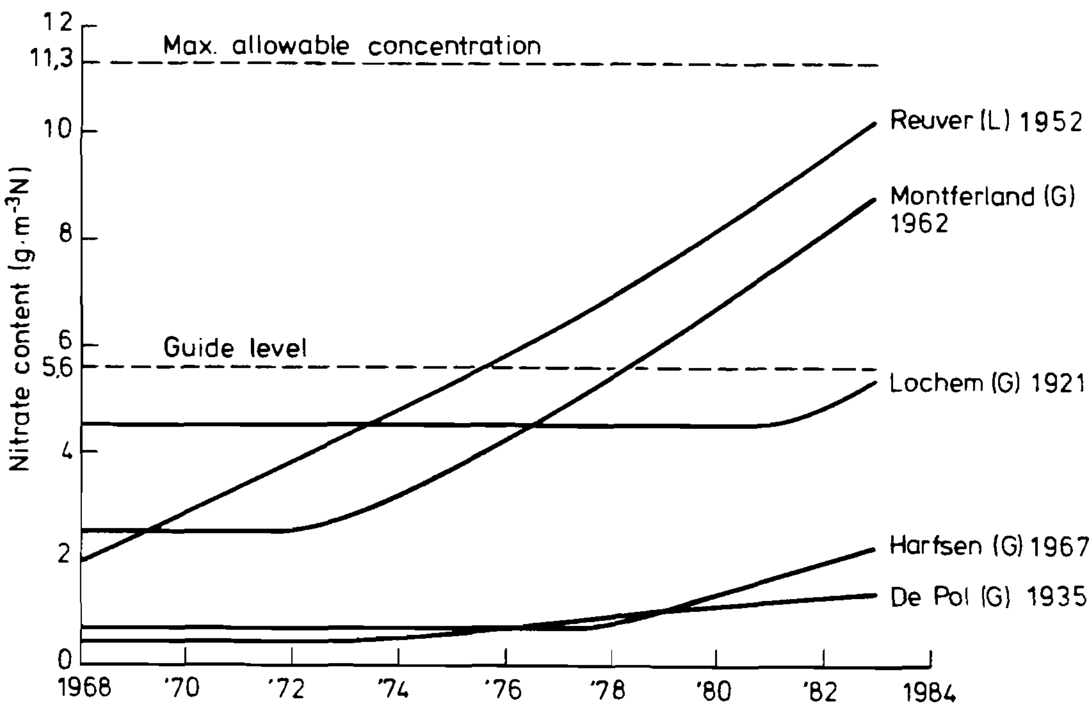


Figure 2.1.6: Course of the nitrate concentration (g/m^3) in the withdrawn groundwater for a few pumping stations in Gelderland and Limburg. The year indicated with the name of a pumping station gives the moment of starting with pumping.

Nature areas

About 10,000 years B.C. after the last glacial period, a major part of the Southern Peel was covered by vast mires located on the divide between the catchments of the rivers Meuse and Aa. Two types of nature were formed in this area: peat areas with specific oligotrophic bog vegetation and brook valleys with characteristic minerotrophic fen vegetation.

Ecologically, distinction is made between nutrient content (N and P) and mineral content (Na, K, Mg,Ca, etc.) of water. The adjectives eutrophic and oligotrophic refer to the nutrient state. The adjectives ombrotrophic and minerotrophic refer to the mineral content.

Originally, the mires became of a minerotrophic fen character, later on, with the thickening of the peat layer, the mires developed ombrotrophic bog features. Nourished by rain water, the bog became an oligotrophic and wet habitat with peat layers of 2–3 m.

Numerous brooklets were formed in this swampy area and are still streaming to the west where they finally enter the river Aa. Discharge of groundwater to the brook valleys causes wet conditions along the borders of the brooklets. This seepage water is enriched by minerals with a composition dependent of the geochemical quality of the underground. Consequently minerotrophic fen vegetation originally bordered the banks of the brooklets.

At the end of the last century peat digging for heating had been developed in this region to become a large-scale activity. Nowadays some 3000 ha of peat land remain, of which 1300 ha is located in the "Groote Peel" and 1700 ha in the Deurnsche/Liesselse and Maria Peel. Both its high natural values and its extensiveness were reasons for the Central Government to give the Groote Peel the status of a national park.

Due to reclamation works during and after the period of peat digging a lot of the brooklets has been widened, deepened and canalized to lower the groundwater levels, damaging the original fen vegetation which was replaced by fen meadows. On a small scale relicts of those fen meadows are preserved in the nature area "De Berken" on the flanks of the brook Astensche Aa.

Both types of nature areas, the ombrotrophic bogs and the minerotrophic fen meadows, are strictly dependent on wet circumstances conditioned by high ground water levels. So they are very vulnerable to groundwater lowering in adjacent areas to which they are linked by the regional groundwater system.

Public water supply

The population, industry and factory farming need in total about 7 million m^3/yr of high quality water for their use. This water is extracted from the aquifers in the Slenk area by two public water supply companies and by the industries. One pumping station extracts water from the first aquifer, the other one from the second aquifer. The resulting lowering of the ground water tables reduces the available quantity of soil moisture for crop growth and deteriorates conditions in nature areas.The quality of the extracted water is still excellent and nitrate levels in wells are hardly increasing yet. But measurements in phreatic aquifers under agricultural lands indicate that the concentrations in "water that is on its way to the wells" are alarming.

Agricultural structure

The agricultural development in the study region can be illustrated by changes in intensities of soil use and a fast increase of factory farming. Table 2.1.3 gives an idea about changes in agricultural activities during the past years.

Table 2.1.3: Development of the soil use (% of agriculture land) and factory farming in the Southern Peel.

year	grassland %	silage maize %	cereals %	horti-culture %	rest %	calves numbers	pigs numbers	chickens numbers
1940	30	0	52	2	16	600	17500	940000
1960	37	0	41	8	14	900	78500	1910000
1980	57	26	1	9	7	22800	411400	5580000

There was no silage maize in the region before 1940 and the area used for cereals was 52%. During the following 40 years the area of grassland has been increased to 57% at the cost of reducing the area of cereals. Silage maize occupies nowadays about 60% of the arable land. The figures for horticulture are related to horticulture under glass as well as outdoor horticulture. Horticulture under glass takes about 10% of the total land.

The explosive growth of factory farming is another phenomenon during that period. In economical terms such an agricultural development is very important. The region develops in that period from a poor to a prosperous area. The economy in the Southern Peel is dominated by agriculture. There is only minor industrial activity in villages. The agricultural economy is an open market type governed by price regulations of the European Community.

Table 2.1.4: Current state of agricultural soil use in the Southern Peel (CBS 1982 and Reinds 1985).

	ha	%
grassland with dairy cattle	10620	48
grassland with rearing cattle	2735	12
cereals	362	2
row crops	1360	6
silage maize	5081	23
horticulture under glass	126	1
outdoor small scale horticulture	916	4
outdoor large scale horticulture	458	2
fruit growing and arboriculture	302	1
mushrooms	5.4	-
total use	21960	100

The farms in the region are private. Besides the farmer and his family hired-labour is employed. The amount of hired labour depends on the farm size and on the farm intensity. Table 2.1.4 shows the current state of soil use in the Southern Peel. There is a lot of farmtypes in the region with a large range of size and intensity. In Table 2.1.5 the current farms are divided provisionally into 4 head-farm types and into a few sub-farm types. The figures in this table give a general impression of the diversity of the agriculture.

Table 2.1.5: The numbers of farms in the Southern Peel divided into four head-farm types and sub-farm types (% of numbers and mean farm surface (ha)).

	numbers of farms	%	mean area of land ha
livestock farming	1377		
- cattle		53	15.6
- pigs		21	
- chickens		7	3.3
- mixed(cattle/pigs)		13	11.6
- rest		6	12.4
arable farming	82		
- cereals		9	9.6
- row crops		40	13.2
- rest		51	12.2
horticulture	411		
- under glass		30	1.9
- outdoor		30	5.3
- fruit growing and arboricult.		23	4.8
- mushrooms		8	-
- rest		9	4.0
mixed holdings	185		
- livestock/arable		46	13.2
- livestock/horticulture		27	7.9
- arable/horticulture		12	15.2
- livestock/arable/horticulture		15	14.9

Many livestock farms have a certain area of land available. The farms with relatively small area of land developed themselves in direction of factory farming. Those farmers do not have enough arable land for an acceptable income. Therefore, they started with building pig houses (for feeding and breeding), calf houses (for feeding) and poultry houses for egg-laying hens or broilers. Nowadays there are many farmers specializing in factory farming without any land.

2.2 Schematization of the Region and the Structure of the Decision Support System

As we discussed in Part 1, the development of a decision support system for a concrete region starts with the schematization of the regional impacts and also of the regional decision making structure.

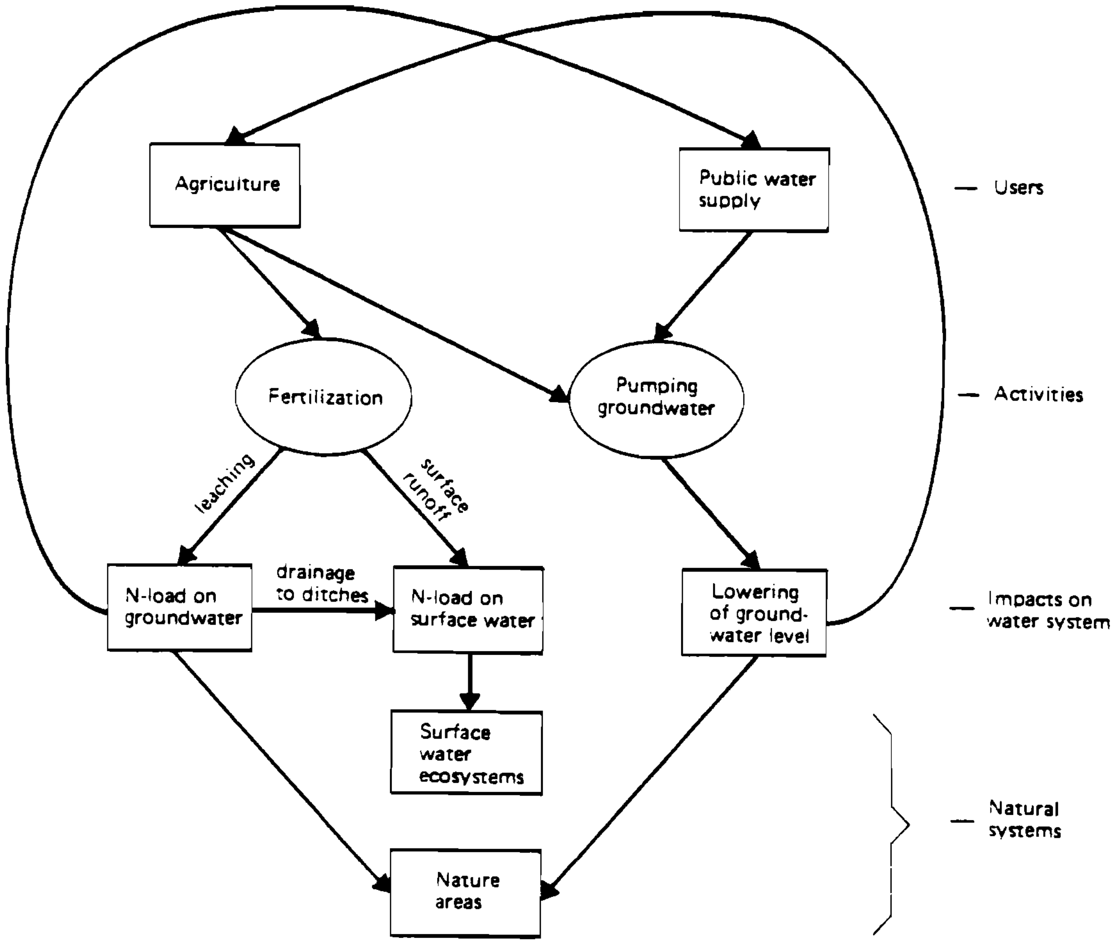


Figure 2.2.1: Impact diagram for the Southern Peel region

The impact diagram indicates major impacts of economic activities in the region and also processes that are to be taken into consideration in the analysis of these impacts. The role and the meaning of the impact diagram for the development of a decision support system has already been discussed in Section 1.2.1 and the diagram itself for the Southern Peel region has been illustrated there, but for the completeness of our presentation here we illustrate it again in Figure 2.2.1. This diagram based on the information about the region outlined in Section 2.1 shows those processes and aspects of the region that are considered in our analysis and models of which are included in the decision support systems. These models are outlined in the subsequent sections.

To further prepare grounds for formalized modeling and structuring the decision support system we shall schematically outline regional institutional aspects including possible types of decision makers as well as their actions that may be considered in a formal framework.

Institutional aspects of the region

The Regional Water Board ("Provinciale Waterstaat") is a department of the provincial government. Some of the ministries of the central government are involved in regional water management too; they are:

- Ministry of Public Works
- Ministry of Agriculture and Fisheries
- Ministry of Welfare, Health and Cultural Affairs
- Ministry of Housing, Physical Planning and Environment

Each of these ministries has its own organisations for guarding its interests and performing tasks at the regional level. The Ministry of Public Works, for instance, is responsible for infrastructure that transcends regional boundaries, like the main drainage canals, which are used for importing surface water in summer. The Ministry of Welfare, Health and Cultural Affairs has responsibilities concerning the drinking water supply for the population.

As set forth in the section on conceptual and methodological framework of this study, we will use the concept of PMA as a surrogate for the institutions mentioned above. We assume that the preferences of the PMA are related to the region as a whole and therefore reflect preferences of all regional interest groups. In this study the following interest groups are considered:

- farmers
- public water supply companies
- nature conservation groups

Reflecting the preferences of farmers the following types of indicators may be considered:

- growth rate of average income
- stability of income

For the public water supply companies the indicators are as follows:

- quantity of extracted water
- quality of extracted water.

For the nature conservation groups they are:

- diversity and stability of authentic ecotypes in nature areas
- quality of surface water.

We may also consider two types of indicators reflecting PMA's expenditures for changing the infrastructure of the region:

- costs of infrastructure for surface water supply
- costs of water purification plants.

The PMA is in the special position of being able to impose restrictions on the other interest groups, albeit that it cannot completely control their behaviour. In view of its concern for the well-being of the region as a whole, the PMA can also take decisions that involve the investment of public money in facilities for the benefit of a particular group.

The possible actions of the PMA considered may be of three different types. The first type affects the regional environmental subsystem in a direct manner, for instance, by:

- changing the allocations of imported surface water,
- investing in infrastructure for the (extra) import and distribution of surface water,
- investing in water purification plants.

The second type of action is *legislative*:

- regulating the extractions of surface water and groundwater for irrigation,
- regulating the extractions of groundwater for public water supply,
- fixing maximum applications of chemical fertilizers and slurries on land.

The third type of action is *motivative*:

- fixing prices for water used and for animal wastes application,
- subsidizing investments of farmers,
- subsidizing transport of animal wastes,
- paying damages to farmers,
- subsidizing investments of public water supply companies,
- paying damages to public water supply companies.

The actions of farmers considered are:

- changing of livestock breeding;
- changing of animal wastes disposal practices by
    - modifying the land application pattern, both temporally (by e.g. not applying in autumn) and spatially (by e.g. applying a especially contaminating type of slurry to environmentally less sensitive areas);
    - processing in a treatment plant;
    - exporting to other regions or even other countries.
- changing of the cropping pattern;

- changing of crop water supply conditions by modifying sprinkling from surface water and groundwater;
- changing of crop fertilization levels.

For the public water supply companies we consider only one type of actions:

- modifying the groundwater extraction pattern
- removal of NO3-N from extracted groundwater.

A number of the listed actions must of course be seen in conjunction with each other. It for instance does not make sense to increase the capacity of sprinkling from surface water and not also at the same time increase the allocation of surface water. Most notably, the changing of the cropping pattern and the fertilization levels should be seen in conjunction with modifying of the animal wastes application to land.

Overview of the structure of the decision support system

According to our framework described in Part 1 the overall analysis of regional water policies based on the use of a decision support system is viewed as consisting of two complementary stages: scenario analysis and policy analysis. The objective of the former is to select reference trajectories of the regional development, and of the latter – to analyse policy devices that can be effective in directing the development along the reference trajectory. The second stage analysis strongly involving subjective components of human decision making behaviour leaves less ground for formalization, and although we discuss in Section 2.8 possible developments in this direction, the greater part of the following presentation concerns the scenario analysis stage.

The scenario analysis includes two major levels: first-level screening analysis and second-level simulation aimed at the verification of preliminary selected scenarios using relatively detailed models. Consequently, the decision support system for scenario analysis includes two major parts: a system of simplified models used for preliminary selection of scenarios of regional development, and a system of relatively detailed (basic) models for simulation. The third part is an interactive software including the comparative data display part designed to support an effective participation of the PMA in the analysis.

All three parts of the decision support system and their interrelationships in the process of analysis are described in the following sections.

2.3 Description of the Basic (Simulation) Models and Modeling Concepts

As outlined in Part 1 and in Section 2.2 of this Report, detailed basic models of the major processes considered in this study are used for the formulation of corresponding simplified models used for preliminary screening of alternatives of regional development as well as for more accurate verification (simulation) of such alternatives. In this section we describe the basic models used for the study of the test region of Southern Peel. More detailed descriptions of some of these models can be found in the papers supplementing this report.

2.3.1 Dynamics of groundwater quantity (FEMSATP)

The groundwater model described hereafter has been developed to simulate the flow of water in the saturated and the unsaturated zone. Effects of irrigation and their impact on water requirements of the surface water system are also included. The model also evaluates effects of water management on evapotranspiration and groundwater depth. The existing computer program FEMSAT (Van Bakel 1978) was extended for this purpose. This program represents a quasi-three dimensional finite element model, recently modified to include a fully implicit calculation scheme and various boundary conditions (Querner 1984, part 1). The unsaturated zone formerly not represented in this model has now also been included, which has resulted in the program FEMSATP. For a detailed description of the model see Querner and Van Bakel 1984.

For the purpose of modeling the Southern Peel region is subdivided into 31 subregions, each with relatively homogeneous soil properties and hydrogeological conditions (Smidt 1983). A subregion is further subdivided into different areas characterized by land-use types, also called technologies. Technologies that do not use land are not of interest here. Therefore only technologies that use land will apply here whenever reference is made to the term technology.

The area related to each technology is expressed in the model as percentage of the total area of a subregion, and in reality can be scattered over a subregion.

The study area can be subdivided into four main categories of land-use types which are important for the calculations of the various water flows. These are agricultural areas, built-up areas, nature reserves, and forests. Each agricultural technology is subdivided into subtechnologies, representing a number of production levels. Each production level is related to water availability conditions, and higher production level would mean a greater water demand in the growing season. The demand is satisfied by means of sprinkling, where each production level has its own criterium for applying the sprinkler irrigation in terms of available moisture in the root zone. The built-up areas are split up into areas with an impermeable surface (e.g. houses, streets, etc.) and the rest. Impermeable surface areas are not connected to the unsaturated zone, and can be neglected, because the runoff from these areas enters the combined stormwater and foul sewer system. The permeable areas in towns are considered to have the same characteristics as grassland. Nature reserves can have grass or forest vegetation. Forests are considered separately because their evapotranspiration characteristics are quite different from those of grass vegetation.

FEMSATP is used to determine certain hydrological parameters, which are then used in programmes SIMCROP and ANIMO for simulation of crop yield and water quality respectively (Sections 2.3.2 and 2.3.3).

Saturated zone

Relatively detailed modelling of groundwater flows in a second level model, requires accurate representation of the hydrogeological situation. Therefore, the region has been subdivided into finite elements. The calculation of the hydraulic head for a nodal point n of an element can be written explicitly as:

$$B(n,t)\,\frac{\Delta h(n,t)}{\Delta t} = \sum Q_{nm}(n,t) + Q_e(n,t) +$$

$$+\ \vartheta \mid \sum \Delta Q_{nm}(n,t) + \frac{dQ_e(n,t)}{dh(n,t)}\,\Delta h(n,t) \mid + \qquad (2.3.1)$$

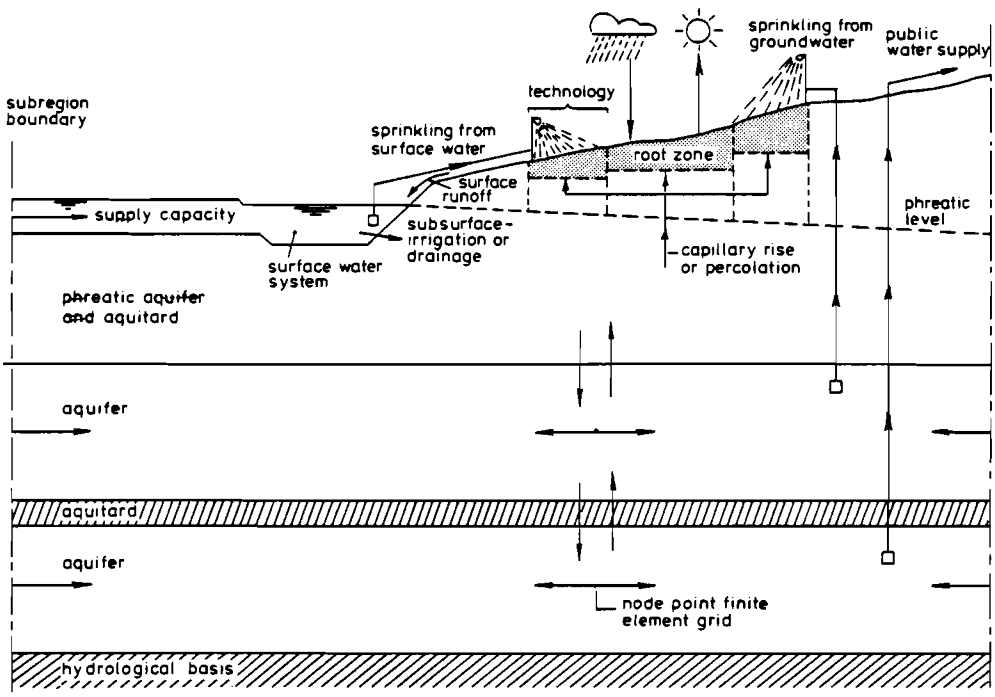


Figure 2.3.1: Schematization of flows in a subregion

$$+ Q_c(n,t) + \vartheta * Q_c(n,t+\Delta t)$$

where $h(n,t)$ is the change of hydraulic head over the time step, $B()$ is the storage coefficient, $Q_{nm}()$ is the flow of water from node n to node m, $Q_e()$ is the total of boundary flows, Q_c is the water extraction (e.g. public water supply, sprinkling, and capillary rise), and ϑ is the weighting parameter between moments t and $t + \Delta t$.

The first two terms in the right hand side of Eq. (2.3.1) represent the flows to or from node n at time t and the third and fourth term are the actual change in the flow over the timestep considered. Equation (2.3.1) requires linear relations between changes of flow and hydraulic head over a timestep. All the boundary conditions must be written as a function of the unknown hydraulic head and in this way can be substituted in Eq. (2.3.1).

For the external flow Q_e (e.g. drainage, seepage, etc.) imposed on a layer it is assumed that it depends on the hydraulic head $h(n,t)$, and that the extraction Q_c is independent of the hydraulic head. The calculation scheme used in Eq. (2.3.1) is the Crank-Nicholson approximation. It uses a central time difference, which is unconditionally stable and does not impose restrictions on the length of the time step used. In this way a time step up to ten days is feasible in general, without occurence of numerical instability.

Unsaturated zone

The unsaturated zone is modelled as consisting of two reservoirs: one for the root zone and one for the subsoil (unsaturated zone between the root zone and the phreatic level). The reservoir for the root zone simulates the storage of moisture in it with inflows and extractions such as rainfall, evapotranspiration, and capillary rise or percolation. If a certain equilibrium moisture content (moisture content corresponding to a steady situation where the capillary rise is zero) is exceeded, the excess of water will percolate to the saturated zone. If the moisture content is below the equilibrium level, the result will be the capillary rise from the saturated zone. From the water balance of the subsoil the height of the phreatic surface is calculated, using a storage coefficient which is dependent on the groundwater depth.

Ideally, the flow and retention of water in the unsaturated zone should be calculated separately for each nodal point and per technology. The groundwater depth is different for each nodal point, the actual and potential evapotranspirations differ per technology, and the capillary rise depends on the physical soil unit and the groundwater depth. With all these specific relations and different flow behaviour in the root zone it would require per nodal point and per technology a model to simulate the unsaturated zone. This would require a great amount of input data and put a heavy demand in both computer time and memory. Therefore, a simplification has been introduced that per subregion and per technology one model (reservoir) is used to calculate moisture content, evapotranspiration, and capillary rise. In this case average hydrological conditions over the subregion are used. As an example, the amount of capillary rise in a subregion is now dependent on the average groundwater depth.

The concept for modelling the unsaturated zone is described in detail elsewhere (Querner and Van Bakel 1984). The major functions are summarized below (Figure 2.3.2).

The change of moisture content Δv over a timestep Δt due to rainfall p, sprinkling igs and evapotranspiration ea is:

$$\Delta v = (p + igs - ea) * \Delta t \quad . \tag{2.3.2}$$

Evapotranspiration is a function of the type of crop and moisture content in the root zone. The measured values for net precipitation and potential evapotranspiration for grassland and forests must be available. The potential evapotranspiration for grassland was derived from open water evapotranspiration muliplied by a factor 0.8. The potential evapotranspiration for each crop and vegetation type were derived from the values for grassland by converting with known factors per technology. The potential evapotranspiration for pine-forest is calculated as the transpiration and interception. An interception reservoir of 2.0 mm and 1.5 mm was taken for the summer and winter period respectively (Working group evaporation 1984).

Without considering percolation or capillary rise the moisture content for the next time step would be:

$$v = v(t) + \Delta v \tag{2.3.3}$$

The equilibrium moisture content in the root zone is a function of soil physical properties s, the groundwater depth h^* and the thickness of the root zone rz. If the moisture content v exceeds the equilibrium value, percolation occurs, otherwise capillary rise is effective. Therefore:

$$vz = f\{s, h^*, rz\} \quad , \quad v < v_{eq} \tag{2.3.4}$$

or

$$vz = \frac{v_{eq} - v}{\Delta t} \quad , \quad v > v_{eq} \quad , \tag{2.3.5}$$

The moisture content for the next time step can now be calculated as:

$$v(t + \Delta t) = v + \Delta t \cdot vz \tag{2.3.6}$$

This model concept was verified with results from a more accurate model SWATRE (Belmans et al. 1983). For sandy soil evapotranspiration and capillary rise in winter did not differ, but for the summer period the simple model gave 3–8% lower actual evapotranspiration, possibly caused by an underestimation of the capillary rise.

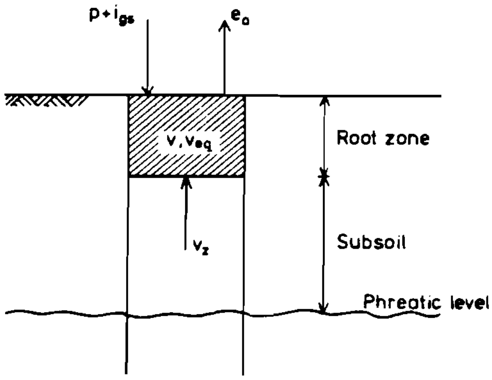


Figure 2.3.2: Schematization of unsaturated zone

In practice sprinkling is operated following a rotation scheme along separate fields. The sprinkling is continued as long as the soil moisture content is below a certain level. The second level model cannot be used for a fully realistic simulation of sprinkling according to a rotation scheme, so it is assumed that sprinkling is operated depending on the production levels of technologies. A rotational scheme of 7 days per technology has been used. A higher production level implies higher water demand, which results in more frequent sprinkling. The criteria of applying sprinkling, therefore, depends on the production level and the relative moisture content in the root zone.

Surface water

The interaction between the surface water and groundwater systems is modelled by means of so-called tertiary and secondary surface water systems. The tertiary system consists of shallow ditches that are intermittently filled with water. The secondary system consists of larger channels, that are nearly always filled with water and the level can be controlled in order to regulate drainage or subsurface irrigation.

The drainage or subsurface irrigation is calculated per node with the equation due to Ernst (1978) as:

$$us(n,t) = \frac{ht(n,t) - h(n,t)}{gf \cdot Yt} + \frac{hs(n,t) - h(n,t)}{gf \cdot Ys} \quad . \qquad (2.3.7)$$

The first term on the right hand side is the discharge to the tertiary system and the second term is the discharge to the secondary system. In the above relations ht is the water level in the tertiary system, hs is the water level in the secondary system, Y is the drainage resistance, and gf is a geometry factor to convert the hydraulic head midway between two ditches to the average hydraulic head calculated for a nodal point. When there is no water in the ditches of either type, the invert level is taken instead for ht and hs.

The functioning of the surface water system for the summer and winter situation is different, and therefore they require each to be modelled separately according to their special characteristics. The summer situation is in general characterized by supply of water. This supply is limited by a certain maximum capacity. Water is extracted from the system for sprinkling and subsurface irrigation. In the normal situation the supply capacity is sufficient to keep the water level at its target level. The supply capacity used for the next time step is calculated directly from other external flows. In the case of a shortage of water the supply capacity is not sufficient to maintain the target level and the water level in the surface water system will drop. From the new storage capacity the water level can be calculated using a given stage-storage relation. The lowering of the water level reduces the amount of subsurface irrigation, until a new equilibrium situation is reached.

In the winter situation drainage of water will dominate. The discharge of water from the subregional surface water system is dependent on weir structures and the capacity of the main outlet channels in the subregion. These effects are simulated with a stage-discharge relation. With the above calculated water level per subregion as a depth below ground level, the actual water level for each node in a subregion can be calculated per nodal point from the given ground level. The reason for this approach is that the ground level over a subregion can vary by some meters. If one level for the surface water system would be taken, it would result in ditches with no water and other with bank full stage. An ideal approach would be by using one reservoir per nodal point, but this would require an excessive amount of input data and computer time.

In the model the surface runoff is computed as shallow subsurface flow and flow over the soil surface to a network of ditches with a drainage base at 0.20 m below ground level. So the surface runoff is computed in a manner analogous to the drainage and subsurface irrigation. Therefore, relations describing the surface runoff are included in the set of relations describing the interaction between the surface water and the groundwater.

Model data

For modelling the saturated groundwater the required data include: layer thickness, vertical resistance, hydraulic conductivity, specific storage, and drainage resistance. As time dependent input data one requires information concerning the flow of water over the regional boundary and extractions in the region. The drainage resistance has been derived from the density of the ditches and brooks. To simplify the derivation of the drainage resistance as a function of groundwater depth, six different classes of drain density have been distinguished (classes A to F). The classes A to F refer to an overall density of ditches and brooks per subregion. Class A has a dense drainage system and class E has hardly any drainage. Class F refers to the two nature reserves in subregions number 16 and 27.

For modelling the unsaturated zone the necessary data are: area per technology, soil physical properties, root zone depths, equilibrium moisture content, capillary rise, and the storage coefficient. The capillary rise and storage coefficient are calculated using the program CAPSEV (Wesseling, Bloemen and Kroonen, 1984). Time dependent input data are daily precipitation and potential evapotranspiration.

For the surface water system of a subregion the storage capacity, a stage-discharge relation for drainage situations, and a summer target level are required.

Verification

In the model FEMSATP the hydrological processes are modelled as realistically as possible, but a lack of data and required computational effort can influence the results to a certain degree. The hydrological schematization and the input parameters are verified by comparing the results of FEMSATP with field measurements. A sensitivity analysis on the hydrogeological parameters is done to determine the accuracy of the results.

The verification is done by comparing measured groundwater levels in eight points during a year. From these results it can be concluded that the calculated results in the Slenk area (left hand side of Peelrand fault) resemble the measured data very well and that in the Horst area (right hand side of Peelrand fault) some differences occur. The calculated levels of the first aquifer for August 1982 are compared with the measured values. In Figure 2.3.3 the isoline patterns of the calculated and measured levels are shown. The calculated map shows a more regular pattern, because in the case of measured values there may be all kinds of local anomalies and also errors in the measurements. Another difference is the more smooth transition in the calculated values in the neighbourhood of the Peelrand fault, caused by the relative coarse nodal network. In general, however, the resemblance between calculated and measured isoline patterns seems satisfactory.

For the sensitivity analysis various parameters have been varied to analyse the effect of this variation on the results. The outcome shows that:

- variation of groundwater depth at the beginning of the summer half year is more pronounced then at the end of the period,
- groundwater depth at the beginning of summer is dominated by the drainage resistance,
- selection of the soil physical unit is important for the correct estimation of the results at the end of the summer period,
- variation in the geohydrological parameters has hardly any effect on the total sprinkling, actual evapotranspiration, and capillary rise.

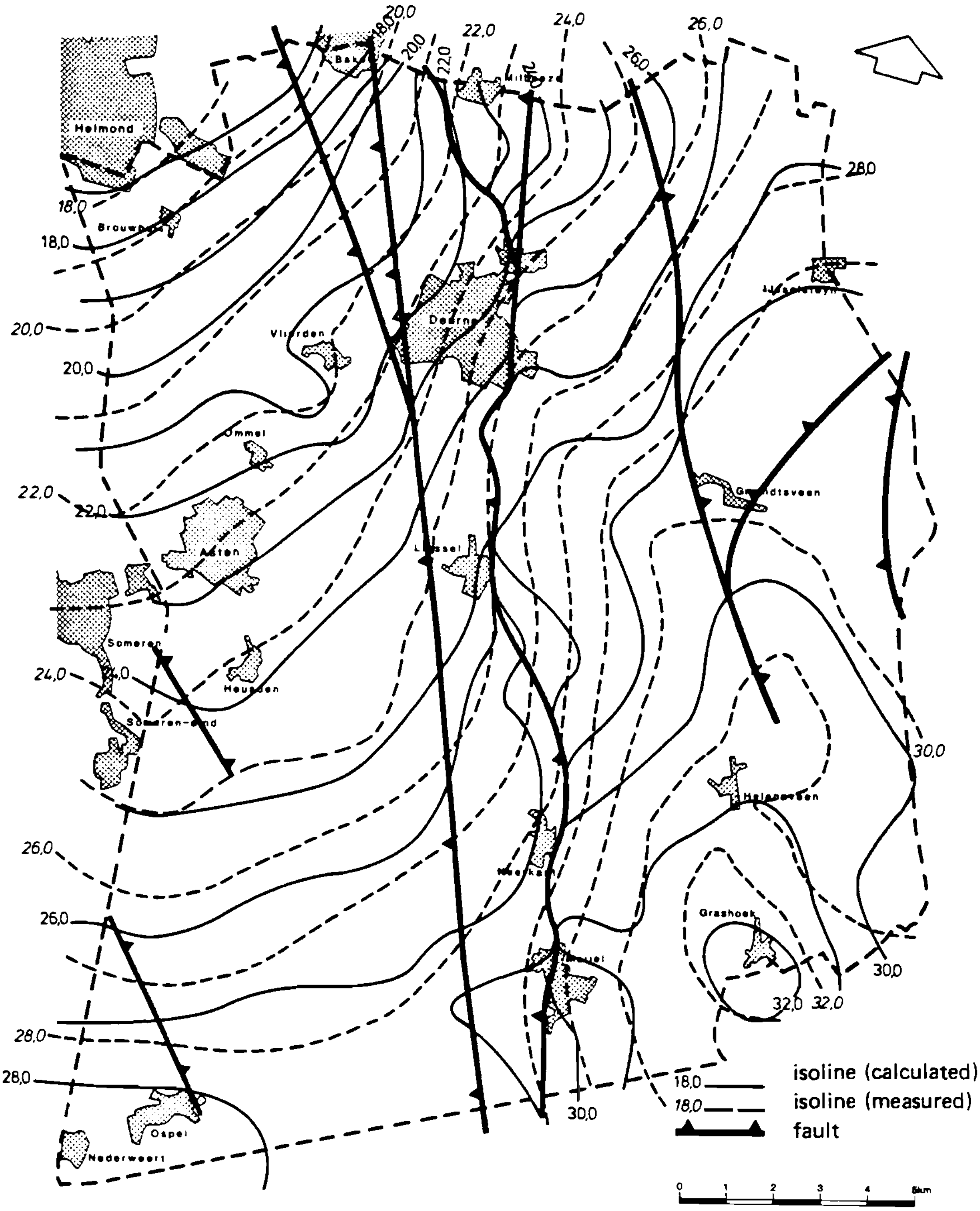


Figure 2.3.3: Measured and calculated hydraulic heads for the first aquifer

2.3.2 Processes of crop growth (SIMCROP)

Introduction

Regional water management plays an important role in agricultural crop production. If certain changes in water management take place, then the important question arises, what is the effect of these changes on agricultural crop production in a region and in connection with this: what is the effect on net income.

It is well known that water shortages cause reduction in transpiration and hence in crop production. If one is able to determine the relationship between transpiration and crop production it will be possible to evaluate effects of water use in the field on crop production. Effects of ground- and open-water level manipulation can then be translated into effects on crop production by means of the intermediate variable of transpiration.

A crop production model that quantifies the effects of water management on dry matter crop yield has been developed by Feddes, Kowalik and Zaradny (1978). They have given a mathematical formulation of crop growth rate as a hyperbolic function of the (normalized) transpiration. The daily production of a crop depends on a water use efficiency factor or/and the potential growth rate during a day mainly determined by solar radiation. The water use efficiency factor and other crop parameters have been derived by using field measurements over a number of years.

Ideally, such production models should be applied separately for each type of crop. Unfortunately the necessary parameters have not been determined for all crop species so far. Therefore, the estimation of the agricultural production in the Southern Peel region has been based on the crop production of potatoes. For potatoes long series of observations are available and the model has been verified extensively (Feddes, Wesseling and Wiebing 1984). Yields for other crops are related to the production of potatoes. A full description of the agricultural production model, called SIMCROP, is given elsewhere (Querner and Feddes 1985).

For the simulation of agricultural crop production one requires actual transpiration data. The crop transpiration depends on the development stage of that crop, meteorological and soil moisture conditions. For the calculation of evapotranspiration the hydrological model FEMSATP is used (see Section 2.3.1). The evapotranspiration rate calculated in the hydrological model is then partioned over the transpiration and soil evaporation, as a function of the leaf area index.

Dry matter production of potatoes

Daily actual dry matter growth rate qa with optimal nutrient supply can be calculated from the equation (Feddes et al, 1978):

$$(1 - \frac{qa}{A \cdot T / \overline{\Delta e}})\ (1 - \frac{qa}{qm}) = \xi \tag{2.3.8}$$

where A is the maximum water use efficiency determined from field experiments, T is the transpiration rate, $\overline{\Delta e}$ is the average vapour pressure deficit of the air, qm is the maximum possible growth rate, and ξ is a mathematical parameter. The relationship is shown in Figure 2.3.4.

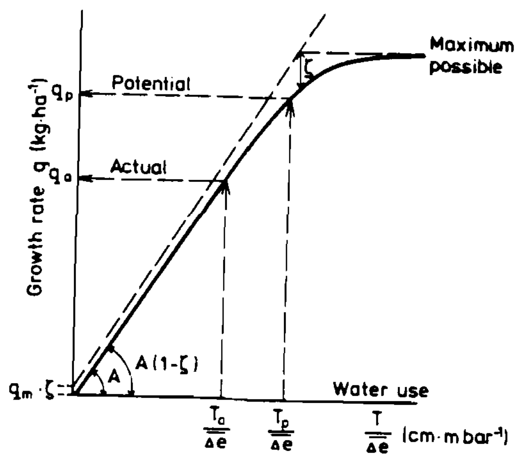


Figure 2.3.4: Actual growth rate versus the growth factor water described as a non-rectangular hyperbola

The development of a crop with time varies from year to year, depending on environmental conditions such as temperature, day length, soil moisture, etc. Therefore, a dimensionless development stage Ds of a crop has been introduced as:

$$Ds = \frac{t - tm}{th - tm} \tag{2.3.9}$$

where t is the time considered, tm is the emergence date and th is the harvest date.

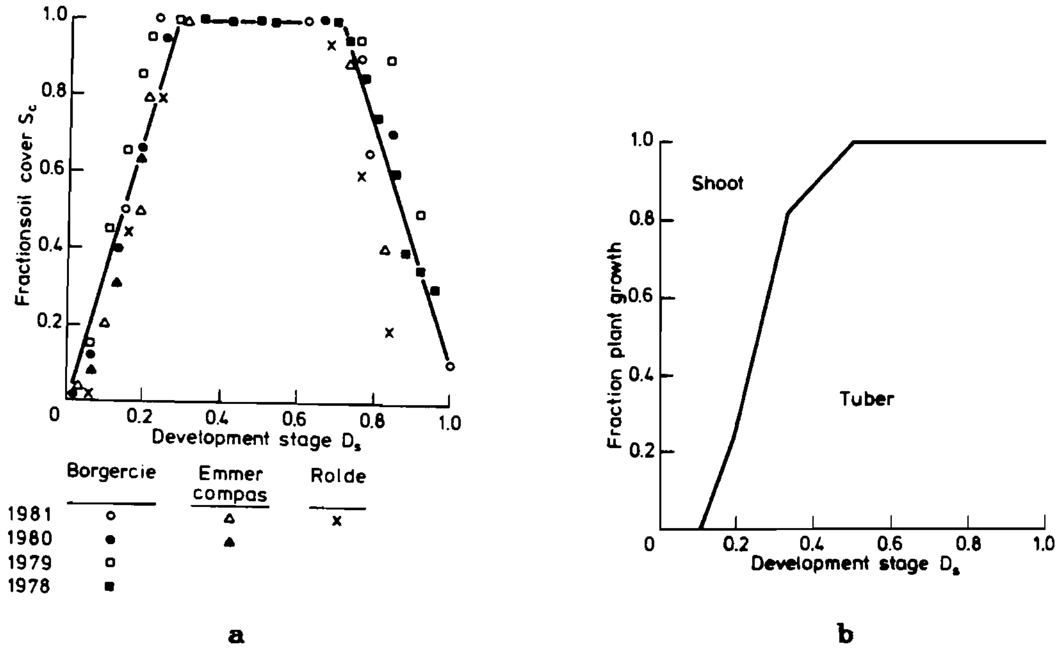


Figure 2.3.5: **a** - Variation of soil cover with development stage for potatoes grown at different places over a number of years
b - Distribution of increase in total dry matter production over shoot and tubers

Analyses of a long series of data from field experiments for two different varieties of potato showed that variation of soil cover Sc with the development stage is approximately constant over years (Figure 2.3.5a). Because there exists a fixed relationship between the leaf area index I and fraction of soil cover Sc:

$$I = 2.6\, Sc + 1.5\, Sc^2 + 0.9\, Sc^3 \quad , \tag{2.3.10}$$

one can link soil cover to leaf area index at various crop development stages. Solving Eq. (2.3.8) for the actual dry matter growth rate qa and actual transpiration rate Ta, one obtains:

$$qa = 0.5 \cdot [A \cdot \frac{Ta}{\Delta e} + qm - \{(qm + A \cdot \frac{Ta}{\Delta e})^2 - 4qm \cdot A \cdot \frac{Ta}{\Delta e} \cdot (1 - \xi)\}^{0.5}] \tag{2.3.11}$$

In a similar way one can calculate potential growth rate qp at potential transpiration rate Tp. Depending on the development stage, the increase in total dry matter for each time step is distributed over the shoot and tubers (Figure 2.3.5b). Having calculated the actual growth rate, the final dry matter yield of potato $Q(p)$ is obtained by summation of the production per time step from emergence to harvest time. The length of the time step used depends on the values of evapotranspiration rates obtained from the hydrological model FEMSATP.

Yields of other crops

The dry matter yield for potatoes is converted to total fresh yield. Having calculated this actual $Qa(p)$ and potential $Qp(p)$ yield of potatoes, the potential fresh yield of other crops is estimated as:

$$Qp(j) = F(j) \cdot Qp(p) \tag{2.3.12}$$

where $F(j)$ is the conversion factor to derive the potential production for the crop considered. The actual production is calculated as:

$$Qa(j) = \frac{Ea(j)}{Ep(j)} \cdot Qp(j) \tag{2.3.13}$$

where the ratio of the actual, E_a, to potential, E_p, evapotranspiration is considered over the period from emergence to harvest time of the crop.

Having obtained the yield under optimal nutrient supply, one has to correct for the actual nutrient supply, of which nitrogen is the most important. A reduction factor n dependent on the ratio of actual to optimal nitrogen supply is introduced (Feddes and Rijtema 1983) as:

$$n = 1 - a(1 - Na/No)^b \quad \text{for} \quad 0 \leq Na/No \leq 1 \tag{2.3.14}$$

$$n = 1 - c(Na/No - 1)^d \quad \text{for} \quad Na/No > 1 \tag{2.3.15}$$

where Na is the amount of nitrogen applied plus the amount available in the soil and No is the demand for optimal crop production. The coefficients a to d are derived from the lines shown in Figure 2.3.6.

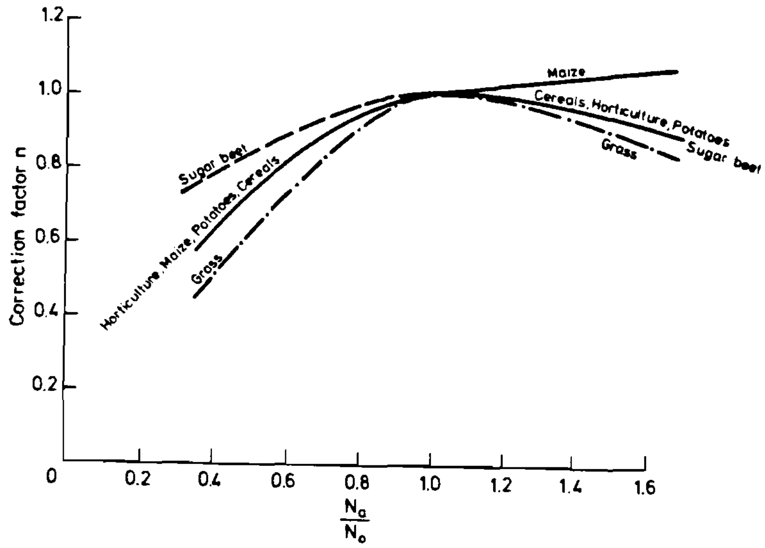


Figure 2.3.6: Reduction in crop production dependent on the nitrogen applied and available in the soil

Finally one has to correct the theoretical yield as calculated, for factors other than those included in the model. They are, for instance, reduction due to lack of management and occurence of diseases. Hence the actual yield has been multiplied by a factor 0.65–0.85 to reach yields that are found in practice.

Income

The income from agricultural crop productions can be determined as:

$$Y(j) = Qa(j) \cdot M(j) - C(j) \qquad (2.3.16)$$

where $M(j)$ is the market price and $C(j)$ are all costs related to the production process, such as replacements, fuel, fertilizer costs, etc.

2.3.3 Quality of groundwater model (ANIMO)

The model ANIMO simulates nitrogen processes in a soil-water-plant system, influenced by:

- soil type,
- soil use,
- water management,
- weather conditions,
- fertilizer use,
- cropping history

using a one-dimensional soil system divided in a number of horizontal layers. In its present form the model can be used on a field scale; the structure of the model, however, gives a possibility of extension to regional use; this extension is now under development (Berghuijs-van Dijk, Rijtema and Roest 1985). The main attention is focussed in the model on the following aspects:

- mineralization/immobilization of N in relation to formation and decomposition of different types of organic matter (organic fertilizer, root material, root exudates, native soil organic matter)
- denitrification in relation to (partial) anaerobiosis and the presence of organic material
- transport, formation and decomposition of NO_3, NH_4 and soluble organic matter.

The model is intended to give predictions for the long term nitrate contamination of groundwater and surface water as well as for the development of organic matter qualities of the soil profile under consideration.

Short Description of Nitrogen Behaviour in Soil

Nitrogen balance of the topsoil

If we consider the topsoil, the part down from the soil surface where agricultural activities concentrate, the nitrogen balance for this system can be illustrated by Figure 2.3.7.

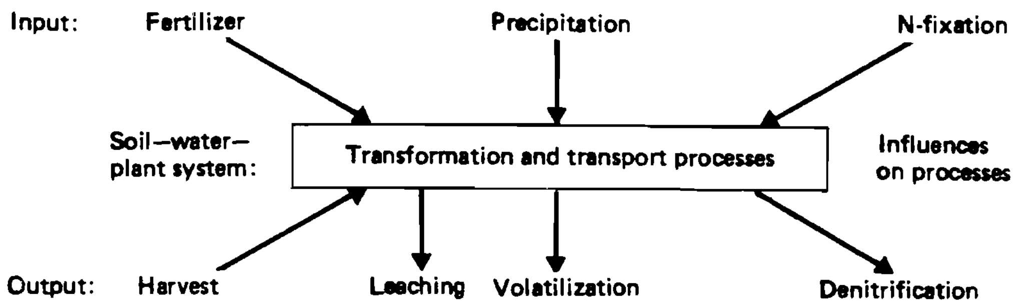


Figure 2.3.7: Nitrogen balance of the topsoil

Inputs of nitrogen can originate from fertilization, inorganic or organic (manure), and soluble N-forms in precipitation. In the soil–water–plant system different forms of nitrogen can be transformed into each other, and some can be transported as solutes to deeper layers. These processes are influenced by environmental factors like temperature, moisture, and pH. The processes and their influencing factors will be qualitatively described in the next two sections. Nitrogen leaves the topsoil by means of harvest, leaching to deeper layers, and by volatilization (gaseous loss of NH_3) and denitrification (gaseous loss of N_2 and N_2O).

Transformation processes

Nitrogen can occur in different forms in soil, which may be transformed into each other through the processes in the nitrogen cycle (see Figure 2.3.8). To understand some of these processes it is necessary to take a look at some processes in the carbon cycle, too, because of the many interdependences between organic material and nitrogen. Figure 2.3.9 illustrates the simplified soil organic matter or carbon cycle in soil.

For convenience, we shall call dead plant parts and organic parts of manure added to soil "fresh organic material". When this material starts to decompose, it is partially oxidized to CO_2 and H_2O and partially transformed into soil organic matter or biomass. The ratio (formed soil org. mat./total amount of fresh organic material decomposed) is called the assimilation factor. At least some of these transformation processes take place via the

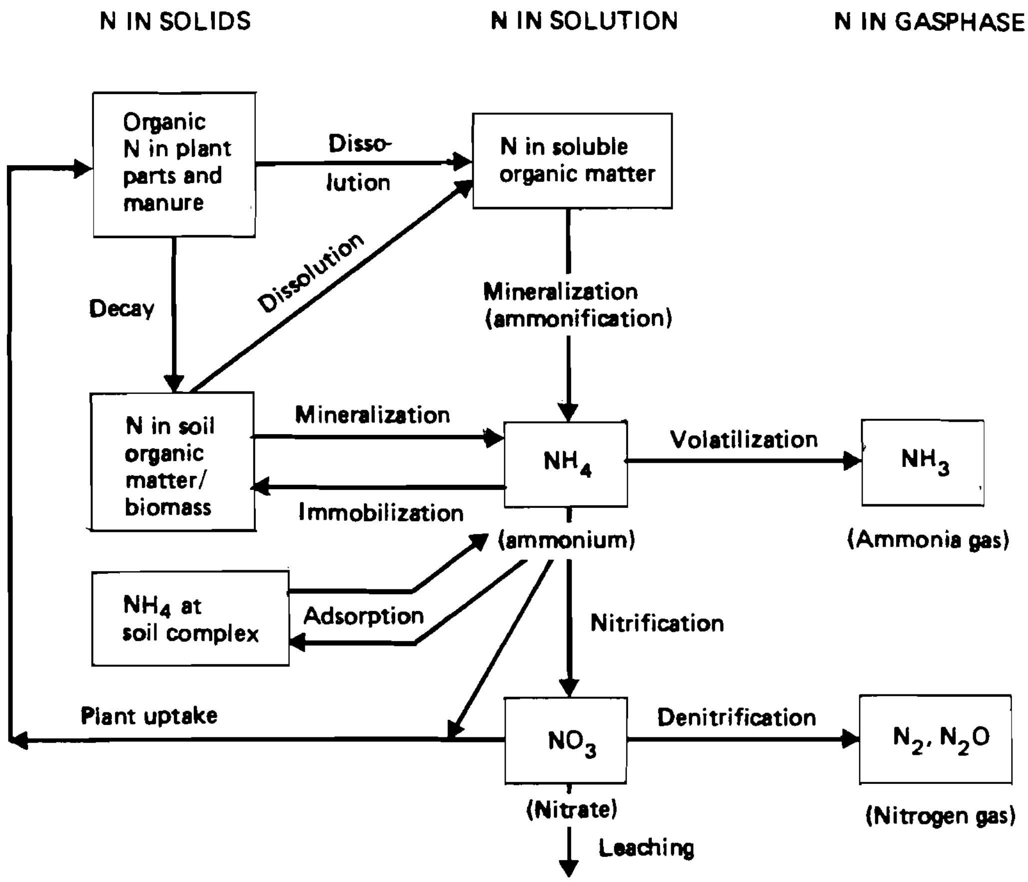


Figure 2.3.8: The nitrogen cycle

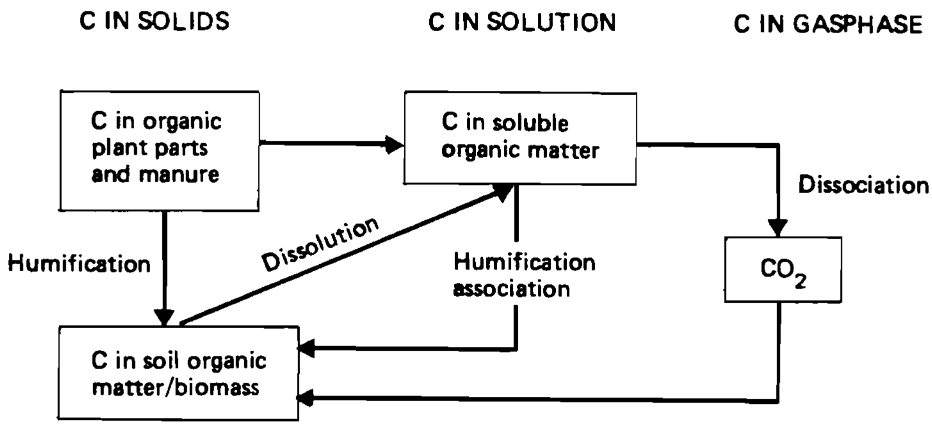


Figure 2.3.9: The carbon cycle

stage of soluble organic matter. The first step in the decomposition process when big solid molecules like cell walls are involved (cellulose, hemicellulose, pectine, lignine) is a splitting up of these molecules to smaller parts. Micro-organisms use exo-enzymes (operating outside the micro-organisms cell) to perform this task. Generally speaking, the smaller the components formed, the higher their solubility is. The smaller molecules can be taken up by the micro-organism cell to be decomposed further. The soil organic matter formed, in its turn, decomposes to CO_2 and H_2O, but at a much slower rate than the organic plant parts. The biomass (micro-organisms) decomposes and renews itself at relatively high but often unknown rates; we can ignore this turnover process, and consider formation and decomposition of biomass as the same kind of process as formation and decomposition of soil organic matter. Because it is quite difficult to distinguish experimentally between the small fraction of living biomass and the total amount of dead soil organic material, these two are often taken together in descriptions, as is done here. During their life, living plant roots excrete soluble organic materials into soil solution; also, dead root cells become available for decomposition; these products are called root exudates; they partake in the carbon and nitrogen transformation cycles, too.

The different organic materials mentioned contain nitrogen as well as carbon (except CO_2), so that transformations in the carbon cycle correspond to transformations in the nitrogen cycle. The processes in the nitrogen cycle which are not directly parallel to those in the carbon cycle, will now be described shortly.

Decay

Generally, the formed soil organic material/biomass has a high N content as compared to plants.

Mineralization

During the decomposition process of organic material mineral N may be released into soil solution in the form of the NH_4^+ ion.

Immobilization

This is the process of NH_4^+ uptake from soil solution during the formation of biomass/soil organic material. If the nitrogen content of the plant parts or soluble organic material is high and the assimilation factor is low, the decomposing material will contain enough N to provide for the N needed to build in the biomass/soil organic matter. The N released into soil solution is the so-called net mineralized N. If the nitrogen content of the plant parts or soluble organic material is low and/or the assimilation factor is high, additional nitrogen may be needed for the formation of biomass/soil organic matter, and this extra nitrogen is taken up from the soil solution. This process is called net immobilization of mineral nitrogen.

Adsorption

The ammonium ion with its positive charge can be adsorbed onto the soil complex consisting of negatively charged clay minerals and organic matter.

Nitrification

The oxidation of ammonium to nitrate is called nitrification. The process takes place in two steps, performed by different groups of micro-organisms:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^-$$

Under normal circumstances the second step is much faster than the first, so that no accumulation of NO_2^- (nitrite) will occur.

Volatilization

This is the process of the formation of ammonia gas from NH_4^+:

$$NH_4^+ + OH^- \rightarrow NH_3 + H_2O$$

which causes gaseous losses of nitrogen from the topsoil.

Denitrification

Denitrification is the process through which organic material is oxidized in the absence of oxygen. Under anaerobic conditions nitrate can be used instead of oxygen as an oxydizing agent. The nitrate itself is transformed into N_2 or N_2O during this process. As an example the aerobic and anaerobic decomposition of glucose is given:

Aerobic: $C_6 H_{12} O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Anaerobic: $C_6 H_{12} O_6 + 4NO_3 \rightarrow 6CO_2 + 6H_2O + 2N_2$

The denitrification process is another way in which nitrogen can leave the soil system.

Plant uptake

NH_4 and NO_3 can be taken up from soil solution by the plant roots by means of the transpiration flux or through diffusion. Although generally NH_4 is preferred by the plant, it is often less available than NO_3 because of adsorption to the soil complex and, under aerobic conditions, because of the rapid transformation into NO_3, so that in practice the main uptake will consist of NO_3.

Transport processes

The soluble species considered in the N- and C-cycle, NO_3, NH_4, and soluble organic matter, can be transported with the different occuring water fluxes (see Figure 2.3.10):

Transpiration and drainage fluxes extract water and solutes from the soil system; capillary rise and evaporation are upward fluxes to and from next layers; leaching is a transport to deeper layers. Because of its negative charge the nitrate ion is not retained by the soil complex and the whole nitrate content of a layer can be transported directly with the water fluxes; from the ammonium ion with its positive charge only the not-adsorbed part is transported.

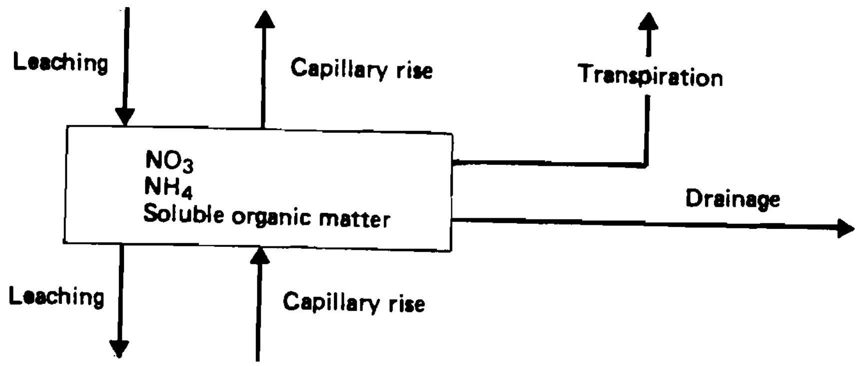


Figure 2.3.10: Transport of soluble N forms to and from a soil layer

Factors influencing the processes

The main environmental factors influencing the transformation processes are temperature, moisture, oxygen, and acidity (pH).

Temperature

For chemical processes, the rate generally increases with temperature (when equilibrium reactions are considered concentrations are often more important than temperature). For biological processes, often involving with enzymes, there is an optimum temperature (range) below and above which the rate decreases. Because the optimum temperature for biological processes is often around 30° C or higher, we can say that for temperatures occuring in soil, biological and chemical reaction rates both increase with temperature. For some processes in the nitrogen cycle this influence has been studied specially (van Huet, 1983). The reaction rates at temperatures considered can be expressed relative to the maximum rate found, so that a reduction factor for temperatures below the optimum on the reaction rate can be applied in calculations. For mineralization or mineralization combined with nitrification many of these studies exist, giving comparable results. However, we must realize that the mineralization rate is first of all determined by the decomposition rates of organic materials and by their nitrogen contents. So, to get a straightforward relation for temperature influences, they should be studied relative to organic matter decomposition. Nitrification increases with temperature; however, the process is more determined by the presence of oxygen; under aerobic conditions nitrification is so fast that ammonification is the rate limiting factor. Denitrification increases with temperature, but this is completely due to the increase of organic matter decomposition with increasing temperature.

Summarizing we can conclude that the most important temperature influences are those on organic matter decomposition. Other temperature influences follow from these or are less important.

Moisture and oxygen

These two factors are strongly related in soil and are therefore treated together. Micro-organisms need moisture to perform their functions. Below wilting point these are disturbed. At low moisture suction reaction rates may slow down by dilution effects or, if oxygen is needed, by absence of oxygen. For mineralization, most authors found a relation with moisture suction showing an optimum near pF 3. If, however, they used topsoil samples for their studies, which are often aerated in field situations, the decrease in mineralization rate at low suction may be due to the necessity for adaptation of the microflora from aerobic to (facultative) anaerobic species the adaptation of which in a poor growth medium as soil is, takes time. In a soil sample used to wetter conditions the decomposition rate may be equal to the optimum found at pF 3. For nitrification, also a relation with a optimum is found. The rate decrease at low suction is, however, determined by a shortage of oxygen. For denitrification it is obvious that the rate of the process increases with lower moisture suction, because this implicates decrease of oxygen availability. Denitrification in unsaturated soil is a result of the presence of anaerobic soil aggregates (partial anaerobiosis). The texture of the soil plays an important part in this aspect. Summarizing, the reduction on mineralization at low moisture suction is important, and oxygen content and distribution are important influences on the processes of nitrification and denitrification.

Acidity (pH)

The value of pH is dependent on the type of reaction and on the preference of the micro-organisms involved. Measurements by several authors indicate a broad optimum pH range for mineralization, nitrification and denitrification (van Huet, 1983). The pH of most soils falls within this range. A reaction that is particularly pH-sensitive is volatization, which is intensified at high pH.

By combining some facts mentioned before we can get an idea of the main factors determining the extent of nitrate leaching on field scale. These are:

Presence of nitrate in solution, influenced by:

- The amount of N added by mineral fertilizers and manure:
  the higher the amount of mineral fertilizer applied, the higher the percentage leaching.
- The rate of formation of NO_3, which is favoured by temperature, high N-content of organic materials added and aeration
- The rate of disappearance of NO_3 from solution, favoured by high moisture conditions and available organic materials.

Soil and water management, as expressed in:

- The presence of a crop: if a crop is present, nitrate added or formed may be taken up by the plant roots. If not, nitrate is subject to leaching. As a result, on arable land after the harvest, when the complete root material starts to decay, all the formed nitrate can be transported to deeper layers, except the part that can be denitrified. On permanent grassland this danger is less.
- The time of application of fertilizer or manure:
  Application in spring or summer is the most favourable for crop nutrition on arable land, because of direct availability of nutrients and low possibility of losses by leaching and denitrification; leaching is mostly limited to wet periods (winter time).

- The rate of water transport to the subsoil:
  In deeply drained soils the retention time of water and solutes in the rootzone is small, and the denitrification possibilities are also small because of poor aeration.
- The groundwater level:
  The same remark applies to the rate of transport. For the highest groundwater table of 1.5 m the amount of nitrate reaching the saturated zone may be 10 times higher than in a situation with highest groundwater table of 0.5 m; of course this is a combination of differences in storage capacities and denitrification possibilities.
- Physical soil characteristics:
  Examples are texture, influencing partial anaerobiosis, and conductivity influencing leaching rate.

Weather conditions:

- Precipitation rate, influencing leaching rate but also denitrification rate
- Temperature, influencing production rate of NO_3.

Basic structure of ANIMO

Flow scheme

As mentioned before, the model ANIMO is intended for applications both on a field scale and on a regional scale. The general flow scheme for the regional scale model can be considered as a part of it, a region consisting of 1 field. The flow scheme is given in Figure 2.3.11. For each simulated year, calculations are made for all the subregions. This is done instead of making all the calculations per subarea for the full simulation period directly, because the method chosen makes it possible to evaluate the deep drainage fluxes of all the areas. The new deep drainage concentration can be used in the next simulated year in calculations of upward seepage, if occuring. The descriptions in this report will only be about the calculations per subarea, which form the main part of the model.

Geometry and time

One-dimensional model is used for calculations in each subregion. The soil is divided in a number of horizontal layers, increasing in thickness with depth. The following data are required from the water quantity model for each time step:

- the moisture content of the rootzone,
- the groundwater level,
- the evaporation flux,
- the transport flux from the rootzone to deeper layers, and
- the fluxes to the different drainage systems.

From these data the water contents of all layers in the water quantity part, the fluxes between these layers and from each layer into the different drainage systems have to be calculated. Important for water quality calculations is the system with which the different drainage fluxes are divided over the different contributing layers. Because of the one-dimensional character of this model, no horizontal streamline components can be discerned; all the drainage fluxes (except deep drainage) are considered to leave immediately the contributing soil layers, in other words, complete horizontal mixing of concentrations is assumed. Of course average residence time for the solutes reaching a channel is greater than for solutes entering a ditch also in this model, because deeper layers, with solutes with a longer history in the profile, contribute to the channel drainage. The time step can be chosen according to the precision of available weather condition input data; the model can work with time steps of one day or more (weeks, decades).

Transport and conservation equation

A central part of the model ANIMO consists of the transport and conservation equation. This equation has to be used for all the soluble species of importance in the nitrogen cycle: NO_3, NH_4 and soluble organic matter. By means of this equation the new concentrations of these soluble species in all the layers after simultaneous transport and transformation processes can be calculated. In Fig 2.3.11 the use of this equation is indicated by "calculate transport, production and decomposition of...". Since the time

- General input data per run and general calculations
- Do year = 1 to nr. of years
  - Do area = 1 to nr. of areas
    - Input data per area and general calculations per area
    - Do step = 1 to nr. of steps per year
      - Input moisture data
      - Calculate moisture fractions and fluxes
      - Calculate root and root exudate production rate
      - Divide additions over the layers
      - Calculate temperature profile
      - Calculate influences of temperature and moisture on rate constants
      - Calculate production rate of soluble organic matter
      - Calculate transport, production and decomposition of organic material in solution
      - Calculate formation and decomposition of (solid) soil organic material and decomposition of (solid) fresh organic material
      - Calculate uptake rate of NH_4 and NO_3 by the crop
      - Calculate oxygen distribution and denitrification rate, and production and decomposition rate of NH_4 and NO_3
      - Calculate transport, production and decomposition of NH_4 and NO_3
      - Calculate carbon and nitrogen balances
      - Calculate concentrations of NH_4, NO_3 and organic matter in solution in drainage fluxes
    - Storage of data obtained at end of simulation year
  - Calculate new concentrations of NH_4, NO_3 and organic matter in solution in surface waters and deep aquifer

Figure 2.3.11: Flow scheme of the model ANIMO

step in FEMSATP is one week, this model also works with the same time step. For each subregion, the soil is divided in a number of horizontal layers, smaller than those used in FEMSATP.

The model FEMSATP supplies data on the groundwater level, the water content of the root zone, and the total fluxes per area to the different drainage systems. To describe the movement of solutes we have to calculate from these data the water contents of all the layers in our model, the fluxes between these layers and from each layer into the different drainage systems. The central point of the model ANIMO consists of the transport and conservation equation, which has to be used for all the important species in solution: for organic matter, for NO_3 and for NH_4. The equation has the general form:

$$dV(n) \cdot c(n,t)/dt = \sum_i f_d(i) \cdot c(n,t) +$$

$$+ f(n-1) \cdot c(n-1) + f(n) \cdot c(n,t) + k_0 \cdot V(n,t) + k_1 \cdot V(n) \cdot c(n,t)$$

where
- n - index of layer
- i - index of drainage system
- t - time
- V - water volume of layer
- c - concentration of species considered
- f - flux between layers
- f_d - flux to drainage system
- k_0 - zero-order rate constant for formation or disappearance
- k_1 - first-order rate constant for decomposition

The $\sum_i f(i) \cdot c(n,t)$ indicates the outgoing fluxes from the layer n to separate drainage systems i. This equation is solved analytically concerning time, and numerically concerning space. For each timestep an average water volume per layer is used, calculated from the data of FEMSATP. The values for the rate constants k_0 and k_1 follow from the detailed calculations for mineralization and denitrification as mentioned before. The order of layers in which the calculations for one species take place, depends upon the direction of the different fluxes. When the fluxes and moisture contents are calculated from the data given by the water management model, the concentrations follow from the last time step, the values of k_0 and k_1 are still needed. They follow from the other calculations per time step mentioned in Figure 2.3.11. Examples are:

The k_0 for formation soluble organic matter follows from the decomposition rate of fresh organic matter, influenced by temperature and moisture effects.

The k_1 for soluble organic matter is the decomposition rate of this material. This k_1 is also influenced by temperature and moisture.

The k_0 for NH_4 formation follows from the rate of decomposition of soluble organic material combined with the rate of formation of soil organic material, taking into account their respective N-contents and the part of the soil system that is anaerobic during the time step (for the aerobic part, NO_3 production is assumed).

2.3.4 Aspects of modeling natural ecosystems

Ecological Background

Ecological research during the last years stressed the importance of groundwater regimes not only for soil moisture supply but especially for the influence of both quantitative and qualitative aspects of nitrogen and phosphorus supply to mire vegetation. (Van Wirdum 1981; Kemmers & Jansen 1985a,b; Grootjans 1985)

In the concept of nutrient availability to mire vegetation the Ca-ion contents of groundwater plays an important role (Kemmers 1985). Groundwater flow through aquifers results in an enrichment of the water by weathering processes causing a predominant presence of Ca- and HCO_3-ions in groundwater. As cause of Ca-ion supply from the groundwater to the root zone a high Ca-saturation on the exchange complex or even secondary calcite deposits so near neutral conditions, occurred in groundwater discharge areas. Availability of phosphorus in such minerotrophic discharge areas is mainly controlled by the low solubility of Ca-P minerals.

Next to the Ca-ion content the solubility of Ca-P minerals is also dependent on soil acidity. Upon exceeding specified pH levels transition to other processes will occur, in which Fe-ions and redox conditions will control P-availability. Because there is a general agreement that the supply of moisture and nutrients like N and P in wet habitats is controlled by groundwater quantity and quality parameters, four main environmental factors related to the groundwater regime can be selected in order to build a simplified model to asses impacts of groundwater lowerings on ecosystems. The influence of groundwater parameters on the four main environmental factors is broadly outlined in Figure 2.3.12.

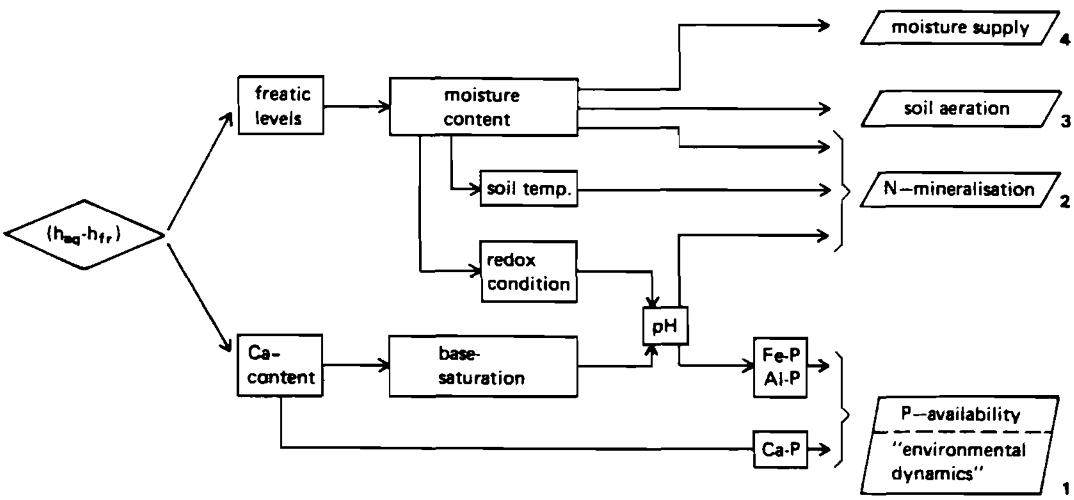


Figure 2.3.12: Outline of the main environmental factors as controlled by groundwater quantity and quality parameters. h_{aq} and h_{fr} refer to the hydraulic head of the aquifer and the phreatic groundwater respectively.

Environmental dynamics

Although this hypothetical factor does not yet have any physical meaning it has become a central item in nature conservation related to socio-economic planning based on ecology in the Netherlands. (van der Maarel & Dauvellier, 1978). In general this factor is used to describe the extent of buffering of the plant environment to changing P-availability. As such environmental dynamics has to do with a complex interacting system of redox processes, Ca-ion contents, and soil acidity, generating P-fluxes.

Nitrogen supply

Lowering the groundwater levels in wet habitats will increase N-availability as cause of increased soil aeration and temperature. An important state variable is the total organic N-pool and type of humus.

Soil aeration

Next to oxidation-reduction processes soil aeration is involved directly in plant performance. Plant species capable of growing in anaerobic environments by aerenchym tissue in the roots are seriously hampered by soil aeration due to groundwater lowering, as plant species adapted to aerobic environments are favoured.

Soil moisture supply

Levelling down the groundwater may cause shortage of water for transpiration purposes. Soil physical properties as capillary rise are important state variables depending on texture and soil type.

Linkage of plant species and environmental factors

Until now ecological knowledge is not sufficient to link response of plant species to changes of hydrological conditions in a physical way like customarily in determining crop water use in agriculture (Querner & Feddes 1985). Several researchers, however, did rank plant species along environmental gradients. Ellenberg (1974) furnished most of the plant species of North-Western Europe with figures indicating optimum plant performance related to moisture supply and nitrogen supply. He designed an ordinal scale of nine nitrogen indices, the lower indicating nitrogen poor, the upper nitrogen rich conditions. In the same way low soil moisture supply is indicated by low indices increasing up to 12 indicating immersed conditions. Londo (1975) made a distinction between plant species being sensitive to environmental dynamics or not.

Bringing together the four main environmental factors controlled by groundwater and the indication indices Reynen & Wiertz (1984) designed the WAFLO-model as an instrument to asses impacts of changed WAter conditions on FLOra. The WAFLO-model stipulates that plant species will disappear from the vegetation if environmental conditions change as a consequence of ground-water lowerings and plants ecological optimum cannot be satisfied any longer. The model does not supply a replacement of other species. WAFLO was designed to asses ecological effects of groundwater lowerings which are constant throughout the year. So a groundwater withdrawal is considered to cause a groundwater lowering at the beginning of summer (dhs) equal to that at the beginning of winter (dhw).

To evaluate the impact of changed water levels both in winter or summer we used a non-stationary model of the unsaturated zone SWATRE (Beltmans et al, 1981). Compilation of WAFLO and SWATRE gave birth to SWAFLO. The SWAFLO-model consists of four submodels each describing the response of plant species to one of the four main environmental factors as related to the groundwater regime (Kemmers & Jansen, 1985a).

Impact—Rresponse Relations

Having linked plant species to the four main environmental factors, we can now start to formulate the behaviour of plant species after a change of one of the environmental factors as cause of a lowering of groundwater levels in spring or late summer.

Environmental dynamics

Plant species response to a change of environmental dynamics is shown in Table 2.3.1. It is stipulated that plant species sensitive to environmental dynamics (Londo, 1975) will disappear as soon as any lowering will occur, assumed that the groundwater levels in the unperturbed situation ($hs0, hw0$) do not fall beneath 80 cm below ground level at the beginning of summer or beneath 120 cm below ground level at the beginning of winter.

Table 2.3.1: Impact response relations concerning changed environmental dynamics. *hs* and *hw* refer to groundwater levels at the beginning of summer or winter respectively (cm-g.l.) $hw0$ and $hs0$ refer to groundwater levels in the unperturbed situation ($dhs = hs0 - dhw = hw0 - hw$).

Impact	Boundary condition	Response
$dhs > 0$	$hs0 < 80$	sensitive species
$dhw > 0$	$hw0 < 120$	disappear

Nitrogen supply

Plant species response to a changed nitrogen supply is shown in Table 2.3.2. Based on empirical knowledge the Netherlands Soil Survey Institute assigned soil types generating increased mineralisation of the organic matter after the lowering of shallow groundwater levels. It is stipulated that the assigned soil types will yield a moderate increase of nitrogen supply if groundwaterlowerings more than 10 cm will occur. As a response plant species with nitrogen indices 1, 2 and 3 having also moisture indices exceeding 6 will disappear (Reynen et al. 1981).

Table 2.3.2: Impact-response relations concerning changed nitrogen supply. *hs* and *hw* refer to groundwater levels at the beginning of summer or winter respectively.

Impact	Boundary conditons	Response
$dhs => 10$	soil type	species with nitrogen
$dhw => 10$	soil type	figures 1,2,3 as well
	pressure head >-200	moisture figures => 1
		will disappear.

Soil aeration

Plant species response to a change of soil aeration is shown in Table 2.3.3. Soil aeration is considered to be of importance only in spring. Consequently the groundwater levels at the beginning of summer (*hs*) will be considered as a measure of soil aeration. Plant species response was deduced from a statistical-empirical survey relating soil moisture figures and groundwater levels in spring (Gremmen,1984). It must be noted that groundwater levels related to soil aeration have to be considered as a boundary condition, irrespective of the amount of change in waterlevels. Plant species with moisture indices exceeding 10 will disappear as soon as *hs* falls beneath 30 cm below groundlevel. In the same way species with moisture indices exceeding 9,8 and 7 will disappear if *hs* falls beneath 50,60 and 70 cm below ground level respectively.

Table 2.3.3: Impact-response relations concerning changed soil aeration. *hs* refers to the groundwater level at the beginning of summer (cm-g.l.)

Impact	Boundary condition	Response: plant species with moisture figures
any *dhs*	*hs* > 30	=> 10
exceeding	*hs* > 50	=> 9
boundary	*hs* > 60	=> 8
conditions	*hs* > 70	=> 7
		will disappear

Soil moisture supply

The relative production of herbacious vegetation can be considered as a measure of water stress which ought to be reflected by the spectrum of moisture indices of the spontaneous vegetation (van Wirdum, 1981). In the Southern Peel study the ratio of actual over potential evapotranspiration (Eact/Epot = α) was used as a measure of relative grass production and related to occurence of plant species with distinct moisture indices. This assesment was based on empirical evidence (Reynen et.al., 1981). Table 2.3.4 schedules plant response related to the exceedence of threshold limits of Eact/Epot by any *dhs* or *dhw*.

The SWATRE model was used to determine Eact/Epot related to groundwater levels at the beginning of summer and winter (Jansen,1983). These calculations have been made with weather data of a 10% dry year assuming that the spectrum of moisture indices will not be changed fundamentally by events with a frequency more than once every ten years. So implicitly it is

Table 2.3.4. Impact-response relations concerning changed soil moisture supply. *hs* and *hw* refer to groundwater levels at the beginning of summer or winter respectively. Eact/Epot is the ratio of actual over potential evapotranspiration.

Impact	Boundary condition		Response species with moisture figures
	Eact/Epot	rel. grass yield (%)	
any *dhs*	< 1.0	< 99	=> 10
or *dhw*	< 0.975	< 95	=> 9
causing	< 0.95	<90	=> 8
exceedence	< 0.89	< 80	=> 7
of one of	< 0.83	< 70	=> 6
the threshold	< 0.71	< 50	=> 5
limits	< 0.55	< 30	=> 4
			will disappear

supposed that the vegetational composition depends on events occuring once every ten years. As an example soil specific (texture,organic matter etc.) threshold limits of Eact/Epot for the Berken subregion (r 10) have been calculated and are shown in Figure 2.3.13.

Appraisal of Ecological Effects

In general disturbance of nature will yield more common species with wide ecological amplitude, being not very valuable. So the appraisal of the ecological effects due to groundwater lowerings will tend to less valuable circumstances.

It is assumed that the vegetation derives its value from the extent of rareness of the compiling species. Rareness of species is based on species frequency in a national grid system (5 x 5 km 2). Nine frequency classes can be discerned and rareness figures are derived from those classes (Kemmers & Jansen, 1985a). Nature values can be calculated as follows:

$$V = \sum_{i=1}^{n} z_i \cdot a_i \qquad (2.3.17)$$

in which: V = nature value

z_i = rareness index of species i

a_i = multiplication factor

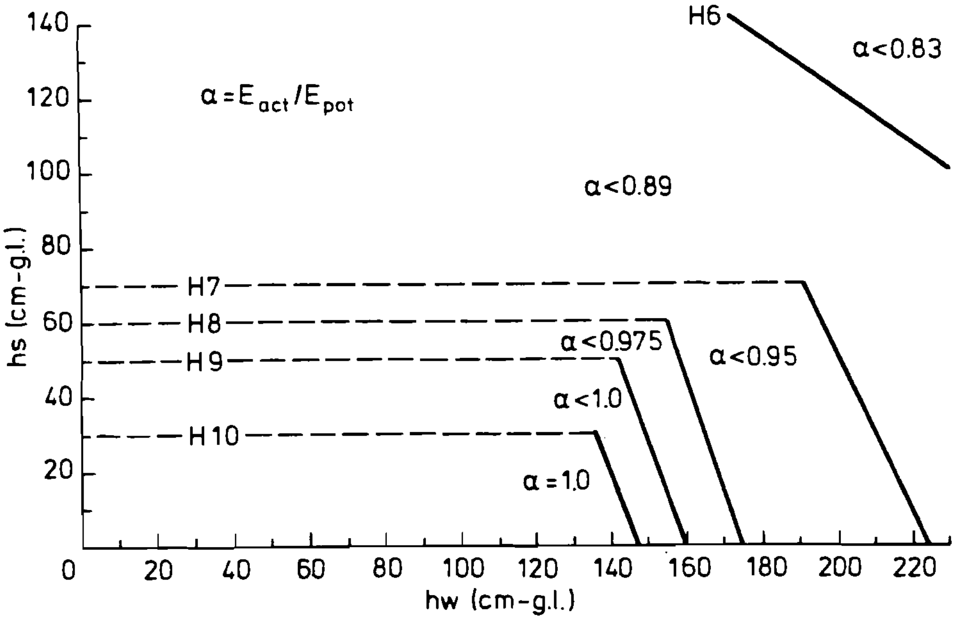


Figure 2.3.13: Ratios of Eact/Epot related to trajectories of groundwater levels at the beginning of summer (*hs*) and winter (*hw*) and plant species response concerning subregion r = 10 (de Berken). Dashed lines are indicating threshold limits of groundwater levels concerning soil aeration. As a response plant species with indicated moisture indices (*Hn*) will disappear as soon as boundaries are passed.

n = number of species

As has been said earlier, groundwater lowerings will cause a loss of species and according to equation (2.3.17) a decrease of nature value. This decrease of value can be expressed as a relative standard using percentage notation.

Application of the SWAFLO-Model

As an illustration the SWAFLO-model will be applied to the " Berken" subregion. This subregion is one of the nature areas of the Southern Peel area. The Berken subregion was devided in two parts. The two parts are different both in groundwater regime and in vegetational composition as a consequence of differences in the altitude of the ground levels (Kemmers & Jansen, 1985a). Groundwater levels at the beginning of summer and winter at high and low plots are shown in Table 2.3.5.

Table 2.3.6: Unperturbed groundwater levels at the beginning of summer ($hs\,0$) and winter ($hw\,0$) in the "Berken" subregion ($r\,10$).

Altitude	cm-g.1	
	$hs\,0$	$hw\,0$
Low plots	15.0	95.0
High plots	29.0	129.0

Both vegetational composition and groundwater measurements are considered to represent the unperturbed situation. Figure 2.3.14 shows the relative loss of nature value in the Berken-subregion after an imaginary change of groundwater levels in winter and summer. Groundwater levels are indicated starting with levels in the unperturbed situation.

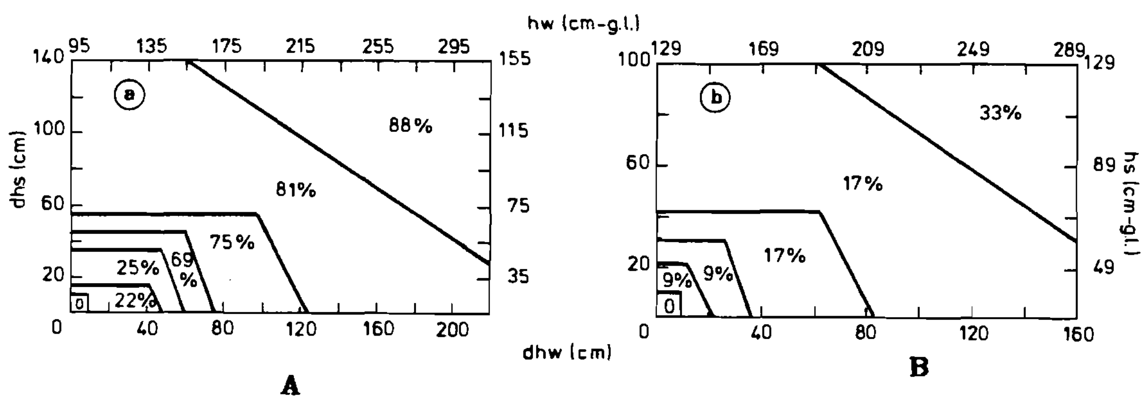


Figure 2.3.14: Relative loss of nature value in "de Berken" nature area (subregion $r = 10$) after changed levels of groundwater at the beginning of summer (dhs) or winter (dhw). Groundwater levels are indicated starting with levels in the unperturbed situation. **A** – High plots; **B** – Low plots.

A marked difference appears between the ecological effects of the high and of the low plots. The vegetation on the low plots is distinctly more sensitive to groundwater lowerings as can be derived from the relative loss of nature value. On high plots with lower levels hs0 and hw0 the vegetation is apparently less sensitive to groundwater lowerings. Comparison of the sensitivity of both vegetation types to groundwater lowerings leads to an affirmation of the expectation: vegetation types on wet plots are more sensitive to groundwater lowerings than vegetation types on dry plots. Generally it can be concluded that the two vegetation types are not sensitive to small groundwater lowerings both in spring and in late summer. If *dhs* or *dhw* exceeds 10 cm species will start to disappear, levelling down nature values. It can be concluded also that the two vegetation types are more sensitive to changes of *hs* than to changes of *hw*. It is decided that the vegetation which is most sensitive to groundwater lowerings must be chosen to represent the whole subregion $r = 10$.

Application of the SWAFLO-Model in the Present Study

The SWAFLO-model is designed to asses ecological effects if groundwater levels exceed tolerance limits of the natural vegetation as cause of any technology in neighbouring subregions. Using the SWAFLO-model simple input-output relations between a decrease of nature values and changed groundwater levels can be derived. Reversely the PMA can put forward that the decrease of nature value of any particular subregion may not exceed any specified relative value. This specified value can be converted to acceptable changes of groundwater levels which are to be considered as requirements to the scenario generating system. The application of the SWAFLO-model and the procedure to put requirements to the scenario generating system concerning nature is depicted in Figure 2.3.15.

Concluding Remarks

The SWAFLO-model presented in this section physically is not underlain substantially of course. Some submodels need further improvement. Perfect linkage of plant species and environmental factors still needs every effort. The SWAFLO-model appears to work however. The model shows distinct sensitivity to different levels of groundwater lowerings and to different physical conditions of the soil in the unperturbed situation (Kemmers & Jansen 1985a). The model indicates less sensitive vegetation on dryer plots after groundwater lowering than on wet plots. Other environmental impacts as for instance acid rain or nutrient input by air pollution are not considered in the model. The model, however, has to be used in a global directive way not to predict vegetational composition in future but just to compare the sensitivity of nature values to several alternatives of the water management. It can be concluded that the SWAFLO-model seems to be

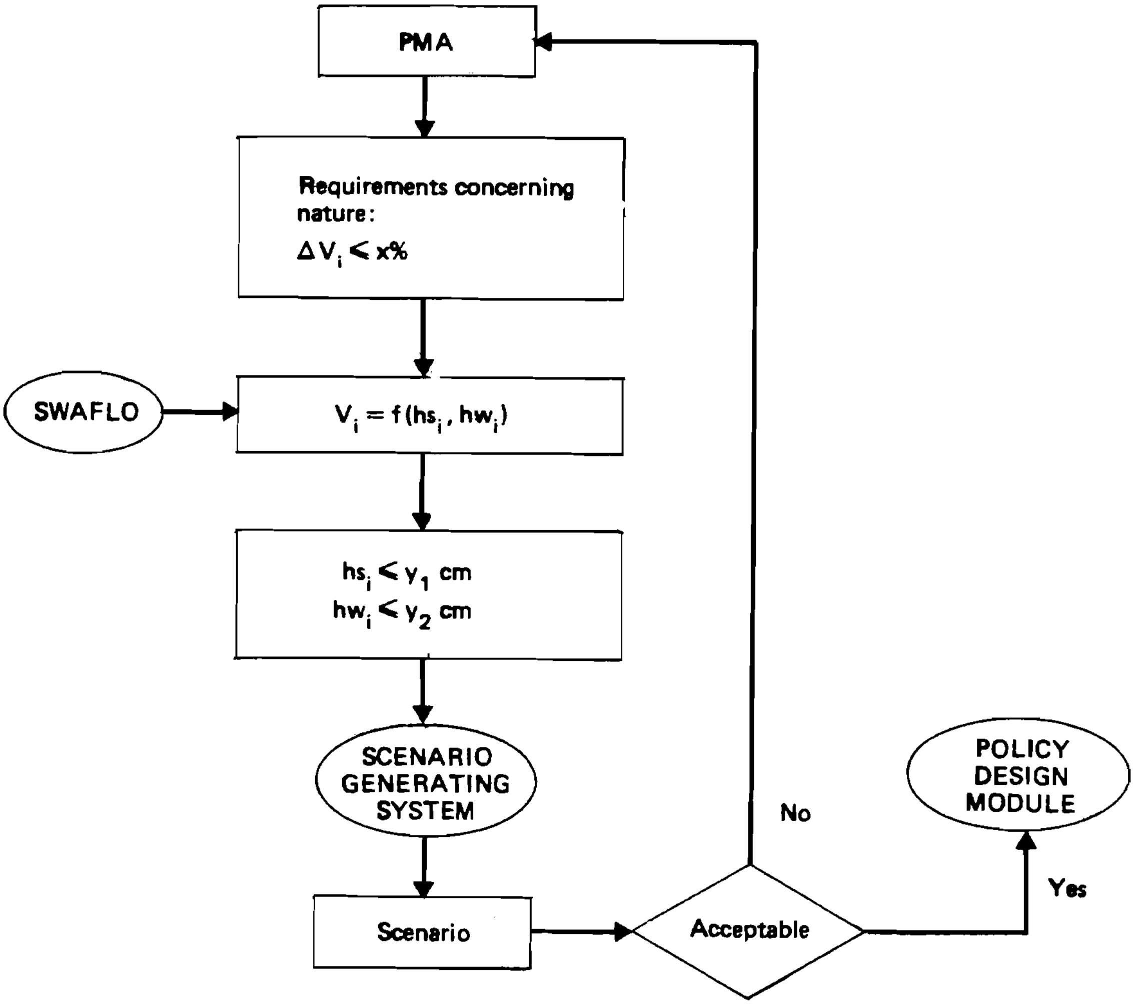


Figure 2.3.15: Application of the SWAFLO-model in the framework of scenario and policy modules.

a usefull module to analyse effects of water management in rural areas in order to evaluate whether preferences of the PMA concerning nature will be achieved or not.

2.4 Aspects of Modeling Agricultural Development

Comprehensive modeling of regional agricultural development is probably the most difficult part in designing a decision support system. Besides physical factors like water resources availability, soil characteristics, and others, this development is based on an interplay of decisions by many individual farmers in the region and all these decisions contain high proportion of subjectivity and uncertainty.

On the other hand, the ability to project future agricultural development can substantially improve the quality of decision maing on the regional level (by the PMA), and therefore, models enabling to make at least qualitative projections are very desirable components of a decision support system.

The work on the development of this type of a model for the Southern Peel region is underway at the Institute for Land and Water Management Research, Wageningen, the Netherlands, and here we present not the model itself but rather a brief outline of the basic considerations underlying its structure (Figure 2.4.1). Such a model as part of a regional decision support system is to be applied to analyse the influence of alternative water management policies on the economic development of the users. Therefore, the major aspects considered by the model should include the interactions between the agriculture and the regional hydrological system (mainly the use of groundwater and surface water, application of fertilizers). The agricultural development itself should be characterized in the model by relevant indicators such as the employment in agriculture, those related to income such as the total income, distribution of income over the region, stability of income, and others.

To achieve this the following process should be described in the model:

The interaction between the production in agriculture and the hydrologic system. This concerns the impacts of the use of water and the application of fertilizers in agriculture on the other users (via the hydrologic system). It also concerns the influence of changes in the hydrologic system (caused by the other users for instance) on the production in agriculture.

The development of the activities, the labour inputs and the income at the farms in the regions. This development is guided by the investments at the farms.

The impacts of potential policies (to be applied by the PMA) on the processes mentioned before. These impacts can be either direct or indirect. Direct impacts are impacts on the yield of the crops, for instance, the reduction of the yield caused by a reduced availability of water. Indirect impacts are impacts on the activities or the management at the farms. These changes can be caused by measures as subsidizing and extension or by the expectations caused by some direct impacts.

The description of these processes requires a model that describes the link with the hydrologic system on the one hand, and forecasts the agricultural activities in the region in the future on the other. The required outputs of the model concern water use, fertilizer applications, labour inputs and income in agriculture.

One approach to modeling agricultural development in a region can be based on classifying farms into a number of farm types. The agricultural development can then be characterized by changes in the numbers of farms per farm type and by variations within a farm type. The definition of a farm type must depend on the problem considered. Another approach may consist in describing the (expected) behaviour of individual farms in the region.

The following combination of the two approaches can be chosen:

- relations between the regional physical system (for instance, hydrologic system and the soil) and the development of agriculture can be based on farm types (the production block).
- variations between individual farms and changes in the numbers of farms per farm type can be based on an approach with individual farms (the development block).

Classification of farms into farm types can be based on the following considerations:

- the number of farm types is smaller possible;
- the types of farming that already exist in the region and the types that may be introduced into the region in the future should be included;

- aspects such as the interactions with the physical system (e.g., the use of water and the application of fertilizers) and the impacts of policies (applied by the PMA) on the behaviour of the farms should be considered. Farms within a farm type should be reasonably homogeneous with respect to these aspects.

For each of the farm types a representative farm can be defined. A representative farm can be characterized by intensities of technologies (considering the size and the composition of the livestock), the cropping pattern, the size of the farm, the availability of specific capital goods (e.g., sprinkler installations), etc. These variables are called the characteristics of the representative farm.

A technology is defined as an agricultural activity or a group of activities using some inputs (labour, water, fertilizer, etc.), and producing some outputs (crop yield, milk, manure, meat, etc.). The technologies differ from each other in at least one of the aspects that are relevant for the problem. For our problem these aspects are the water requirements, the fertilizer applications, the labour inputs, the capital inputs and the development of prices. The technologies are divided into landuse technologies and nonlanduse technologies.

In Figure 2.4.1 an overview of a possible simulation model is given. Exogenous inputs to this model may reflect the development of employment in agriculture, limitations on the use of water and the application of fertilizers posed by the PMA (this can also include restrictions stemming from the other users), and the (national) economic development.

The model links characteristics (intensities of technologies) of a representative farm with the exogenously defined production functions, describing production depending on the inputs of water and fertilizer conditioned on soil type and weather conditions. Production of a representative farm can be evaluated in this way.

For individual farms belonging to a farm type characteristics will differ from those of the representative farm since the latter is an average over the region. The determination of productions of individual farms can be based on the production of the representative farm and on the differences in the characteristics between the representative farm and individual

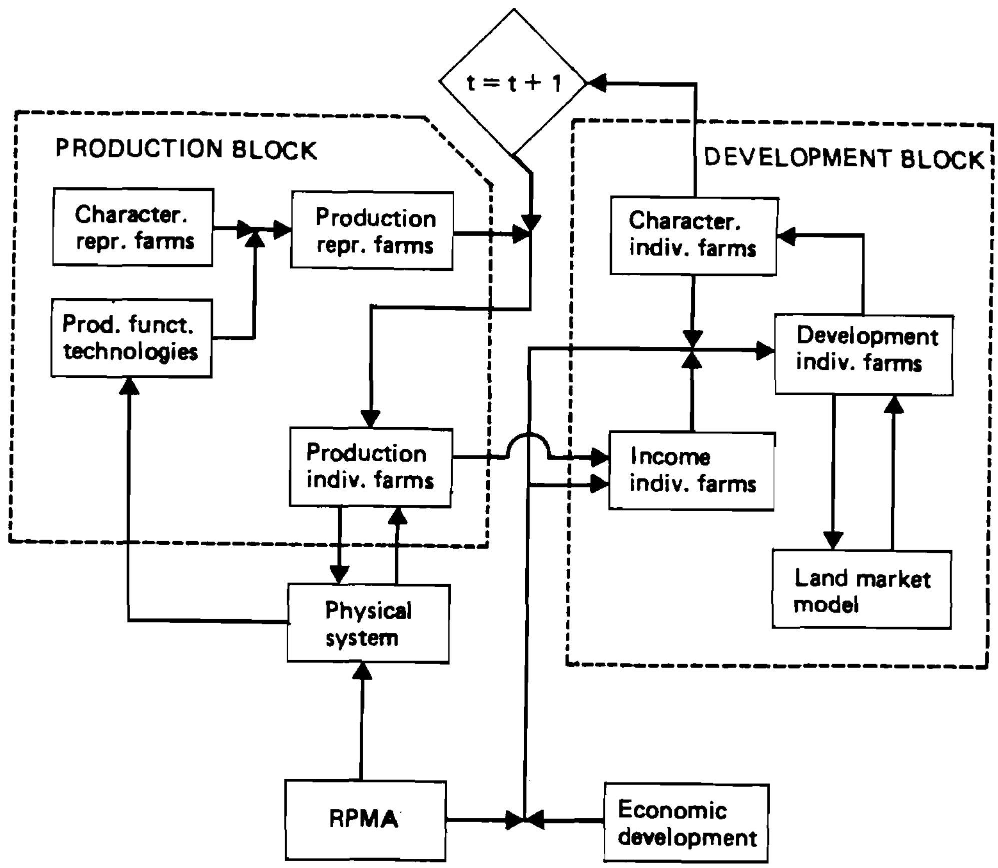


Figure 2.4.1: Schematic overview of the second level model

farms. The compatibility of water inputs, fertilizer inputs and labour inputs at a farm coupled to the production can be verified by introducing results of the production calculations into the model of the physical system.

The productions of individual farms are inputs to the development block where the income of the farms is calculated. Income is one of the pivot variables in the generation of changes in the characteristics of a farm. Other inputs can be economic characteristics (e.g. prices), policies applied by the PMA (for instance, subsidies), and outputs of a land market model that relates demand with supply of land (by individual farms). The output of the development block is a set of revised characteristics of the farm. This revised set is an input to the production block for the next year.

The production block and the development block are outlined in more detail in the next sections.

Outline of the production block

The objective of the production block is to evaluate productions of farms in the region taking into account differences between individual farms, physical conditions in the region (hydrologic system and soil type), requirements of the other users (via the physical system), and of the PMA, (besides water quality and water quantity this also concerns the employment in agriculture). Crop yields depend on water and fertilizer inputs, the soil type, and on a number of farm characteristics such as the availability of specific capital goods.

For a number of crops models can be formulated outside the simulation model, to evaluate crop yields depending on the physical system, additional water input (sprinkling), fertilizer input and weather conditions. The yield is calculated for one point in the field, and all aspects that are not explicitly considered can be assumed to be fixed (for instance crop protection practices). Production functions of the landuse technologies can be derived from these production models. A landuse technology is characterized by a crop, or, a combination of crops, and a specific farm management. The farm management is determined for the representative farm and so it may be different for different regions.

An example of a landuse technology is grassland with milking cows, in this case the factor farm management concerns the number of cows per ha, the type of stables, grassland cultivation and use, etc.

An example of the influence of the farm management on the definition of the technologies can be silage maize. Silage maize with application of fertilizers at the optimum level is one technology, silage maize with an overdose of fertilizers (dumping of manure) is another technology.

For non-land use (livestock) technologies production functions can also be formulated. For these technologies manure will often be one of the outputs.

An advantage of an approach based on representative farms is that the expected development of the farms can be evaluated using the definition of the representative farm as a reference. The differences may be caused by technological changes, by market conditions (changes in prices or demand), or by policies applied by the PMA (for instance, a reduction in permitted levels of application of fertilizers).

The last step in this approach is the evaluation of productions of individual farms. In reality, variations in productions of farms belonging to a farm type are observed. These variations concern quantities of factor and nonfactor inputs, and the crop yield. These variations can be explained by a large number of factors some of which are:

- size of the farm, related to both the total area of cultivated land and the effectively used area of cultivated land (determined by the shape of the parcels and the border characteristics);
- parcelling and opening up;
- hydrologic and soil characteristics;
- production scheme and capital stock (buildings, cattle, machinery and tools);
- nonfactor inputs: fertilizers, crop protection practices, etc.
- amount (and quality) of labour that is available at a farm;
- quality and objectives of farm management. One of the reasons to mention this aspect is to focus attention to farming for pleasure and to farmers with the intention to terminate farming.

Some of these factors can be taken into account in the evaluation of the production of individual farms. In the production block an adjustment procedure should be used to generate variations in production between farms belonging to one farm type. This procedure can be based on comparisons between (some of) the characteristics of the representative farm and of the individual farms. A description of possible adjustment procedures can be found in Vreke, Nota 1311.

After productions of all farms in the region have been evaluated the next step can be the verification of their compatibility with:

- the hydrologic system and with the constraints posed by the PMA (and by the other users) concerning both the water quantity and the water quality;
- the desired level of employment in agriculture.

Other aspects can be added to this list. If one or more of such type of requirements are not met the results can be adapted, for instance, by proportional decreases (or increases).

Major factors influencing farm development (Development block)

While the previously outlined production block was focused on the evaluation of actual productions of farms in the region, basing on hydrologic, economic, etc. conditions related to one year, the development block is an attempt to relate performance of a farm in one year with resultant decisions influencing its future performance. A possible approach to structuring a model of this type is outlined in Locht and Vreke 1985. Here we present basic factors considered in this approach using Figure 2.4.2 as an illustration.

The major factors that influences decisions of farmers according to this approach are incomes of farmers. Important variables in the evaluation of income are the (physical) production and the cost of hired labour, additional water inputs (sprinkling), fertilizer inputs, other non-factor inputs, and the cost of land and capital. Prices can be exogenously determined (general economic development). Besides these aspects the financial position, the income from labour inputs outside the farm and taxes may also be considered. Basing on the evaluation of the income, the savings can be determined as the difference between income and consumption. The spendings for consumption can either be evaluated using a separate model or exogenously determined.

The following types of decisions can be considered:

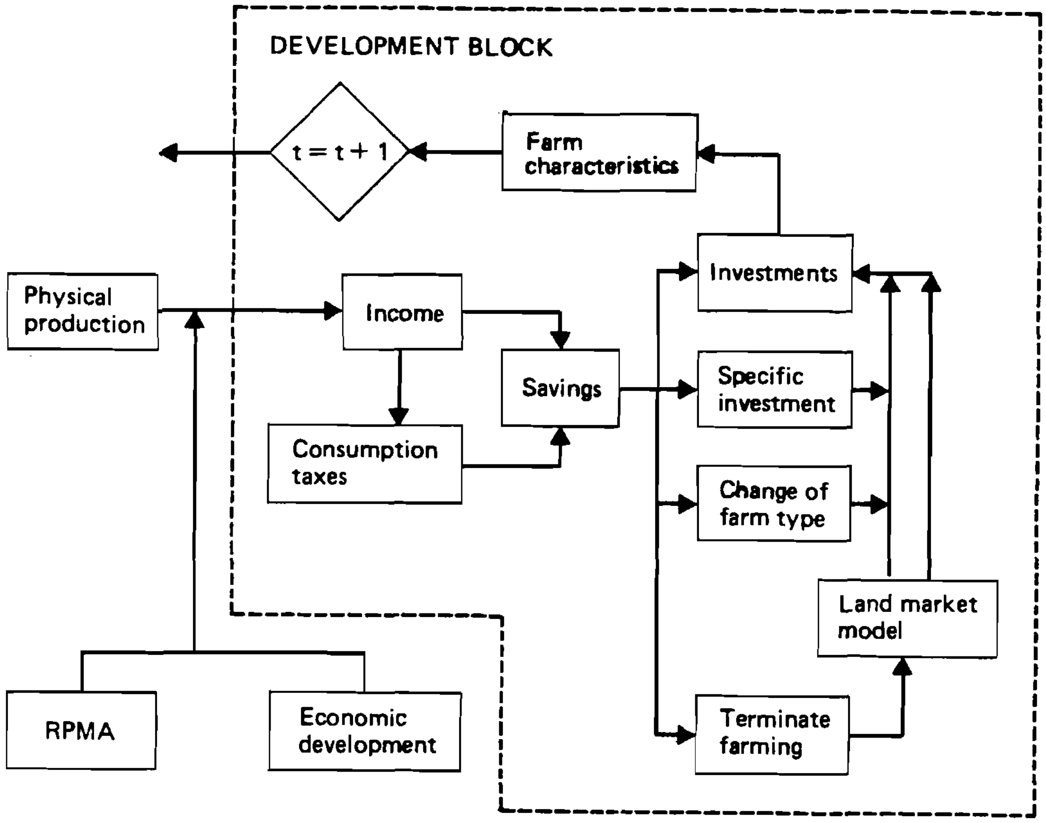


Figure 2.4.2: Farm development block

- *Terminate farming*: The reason to terminate farming can be the retirement of the farmer or his death if there is no successor, the low income earned at the farm, or it can be that the expectations with respect to the income that can be earned outside the farm are better than the expectations when the farm is continued. This aspect is linked with the general economic development. If employment situation outside agriculture is good the pressure to continue farming is less than if the employment outside agriculture is bad.
- *Change of farm type*: The change from one farm type to another can be caused by the normal development of the farm (for instance, a growing specialization), or it can be the result of a specific decision. In the latter case the change will be into a completely different farm type (for instance, a change from cattle breeding to glass horticulture).

This type of changes may be caused by the fact that prospects in the current farm type are bad because of changing market conditions, the impossibility to expand the farm (shortage of land in the region), or because of the introduction of regulations (for instance, a restriction on the application of fertilizers or on the sprinkling capacities). The change into another farm type can be hampered by the following:

– the amount of investments required. Most types of farming require large amounts of specific (to a particular farm type) investments. The value of capital goods is rather low when they are sold after a few years. So when the investments are made the farmer is more or less trapped in the current farm type. Moreover, changing into another farm type often requires substantial investments which may be difficult to finance;

– professional ability of the farmer. Each farm type requires a lot of specific knowledge (and experience) of the farmer. So if a farm changes from one type to another the required professional expertize changes too. This may be a reason to abandon the change.

- *Investments for specific capital goods*: In some cases the investment in one or more specific capital goods can be an important factor. An example is the investment in sprinkling equipment when the potential demand for water is analysed. It is also possible to use specific investments as an indicator of the impacts of a certain policy (applied by the PMA).

The types of decisions mentioned are very much interrelated because they are all concerned with the prospects of the farm. As a consequence explanatory variables for these types of decisions will be almost the same. Some of the most important are the following:

- size of the farm concerning both the size and shape of the area and also the size and composition of the livestock;
- financial position of the farm (size of properties and debts, and the difference between them);

- income (or expected income) earned at the farm;
- age of the farmer and the existence of a succesor;
- possession of one or more specific capital goods.

Another similarity between the three types of decisions is that they all involve "yes/no" types of decisions (for instance, an investment is made or not made). Besides objective aspects subjective aspects also play an important role in these decisions. These decisions may be taken into account in the following way:

- deterministic: if the value of a specific variable or a combination of variables exceeds a certain threshold then the decision is *yes* (that is the investment is made, the farm is terminated, or the farm changes into another farm type); otherwise the decision is *no* (nothing happens). An example can be a specific investment that is made only when the revenues of this investment are larger than the cost. In this case, the decision is *yes* when the value of the revenues less costs is positive, otherwise the decision is *no*. In practice, however, decisions will not be as simple as the one in the example.
- stochastic: values of the above variables can be parameters of a probability distribution function used to generate decisions of farmers by a random mechanism.

An important consideration is also land availability that can be accounted for by using a land market model describing the demand and supply of land. The supply of land consists (for a large part) of the land stemming from terminated farms. The demand for land is coming from expanding farms, from farms that change into another farm type and from newly established farms. A mechanism that determines the price of land and allocates land to the individual (entering and existing) farms may also be incorporated in the land market model.

An important part of the development block should also be an investment model. In this model the normal investments (for expansion and replacement) are generated. They determine together with the investments that are required for the generated yes/no decisions the demand for investment funds. The amount that is available for investments is determined on the basis of the savings and the financial position of the farm. The last step in the development block is to determine the changes in the characteristics of the farm. This includes a verification of the farm type because it can happen that the farm changes from farmtype because of expansion in one direction of production.

Remarks

We outlined a concept of a model that stimulates the development of the farms in a region and the impacts of potential policies to be applied by the PMA on this development. For the other users of ground and surface water in the region a model of the same kind is required. One of the reasons for this requirement is that the creation of sufficient hydrologic conditions for the required development of the other users does not guarantee that this development will be realized. The development also depends on other aspects. With respect to environmental areas, for instance, the realisation also depends on maintenance, and the cost of maintenance are high. This is a fact that is very often left out of consideration in regional planning.

2.5 Description of Simplified Models for Screening Analysis (First Level Models)

2.5.1 Introduction

The scenario generation system takes into account the following inter-related processes:

1. Agricultural production and economic development of agriculture in terms of incomes, consumptions, savings, investments, changes in land use, changes in livestock breeding, changes in farm management practices.

2. Water quantity processes: flows in the unsaturated zone, i.e. in the soil, groundwater flows, overland flows (surface runoff), and surface water flows.

3. Soil nitrogen processes: fertilization of soils by application of chemical fertilizers and animal wastes, nitrogen mineralization of slurries, leaching of nitrate to groundwater, and denitrification processes.

4. Water quality processes: transport and modification of solutes in groundwater and surface water.

In the preceding sections we outlined the relatively detailed (basic) models to be used for the second level of scenario analysis (simulation). In the following, short descriptions will be given of first-level simplified models and of the ways they are linked to each other. Some of these models existed already but most have been formulated specially for the purpose of this study. With the intention of using linear programming as the basic computational tool (problem solver) for multiobjective screening analysis linear (or piecewise linear) simplified models were formulated and their coefficients were quantified basing on the data generated using the basic models.

The spatial resolution for the models is provided by a division into 31 subregions (Fig. 2.5.1), based on classes of groundwater conditions and soil physical units. The groundwater classes range from "I" for extremely high groundwater levels to "VII" for relatively deep groundwater levels (Table 2.5.1). Classes I–III are generally found in valleys, and classes V–VII on the plateaus. The combination of conditions required for class IV is not found in the Southern Peel.

2.5.2 Technologies

Definition

The term technology is used for a combination of agricultural activities involved in growing and processing of certain crops and/or livestock. For convenience, the distinction is made between agricultural technologies that use land and those that do not. The set of the former is denoted by J_X, the set of the latter by J_Z. It is also convenient to further subdivide the set J_X into subset J_{X_1} of land-use technologies not involving livestock and the subset J_{X_2} of land-use technologies that do involve livestock. This subdivision corresponds with the subdivision into arable land technologies and grassland ones. Lists of landuse and non-landuse technologies considered in this study are given in Tables 2.5.2 and 2.5.3. As can be seen from the lists, the respective technologies represent certain ***categories*** of agricultural

Table 2.5.1: Classes of groundwater conditions

The groundwater classes are defined in terms of the "average highest groundwater level" (GHG) and the "average lowest groundwater level" (GLG). The GHG and GLG values are determined from sequences of groundwater level observations that have a time interval of 14 days. Of every year for which there are observations, the three highest and the three lowest observed values are determined. The GHG and GLG are then calculated as the long-term average of respectively the three highest and the three lowest levels.

Class	I	II	III	IV	V	VI	VII
GHG (cm-GL) *	<40	<40	<40	>40	<40	40–80	>80
GLG (cm-GL)	<50	50–80	80–120	80–120	>120	>120	>120

* The GHG and GLG-values are in *cm below ground level.*

activities.

All technologies are explicitly characterized by inputs of labour and capital. Land use technologies are additionally characterized by the input of (soil) water and nitrogen*. For each landuse technology, a number of options concerning combinations of water and nitrogen inputs have been taken into consideration. The index k ($k = 0, 1, 2$) is used for a water supply option; the index n ($n = 1, 2$) is used for a nitrogen supply option. These options, termed "*subtechnologies*" are:

*The reason for explicitly considering only nitrogen in our model lies in that in the region considered nitrogen compounds contained in excessive quantities of animal slurries produced, are also the major pollutants of groundwater.

1. without sprinkling ($k = 0$), 75% of optimal N supply ($n = 1$);

2. with sprinkling of 25mm/2 weeks ($k = 1$), 75% of optimal N supply ($n = 1$);

3. with sprinkling of 25mm/week ($k = 2$), 75% of optimal N supply ($n = 1$);

4. without sprinkling ($k = 0$), optimal N supply ($n = 2$);

5. with sprinkling of 25 mm/2 weeks ($k = 1$), optimal N supply ($n = 2$);

6. with sprinkling of 25mm/week ($k = 2$), optimal N supply ($n = 2$).

The choice of the above options is based on expert judgements and is considered as the sufficiently representative set for the scenario analysis.

For the grassland technologies, a suboptimal N-supply also involves a lower stocking density: the grass production under suboptimal N-conditions can support less cattle than under conditions of optimal N.

Each technology is also characterized by the output or production of the respective goods (crop yields, livestock products). Technologies that involve livestock are additionally characterized by outputs of animal wastes produced as byproducts.

The use of agricultural technologies is described in terms of their intensities. For land-use technologies intensities have the meaning of areas of land allocated to these technologies. For technologies that do not use land and that involve livestock intensities have the meaning of a number of livestock heads; the only technology mushrooms, from set J_Z that do not involve livestock has the intensity measured in m^2.

In the remaining part of this section we describe those aspects of technologies that are not related to environmental processes. Those aspects that *are* related to environmental processes – the satisfaction of water and the nitrogen requirements – are described in subsequent sections.

We should make one remark here before proceeding to introduce notations and describe the models. All agricultural activities and aspects of water processes are related to years and, therefore, the corresponding variables introduced in the following should in principle have time parameter t as one of the indices. But, as will be discussed in Section 2.6, the

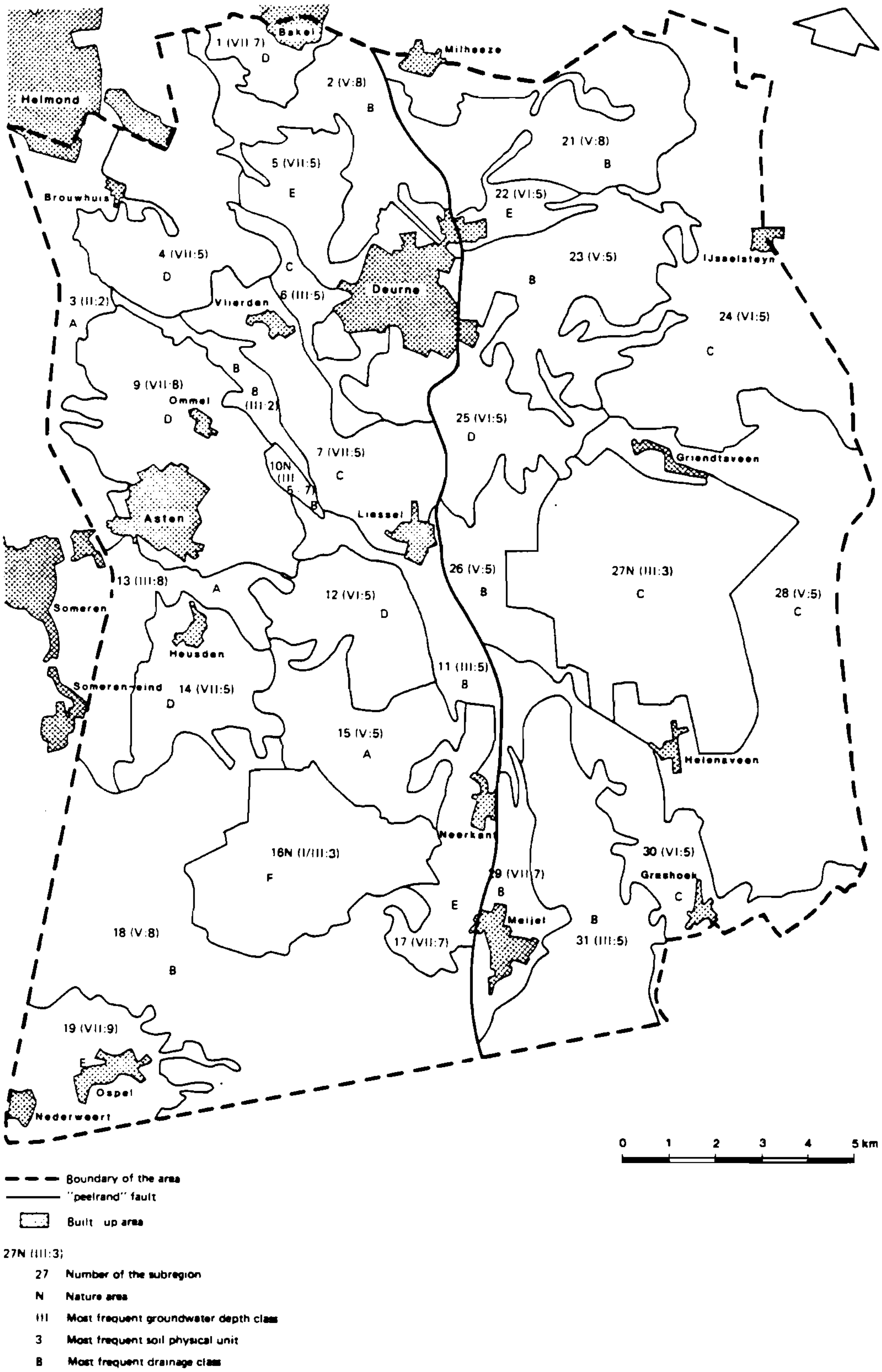


Figure 2.5.1: Division into subregions

Table 2.5.2: Land use technologies – set J_X. The subset J_{X_1}, contains the arable land technologies, the subset J_{X_2} the grassland ones.

	Technology	subset
1.	Glasshouse horticulture	J_{X_1}
2.	Outdoor small scale horticulture	J_{X_1}
3.	Outdoor large scale horticulture	J_{X_1}
4.	Row crops	J_{X_1}
5.	Cereals	J_{X_1}
6.	Silage maize	J_{X_1}
7.	Grassland with dairy cattle	J_{X_2}
8.	Grassland with rearing cattle	J_{X_2}

Table 2.5.3: Non-land use technologies – set J_Z.

	Technology
1.	Calves for feeding
2.	Pigs for feeding
3.	Pigs for breeding
4.	Egg-laying hens
5.	Broilers
6.	Mushrooms

determination of trajectories of regional development based on changes in time of all the variables introduced over the planning horizon T will be reduced to the consideration of only the final year of this period. The resultant problem will therefore be essentially a "one year" problem and for this reason we prefer to omit index t from the notations introduced in this section.

Intensities of technologies

We introduce the following notation for intensities of technologies and subtechnologies (r - subregion, j - technology, k - option for water, n - option for nitrogen).

$x(r,j)$ - area of land allocated to technology $j \in J_X$

$xw(r,j,k,n)$ - area of land allocated to subtechnology k , n of technology $j \in J_X$

$z(r,j)$ - intensity of technology $j \in J_Z$.

Then we obviously have

$$x(r,j) = \sum_k \sum_n xw(r,j,k,n) \quad . \tag{2.5.1}$$

for all r, $j \in J_X$.

If we denote by $x_a(r)$ the total area of agricultural land in subregion r, then we also have that

$$\sum_j x(r,j) \leq x_a(r) \quad . \tag{2.5.2}$$

Other area constraints on (groups of) technologies follow for instance from the diversity that is required for crop rotation-schemes and to avoid excessively high risks due to pests.

Large scale horticulture, row crops, and cereals are always part of a crop rotation scheme. The crop rotation areas are given by

$$x_r(r) = x(r,3) + x(r,4) + x(r,5)$$

where $x_r(r)$ - crop rotation area in subregion r (ha)
$x(r,j)$ - area of technology j in subregion r (ha)

The flexibility limits of the rotation scheme are given by the conditions that both row crops and cereals are each allowed to occupy at maximum 2/3 of the total crop rotation area; for large scale horticulture this is 1/3 of the total crop rotation area. So we have the constraints

$$x(r,3) \leq (1/3) \cdot x_r(r) \quad ,$$

$$x(r,4) \leq (2/3) \cdot x_r(r) \quad ,$$

$$x(r,5) \leq (2/3) \cdot x_r(r) \quad .$$

for all r.

The stocking of dairy cattle is related to the stocking of rearing cattle and that of calves for feeding. A dairy cow normally gives birth to one calf per year. One hectare with a stocking of 4 LSU (livestock units) involves 3 dairy cows. Of the 3 calves produced per year by these cows, one calf has to be kept as a replacement of one of the cows; the remaining two can be sold as calves for feeding. The assumption is made that it is not possible to import from *outside* the region more calves for feeding than those "produced" by the dairy cows *inside* the region. The reason for making this assumption is simply that if no upper bound is set on the import of calves, the analysis procedure can produce scenarios involving a "drain" of calves to the region, which is quite unrealistic from the national point of view. For every permanently occupied "place" for a feeder calf, two calves must be supplied per year, because a newly arrived calf is only "held" for 6 months. So one hectare of grassland with 4 LSU/ha, which produces 2 calves for feeding per year, can only support one "permanent" place for a calf. A second place can be occupied by calves imported from outside the region, based on the assumption described above. In the constraint reflecting the considerations described above, the fact is taken into account that grassland with a suboptimal nitrogen supply supports a lower stocking density than grassland with an optimal supply:

$$\sum_r z(r,1) \leq 2 \cdot \frac{1}{4} \sum_r \sum_k \sum_n nx(7,n) \cdot xw(r,7,k,n)$$

where

$z(r,1)$	-	intensity of calves for feeding
$nx(7,n)$	-	number of livestock units per unit of $xw(r,7,k,n)$
$xw(r,7,k,n)$	-	subtechnology k,n of grassland with dairy cattle ($j = 7$)

Deriving from the rate with which pigs for breeding ("old pigs") give birth to pigs for feeding ("young pigs") and the time it takes for the maturation of these pigs, the natural ratio between young pigs and old pigs is 6 to 1. If the ratio is lower than 6 to 1, there must be a continuous "export" of surplus young pigs. If in the opposite situation the ratio is higher than 6 to 1, there must be a continuous import of young pigs to sustain such a ratio. Import or export of young pigs involves extra costs (transport, functioning of the pig market). In order to be able to take these costs into account, the following relationship is introduced:

$$\sum_r [6 \cdot z(r,3) - z(r,2)] = zs(2) - zd(2)$$

where $z(r,3)$ - amount of pigs for breeding,
$z(r,2)$ - amount of pigs for feeding,
$zs(2)$ - surplus of pigs for feeding (= export of young pigs),
$zd(2)$ - deficit of pigs for feeding (= import of young pigs).

Both $zs(2)$ and $zd(2)$ are non-negative variables, and of course always one of them should be equal to zero, because it does not make sense to import and export simultaneously.

In order to avoid the generation of scenarios that are not realistic bounds are set on the ratio between young pigs and old ones. This is done by introducing the constraint

$$\sum_r z(r,2)/9 \le \sum_r z(r,3) \le \sum_r z(r,2)/4 \qquad (2.5.3)$$

where $z(r,2)$ - amount of pigs for feeding,
$z(r,3)$ - amount of pigs for breeding.

The area of silage maize of which the crop production can be consumed by the cattle that are present in the region is 0.1 *ha* per livestock unit. Silage maize produced in excess of the amount that can be consumed has to be sold to farmers outside the region. The net income from this maize is lower than the yield of the maize that is consumed within the region.

To be able to take this income reduction into account, the following relationship is introduced:

$$\sum_r x(r,6) + xd(6) - xs(6) = \sum_r [0.4 \cdot x(r,7) + 0.2 \cdot x(r,8)] \quad ,$$

where $x(r,6)$ - area of silage maize,
$x(r,7)$ - area of grassland with dairy cattle,
$x(r,8)$ - area of grassland with rearing cattle,
$xd(6)$ - deficit area of silage maize for the whole region,
$xs(6)$ - surplus area of silage maize for the whole region.

Expansion of a technology can involve the investment in "capital goods"; contraction can involve disinvestment. The liquidation value of capital goods is of course much lower than the cost of procuring them. To be able to take this into account in the model (Section 2.5.3) we introduce the *increments* and *decrements* of intensities of certain technologies as (nonnegative) variables:

$$x(r,j) = x_0(r,j) + x_i(r,j) - x_d(r,j) \quad , \tag{2.5.4}$$

$$z(r,j) = z_0(r,j) + z_i(r,j) - z_d(r,j) \quad , \tag{2.5.5}$$

where 0 - suffix for current state,
i - suffix for increment,
d - suffix for decrement.

Sprinkling capacities

Implementation of land-use technologies in a subregion may be supported by sprinkling irrigation. This option is embodied by the subtechnologies that involve sprinkling. Sprinkling can either be from surface water or from groundwater. The sprinkling capacity in a subregion is governed by the outlay of sprinkler canons and accompanying equipment. The total sprinkling capacity in a subregion should equal the sum of the sprinkled areas times the respective capacities per unit area (times a unit conversion of factor which is not included here):

$$sc(r) + gc(r) = \sum_j \sum_n [xw(r,j,1,n) \cdot 25/14 \tag{2.5.6}$$
$$+ xw(r,j,2,n) \cdot 25/7] \quad ,$$

To take into account possibilities for changing these capacities in subregions we introduce the following equations:

$$sc(r) = sc_0(r) + sc_i(r) - sc_d(r) \quad , \tag{2.5.7}$$

$$gc(r) = gc_0(r) + gc_i(r) - gc_d(r) \quad , \tag{2.5.8}$$

where 0 is suffix for the current state; i and d are suffices for increments where $sc(r)$ - capacity of sprinkling from surface water (m^3/day);

$gc(r)$ - capacity of sprinkling from groundwater (m^3/day);

$xw(r,j,1,n)$ - area of a sprinkled subtechnology with sprinkling capacity of 25 mm/2 weeks (ha);

$xw(r,j,2,n)$ - area of a sprinkled subtechnology with sprinkling capacity of 25 mm/week (ha).

and decrements of the corresponding capacities, respectively.

Animal wastes byproducts

The technologies that involve livestock produce animal wastes as byproducts. These wastes can be used as fertilizers for land-use technologies in the region itself, or be transported to outside the region (where they can also be used as fertilizers). Excess animal wastes can temporarily be stored in tanks; from a water quality point of view, animal wastes that are produced during the summer can best be stored until the next spring and only then be applied to the land because application of animal wastes in autumn increases the nitrogen and phosphorus content of surface runoff and the nitrogen content of the winter percolation to the groundwater. A "permanent" way of animal wastes disposal is by transporting it to a different subregion, or, even to outside the region. (Especially the latter alternative, however, can be prohibitively expensive.)

In the following, the assumption is made that the transport and export are continuous throughout the year and that the intensity does not vary with time. Though in reality the application of animal wastes to land can take place in the course of extended periods, application is here schematized to application on October 1 ("application in autumn") ad application on April 1 ("application in spring"). Two "directions" of application are considered-application to arable land and to grassland. This distinction is made because the nitrogen in animal wastes applied to arable land is more easily leached to the groundwater than that in wastes applied to grassland (see also Section 2.5.5).

With respect to the "running animal wastes balance", it is assumed that after the spring application the storage tanks are empty. For the application in autumn this means that there cannot be more applied than the amount that becomes available during the period April 1—October 1. This is given by

$$\sum_{l} ma(r,l,m) \leq 0.5 \cdot [\sum_{j \in J_Z} mp(j,m) \cdot z(r,j) \qquad (2.5.9)$$

$$- me(r,m) - mt_0(r,m) + mt_i(r,m)] \quad ,$$

where $mp(j,m)$ - annual production of animal wastes m per unit of technology j,

$me(r,m)$ - annual export of animal wastes m,

$mt_0(r,m)$ - annual transport of animal wastes m *to* a different subregion,

$mt_i(r,m)$ - annual import of animal wastes m *from* a different subregion,

$ma(r,l,m)$ - autumn application of animal wastes m to type of land l.

The factor 0.5 takes into account that a half-year period is being considered (April 1—October 1).

The summer animal wastes production of land-use technologies that involve livestock (i.e. grassland with cattle) is not included in these equations because the animal wastes are in virtue of their nature inherently applied to land.

The slurry storage at the end of winter just before the spring application is given by

$$md(r,m) = \sum_{j \in J_Z} mp(j,m) \cdot z(r,j) + \sum_{j \in J_{X_2}} mp(j,m) \cdot x(r,j) \qquad (2.5.10)$$

$$- me(r,m) - mt_0(r,m) + mt_i(r,m) - \sum_{l} ma(r,l,m)$$

* A year is taken from October 1 till September 31.

where $md(r,m)$ - storage of animal wastes m at the end of winter.

This storage must not exceed the available storage capacity $mc(r,m)$:

$$md(r,m) \leq mc(r,m) \quad ,$$

for all r and m.

Finally, the assumption that after the spring application the storage tanks are empty is only valid if the total application in spring is equal to the storage at the end of winter:

$$\sum_{l} ms(r,l,m) = md(r,m)$$

for all r and m,

where $ms(r,l,m)$ - spring application of animal wastes type m to type of land l.

Possibilities for changes in slurry storage capacities in subregions are taken into account using the following equation:

$$mc(r,m) = mc_0(r,m) + mc_i(r,m) - mc_d(r,m) \quad .$$

The animal wastes transports within the region must balance each other. This is given by

$$\sum_{r} mt_i(r,m) = \sum_{r} mt_0(r,m)$$

2.5.3 Economic aspects

Labour requirements

Due to the difference between local and hired labour, both types of labour are introduced into the Scenario Generating System. The types of labour differ in their attitude towards mobility and towards earnings (in agriculture). With respect to both types of labour constraints are formulated. In this respect it is important to realize that imposing separate constraints for each of the subregions may have impacts on the intensities of the technologies that differ from the impacts in the case that constraints are imposed for the Southern Peel region as a whole (Vreke 1985).

For local labour separate constraints for each of the subregions are preferred because:

- Local labour is coupled to capital and (often) to land, which is not the case for hired labour. Because of this the mobility of local labour is low and the transfer to another (sub)region is expensive. Moreover, putting constraints on local labour provides an opportunity to connect cost to the mobility of local labour.
- The combination of separate constraints on the local labour per subregion and one constraint on the employment in agriculture (including hired labour) for the region as a whole provides the opportunity to have some variation (over the subregions) in income for local labour. There may, for instance, exist a region where the local labour exceeds the labour requirements (determined by the intensities of the separate technologies). In this case (average) income will be low. At the same time there may exist a subregion with both local labour and hired labour. In this subregion the (average) income for local labour will be higher.
- The link between the Scenario Generating System and the second stage in the analysis (policy analysis) becomes more direct. In the policy analysis sets of measures (policy alternatives) for the regional water management are analysed, taking into account the expected behaviour of the users of groundwater and surface water (for instance the farmers). These policies are generated by the PMA in order to influence the behaviour of the users. In this respect the local labour (being the owner of capital and often also of land) is the group, in agriculture, that has to be influenced because it is the group that takes the decisions.

For hired labour no separate constraint is formulated. Hired labour is constrained implicitly via the constraint on the employment in agriculture for the regiion as a whole.

$$l(r) = \sum_{j \in J_X} [l_x(j) \cdot x(r,j) + l_{fs} \cdot fs(r,j)] +$$

$$\sum_{l}\sum_{m}[l_{ms}(m)\cdot ms(r,l,m)+l_{ma}(m)\cdot ma(r,l,m)]+$$

$$l_{is}(r)\cdot is(r)+l_{ig}(r)\cdot ig(r)+\sum_{j}l_z(j)\cdot z(r,j) \quad ,$$

where $l(r)$ - labour required in subregion r,

$l_x(j)$ - labour requirement per unit intensity of technology $j \in J_X$,

$l_z(j)$ - labour requirement per unit intensity of technology $j \in J_Z$,

$fs(r,j)$ - amount of chemical fertilizer applied to technology j in spring,

l_{fs} - labour requirement for application of chemical fertilizer;

$ms(r,l,m)$ - spring application of slurry m to type of land l,

$ma(r,l,m)$ - autumn application of slurry m to type of land l,

$l_{ma}(m)$ - labour requirement for autumn application of slurry (per unit amount),

$l_{ms}(m)$ - labour requirement for spring application of slurry (per unit amount),

$is(r)$ - amount of sprinkling from surface water,

$ig(r)$ - amount of sprinkling from groundwater,

$l_{is}(r)$ - labour requirement for sprinkling from surface water (per unit amount),

$l_{ig}(r)$ - labour requirement for sprinkling from groundwater (per unit amount).

The respective labour requirement data are given by Reinds (1985). Of importance in the region considered is the difference between "local" workers and hired workers. By local workers are meant people who own capital goods and sometimes even land, i.e. the farmers and their families. Local workers differ from hired workers in their mobility and in their attitude towards income. Hired workers are more mobile and are paid a fixed amount per unit of time. In contrast, local workers are very immobile: to move them would require also the relocation of their capital goods, which usually is prohibitively expensive. Because local workers also derive immaterial benefits from their work, like housing and a feeling of independence, their attitude to income is rather flexible: in many situations a reduction of income can be acceptable as long as other forms of remuneration remain intact or are increased.

The dynamics of the local worker population is governed by a number of forces like:

- fertility,
- economic opportunity,
- cultural development.

Due to the complexities and uncertainties involved, it is hardly possible to capture the dynamics of the local labour force in a simple model as part of the screening level of the scenario analysis. Neither is there available a "comprehensive" model of such dynamics. So here this dynamics is assumed to be specified exogenously to the scenario module. If the amount of required labour is more than the amount available from the local labour force, then hired workers can be employed to fill the gap. For subregion r this can be represented by

$$l_h(r) \geq \max \{0, l(r) - l_p(r)\} \quad ,$$

where $l_h(r)$ - amount of hired labour,

$l_p(r)$ - amount of labour from local workers,

$l(r)$ - amount of required labour.

When necessay the relative immobility of the local labour may be taken into consideration in a simplified form by imposing exogenously upper and lower bounds on subregional local labour:

$$l_p^{\min}(r) \leq l_p(r) \leq l_p^{\max}(r) \quad .$$

Another constraint that might be useful for avoiding the generation of scenarios which are not realistic from the employment point of view, may have the form of upper and lower bounds on total labour used in the whole region:

$$l^{\min} \le \sum_{r} [l_h(r) + l_p(r)] \le l^{\max}$$

Income

The income equation does not include terms that pertain to investments and disinvestments in certain technologies. These terms appear in the equation for the cumulative savings. But the income equation does include terms for the replacement costs of capital goods. For capital goods that are "tied" to a technology these costs are implicitly included in the coefficient for a net income of a technology. For the capital goods that are not "tied" to a technology (sprinkler equipment, slurry storage tanks) the replacement costs should be included explicitly.

Let us introduce the following notation:

y	-	income from agriculture in the region,
$y_x(j,k,n)$	-	income per unit area of land for a subtechnology k, n,
$y_z(j)$	-	income per unit intensity of technology $j \in J_Z$,
p_{is}	-	energy cost of sprinkling from surface water,
p_{ig}	-	energy cost of sprinkling from groundwater,
$p_{ms}(m)$	-	cost of animal wastes application in spring,
$p_{ma}(m)$	-	cost of animal wastes application in autumn,
$p_{mt}(m)$	-	cost of transporting animal wastes in the region,
l_h	-	amount of hired labour used in the region,
p_l	-	price of hired labour,
r_{sc}	-	replacement cost of capacity for sprinkling from surface water,
r_{gc}	-	replacement cost of capacity for sprinkling from groundwater,
$r_{mc}(m)$	-	replacement cost of slurry storage capacity,
p_{xs}	-	cost of surplus silage maize,
p_{zs}	-	cost of surplus of pigs for feeding,
p_{zd}	-	cost of deficit of pigs for feeding.

In these notations the equation for the income of the region reads:

$$y = \sum_r y(r) = \sum_r [\sum_{j,k,n} y_x(j,k,n) \cdot xw(r,j,k,n)$$

$$+ \sum_{j \in J_z} y_z(j) \cdot z(r,j) - p_{is} \cdot is(r)$$

$$- p_{ig} \cdot ig(r) - \sum_m \{ \sum_l [p_{ms}(m) \cdot ms(r,l,m) \tag{2.5.11}$$

$$+ p_{ma}(m) \cdot ma(r,l,m)] + p_{mt}(m) \cdot mt_0(m) + r_{mc}(m) \cdot mc(r,m) \}$$

$$- r_{sc} \cdot sc(r) - r_{gc} \cdot gc(r)]$$

$$- p_l \cdot l_h - p_{xs} \cdot xs(6) - p_{zs} \cdot zs(2) - p_{zd} \cdot zd(2) \quad .$$

Transport of animal wastes *into* a subregion is not included here because the cost of transport is attributed to the *outgoing* transports.

Investments and capital liquidation funds

Investments are related to increases in capital goods associated with increases in intensities of technologies relative to the current situation in the region. In the screening models we assume that investments can only be financed from:

- savings by farms, understood as the difference between the income and expenditures on consumptions;
- capital liguidation funds that stem from replaced and liquidated capital goods of the technologies whose intensities have been decreased.

The total regional amount of investments associated with increaments of intensities of technologies and other capital funds (sprinkling, manure storage capacities, etc.) is formulated as follows:

$$inv = \sum_r [\sum_{j \in J_X} px_i(j) \cdot x_i(r,j) +$$

$$+ \sum_{j \in J_Z} pz_i(j) \cdot z_i(j) + psc_i(r) \cdot sc_i(r) + pgc_i(r) \cdot gc_i(r) \tag{2.5.12}$$

$$+ \sum_m pmc_i(m) \cdot mc_i(r,m)] \quad .$$

The liquidation capital funds are formulated as:

$$liq = \sum_r \Big[\sum_{j \in J_X} px_d(j) \cdot x_d(r,j) + \sum_{j \in J_Z} pz_d(j) \cdot z_d(r,j) \qquad (2.5.13)$$

$$+ psc_d \cdot sc_d(r) + pgc_d(r) \cdot gc_d(r) +$$

$$+ \sum_m pmc_d(m) \cdot mc_d(r,m) \Big] \quad ,$$

where:

$px_i(j)$, $px_d(j)$	-	investments and liquidation values, respectively, per unit of technology $j \in J_X$,
$pz_i(j)$, $pz_d(j)$	-	similar coefficients for technologies $j \in J_Z$,
psc_i , psc_d , pgc_i , pgc_d	-	investments and liquidation values per unit of respective sprinkling capacities,
$pmc_i(m)$, $pmc_d(m)$	-	investment and liquidation values per unit of manure storage capacity for manure of type m.

The investments required in a certain year can be covered from unspent investment funds accumulated during proceeding years. We discuss this aspect in Section 2.6.

2.5.4 Water quantity processes

Apart from the relationship between the total sprinkling capacity and sprinkled area as given by Eq. 2.5.6, a number of other relationships govern the separate capacities of sprinkling from groundwater and surface water. Extraction of groundwater for sprinkling can be impeded by local hydrogeological conditions (especially low permeability). In such a case, it has no sense to install more than a certain amount of equipment; this is reflected by the upper bound

$$gc(r) \leq \hat{gc}(r).$$

The amount of sprinkling from surface water is limited by the area that can be reached from surface water: only land that is within a certain distance of a ditch can be sprinkled from surface water. This land can either be sprinkled with an intensity of 25 mm/14 days (subtechnology $k = 1$) or 25 mm/week (subtechnology $k = 2$). Within a linear model, the possibility of these two options cannot be taken into account when translating the limitation on surface water sprinkling from an area to a volumetric capacity. So a "conservative" constraint is introduced, which is based on sprinkling with an intensity of 25 mm/14 days (the unit conversion from $mm * ha$ to m^3 is not included):

$$sc(r) < (\hat{sc}(r)/100) \cdot x_a(r) \cdot \frac{25}{14} \quad , \tag{2.5.14}$$

where $\hat{sc}(r)$ - maximum percentage of agricultural land that can be sprinkled from surface water,

$x_a(r)$ - area of agricultural land in subregion r (ha),

The capacity of sprinkling from surface water plus the supply capacity that is available for infiltration of surface water must of course also be less than the amount of surface water supply that is allocated to a subregion, therefore:

$$sc(r) + uc(r) < SC(r) \quad , \tag{2.5.15}$$

where $sc(r)$ - capacity of sprinkling from surface water,

$uc(r)$ - surface water supply capacity available for infiltration,

$SC(r)$ - surface water supply capacity to subregion r.

Surface water supply to a subregion will always lead to some infiltration, even if it is not intended. This is embodied by the constraint

$$uc(r) \geq f_u(r) * SC(r)$$

where $uc(r)$ - surface water supply capacity available for infiltration

$f_u(r)$ - infiltration fraction

$SC(r)$ - total surface water supply capacity to a subregion.

The values of $f_u(r)$ were derived from runs with the comprehensive model FEMSATP. The allocated supply to a subregion must not exceed the capacity the infrastructure can convey:

$$SC(r) < \hat{SC}(r) \quad , \tag{2.5.16}$$

where $SC(r)$ - surface water supply capacity to subregion r,

$\hat{SC}(r)$ - infrastructure conveyance capacity to subregion r.

And the sum of the supply capacities to the subregions must not exceed the supply capacity for the whole region; this capacity can vary (depending on decisions made by the PMA) between 175,000 and 350,000 m^3/day, where 175,000 is the current value and 350,000 the upper bound as follows from the infrastructure present in the supply system. The constraint for the whole region is:

$$\sum_r SC(r) < ST \tag{2.5.17}$$

where ST - total surface water supply capacity to the region (m^3/day).

It is necessary to be able to translate the sprinkling capacities $gc(r)$ and $sc(r)$ to the actual amounts of sprinkling $ig(r)$ and $is(r)$. These actual amounts will depend on the weather conditions – in a dry year more use will be made of sprinkling installations than in a wet one. To a certain extent the amount of time that sprinklers are used will also depend on the activities in the region (more groundwater pumping will increase the water demand in a subregion as a consequence of reduced capillary rise), but this is a secondary effect that can be neglected in a first-level model. The following simple relationships are used for translating capacities to amounts:

$$ig(r) = P_{wds}(r) \cdot gc(r) \quad , \tag{2.5.18}$$

$$is(r) = P_{wds}(r) \cdot sc(r) \quad , \tag{2.5.19}$$

where $P_{wds}(r)$ - period of water demand for sprinkling days.

Similarly, a relation can be given between the actual amount of surface water infiltration and the SW supply capacity that is available for infiltration at peak supply time, namely $SC(r) - sc(r)$:

$$u_s(r) = P_{wdi}(r) \cdot (SC(r) - sc(r)) \tag{2.5.20}$$

where $P_{wdi}(r)$ - period of infiltration at peak capacity.

However, the extrapolation of the above equation is subject to an upper bound because the infiltration capacity of the hydrologic system can become the limiting factor, instead of the supply of water. This is taken into account by introducing the upper bound $\hat{u}_s$ and taking the **maximum** value of the one given in Eq. 2.5.20 and $\hat{u}_s$:

$$u_s(r) = \max \{P_{wdi}(r) \cdot uc(r) \;\; ; \;\; \hat{u}_s(r)\} \quad .$$

Groundwater level lowerings in nature areas are of interest because of their ecological consequences. Both the lowering at the end of winter and at the end of summer are of interest: these lowerings can be translated to "ecological damage", using a procedure described in Section 2.3.4. For computing the lowerings, a simple influence matrix approach is used:

$$\Delta hw(r) = \sum_{i=1}^{31} a(r,i) \cdot q(i) \quad ,$$

$$\Delta hs(r) = \sum_{i=1}^{31} [b(r,i) \cdot q(i) + c(r,i) \cdot ig(i) + d(r,i) \cdot u_s(i)] \quad ,$$

where $\Delta hw(r)$ - lowering at the end of winter in subregion r,
$\Delta hs(r)$ - lowering at the end of summer in subregion r,
$q(i)$ - groundwater extraction for public water supply in subregion i,
$ig(i)$ - groundwater extraction for sprinkling,
$u_s(i)$ - amount of surface water infiltration,

$a(r,i)$, $b(r,i)$, $c(r,i)$, $d(r,i)$, – elements of influence matrices, obtained using model FEMSATP described in Section 2.3.1.

2.5.5 Nitrogen processes in the soil

Fertilization, mineralization of organic-N

Each technology that uses land ($j \in J_X$) has a specified level of the amount of nitrogen that is required for crop growth $n_r(r,j)$. These levels are given in Reinds 1985. This nitrogen can come from different sources, i.e. chemical fertilizers and various types of animal wastes. The nitrogen in animal wastes and in the soil is present in different forms. Some of it is already mineralized, some of it is bound in easily degradable organic compounds, and the remainder is contained in compounds that are rather stable. The first fraction is immediately available after application of the animal wastes, the second fraction in the course of the first year after application, and the third fraction only in subsequent years.

In the model, we do not include the dynamics of the third fraction. Instead, we assume that the soil content of stable nitrogen is in a "steady state" corresponding to the animal wastes application in a certain year. In this steady state, the amount of stable nitrogen remains constant; so the amount of stable nitrogen that is mineralized must equal the amount that (yearly) is added by application of animal wastes. As described by Lammers (1983), it is then possible to compute the amount of nitrogen available for crop growth by simply multiplying the animal wastes applications by nitrogen effectivity coefficients.

Using the above-mentioned simplified representation of nitrogen mineralization, the constraints prescribing the satisfaction of nitrogen requirements of technologies become for respectively the arable land ($l = 1$) and the grassland ($l = 2$) technologies in a subregion (the effectivity of nitrogen in applied chemical fertilizer is assumed to be 1.0):

$$\sum_m [e_{ma}(l,m) \cdot ma(r,l,m) + e_{ms}(l,m) \cdot ms(r,l,m)] + \qquad (2.5.21)$$

$$\sum_{j \in J_{X_l}} fs(r,j) = \sum_{j \in J_{X_l}} \sum_k \sum_n nr(j,n) \cdot xw(r,j,k,n) \quad ,$$

where J_{X_l} - subset of technologies: $l = 1$ for arable land; $l = 2$ for grassland,

$ma(r,l,m)$ - amount of slurry m applied in autumn,
$ms(r,l,m)$ - amount of slurry m applied in spring,
$e_{ma}(l,m)$ - nitrogen effectivity coefficient, autumn application,
$e_{ms}(l,m)$ - nitrogen effectivity coefficient, spring application,
$fs(r,j)$ - amount of nitrogen in applied chemical fertilizer,
$nr(j,n)$ - nitrogen requirement (per unit area) of subtechnology n of the technology j.

These constraints have been formulated on the aggregation level of the subsets arable land and grassland technologies because the nitrogen effectivities are assumed to vary only between these two categories. The same assumption has been made with regard to the leaching of nitrogen as will be seen from the relationships given in the next section.

The seedlings of certain crops require an amount of chemical fertilizer nitrogen applied in spring:

$$fs(r,j) = \sum_k \sum_n r_{fs}(j,n) \cdot xw(r,j,k,n) \quad , \qquad (2.5.22)$$

where $fs(r,j)$ - amount of nitrogen in applied chemical fertilizer,
$r_{fs}(j,n)$ - requirement (per unit area) for chemical fertilizer.

Nitrogen leaching

The nitrate load on phreatic water can approximately be described by a function of the form (Rijtema, pers. comm.):

$$n_p(r) = f_1(r) \cdot f_2(r) \quad , \qquad (2.5.23)$$

where $n_p(r)$ - nitrate load on phreatic water,
$f_1(r)$ - nitrate leaching,
$f_2(r)$ - groundwater-level reduction factor; $0.0 \leq f_2 \leq 1.0$.

In the function f_1, the coefficients of variables that pertain to grassland technologies (from set J_{X_2}) differ from those of variables that pertain to arable land technologies (from set J_{X_1}). To the applications in autumn are added the amounts that are applied to land by virtue of their nature, i.e. the cow dung applied to grassland during summer. These amounts are not included in the equation (2.5.21) for the satisfaction of nitrogen requirements because the nitrogen effectivity of these applications is very low. The function $f_1(r)$ is of the form:

$$f_1(r) = c_1 \cdot \sum_{j \in J_{X_2}} x(r,j) + c_2 \cdot \sum_{j \in J_{X_1}} x(r,j) + c_3 \cdot \sum_{j \in J_{X_2}} fs(r,j)$$

$$+ c_4 \cdot \sum_{j \in J_{X_1}} fs(r,j) + \sum_m c_5(m) \cdot [ma(r,2,m) + \qquad (2.5.24)$$

$$\sum_{j \in J_{X_2}} \sum_k \sum_n mx(j,n,m) \cdot xw(r,j,k,n) + c_6(m) \cdot ms(r,2,m)] +$$

$$\sum_m c_7(m) \cdot \sum_{j \in J_{X_1}} [ma(r,1,m) + c_8(m) \cdot ms(r,1,m)] + c_9 \cdot [x_f(r) + x_n(r)]$$

where

$x(r,j)$	-	area allocated to a technology j,
$fs(r,j)$	-	amount of nitrogen in applied chemical fertilizer,
$ma(r,l,m)$	-	application of slurry m in autumn,
$ms(r,l,m)$	-	application of slurry m in spring,
$mx(j,n,m)$	-	production of wastes type m per unit area of subtechnology (j,n),
$x_f(r)$	-	area of forest in subregion r,
$x_n(r)$	-	area of nature reserves in subregion r.

The values of the coefficients c_1 ..., c_7 have been derived by Lammers (1983) and Rijtema (personal communication) from field experiments that did not include sprinkled crops. There is reason to believe that moderate irrigation by sprinkling reduces the nitrate leaching to groundwater, because sprinkling increases crop growth and thereby the nitrogen uptake by crop roots; possibly sprinkling also causes some denitrification because it can for short intervals create anaerobic circumstances, which enhances this process. Also, the groundwater level at the end of winter influences the denitrification. The various factors that determine the denitrification are summarized by the function f_2, the values of which are derived from a run with the comprehensive model ANIMO, described in Section 2.3.3 and in Berghuijs-van Dijk et al. 1985.

2.5.6 Nitrogen processes in groundwater

In the first-level model for groundwater quality, a steady-state approach is used. By this is meant that the nitrogen concentrations are computed that would have been reached if the animal wastes applications of a certain scenario had been repeated each year, for infinite number of years. Instead of "tracing" the flow of nitrogen, a "mixing-cell" approximation is used, basing on the principle of conservation of matter, in this case nitrogen. Per subregion there are two mixing cells, one for the phreatic layer and one for the aquifer directly beneath it. Then there is one total mixing cell for the deep aquifer in the Slenk Region (Figure 2.5.2). The further assumptions are that:

– decomposition of nitrate in the cells can be taken into account by factors α, β and γ (that depend on the organic matter content of the subsoil);

– N-concentration of water entering the region through a boundary section is equal to the concentration of the mixing cell to which the water goes to.

In the mass balance equations of the mixings cells the left-hand sides contain the yearly decomposition of the nitrate and the right-hand sides the net influx of nitrate. The equilibrium state is reached when the decomposition becomes exactly equal to the net influx. For the phreatic cells we have

$$\alpha \cdot c_p(r) \cdot v_p(r) = n_p(r) - u_w(r) \cdot c_p(r) - p_c(1,r) \cdot c_p(r) + s_p(1,r) \cdot c_d(1,r) \tag{2.5.25}$$

where $c_p(r)$ - nitrogen concentration in the phreatic cell of subregion r,

$v_p(r)$ - volume of water in the phreatic cell of subregion r

α - factor controlling denitrification ($0 \leq \alpha \leq 1$),

$n_p(r)$ - nitrogen leaching,

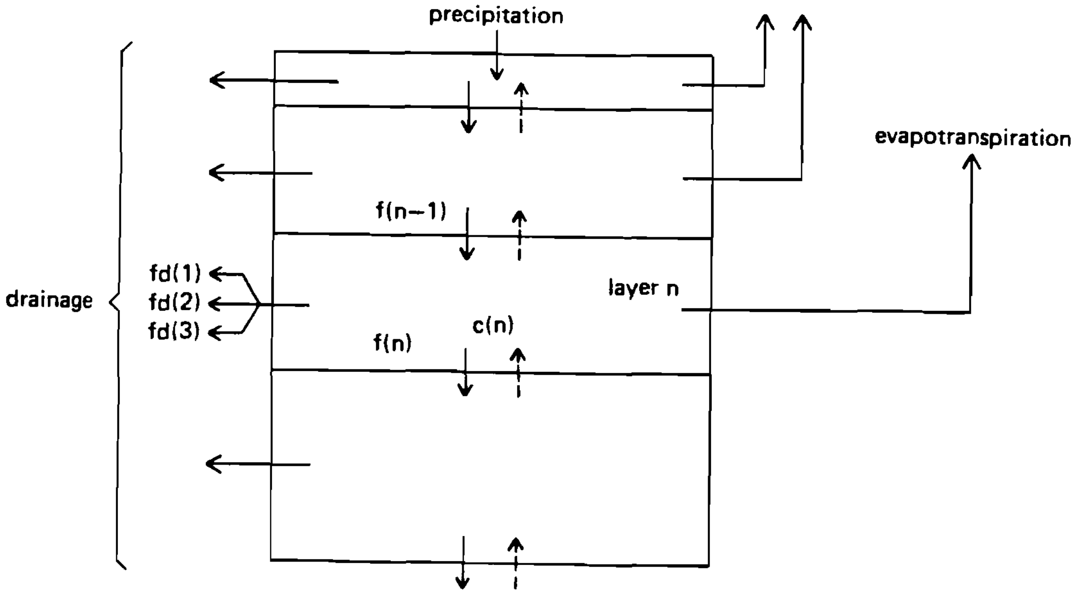


Figure 2.5.2: Mixing-cell model of groundwater quality (nitrogen)

$u_w(r)$	-	drainage to surface water,
$p_c(1,r)$	-	percolation from phreatic to the first aquifer cell (downwards, positive),
$s_p(1,r)$	-	seepage from the first aquifer cell to the phreatic cell (upwards, positive),
$c_d(1,r)$	-	nitrogen concentration in the first aquifer cell.

Depending on the direction of flow being downwards or upwards, the seepage $s_p(1,r)$ or deep percolation $p_c(1,r)$ is zero, respectively. For the mixing cells in the first aquifer we have

$$\beta \cdot c_d(r) \cdot v_d(r) = p_c(1,r) \cdot c_p(r) - s_p(1,r) \cdot c_d(r) -$$

$$p_c(2,r) \cdot c_d(r) + s_p(2,r) \cdot c_{dd} + \tag{2.5.26}$$

$$\sum_i [f_h(i,r) \cdot c_d(i) - f_h(r,i) \cdot c_d(r)] +$$

$$[f_h(32,r) - f_h(r,32)] \cdot c_d(r) \quad ,$$

where $c_d(r)$ - nitrogen concentration in mixing cell in the first aquifer,

c_{dd} - nitrogen concentration in the deep aquifer of the Slenk,

$v_d(r)$ - volume of water present the first aquifer cell r

β - factor controlling denitrification,

$p_c(1,r)$ - percolation from phreatic to the first aquifer cell (downwards, positive),

$s_p(1,r)$ - seepage from the first aquifer cell to phreatic cell (upwards, positive),

$p_c(2,r)$ - percolation from the first aquifer cell Slenk aquifer (downwards, positive),

$s_p(2,r)$ - seepage from Slenk aquifer to the first aquifer cell (upwards, positive),

$f_h(i,r)$ - horizontal flow in the first aquifer, from subregion i to r (positive),

$f_h(32,r)$ - horizontal flow in the first aquifer from outside region boundary to subregion r (positive),

$f_h(r,32)$ - horizontal flow in the first aquifer from subregion r to outside region boundary (positive).

Equation (2.5.26) does not contain a term for the removal of nitrogen by extractions for sprinkling or public water supply because these terms would make the model quadratic. On the regional scale these terms are of low significance, but on the subregional scale they can in reality cause significant reductions of the amount of nitrogen that is present in the subsoil. By not taking these reductions into account, the model yields "safe" estimates of the nitrogen concentrations.

For the mixing cell of the deep aquifer in the Slenk we have

$$\gamma \cdot c_{dd} \cdot v_{dd} = \sum_{r=1}^{19} [p_c(2,r) \cdot c_d(r) - s_p(2,r) \cdot c_{dd}] \qquad (2.5.27)$$

where the symbols have the meaning following the same logic as above, γ is the denitrification coefficient. The summation here is restricted to those subregions in the Slenk.

The water quantity variables in the above equations are fixed, i.e. they enter as parameters into the model. If these variables had been described using relations involving decision variables that impact them (e.g. groundwater extractions), then the model as a whole would have become quadratic, because the nitrogen concentrations are implemented as "decision variables" to which the LP-algorithm attaches a value in the course of solving a "problem". (Equations (2.5.25–2.5.27) contain product terms of water quantity variables and nitrogen concentrations.) Quadraticity in the model would have greatly increased the computational burden when using it, and would have gained relatively little in terms of model adequacy.

The dynamics of nitrogen in a groundwater system have a very long characteristic time; therefore it was deemed irrelevant to include the effect of weather-variability on the time-dependency of nitrogen concentrations in the deeper groundwater. This reasoning provides further justification for only considering the *equilibrium* concentrations in the first-level models. For obtaining the values of water quantity parameters, a multi-year run was made with the model FEMSATP. All water quantity parameters were then simply averaged over the considered period. Values of denitrification factors α, β, γ are obtained using model ANIMO.

2.5.7 Public water supply

If the demands of public water supply are given, then the total of the extractions in the subregions must satisfy

$$\sum_r q(r) \geq Q_d + \sum_r \sum_j \sum_k \sum_n w_x(j,n) \cdot xw(r,j,k,n) + $$
$$+ \sum_r \sum_j w_z(j) \cdot z(r,j) \quad ,$$

where $q(r)$ - extraction of groundwater in subregion r,

Q_d - demand of public water supply,

$w_x(j,n)$, $w_z(j)$ - demands for public water supply of respective technologies.

The costs of installing new wells and linking them up with the existing distribution system are not taken into account here.

With a view to maintaining the potability of groundwater, but also out of general environmental concern, constraints can be imposed on the nitrogen concentrations of the water in the mixing cells. This is given by

$$c_p(r) < \hat{c}_p \quad ,$$

$$c_d(r) < \hat{c}_d \quad ,$$

$$c_{dd} < \hat{c}_{dd} \quad ,$$

where $c_{p(r)}$ - N-concentration in phreatic cell,
$\hat{c}_p(r)$ - upper bound on $c_p(r)$,
$c_d(r)$ - N-concentration in first aquifer cell,
$\hat{c}_d(r)$ - upper bound on $c_d(r)$,
c_{dd} - N-concentration in second aquifer mixing cell,
$\hat{c}_{dd}$ - upper bound on c_{dd}.

2.5.8 Natural ecosystems

Ecological processes in nature areas are influenced in a complex manner by the groundwater regime. No attempt is made to describe the dynamics of the involved processes. Instead, an interpretation procedure has been developed for the effect of groundwater level *lowerings* on the ecological value of nature areas (Section 2.3.4). For a certain value of a nature area, the constraints on the lowerings are

$$\Delta hs(r) < \Delta \hat{hs}(r) \quad ,$$

$$\Delta hw(r) < \Delta \hat{hw}(r) \quad ,$$

where $\Delta hs(r)$ - groundwater level lowering at the end of winter,
$\Delta \hat{hs}(r)$ - upper bound on Δhs,

$\Delta hw(r)$ - groundwater level lowering at the end of summer,

$\Delta \hat{hw}(r)$ - upper bound on Δhw.

An example of the relation between combination of $\Delta hs(r)$ and $\Delta hw(r)$ and a measure for the ecological value of a nature area is given in Figure 2.3.14 (Section 2.3.4).

2.6 Scenario Analysis

In this section we outline the logic of the scenario analysis based on the models introduced in the preceding sections. In doing this we use a generalized representation of these models to avoid details that are not relevant for our current purpose and as we hope to make the description more clear.

As has been said previously in this Report the purpose of the scenario analysis is to determine sequences of planning decisions which generate trajectories of the regional development satisfactory from the viewpoint of the PMA in their economic and environmental aspects. In this section, we shall concretize this thesis for the context of the Southern Peel region.

2.6.1 First level: screening analysis

As has been assumed in Part 1, during the scenario analysis stage the PMA considers all the planning decision variables as being under his control. The variables used in the screening models include intensities of various technologies in different subregions, capacities for irrigation from groundwater and surface water in subregions, applications of various types of manures and chemical fertilizers and others. We shall denote here by x vector of all the decision variables used in the simplified models of the scenario generation system. To account for changes in these decision variables from year to year we shall use notation x_t for the vector of values of the decision variables in year t. If we denote by x_0 such a vector representing the current state of the region, then a sequence

$$x_0, x_1, \ldots, x_t, \ldots$$

will represent future year-to-year changes in the structure of the regional agriculture starting from the current state.

The simplified models described in Section 2.5 have the form of linear equations and inequalities representing relations between the decision variables, i.e. between components of vector x, which should be satisfied every year. As was outlined in the preceding sections these relationships are related to crop rotation schemes, to requirements of some technologies for fertilizers, labour, irrigation, etc., economic and other aspects. For our purpose here we can conveniently represent the overall system of these linear equations and inequalities in the following matrix-vector form:

$$A(\xi_t) \cdot x_t \leq b \quad , \tag{2.6.1'}$$

where matrix A and vector b are determined by coefficients and free terms in the simplified models. Some of the elements of matrix A (coefficients of simplified models), are uncertain (for instance, may have different values depending on weather conditions, or, in other words, for different weather years). To indicate this here ad in the following we use notation $A(\xi_t)$ understanding ξ_t as vector of uncertain parameters relating values of the coefficients to weather years. Mathematically speaking system (2.6.1') should be satisfied by every member (every year) of a feasible sequence $x_0, x_1, \ldots, x_t, \ldots$ of planning decision variables.

Apart from these "yearly" relationships between components of vector x we should also take into account that only limited changes in these components are practically feasible due for instance to a certain degree of conservatism in farmers' behaviour. To take this consideration into account we introduce relationships of the form:

$$\alpha^i x_{t-1}^i \leq x_t^i \leq \beta^i x_{t-1}^i \tag{2.6.1''}$$

which are to be satisfied every year t for every component of vector x. Coefficients α^i, β^i represent maximum percentages of changes in the year t relative to the preceding year. Sequences $x_0, x_1, \ldots, x_t, \ldots$ satisfying systems (2.6.1') and (2.6.1") are considered feasible in our model.

Different trajectories of the future regional development represented by sequences $x_0, x_1, \ldots, x_t, \ldots$ are compared with each other by the PMA on the basis of indicators quantifying some economic and environmental aspects of trajectories.

Economic indicators are related to agricultural income and investments. Clearly, various income indicators can be considered related to the distribution of income between subregions, between land-use and non-land-use technologies, etc. The same applies to investments. For simplicity we consider here regional total agricultural income as a sufficient income-related indicator, noting that more detailed indicators may easily be incorporated into the scheme outlined here.

Total agricultural income in the region is given by Eq. (2.5.11) in Section 2.5.3. For our purpose here we can describe this income in year t as a linear function

$$y(x_t, \xi_t) = c(\xi_t) \cdot x_t \tag{2.6.2}$$

depending on vector x_t used here to represent all the decision variables. $c(\xi_t)$ is a vector of coefficients corresponding to coefficients in Eq. (2.5.11). Some of these coefficients are uncertain, for instance, those corresponding to coefficients $y_x(\cdot)$ in Eq. (2.5.11) (incomes per unit areas of land use subtechnologies), which can have different values for different weather years ξ_t.

Investments as was discussed in Section 2.5.3 are related to increases in capital goods associated with changes in intensities of technologies, and are given by Eq. 2.5.12. To analyse changes relative to the current situation characterized by vector x_0 used here we consider incremental investments with the current situation as the reference. Having this in mind, we use here notation $inv(x_t - x_0)$ for investments related to changes in the decision vector from x_0 to x_t. Basing on Eq. 2.5.12 we can describe this function in the following compact form:

$$inv(x_t - x_0) = \sum_i p_i^+ \cdot [x_t^i - x_0^i]^+ \quad , \tag{2.6.3'}$$

where

$$[x_t^i - x_0^i]^+ = \begin{cases} x_t^i - x_0^i \; , & \text{if } x_t^i \geq x_0^i \\ 0 \; , & \text{otherwise} \end{cases} \quad ,$$

and coefficients p_i^+ denote investments per unit change of respective components x^i of vector x.

To take into account funds stemming from replaced or liquidated capital goods we use in Section 2.5.3 *liquidation capital funds* (Eq. 2.5.13). Similar to Eq. 2.6.3 we can write these funds in the following compact form:

$$liq(x_t - x_0) = \sum_i p_i^- \cdot [x_t^i - x_0^i]^- \quad , \tag{2.6.3''}$$

where

$$[x_t^i - x_0^i]^- = \begin{cases} 0 & , \text{ if } x_t^i - x_0^i \geq 0 \\ x_0^i - x_t^i & , \text{ otherwise} \end{cases} \quad ,$$

and p_i^- denote liquidation values per unit change of respective components x^i of vector x.

Environmental indicators are related to groundwater lowerings in the three nature areas in the region, and also to concentrations of nitrogen in subregional sections of the phreatic aquifers as well as in the deep groundwater aquifer. As has been assumed previously these concentrations represent not the immediate consequences of the regional activities, but the so-called equilibrium values that may be reached in future if these activities are maintained. The groundwater lowerings and concentrations are determined by vector x_t as used here.

Since the lowerings describe one year effects of the activities in the region they also depend on the weather conditions in a respective year. Therefore, we can describe the lowerings as a vector function $h(x_t, \xi_t)$ with uncertain vector ξ_t relating these lowerings to different weather years. As before, having in mind the linearity of the corresponding relationships in the simplified models we can write function $h(x_t, \xi_t)$ in the form:

$$h(x_t, \xi_t) = H(\xi_t) \cdot x_t \tag{2.6.4}$$

with $H(\xi_t)$ being a generalized influence matrix combining coefficients used in the corresponding relationships in Section 2.5.4.

Finally, we denote by $g(x_t)$ vector representing values of nitrogen concentrations in the subregional sections of the phreatic aquifer and in the deep groundwater aquifer. As is defined in the simplified models (Section 2.5.7) these concentrations are evaluated basing on averaged groundwater flows and, therefore, do not include uncertain weather parameters. As before, we can write this vector in the form:

$$q(x_t) = Q \cdot x_t \quad , \tag{2.6.5}$$

where Q is a matrix of coefficients determined by fixed groundwater flows and other parameters used in the simplified models.

For convenience we present here the list of the relationships introduced in this section:

$x_0, x_1, \ldots, x_t, \ldots$	-	sequence of vectors of decision variables,
$A \cdot x_t \leq b$	-	linear relationships between components of vector x_t,
$\alpha^i \cdot x_{t-1}^i \leq x_t^i \leq \beta^i \cdot x_{t-1}^i$	-	feasible changes in components of vector x from year to year,
$y(x_t, \xi_t) = c(\xi_t) \cdot x_t$	-	total agricultural income,
$inv(x_t - x_0)$	-	investments related to changes from x_0 to x_t
$liq(x_t - x_0)$	-	liquidation capital funds related to changes from x_t to x_0,
$h(x_t, \xi subt) = H(\xi_t) \cdot x_t$	-	vector of groundwater lowerings,
$q(x_t) = Q \cdot x_t$	-	vector of nitrogen concentrations.

Problem formulation

The current situation in the region is characterized by the following values of the indicators considered:

$$y^0 = y(x_0, \xi)\ ,\ h^0 = h(x_0, \xi)\ ,\ q^0 = q(x_0) \quad .$$

Assuming that values y^0, h^0, q^0 are not satisfactory, we are looking at this stage for combinations of values of control variables x characterized by more satisfactory values of these indicators. But starting from the current situation x_0 we can change components of vector x only gradually due to constraints (2.6.1"). This means that the transition of the system from its current situation x_0 to a situation with more satisfactory values of the indicators would require a certain time period. We refer to this period as the transition period and denote by T the respective number of years, viewing this period as one of the unknowns of the system that is to be estimated in the course of the analysis.

Suppose x_T is a vector of values of planning control variables such that the values

$$y^T = y(x_T, \xi) \ , \ h^T = h(x_T, \xi) \ , \ q^T = q(x_T)$$

are satisfactory from the viewpoint of the RPMA. Then we assume that these satisfactory values of the indicators can be maintained in the future by using the practices as in x_T in all subsequent years. In other words, we can consider sequences of control variables (trajectories) of the form:

$$x_0 \ , \ x_1 \ , \ldots , \ x_t \ , \ldots , \ x_T \ , \ x_T \ , \ldots \qquad (2.6.6)$$

where T is the number of years after which satisfactory values of the indicators have been achieved. Using this reasoning, instead of sequences of infinite duration (2.6.6) we can consider finite sequences

$$x_0 \ , \ x_1 \ , \ldots , \ x_T$$

with T unknown.

Now our problem can be formulated as follows:

Problem IS

determine a sequence $x_0 \ , \ x_1 \ , \ldots , \ x_T$ such that

1. $A \cdot x_t \leq b$

2. $-\alpha \cdot x_{t-1}^{i} \le x_{t}^{i} \le \beta^{i} \cdot x_{t-1}^{i}$

3. $\sum_{\tau=1}^{t} c(\xi_{\tau}) \cdot x_{\tau} + liq(x_t - x_0) - inv(x_t - x_0) - cons \cdot t \ge 0$

4. $c(\xi_T) \cdot x_T \ge y^T$

5. $H(\xi_T) \cdot x_T \le h^T$

6. $Q \cdot x_T \le q^T$

7. $inv(x_T - x_0) \le inv^T$

8. $(y^T, inv^T, h^T, q^T, T) \longrightarrow$ satisfactory to the PMA.

Inequality 3 in this formulation requires that in every year the total investments for changes in x be covered from the total cumulative savings in agriculture. In this inequality we denoted by *cons* total expenditures for consumption in the region per year.

Simplified formulation

To reduce the computational effort associated with the high dimension of Problem IS, we consider in this section its simplification that has been implemented in the screening analysis for the Southern Peel region.

In order to arrive at this simplification we consider not all possible sequences $x_0, x_1, \ldots, x_T$ as potential candidates for solution to Problem 1S, but only what may be called linear sequences, i.e. sequences generated as follows:

$$x_t = x_0 + \frac{t}{T}(x_T - x_0) \quad . \tag{2.6.7}$$

Any trajectory generated by this rule can be visualized as a straight line connecting points x_0 and x_T in the vector space of x. Therefore, with the point x_0 fixed as the current situation any such sequence is determined by its other end point x_T. In other words, our problem for such class of sequences $x_0, x_1, \ldots, x_T$ is reduced to a problem of determining x_T. As can be verified this latter problem deduced from Problem 1S has the form:

Problem IIS

determine x_T and T such that:

1. $A \cdot x_T \leq b$

2. $\frac{1}{1+\alpha^i T} \cdot x_0^i \leq x_T^i \leq (1+\beta^i T) \cdot x_0^i$

3. $c(\xi) \cdot x_0 - cons + \frac{1}{T}[c(\xi)(x_T - x_0) - inv(x_T - x_0) + liq(x_T - x_0)] \geq 0$

4. $c(\xi) \cdot x_T \geq y^T \geq y^0 = c(\xi) \cdot x_0$

5. $H(\xi) \cdot x_T \leq h^T$

6. $Q \cdot x_T \leq q^T$

7. $inv(x_T - x_0) \leq inv^T$

8. $(y^T, inv^T, h^T, q^T, T) \rightarrow$ satisfactory to the PMA.

As we discussed earlier, T is the duration in years of the transition period after which the satisfactory values of indicators are achieved. In the above formulation T is the only variable (and indicator) making the above problem nonlinear (Eq. 2 and 3). To avoid unnecessary computational difficulties we consider T as a parameter and fix its value (say, 20 years) prior to solving the problem. Clearly, lower values of T leave through constraints (2) less freedom in choosing x_T and therefore, less possibilities of achieving satisfactory values of indicators h^T, q^T.

Uncertain coefficients $c(\xi)$ and $H(\xi)$ in this formulation are chosen basing on the reasoning of deterministic equivalents (see Section 1.5.2) to represent weather years unfavourable to a chosen degree.

Solving Problem IIS

Problem IIS is a typical problem of multiobjective choice with a number of indicators: y^T, inv^T, h^T, q^T, T quantifying various aspects of the regional performance. Clearly, the PMA has certain preferences with respect to each of them that can be described as follows:

y^T $\rightarrow$ greater possible

z^T $\rightarrow$ lower possible

$h^T \quad \longrightarrow \quad$ lower possible

$q^T \quad \longrightarrow \quad$ lower possible

$T \quad \longrightarrow \quad$ lower possible.

Since achievable values of these indicators are interdependent through all the relationships present in the above formulation, improvements in some of them can often be made only at the cost of deterioration in the others. Furthermore, different combinations of these values may be incomparable with each other basing on the preferences described above. For example, none of the two combinations:

$$(y^T = 200 \, , \, inv^T = 100 \, , \, h^T = 3 \, , \, q^T = 20 \, , \, T = 20)$$

$$(y^T = 250 \, , \, inv^T = 120 \, , \, h^T = 3 \, , \, q^T = 50 \, , \, T = 20)$$

can be preferred with respect to each other since income in the second is better than in the first, but at the same time quality of groundwater is worse in the second than in the first. Since there is no formal rule of preference in such cases we cannot speak about any optimal combinations of values of the indicators, but have to rely on the judgement of the PMA with regard to what combinations are satisfactory (preferable) to him/her. But this means that the overall problem can be solved only with the PMA participating in the solution process. This participation is the intrinsic requirement of any multiobjective analysis. The solution process becomes a dialogue between the decision support system and the PMA in the course of which the PMA sequentially poses various questions to the system and obtains information guiding him to a satisfactory solution. And the wider the scope of questions accepted by the decision support system the more efficient is the system as a decision support tool.

The screening analysis part of the scenario module for the Southern Peel region is designed for solving a variety of linear programming problems basing on the above formulation of Problem IIS. Using this system the PMA can fix desirable requirements for values of all of the indicators y^T, z^T, h^T, q^T (a value of T is fixed as a parameter) and then find solution x_T fulfilling these requirements. It is also possible to fix desirable requirements for all the indicators except one and optimize the value of the remaining indicator.

To exemplify the first case, suppose that the RPMA wishes to achieve values $\hat{y}^T$, $\hat{inv}^T$, $\hat{h}^T$, $\hat{q}^T$, $\hat{T}$ of the indicators. Then the underlying mathematical problem will have the form:

determine $x_{\hat{T}}$ such that

$$A \cdot x_{\hat{T}} \le b$$

$$\frac{1}{1+\alpha^i \hat{T}} x_0^i \le x_{\hat{T}} \le (1+\beta^i \hat{T}) \cdot x_0^i$$

$$c(\xi) \cdot x_0 - cons + \frac{1}{T}[c(\xi)(x_{\hat{T}} - x_0) - inv(x_{\hat{T}} - x_0) + liq(x_{\hat{T}} - x_0)] \ge 0$$

$$c(\xi) \cdot x_{\hat{T}} \ge \hat{y}^T$$

$$H(\xi) \cdot x_{\hat{T}} \ge \hat{h}^{\hat{T}}$$

$$Q \cdot x_{\hat{T}} \le \hat{q}^T$$

$$inv(x_{\hat{T}} - x_0) \le \hat{inv}^T \quad .$$

In the second case, suppose that the PMA wishes to achieve values $\hat{y}^{\hat{T}}$, $\hat{h}^{\hat{T}}$, $\hat{q}^{\hat{T}}$, $\hat{T}$ with a minimum possible value of $inv^{\hat{T}}$. Then the problem will have the form

$$inv(x_{\hat{T}} - x_0) \longrightarrow \min_{x_{\hat{T}}}$$

$$A \cdot x_{\hat{T}} \le b$$

$$\frac{1}{1+\alpha^i \hat{T}} x_0^i \le x_{\hat{T}} \le (1+\beta^i \hat{T}) \cdot x_0$$

$$c(\xi) x_0 - cons + \frac{1}{\hat{T}} [c(\xi) \cdot (x_{\hat{T}} - x_0) - z(x_{\hat{T}} - x_0) + liq(x_{\hat{T}} - x_0)] \ge 0$$

$$c(\xi) \cdot x_{\hat{T}} \ge \hat{y}^T$$

$$H(\xi) \cdot x_{\hat{T}} \le \hat{h}^T$$

$$Q \cdot x_{\hat{T}} \le \hat{q}^T \quad .$$

The solution x_T to this latter problem allows to achieve the desired values $\hat{y}^T$, $\hat{h}^T$, $\hat{q}^T$ with minimum incremental investments.

If a problem of the above two types has no solution, it means that the requirements fixed are not achievable (too tight).

2.6.2 Second level: simulation

As has been discussed in Section 1.6, the objective of the second level simulation analysis is to obtain relatively more precise and more detailed information about scenarios of regional development preliminary chosen as a result of screening analysis. This is achieved by using models more detailed than those of the first level and also by repeating cmputations for conditions of various weather years. The structure of the system of models for the second level analysis is illustrated in Figure 2.6.11.

The aggregated (per year) data characterizing a scenario chosen at the first level screening analysis and used as input data for simulations concern amounts of animal wastes applications over the region, extractions of groundwater for public water supply, capacities for sprinkling from surface water and groundwater, areas of sprinkled subtechnologies, levels of nitrogen supply for these subtechnologies.

One of the basic questions to be answered by simulation experiments concerns whether the irrigation capacities and pumping rates recommended by the screened scenario are compatible with the recommended areas and production levels of land-use technologies. Also the important related question is whether the resultant groundwater lowerings are tolerable as far as the sustainable evolution of the nature reserves is concerned. And, of course, groundwater quality aspects require more careful verification during simulation runs.

The second level models used in simulation runs (Figure 2.6.1) were outlined in Section 2.3. As discussed in Section 1.6, model FEMSATP includes a fixed operating rule for calculating "actual" amounts of irrigation for each time step (7 days) basing on weather conditions (precipitations, temperatures, etc.), taking into account production levels and areas of subtechnologies and sprinkling capacities fixed as inputs from the screened scenario (see Section 2.3.1).

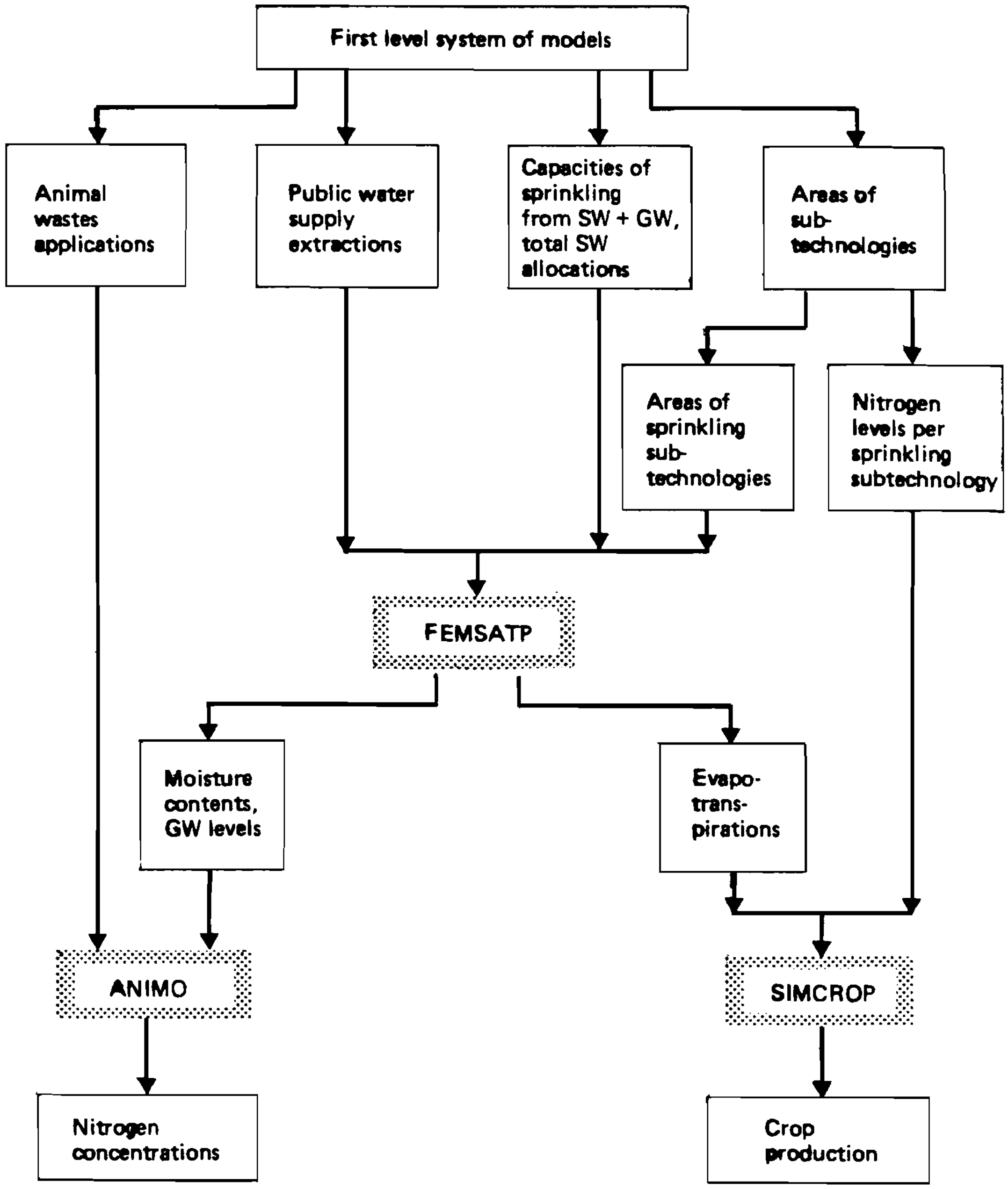


Figure 2.6.1: Simulation of screened scenarios

As is seen from Figure 2.6.1, disaggregated hydrologic and evapotranspiration data obtained from FEMSATP together with additional data from the first level analysis are used by submodels SIMCROP (Section 2.3.2) and ANIMO (Section 2.3.3) to produce more detailed evaluations of crop productions, and concentrations of nitrogen in groundwater. Crop production data can further be used to obtain more details about economic aspects of the scenario considered using a model of the type indicated in Section 2.4.

Performing simulation runs using these models with data for a number of weather years observed in the past or synthetically generated gives information about the performance of the scenario analysed under varying weather conditions. Depending on these results this scenario can be recommended as an acceptable reference for policy analysis (second stage), or the repetition of the screening analysis may be required to look for a modified scenario.

2.7 Computer Implementation of the Decision Support System for the Scenario Analysis

The computer implementation of the scenario analysis procedures should be done in such a manner that the models described in the previous sections can be used with maximum effectiveness for improving the quality of regional decision making. As we discussed earlier for this computer implementation to be a flexible decision support tool of real practical value it should incorporate such features as (see Section 1.7) simplicity in operation, relatively fast response, capability of responding to a wider possible scope of questions relevant to the given problem area, and also ability to present information in a convenient and easily comprehendable form.

The decision support system for the test region of Southern Peel implemented on VAX 11/780 at IIASA and subsequently at the Institute for Land and Water Management Research, Wageningen, the Netherlands, includes two major parts: scenario generation system and an interactive comparative display system. We outline both these parts in the following sections.

2.7.1 Scenario generation system

As has been outlined earlier scenario generation system is designed for answering questions that the PMA may have with respect to possible future scenarios of regional development. This questions may, for example, be of the following form:

- what maximum total agricultural income per year can be obtained under the condition that the maximum nitrogen concentration of phreatic groundwater should not exceed 20 mg NO_3-N/l and the amount of additional investments in agriculture is limited by 100 mln Dfl?
- what lowest nitrogen concentration of deep groundwater can be achieved if a reduction of the total agricultural income by 10% is admissible?
- given desired decrease in nitrogen concentration of phreatic groundwater what may be the lowest upper bound on manure application in the region?

These are only some examples of numerous questions that can be "answered" by the scenario generation system. Each of such questions is formulated by fixing desired values for the indicators considered and/or by treating any one of the indicators or their combination as an objective function. The "answer" is obtained by solving the corresponding linear programming problem as a step in the screening analysis. Together with the desired values of the indicators the solution represents an alternative (re)allocation of agricultural activities in the region that facilitates the achievements of these values.

Since the PMA should be able to put diverse types of questions to the system requiring structural changes in the underlying LP problems there should be provisions in the system allowing to do this in a flexible way. This is achieved by using the system GEMINI developed by V.Y. Lebedev at the Computing Center of the USSR Academy of Sciences (see Lebedev 1984). GEMINI is a cross compiler that not only recognizes common formula-like description of LP problems and translates them in a form suitable for further automated processing, but also allows for the inclusion of conditional statements that react to certain option parameters. Using these parameters the user can very flexibly modify the structure of the LP formulation in order to adapt it to a new type of question put to the system.

GEMINI creates two FORTRAN codes. The first is the code for generating an input file for the LP problem solver MINOS 40 that was developed by Murtagh and Saunders (1980). The second FORTRAN code that is generated is for reading MINOS output and interpreting it in terms of the problem formulation.

As is indicated in the scheme in Figure 2.7.1, after obtaining a "desired" scenario using the system of first-level models coupled to GEMINI–MINOS, a run can be made with the second-level models, in order to obtain more accurate evaluations aspects of interest of the scenario obtained at the first level. Of special interest to the user are of course the values of the indicators obtained at the second level. If the user is not satisfied with a certain values of the indicators obtained with the second-level models, he can repeat the procedure and set a stronger requirement on the respective indicators in the first-level model: since the first-level models are highly simplified in comparison to the second-level ones, it is natural that the values of indicators computed by the former will differ from those computed by the latter models. By "tuning" the requirements on objectives on the basis of computational experiments with the system, the user can obtain scenarios that meet his requirements at the second level. Runs with the second-level models for different weather years are also used to generate data for the statistical evaluation of scenarios.

The complete procedure of running the first and the second levels of scenario analysis requires at least one hour of CPU time, therefore, it made no sense to implement this procedure in an "on-line" interactive mode. The scenario analysis system is designed in such a way that the user can specify a sequence of questions by setting a number of specially used option parameters that are contained in one command file of a disk storage system. After the initialization of the command file the system automatically generates a sequence of corresponding scenarios and stores the data in a structured way. Then the scenarios generated in this type of "batch" operation can be analysed by the PMA using the comparative display system described in the next section.

2.7.2 Interactive comparative display system

Apart from the very condensed form of describing a scenario in terms of multi-indicators, the user may also be interested to know the regional distribution of the many control and state variables describing the regional system. For easy user access and interpretation of results, an interactive comparative display system with colour graphics has been developed. The

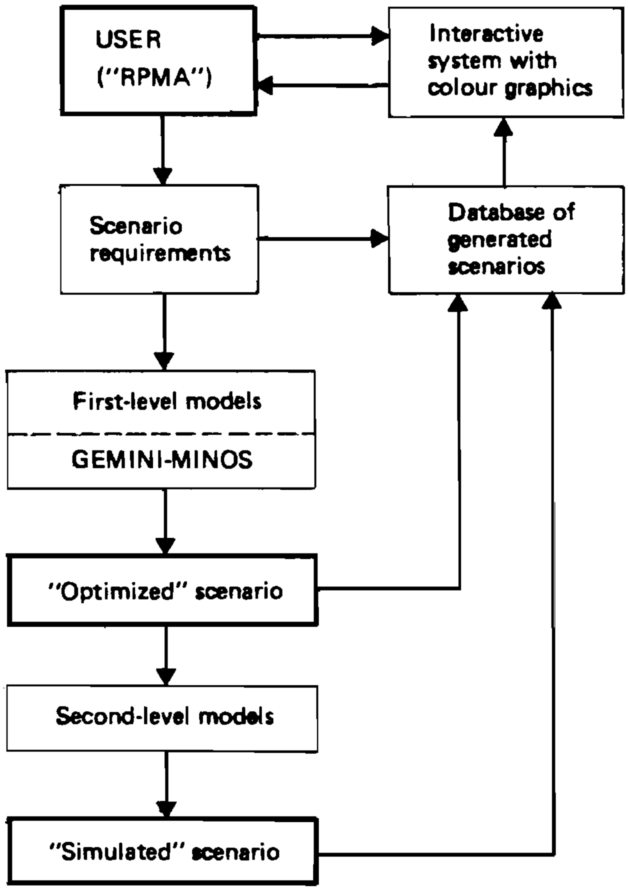


Figure 2.7.1: Scenario analysis procedure

structure of this system is presented in Figure 2.7.2. The system makes possible the visual comparative analysis of scenario data using colourings of subunits on a map, or using coloured pie and bar charts. This mobilizes the excellent human capability of usually comparing two objects, in this case images on a screen.

An essential characteristic of the system is that it is user-friendly: at each step the user is presented with a self-explaining menu from which the user has to choose an item. He does this by typing the appropriate number and then hitting the "RETURN" key. The menus are organized in a hierarchical manner: going down the hierarchy the user at each time chooses which branch he will follow next by choosing a certain menu-item. The position of

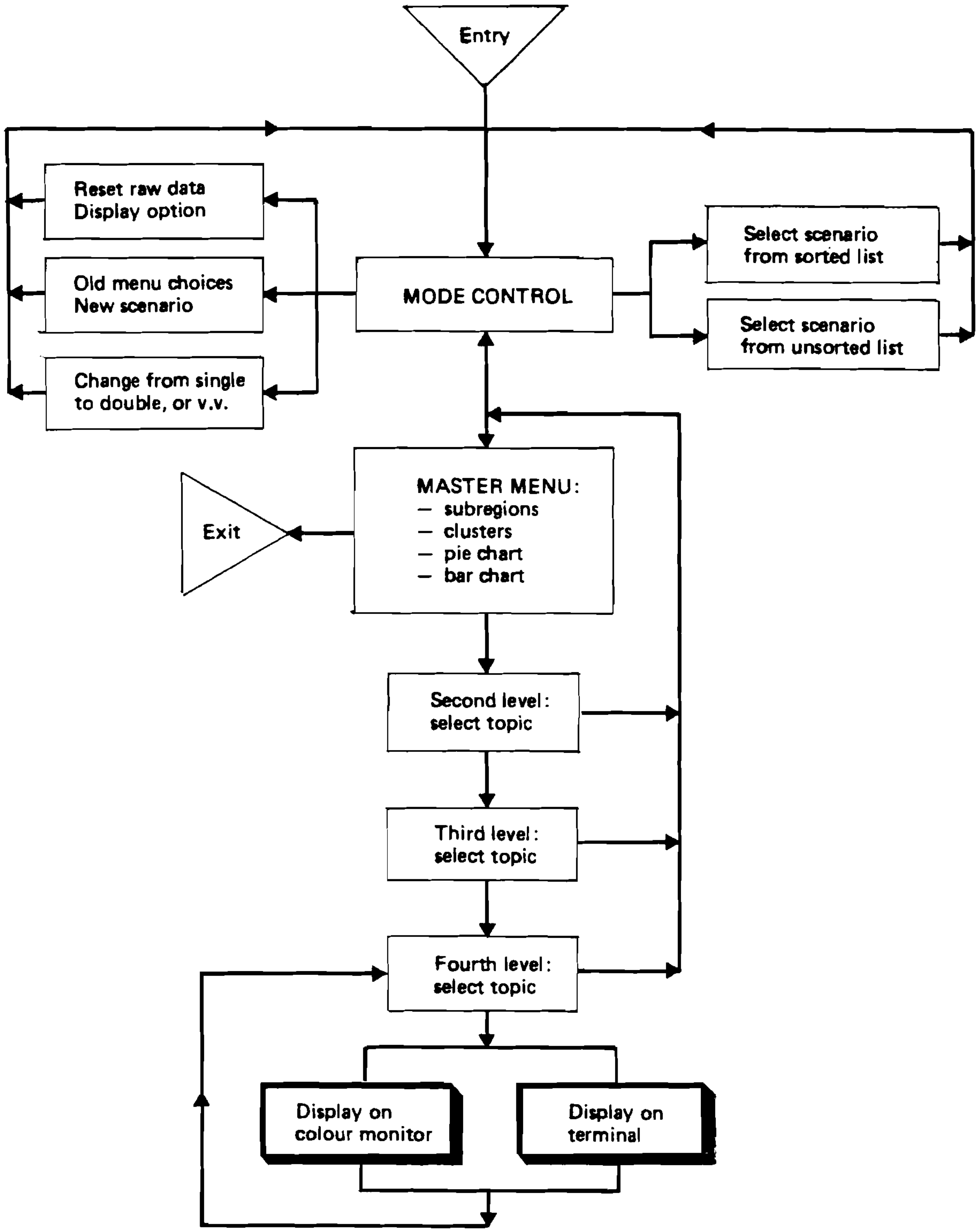


Figure 2.7.2: Flow chart of interactive system with colour graphics

the user in the menu-hierarchy is always indicated by text along the top of the computer terminal. So the user can never "get lost" in the system. A number of "short-cuts" are also provided, in order to avoid that the user repeatedly has to enter a sequence of menu-choices that differ only with respect to the scenario that is being displayed. After a brief outline of the system we present an example of an interactive session.

After initialization of the programme, two identical maps are projected on the colour display unit. The spaces to the left and right sides of the maps are available for pie and/or bar charts (there is space for one chart on each side). On the computer terminal the user is presented with the MODE CONTROL menu, as shown in Section 2.7.3. This menu-level offers various ways of selecting data-sets from the ones that are available, and also for setting options of the programme. The "indicators" describing the data sets are used for the purpose of data-set selection.

Selection of a scenario can either be done by paging through an unsorted list of pregenerated scenarios (each line of the list containing the values of indicators) and then choosing one of them by typing its number, or by making use of the "sorted list" options of the programme. For the latter one must define a set of reference values of the indicators. The system then searches for 10 scenarios that come closest to the reference one. The user can influence the calculation of the "distance" between a scenario and the reference one by modifying weights associated with the separate indicators. The mentioned distance is simply defined as the weighted sum of the absolute values of the differences between the scenario values of the indicators and the reference ones. After having set the options of the sorting procedure, the user is presented with a list of scenarios, showing the values of the indicators and the "distance" from the reference scenario.

After a data set has been chosen, the values of the indicator are displayed along the bottom of the colour display. The system also allows for the display of indicator values in certain subunits of the maps. In the current setup numbers displayed in the green coloured nature areas indicate the extent of the "damage" done to the natural vegetation by the groundwater pumping in the region.

The main option switch is the one for SINGLE/DOUBLE MODE. In SINGLE MODE, data from only one scenario are displayed at a time. In this mode the two maps on the colour screen can be used for displaying two different aspects of the same "scenario". In DOUBLE MODE the maps are used for displaying the same aspect of two different scenarios. The SINGLE/DOUBLE MODE switch applies of course also to the pie and/or bar charts in the spaces on the left and right sides of the maps.

After the user has finished interacting on the MODE CONTROL level, the MASTER MENU level is accessed. The MASTER MENU level is the main node of the programme. There are four topics that the user can choose from at this level: subregions, clusters, pie chart and bar chart. Both "subregions" and "clusters" pertain to the displaying of data by colouring of subunits on a map: a cluster is simply a more aggregated unit, involving a number of subregions. In the current setup there are 31 subregions and 5 clusters.

If the user is in SINGLE MODE, he may want to modify the side of the colour display unit that the subsequently selected data are to be displayed on. This modification can only be done at the MASTER MENU level. The default setting after initialisation of the programme is LEFT SIDE. By typing the appropriate number this can be modified to RIGHT SIDE, or vice versa. When one is working in DOUBLE MODE, one does not have to bother about sides: whenever a topic is selected, the data of the two selected scenarios are shown on respectively the left and right side of the screen without any further intervention of the user being required.

Proceeding down the hierarchy from the MASTER MENU level is straightforward. And, at all times the user can jump back to MASTER MENU level if he wants to do so.

2.7.3 Illustration of an interactive session

After starting the system the following output is displayed on the alphanumerical screen.

```
*****************************************************************************
              INTERACTIVE SYSTEM FOR ANALYSIS OF WATER POLICIES
                     IN REGIONS WITH INTENSE AGRICULTURE

                        Regional Water Policies Project

   INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS,  Laxenburg  Austria

           Programs set up for a test region in the Netherlands
           in collaboration with:

           - Institute for Land & Water Management Research (ICW)
              Wageningen, The Netherlands

           - USSR Academy of Sciences, Computing Centre, Moscow



                         reading map input data ........
*****************************************************************************
```

and after the necessary data have been read the menu of the mode control level appears:

```
*****************************************************************************
                                                          MODE CONTROL LEVEL
                                                          SCREEN HALF: LEFT


You are in  SINGLE   mode,    displaying scenario        0  ;

To select  other scenario,                   type its number ;
To obtain  a  sorted   list of scenarios,    type       95   ;
To obtain  an unsorted list of scenarios     type       96   ;
To move    to master menu level,             type       97   ;
To display old choices for new scenario,     type       98   ;
To reset   the raw data display option,      type       99   ;
To select  DOUBLE   mode,                   press    RETURN  ;

............................................ type:
*****************************************************************************
```

Two schematized maps of the region appear on the graphical screen.

After typing "96" a list of scenarios represented by values of the indicators appears on the screen:

List of scenarios

RD	L10	L16	L27	INC	PWS	QGW	QPW	SWC	INV	
99	5.0	1.0	0.0	251.3	5.0	7.0	65.6	2.0	0.	(1)
99	5.0	1.0	0.0	251.3	5.0	14.3	142.5	2.0	0.	(2)
99	5.0	1.0	0.0	251.3	5.0	5.0	47.9	2.0	0.	(3)
99	5.0	1.0	0.0	247.5	5.0	3.3	22.4	2.0	54.	(4)
90	3.0	0.5	0.0	267.0	5.0	7.2	58.6	2.0	0.	(5)
90	3.0	0.5	0.0	267.0	5.0	3.3	22.4	2.0	91.	(6)

where RD - weather year represented by percentage of occurence of the total precipitation

L10,L16,L27 - lowerings of GW in cm

INC - total regional incme in mln fl.

PWS - yearly public water supply in mln m^3

QGW - equilibrium concentration of nitrogen in deep aquifer

QPW - the same for phreatic aquifer

SWC - yearly surface water supply (mln m^3)

INV - total incremental investments (mln m^3)

After selecting a scenario for display (by typing its number) the user can choose a SINGLE or a DOUBLE mode described earlier. If the user chooses scenario 5 and the single mode then the display is as follows:

```
******************************************************************************
                                                             MODE CONTROL LEVEL
                                                             SCREEN HALF: LEFT

You are in SINGLE mode,  displaying scenario          5  ;

To select  other scenario,                     type its number ;
To obtain  a sorted   list of scenarios,       type      95    ;
To obtain  an unsorted list of scenarios       type      96    ;
To move    to master menu level,               type      97    ;
To display old choices for new scenario,       type      98    ;
To reset   the raw data display option,        type      99    ;
To select  DOUBLE   mode,                     press    RETURN  ;

............................................ type:
******************************************************************************
```

To proceed the user chooses 97 to move to the MASTER MENU which looks as follows:

```
******************************************************************************
                                                            MASTER MENU LEVEL
                                                            SCREEN HALF: LEFT
 Select  a  topic  for DISPLAY:

     ( 1)    SUBREGIONS
     ( 2)    CLUSTERS
     ( 3)    PIE CHART
     ( 4)    BAR CHART




 To  select  a topic for  display,    type its number ;
 To  select  other half of screen,    type        98  ;
 To  move    to mode control level    type        99  ;

 ..................................... type :
******************************************************************************
```

Then, if the user wishes, for example, to display the distribution of N-concentrations in the phreatic aquifer for the scenario chosen he proceeds through the following sequence:

```
******************************************************************************
 TOPIC SELECTED:                                             SUBREGIONS
                                                             SCREEN HALF: LEFT
 Select  a  topic  for DISPLAY:

     ( 1)    Land use techs
     ( 2)    Animal wastes
     ( 3)    Water balance
     ( 4)    N-concentr.
     ( 5)    P-terms


 To  select  a topic for  display,    type its number ;
 To  return  to the previous level,   press    RETURN ;
 To  return  to the master menu level,type       97   ;

 ..................................... type :
******************************************************************************
```

```
******************************************************************************
 SUBREGIONS                                                  N-concentr.
                                                             SCREEN HALF: LEFT
 Select  a  topic  for DISPLAY:

     ( 1)    Phreatic  layer
     ( 2)    First aquifer


 To  select  a topic for  display,    type its number ;
 To  return  to the previous level,   press    RETURN ;
 To  return  to the master menu level,type       97   ;

 ..................................... type :
******************************************************************************
```

As a result he obtains the following data on the alpha-numerical screen:

****

SUBREGIONS N-concentr. Phreatic layer

SCREEN HALF: LEFT

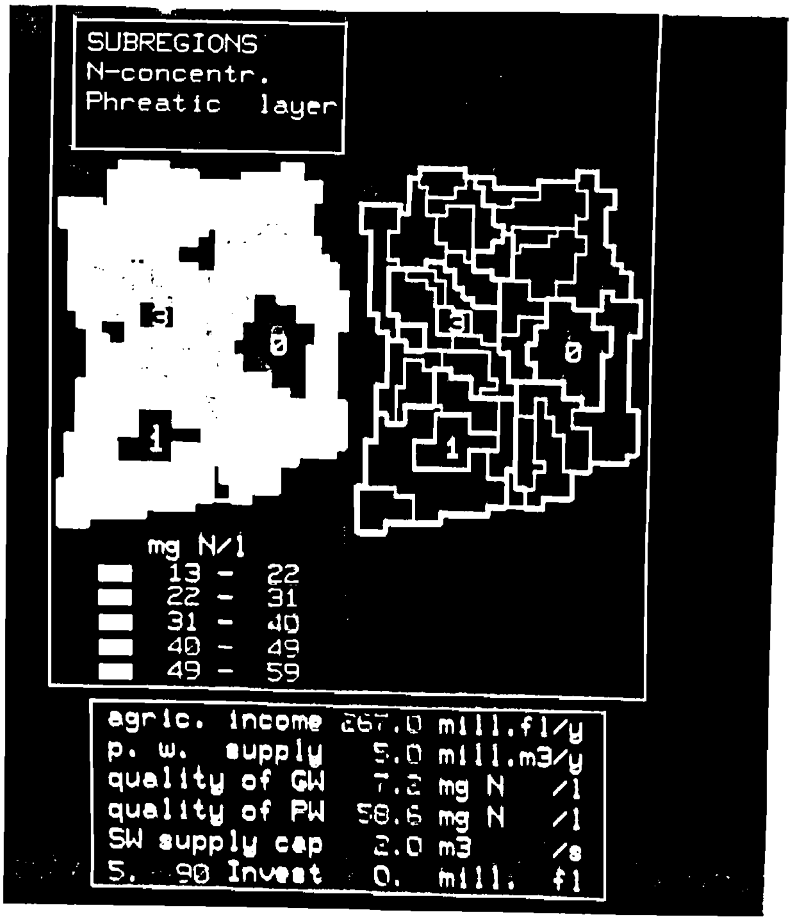
Displaying data for LEFT-side of screen
units: mg N/l

(1)	59	(2)	26
(3)	22	(4)	13
(5)	21	(6)	23
(7)	34	(8)	30
(9)	35	(10)	19
(11)	31	(12)	33
(13)	30	(14)	30
(15)	39	(16)	19
(17)	44	(18)	27
(19)	58	(20)	59
(21)	23	(22)	19
(23)	35	(24)	25
(25)	35	(26)	48
(27)	1	(28)	14
(29)	30	(30)	22
(31)	22		

Press RETURN to continue:

****

and a correspondingly coloured map on the left-hand side map on the graphic screen:



Similar type of data can be displayed on the map for other topics. This data include various aspects of the use of land-use technologies, of animal wastes application, of irrigation, etc.

The other two types of data representation include pie charts and bar charts. For example, to display land allocation among land-use technologies for the whole region the user can proceed as follows:

```
******************************************************************************
                                                              MASTER MENU LEVEL
                                                              SCREEN HALF: LEFT
Select  a  topic  for DISPLAY:

    ( 1)   SUBREGIONS
    ( 2)   CLUSTERS
    ( 3)   PIE CHART
    ( 4)   BAR CHART


To  select  a topic for  display,   type its number ;
To  select  other half of screen,   type       98  ;
To  move    to mode control level   type       99  ;

 .................................. type :
******************************************************************************
```

```
******************************************************************************
PIE CHART                                                     Aggregated
                                                              SCREEN HALF: LEFT
Select  a  topic  for DISPLAY

    ( 1)   Region
    ( 2)   Cluster 1
    ( 3)   Cluster 2
    ( 4)   Cluster 3
    ( 5)   Cluster 4
    ( 6)   Cluster 5


To  select  a topic for  display,   type its number ;
To  return  to the previous level,  press    RETURN ;
To  return  to the master menu level,type      97   ;

 .................................. type :
******************************************************************************
```

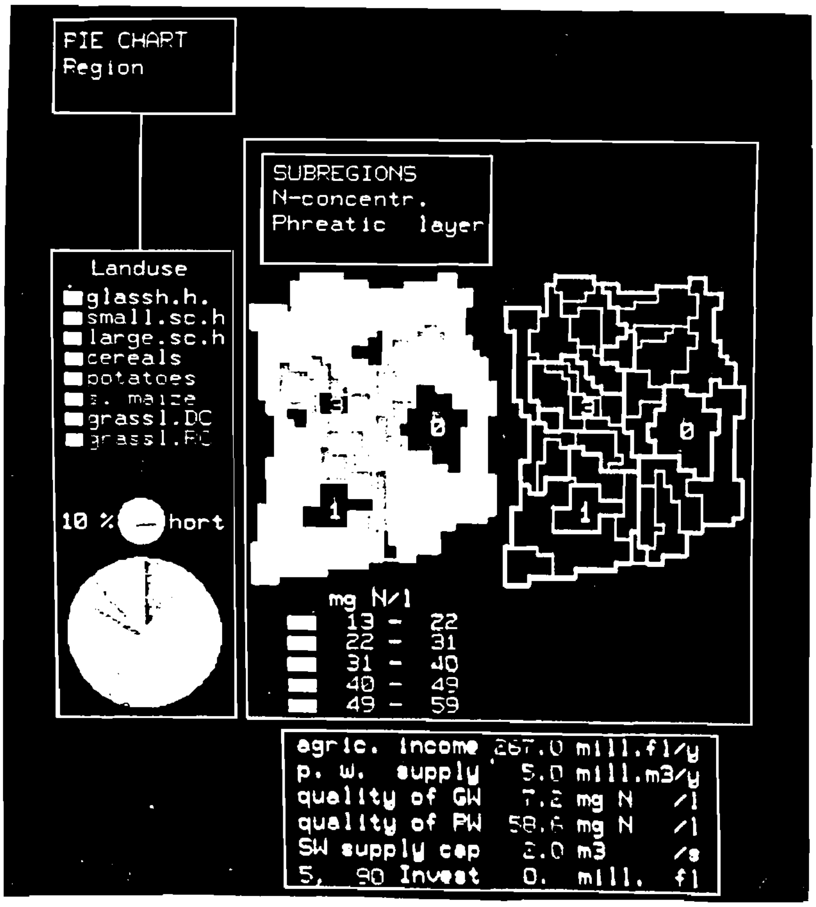
After typing 1 (Region) the following information is displayed:

alpha-numeric screen

```
*****************************************************************************
PIE CHART   Aggregated                Region
                                                        SCREEN HALF: LEFT
    Displaying data for LEFT-side of screen
          units: %. of ag.area

    ( 1)          4   glassh.h.
    ( 2)         52   small.sc.h.
    ( 3)         41   large.sc.h.
    ( 4)         14   cereals
    ( 5)         54   potatoes
    ( 6)        262   s. maize
    ( 7)        454   grassl.DC
    ( 8)        117   grassl.RC
    ( 9)          0
    (10)          0
-------------------------------------------------------------------------------
Press  RETURN  to continue:
*****************************************************************************
```

graphic screen



Choosing the right-hand part of the screen the user can in a similar way display additional information:

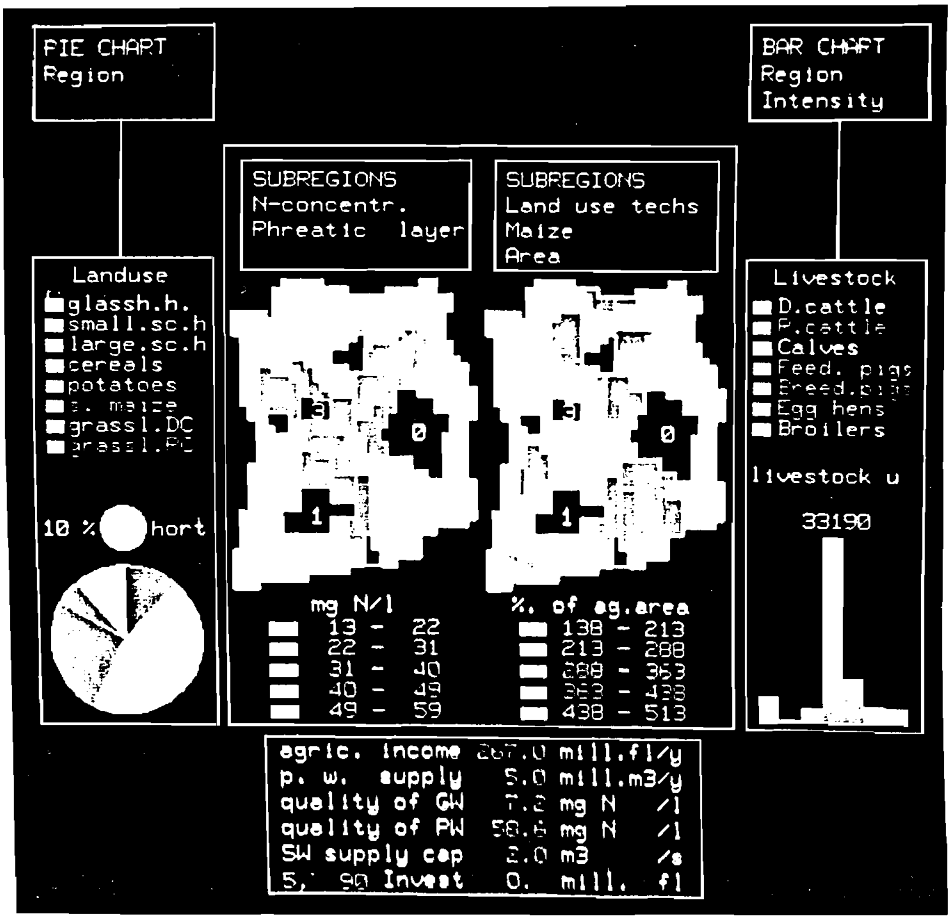
```
*****************************************************************************
SUBREGIONS  Land use techs          Maize                        Area
                                                                 SCREEN HALF: RIGHT
    Displaying data for RIGHT-side of screen
          units: %. of ag.area

  ( 1)       513        ( 2)        166
  ( 3)       218        ( 4)        446
  ( 5)       407        ( 6)        300
  ( 7)       509        ( 8)        138
  ( 9)       505        (10)          0
  (11)       255        (12)        217
  (13)       156        (14)        402
  (15)       145        (16)          0
  (17)       356        (18)        218
  (19)       416        (20)        381
  (21)       190        (22)        426
  (23)       223        (24)        173
  (25)       373        (26)        209
  (27)         0        (28)        188
  (29)       328        (30)        340
  (31)       237
-------------------------------------------------------------------------------
Press  RETURN  to continue:
*****************************************************************************
```

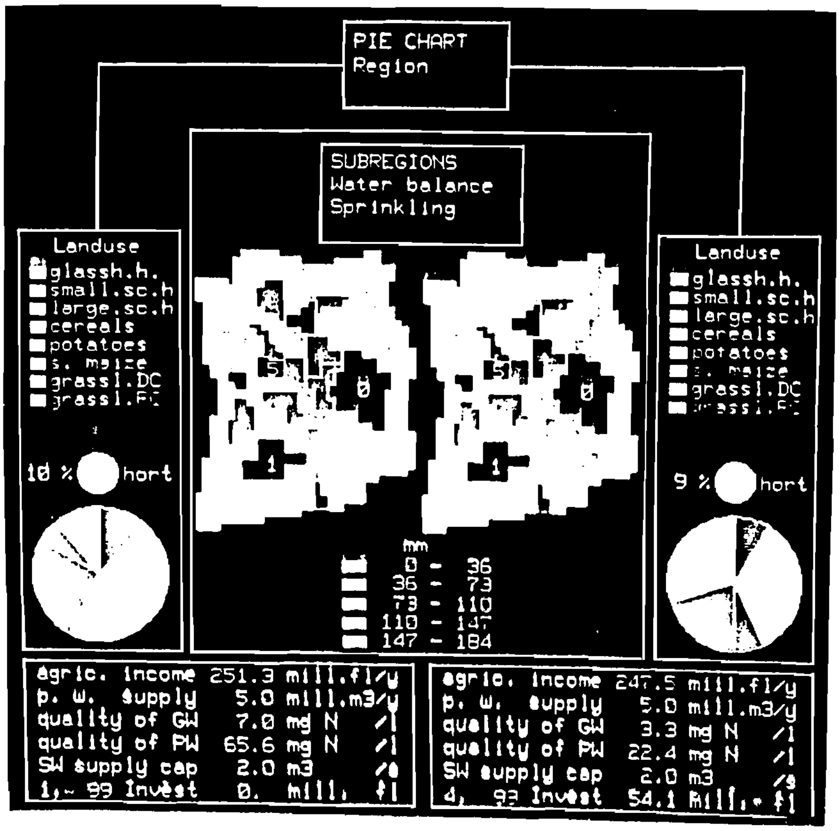
```
*****************************************************************************
BAR CHART                          Region                        Intensity
                                                                 SCREEN HALF: RIGHT

    Displaying data for RIGHT-side of screen
          units: livestock u.

      ( 1)       4568    D.cattle
      ( 2)        593    R.cattle
      ( 3)       2280    Calves
      ( 4)      33190    Feed. pigs
      ( 5)       7946    Breed.pigs
      ( 6)       2954    Egg hens
      ( 7)       2626    Broilers
-------------------------------------------------------------------------------
Press  RETURN  to continue:
*****************************************************************************
```



The DOUBLE mode gives the possibility to display the same type of data for two different scenarios chosen by the user. For example, for scenarios 1 and 4 we can have the following display



2.7.4 Comments on software*

Comparative Display System consists of a set of FORTRAN (sub)programmes, an AED-512 interface library and a couple of input files, which determine the hardware environment and the input control. In the following, a limited number of aspects of the system are explained – the intention of these short explanations is to aid a potential (trained) programmer in adapting the programme for use within a different context. The extensive use of comments in the programme code is, however, the most important form of documentation.

Main program MENU:

After defining the default setup of the program and opening the port to the AED unit, the program reads the coordinates from the file "map.dat" and consequently draws a map on the color display (see PLOT). Then the text file "menu.text" is read, which supplies the information about the structure of the topics and its text. Finally the indicatores are transfered from the datafiles "data.xx", where "xx" are numbers between 01 and 94. The maximum number of scenarios to be considered is 94. The "mode control" section contains the switches to various run parameters, a jump to the scenario selection routines SEARCHR and SELECT. SEARCHR searches for the "closest" scenarios in relation to the reference indicators and presents a table of the ten best choices. SELECT, on the other hand, is a straightforward selection procedure. The program control depends on the number of scenarios (NRUN) shown (SINGLE or DOUBLE mode). After selection of a scenario the program jumps to the subroutine READDATA, the main input subroutine, which reads the complete data set of the selected scenario that is going to be shown on the color display from a file, which is named "data.xx". "xx" corresponds to the number of the selected scenario. From the MASTER MENU level downwards the the structure of the program is roughly the same for each level. The subroutine SHOW controls the dialogue and checks the input for the topic selection procedure, finally leading to the display program DATA, which in turn calls PLOT, the subroutine,

*This section is a brief technical guide and we assume that the reader has acces to the programme code.

which does the final work of painting the color screen.

Subroutine PLOT:

PLOT is split into five parts, corresponding to the topics of the MASTER MENU Level and the initial drawing of the map. The first part contains the data declarations of colors, the coordinates of the interior filling points of each segment and text for the data description on the color display. Next come the scaling and shift factor definitions. The size of the map is defined by the variable BLOW, which is currently set to 1.05. Horizontal shift HOR=0. and vertical shift VER=100. Thereafter the connection with the color display unit is established, which has the system name "/dev/aed" in the program. Then the drawing routine SEG is called consecutivly in a loop, which draws one "segment" at a time. The rest of the first section deals with the color definition by reading the "col.." files and associating the input to particular numbers in the color lookup table.

The next four parts deal with the painting of the map according to the data in "data.xx" and each have roughly the same structure. First the text to be displayed is prepared to be output by the routine PTEXT and then, depending on the topic, the map is painted for topics SUBREGIONS or CLUSTERS, or else a call is made of the graphical subroutines BAR or PIE. The complete information for the graphical output is contained in the buffer BUFFER, which was prepared by the routine DATA.

Menu-hierarchy representation

With respect to the organisation of the data into topics, subtopics, etc. the programme allows for a certain degree of flexibility; however, certainly not any hierarchical structure can be handled. Down to the third level the only limitation is that each menu-node should at least have one and at most 9 menu-items. There does not have to be a fourth level of menu-choices: the menu can end at the third level. But in this case it should end at the third level for *all* of the branches stemming from the respective second-level branch, as in Figure 2.7.3a: none of the third level branches lead to further branching at the fourth level. If there is a fourth level, then all the fourth-level menus associated with a certain second-level branch should be the *same*, as indicated by the two-item menus at the bottom of the hierarchy in Figure 2.7.3b.

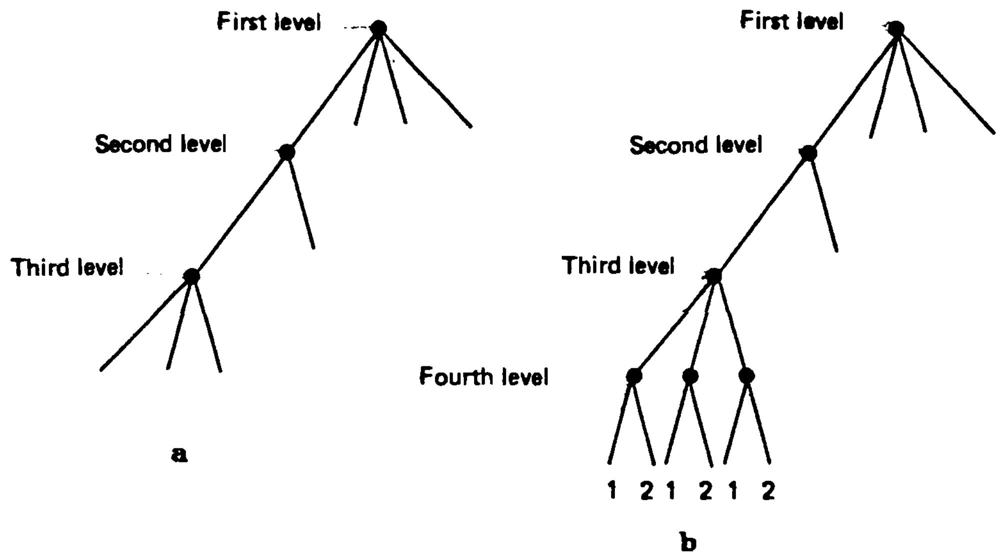


Figure 2.7.3 **a:** Example of second-level ending at the third level
b: Example of second-level branch ending at the third level branch ending at the fourth level.

The text-file containing the menus that constitute the menu hierarchy should be in the following form:

record 1: number of menu-choices at the MASTER MENU level (=first level)

records 2-5: items of the MASTER MENU

record 6: number of items on second-level menu of first menu-item on MASTER MENU

records 7-11: items on second-level menu of first item on MASTER MENU

record 12: number of items on third-level menu of first item on second-level menu of first item on MASTER MENU

records 13-30: items of the third-level menu first item on second-level etc. (see above)

record 21: number of subelements associated with the first item on the second-level of the first item on the MASTER MENU records 22-30: items on fourth-level menu (subelements)

record 31: number of items on the third-level menu of the second item on the second-level menu of the first item on the MASTER MENU etc etc.

So the menu-hierarchy is specified from "top to bottom" and "left to right"; when the bottom has been reached, the specification is resumed at the first node with branches that have not been specified yet, that is encountered going from the bottom back to the top.

The first record of a file with data of a scenario contains the numerical values of the "regional indicators of development". The data corresponding to the items on the menu hierarchy are organised somewhat differently than the file with the menu text. the second record contains the *unit* of the data belonging to the first fourth level element of the first item on the third level of the first item on the second level of the first item on the MASTER MENU: this is the most left fourth level branch in the two-dimensional depiction of the hierarchy in Figure 2.7.3b. The subsequent two records contain the 31 (subregional) values in 16i5 format. Then, instead of following a strict left-to-right sequence along the bottom of the menu-hierarchy, the data file "hops" along the *same* fourth-level element of the respective third-level branches coming from the same second-level branch. This partial reversal of following the menu-hierarchy is done to avoid the unnecessary repetition of the *unit* of the data for a certain fourth-level element.

2.8 Second stage: policy analysis

2.8.1 Introduction

The changes recommended by a scenario selected at the first stage may include reductions in manure applications in some subregions, and allow for increases in the other, or similar changes in livestock technologies, changes in land-use technologies, etc. And the scenario implies that if these recommendations were observed then with an economically satisfactory performance of the region the environmental impacts would be reduced to desired levels. The next step is to analyse policy instruments that can bring about these changes by influencing the behaviour of the farmers.

Policy instruments can be divided into two main groups: voluntary and imperative. The utilization of voluntary instruments, such as supply of advice and recommendations, education programmes, etc. concerning water conserving production technologies depend on free choices of farmers. On the contrary, imperative policies are more difficult to ignore and such policies are more likely to reach the desired effects. Since the implementation of water conserving measures in the Southern Peel region might cause significant demands on changes in agricultural practices and affect incomes of farmers, voluntary measures alone will probably be not very effective. For this reason we should also consider imperative instruments.

Three major types of such policy devices are considered in the literature*: regulation or direct control, taxes, and permit markets. All these devices can be applied to control directly environmental effects or damages resulting from economic activities, or to control these effects indirectly by controlling the economic activities causing these effects. Policy devices of the first type are applied basing on actual amounts of environmental damages such as amounts of pollutants discharged, or, the extent of depletion of water resources (i.e. groundwater lowerings, etc.). One necessary condition for the effectiveness of such policies is the possibility to monitor the environmental damages operationally. This is not always possible. For example, in the Southern Peel region the major types of environmental impacts considered are lowerings of groundwater tables and pollution of groundwater. Besides the technical difficulties of monitoring these impacts, a probably more important consideration, in particular concerning pollution, is that the policy device should be preventive rather than remedying. A policy device sensitive to already existing pollution of groundwater is hardly effective, because its remedying action will not be felt until probably long time in the future, due to very long characteristic times of the natural processes involved.

See, N.J. Baumol and W.E. Oates (1979) for a useful comparative survey and qualitative analysis.

The second type of imperative policy devices are applied basing not on environmental damages that have already occurred and been measured, but on types and levels of production technologies which cause these damages. For the Southern Peel region, for example, the major activities considered as causing the environmental damages are pumping groundwater for irrigation and water supply, and the application of animal wastes. Therefore, all production technologies related to these activities are potential subjects for control by policy devices of the second type. Monitoring is, of course, also essential for their effectiveness, but in this case monitoring is related to types and levels of technologies and is in principle more feasible. We should note here that the potential character of the environmental damages in the Southern Peel region is one of the reasons necessitating the scenario analysis. In a scenario chosen at the first stage of analysis tolerable future environmental effects have been in a certain "translated" into a structure of admissible rates of groundwater pumping and application of animal wastes over the region. Figuratively speaking, a scenario conveys the message to PMA: ensure the recommended rates of groundwater pumping and animal wastes application in subregions and future environmental impacts in the region will be tolerable. And we shall assume that following these recommendations is the goal of the second stage analysis.

In the following sections we outline the basic types of policy devices and then discuss some approaches to assisting their analysis.

2.8.2 Outline of policy devices

In the context of our problem *regulation* or *direct control* policy is based on legislative introduction of permissible levels of groundwater pumping and application of animal wastes for each individual farmer and public water supply company. This approach is hardly feasible in our case also due to the great number of farms in the region (ca. 2000), differences in their size, specialization, management modes, etc., and it is hardly possible to find a rationale for fixing specific standard levels of their activities. Therefore, we pay greater attention here to more flexible pricing policy instruments such as taxes and permit markets, or distribution of licences with legalized resale.

We can illustrate these mechanisms on the example of their use to achieve desirable animal wastes application. Similar reasoning is applicable to the use of groundwater for irrigation.

Pricing mechanisms affect incomes of farmers and assume that their sensitivity to incomes would influence them to make changes in their decisions. Of course, changes in income are probably not the only motivating force in farmers' decision-making, therefore, explaining their behaviour by income maximization as is frequently suggested is not an entirely adequate model. In fact, several studies which empirically test the profit maximization hypothesis (see, for example, Lin et al. 1974) arrive at the conclusion that farmers do not maximize profits. But on the other hand, income is an indicator playing an important role in farmers' behaviour.

Let us denote by $y(m,\cdot)$ annual income of a farm depending on the amount of manure m applied to land and, of course, other factors that we assume fixed. The sensitivity of the income to application of animal wastes in this case can be described by a function

$$MV(m,\cdot) = \frac{\partial y}{\partial m}(m,\cdot)$$

that can commonly be referred to as marginal value of manure application. An example of this function is presented in Figure 2.8.1.

For every value of m the corresponding value $MV(m,\cdot)$ represents the increase (decrease) in the income corresponding to per unit increase (decrease) in the amount of manure applied. Value m_0 in this Figure represents the amount of manure corresponding to a maximal income (with respect to m). Since we do not assume income maximizing behaviour of farmers, the actual amount m_a of manure used by a farmer can be in the vicinity of m_0, and the lesser the degree of income maximization in the farmer's behaviour, the farther may be the actual amount from m_0.

If a tax t per unit amount of manure application is introduced, the farmer's income will decrease by the amount equal to the shaded area D in the Figure 2.8.1. This will motivate him to decrease the amount of manure application. The value m_0^t represents the new amount of manure used by an abstract farmer with income maximizing behaviour. A more "real" farmer

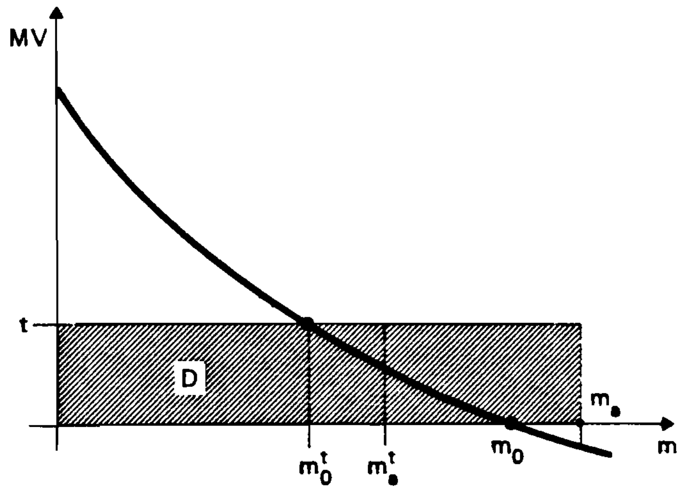


Figure 2.8.1: Marginal value of manure application

will change manure application from m_a to some amount m_a^t more or less close to amount m_0^t. Tax can be imposed not on the total amount of manure used by the farmer but only on the excessive amount with respect to some fixed permitted amount m_a^t. As is seen from Figure 2.8.1 in this case the corresponding decrease in income represented by a shaded area between points m_a^t and m_a is smaller than in the previous case.

A permits market policy is a combination of incentive and regulation. According to this mechanism a total permissible level of manure application is fixed for a number of farmers (for example, all farmers in a subregion for the Southern Peel region). A limited number of licences each of which permits a specified quantity of manure for application is auctioned off. Rather than directly setting a price in the form of a tax, the PMA in this case determines the maximum subregional total amount of manure application that will be tolerated, and then uses the market to ration this fixed amount among farmers. Besides using a direct auction, the issuance of licences can be done on some equitable basis with provision for legalized resale.

To illustrate this policy consider two farmers A and B with MV_A and MV_B being their respective marginal value functions for manure application (see Figure 2.8.2). Suppose that initially farmers A and B possess licences allowing them to apply m_A^0 and m_B^0 tons of manure, respectively. Since additional amounts of manure are more valuable for farmer B than for farmer A the former will want to buy additional licences from the latter by paying a price, which would make the sale profitable to farmer A. In the case when both the farmers are very sensitive to their incomes the resultant situation will be as that illustrated on Figure 2.8.2: licences for amount Δm of manure will be sold by A to B at an equilibrium price p^e (equilibrium in the sense that at a higher price farmer B will buy less than Δm, and at a lower price farmer A will sell less than Δm). In a more real case the price and the amount Δm will probably be not at their equilibrium values, but at some values more or less to equilibrium.

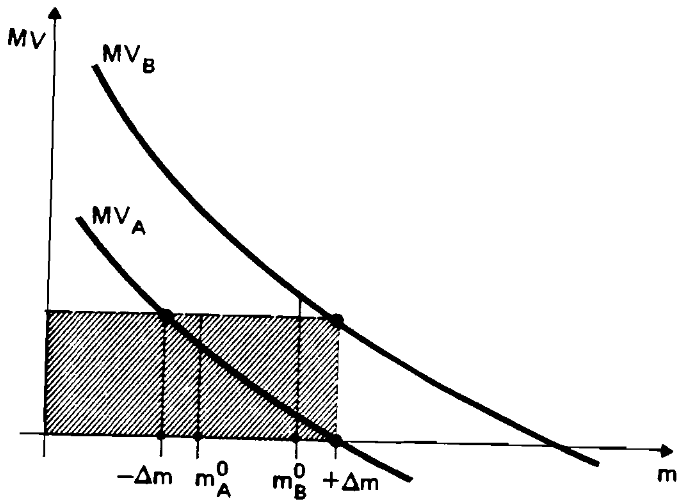


Figure 2.8.2: Permits market for two farmers

2.8.3 Comparing policy devices

Since many interest groups are affected by the introduction of policy devices it is important to compare various policies according to different criteria. For example, economists tend to evaluate environmental policies in terms of total costs. Politicians often regard employment and income distributin effects as the most important factors. There also can exist dissimilarities in the information on which they base their arguments. Different considerations (criteria) of these groups can be summarized as follows:

- *efficiency*, which implies that a certain change in the agricultural structure be achieved at minimum loss of total regional income,
- *income distribution effects*, which implies that income losses be in some sense equally distributed among the farmers,
- *enforcement* and *operating costs*. These criteria are of concern for an implementing authority. The size of the costs associated with the implementation of a policy depends among other factors, on how much monitoring and control of compliance is needed,
- *dynamic effects*. A policy device should be flexible enough to allow for the adaptation to altered environmental conditions without requiring too high adjustment costs both from farmers and authorities,
- *employment aspects*. A reduced level of output caused by a policy may decrease the demand for labourer. This factor may be of considerable importance in countries with already existing unemployment problems,
- *effectiveness*, which is characterized by a degree of reaching desired environmental objectives.

Among other factors that should be considered in the analysis of policy devices are impacts on

- *sellers of inputs* used in the agricultural sectors. If the farmers reduce some of their activities they might reduce their purchases of equipment and other inputs from subcontractors;

- *buyers of agricultural products*. The reduced output of some agricultural activities affected by the policies introduced may lead to increased prices of final products. In its turn, this can affect processing industrial firms. We should note, however, that the last two aspects are hardly of concern in this study because of a relatively small size of the region considered.

In most of the studies concerned with policy devices to control impacts on water resources total costs minimization is a common objective. The majority of them consider well defined point sources (firms) as potential water users and polluters.

Most comparative studies of policy devices are related to air pollution and as is common they consider minimization of treatment costs for a given improvement of air quality. And almost all of them show that pricing and permits market policies are less costly than regulation. As an example and as a comprehensive survey of these studies we refer to Tietenberg 1984, see also Bohm and Russel 1985, Andreasson 1985, Joerses and David 1983, Weitzmann 1974.

2.8.4 Decision support for policy analysis

The comparative analysis of different policies for a given region should be based on many factors such as farmers' responses to policies, various effects of these policies such as efficiency, income distribution, employment and many others. Obviously, no formal analysis alone can encompass all these factors and produce a meaningful policy instrument that can directly be applied. Computerized models and procedures can play only an auxiliary role in this highly informal process by providing the PMA with useful information, insight, hints, etc. And, in particular because of the difficulties in projecting farmers' behaviour the role of informal resoning and expertise is much higher at this stage of analysis than it is at the first stage.

In the following we suggest illustrative examples of some types of questions that can be analysed formally and give results that might be useful to the PMA in making choices of policy devices.

As we said one of the most important aspects in policy analysis is modeling farmers' responses. It is hardly possible to consider all individual farmers in a region with all variations in their behaviour both due to the great number of them in the region and due to the lack of the necessary information. On the other hand, considering groups of farmers can be more justified since in such a case some differences in their behaviour can be in a certain sense averaged to unmask more regular tendencies. In the following we shall consider subregions as separate farms without going into details of individual farms located in a subregion.

Considering subregions as possible objects of regulation and/or application of pricing policy instruments is of course not the only possible approach but on the other hand in this way one can hope to extract auxiliary information that can be useful for choosing appropriate policies. In this way the PMA can separately consider different subregions and analyse their responses to similar types of policies, or analyse responses of the same subregion to different policies. Considering subregions separately allows for the use of more detailed models compared to those used for the scenario analysis. And finally, it may be sufficient to analyse rather than every subregion only some of them which can be considered as representative in a certain sense.

In the following we shall denote by x vector of all variables used to determine agricultural activities in a subregion: intensities of land-use and nonland-use technologies, export and import of manure, manure storage and irrigation capacities, rates of application of different types of animal wastes, etc. For convenience of our presentation we also use separate notations:

ig - total irrigation capacity in the subregion,

m - vector of amounts of animal wastes applied to the fields.

Subscript t will be used with these variables to relate them to different years.

We shall also denote by $y(x)$ total net income of farmers in the subregion, that is calculated as their revenues less maintenance, labour costs as well as expenditures on consumption. We assume that components of vector x are interrelated by means of relationships of the form

$$\varphi(x) \leq b \quad ,$$

where $\varphi(\cdot)$ and b are respectively an appropriate vector function and a vector used to model these interrelationships. This system of equations and inequalities constitutes the basic part of the model used to describe the subregion. The degree of detailization of this model can be similar to that used in the scenario analysis, or, it can be higher to account for additional details compared to the scenario analysis.

In modeling decision-making mechanisms in the subregion we can consider two major tendencies: net income maximization, and pure resistance to changes (conservatism); the latter can be modeled as the tendency to minimize a distance $\|x_c - x\|$ of state x from the current state x_c (an example of a distance function has been given in Section 2.6). Using weighted sums of the form:

$$\alpha \cdot y(x) - \beta \|x_0 - x\|$$

as objective functions to be maximized with $\alpha + \beta = 1$ and varying coefficients α, β we can in principle model gradual shifts from pure income maximization to pure conservative behaviour of farmers in the subregion.

Let us now assume that the scenario analysis resulted in defining desirable target values ig^T and m^T for the respective activities in the subregion considered. T is defined by the scenario as the number of years in the course of which these target values may be achieved.

Now we can suggest formulations that allow to at least qualitatively analyse possible paths of the development of the subregion to achieve the desired targets ig^T, m^T.

Problem I

$$\min_{1 \le t \le T} [\alpha y(x_t) - \beta \cdot \|x_t - x_{t-1}\|] \rightarrow \max_{x_1, \ldots, x_T}$$

$$\varphi(x_t) \le b_t \quad , \quad t = 1, \ldots, T$$

$$\sum_{\tau=1}^{t} y(x_\tau) - inv(x_t - x_0) + liq(x_t - x_0) \ge 0 \quad , \quad t = 1, \ldots, T \quad ,$$

$$ig_T \le ig^T$$

$$m_T \le m^T \quad .$$

In this formulation functions $inv(x_t - x_0)$ and $liq(x_t - x_0)$ stand as before for investments and liquidation capital funds related to the change from the current state x_0 to state x_t. As can be clearly seen, the maximization of the seemingly complex objective function in this formulation can easily be treated in the following equivalent way:

$$\lambda \longrightarrow \max_{x_1, \ldots, x_T}$$

$$\alpha \cdot y(x_t) - \beta \cdot \|x_t - x_{t-1}\| \geq \lambda \ , \quad 1 \leq t \leq T$$

Problem I is analyzing possible trajectories over the fixed period of time T that reach desirable irrigation rates and rates of animal wastes application at the end of the period T. If in this formulation $\beta > 0$, i.e. a certain degree of conservatism is assumed in the average behaviour of the subregional farmers, then changes in x will be in a certain sense uniformly distributed over the years and the trajectories obtained will be more or less realistic.

This model can have various interpretations. One may be that it is announced in advance that direct limitations ig^T, m^T on irrigation capacities and on the rates of manure application will be introduced after T years. The upper bounds announced for each individual farmer can be chosen out of some consideration which are beyond the grasp of this model. What is captured by the model is that the total of these individual limitations equals the desired subregional targets. The trajectories generated can be interpreted in this case as the adaptation of farmers in advance to the forthcoming regulations. Of course, the forms of these trajectories may be different depending on the degree β of conservativism of farmers assumed. But it might be of interest to analyse families of such trajectories for different hypotheses about α and β.

Another possible interpretation of this model can be related to a permits market also announced in advance. In this case, the farmers are informed that after T years each of them will be granted rights to use certain limited irrigation capacities and limited amount of manure for application on their fields. They will also have the right to sell extra rights and/or buy additionally needed rights at market prices inside the subregion. Because reselling the rights simply means redistribution of the total subregional income, the above model can be applied in this case.

One variation of this model can consist in introducing gradually "tightening" regulations from year to year so that after T years the limits become the target values ig^T, m^T. In the above mathematical formulation this would mean additional constraints on ig_t and m_t for every year t. But since changing regulations may probably be even less realistic than introducing them once such a model may have less practical significance than the first one.

Problem II

A similar model can be used to perform qualitative analyses of charges (taxes) on irrigation capacities and/or on rates of animal wastes application exceeding levels ig^T , m^T. Two cases may be considered: taxes that are announced but will have become effective after T years, and taxes effective immediately. In the first instance the model can be as follows:

$$\min \{ \min_{1 \le t \le T-1} [\alpha y(x_t) - \beta \| x_t - x_{t-1} \|] \; ; \; \alpha y(x_T) - \beta \cdot \| x_T - x_{T-1} \|$$

$$- p_{ig} \mid ig_T - ig^T \mid^+ - p_m \mid m_T - m^T \mid^+ \} \longrightarrow \max_{x_1, \ldots, x_T}$$

$$\varphi(x_t) \le b_t \quad , \quad t = 1, \ldots, T$$

$$\sum_{\tau=1}^{t} y(x_\tau) - inv(x_t - x_0) + liq(x_t - x_0) \ge 0 \quad , \quad t = 1, \ldots, T \quad .$$

In the second case the following model can be applied:

$$\min_{1 \le t \le T} [\alpha y(x_t) - \beta \| x_t - x_{t-1} \| - p_{ig} \mid ig_t - ig^T \mid^+ - p_m \mid m_t - m^T \mid^+] \longrightarrow \max_{x_1, \ldots, x_T}$$

$$\psi(x_t) \le b_t \quad , \quad t = 1, \ldots, T$$

$$\sum_{\tau=1}^{t} [y(x_\tau) - p_{ig} \mid ig_\tau - ig^T \mid^+ - p_m \mid m_\tau - m^T \mid^+] -$$

$$- inv(x_t - x_0) + liq(x_t - x_0) \ge 0 \quad , \quad t = 1, \ldots, T \quad .$$

Problems of the maxmin type in these formulations can be treated as has been illustrated for the above Problem I. Multiple variations of these formulations are of course possible both in structure and complexity. For example, instead of, or together with, the rates of application of animal wastes, intensities of manure producing livestock technologies can be considered as possible objects of application of policy devices analysed using this type of models. Subsidizing export of subregional manure can also be considered. These forms of simplistic models allow for relatively inexpensive computer experimentation, and the data obtained if adequately interpreted can give the PMA valuable insights for determining regional policy devices.

2.9 Conclusions

We basically outlined here the decision support system for the Southern Peel region that can also be used as a prototype for other regions similar in their hydrogeological and economical conditions. This system includes three major parts: (1) subsystem of simplified models for screening analysis, (2) subsystem of relatively detailed models for the verification of screened scenarios by means of simulation runs, and (3) interactive comparative display system designed as a user-friendly interface.

The major methodological and modeling principles underlying the design of the system as well as its constituent models were discused at a number of international working meetings organised by the IIASA project. The operation of the system was on-line demonstrated at IIASA during two workshops of the project in 1984 and 1985 as well as to groups of scientists and policy makers from different countries visiting IIASA. The general opinion was that this system is indeed a useful and flexible tool for enhancing procedures of regional policy making.

We should however remark here that this system developed at IIASA of course requires further work for its practical finalization. This work should concern, among other things, more extensive computational experiments for a greater coordination of its screening and simulation parts. More accurate evaluation of economic aspects of the region should also be in the agenda of further research. Of course, further work concerned with the second stage policy analysis along the lines indicated in Section 2.8 would be very desirable.

Although this system has been developed at IIASA with very close participation of scientists from the Netherlands, its finalization would also require a more close participation of the regional policy makers. Only through this participation can the system be appropriately modified and "tuned" to become a practically working tool. This process is now underway at the Institute for Land and Water Management Research in Wageningen, where the whole system has been installed on the VAX 11/780 computer.

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PART 3
DECISION SUPPORT SYSTEM FOR OPEN-PIT LIGNITE MINING AREAS

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PART 3: DECISION SUPPORT SYSTEM FOR OPEN-PIT LIGNITE MINING AREAS

3.0 Introduction

Open-pit mining for mineral resources is one of economic activities resulting in severe environmental impacts. Size and type of these impacts depend on the specific environmental setting of the site. In case of large scale open-pit *lignite* mining the major impacts are related to water resources systems. These problems concern especially countries in Central and Eastern Europe, in particular, the GDR, FRG, CSSR, USSR and Poland, but also in Asia and the USA.

Due to the specific geological history of lignite deposits lignite seams are commonly embedded in water bearing stratas (aquifers). Consequently, it is necessary to dewater mines by pumping groundwater throughout, and prior to, the whole mine operation period. In loose rocks the surrounding aquifers have to be drained also in order to maintain the geo-mechanical stability of the slopes and the bottom of the open-pit mines. The amount of water to be pumped for mine drainage frequently exceeds by weight the output of lignite by a factor between 5 and 10.

In the GDR, for example, the annual production of lignite amounts to more than 300 million tons/year (almost one-third of the world production). For mine drainage about 1.8 billion m^3/year of water have to be pumped out using about 7000 dewatering wells. Compared with the stable runoff (subsurface runoff) of the GDR of about 9 billion m^3/year the amount of mine drainage water exceeds 20% of the stable runoff of the whole country. Another example is the Rheinish lignite district in the Federal Republic of Germany where in 1981 about 1.2 billion m^3/year was pumped out for mining of about 120 million tons of lignite (Boehm 1983).

In sandy aquifers in particular, the mine drainage leads to the formation of large cone-shaped groundwater depressions. As a result water supply wells often fall dry, small rivers fall dry or large ones lose a part of their runoff due to the infiltration of water from them into the depression cone. Agricultural crop production also suffers from the lowering of the groundwater table due to reductions in the moisture supply to plants by capillary rise. To maintain a stable crop production supplementary irrigation becomes necessary which implies higher costs and a higher agricultural water demand as compared to natural conditions.

In the post-mining period, when the groundwater table rises to its former elevation its depth under the soil surface might be less than in the pre-mining period. As a result artificial drainage systems are sometimes necessary to protect municipalities and factories located in former mining areas. Often agricultural land and forest also have to be drained.

Essential changes in groundwater recharge are caused by the extensive alterations of geographical and ecological conditions in open-pit mining areas, such as

- changes in land use, in soil-geological and biological conditions due to devastation and recultivation;
- changes of the groundwater level in connection with the disappearance of surface water or, in some cases, rising of surface water levels.

As an example, under the climatic conditions of the GDR the natural groundwater recharge of an agricultural area with sandy soils may change from about 200 $mm \cdot yr^{-1}$ up to 350–400 $mm \cdot yr^{-1}$ after devastation, see Kaden et al. 1985b.

In lignite mining regions the groundwater quality and consequently the quality of mine drainage water may strongly be affected by the oxidation of ferrous minerals (e.g. pyrite) in the dewatered underground layers. In the cone of depression the overburden is aerated. With the natural groundwater recharge the oxidation products are flushed out, and the percolated water becomes very acidic. Consequently, the acidity of the groundwater increases. The same effect occurs during the groundwater rise after the mines are closed. The acidity of groundwater in spoils, in particular, is very high if the geological formations have low neutralisation capacity.

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

Additional risks are related to salt water intrusion or salt water upconing. In some lignite deposits high mineralized groundwater can be found not deep below the lignite seams. Hence, pumpage causes the risk of salt water upconing (inrush of salt water from deeper aquifers). High salt content of mine drainage water causes many problems for water treatment. The discharge of the polluted mine water into streams may affect downstream water yields significantly.

Finally, ecological conditions in the region are often drastically disturbed by lowering the groundwater level. Old areas or park landscapes are particularly in a great danger when the groundwater table drops down, and surface water ecosystems suffer from water depletion and pollution.

Already these examples indicate that large scale mining causes major impacts on the regional water resources systems and consequently on the regional environment as well as on other economic activities in the region, such as agriculture, industry, municipal water supply. And, as outlined in Part I of this Report a computerized decision support system can be an efficient tool for the analysis of various water use problems in mining regions, recognizing vast amounts of information to be considered, and complexity of the processes involved. In this Part we describe such a system developed on the basis of a test region in Lusatia in the GDR, starting with a general description of the region.

3.1 The Test Region in the Lusatian Lignite District, GDR

Environmental Setting

The test region considered here is located in the eastern Lusatian Lignite District in the lowlands of the south-east of the GDR. Its entire area is 1000 km^2. Figure 3.1.1 gives an overview.

The quarternary/tertiary aquifer system of the test area can be schematized in three aquifers (the first being unconfined) separated by aquitards (lignite), (Figure 3.1.2).

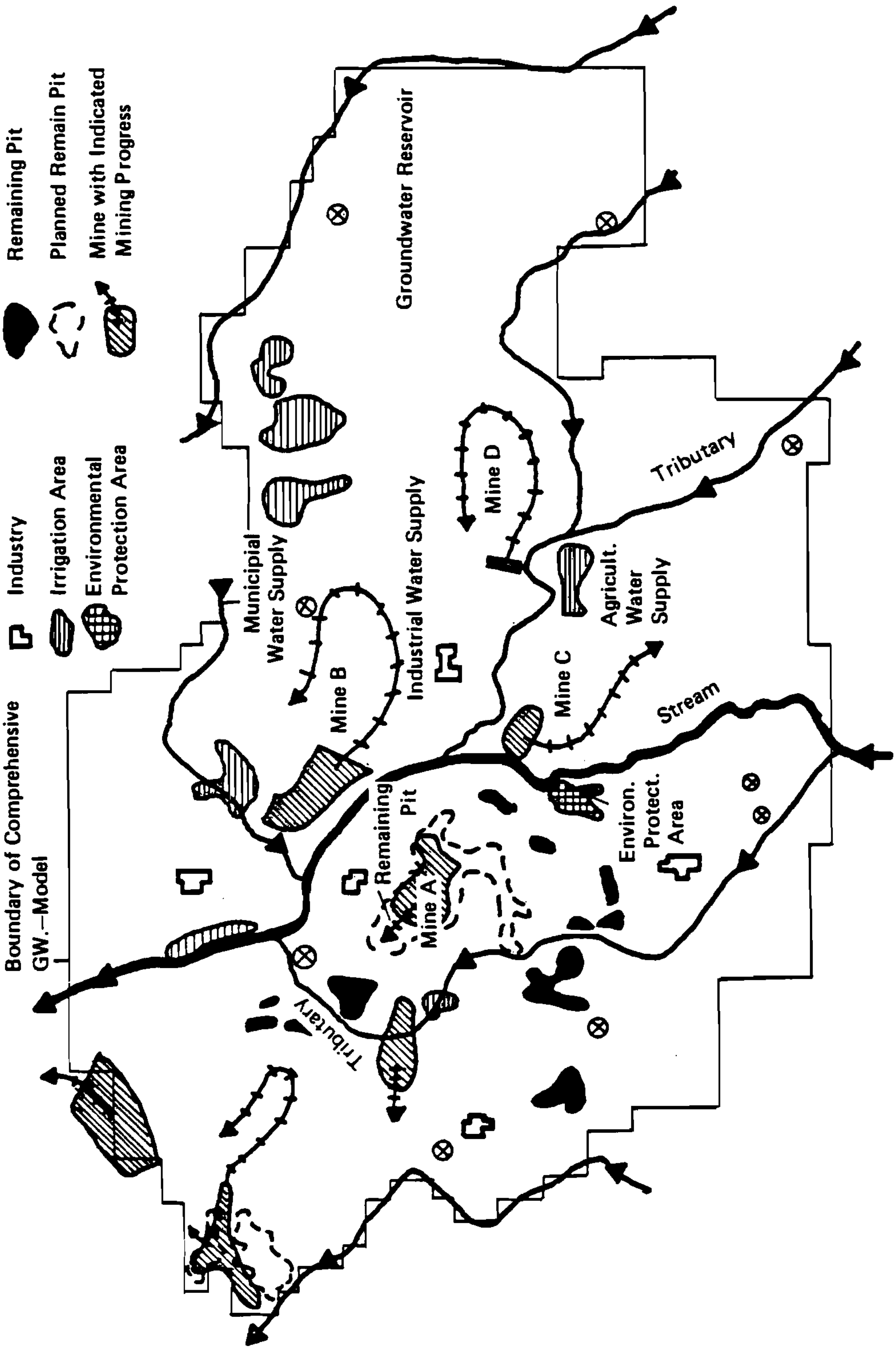


Figure 3.1.1: Geographical overview of the mining test region of Lusatia, GDR

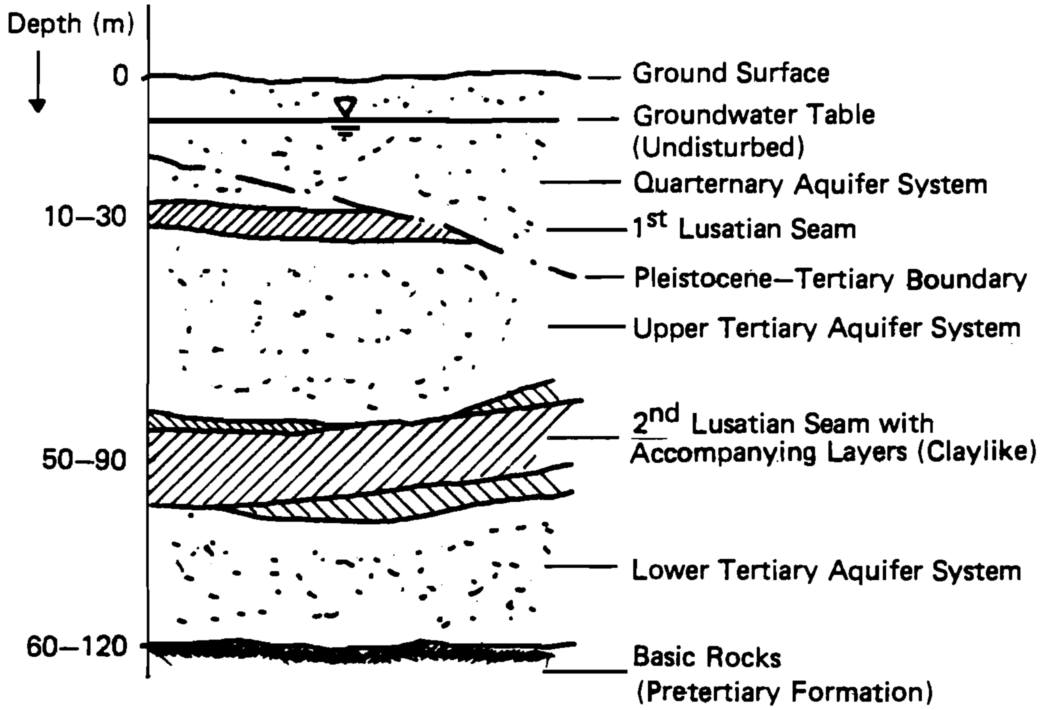


Figure 3.1.2: Hydrological schematization

The boundary of the test area does not correspond to the subsurface catchment area, and therefore groundwater inflows and outflows should be taken into account in the analysis. The region is crossed by a stream and a number of tributaries. The groundwater and surface water systems are closely interrelated (baseflow into surface waters under natural conditions, infiltration (percolation) of surface water into the aquifer resulting from the groundwater lowering due to mine drainage). The natural inflows of water into the region from the stream and the tributaries depend on the hydro-meteorological situation in the upstream catchment areas.

From the point of view of geohydrochemistry, the processes of weathering of ferrous-disulphide minerals in the first and second aquifer are most important. The third and the deepest aquifer frequently contains highly mineralized groundwater (sodium chloride, etc.).

Oxidation of ferrous-disulphide by gaseous oxygen contained in porous soil releases iron(II)-, sulphate-, and hydrogen ions resulting in increased acidity of groundwater. The oxidation products are flushed out with the percolated water from aerated zones and transported by the rise of groundwater. Iron and acid concentration in the percolated water in spoils is significantly high. Furthermore, the groundwater is characterized by increased concentrations of CO_3^{2-}-ion resulting from biochemical degradation processes. The discharge of acid ferruginous minewater into the stream or remaining pit is the decisive water quality impact caused by mining.

For the given study the iron(II)-concentration and the pH-value have been selected as the major water quality indicators . Figure 3.1.3 illustrates a typical relationship between these indicators and the dewatering time (Mine A).

Human activities and their impacts

The major human activities in the region are those related to lignite mining, municipal water supply, industry, and agriculture. These activities are interrelated in a complex way through various natural and economic links. As we reasoned in Part 1 of this report, for the concrete problems oriented study as the one described here we need a concentrated and necessarily limited portrait of the region that includes aspects considered to be the most important for the design of our decision support system.

With this purpose in mind we outline in this section only those economic activities and their impacts in the region which belong to our problem area and will be taken into account in the design of our decision support system. The extent and the duration of some of these activities are exogenously predetermined in the context of our study, others may be considered as controllable. In particular, operations of mines are predetermined long lasting activities in the region with a projected time schedule and duration of 30–50 years.

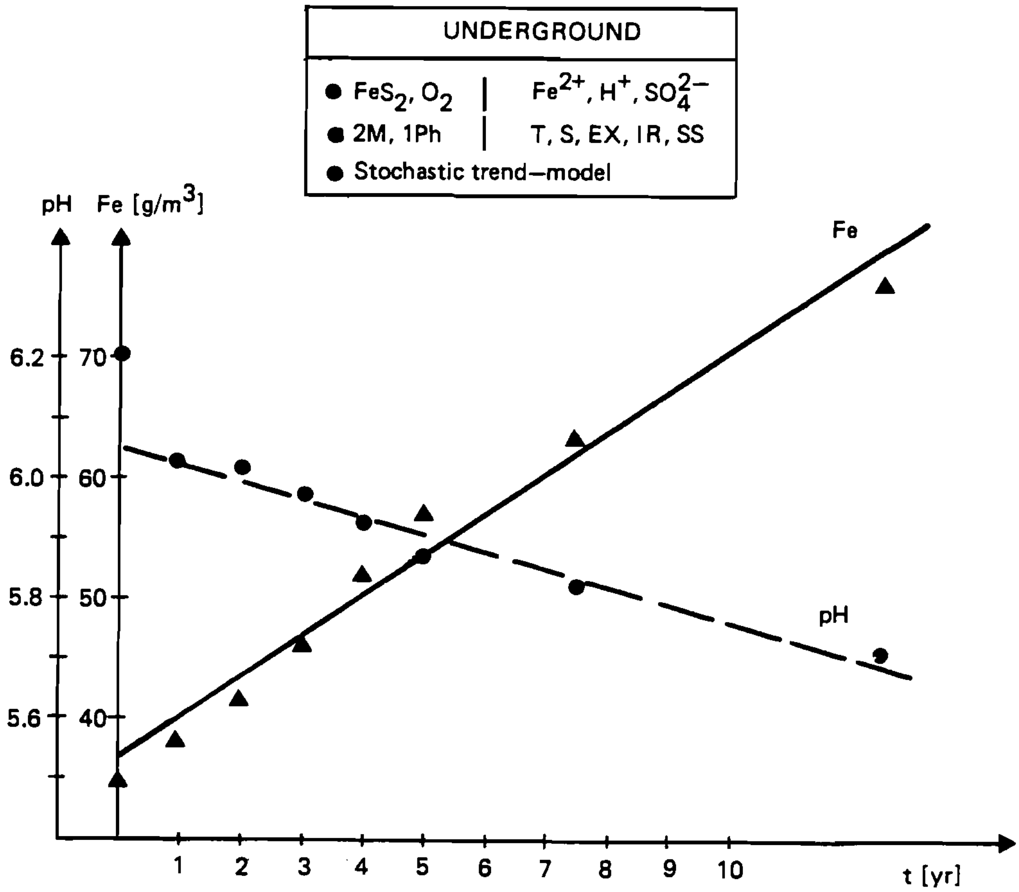


Figure 3.1.3: Quality of mine-drainage water

Mine operation and drainage

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

MINE	A	-	going out of operation within the planning horizon; the REMAINING PIT will be used as a water reservoir;
MINE	B	-	operating within the whole planning horizon; one selected drainage well gallery has been especially designed for municipal water supply;
MINE	C	-	operating within the whole planning horizon;
MINE	D	-	opening within the planning horizon.

The mine drainage is done by extraction wells surrounding the mines (border well galleries) and within the mine field (field well galleries). Different mine drainage technologies such as the use of side walls will not be considered here. The schedule of mining (closing mine A, opening mine D), as well as the mining capacities are supposed to be exogenously fixed recognizing the national priority of lignite mining for the energy supply of the country. Consequently, the groundwater tables within the mines during the operation time are fixed. The amount of mine water to be pumped can be controlled only by the timing of mine drainage activities and by the filling process of the remaining pit, see below. Therefore, for the test region we will consider as decisions the start time of the mine drainage for mine D and the artificial filling of the remaining pit as well as its management. In Figure 3.1.4 the expected amount of mine water to be pumped is depicted for a predrainage period of 3 years for mine D, and the artificial filling of the remaining pit with water at the rate of 3 m^3/s.

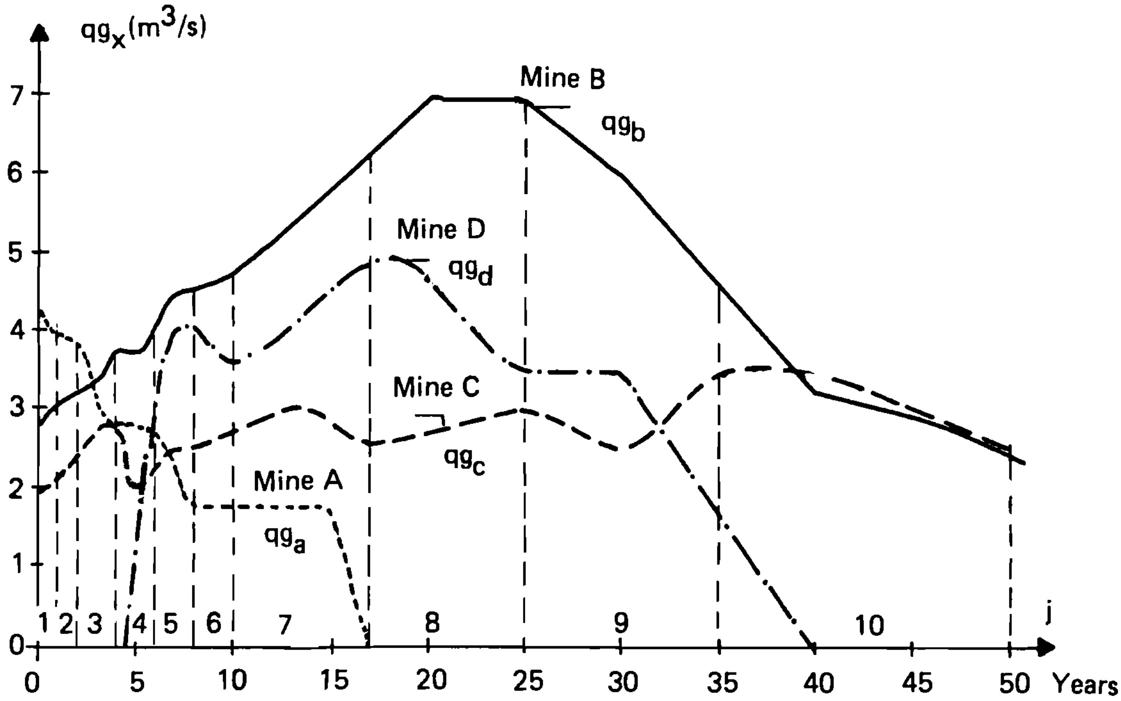


Figure 3.1.4: Expected mine water drainage

The drainage of the mines A–D as well as of some other mines in the region resulting in a large cone-shaped groundwater depression affecting the regional system is characterized below.

Municipal Water Supply

The capacity of extraction wells for water supply depends on the groundwater table near the wells. A well can only operate if the groundwater table is above the well screen. Due to the drastic change in groundwater table in the mining region a reconstruction of wells is very uneconomical. To satisfy the municipal water demand other additional but also costly sources have to be used. Principle alternatives are the use of mine drainage water (MINE B) from specially designed mine drainage galleries, surface water (with complex and expensive water treatment), water import from other regions (high cost for water allocation).

Agricultural Water Supply

The agricultural crop production is an important economic sector in the region considered and it largely depends on the soil moisture content in the rootzone. Normally, a substantial part of moisture required for the crop growth is supplied by the capillary rise from the aquifer to the rootzone. With lowered groundwater tables the capillary rise decreases and supplementary irrigation becomes a necessity (sometimes additional to already implemented irrigation schemes). In principle, the demand for supplementary irrigation can be satisfied by both surface and mine drainage water (MINEs C and D).

Environmental Protection Area

The survival of valuable flora depends on the stability of groundwater tables and groundwater quality within a narrow range. With ongoing mining activities in the region the satisfactory groundwater regime in the environmental protection area can only be maintained by artificial groundwater recharge. Taking into account the insufficient water quality in the stream, mine drainage water (MINE C) and also water from the REMAINING PIT are the only alternative sources of the recharge.

Exchange of Water Between the Stream/Tributaries and the Groundwater Reservoir

Depending on the groundwater and the surface water table we have baseflow to the stream from the aquifer, or, infiltration from the stream into the aquifer. Increased infiltration losses of surface water may affect both DOWNSTREAM WATER YIELDS and the INDUSTRIAL WATER SUPPLY in the region. One possible alternative is the use of mine drainage water for industrial water supply.

Filling Process of the Remaining Pit

Because the remaining pit is considered as a reservoir to control the surface water flow for downstream water users (flow augmentation), a technologically substantiated minimum water table in it should be reached. Consequently, from the water management point of view the artificial filling of the remaining pit with surface water or mine drainage water becomes a favourable alternative to speed up the filling process. On the other hand, high water tables in the remaining pit, cause increased infiltration of water into Mine B and, therefore, necessitate increased mine drainage.

Quality of Water in the Groundwater Reservoir and the Remaining Pit

The mine drainage water can either be allocated to different water users (including water export from the region), or discharged into surface water streams and/or reservoirs. In order to meet quality requirements of the users as well as standards for surface water quality, the drained water has to be processed in MINE WATER TREATMENT PLANTS. The degree of purification provided by a treatment plant is primarily controlled by varying the amount of the added lime hydrate. Deacidification of water in the remaining pit can also be achieved to a certain degree by adding lime hydrate to it.

The concentrated illustration of the impacts outlined is presented in the form of an impact diagram in Figure 3.1.5.

All mining activities cause mainly long-term changes in the system, since medium-term variations (within a year) of mining activities are negligible. On the other hand, medium-term variations (monthly) of surface water flows caused by random changes in hydro-meteorological conditions,

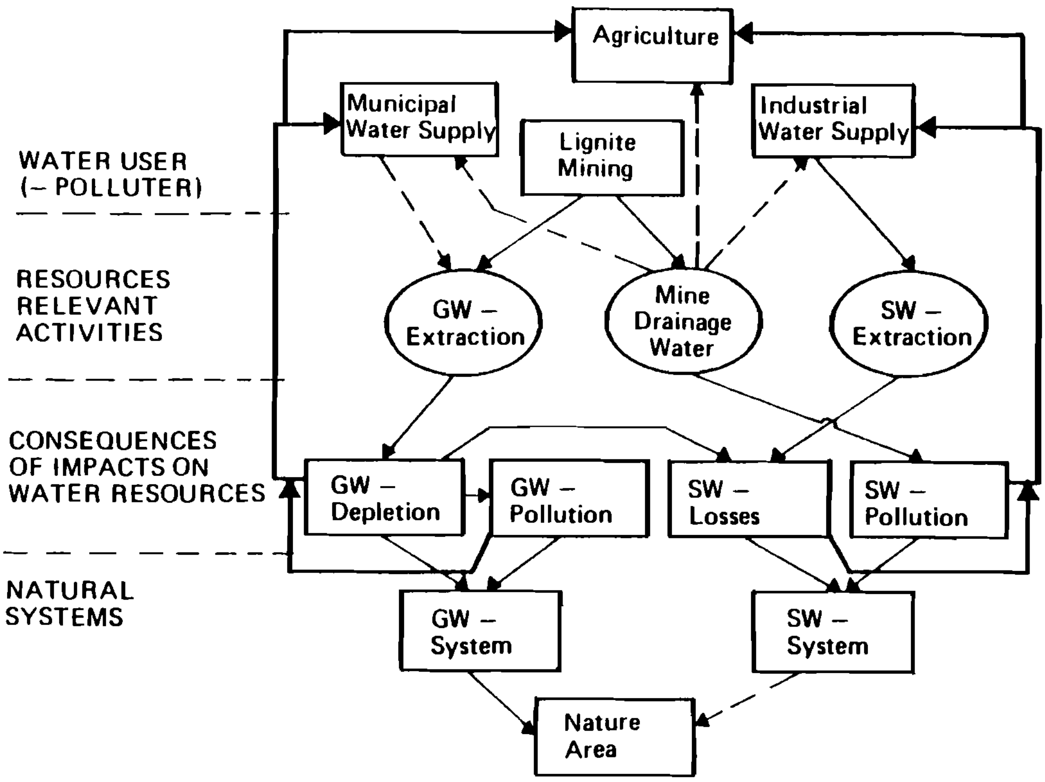


Figure 3.1.5: Impact diagram for open-pit lignite mining areas

should be taken into account. Partly correlated to these conditions, the water demand of water users is also characterized by monthly variations. The monthly time step is typical for long-term water management and planning.

3.2 Outline of the Decision Support System

3.2.1 General structure

In Part 1 we have substantiated that hierarchical model systems are required to support the analysis of regional water policies. Generally, time-discrete dynamic systems models have to be used. This discretization corresponds to the decision making reality also characterized by typical time intervals. The step-size and the available mathematical methods are the structural factors of the necessary model hierarchy. For the regional systems of the type studied it was suggested in Part 1 to combine simplified *screening models* for scenario generation with more comprehensive *simulation models* for more detailed investigations of the scenarios. This hierarchy fits well to the practice in water management and planning in the GDR outlined in Kaden et al. 1985b:

- application of *planning models* as screening models putting particular emphasis on socio-economic aspects,
- application of *management models* as simulation models with detailed consideration of the optimum long-term water supply problem,
- application of *operational models* reflecting in detail the real time behaviour of individual water management systems and considering extreme hydrologic or water quality situations.

Frequently, already a two-level model hierarchy satisfies most requirements. This is the case for regions with negligible short-term systems variations (daily) as it is typical for open-pit lignite mining regions located in flat areas. Even if there are operational problems to be solved it may be assumed that they do not affect significantly higher levels of decision making. That is why according to the general concept developed in Section 1.5 for the DSS MINE such a two-level system has been realized, combining a first-level *Planning Model* with a second-level *Management Model*.

Both models have to be based on a large number of submodels describing all relevant complex environmental and socio-economic processes in the region under consideration. As it was stated in Section 1.9 of this Report these submodels have to be simple enough to fit in a complex model system but they have to describe the process with sufficient accuracy. Our principle approaches to the development of simplified models are explained in Part 1. It is assumed that comprehensive models are available as a basis for model simplification. The basic models available and developed for our DSS MINE are described in Section 3.3.

The first level **Planning Model** is designed for screening of principal management/technological decisions by means of a dynamic multi-criteria analysis for a relatively small number of *planning periods*, $j = 1, \ldots, J$ representing a characteristic time step for such 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 as well as data preparation and computational effort, for the DSS MINE progressively increasing time steps are used, starting with one year and incresing with time upto 15 years. This has been done taking into account the uncertainties in model inputs and the required accuracy of model results, decreasing with time as it is illustrated in Section 3.4.1, Figure 3.4.1.

The planning model is the basis for the analysis of rational strategies of long-term systems development. These strategies are selected in the course of 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 integrated values over the whole planning horizon. In Sections 3.4.1 and 3.4.2 the general structure of the planning model and its submodels are outlined. For the multi-criteria analysis the *reference point approach* (Wierzbicki 1983) is used, see Section 3.4.3. This approach results in our case in non-linear optimization problems of a special structure. For its solution an adequate problem solver MSPN has been developed, see Section 3.4.4.

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 system 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; consequently, managerial decisions and that consequences are smoothed,
- the neglect of uncertainties in model inputs,
- the application of simplified environmental submodels based on comprehensive models,
- the neglect of some environmental subprocesses such as the interaction between groundwater and surface water depending on the surface water table.

This is why a second-level **Management Model** for the simulation of systems behaviour for a large number of smaller *management periods* (monthly and yearly time steps) is applied. It is used to analyse managerial decisions by means of stochastic simulation and to verify results obtained using the planning model. In Section 3.5 the management model is described.

In Figure 3.2.1 the general structure of the DSMS is depicted. As the figure illustrates the choice of fundamental technological alternatives (e.g. decisions on the construction of a treatment plant, of a pipeline, the dimension of pipes, etc.) are supposed to be fixed exogenously and might be considered as different scenarios. For the time being the DSS analyses continuous management/technological decisions for planning periods only. In Section 3.6 the computer implementation of the DSS MINE and its practical application are illustrated.

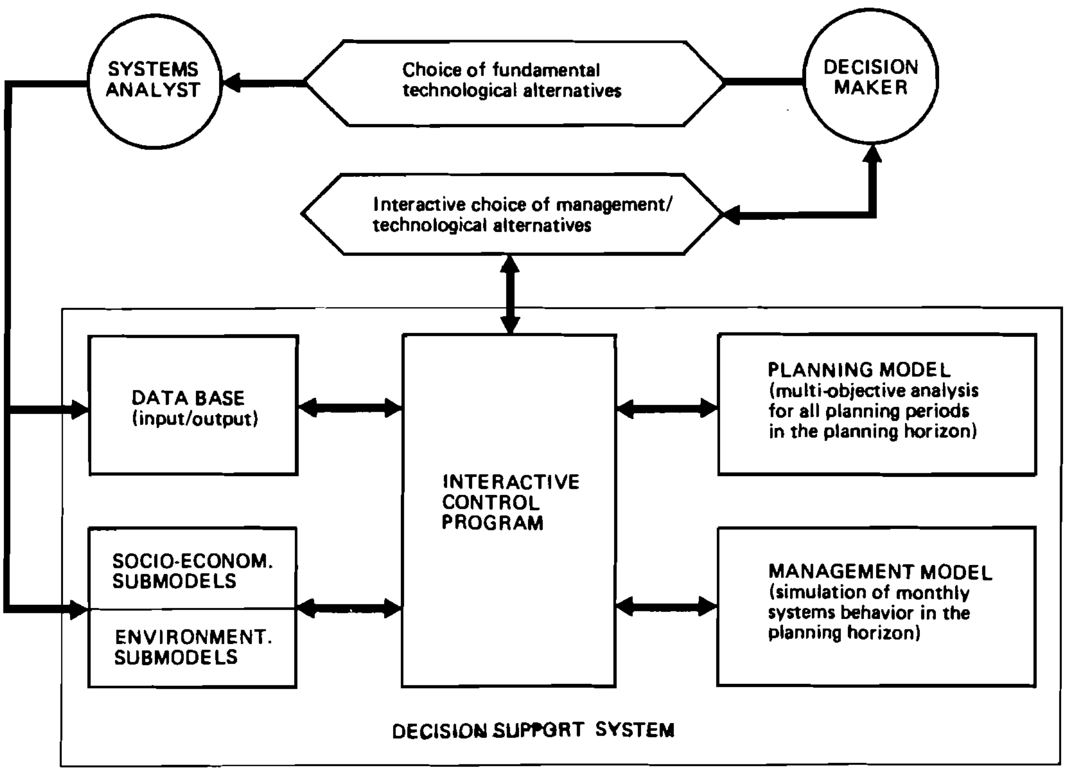


Figure 3.2.1: General structure of the Decision Support System MINE

3.2.2 Implementation for the GDR test area

The DSS MINE has been implemented for the test area in the Lusatian lignite district introduced in Section 3.1. We consider a planning horizon of 50 years, divided into 10 planning periods. Table 3.2.1 shows the time discretization used.

Table 3.2.1: Time discretization of the model for the GDR Test-Area

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

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

In Figure 3.2.2 a scheme of the test region is given, depicting the essential ***decisions*** on the systems development and ***parameters*** of the systems development. In this scheme only those elements are included which are supposed to be affected by decisions. For instance, we neglect here a few tributaries (compare Figure 3.1.1).

We consider the following ***decisions*** on systems development (the indices used are given in Figure 3.2.2).

$\mathbf{q}_{\alpha,\beta}$ - flux from α to β (water allocation)

α = (a|b|c|d|s|g|p|im|i)

β = (s|m|i|ag|ex|p|e)

$\mathbf{cq}_\alpha$ - supply of lime hydrate for water treatment

α = (a|b|c|d|p)

$\Delta\mathbf{tm}_d$ - duration of mine drainage mine D before starting its operation

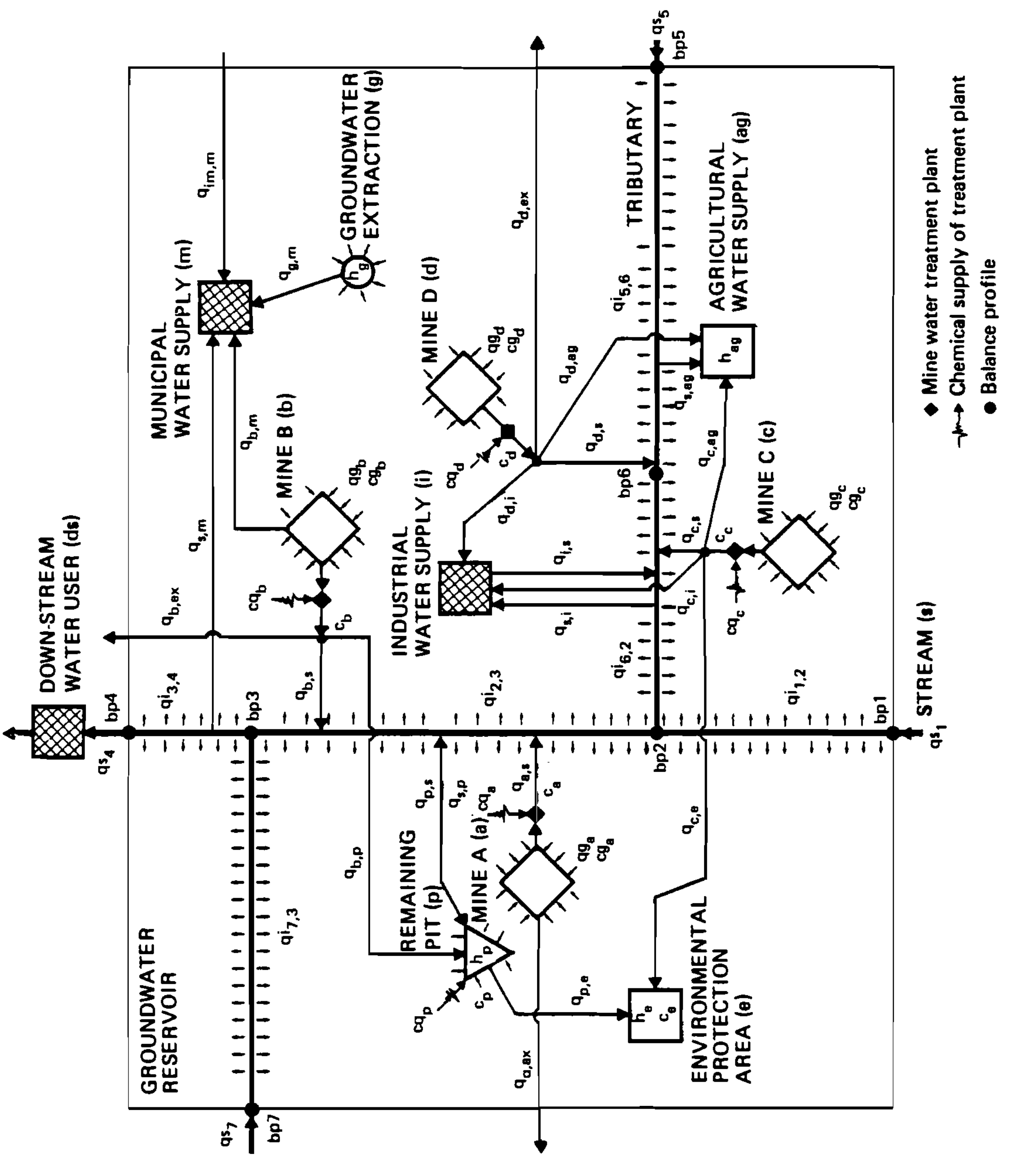


Figure 3.2.2: Detailed scheme of the test region

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.

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

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. Therefore, it is assumed that all decisions and state paramenters 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 and state parameters depend on managerial aspects to be considered on a monthly basis within the management model.

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

For the evaluation of scenarios the following types of indicators are taken into the account:

- *deviation between water demand and supply*
- *enivironmental quality* for typical water quality parameters (Fe^{2+},H^{+})
- *economic characteristics* of regulating activities.

Details on the indicators used are given in subsequent sections.

3.3 Description of the Basic Models

Comprehensive models of the relevant environmental processes form the basis for the development of the DSS. These models referred to as basic cannot be incorporated directly into the DSS, but they are used both for the development of simplified models according to the approaches described in Section 1.9, and for the verification of results obtained with these models. In the following the basic models for the DSS MINE are described. First we give an overview on the groundwater flow model. This model which was already available considers groundwater–surface water interactions. But for modeling these processes it turned out to be not computationally effective and economical. Therefore, conceptual submodels of groundwater–surface water interaction have been developed. They will be described below. Finally the water quality submodels developed will be discussed.

3.3.1 Groundwater flow model (HOREGO)

During the last decade a system of comprehensive models for groundwater management has been elaborated in the GDR, see Kaden 1984. For modeling groundwater quantity a set of computerized models is available, based on finite difference and finite elements methods. Especially for the analysis of mine drainage problems multilayer horizontal-plane flow models have been designed with boundary conditions specific for mining. One such model considering steady and nonsteady groundwater flow problems is the HOREGO-model (Gutt 1984). It is based on the mathematical model of the non-steady horizontal plane groundwater flow for confined and unconfined conditions. The discretization of the flow field is done by a grid of orthogonal finite elements. Such type of groundwater flow models is common in hydrogeology, therefore it needs no further explanation. But the HOREGO-model considers boundary conditions specific to mining regions.

3.3.1.1 Specific boundary conditions for modeling groundwater flow on a regional scale

Generally, the analysis of regional groundwater flow problems necessitates the consideration of:

- natural groundwater recharge,
- infiltration/exfiltration from/into surface water systems, that is, groundwater-surface water interactions.

Additionally in areas with open-pit mining activities we have to deal with substantial boundary conditions for groundwater:

- moving open-pit mine slopes during operation of mines,
- remaining pits after abandoning of mines being filled by natural groundwater flow, in case with artificial surface water inflow.

The character of the boundary condition ***groundwater recharge*** strongly depends on the distance between the earth surface and groundwater table, in other words, on the depth of the unsaturated zone. If this depth is larger than 2 m, the natural groundwater recharge practically does not strongly depend on the groundwater table, and this holds true for mining regions in general. Nevertheless, natural groundwater recharge in mining areas is subject to strong temporal alterations, caused by the accompanying devastation and reclamation/recultivation of large areas. Changes in soil exploitation and morphological and soil geological conditions are caused by mining and overburden disposal coupled with the following recultivation. Furthermore, changes of groundwater and surface water tables due to mine drainage should be considered. The size and duration of these alterations depend on the extent of the changes due to the mining process in comparison with the original conditions and its duration. All these alterations are long lasting, therefore, the estimations of groundwater recharge can be based on long-term mean values. The program RASTER (Gluga et al. 1976, Enderlein et al. 1980) is used for that purpose, considering the above aspects, but neglecting seasonal variations of groundwater recharge. Generally groundwater recharge increases in mining areas in the GDR up to about 10 l/s km^2 in former forestral areas and about 5 l/s km^2 in agricultural areas.

Surface water/groundwater interactions are typical for all natural catchment areas. However, in mining areas extensive cone-shaped groundwater depressions influence these interactions particularly strongly resulting in runoff balance variations of whole regions.

A common approach to modeling regional water resources systems is to model the major subsystem (groundwater or surface water) and to take into account the other system by means of boundary conditions. This method is based on the assumption that the flow process of the subsystem represented by a boundary condition does not depend on the flow process of the modeled subsystems. In this case for the groundwater flow model the surface water systems are modeled via inner boundary conditions of the third kind. In systems with strong interactions between the subsystems as in mining areas this assumption is not adequate for short-term variations. For this reason in mining regions surface water and groundwater interactions sometimes have to be considered explicitly in coupling the models of the subsystems (compare Section 3.3.2).

In surface water management for regional problems hydrological one-dimensional flow models are used. In groundwater management system-descriptive deterministic models of quasi horizontal-plane flow processes are typical choices. Variables essential for coupling are water tables (groundwater and surface water) and the flux between surface and groundwater. In principle the models may be coupled over the grid nodes (groundwater flow model) and balance segments (surface water flow model). Therefore, a large number of grid nodes is required, resulting in relatively high expenses for data acquisition and computation. It is reasonable to substitute each balance segment of the surface water flow system by a imaginary well (point-source, sink, respectively) situated in the center of this system. The coupled model system is solved either solving the entire system of equations or by iteration.

The main problem of modeling groundwater flow in mining areas is to take into account the hydraulic effect of the mining position, varying in time, caused by the ***movement of the open-pit mine slopes***. In this case the groundwater table is lowered to the bottom of the lignite seam to be exploited. This boundary condition becomes complicated due to the movement of the mine and consequently the movement of the boundary condition in time.

Figure 3.3.1 shows how the process of the passage of a moving slope over a node can be modeled by means of an additional hydraulic resistance. As the simulation result we obtain the amount of drainage water at the node as a function in time.

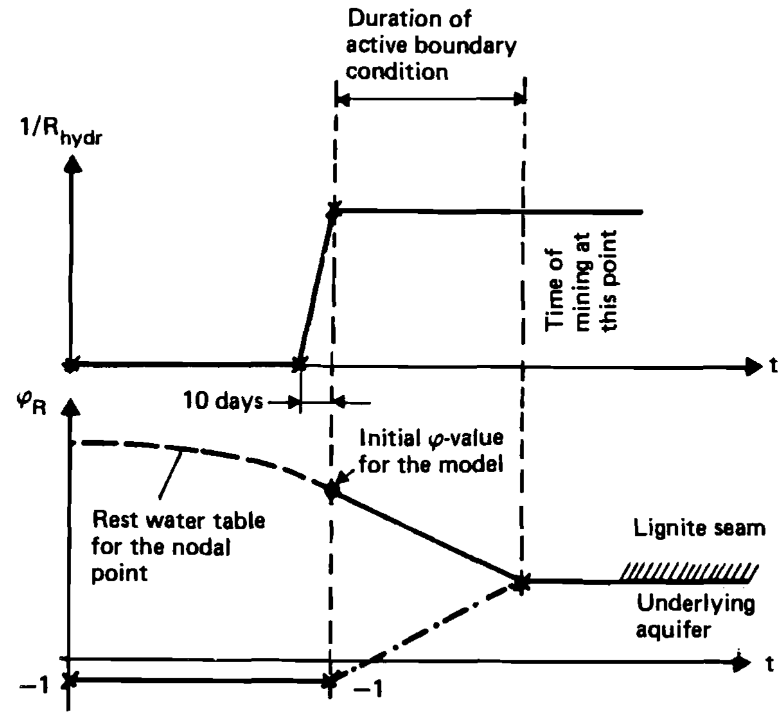


Figure 3.3.1: Simulation of a moving slope by an additional hydraulic resistance

Generally, this approach is sufficiently accurate for regional studies. But by investigations with lower level models as strip mine models more detailed informations concerning the amount of water pumpage of all dewatering wells are required for the proper design of the dewatering system. Appropriate solutions are embedded into the HOREGO model.

Water bodies such as lakes or remaining pits being in direct interaction with the groundwater system can be considered as boundary conditions of the third kind. The water body and the aquifer are coupled in the model by means of a hydraulic resistance, taking into account the area of the water body belonging to the finite element under consideration as well as an additional hydraulic resistance for the transformation of vertical flow into horizontal ones, see Figure 3.3.2. The water body is modeled as a nonlinear function between water table and storage volume. The solution is obtained iteratively. First, the water table of the water body is estimated taking into account the previous water table and the inflow/outflow during the time-step considered. Then, the groundwater model is applied to estimate the flow between the water body and aquifer via the hydraulic resistance. This flow is used to correct the water table of the water body fixed at the first step. This approach is particularly useful in modeling processes related to remaining pits in mining areas.

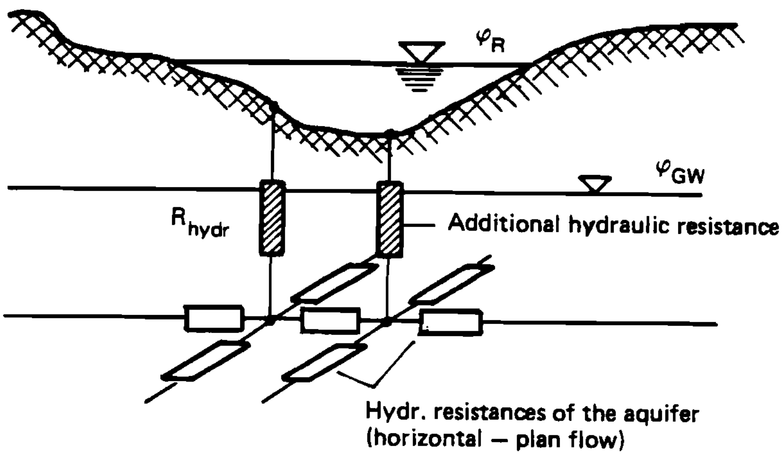


Figure 3.3.2: Interaction between water bodies and aquifer

3.3.1.2 Continuously Working Model (CWM) for the test region

Simulation models of environmental processes such as groundwater flow form only an image of the reality with a certain accuracy. The accuracy of results obtained using simulation models depends on the model structure as well as on the completeness and quality of input data. The lack of knowledge of processes and data in preliminary steps of analysis, in particular, requires the gradual improvement of the models and their data. For groundwater systems with their strong dampening and phase shifting between impact on the system and observable system response this can well be done by comparing simulation results with real systems responses. Based on this, Continuously Working Models can be implemented. In the GDR, Continuously Working Model (CWM) refer to a methodology and a model system for monitoring and controlling long-term man-made impacts on groundwater resources (Luckner 1973, Peukert et al. 1982, Kaden & Luckner 1984).

Usually a hierarchical system of models is needed to meet different requirements for spatial and temporal resolution. For groundwater management in lignite mining areas a three-level hierarchy proved to be suitable (see Kaden & Luckner 1984; Peukert et al. 1985). With respect to the analysis of regional water policies the high level regional CWMs are of major interest. Such a regional CWM was developed for the south-east of the Lusatian Lignite District (Peukert et al. 1982). The test region includes major parts of the modeled region, which is why the CWM is an excellent basic groundwater flow model for the DSS MINE.

The CWM for the Lusatian lignite region is in its third stage of improvement and complementation. It is based on the model HOREGO and takes into account the following boundary conditions related to:

- development of all open-pit mine dewatering measures,
- operation of all existing and newly formed remaining pits used for water resources management or disposal of industrial wastes,
- operation of all waterworks, incuding their planned development,
- operation of irrigation systems for agricultural purposes,
- natural recharge of groundwater depending on the operation of mines, including their reclamation,
- infiltration/exfiltration of rivers and ponds.

The finite elements grid of the modeled region consists of about 1000 elements each with an area of 1–4 km^2. The model has been calibrated for a period of 8 years. Sufficient measurements of the groundwater table and of water pumpage in individual open-pit mines have been available for that period.

3.3.2 Groundwater—surface water interaction

In the mining test region considerable interactions between groundwater and surface water take place along the stream and its tributaries as well as at the site of the remaining pit. In principle, both types of interactions can be studied with the above described groundwater flow model and its specific boundary conditions. But for monthly time steps as the minimal time interval for managerial decisions to be studied in the management model the groundwater flow model is not computationally effective and economical. This is why we do not use it as a basic model for groundwater-surface water interaction within the framework of the DSS MINE. For this purpose simple conceptual models have been developed, Kaden et al. 1985b. The comprehensive groundwater flow model has only been used to verify selected results of these models.

3.3.2.1 Remaining pit submodel

Hydrologically remaining pits formed after abandoning of mines are stagnant surface water bodies located in an unconfined aquifer. The water exchange between the pit and the aquifer is determined by the hydraulic conductivity of the aquifer, i.e. practically free exchange occurs. The hydrological utilization of the remaining pits in mining areas is a natural solution for a reasonable recultivation of the mining areas, to avoid water deficits, and to satisfy flood protection for neighbouring streams.

Two stages have to be distinguished, the stage of filling (recharging) the remaining pit, and the management stage for its utilization in the framework of the regional water management.

The management of remaining pits takes place within a "usable storage layer". In order to get the water table of the remaining pit within this layer it is necessary to fill the remaining pit after abandoning the drainage wells around the open-pit mine. This can either be done by natural groundwater inflow or additionally by artificial intake of surface water or mine water. The latter results in water losses by infiltration from the remaining pit into the aquifer.

After reaching the usable storage layer the remaining pit can be used as a water reservoir. In such a case, the management is analogous to common reservoir management in river basins, including flood protection. One difference is that the storage basin is located in the by-pass of the stream.

The objective was to develop a simple conceptual model of the remaining pit management considering the groundwater surface water interaction. A known analytical solution for the water table of a finite diameter well has been used as a fundamental solution and has been modified according to the specifics of a remaining pit.

Derivation of the fundamental solution for a finite diameter well

In simplifying its geometry, a remaining pit can be considered as a well with a large diameter. Consequently, it is possible to use analytical solutions of the well hydraulics as a transition function. The inner boundary condition of the classical THEISS-solution ($r \rightarrow 0$) has to be replaced by an adequately modified one since the storage effect of the "well" (remaining pit) is not negligible (see Figure 3.3.3). According to Cooper et al. 1967 we get the following approach applying the **Laplace**-transformation:

Differential equation:

$$\frac{\delta^2 h}{\delta r^2} + \frac{1}{r} \cdot \frac{\delta h}{\delta r} = \frac{S}{T} \cdot \frac{\delta h}{\delta t} \tag{3.1a}$$

Boundary and initial conditions:

$$h(r_s, t) = H(t) \ , \ h(\infty, t) = 0 \ , \ h(r, 0) = 0 \tag{3.1b}$$

$$H(0) = \frac{\Delta V}{\pi \cdot r_c^2}$$

$$2\pi r_s T \cdot \frac{\delta h(r_s, t)}{\delta r} = \pi r_c^2 \cdot \frac{\delta H(t)}{\delta t}$$

Solution of **Laplace**-*transformed differential equation:*

$$\bar{h}(r, p) = \frac{S \cdot r_s \cdot H(0) \cdot K_0(\sigma \cdot r)}{\sigma \cdot T \cdot [\sigma \cdot r_s \cdot K_0(\sigma \cdot r_s) + 2\alpha \cdot K_1(\sigma \cdot r_s)]}$$

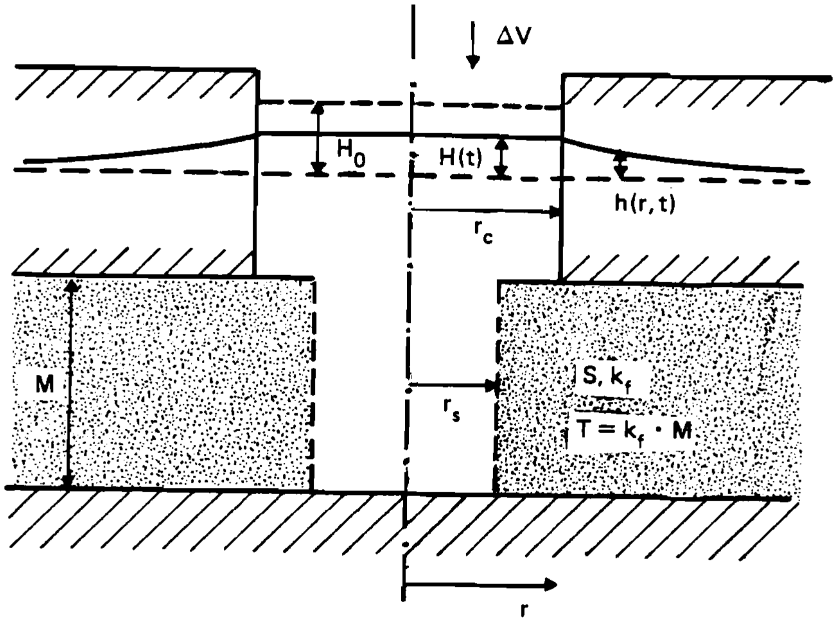


Figure 3.3.3: Idealized representation of a finite-diameter well

with K_0,K_1	-	**Bessel**-functions	
r	-	space coordinate	[m]
t	-	time	[sec.]
r_c,r_s	-	see Figure 3.3.3	
α	-	geohydraulic time constant	[sec/m^2]
S	-	storage coefficient	[-]

$$\alpha = \frac{r_s^2}{r_c^2} \cdot S \quad \sigma = \sqrt{p \cdot \frac{S}{T}} = \sqrt{p \cdot \alpha} \quad .$$

Solution of the problem by inverse **Laplace**-*transformation:*

$$H(t) = h(r_s,t) = F \cdot H(0) = L^{-1}\{\bar{h}(r_s,p)\} \cdot H(0) \tag{3.2}$$

The factor F results from the inverse **Laplace**-transformation. From the analytical inverse transformtion we get according to Carslaw, Jaeger 1959:

$$F = 8\alpha / \pi^2 \int_0^{\infty} \frac{e^{-\beta u^2/\alpha}}{u \cdot \Delta(u)} \cdot du \tag{3.3}$$

with

$$\beta = \frac{T \cdot t}{r_c^2}\ ,\ \alpha = \frac{r_s^2}{r_c^2} \cdot S$$

$$\Delta(u) = [u \cdot J_0(u) - 2\alpha \cdot J_1(u)]^2 + [u \cdot Y_0(u) - 2\alpha \cdot Y_1(u)]^2$$

and J_0, J_1, Y_0, Y_1 - generalized **Bessel**-functions.

Modification of the fundamental solution

For modeling of the remaining pit the solution Eq. (3.2) is in the given form not yet applicable because a few typical conditions have not been considered:

1. Variations of groundwater flow due to external boundary conditions.
The influence of external boundary conditions on the groundwater flow near the remaining pit is eliminated by the help of separation calculations. The actual variation of the storage volume v_p of the remaining pit results on the one hand from the inflow/outflow due to external boundary conditions (natural recharge q_p^0) and on the other hand from intakes/discharges Δq_p and exfiltrations/infiltrations qi_p resulting therefrom (see Figure 3.3.4). The following balance equation holds for a planning horizon from time t_B to t_E:

$$v_p(t_E) = \int_{t_B}^{t_E} (q_p^0 + \Delta q_p - qi_p)dt + v_p(t_B)$$

with

$$h_p(t_p) = fh_p(v_p(t_p)) \quad .$$

2. Differing geometry of the remaining pit from the cylindrical well form (nonlinear dependency between storage water table and volume).
The geometrical deviation of the remaining pit from a cylindrical form is characterized by the relationship $r_c = f(h_p)$. This nonlinearity is dealt by updating the radius r_c gradually (step-by-step linearization).

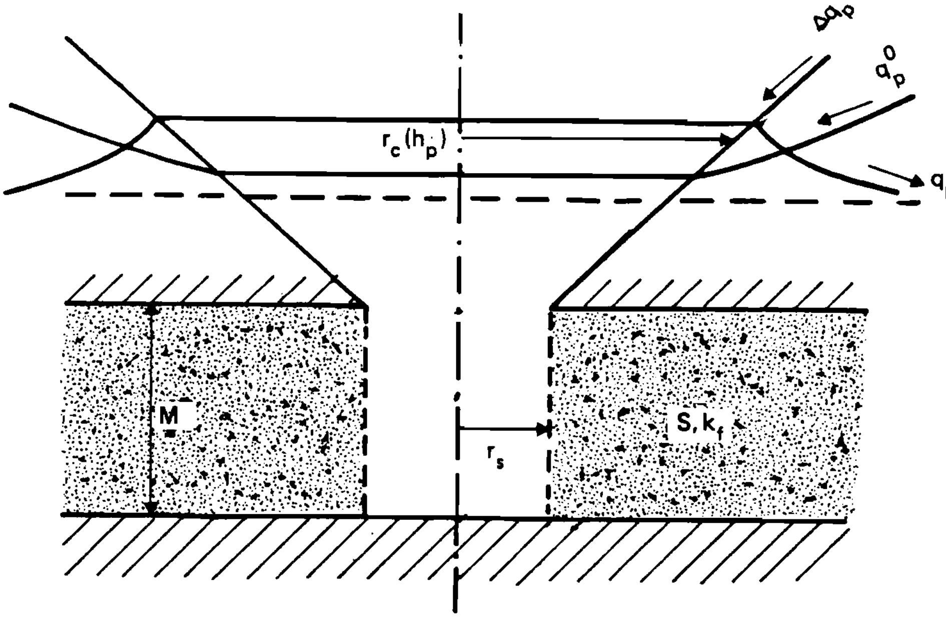


Figure 3.3.4: Separation of balance components

3. Unconfined flow conditions.
The unconfined flow condition (transmissivity $T = f(h_p)$) is simplified by introducing a mean constant transmissivity.

4. Time-variable management (artificial inflow).
The consideration of the time-variable management is possible on the basis of the superposition principle by the use of the convolution operation.

5. Consideration of an additional hydraulic resistance reflecting the transformation of flow from vertical to horizontal direction.

Within the comprehensive groundwater flow model the remaining pit is taken into account by an inner boundary condition of the third kind. This is considered in the above conceptual model by reducing the relevant radius for the exchange area, $r_{s,old}$, at the recommendation in Busch, Luckner 1972:

$$r_{s,new} = \frac{r_{s,old}}{e^{2\pi T R_{hydr}}}$$

The reciprocal value of R_{hydr} is a sum of the reciprocal additional hydraulic resistances (parallel circuit) used in the boundary condition in the comprehensive flow model.

Based on all mentioned modifications we obtain the following time-discrete algorithm with $t_k = k \cdot \Delta t$, $k_B \leq k \leq k_E$:

$$v_p(t_E) = v_p(t_B) + \sum_{k=k_B}^{k_E-1} [v_p^0(t_k) + \Delta v_p(t_k) - vi_p(t_k)]$$

The individual components are determined as follows:

$$v_p^0(t_k) = fv_p(h_p^0(t_{k+1}) - fv_p(h_p^0(t_k))$$

$$\Delta v_p(t_k) = \Delta q_p(t_{\frac{k+1}{2}}) \cdot \Delta t$$

$$vi_p(t_k) = qi(t_k) \cdot \Delta t$$

with

$$qi(t_k) = \sum_{l=k_B}^{k} (fv_p(h_p(t_l) + \Delta h_p(t_l)) - fv_p(h_p(t_l) + F(t_{k+1} - t_l) \cdot \Delta h_p(t_l))$$

$$F(t_k - t_l) = L^{-1}\left\{\frac{S \cdot r_s \cdot K_0(\sigma \cdot r_s)}{\sigma \cdot T \cdot [\sigma \cdot r_s \cdot K_0(\sigma \cdot r_s) + 2\frac{r_s^2}{r_{c,l}^2} K_1(\sigma \cdot r_s)]}\right\}$$

$$\sigma = \sqrt{p \cdot \frac{S}{T}} = \sqrt{p \cdot a}$$

$$r_{c,l} = \sqrt{\frac{\Delta v_p(t_l)}{\pi \cdot \Delta h_p(t_l)}}$$

$$\Delta h_p(t_l) = fh_p(v_p(t_l) + \Delta v_p(t_l)) - h_p(t_l) \quad .$$

h_p^0 is the water level in the remaining pit for natural recharge.

The computer programme for this algorithm is given in Kaden et al. 1985b. The inverse **Laplace**-transformation is done numerically by an effecient numerical algorithm applying the residue theorem. On the basis of the numerical integration the computing time is reduced by a factor of about 15 as compared with the computation of F in Eq. (3.2).

In Figure 3.6 Section 3.4.2.3 some numerical results are presented, compared with experimental runs wth the comprehensive groundwater flow model.

3.3.2.2 Submodel of exchange between streams and groundwater

Model structuring

In the water balance of lowland areas, the balance component *infiltration/exfiltration* is of similar magnitude as the other balance components (discharge, inflow, natural groundwater recharge, etc.). Especially in areas with significant man-made impacts on the water resources system the importance of this balance element is severe increasing.

For the estimation of *long-term mean values* of the infiltration/exfiltration (yearly and larger time intervals) the spatial and temporal changes of groundwater tables are the primary independent influence parameter. Changes of the water level in the stream in this case can be neglected because they are assessed to be minimal in comparison with the changes of groundwater tables and are not subject to trends. In this case computations with a comprehensive groundwater flow model give detailed informations about the development of infiltration/exfiltration behaviour. In models for operational/managerial aspects shorter time intervals have to be considered, i.e. *monthly mean values*. In this case the exfiltration/infiltration conditions are different. Processes with shorter time constants become essential, such as the variation of exfiltration/infiltration due to changes of the water level in the stream. In the areas of groundwater depression this process practically represents the only natural and rapid component which influences the runoff in the stream. Hypodermic and groundwater runoffs do not occur and surface runoff is in lowland areas almost negligible.

Consequently, only two subprocesses have to be simulated in order to model the exfiltration/infiltration processes in mining regions (also in most lowland regions in general) sufficiently accurately. Due to the fact that the time constants differ between each subprocesses by magnitudes it is possible to consider them separately in mathematical submodels. The results of both submodels have to be superimposed to get the appropriate balance values, see Figure 3.3.5 and Eq. (3.5).

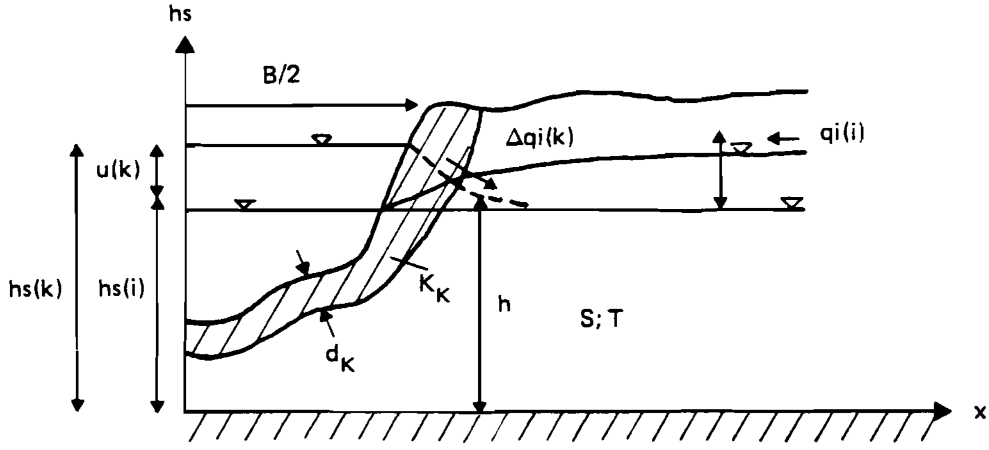


Figure 3.3.5: Exfiltraton/infiltration process between stream and groundwater

$$qi\,(k) = \Delta qi\,(k) + qi\,(i) \tag{3.5}$$

with $\Delta qi\,(k)$ - exfiltration/infiltration due to change of water level

$qi\,(i)$ - exfiltration/infiltration for mean water level in the stream

The component $qi\,(i)$ can be estimated for instance as time series directly by computations with a comprehensive groundwater flow model (see Section 3.4.2). This is sufficiently to describe the exchange process due to changes in the groundwater system in the long-term run. A different situation is given for the component $\Delta qi\,(k)$ which cannot directly be obtained from that model (work effort, computing time). For this reason, the comprehensive groundwater flow model can only be used as an aid for the construction of simplified models. In Kaden et al. 1985 numerical results of these test calculations are presented. By the help of experiments with a comprehensive groundwater flow model it could be shown for the mining test region:

- The variation of exfiltration/infiltration due to the change of the water level in the stream is a relevant balance component for the stream segments under consideration.

- The effects of variations of the water level in the stream on the groundwater tables are locally limited and do not effect the external boundary conditions of the flow field.

For the model concept of the conceptional model we obtain the following requirements or simplifications respectively:

- Groundwater process modeling as one-dimensional horizontal-plan groundwater flow;
- Formulation of the external boundary condition at infinity;
- Consideration of a potential-dependent resistance formulating the inner boundary condition (colmation).

Conceptual model

Based on these assumptions the process of exfiltration/infiltration is described by the linear differential equation of one-dimensional horizontal-plan groundwater flow to a channel:

Differential equation

$$\frac{\delta^2 h}{\delta x^2} = a \cdot \frac{\delta h}{\delta t}\,, \quad a = \frac{S}{T} \tag{3.6a}$$

Boundary and initial conditions

$$h(\infty,t) = 0\,, \quad h(x,0) = 0 \tag{3.6b}$$

$$h(0,t) = A\,\frac{dh(0,t)}{dx} = H(0)\,, \quad A = \frac{K}{K_K} \cdot d_K$$

with	h	-	variation of groundwater table	[m]
	x	-	space coordinate	[m]
	t	-	time	[sec]
	K	-	hydraulic conductivity of the aquifer	[m/sec]
	ΔH	-	variation of the water level in the stream (step)	[m]
	S	-	storage coefficient	[-]
	T	-	transmissivity	[m^2/sec]
	K_k	-	hydraulic conductivity of the colmated layer	[m/sec]
	d_K	-	depth of the layer	[m]

Numerical solution

By means of Laplace-transformation we obtain from Eq. (3.6a) and (3.6b)

Differential equation

$$\frac{\delta^2 \bar{h}}{\delta x^2} = a \cdot p \cdot \bar{h} - h(x,0) \tag{3.7a}$$

Boundary conditions

$$\bar{h}(\infty,p) = 0\ ,\ \ \bar{h}(0,p) - A\ \frac{d\bar{h}(0,p)}{dx} = \frac{\Delta H(0)}{p} \tag{3.7b}$$

with p - time coordinate [1/sec].

The solution is:

$$\bar{h}(x,p) = \frac{\Delta H(0)}{p \cdot (1+A\ \sqrt{a \cdot p})}\ e^{-\sqrt{a \cdot p}x}$$

For the actual volumetric flux we obtain with

$$q(x,t) = -2T \cdot L\ \frac{dh(x,t)}{dx}\ :$$

$$\bar{q}(x,p) = \frac{2T \cdot L \cdot \Delta H(0) \cdot \sqrt{a \cdot p}}{p \cdot (1+A\ \sqrt{a \cdot p})} \cdot e^{-\sqrt{a \cdot p}x} \quad .$$

The total exfiltration/infiltration for $x = 0$ is:

$$Q(t) = \int_0^t q(0,t)dt = L^{-1}\{\frac{1}{p} \cdot \bar{q}(0,p)\}$$

$$Q(t) = L^{-1}\{\bar{Q}(p)\} = L^{-1}\ \{\frac{2T \cdot L \cdot \Delta H(0) \cdot \sqrt{a \cdot p}}{p^2 \cdot (1+A\ \sqrt{a \cdot p})}\}$$

For the monthly mean values of exfiltration/infiltration we get with $\Delta t = 2.625 \cdot 10^5$ sec. ~ 1 month:

$$\Delta qi\,(t_k) = \frac{1}{\Delta t} \cdot [L^{-1}\ \{\bar{Q}(\frac{1}{t_k})\} - L^{-1}\ \{\bar{Q}(\frac{1}{t_{k-1}})\}] \tag{3.8a}$$

To consider a time-variable step function the superposition principle of the individual step is used by the help of the convolution operation ($k = t_k$).

$$\Delta qi(k) = \frac{u(m)}{\tilde{R}_{hydT}} + \sum_{l=1}^{k} w(k+1-l) \cdot S(l) \qquad (3.8b)$$

$$u(k) = hs(k) - hs(i)\,,\; w(k) = u(k) - u(k-1)$$

with
k - actual month
i - actual year
$S(l)$ - step response function [m^2/sec]
hs - surface water level above its bottom [m]
$\tilde{R}_{hydT}$ - hydraulic resistance for free percolation [sec/m^2]

For the estimation of the step-response function an effective computer programme CHANGE has been developed based on numerical **Laplace**-transformation. It is listed in Kaden et al. 1985b.

In Section 3.5.1.4 in Figure 3.5.4 a comparison of numerical results obtained with the above conceptual model and the comprehensive groundwater flow model is depicted.

3.3.3 Water quality

3.3.3.1 Introduction

We consider the discharge of acid ferruginous mine water into rivers as the most important impact on water quality in our test region.

The chemical reactions which play a major role in the formation and treatment of acidic ferruginous mine water are the following:

Underground ferrousdisulphide is oxidized by oxygen in the soil-air. At the same time, iron(II)-, sulphate- and hydrogen ions originate, and the acidity of groundwater increases. The reaction products are flushed out with the percolated water from aerated zones and transported by the rise of groundwater. The iron and acid concentration is especially high in the percolated water in spoils. Furthermore, the groundwater is characterized by increased concentrations of CO_3^{-2} resulting from biochemical degradation processes. All of these parameters are influenced in the mine water treatment plant by adding lime hydrate. The remaining iron(II) in the treated water is oxidized by air in the river, the remaining pit, respectively, hydrolized and precipitated according to the kinetics of reactions and residence times. The kinetics of all these reactions depends among others on the pH-value. Unfortunately there were no comprehensive computerized water quality models available. The development of appropriate models had to be based on the formulation of a basic comprehensive process model and its subsequent reduction. In Luckner et al. 1985 a methodology for obtaining comprehensive water quality process models is described. These models can be reduced by the help of different simplifications such as:

- *minimization of* the number of mixed *phases* of the multiphase system e.g. to a two- or to a one-single-phase model,
- *minimization of* the number of considered *migrants*, e.g. to Fe^{2+} and H^{+}, which have often the greatest importance in lignite mining districts,
- *parameter-lumping* by averaging of the parameters in space as well as in time,
- *space-lumping* leading to the neglect of all the transportation processes, this also includes parameter-lumping,
- *time-lumping* leading to the neglect of all storage processes and the consideration of equilibrium exchange processes and reaction processes (this method also includes parameter-lumping).

For real situations it is usually necessary to use several of these approaches together.

In the following the model reduction for the typical subsystems in regions with open-pit lignite mines, which are coupled with each other are outlined:

- the groundwater as the source of pollution,
- a mine water treatment plant as the control unit,

- a river section with an intake of acid ferruginous water, and
- a remaining-pit, which can also be used as an effective control unit in mining areas.

To characterize the *model reduction procedure* in a uniform way for each of the four above mentioned subsystems, we are using a *box-symbol* reflecting the system under consideration with a *headline* marking the system's name. Around the box are symbolized all the *inputs* and *outputs* as well as the considered migrants (left and right), e.g. Fe^{2+} and H^+, and also the chemical control substances (on the top), e.g. lime hydrate or oxygen.

Figure 3.3.6 shows the connections between the four subsystems respectively the connections between their water quality models in mining areas with acid ferruginous mine water. The characteristic chemical species (migrants) in the whole system are Fe^{2+} and H^+.

In the *first line* (internal of the box-symbol) are marked all the substances reacting with each other in the system, left the initial substances and right the reaction products. The stoichiometric balance equation quantifies their interactions.

In the *second line* are marked left the number of the considered migrants and the considered phases, and on the right hand side are specially marked the considered processes.

In the *third line* the names of the reduced models are given, e.g. "balance model with source/sink term and reaction" in the case of the mine water treatment plant.

With the development of the reduced conceptual mathematical model the procedure is not finished. These models usually in the form of systems of differential equations still have to be solved either be analytic or numerical means.

According to Figure 3.3.6 for groundwater quality a simple statistical model (stochastic trend) is used assuming that there are no short-term or significant changes in groundwater quality. In this case no further considerations are required. More detailed processes and models are to be considered for water quality processes related to surface water due to its short-term variations.

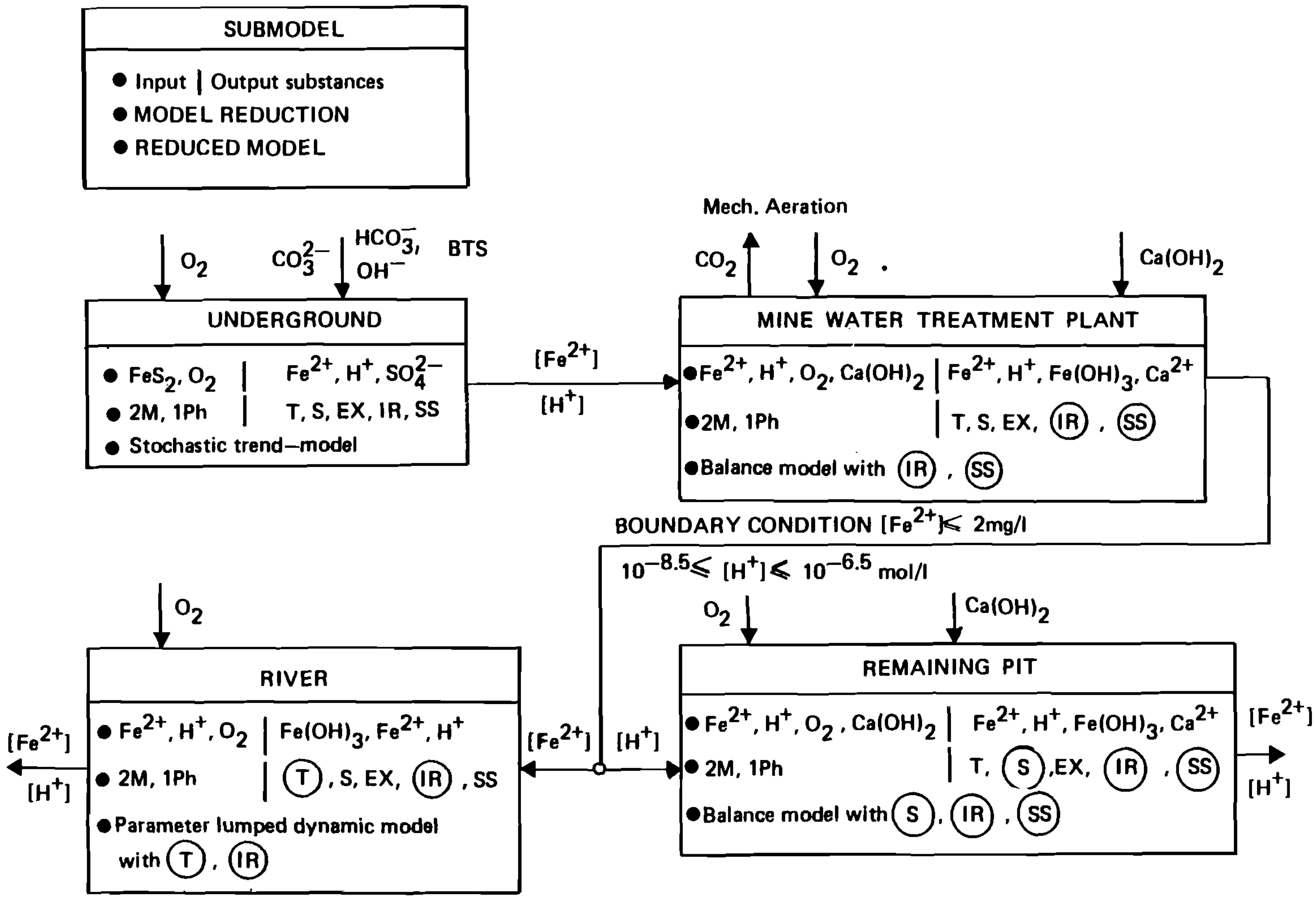


Figure 3.3.6: The complex scheme of the reduced conceptual quality models in a region with open-pit lignite mining

3.3.3.2 Basics of the surface water quality submodels

Submodels reflecting the water quality processes in the mine water treatment plant, the river system and the remaining pit are developed under the following assumptions:

- *chemical reactions* in the water bodies are considered as nonequilibrium reactions with complete stoichiometric turnover of the initial substances,
- *carbonic acid dissolved* in the drained groundwater is removed at the mine water treatment plant by mechanical de-acidification and in the rivers by de-gasification during the flow processes; similar reactions also occur in the remaining pit,
- *buffer capacity* of water with reference to hydrogen carbonate is neglected; this is only allowable for water with low carbonate hardness, which is typical for the GDR test area,
- surface water bodies contain excessive concentrations of *oxygen for oxidation* processes, and the partial pressure is constant (p_{O_2} = 0.21 *bar),*
- *transport processes* are one-dimensional,
- all ferrous hydroxide formed is sedimented within the reaction time; no mathematical modeling is therefore necessary to reflect the *sedimentation process,*
- *biochemical and chemical analysis* of ferrous hydroxide and ferrous oxidehydrates are not considered in the coefficient k of the reaction rate model.

The characteristic chemical reactions for all further submodels in the one-phase system "water" are the *oxidation* reactions of $Fe(II)$ and the *hydrolysis* of $Fe(III)$, Eq. (3.9a). The hydrogen ions thus formed will be neutralized in the mine water treatment plant, and, if necessary and possible, in the remaining pit by means of the treatment with lime hydrate, Eq. (3.9b). The total reaction is defined by Eq. (3.9c).

$$Fe^{2+} + \frac{1}{4}O_2 + \frac{5}{2}H_2O \rightarrow Fe(OH)_3 + 2H^+ \tag{3.9a}$$

$$Ca(OH)_2(s) + 2H^+ \longrightarrow Ca^{2+} + 2H_2O \tag{3.9b}$$

$$Fe^{2+} + \frac{1}{4} O_2 + Ca(OH)_2 + \frac{1}{2} H_2 \longrightarrow Fe(OH)_e \downarrow + Ca^{2+} \quad . \tag{3.9c}$$

The *kinetics* of ferrous ion oxygenation in laboratory systems has been previously studied and the general law of rate was found to be:

$$r_{Fe} = \frac{d[Fe^{2+}]^{*)}}{dt} = -k \cdot [OH^-]^2 \cdot p_{O_2} \cdot [Fe^{2+}] \quad , \tag{3.10}$$

where k is the velocity constant in $mol^2 l^2 \mathrm{min}^{-1} \mathrm{bar}^{-1}$, $[OH^-]$ denotes the concentration of hydroxyl ions, and $[Fe^{2+}]$ denotes the concentration of ferrous ions. At constant p_{O_2} Eq. (3.10) is reduced to a reaction rate model of pseudo-first-order kinetics:

$$r_{Fe} = -\frac{d[Fe^{2+}]}{dt} = k_1 \cdot [Fe^{2+}]$$

with

$$k_1 = \frac{k \cdot p_{O_2} \cdot K_W}{[H^+]^2} = \frac{k^*}{[H^+]^2}$$

k_1 has the unit of inverse time.

The weathering of pyrite or marcasite forms protons. They can be neutralized by a corresponding quantity $Ca(OH)_2$. The neutralization capacity K_{H^+} is stoichiometrical:

$$K_{H^+} = \frac{[H^+]}{[Ca(OH)_2]} \quad .$$

For a ***technical lime hydrate*** the constant K_{H^+} is in the range of 0.015 ... 0.025 $mol\ H^+/g\ Ca(OH)_2$. This means the effective substance of technical lime hydrate amounts to between 56 and 93 per cent. The exact value has to be determined in the laboratory.

---

*) In the following brackets [ ] are used to denote the concentration of a chemical substance.

In the transposition of $Fe(II)$ into $Fe(III)$-hydroxide, the stoichiometric ratio between mass protons and ferrous formation rate K_{Fe} is:

$$K_{Fe} = \frac{[H^+]}{[Fe^{2+}]} = 3.58 \cdot 10^{-2} \frac{mol\ H^+}{g\ Fe^{2+}} \quad .$$

3.3.3.3 Mine water treatment plant

In the mine water treatment plant the precipitation of $Fe(III)$ occurs by simultaneous neutralization through dosage of lime hydrate. The reduced model allows to simulate the output concentration and dosage of $Ca(OH)_2$. Mass transport is neglected.

Internal reaction (IR) processes (Eq. (3.10)) and the *external sink* for protons *(SS)* through a neutralization substance have to be considered. Under these assumptions the reduced model has the form:

$$Fe^{2+}: \; -\frac{d[Fe^{2+}]}{dt} = \frac{k^*}{[H^+]^2} \cdot [Fe^{2+}] + \sum Q_A \cdot [Fe^{2+}] - \sum Q_Z \cdot [Fe^{2+}]_Z \qquad (3.11a)$$

$$H^+: \; \frac{d[H^+]}{dt} = K_{Fe} \cdot \frac{d[Fe^{2+}]}{dt} + K_H[CA(OH)_2] + + \sum Q_A \cdot [H^+] - \sum Q_Z \cdot [H^+]_Z \quad . \qquad (3.11b)$$

An ***underdosage*** of lime hydrate results in incomplete neutralization of protons, that is, only a partial precipitation of the ion occurs and the pH-values remain less than 7.

The alkalinization substance $Ca(OH)_2$ guarantees a definite saturation pH-value of 12.6 for 20° C in the case of ***overdose*** because $Ca(OH)_2$ has a relatively low water solubility (1.6 g/l in the case of 20° C). In accordance with the limits for the discharge of water into public surface water systems the pH-value should be held in the range of $6.5 < pH < 8.5$. In mine water treatment plants the residence time of waste water is usually in the range of 2.0 ... 2.5 hours. Typical for the GDR, e.g. are sedimentation tanks with a capacity of 3 m^3/s and a volume of 27000 m^3. Figure 3.3.6 shows some numerical results of the submodel Eq. (3.11).

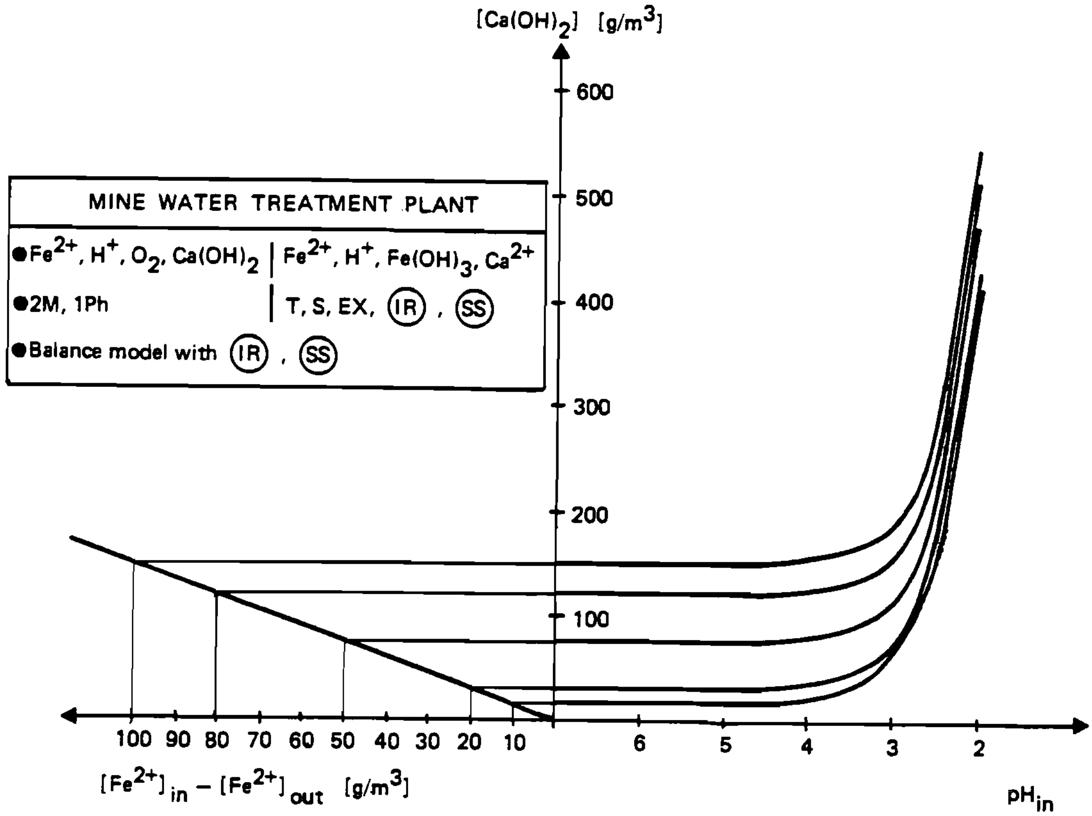


Figure 3.3.7: Demand of lime hydrate dependending on the input pH-value and the difference of Fe^{2+}-input and -output concentration

The graph in Figure 3.3.7 shows the required demand of calcium hydroxide in the case of a reference pH-value of 7.0 in the discharge depending on the input pH-value and the input $Fe(II)$-concentration. For the graph a neutralization capacity of the lime hydrate (as technical product) of 0.025 $mol\ H^+$ per $g\ Ca(OH)_2$ is presumed. At pH-values less than 4 a substantially increased amount of lime hydrate is required for neutralization. By optimal dosage of $Ca(OH)_2$, the treated mine water does not contain Fe^{2+} and has a pH-value of 7.

3.3.3.4 Water quality in streams

An intensive aeration of the stream water provides enough oxygen for the *iron precipitation* according to Eq. (3.9a). The protons formed will be neutralized up to the exhaustion of the buffer capacity of the carbonate and hydrogencarbonate ions. A pH-change occurs at about $3.58 \cdot 10^{-2}$ $mol\ H^+$ per each $g\ Fe^{2+}$ if all CO_3^{2-} and HCO_3^- ions are converted.

The stream water, e.g. in the Lusatian lignite mining district has a low buffer capacity so that it can be neglected in order to simplify the submodels. The hydrodynamic dispersion and diffusion is also neglected. The surface water system is subdivided into ***balance profiles*** and ***stream sectors*** between them. External sinks and sources (water diversion and intake) are arranged on the balance points (junctions). Storage changes are neglected. The conversion of the Fe^{2+} concentration in the stream by oxidation and hydrolysis is approximated as a reaction of the first order, and the variation of the H^+ concentration is regarded as a reaction of the zero order.

Based on the assumption that $v\ dc/dx = dc/dt$ holds true in the stream sectors, the submodel has the form:

$$Fe^{2+}:\quad -v\,\frac{d[Fe^{2+}]}{dx} = -\frac{d[Fe^{2+}]}{dt} = \frac{k'}{[H^+]^2}\,[Fe^{2+}] \tag{3.12a}$$

$$H^{+}:\quad -v\,\frac{d[H^{+}]}{dx} = -\frac{d[H^{+}]}{dt} = K_{F_e}\,\frac{d[Fe^{2+}]}{dt} \quad . \tag{3.12b}$$

On the junction the Fe^{2+} or the H^+ concentration in the water will be determined under the assumption that perfect mixing exists:

$$Q \cdot c = Q_Z \cdot c_z + \sum_{j=1}^{n} Q_{in,j} \cdot c_j - \sum_{l=1}^{m} Q_{out,l} \cdot c_l \quad . \tag{3.13}$$

In Luckner et al. 1985 numerical results are presented.

3.3.3.5 Water quality in the remaining pit

In remaining pits the *oxidation* of Fe^{2+} by air-originated oxygen takes place as well as an additional *hydrolysis* of the produced Fe^{3+}. The reactions depend on the pH-value. For pH-value less than 6.0 no important oxidation rate exists. By adding *lime hydrate* to the water body of a remaining pit, protons which are in the water and are formed by Fe^{2+} oxidation will be neutralized. If the pH-value is less than 4.0 a large amount of lime hydrate is required to neutralize the water (see Figure 3.3.7). Under these conditions this method is uneconomical. Another possibility for neutralization is the flooding of the remaining pit with surface water, which has a higher pH-value. All transportation processes are neglected in the submodel "Remaining Pit". Only the following processes are taken into account:

- storage processes,
- reaction processes with
  - reaction kinetics of first order for Fe^{2+} oxidation
  - reaction kinetics of zero order for the neutralization process,
- external inputs and outputs (external exchange).

Based on this we obtain:

$$Fe^{2+}\colon\ 0 = \frac{d(V\cdot[Fe^{2+}])}{dt} + \frac{k^{*}}{[H^{+}]^{2}}\cdot V\cdot[Fe^{2+}] + \sum Q_A\cdot[Fe^{2+}] - \\ - \sum Q_Z\cdot[Fe^{2+}]_Z$$

$$H^{+}\colon\ 0 = \frac{d(V\cdot[H^{+}])}{dt} + K_{Fe}\cdot V\,\frac{d[Fe^{2+}]}{dt} - K_H\cdot[Ca(OH)_2]\cdot V + \\ + \sum Q_A\cdot[H^{+}] - \sum Q_Z\cdot[H^{+}]_Z \quad .$$

With $d(V\cdot[i])/dt = V\cdot d[i]/dt + \Delta V/\Delta t$ the following differential/ difference equations can be formulated:

$$Fe^{2+}\colon\ \frac{d[Fe^{2+}]}{dt} = -\frac{k^{*}}{[H^{+}]^{2}}[Fe^{2+}] - [Fe^{2+}]\cdot\left[\frac{\Delta V}{\Delta t\cdot V} + \frac{\sum Q_A}{V}\right] + \\ + \frac{\sum Q_Z[Fe^{2+}]_Z}{V} \tag{3.14a}$$

$$H^{+}\colon\ \frac{d[H^{+}]}{dt} = -K_{Fe}\,\frac{d[Fe^{2+}]}{dt} - [H^{+}]\cdot\left[\frac{\Delta V}{\Delta t\cdot V} + \frac{\sum Q_A}{V}\right] + \\ + \frac{\sum Q_Z[H^{+}]_Z}{V} - K_H\cdot[Ca(OH)_2] \quad . \tag{3.14b}$$

For numerical results see Luckner et al. 1985.

3.3.3.6 Computer model of surface water quality

The submodels described above can be given in a general form with

$x = [Fe^{2+}]\ ,\ y = [H^+]$:

$$\frac{dx}{dt} = -A \cdot \frac{x}{y^2} - G \cdot x + E$$

$$\frac{dy}{dt} = -D \cdot \frac{dx}{dt} - G \cdot y + F \quad .$$

The finite difference analogue of these equations is:

$$\frac{x^t - x^{t-\Delta t}}{\Delta t} = -x^t \cdot \left[\frac{A}{(y^t)^2} + G \right] + E \tag{3.15a}$$

$$\frac{y^t - y^{t-\Delta t}}{\Delta t} = -D \, \frac{x^t - x^{t-\Delta t}}{\Delta t} - G \cdot y^t + F \quad . \tag{3.15b}$$

From Eq. (3.15a) we obtain:

$$x^t = \frac{x^{t-\Delta t} + E \cdot \Delta t}{1 + \Delta t \cdot \left[\frac{A}{(y^t)^2} + G \right]} \quad . \tag{3.16}$$

A polynomial function of the third order results if we insert Eq. (3.16) into (3.15b). The solution is to be found in the range of $10^7 < y < 10$, this means in the range of $2 < \mathrm{pH} < 10$.

$$0 = (y^t)^3 \cdot (1 + \Delta t \cdot G)^2 +$$

$$+ (y^t)^2 \cdot [D \cdot (x^{t-\Delta t} + \Delta t \cdot E) + (1 + \Delta t \cdot G) \cdot (-y^{t-\Delta t} - \Delta t \cdot F - D \cdot x^{t-\Delta t})] +$$

$$+ y^t \cdot (1 + \Delta t \cdot G) \cdot A \cdot \Delta t + A \cdot \Delta t \cdot (-y^{t-\Delta t} - \Delta t \cdot F - D \cdot x^{t-\Delta t}) \quad .$$

The computer programme FEMO was developed for the generalized mathematical model for the three subsystems described above. The equation is solved with **Newton** approximation method for a given range. If no solution with the assumed time step is possible then it is to be corrected. The time step will also be corrected when the change of pH-value is greater than a given value. The programme stops if

- the changes in pH-values are less than 0.01 pH-units,

- the Fe^{2+} concentrations are less than 0.1 g/m^3,

- the end of residence time is reached, and

- in the submodel "Mine Water Treatment Plant" the pH-limits are exceeded.

An expansion of the model including pH-buffer reactions and catalytic reactions is possible. The computer programme is given in Lucker et al. 1985.

3.4 Screening of Long-Term Policies – the Planning Model

3.4.1 Structure of the planning model

The planning model covers a *planning horizon* of 50 years divided into maximum 10 planning periods, see Figure 3.4.1. The figure illustrates that the highest accuracy is achieved for the first planning periods. The later planning periods give rough estimates of future systems development. Their consideration ensures a rational systems development in the long-term run.

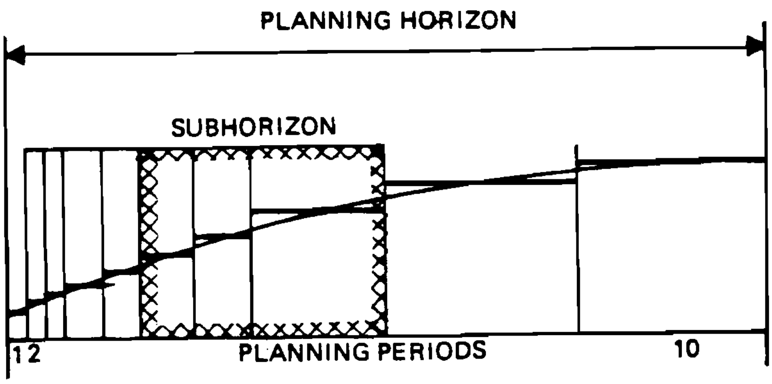


Figure 3.4.1: Time discretization for the planning model

The planning model of the DSS MINE 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.

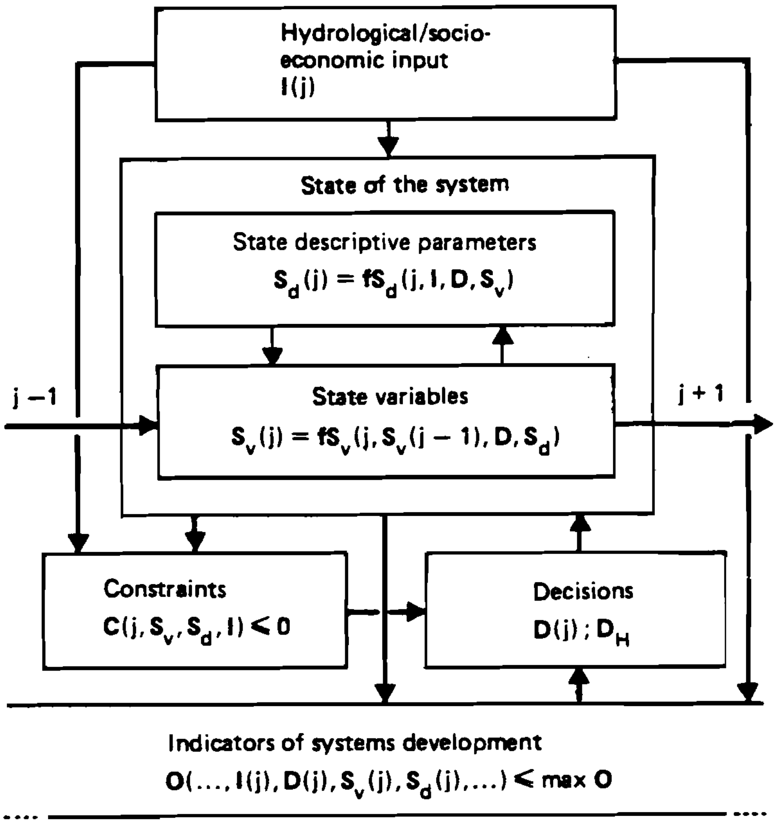


Figure 3.4.2: Block schema of the planning model

A block scheme of the planning model is presented in Figure 3.4.2. The system 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 also results of that analysis being of interest for the model user. The state variables are treated as variables in the multi-criteria analysis.

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

$$O_l \longrightarrow Minimum \;!\; l \in L_0 \tag{3.17a}$$

subject to inequality constraints

$$\mathbf{O} \leq \mathbf{O}^{max} \tag{3.17b}$$

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

equality constraints

$$\mathbf{C}_{eq}(j) = 0 \;,\; j = 1,\ldots,J \tag{3.17c}$$

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

bounds

$$\mathbf{D}(j)^{\min} \leq \mathbf{D}(j) \leq \mathbf{D}(j)^{\max} \;,\; j = 1\,, \ldots\,, J \tag{3.17d}$$

$$\mathbf{D}_H^{\min} \leq \mathbf{D}_H \leq \mathbf{D}_H^{\max}$$

This model describes a non-linear dynamic multi-criteria problem. For mining areas it can be assumed that the system dynamic is primarily determined by the exogenously fixed rates of mine drainage. Inter-period relationships are relatively weak, i.e. the internal system dynamic characterized by the state variables is not significant with respect to the total indicators of systems development. Consequently the problem Eqs. (3.17a–d) may be divided into subproblems for a few *subhorizons* m, $m = 1\,, \ldots\,, M$, see Figure 3.4.1.

$$\mathbf{o}^{*}(m) \Rightarrow Minimum!\; m = 1\,, \ldots\,, M \tag{3.18}$$

subject to Eq. (3.17b)–(3.17d) for subhorizon m. This approach reduces the computational effort due to the smaller dimension of the non-linear programming problem.

In Figure 3.4.3 the structure of the Jacobian matrix of the gradients is depicted for a subhorizon with two planning periods. The numbers give the actual size of the problem for the GDR test area. The Figure illustrates the sparse character of the matrix. With the increasing number of planning periods per subhorizon the matrix is getting more sparse. The algorithm for non-linear programming has to consider this property in order to reduce storage consumption and computational effort.

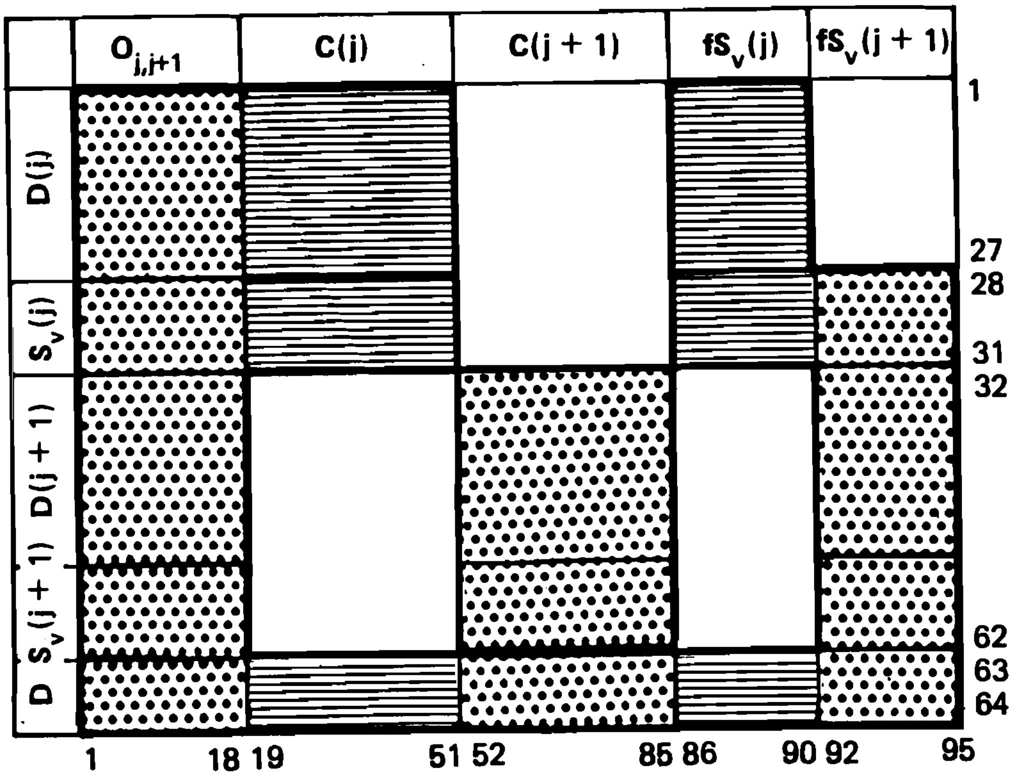


Figure 3.4.3: Structure of the Jacobian matrix

3.4.2 Description of submodels

It is not possible to give in this report a detailed description of all used submodels. In the following typical examples of submodels characterizing the model system will be described, for details see Kaden et al. 1985a.

3.4.2.1 Indicators of systems development

Water demand—water supply deviation

From the point of view of water management the satisfaction of the water demand of different users in the region (municipality, industry, agriculture, environmental protection and downstream users) is the most important indicator. For the municipal and industrial water demand we use deterministic trend models for the planning model (compare Section 3.5.1.2). On the contrary to that the agricultural water demand and the water demand for environmental protection (artificial groundwater recharge) depend on the actual state of the system. This will be explained for the agricultural water demand.

In the test area we take into account agricultural water demand for irrigation only. This demand depends primarily on the groundwater tables in the agricultural area and on the actual precipitation. If the groundwater table is above one meter below the surface, the water demand by plants is assumed to be satisfied by precipitation and capillary rise. If the groundwater table is lower than 2 m below the surface, capillary rise is neglected. We use a simplified linear function. For an arable land of 10 km^2 with a maximum supplementary irrigation rate of 200 mm/year and the surface level 141.5 m we obtain:

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

Based on the demand function we use the following indicator for the mean *deviation between agricultural water demand and supply* in planning periods.

$$dev_{ag}(j) = | dem_{ag}(j) - (\mathbf{q}_{s,ag}(j) + \mathbf{q}_{c,ag}(j) + \mathbf{q}_{d,ag}(j)) | \quad (3.19)$$

Total criteria for the planning horizon:

$$sdev_{ag} = \sqrt{\sum_{j=1}^{J} (dev_{ag}(j) \cdot \gamma(j))^2} \quad (3.20)$$

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

$$\gamma(j) = (i_E(j) - i_B(j) + 1) / i_E(J)$$

The submodels for the other water users are similar.

Environmental quality

The state of the environment in the mining region is above all characterized by the water quality in the stream (outflow from the region), in the remaining pit, and in the environmental protection area. The decisive water quality parameters are the Fe^{2+} and H^+ concentrations. Assuming given desired values for these parameters we define the environmental criteria in terms of the deviation from these optimal values in the mean for planning periods.

$$env_a(j) = \frac{1}{2} \sum_{l=1}^{2} \frac{c_a(l,j) - optc_a(l)}{optc_a(l)} \tag{3.21}$$

with $c_a(l,j)$ - concentration of ion l for *period* j

$optc_a(l)$ - desired concentration of ion l.

Economic Indicators

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

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

- the maintenance and operational cost of technical installations M;

- benefits B from water allocation for water users fixed by governmental laws (see below).

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

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

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

$$E = \sum_i \, [I(i) + (M(i) + B(i)) \cdot \delta_d^i] \cdot \delta_\alpha^{-i} \quad . \tag{3.22}$$

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

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

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

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

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

with D - diamenter of the pipe in [mm]

L - length of the pipe in [m] between "x" and "y".

For the *amortization of mine water treatment plants* we have:

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

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

Maintenance costs are defined as follows:

Water treatment plants (municipal and industrial water supply)

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

with $\beta_{t,x}$ - specific maintenance costs depending on water quantity [Mark/m^3].

γ_x - specific maintenance costs depending on load of pollutant [Mark/g]

c_x - concentration of Fe^{2+} [g/m^3]

q_x - flow through treatment plant [m^3/sec]

Mine water treatment plants

$$M_{mt} = (\beta_{t,x} + \gamma_t \cdot cq_x) \cdot q_x \cdot 31.5 \quad [\text{Mill./Mark/year}]$$

with $\beta_{t,x}$ - see above

γ_t - specific expenses for lime hydrate [mark/g]

cq_x - supply with lime hydrate [g/m^3]

q_x - see above

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

Mine water pumpage

$$M_p = \beta_{w,x} \cdot q_x \cdot 31.5 \qquad [\text{Mill.Mark/year}]$$

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

q_x - flow [m^3/sec.]

Specific benefits and expenses for water allocation, discharge are considered in the models. For instance, in the GDR at present the following economic indicators are fixed:

β_i - specific benefit for water allocation from mines for industrial water supply = 0.16 Mark/m^3

β_m - specific benefit for water allocation from mines for municipal water supply
= 0.16 Mark/m^3 (not drinking water quality)
= 0.70 Mak/m^3 (drinking water quality)

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

$$B_s = \gamma_s(c_x)\cdot c_x \cdot q_x \cdot 31.5 \quad [Mill.Mark / year]$$

with γ_s - $0.00005 \cdot c_x - 0.001$ Mark/g]
c_x - concentration of Fe^{2+} [g/m^3]
q_x - flow [m^3/sec.]

Based on the above assumptions, the detailed economic indicator functions may be defined. For example, the indicator for mine drainage mine A is given.

$$\begin{aligned} cost_a(j) = {} & \delta_1(j)\cdot(a_{t,a} + a_{a,ex} + \\ & + [\beta_{w,a} \cdot qg_a(j) + (\beta_{a,ex} - \beta_i)\mathbf{q}_{a,ex}(j) + \qquad (3.23) \\ & + (\beta_{t,a} + f\,\gamma_s(c_a(1,j))\cdot c_a(1,j) + \gamma_t\,\mathbf{cq_a}(j))\cdot \mathbf{q}_{a,s}(j)]\cdot\delta_2(j)\cdot 31.5)\cdot\Delta T_j \end{aligned}$$

Based on such models one obtains for the planning horizon:

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

$$scost = \sum_{j=1}^{J} cost(j)\ ,\ x = (a\,|\,b\,|\,c\,|\,d) \qquad (3.24)$$

Total costs for mine drainage:

$$scost_{mine} = scost_a + scost_b + scost_c + scost_d \tag{3.25}$$

The submodels for the economic indicators of water supply and environmental protection are defined in a similar manner.

3.4.2.2 State descriptive parameters

According to our previous definitions state descriptive parameters are auxiliary parameters characterizing systems behaviour in the planning period, not explicitly depending on previous ones. For the development of simplified submodels for these parameters the methods described in Part II have been applied.

Water quantity

The submodels for water quantity state parameters are developed in form of time series based on experiments with the comprehensive groundwater flow model, see Section 2.3.2. An example of the development of the submodel for groundwater flow to mine D is given in Figure 3.4.4.

In a similar form the submodels for groundwater tables and for the infiltration (exfiltration) from stream segments have been developed, e.g.:

Infiltration (exfiltration) for a stream segment

$$qi_{6,2}(j) = b_1(j) + b_2(j) \cdot \Delta \mathbf{tm}_d + b_3(j) \cdot \Delta \mathbf{tm}_d^2 \tag{3.26}$$

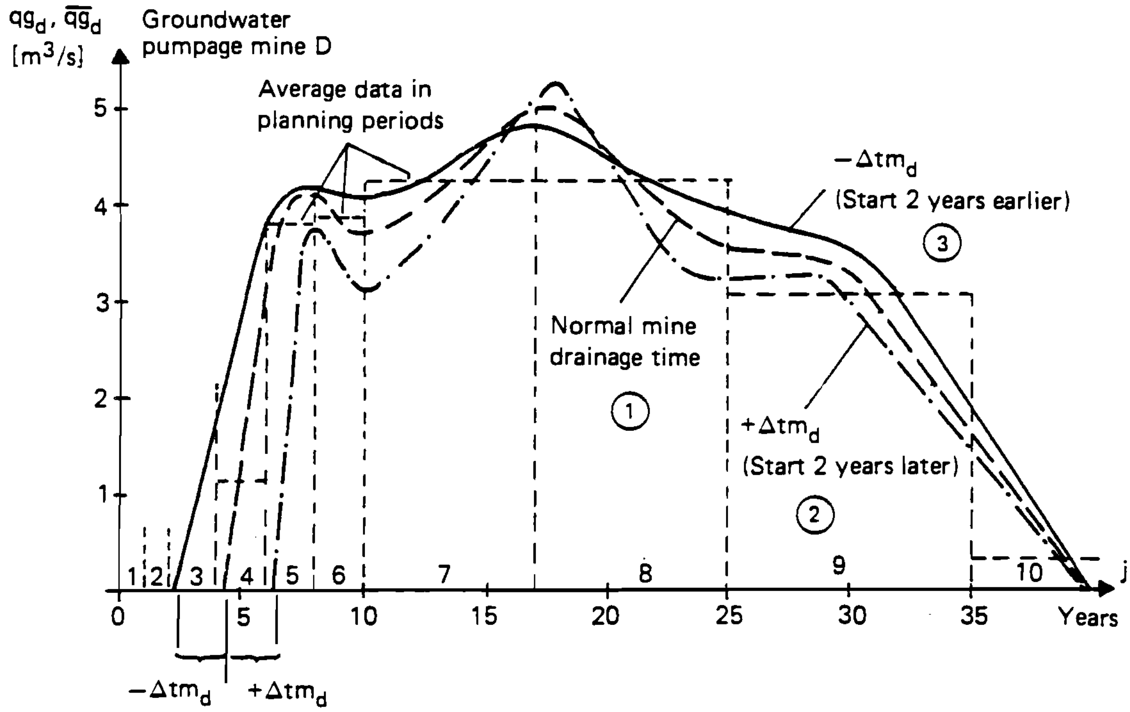
Groundwater table in the agricultural area

$$h_{ag}(j) = a_1(j) + a_2(j) \cdot \Delta \mathbf{tm}_d + a_3(j) \cdot \Delta \mathbf{tm}_d^2 \tag{3.27}$$

For ***surface water inflow*** at present long-term mean values are considered, estimated by a stochastic runoff model, see Section 3.5.1.2.

According to Figure 3.2.2, the stream and its tributaries are divided into segments bounded by balance profiles. The flow through balance profiles is estimated with a simple balance equation, for instance

REDUCED GROUNDWATER FLOW MODELS



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

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

Δtm_d: Decision value with -2 years $\leqslant \Delta tm_d \leqslant +2$ years, characterizing the predrainage time mine D.

Figure 3.4.4: Submodel groundwater flow to mine D

Surface water flow balance profile bp2

$$qs_6 = qs_1 + qs_5 + qi_{1,2} + qi_{6,2} + \mathbf{q}_{s,t} - \mathbf{q}_{c,s} - \mathbf{q}_{t,s} + 4.9 \qquad (3.28)$$

Water quality

Groundwater quality

The representative water quality parameters are the iron concentration Fe^{2+} and the hydrogen concentration H^+. For the forecast of these values no comprehensive groundwater quality model was available. Based on samples a linear trend of the groundwater quality has been estimated (see Figure 3.1.3).

Surface water quality

The basic model for surface water quality is described in Section 3.3.4 in the form of a system of partial differential equations solved by an iterative procedure. It was simplified in order to be able to apply it to the planning model.

Self-purification capacity is important for the water quality in the stream. We consider a stream section α,β of the length $\Delta s_{\alpha,\beta}$ as a "black-box". The Fe^{2+}-concentration is described by the differential equation (Section 3.3.4.3, Eq. (3.12a))

$$-v \frac{d[Fe^{2+}]}{dx} = \frac{k^{*}}{[H^+]^2} [Fe^{2+}] \qquad (3.29)$$

If we assume a constant $[H^+]$-concentration for a balance section $\Delta s_{\alpha,\beta}$ (equal to the $[H^+]$-concentration of inflow), Eq. (3.29) can be solved analytically by obtaning for the $[Fe^{2+}]$-concentration at the outflow balance profile β:

$$[Fe^{2+}]_\beta = [Fe^{2+}]_\alpha \exp\left(-\frac{k^{*} \cdot \Delta s_{\alpha,\beta}}{v_{\alpha,\beta} \cdot [H^+]^2}\right) \qquad (3.30)$$

For the velocity an average constant value is assumed. In the next step the $[H^+]$-concentration at the outflow balance profile β is estimated:

$$[H^+]_\beta = [H^+]_\alpha + 3.58 \cdot 10^{-5}([Fe^{2+}]_\alpha - [Fe^{2+}]_\beta) \tag{3.31}$$

With the self-purification model Eq. (3.30–4.31) we can describe the principle quality balance equations for the stream segments. Using the notations of the DSS $cs(1) = [Fe^{2+}]$, $cs(2) = [H^+]$ we obtain, for instance:

Water quality balance profile bp3

$$cs_3(l) = (cs_3^2(l) \cdot qs_2 + cs_3^7(l) \cdot qs_7 + c_a(l) \cdot q_{a,s} + c_b(l) \cdot q_{b,s} \tag{3.32}$$

$$+ c_p(l) \cdot q_{p,s} - cs_2(l) \cdot q_{s,p}) / qs_3$$

Mine water treament

For the purification capacity of the mine water treatment plants as a simplified approach the following model has been developed, considering the addition of lime hydrate $[Ca(OH)_2]$:

$$C = [Fe^{2+}]_{in} - 0.698 \cdot [Ca(OH)_2]$$

$$[Fe^{2+}]_{out} = \begin{cases} 0 & \text{for } C \le 0 \\ C & \text{for } C > 0 \end{cases}$$

$$[H^+]_{out} = \begin{cases} [H^+]_{in} & \text{for } C > 0 \\ [H^+]_{in} - 0.025 \cdot [Ca(OH)_2] & \\ \quad + 0.0358 \cdot ([Fe^{2+}]_{in} - [Fe^{2+}]_{out}) & \text{for } C \le 0 \end{cases} \tag{3.33}$$

$$10^{-8.5} \le [H^+]_{out} \le 10^{-6.5}$$

In the planning model the unsteadiness of the model (3.33) causes numerical problems. Therefore, we use the following smooth model (in terms of the common model parameter)

$$c_a^0 = cg_a(1,j) - 0.698 \cdot cq_a(j)$$

$$\gamma = \frac{1}{\pi} \cdot arctan(1000 \cdot c_a^0) \tag{3.34}$$

$$c_a(1,j) = c_a^0 \cdot (\gamma + 1/2)$$

$$c_a(2,j) = cg_a(2,j) +$$

$$+ (0.025 \cdot \mathbf{cq}_a(j) - 0.0358 \cdot (cg_a(1,j) - c_a(1,j)) \cdot (1/2 - \gamma)$$

$$\text{for } \alpha = a \mid b \mid c \mid d$$

3.4.2.3 State variables

All submodels described above are based on our time series approach. For each planning period an appropriate submodel is estimated describing the dependency of decision variables on state descriptive parameters. The process memory is only considered implicitly in the coefficients of these models.

This simplification is not reasonable for the dynamic process of the filling and the management of the remaining pit. Due to the strong influence of decisions on the state of the remaining pit and the significant interactions between the remaining pit and the surrounding aquifer the process memory has to be considered explicitly, i.e. the actual state of the remaining pit depends on previous systems states, which is why the water table and the water quality of the remaining pit are treated as dynamic state variables.

Water table in the remaining pit

In Section 3.3.2.1 a conceptual model of the remaining pit has been given as a basic model. This model is still far too complicated for its use in the planning model. As an alternative a simpler ***grey-box model*** was developed, Kaden et al. 1985b.

The model structure is derived by the help of a block concept subdividing the area under consideration into three blocks:

- the remaining pit,
- the aquifer around the remaining pit (GWL1) which is directly influenced by the remaining pit,

- the neighboured part of the aquifer (GWL2) which is undisturbed by the other blocks (see Figure 3.4.5).

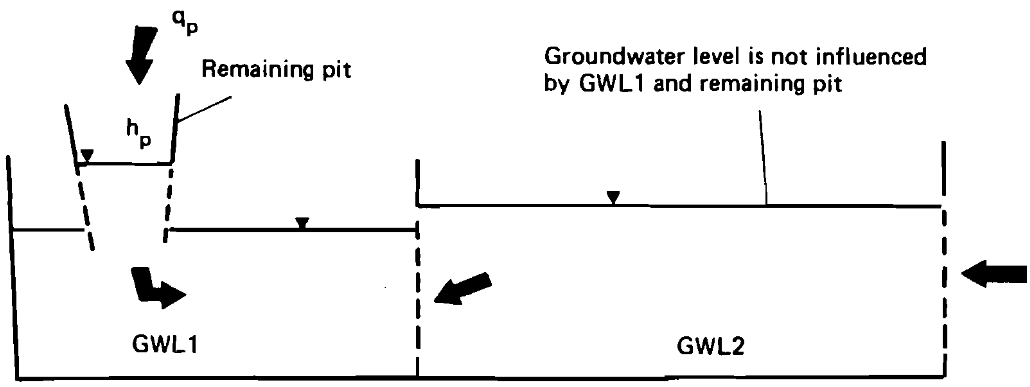


Figure 3.4.5: Block structure of the grey-box model

The water table in the remaining pit and the groundwater table are the state variables, assumed to be constant within their blocks. The blocks are connected by the continuity equation and a kinetic equation. In order to get a simple model structure two assumptions have been formulated which enable an approximate linearization of the problem:

(1) The horizontal area of the remaining pit at any water level is proportional to the corresponding area of exchange between the remaining pit and the GWL1. Such an assumption permits the linearization of the dynamic behaviour if the reaction of the storage GWL1 on the remaining pit is negligible.

(2) The influence of the remaining pit management on the dynamic systems behaviour is small and is assumed to be approximately linear. For example, this holds true if the variation of the exchange area of the remaining pit is small in relation to its water table.

Especially within the usable storage layer both assumptions are justified. Possible influences of external boundary conditions on the dynamic systems behaviour are separated by subtraction of two different management variants with the same external boundary conditions.

Based on the assumptions above we obtain for the dynamic behaviour of the water table for two interacting storages (Kindler 1972):

$$D_1 \cdot D_2 \cdot \frac{d^2\tilde{h}_p}{dt^2} + (D_1+D_2) \cdot \frac{d\tilde{h}_p}{dt} + \tilde{h}_p = K \cdot q_p \tag{3.35}$$

with

D_1, D_2	-	time constants
K	-	proportionality constant
q_p	-	constant inflow into (>0) or discharge from (<0) the remaining pit
$\tilde{h}_p$	-	difference between the actual water table and that for natural recharge.

The homogeneous solution of the differential equation (3.35) can be given as a homogeneous recurrence equation of second-order:

$$\tilde{h}_p(t_j) = (P_1+P_2) \cdot \tilde{h}_p(t_{j-1}) - P_1 \cdot P_2 \cdot \tilde{h}_p(t_{j-2})$$

$$\text{with:} \quad P_1 = e^{(-\frac{\Delta t}{D_1})}, \quad P_2 = e^{(-\frac{\Delta t}{D_2})}, \quad \Delta t = t_j - t_{j-1}$$

After integration of the differential equation (3.35) with the initial conditions

$$\tilde{h}_p(0) = 0, \quad \frac{d\tilde{h}_p(0)}{dt} = \frac{\Delta t}{D_1 \cdot D_2} \cdot K \cdot q_p$$

we get the transition function $S(\Delta t)$ in the following form:

$$S(\Delta t) = 1 - c_1 \cdot P_1 - c_2 \cdot P_2, \text{ with } c_1 = \frac{\Delta t - D_1}{D_2 - D_1}, \quad c_2 = 1 - c_1 \quad .$$

Through superposition of the discrete time-dependent inflow into or discharge from the remaining pit we obtain based on the homogeneous solution:

$$h_p(i) = h_p^0(i) + (P_1+P_2) \cdot \tilde{h}_p(i-1) - P_1 \cdot P_2 \cdot \tilde{h}_p(i-2) + \tag{3.36}$$

$$+ (1-c_1 \cdot P_1 - c_2 \cdot P_2) \cdot K \cdot q_p(i) + (P_1 \cdot P_2 - c_2 \cdot P_1 - c_1 \cdot P_2) \cdot K \cdot q_p(i-1)$$

with i - time step in years

$h_p^0(i)$ - water table in the remaining pit for natural recharge at the end of the year i

$h_p(i)$ - water table in the remaining pit at the end of the year i

$q_p(i)$ - inflow into or discharge from the remaining pit within the year i in $\frac{Mill.m^3}{year}$.

This inhomogeneous recurrence equation of second-order has three parameters – the two time constants D_1, D_2 and the proportionality constant K. These parameters are quantified by adaptation of Eq. (3.36) to discrete annual values of the water level in the remaining pit (calculated by means of the comprehensive groundwater flow model and of the conceptual model for different management variants).

Based on that, the ***grey-box model*** for yearly time steps gets the following form:

$$h_p(i) = h_p^0(i) + a_1 \cdot \tilde{h}_p(i-1) + a_2 \cdot \tilde{h}_p(i-2) + \qquad (3.37)$$

$$+ b_0 \cdot q_p(i) + b_1 \cdot q_p(i-1)$$

with $\tilde{h}_p(i) = h_p(i) - h_p^0(i)$.

Through modification of the time interval in the annual model (modification of parameters P_1 and P_2) we get the monthly model, see Section 3.5.1.4.

In Figure 3.4.6 the water table in the remaining pit is depicted for different management variants comparing the results of the grey-box model, the conceptual model and the comprehensive groundwater flow model.

It was originlly planned to use the annual model Eq. (3.37) directly in the planning model. In the planning model the water table in the remaining pit is considered only as mean value for the planning period. Applying the recursive model (3.37) we can estimate this value by averaging the yearly results. This model is included as a constraint in the algorithm for multi-criteria analysis. According to the implemented problem solver, see Section 3.4.4, the gradients of constraints with respect to decision variables (inclusive

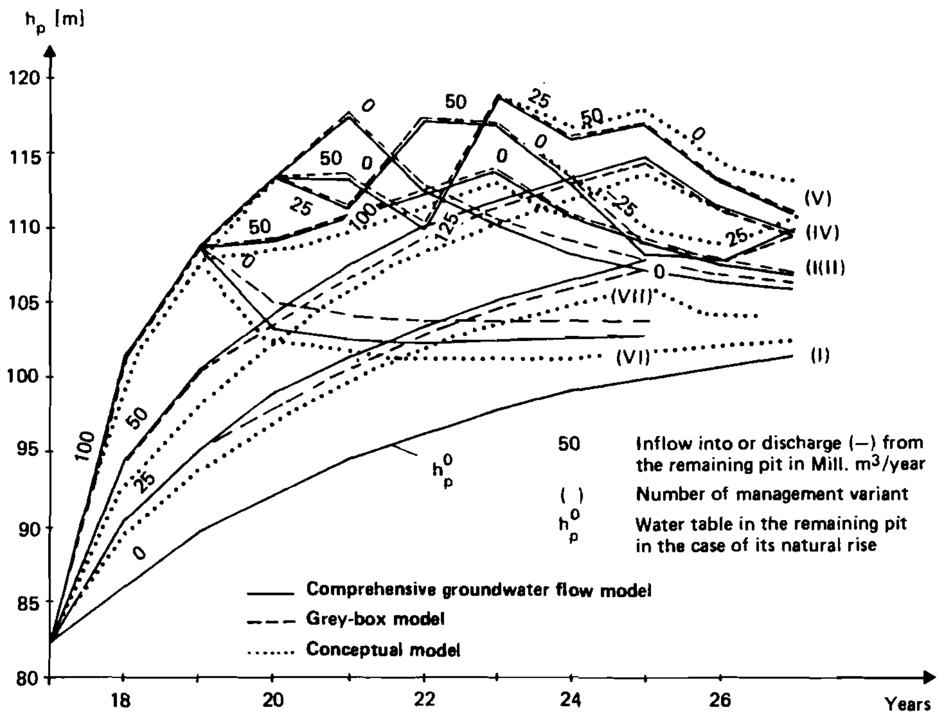


Figure 3.4.6: Water table in the remaining pit for different management variants

state variables) have to be estimated. Due to the recursive model (3.37) the gradients of this constraint become very large in comparison with those of other constraints. This caused numerical problems for the nonlinear problem solver. In order to avoid it, the model (3.37) has been further simplified to the form:

$$h_p(j) = a_0 + a_1 \cdot h_p(j-1) + a_2 \cdot h_p^2(j-1) + a_3 \cdot \Delta q_p(j) + a_4 \cdot \Delta q_p^2(j) \tag{3.38}$$

The model (3.37) was used for synthetic data generation varying the inflow/outflow Δq_p. The model (3.38) has been adapted to those data for each relevant planning period separately by means of least square approximation. Control calculations have shown that the error due to this simplification is 1 m at maximum.

Water quality in the remaining pit

We use the model developed in Section 3.3.4.4 Eq. (3.14), (3.15–3.16). Inserting the coefficients from Eq. (3.14) into Eq. (3.15), (3.16) we easily obtain the equations for the $[Fe^{2+}]$ and $[H^{+}]$ concentration in the remaining pit in an implicit form. These equations are considered as constraints in the planning model, i.e. the concentrations have not to be estimated explicitly in advance.

3.4.2.4 Constraints on systems development

We have to consider a set of constraints characterizing the water balance for mines (equality constraints) and bounding the decisions. In the following a few examples are given.

Water balance equations for mines, e.g. Mine A

$$wb_a(j) = qg_a(j) - \mathbf{q}_{a,s}(j) - \mathbf{q}_{a,ex}(j) = 0 \ , \quad \text{for } j \leq j_a \qquad (3.39)$$

Possible groundwater extraction

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

$$pq_{g,m}(j) = -\frac{uq_g}{uh_w - lh_w} \cdot (h_g(j) - lh_w) + \mathbf{q}_{g,m}(j) \leq 0 \qquad (3.40)$$

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

These constraints are of the form (e.g. municipal water supply)

$$pq_{b,m}(l,j) = -(uc_m(l) - cg_{b1}(l,j)) \cdot \mathbf{q}_{b,m}(j) \leq 0 \qquad (3.41)$$

with $uc_m(l)$ - upper bound for water quality for municipal water supply.

3.4.3 Approach to multi-criteria analysis

Instead of the problem oriented model formulation in Section 3.4.1 for simplicity and convenience in the following a more compact mathematical formulation of the multi-criteria problem Eq. (3.17) is used. We consider a nonlinear optimization problem of the form:

$$f_i(x) \rightarrow min \ , \quad i \in I_0 = \{1 , \dots , n_g\} \tag{3.42a}$$

subject to:

nonlinear inequality constraints

$$f_i(x) \leq b_i \ , \quad i = 1, \dots, n_g \tag{3.42b}$$

nonlinear equality constraints

$$f_i(x) = b_i \ , \quad i = n_g + 1, \dots, n_h \tag{3.42c}$$

and bounds for all variables

$$l_j \leq x_j \leq u_j \ , \quad j = 1, \dots, n \tag{3.42d}$$

The nonlinear functions $f_i(x)$, $i = 1,\dots,n_h$ are assumed to be differentiable and that values of their gradients can be calculated (preferable analytically). These functions, together with the right hand sides b_i , $i = 1,\dots,n_h$, the lower bounds l_j , $j = 1,\dots,n$, and the upper bounds u_j , $j = 1,\dots,n$, constitute the model of systems behavior.

As explained above some of the values $f_i(x)$, $i = 1,\dots,n_g$ calculated in the model are defined as indicators of systems development. Indices from the set I_0 are related to functions $f_i(x)$ selected as objectives of interest for the decision maker applying the DSS MINE. This set can be changed at any time.

Most frequently the set I_0 has more than one element and in such a case problem (3.42) is the problem of *multiobjective optimization*. To find solutions for such a problem, a common approach is to *scalarize* it, i.e. reduce it to single criteria equivalent using a *scalarizing function*.

For the DSS MINE the Reference Point Approach (Wierzbicki, 1983) is applied. In this method the reduction of the multiobjective optimization problem to a single objective one must be interactively defined by the decision maker (the model user). The preferences among several criteria are unknown a priori and are determined during the interactive procedure. For this purpose, the decision maker defines a reference value r_i for each selected objective function $f_i(x)$. These values should reflect in some sense desired values of the objectives.

The scalarizing function used in our system has the form:

$$s(w) = \left[\frac{1}{n_0} \sum_{i \in I_0} \left[s_i w_i \right]^{\rho}\right]^{1/\rho} \tag{3.44}$$

with n_0 - number of objectives;

s_i - scaling factor for i-th objective;

$w_i = \dfrac{f_i(x) - \overline{f_i}}{r_i - \overline{f_i}}$ - measure between $f_i(x)$ and r_i ;

$\overline{f_i}$ - lower bound for $f_i(x)$ and r_i ;

ρ - positive (even) integer, in our system $\rho = 4$ or 6 is used.

For the lower bound $\overline{f_i}$ the ***utopia (ideal) value*** may be used minimizing objective i separately. Some more details are given in Kaden and Kreglewski 1986.

3.4.4 Non-linear problem solver MSPN

Within the framework of the collaboration between the Regional Water Policies Project of IIASA and the Institute of Automated Control at the Technical University of Warsaw, a nonlinear problem solver MSPN has been developed for the solution of the problem Eq. (3.42). It is especially designed to the specifics of the planning model of the DSS MINE. Due to this specific a high computational efficiency could be achieved. In the following the theoretical background of the solver is outlined, for details see Kaden and Kreglewski 1986.

General description of the algorithm

For a given fixed set of indices I_0 , fixed reference point values r_i and scaling factors s_i , the resulting optimization problem takes the form:

$$\min_{x \in X} \left[s_w(x) = s(w(x)) \right] \tag{3.45}$$

The feasible set X is determined as a intersection of two other sets:

$$X = X_N \cap X_L$$

X_N is the set described by nonlinear inequalities (3.42b) and equalities (3.42c).

$$X_N = \left\{ x \in R^n : f_i(x) \leq b_i \, , i = 1, \ldots, n_g \, , f_i(x) = b_i \, , i = n_g + 1, \ldots, n_h \right\}$$

X_L is the set described by lower and upper bounds (linear inequalities) (3.42d).

$$X_L = \left\{ x \in R^n : l_j \leq x_j \leq u_j \, , j = 1, \ldots, n \right\}$$

Thus, the problem (3.45) is a standard nonlinear constrained optimization problem. In this package a ***double iterative penalty algorithm*** is used for the problem solver.

The lower level algorithm solves the problem:

$$\min_{x \in X_L} \left[F(x) = s_w(x) + p(x, v, k) \right] \tag{3.46}$$

The objective function used here, called penalty function, consists of the sum of the original objective function and a penalty term $p(x,v,k)$ (the precise form of this term is given later, see (3.47)). Linear constraints are satisfied at each step of the algorithm because a special method of reduced gradient is used for this purpose. Nonlinear constraints, however, are violated and the penalty term in (3.46) is related to this violation.

The upper level algorithm adjusts parameters v and k in the penalty function to satisfy nonlinear constraints. At each step of this algorithm, the lower level problem (3.46) is solved. However, the accuracy of its solution depends on the violation of nonlinear constraints. Nonlinear constraints are strongly violated in very first iterations of the upper level algorithm and, therefore, the lower level problem can be solved very roughly.

Reduced gradient algorithm

The algorithm described here and applied in the software package uses gradient reduction, that is, an elimination of some gradient components. If, at some point, the value of a particular variable x_i is between its bounds l_i and u_i, then this variable can be either increased or decreased. However, if this value is equal to one of the bounds, say, to the upper bound u_i, then this variable can be only decreased. In such a case, negative values of the objective gradient component can not be accepted and are set to zero; this variable will remain unchanged in the next direction of search. This modified gradient is called reduced because some of its components are set to zero and it acts only in some subspace of the space of all variables.

The algorithm begins by calculating the gradient of the penalty function (3.46) at some starting point x^0. This gradient is then reduced in such a way that a nonzero step in the direction of search can be performed inside the set X_L. The step-size in this direction is calculated using quadratic approximations in the line search method. In the resulting point, the gradient is calculated and reduced again. First direction is just opposite to the reduced gradient (minus gradient), the next directions are conjugate directions constructed on reduced gradients. After some number of iterations the algorithm resets itself and uses minus gradient direction again.

Penalty shift algorithm

The penalty term in (3.46) has the following form:

$$p(x,v,k) = \sum_{i=1}^{n_g} k_i \left[f_i(x) - b_i + v_i\right] * \max\left[0, \left[f_i(x) - b_i + v_i\right]\right] \tag{3.47}$$

$$+ \sum_{i=n_g+1}^{n_h} k_i \left[f_i(x) - b_i + v_i\right]^2$$

with k_i - positive penalty coefficients,

v_i - penalty shifts,

v_i non-negative for $i = 1, \ldots, n_g$,

v_i unconstrained for $i = n_g + 1, \ldots, n_h$.

Standard penalty algorithms use any method of unconstrained optimization to solve (3.46). The penalty coefficients are then increased according to the violation of constraints obtained and (3.46) is solved again. This procedure is repeated until the solution of (3.46) is forced by the penalty term to be sufficiently close to the feasible set. Most frequently, the penalty coefficients become very large which makes problem (3.46) ill-conditioned.

In the *shifted penalty function algorithm* there is no need to increase penalty coefficients as strongly as in standard penalty algorithms; penalty shifts are used instead to increase the penalty effect. The penalty function is shifted in the direction opposite to the constraint violation. In the case of inequality constraints, this leads to a shift "inside" the admissible set X_N ; to shift a constraint $f_i(x) \leq b_i$ inside, one must decrease the right hand side b_i or, equivalently, set a positive value of the shift parameter v_i in (3.46). The penalty term becomes then active in a band measured by v_i along the corresponding boundary of the set X_N . In the case of equality constraints, penalty shifts can be either positive or negative; the adequate shift is just in the direction opposite to the current violation of constraints when solving (3.46). In both cases, penalty shifts increase the related penalty term in (3.47). Additional safeguards are employed to avoid stopping the algorithm inside the feasible set with respect to the active constraint.

Verification of gradients

Depending on the number of time periods taken into account in the model, compare Section 3.4.1, the number of functions $f_i(x)$ in the general form (3.42) of the model changes from about thirty to several hundreds. The number of nonzero gradient elements changes from several hundreds to several thousands. The model of the system itself is rather complicated: it is not a single FORTRAN subroutine, but rather large set of interconnected subroutines and data blocks. Thus it is very easy to make a mistake calculating analytical forms of the derivatives of complex expressions in the model.

Unfortunately, optimization algorithms are very sensitive to such mistakes and become inefficient or even fail if the changes of objective values and constraints are inconsistent with their gradients.

Therefore it is necessary to check the consistency of all gradients after each modification of the model. For this purpose, a special numerical algorithm was included in the optimization package. In this algorithm gradients are checked numerically by applying a finite difference method.

Programme structure

The problem solver MSPN for non-linear multi-criteria analysis is embedded in the complex DSS MINE as it is illustrated in Section 3.6.1 Figure 3.6.2. The MSPN package is a set of 21 interlinked FORTRAN subroutines and functions. It contains only the algorithms for multiobjective optimization. All input data and the mathematical model (Eq. (3.42)) are prepared outside ouf MSPN in the DSS MINE. The same holds true for the storage, processing and output of optimization results. A detailed description is given in Kaden, 1986.

Since the Jacobian matrix is sparse (compare Section 3.4.1) its columns (gradients of constraints) are stored in a special way using an indirect indexing method. The gradients of constraints are not stored as n-dimensional vectors (sequences of n elements) but rather as sequences of elements known to be 'active' i.e. such elements which can have nonzero values. The remaining elements ('non active') must be known to be equal to zero during the entire optimization process.

The active elements are assumed to be listed as sequences of elements ordered according to their place in the original n dimensional vector. This method of listing is not obligatory but the package is more efficient if active elements are ordered in such a way.

In Kaden and Kreglewski 1986 the nonlinear problem solver is explained in more details, including a programme description.

3.4.5 Computational tests

3.4.5.1 Robustness of MSPN solver

According to the optimization algorithm described in the previous section, a number of control parameters is required:

In order to analyze the robustness of the MSPN algorithm with respect to the these parameters a series of numerical tests with the DSS MINE have been performed.

The tests have been done for a planning horizon of 7 planning periods. As criteria the following had been selected:

dev-m - Deviation municipal water demand/supply,
dev-i - Deviation industrial water demand/supply,
cost-mi - Total mine drainage cost,
cost-m - Cost for municipal water supply,
cost-i - Cost for industrial water supply.

For each criteria the utopia point was selected as reference point. As the starting point one with significant deviation to the expected solution was used in order to realize a large number of iterations.

In Figure 3.4.7 some results are depicted illustrating the influence of control parameters on the results. Only those criteria are shown which are strongly affected by the parameters. For the criteria ***dev-m, dev-i, cost-m*** the influence is almost negligible. From these tests the following conclusions can be drawn:

Range (rk):

This parameter is a rough estimate of the range of changes of variables during the optimization process, scaling of variables is useful; default: ***rk*** $=1$.

The influence of this parameter on the numerical results is negligible. The variations are less then 1%. But a to small value affects the number of iterations significantly. According to Figure 3.4.7a values between 0.1 and 5 are reasonable.

Violation (eta):

The stop test in the penalty shift algorithm checks whether all constraints are violated less than eta; default: *eta* $= 10^{-3}$

The influence of this parameter is again small, less then 1%. Smaller numbers of *eta* increase the number of iterations. As a compromise *eta*$=10^{-3}$ should be chosen.

Norm (eps):

The stop test in the reduced conjugate gradient algorithm checks whether the norm of gradients of the penalty function is less than the value of *eps*, if *eps* is to small the algorithm is stopped; default: *eps* $= 0.1$.

As expected this parameter stronger effects numerical results and number of iterations. Only values greater/equal 0.05 could be chosen. For the value *eps* $=0.01$ the required accuracy has not been attainable. The results deviate in a range between maximum 5 and 10% - quite acceptable from the practical point of view. Furthermore in each case Pareto-optimality (at least locally) was achieved, compare results for *cost-mi* and *cost-i* in Figure 3.4.7c. As a good compromise between accuracy and number of iterations *eps* $=0.1$ should be chosen.

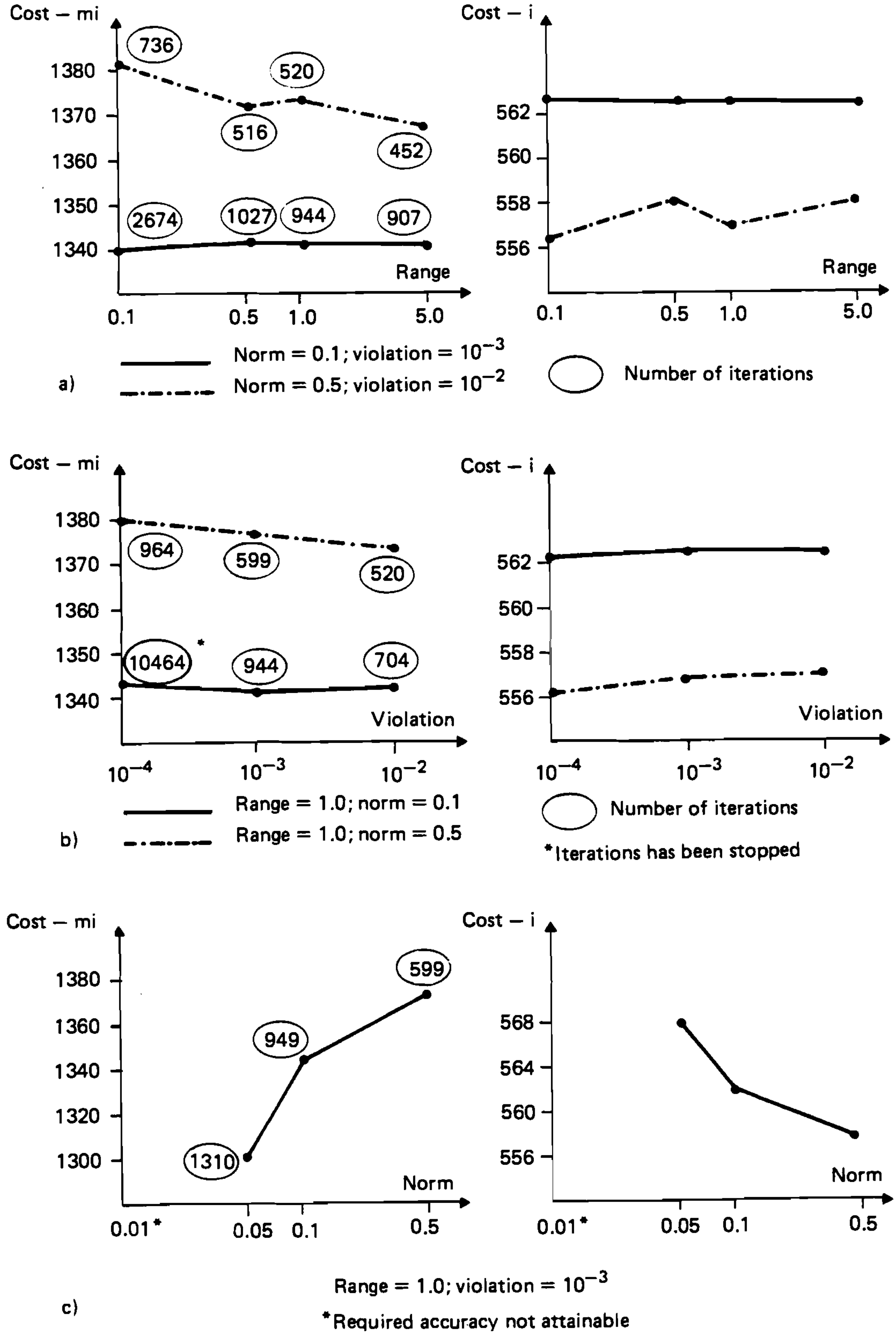


Figure 3.4.7: Influence of optimization control parameters

Penalty (penco):

This parameter is the initial value of penalty coefficients in the penalty shift algorithm. As an estimate the ratio of gradients of the objective function to gradients of constraints should be used; default: *penco* = 1

The initial penalty coefficient has been varied between 0.5 and 10. It does practically not effect the numerical results. The influence on the number of iterations is small for values between 0.5 and 5. Only in the case of *penco* =10. the number of iterations increased. As a good compromise *penco* =1. is proposed.

Above the influence of optimization parameters on the criteria as integral parameters has been analyzed. Another interesting question is their influence on the variables (decisions).

The same parameter combinations as depicted in Figure 3.4.7 have been analyzed with respect to their impact on the variables. Analogously to the criteria the MSPN-algorithm is also very robust with respect to the variables. The influence of varying **range** and **violation** is almost negligible. The deviations are less then 5%, in most cases even less then 1% (related to the value of the variable). Only in one case the deviations are stronger. This is depicted in Figure 3.4.8 for the variables $\mathbf{q}_{b,s}$ and $\mathbf{q}_{b,ex}$ as decisions on water allocation (water quantity).

The solution for period 1 divers significantly in the case of **range** *rk* =0.1 from the other solutions. For that two reasons are seen:

- the optimization is performed with respect to criteria as integral values over the whole planning horizon. Due to the increasing time steps of planning periods later planning periods represents a larger part of the criteria, get a higher weight.
- the parameter combination of a small **norm** *eps* =0.1 with a rough **violation** *eta* = 0.01 is not very reasonable.

Nevertheless the water balance is satisfied. The increased $\mathbf{q}_{b,s}$-value is compensated by a reduced $\mathbf{q}_{b,ex}$.

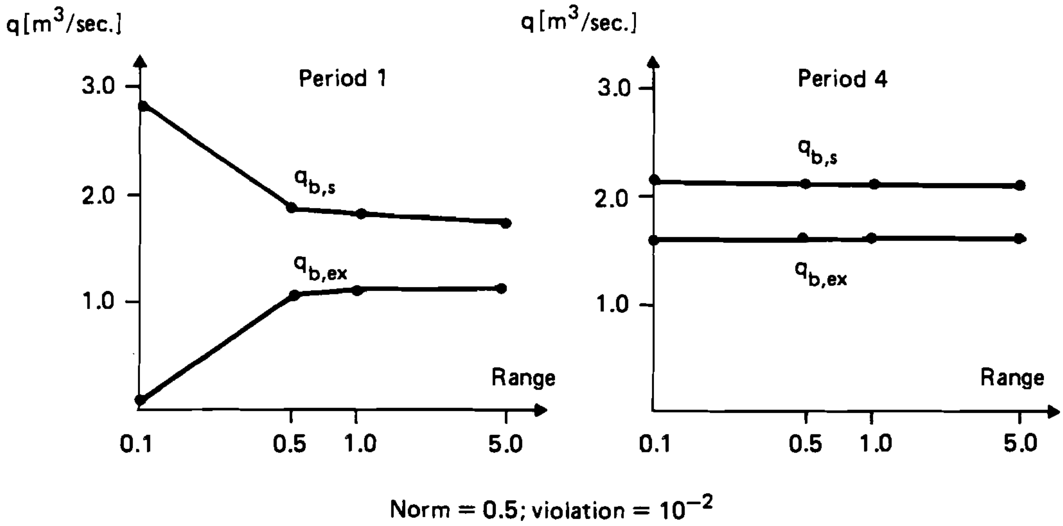


Figure 3.4.8: Influence of optimization parameters on variables

The effect of the **norm** is more significant as it should be expected from the results for criteria, see Figure 3.4.7c. In Figure 3.4.9 the results for four variables are depicted. These are the variables with the strongest deviations. For all other variables the deviations are less then 5%. The deviations are hardly to be explained. Probably they are above all caused by flat objective functions with respect to the given variables. Small numerical deviations due to different accuracy could lead to different solutions.

3.4.5.2 Influence of starting point values

The optimization problem to be solved is non-linear in most of its parts. For such a complicated mathematical model as it is given for the DSS MINE it is practically impossible to analyze analytically the properties of the objective function with respect to convexity and extremal values. The existence of local optima has to be expected. Or, with other words, the estimated solution is not necessarily a global optimal solution.

Two principle possibilities are available to check the solution behavior with respect to local/global optima:

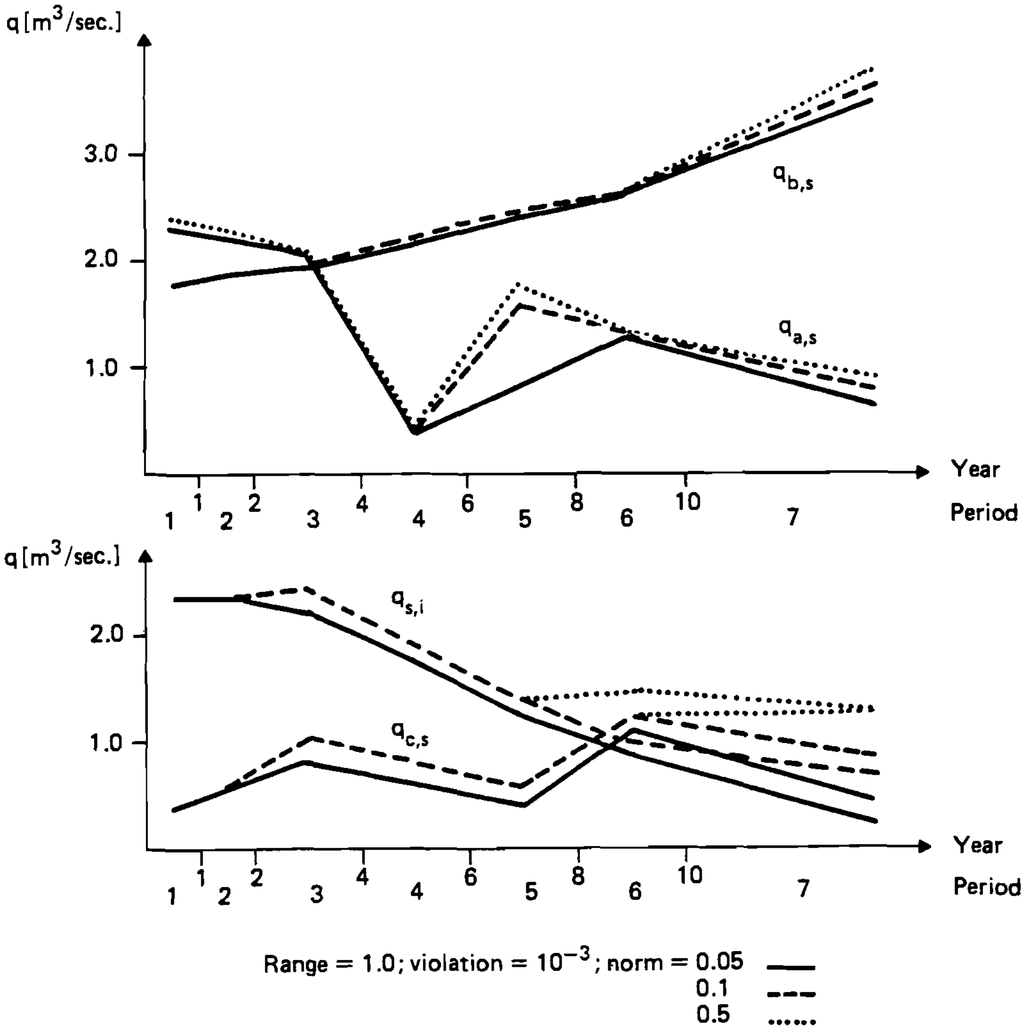


Figure 3.4.9: Influence of the **norm** on variables

- Application of an optimization procedure resulting per definition in a solution being a global optimum. Such property posses some random search methods, e.g. ASTOP, Born 1985. The numerical effort of such methods is extremely high, their applicability for the given problem is still under study.
- Experimental analysis varying the starting points for optimization.

In the following a few results for an experimental analysis are given.

The most logical way to analyze the influence of starting point values is the random selection of the starting points between upper and lower bound. This has been done using a random generator for uniform distributed random numbers. For the tests the same criteria as described in Section 3.4.5.1 have been considered. Results for selected criteria are listed in Table 3.4.1.

Table 3.4.1: Solutions for randomly selected starting point values

criteria	ref.- point	utopia- point	nadir- point	solutions										
dev −m [*l / sec.*]	0	0	31	7	8	8	8	8	8	8	8	8	8	8
dev −i [*l / sec.*]	0	0	106	3	2	4	4	1	2	1	1	1	1	1
cost −mi [*Mill.M*]	1151	1151	1476	1261	1261	1466	1315	1415	1411	1359	1443	1381	1446	1459
cost −m [*Mill.M*]	12	12	36	13	13	13	13	13	14	13	13	13	13	13
cost −i [*Mill.M*]	509	509	561	561	562	534	553	551	550	545	532	540	538	551

The Table illustrates that only the criteria *cost −mi* and *cost −i* significantly depend on starting point values. The maximal deviation is in the range of 10%.

An interesting question is, whether the different starting points result in different local optima, or the results are simply different Pareto-optimal solutions. In Figure 3.4.10 the results for two criteria are graphically illustrated.

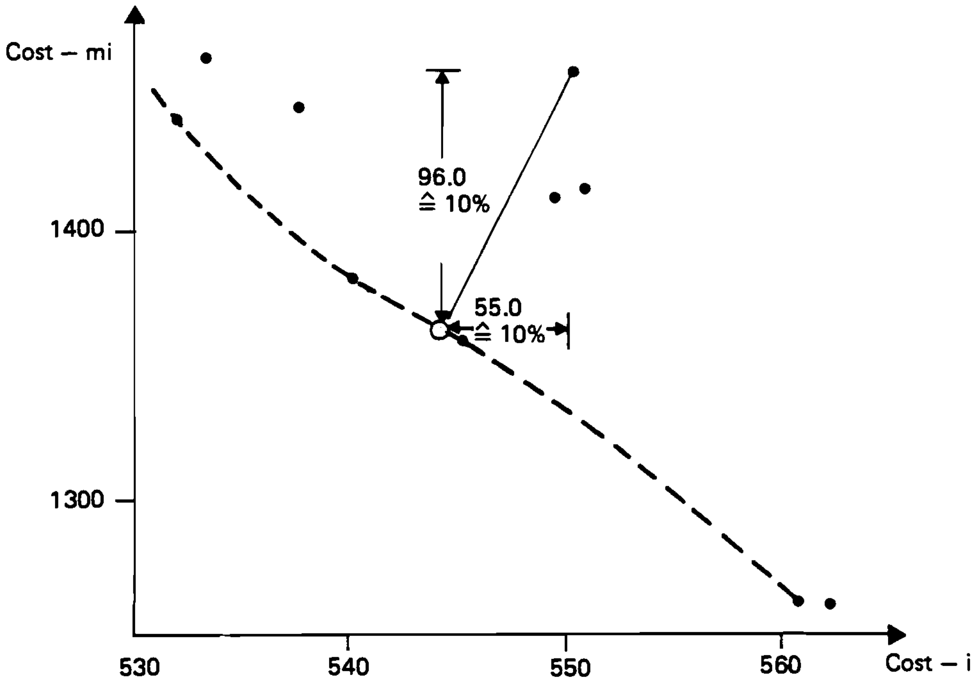


Figure 3.4.10: Solutions for different starting point values

It is out of question that only 11 tests are statistically not sufficiently for generalization. Nevertheless from the Figure 3.4.10 could be concluded that some of the solutions (connected by the dashed line) are global Pareto-optimal, a few others only local. But even for the "worst solution" the distance to the next hypothetic global Pareto-optimal point is less then 10% of its value.

Another series of numerical tests has been done chosing lower and upper bounds of variables as starting point values. For these tests only one planning period has been analyzed. For each variable one run was made with lower and upper bound, the results were compared with an arbitrary "nominal" solution. The results have illustrated the small influence of variations of single starting points for one period. The effect is accumulating if more planning periods are under consideration. In all cases for reasonable starting values the deviations are in the range of practical acceptance.

3.4.5.3 Conclusions

A series of numerical tests has been performed in order to analyze the robustness of the MSPN-algorithm with respect to optimization parameters and to check the influence of starting point values. From the results can be concluded that the MSPN-algorithm is well suited for the given problem. Variations in optimization parameters do not effect the solutions significantly.

The mathematical model of the DSS-MINE behaves robust with respect to the selection of starting points. It can not be excluded that local optima are estimated, but the local optima are expected close to global optima.

For all tests deviations in criteria values have been found less then about 10%. Taking into the account the accuracy of input data, the simplified mathematical models of environmental and socio-economic processes, this deviation is fully acceptable.

Some of the tests are from the practical point of view not realistically, especially the random generation of starting point values. For the practical problem the starting point values are in most cases known quite well and a consistency of variables in time has to be considered. (It does not make much sense to change variables as water allocation drastically between planning periods). Consequently the problem of starting point selection and local/global optima is from the practical point of view less significant. Furthermore the results of the multi-criteria analysis within the *planning model* serves only as a guideline for a more detailed analysis with the second level *management model.*

3.5 Simulation of Management Strategies — the Management Model

3.5.1 Stochastic simulation of management strategies

3.5.1.1 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 $\mathbf{C}_{in}(j)$, $\mathbf{C}_{eq}(j)$ and bounds, compare Eq. (3.17b–3.17d).

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.

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

$$\sqrt{\sum_{j=1}^{J}\left[dem_l(j) - sup_l(j)\right]^2} \longrightarrow Minimum\ !\ ,\ l=1,\dots,L \qquad (3.48)$$

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

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

$$prob\left\{ dem_l^*(i,k) - sup_l^*(i,k) \le 0 \right\} \ge pdem_l\ ! \qquad (3.49)$$

with i - year, k - month, where $pdem$ is the probability of satisfying water demand.

Now it has to be checked whether the strategy obtained based on criteria (3.48) satisfies criteria (3.49). And this is the first task for 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 3.5.1.
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. Considering the results of the planning model (decisions) a ***management rule***

$$\Psi(i,k) = \mathbf{f}\Psi(i,k,\Psi(i,k-1),\Phi(i,k-1),\Gamma(i,k-1)) \tag{3.50a}$$

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):

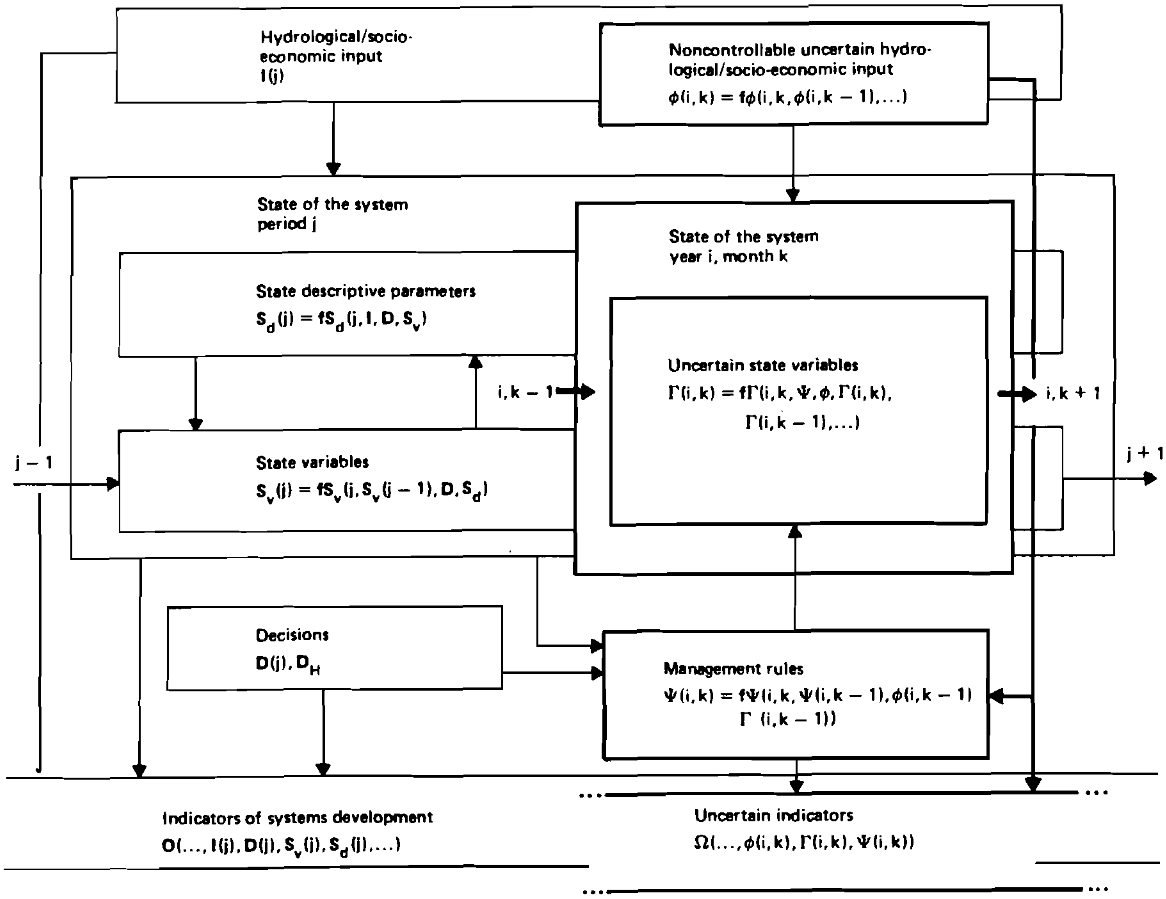


Figure 3.5.1: Block scheme of the management model
Part 1 – stochastic simulation of management strategies

$$\Gamma(i,k) = f\Gamma(i,k,\Psi(i,k),\Phi(i,k),\Gamma(i,k),\Gamma(i,k-1),\ldots) \qquad (3.50b)$$

In Figure 3.5.2 a simplified scheme of the test region is given illustrating the decisions, inputs and state variables being considered in the stochastic simulation (compare Figure 3.2.3). In comparison to Figure 3.2.3 a few additional balance points have been introduced.

The major simplifications for stochastic simulation are:

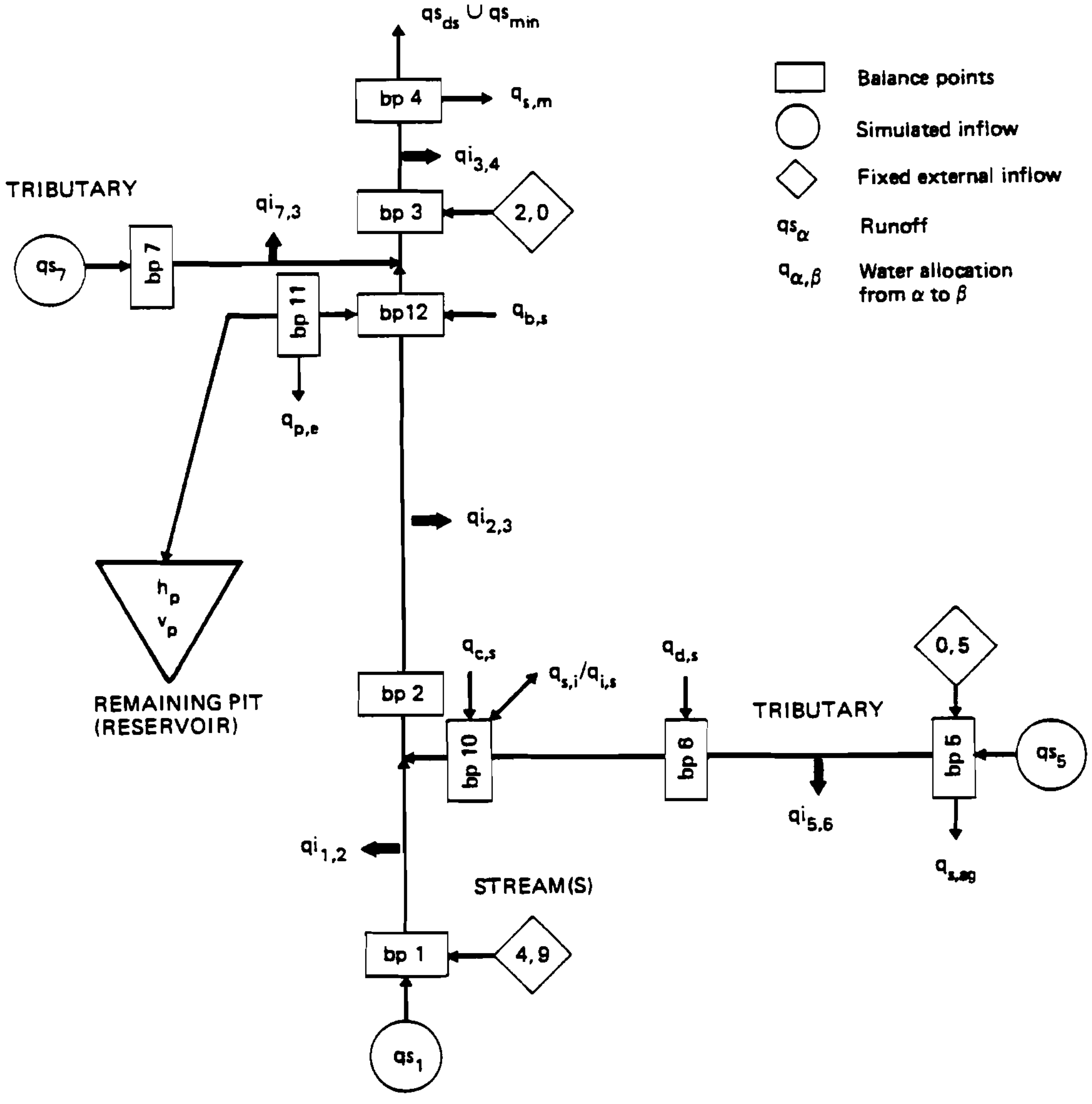


Figure 3.5.2: Simplified scheme of the test region for stochastic simulation

- 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 relatively slow 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.

3.5.1.2 Stochastic simulation of input data

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

$$X = F(Q) = \frac{ln(Q - q_0) - \bar{q}}{\sigma} \tag{3.51}$$

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. Four river gauges are located close to these balance points. The above mentioned assumptions have been validated for the runoff $\bar{q} = (q_1, q_2, q_3, q_4)^T$ through these 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:

$$\bar{q}_N(k) = A(k)\cdot\bar{q}_N(k-1) + B(k)\cdot\bar{q}_N(k) + \bar{\sigma}(k)\cdot\bar{\varepsilon} \qquad (3.52)$$

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

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

$$\bar{q}(k) = \bar{q}_0(k) + e^{\bar{s}(k)\cdot\bar{q}_N(k) + \overline{qm}(k)} \qquad (3.53)$$

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

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, see Kaden et al. 1986.

Water demand

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

$$dem(i,k) = (trend(i,k) + osci(k) + auto(i,k))\cdot rand \tag{3.54}$$

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

As an example, the model for the *municipal water demand* is given. 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.

$$\begin{aligned} dem_m(i,k) = \Big[& \min[\,(2826. + 309.\cdot(i + k/12))\,,\, 25000.\,] + \\ & + 0.726\cdot dem_m(i,k-1) + \\ & - 816.\cdot\sin(\tfrac{\pi}{6}k) - 481.\cdot\cos(\tfrac{\pi}{6}k) + \\ & + 592.\cdot\sin(\tfrac{\pi}{6}(k-1)) + 349.\cdot\cos(\tfrac{\pi}{6}(k-1))\Big]\cdot rand \end{aligned}$$

For the other demand models see Kaden et al. 1986. The *random* component is estimated as follows:

$$rand = (1. - fac\cdot\varepsilon)$$

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.

3.5.1.3 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.

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:

$$dq_{s,u}(j,i,k) = dem_u(j,i,k) - \sum_{l=1}^{L} \mathbf{q}_{l,u}(j) \tag{3.55}$$

with
- $dem_u(j,i,k)$ - total demand of user u, planning period j, year i, month k
- $\mathbf{q}_{l,u}(j)$ - 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 3.5.2 the balance equations for each user can be given (downstream requirements can only be satisfied by the stream):

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

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

$$dq_{s,ag}(j,i,k) = dem_{ag}(j,i,k) - q_{c,ag}(j) - q_{d,ag}(j)$$

$$dq_{p,e}(j,i,k) = dem_e(j,i,k) - q_{c,e}(j).$$

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.

Remaining pit management

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 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. 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.

$$dq_{s,p}(j,i,k) = \mathbf{q}_{s,p}(j) \tag{3.56}$$

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. (3.56) 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 $dq^{*}_{s,p}(i,k)$. Both alternatives can be checked with the simulation model.

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.

3.5.1.4 Simulation of systems development

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

$$\Delta S = P + Z - E - R$$

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

cannot 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 3.5.3. It demonstrates the effect of different management strategies during one year on the state of the reservoir at the end of the year.

According to the methodology described in Section 3.4.2.3 the following monthly model has been developed as a grey-box model:

$$h_p(i,k) = h_p^0(i,k) + a_1 \cdot \tilde{h}_p(i,k-1) + a_2 \cdot \tilde{h}_p(i,k-2) + \\ + b_0 \cdot q_p(i,k) + b_1 \cdot q_p(i,k-1) \tag{3.57}$$

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

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

with $h_p(i,k)$ - 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.

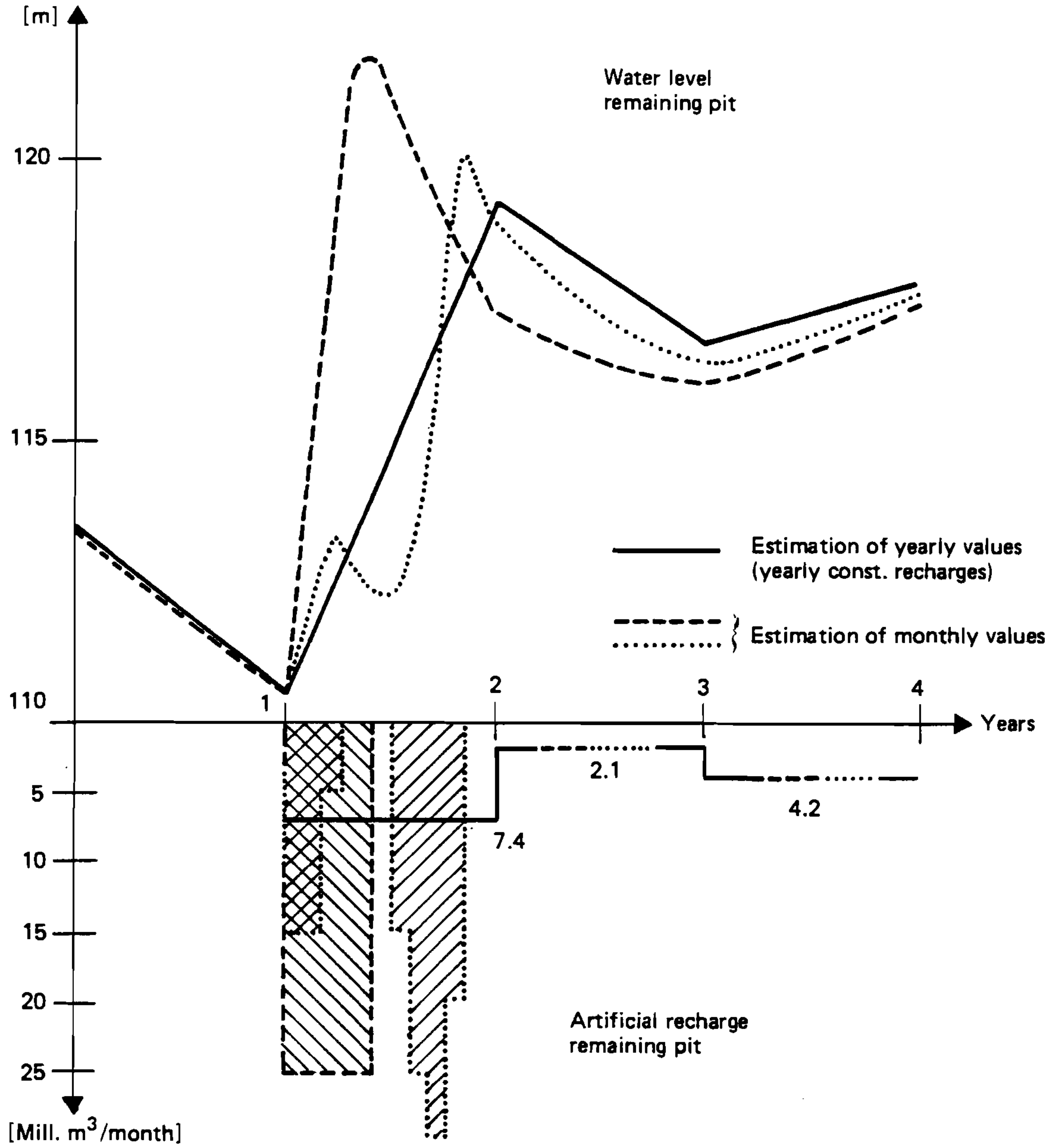


Figure 3.5.3: Impact of different management strategies on the water level in the remaining pit

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 3.5.1.3. 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.

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 minimum of the free discharge (not used) $qs_{min}(i,k)$ of all balance points.

For a detailed description of the algorithm and the computer program see Kaden et al. 1986.

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. For each balance segment (compare Figure 3.5.2) black-box models of the following structure have been developed, applying the conceptual model for synthetic data generation, see Section 3.3.2.2:

$$\Delta qi(i,k) = a_1 \cdot \Delta qi(i,k-1) + a_2 \cdot \Delta qi(i,k-2) +$$

$$+ b_0 \cdot u(i,k) + b_1 \cdot u(i,k-1) + b_2 \cdot u(i,k-2) \qquad (3.58)$$

$$u(i,k) = h_s(i,k) - \bar{h}_s(i)$$

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).

In Figure 3.5.4 numerical results of the black-box model are compared with those of more comprehensive models.

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 points for the effective impulse a weighted mean is used. The weighting factor is γ, $0 \le \gamma \le 1$, usually $\gamma = 0.5$.

$$u_{\alpha,\beta}(i,k) = \gamma \cdot u_\alpha(i,k) + (1-\gamma) \cdot u_\beta(i,k) \tag{3.59}$$

With Eq. (3.59) 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:

$$u_\beta(i,k) = fh_{s,\beta}\left[qs_\alpha(i,k) - (\overline{qi}_{\alpha,\beta}(i) + \Delta qi_{\alpha,\beta}(i,k) + dq_\beta(i,k))\right] - \bar{h}_s(i) \tag{3.60}$$

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

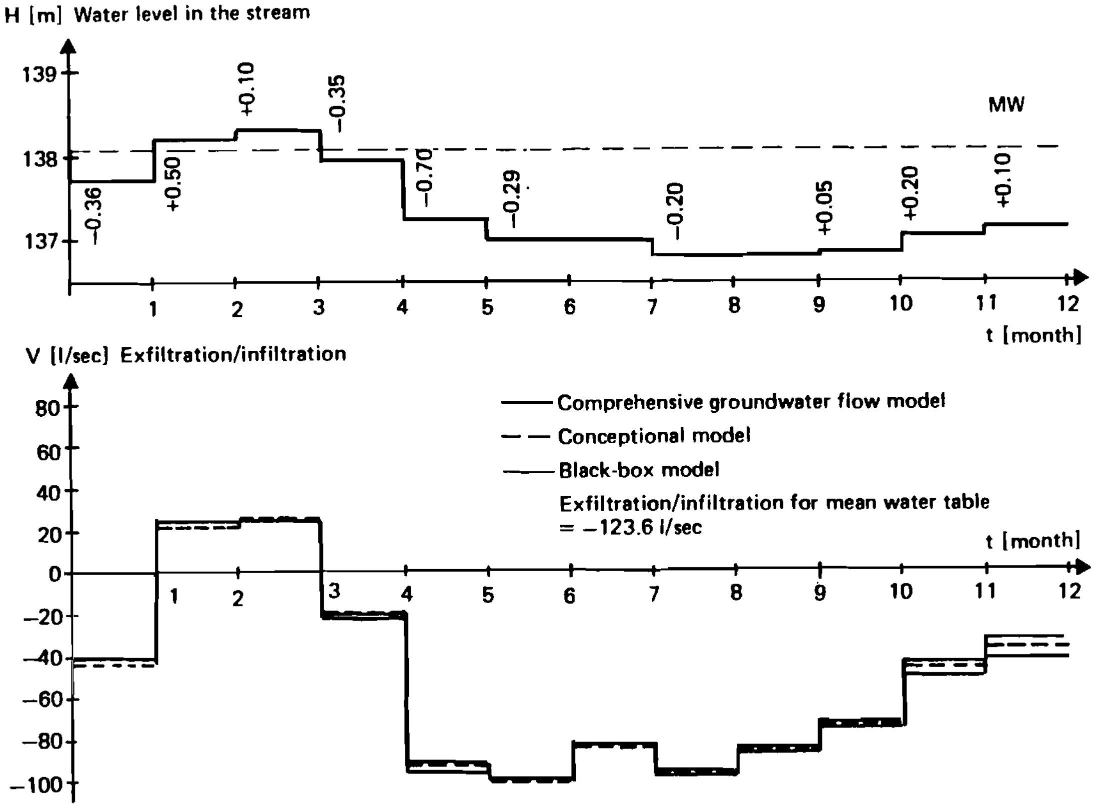


Figure 3.5.4: Comparison of model results for the infiltration submodel

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

The actual discharge at the downstream profile β can be estimated iteratively applying Eq. (3.58)−(3.60). The above mentioned difficulty in balancing under consideration of infiltration becomes now obvious.

In Kaden et al 1986 the computer code for the infiltration submodel of the management model is given.

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. (3.60) 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 Kaden et al. 1986 the computer code of the subroutine balance of the management model is given.

3.5.1.5 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.

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

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

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. We define $(sclass(l), l=1,\ldots,KL)$ as 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

$$P_S\left(\left(\frac{sup}{dem}\right)^0 \right) = Prob \left\{ \frac{sup}{dem} > \left(\frac{sup}{dem}\right)^0 \right\} \tag{3.61}$$

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

$$P_I(ind^0) = Prob \; \{ ind < ind^0 \} \tag{3.62}$$

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.

$$P_P(par^0) = Prob \; \{ par^0 \leq par < par^0 + \Delta par \} \tag{3.63}$$

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).

3.5.1.6 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.

The simulation has been performed with 60 realizations. Therefore 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 3.5.1 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.

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 3.5.2 the result for one period with respect to industrial water supply is depicted.

Table 3.5.1: 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

Table 3.5.2: Reliability of satisfaction of water demand

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).

3.5.2 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.

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.

3.6 Computer Implementation and Model Applications

3.6.1 Computer implementation

Model systems do not replace real-world policy analysis and decision making. But they should be designed to support it effectively. To be accepted and used any Decision Support Model System must fit in the decision making reality, it has to be user-friendly, reliable, robust and credible. Our principle considerations in this respect have been outlined in Part 1.

The development of the DSS MINE for the analysis of regional water policies in open-pit lignite mining areas was directed towards those goals. With the proposed methodological approach the policy making reality is well reflected. The model system focuses on the necessary decisions and common criteria for regional water management. The underlying time discretization corresponds to the common planning and management practice. The reference point approach is well suited for an interactive multi-criteria analysis and it is close to engineering-like policy making.

Special attention was directed towards the interactive and user-friendly model handling and data management. The following aspects have been considered:

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

The use of the hierarchical data base is menu-driven. Each data base level characterizes a menu and the user can either move downwards according to the menu or upwards to the previous level, or return to one of the models. In Figure 3.6.1 an overview on the structure of the data base is given.

For data editing a simple screen editor has been developed. Data checks realize the graceful recovery from failures. For the menu description we use as far as possible linguistic elements according to the practical language. In Section 3.6.2 a terminal session at the computer is demonstrated illustrating the interactive user-friendly features of the DSS MINE.

As it was stressed in the Preface, any systems analytic study is based on a concrete real object, and is, therefore, unique in a certain sense. Consequently, also the software, e.g. in form of a DSS for that study, will possess this feature. And, this gets even more emphasize considering the above given aspects of interactive and user-friendly model handling and data management, which is why the DSS MINE has been especially designed

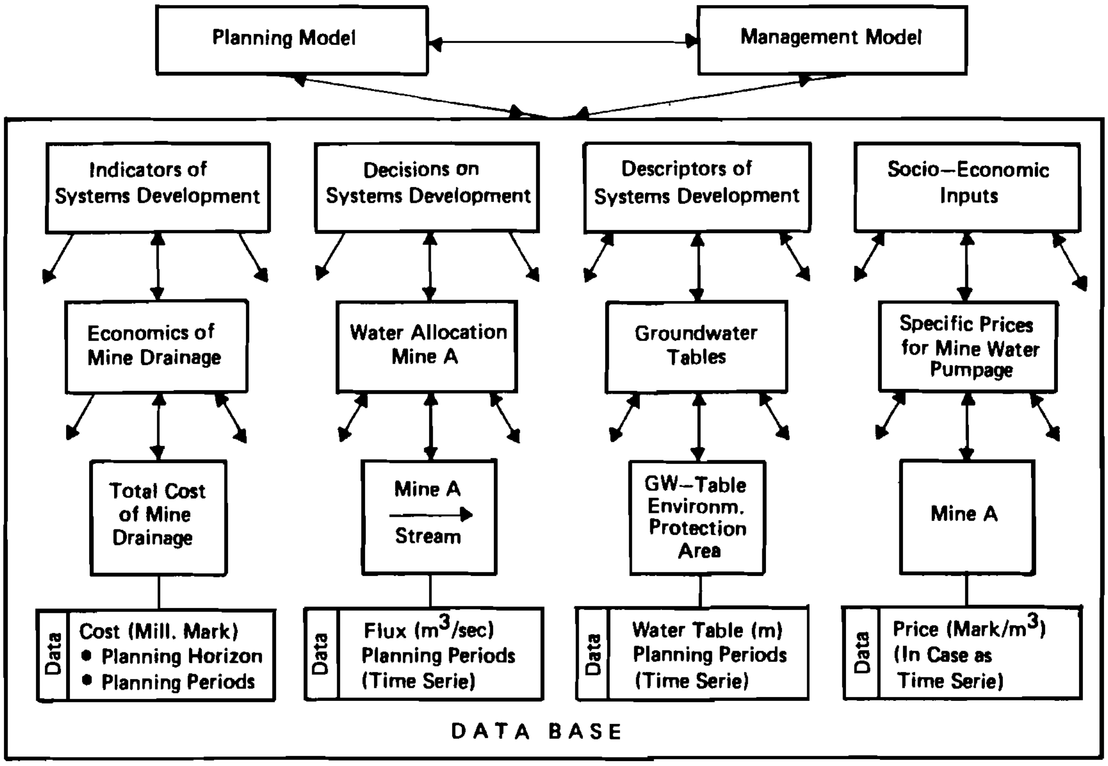


Figure 3.6.1: Hierarchical data base

for the test area in the Lusatian lignite district, see Section 3.1 and 3.2.3. On the other hand, when developing this system it was tried to make it easily adaptable to other regions of similar character. Therefore, the following design principles have been realized:

- adaptation of the system to the practical problem as much as possible by input data or parameters, not by submodels;
- modular structure of the model system in order to simplify necessary changes of submodels (presently the DSS MINE consists of 210 modules).

In Figure 3.6.2 the principle structure of the model system is depicted.

The DSS MINE has been developed in FORTRAN 77 for the computer VAX 11/780 with an AED-512 colour graphics system. A detailed description of it including a user manual is given in Kaden 1986.

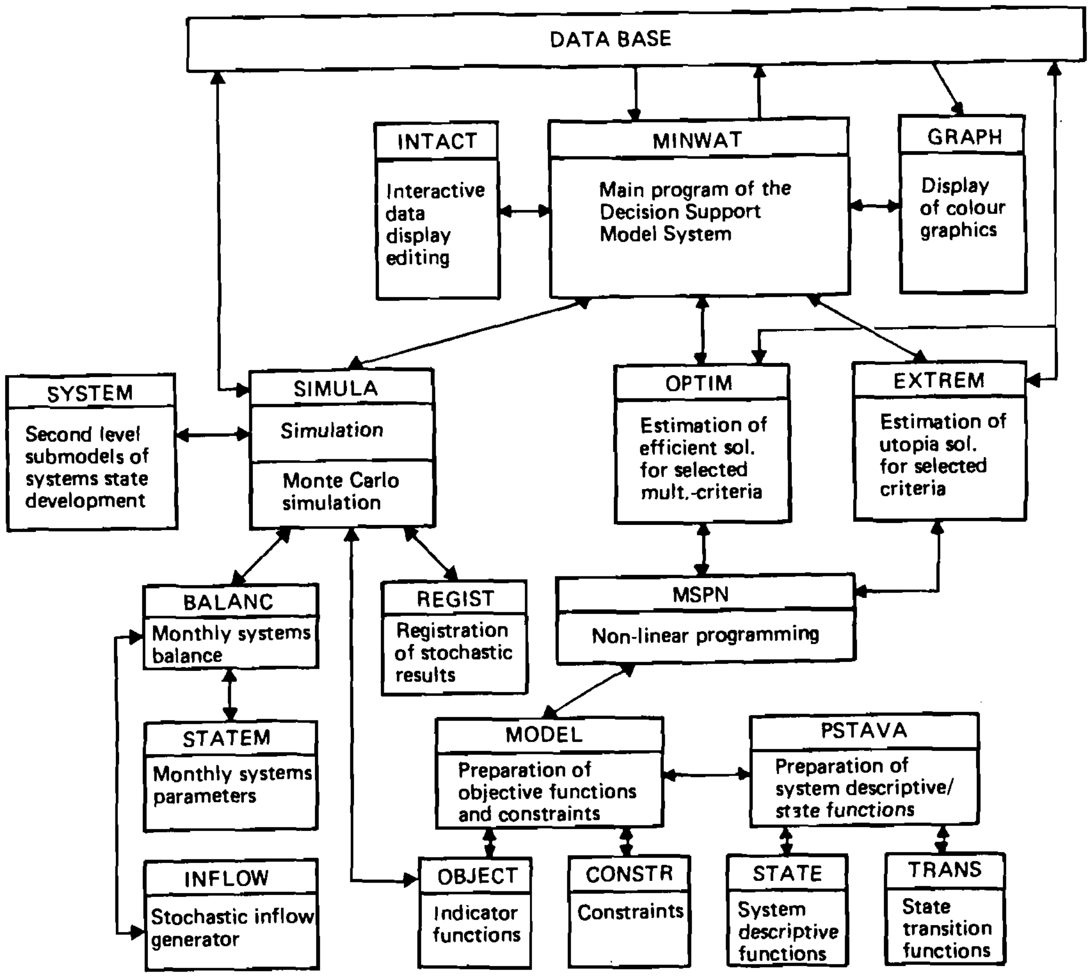


Figure 3.6.2: Principle structure of the DSS MINE

The DSS MINE has been designed to support decision making for regional water policies in open-pit lignite mining areas. How far this goal can be achieved only the future implementation and application in the region studied by regional authorities can reveal. In the following subsections relevant aspects and possibilities of applications of the DSS MINE are given in order to illustrate its qualification for real world decision making purposes as we hope.

3.6.2 Demonstration of a terminal session at the computer

In Figure 3.6.3 an overview of the major steps of model application is given. The figure illustrates the possible choices in the course of interactive model use and the related terminal output. The DSS MINE is mostly self explanatory. All alternatives are verbally displayed and menu-controlled.

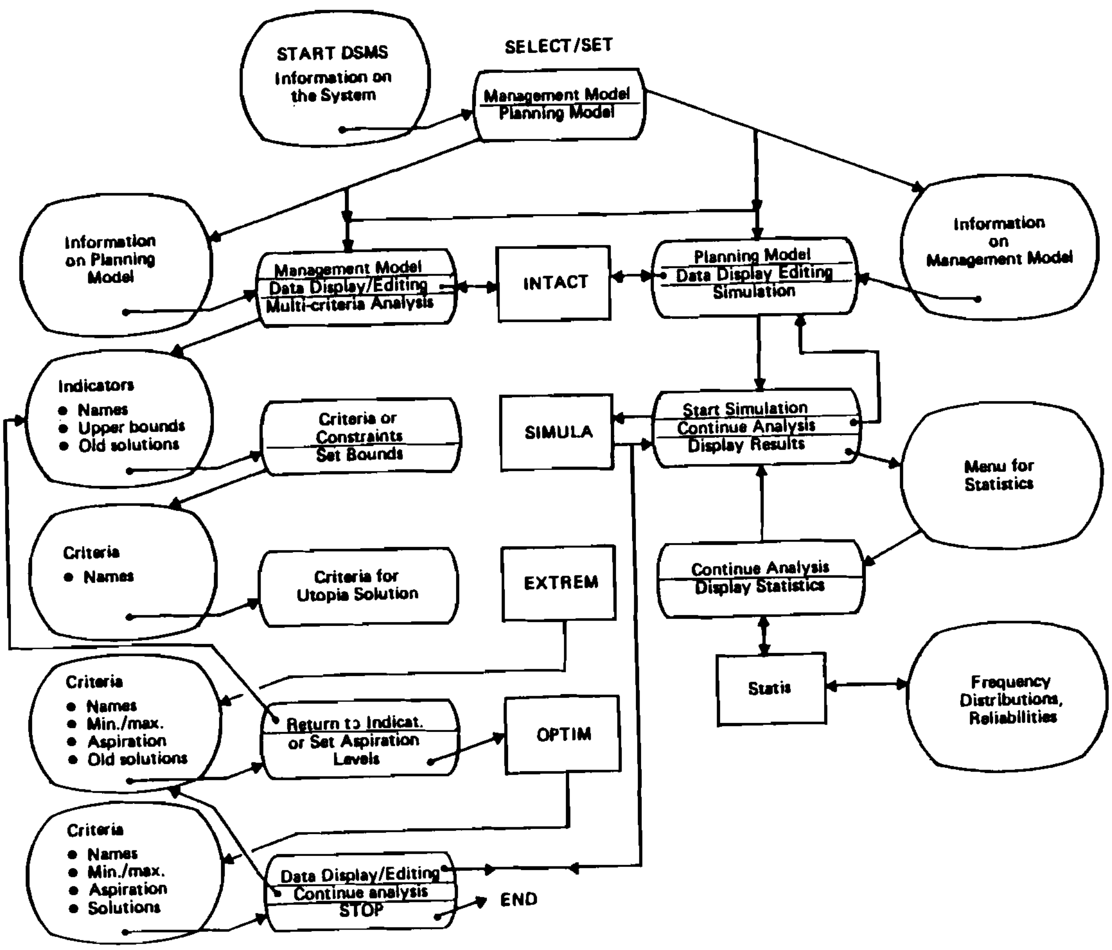


Figure 3.6.3: Interactive use of the DSS MINE

A detailed description of all features of the system is impossible in this paper. In the following some major aspects will be illustrated. Thereby outputs of both an alpha-numeric terminal and a colour graphic terminal are depicted, unfortunately black and white prints only. Due to the "page"-oriented display (spread-sheet type) instead of the common serial output the demonstration of terminal outputs in serial form in a paper is difficult. Originally, the "pages" are often not changed, only corrected, for instance, by a newly typed number. In the following for better understanding the full "pages" are listed again after any change. In order to save space, the outputs are condensed. A new "page" at the terminal is signed by ***********. For some outputs reverse mode is used; this is signed here by underlining.

The analysis can be started with a prepared data set without any additional data input, but all data can be displayed and edited interactively as it will be demonstrated below. After starting the system the following output is displayed:

```
******************************************************************************
           *** MINWAT ***  INTERACTIVE DECISION SUPPORT SYSTEM
        DESIGN OF REGIONAL WATER POLICIES IN LIGNITE MINING AREAS

  INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, Laxenburg  Austria
                  -- Regional Water Policies Project --

 Implementation:        GDR MINEWATER STUDY, stage 1 for the test area.


 To GET  Full  graphics                                type F       ;
 To GET  Short graphics                                type S       ;
 To OMIT color graphics                                press RETURN ;
 ..................................................... type ANSWER  :F
******************************************************************************
```

The user has to decide on the amount of colour graphic output. Only significant answers are accepted, i.e. 'F', 'S' or 'RETURN'. Any wrong answer, e.g. wrong characters, numbers or any garbage, is neglected. This dialogue principle holds true for the entire system. If numbers have to be typed a series of data checks (mostly minimum-maximum tests) is realized. Consequently even unexperienced users can apply the system without unexpected crashes.

After typing 'F' on the colour terminal a series of colour graphics is displayed. First a simplified map of the whole test region is shown, see Figure 3.6.4, left-hand side. In this map all elements of the regional water system are depicted. But not all of these elements are significant for policy-making. Some of the elements are either not significant or due to some reason not to be controlled. In Figure 3.6.4, right-hand side, the essential elements are signed being selected for the DSS MINE. These elements are also typical elements for open-pit lignite mining areas in general.

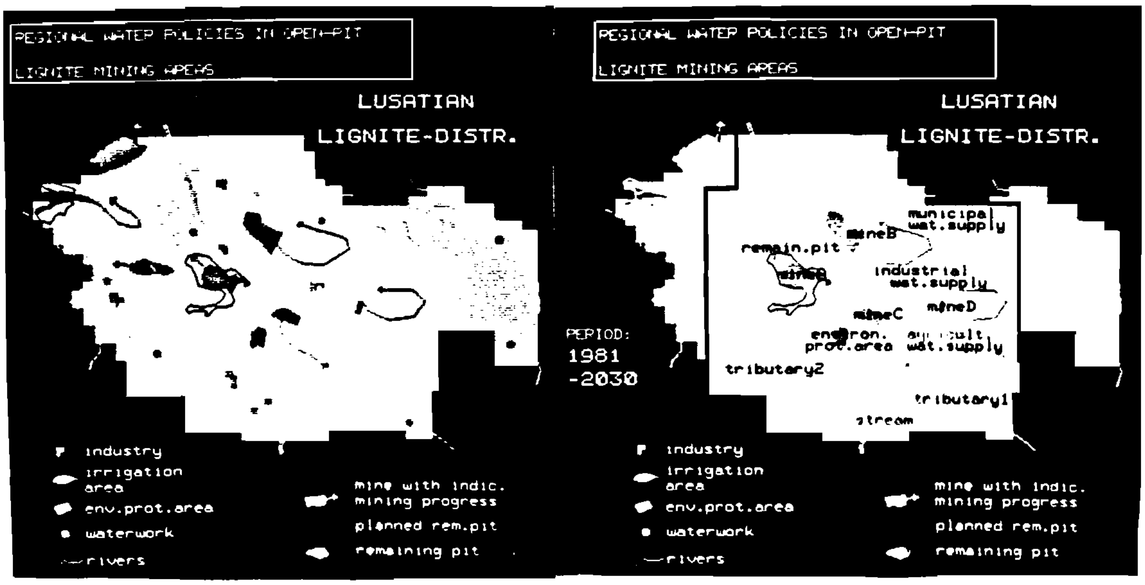


Figure 3.6.4: Schematic map of the GDR test area

The next picture shows a scheme of the test area, Figure 3.6.5. The thickness of lines indicates the water quantity, i.e. the flux through the stream and its tributaries and through the allocation pipe lines. It is scaled between 0.0 and 10.0 m^3/sec.

The colour indicates the water quality coordinated to given ranges of the pH-value and the Fe^{2+}-concentration, varying between 'excellent' and 'very bad'. The same scheme is used in a reduced size to display model results, see Figure 3.6.6.

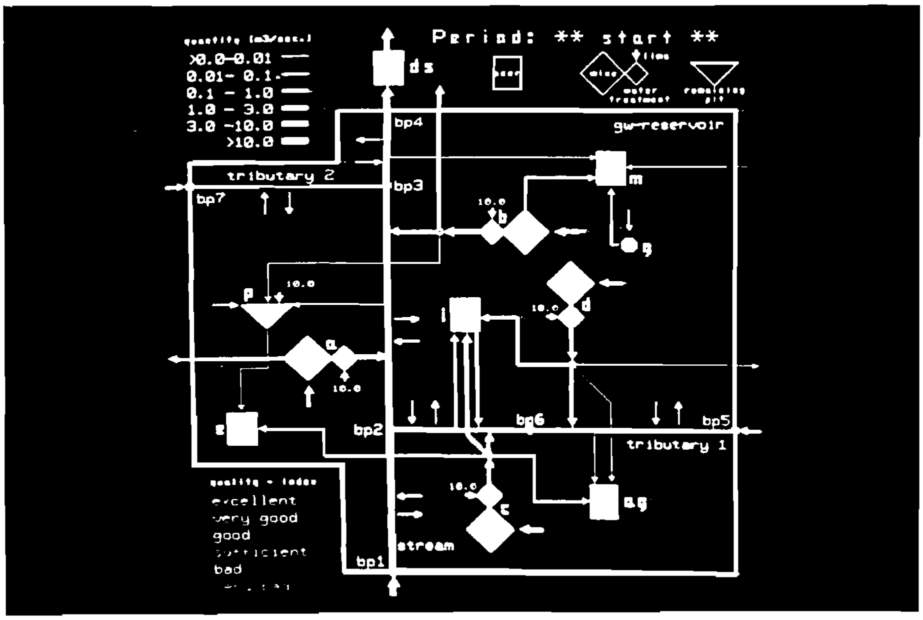


Figure 3.6.5: Scheme of the test area

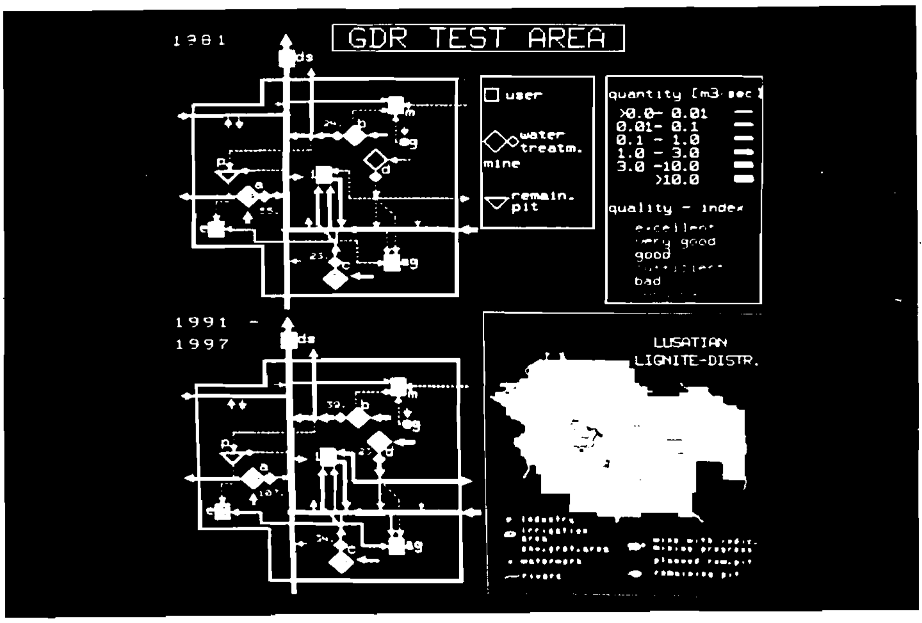


Figure 3.6.6: Comparison of results for different planning periods

After this graphical information the user has to select the submodel he wants to run:

```
****************************************************************************
         *** MINWAT ***  INTERACTIVE DECISION SUPPORT SYSTEM
     DESIGN OF REGIONAL WATER POLICIES IN LIGNITE MINING AREAS

  INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, Laxenburg  Austria
                  --  Regional Water Policies Project  --

 Implementation:        GDR MINEWATER STUDY, stage 1 for the test area.
 Components of the Model System:

 (1) PLANNING MODEL for the analysis of the planning horizon 1981 - 2030
     with the planning periods:
       1      2      3      4      5      6      7      8      9      10
     ------------------------------------------------------------------
     1981   1982   1983-  1985-  1987-  1989-  1991-  1998-  2006-  2016-
                   1984   1986   1988   1990   1997   2005   2015   2030

 (2) MANAGEMENT MODEL for the stochastic simulation and statistic
     evaluation of monthly systems behavior in the planning periods.

  To SELECT a model                                type  NUMBER  ;
  ................................................ type  VALUE   :1
****************************************************************************
```

Having started the planning model by typing '1' the user selects between:

```
****************************************************************************
  CURRENT MODEL SELECTION:                         LONG-TERM PLANNING MODEL


                         MENU FOR PLANNING MODEL


 To DISPLAY/EDIT model data                        type  D       ;
 To GET Informations on the planning model         type  I       ;
 To RETURN to MANAGEMENT MODEL                     type  R       ;
 To CONTINUE with analysis                         press RETURN  ;
 ................................................. type  ANSWER  :D
****************************************************************************
```

In the data display/editing mode 'D' the user gets access to the hierarchical data base for input as well as output data. The topics or data are selected by their number. Data are changed by defining the number of rows and if required of columns, and by typing the new value. The handling is depicted below:

```
****************************************************************************
  CURRENT MODEL SELECTION:                         LONG-TERM PLANNING MODEL

                    TOPICS


 ( 1)           INDICATORS        of systems behavior
 ( 2)           DECISIONS         on systems development
 ( 3)           DESCRIPTORS       of systems development
 ( 4)           SOCIO-ECONOMICS   for systems development

 To SELECT a topic for DISPLAY/EDITING             type  NUMBER  ;
 To RETURN to GENERAL INFORMATIONS                 type  R       ;
 To CONTINUE with analysis                         press RETURN  ;
 ................................................. type  ANSWER  :1
```

```
******************************************************************************
TOPIC SELECTED:                                                  INDICATORS

       SUB-TOPICS

( 1)   WATER DEMAND-SUPPLY       deviation
( 2)   ENVIRONMENTAL CRITERIA  (water quality index)
( 3)   ECONOMICS MINE DRAINAGE
( 4)   ECONOMICS WATER SUPPLY
( 5)   ECONOMICS ENV. PROTECT.

To SELECT a sub-topic for DISPLAY/EDITING          type  NUMBER  ;
To RETURN to GENERAL TOPICS                        type  R       ;
To CONTINUE with anaiysis                          press RETURN  ;
.................................................. type  ANSWER  :2
******************************************************************************
TOPIC SELECTED:                                       ECONOMICS WATER SUPPLY

        [Mill.Mark]
                                        upper bound     sol-1     sol-2     sol-3

( 1) cost-m  : MUNICIPALITY                900.00 !     28.12     28.12     28.12
( 2) cost-i  : INDUSTRY                   2500.00 |   1304.37   1304.17   1157.31
( 3) cost-ag : AGRICULTURE                  40.00 |      7.40      7.44      7.46

To EDIT upper bound of a topic                     type  NUMBER  ;
To DISPLAY Time series                             type  T       ;
To RETURN to         INDICATORS                    type  R       ;
To CONTINUE with anaiysis                          press RETURN  ;
.................................................. type  ANSWER  :2
******************************************************************************
TOPIC SELECTED:                                       ECONOMICS WATER SUPPLY

        [Mill.Mark]
                                        upper bound     sol-1     sol-2     sol-3

( 1) cost-m  : MUNICIPALITY                900.00 !     28.12     28.12     28.12
( 2) cost-i  : INDUSTRY                   2500.00 |   1304.37   1304.17   1157.31
                                          -------
( 3) cost-ag : AGRICULTURE                  40.00 |      7.40      7.44      7.46

To EDIT upper bound of a topic                     type  NUMBER  ;
To DISPLAY Time series                             type  T       ;
To RETURN to         INDICATORS                    type  R       ;
To CONTINUE with anaiysis                          press RETURN  ;
.................................................. type  VALUE   :2000
******************************************************************************
TOPIC SELECTED:                                       ECONOMICS WATER SUPPLY

        [Mill.Mark]
                                        upper bound     sol-1     sol-2     sol-3

( 1) cost-m  : MUNICIPALITY                900.00 |     28.12     28.12     28.12
( 2) cost-i  : INDUSTRY                   2000.00 |   1304.37   1304.17   1157.31
                                          -------
( 3) cost-ag : AGRICULTURE                  40.00 |      7.40      7.44      7.46

To EDIT upper bound of a topic                     type  NUMBER  ;
To DISPLAY Time series                             type  T       ;
To RETURN to         INDICATORS                    type  R       ;
To CONTINUE with analysis                          press RETURN  ;
.................................................. type  ANSWER  :'RETURN'
******************************************************************************
```

In the illustrated way all input data can be specified by the user, e.g. the bounds for decisions or indicators.

After starting the multi-criteria analysis a list of all indicators considered is displayed. The user has to define the criteria for multi-criteria analysis, the remaining indicators are treated as constraints with an upper bound. The upper bound can be changed interactively. In the given test run the deviation between municipal as well as industrial water demand and supply, the total cost for mine drainage and the cost for water supply have been selected as criteria (indicated by '*').

```
******************************************************************************
   SPECIFICATION of INDICATORS as CRITERIA (*)  or  CONSTRAINT  ( )

                                          upper bound     sol-1    sol-2    sol-3
( 1)   dev-m    : MUNICIPALITY          *    10.00  !     16.20    16.21    16.20
( 2)   dev-i    : INDUSTRY              *   100.00  !      3.54     3.68    17.52
( 3)   dev-ag   : AGRICULTURE                50.00  !     22.40    21.50    19.97
( 4)   dev-e    : ENV. PROTECT.              50.00  !     27.98    24.93    25.24
( 5)   dev-ds   : DOWN-STREAM                 0.    !     -8.42    -8.40    -8.41
( 6)   c-ds     : Quality DOWN-STREAM         3.00  !      0.80     0.80     0.80

(13)   cost-mi  : TOTAL DRAINAGE COST   *  6000.00  !   3079.78  3077.10  3401.48
(14)   cost-m   : MUNICIPALITY          *   900.00  !     28.12    28.12    28.12
(15)   cost-i   : INDUSTRY              *  2000.00  !   1304.37  1304.17  1157.31
(16)   cost-ag  : AGRICULTURE                40.00  !      7.40     7.44     7.46
(17)   cost-e   : ENV. PROTECT. AREA         40.00  !      3.30     3.36     3.35

To SELECT an indicator as CRITERIA                   type  NUMBER   ;
To SELECT an indicator as CONSTRAINT                 type  -NUMBER  ;
To CONTINUE with multi-criteria analysis             press RETURN   ;
.............................................         type  ANSWER   :
******************************************************************************
```

In the next step the so-called utopia solution can be estimated for selected criteria (each criteria is optimized separately without considering of the others). Next, the multi-criteria analysis is prepared finally with following the display:

```
******************************************************************************
        SPECIFICATION of ASPIRATION LEVEL for selected INDICATOR

   indicator      minimum   maximum  aspiration          sol-1    sol-2    sol-3
 1 dev-m            0.05    239.80      0.05             16.20    16.21    16.20
 2 dev-i            0.09    113.18      0.10              3.54     3.68    17.52
13 cost-mi       2598.45   3371.30   2598.45           3079.78  3077.10  3401.48
14 cost-m          20.93    935.47     20.93             28.12    28.12    28.12
15 cost-i        1205.81   1381.67   1205.81           1304.37  1304.17  1157.31

To CHANGE the ASPIRATION LEVEL of an indicator      type  NUMBER  ;
To RETURN to SELECT CRITERIA/CONSTR.                type  R       ;
To CONTINUE with analysis                           press RETURN  ;
.............................................        type  ANSWER  :2
******************************************************************************
```

The user gets informations on the possible minimum and maximum value, as well as the last three solutions for each criteria. He has to define for each of the criteria his aspiration level (the reference point). After typing the number of row the new value has to be entered.

```
*****************************************************************************
        SPECIFICATION of  ASPIRATION LEVEL for selected INDICATOR

   indicator      minimum  maximum aspiration         sol-1    sol-2    sol-3
 1 dev-m            0.05   239.80      0.05           16.20    16.21    16.20
 2 dev-i            0.09   113.18      0.10            3.54     3.68    17.52
                                       ----
13 cost-mi       2598.45  3371.30   2598.45         3079.78  3077.10  3401.48
14 cost-m          20.93   935.47     20.93           28.12    28.12    28.12
15 cost-i        1205.81  1381.67   1205.81         1304.37  1304.17  1157.31

To CHANGE the ASPIRATION LEVEL of an indicator    type  NUMBER  ;
To RETURN to SELECT CRITERIA/CONSTR.              type  R       ;
To CONTINUE with analysis                         press RETURN  ;
...............................................   type  ANSWER  :50.
*****************************************************************************

        SPECIFICATION of  ASPIRATION LEVEL for selected INDICATOR

   indicator      minimum  maximum aspiration         sol-1    sol-2    sol-3
 1 dev-m            0.05   239.80      0.05           16.20    16.21    16.20
 2 dev-i            0.09   113.18     50.00            3.54     3.68    17.52
                                       -----
13 cost-mi       2598.45  3371.30   2598.45         3079.78  3077.10  3401.48
14 cost-m          20.93   935.47     20.93           28.12    28.12    28.12
15 cost-i        1205.81  1381.67   1205.81         1304.37  1304.17  1157.31

To CHANGE the ASPIRATION LEVEL of an indicator    type  NUMBER  ;
To RETURN to SELECT CRITERIA/CONSTR.              type  R       ;
To CONTINUE with analysis                         press RETURN  ;
...............................................   type  ANSWER  :'RETURN'
*****************************************************************************
```

If the aspiration levels for all criteria are defined the multi-criteria analysis can be started. During the solution intermediate results are graphically displayed. The results are listed in a similarr table as that above, but with the new solution. Now the user can display the results in detail in the hierarchical data base as it was illustrated above for the input data. Furthermore, results can be displayed graphically. For instance, the results for different planning periods can be compared, see Figure 3.6.6.

The values of selected indicators can be displayed in a bar chart, comparing the last three solutions, as depicted in Figure 3.6.7. Time series of selected data can be displayed in the form of step functions, see Figure 3.6.8.

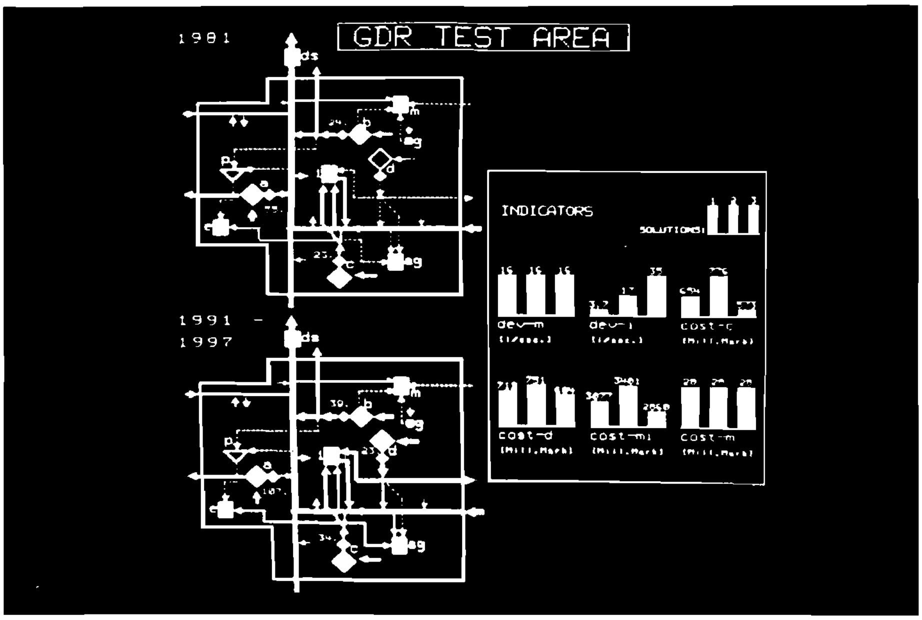


Figure 3.6.7: Bar charts for selected indicators

After display of model results the multi-criteria analysis can be continued at any of the previous steps, e.g. input data editing, definition of criteria or aspiration levels, etc.

If the results of the planning model are satisfactory the management model can be started:

```
*****************************************************************************
 CURRENT MODEL SELECTION:                                    MANAGEMENT MODEL

                          MENU FOR MANAGEMENT MODEL

 To DISPLAY/EDIT model Data                             type  D        ;
 To GET Informations on the management model            type  I        ;
 To RETURN to PLANNING MODEL                            type  R        ;
 To CONTINUE with analysis                              press RETURN   ;
 ...............................................        type  ANSWER   :
*****************************************************************************
```

The results of Monte Carlo simulation are displayed in different ways. For example, for the indicators of systems development an empirical distribution function is tabulated:

```
*****************************************************************************
     SOLUTION  for  INDICATORS    -    PLANNING MODEL  ** MANAGEMENT MODEL

          planning m.  |                    management model
  indicator   solution|mean value|   95 %      90 %      80 %      70 %      50 %
 1 dev-m        16.20 |    0.    |   0.        0.        0.        0.        0.
 2 dev-i         3.54 |    3.95  |   0.37      0.37      0.37      0.37      0.34
 3 dev-ag       22.40 |    0.    |   0.        0.        0.        0.        0.
 4 dev-e        27.98 |    0.50  |   0.19      0.18      0.16      0.15      0.12
 5 dev-ds       -8.42 |    1.92  |   0.50      0.46      0.46      0.45      0.41
 6 c-ds          0.80 |    7.44  |   0.71      0.71      0.71      0.71      0.71

13 cost-mi    3079.78 |       ***** long-term mean value *****
14 cost-m       28.12 |   30.00  |  30.19     30.15     30.12     30.05     29.99
15 cost-i     1304.37 | 1191.95  | 1203.94   1203.06   1200.60   1199.80   1189.50
16 cost-ag      7.40  |    0.35  |   0.35      0.35      0.35      0.35      0.35
17 cost-e       3.30  |    1.09  |   1.09      1.09      1.09      1.09      1.09

To DISPLAY statistics                              type  S        ;
To DISPLAY/EDIT model data                         type  D        ;
To CONTINUE with analysis                          press RETURN   ;
.................................................. type  ANSWER   :
*****************************************************************************
```

Furthermore, the reliability of water supply can be displayed:

```
*****************************************************************************
TOPIC SELECTED:                                      industrial water supply

             Reliability of water supply; month: May        [ % ]

     Period av.demand   >  95%    >  90%    >  80%    >  70%    >  50%
        1      4.29       30.0      30.0      30.0      40.0      50.0
        2      3.97       40.0      40.0      40.0      40.0      90.0
        3      4.11       40.0      50.0      60.0      70.0      90.0
        4      3.99       35.0      40.0      50.0      60.0      75.0
        5      3.88      100.0     100.0     100.0     100.0     100.0
        6      4.07      100.0     100.0     100.0     100.0     100.0
        7      3.98       98.6      98.6      98.6      98.6      98.6
        8      4.02      100.0     100.0     100.0     100.0     100.0
        9      4.07       99.0      99.0      99.0      99.0     100.0
       10      3.96       50.7      52.0      54.7      58.7      73.3

 To CONTINUE                                       press RETURN  ;
 ................................................. type  ANSWER  :
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Besides the Monte-Carlo simulation, a simulation with comprehensive submodels can be started for model verification. After the simulation the analysis can be continued running again the planning or the management model.

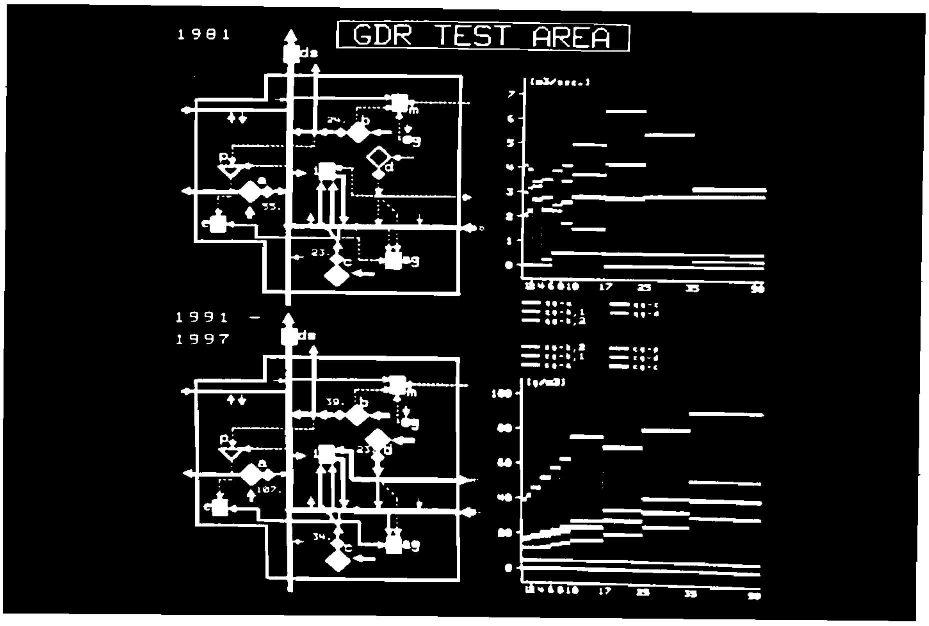


Figure 3.6.8: Step functions of time series for selected data

3.6.3 Practical analysis of regional water policies

3.6.3.1 Introduction

The policy making process related to regional water policies in mining areas is fairly complicated. In the centrally planned economic system in the GDR it includes all decision levels from the government (Central Planning Authority, different ministries), regional authorities (District Planning Authority, Regional Water Authority, etc.) upto the lowest level (mines, farms, municipal water supply agencies, etc.) interacting directly with the water resources system. Between and within these levels manifold interdependencies occur and have to be considered in practical decision making. But it was out of the scope and the possibilities of our study to consider all the complexity of the hierarchical policy making. Nevertheless, it has been tried to design our DSS MINE that it fits well in the practical policy making process. The basic simplifications, therefore, have been described in Part 1, emerging in an upper level decision maker (PMA) and lower level decision makers (water users) as it is depicted in Figure 3.6.9.

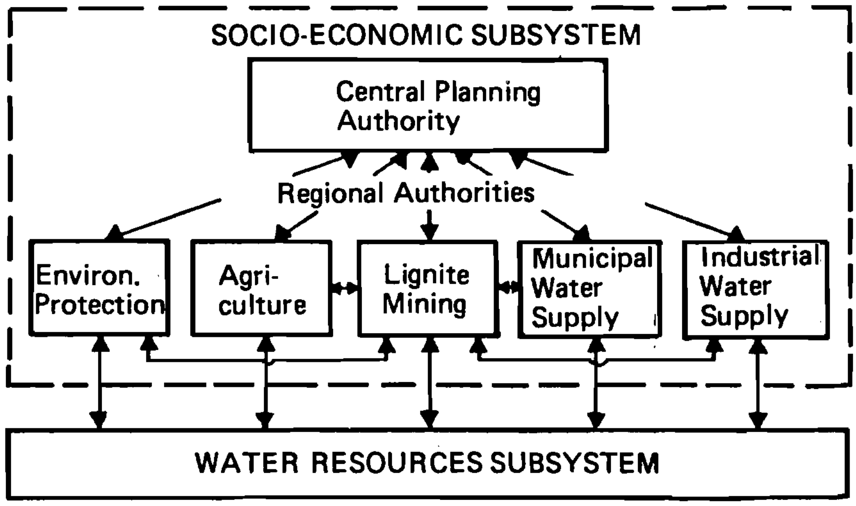


Figure 3.6.9: Schematized policy making structure

Taking this into account we have proposed to decompose the analysis of regional water policies into two stages:

– the *scenario analysis* aimed at determining a trajectory (scenario of regional development) that appears satisfactory to the respective PMA (policy making authority) in its economic, environmental and other aspects,

– the *policy analysis* concerned with the search for those feasible policy instruments at the disposal of the PMA that influence the behaviour of the lower level decision makers in order to direct regional development along or close to the rational trajectory determined at the first stage.

Both stages are closely interrelated. On the one hand, scenario analysis has to consider the feasibility of underlying policies, on the other hand, policy analysis has to be based on rational scenarios. Therefore, these stages should be embedded into an interactive, iterative decision making process. The DSS MINE has been designed to support it. Both stages of analysis are related to subjective, behavioural, not computerized aspects of the policy making process. Therefore, practical analysis cannot be done outside of the "environment" of the policy making. What can be done here at IIASA is to visualize such an analysis illustrating the features of the DSS MINE, see Sections 3.6.3.2 and 3.6.3.3.

The DSS MINE in its combination of a screening model based on multi-criteria analysis with a simulation model is an abstract mathematical tool. In applying the system especially in the stage of policy analysis, behavioural aspects of water users have to be considered. These aspects can hardly be modeled formally. For the model supported policy analysis simplified assumptions on the users' behaviour, e.g. cost minimization have to be made. Another less formal approach is the direct involvement of the decision makers into modeling process for policy analysis. One attempt therefore is the application of *gaming*. In Section 3.6.3.4 the developed game MINE and its practical application will be outlined.

3.6.3.2 Scenario analysis

The first task of scenario analysis is the *screening* of rational scenarios of regional development with the planning model of the DSS. As has been described in Section 3.4 we use the reference point approach for the multi-criteria analysis. In order to start this analysis the following steps have to be realized:

1. Preparation of variable input data as
   - upper and lower bounds of control variables (decisions), e.g. minimum and maximum flow through pipelines (allocation capacity),
   - socio-economic parameters, e.g. water demand, price index, standards on water quality.

This step already includes some policy considerations. Upper and lower bounds of control variables should be fixed as such that unrealistic scenarios are omitted, on the other hand, the bounds of these variables do not reduce the solution space too strongly.

The selection of the socio-economic parameters being partly uncertain depends on the kind of parameter and the focus of the analysis. In case of uncertain parameters, either some expected values, pessimistic or optimistic values can be chosen; this aspect has been discussed in detail in Part 1. Most of these parameters is known due to fixed governmental regulations and standards.

2. Selection of criteria for multi-criteria analysis. As it has been illustrated in Section 3.6.2 the user can select from a set of indicators those of his major concern. The remaining indicators are considered as constraints with a chosen upper bound. Looking at the problem from the point of view of the PMA one could select, e.g. the satisfaction of municipal and industrial water supply, downstream water quality and total cost of mine drainage as significant criteria. At this point the subjective character of the analysis becomes already obvious. It depends on the view of the user as to which indicators he defines to be most important. Different users will have different objectives. Let us assume that the above defined criteria are the relevant criteria for rational regional development from the point of view of the PMA.

3. Determination of the aspiration level for the criteria selected. According to the reference point approach the user has to determine his aspiration with respect to criteria values. To define this value he is supplied with the possible lower and upper value of each criteria and the results of previous solutions. Again this determination is a very subjective one. The user can consider all his preferences with respect to single criteria and to the relation between criteria.

4. Evaluation of the result. After running the analysis the user has to evaluate the results obtained comparing them with his aspirations. In case, he is not satisfied the analysis has to be continued at one of the previous steps.

This short verbal description of the process of screening of rational scenarios elucidate the "soft" character of this analysis. The DSS does not *solve* the problem but supports rational selection of scenarios. In Figure 3.6.10 results of such screening analysis are displayed.

Having selected one or a few rational scenarios with the planning model it has to be checked whether these scenarios are applicable for the long-term development considering managerial aspects. Therefore the *management model* of the DSS is applied, see Section 3.5. The user gets a statistical evaluation of the criteria values and above all a statistical evaluation of the satisfaction of water demand. See Section 3.6.2 for numerical results.

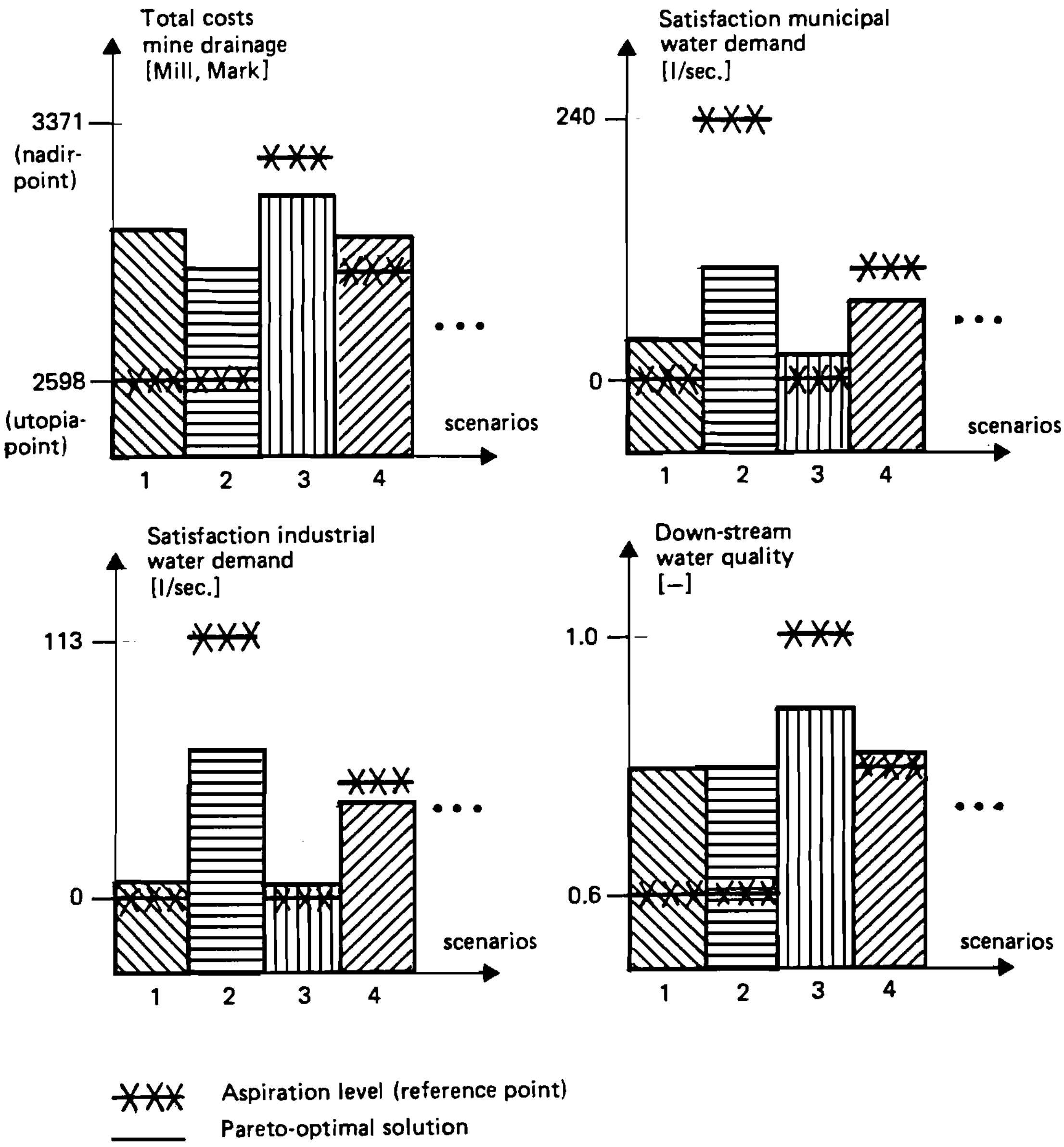


Figure 3.6.10: Results of screening for rational scenarios

At this point it depends again on the objective or subjective considerations of the user whether he accepts the results. If not, either a new scenario has to be selected or the management rules underlying the management model have to be changed.

The model system can be used in the same way as described above by each of the lower level water users (or even jointly) in order to find strategies for long-term regional development from the point of view of the water user. Such analysis is frequently required within the interactive process of planning in the GDR economy.

3.6.3.3 Policy analysis

As we said before the policy analysis should be concerned with the search for feasible policy instruments in order to direct the regional development along rational trajectories. In Section 2.8 approaches to policy analysis for regions with intense agriculture have been discussed. To visualize a similar kind of analysis for regions with open-pit lignite mining in a centrally planned economic system one has to consider a number of different aspects. Describing these aspects we will base on the schematized policy making structure according to Figure 3.6.9.

1. We have to deal with a small number of water users characterized by strong impacts on the water resources system.

2. The water users are partly economically interdependent above all due to the allocation of water between them.

3. The basic figures of regional development are controlled by the central planning authority. Strategies and plans of regional development are elaborated during a permanent and iterative planning process between this authority and the water users.

   The DSS MINE seems to be well suited to support this process as a tool for regional planning.

4. Most all activities of water users affecting the water resources system are already controlled by governmental policy instruments. These include regulations and direct control (e.g. standards for water quality) as well as incentive schemes (taxes, fines, subsidies, etc.). These instruments are fixed by governmental laws and regulations, e.g. the *Water Law* of the GDR.

6. The policy instruments are implemented for the entire country, specifications for regions (e.g. different taxes) are not common.

According to this, policy analysis should not be directed towards initiation of new policy instruments. The basic question of policy analysis should be in how far the policies implemented in reality result in those affects they have been designed for, or how variations of these instruments would change the users' behaviour and systems development. For example, in order to stimulate the mining industry to produce water for municipal water supply they obtain as a specific benefit 0.70 M/m^3 (if the water is drinkable).

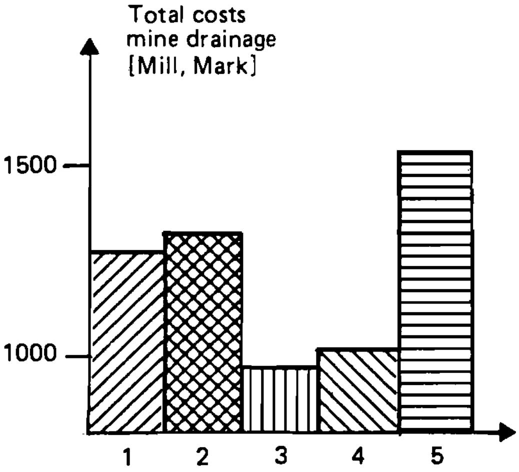
Does this policy affect the behaviour of the mining industry? If not, the results required can either be achieved through the plan or by changing this stimulus.

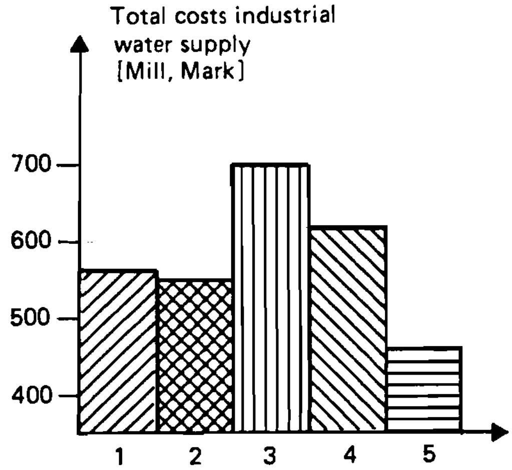
The DSS MINE can be used for the analysis of the second alternative. For the implementation of the DSS MINE for the GDR test region the following policy instruments are considered:

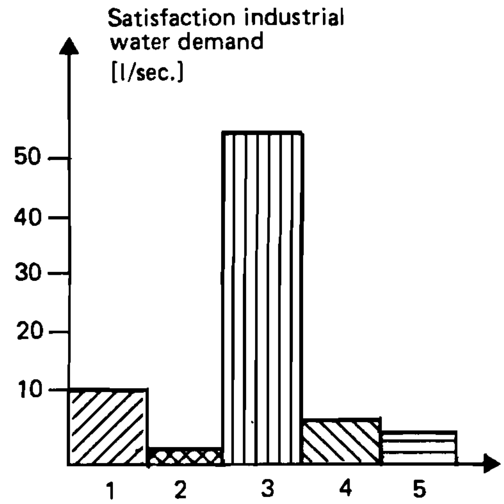
- *Specific benefits for water allocations* from mines to industry, municipality, agriculture and environmental protection,
- *specific expenses for water allocation*, i.e. surface water use and waste water allocation,
- *standards on water quality* of water allocated to water users and to surface water.

By varying these instruments, e.g. reducing or increasing benefits, their effect on the behaviour of water users and through this on regional development can be analyzed. In Figure 3.6.11 some results are depicted illustrating the effect of the specific benefit for water allocation from mines to the industry.

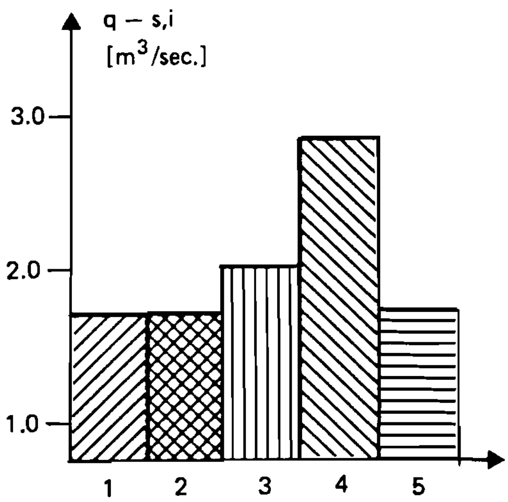
In doing such an analysis one must realize that the results may be specific for the test region and that the policy instruments are not easily to be adopted for the region under consideration only. But such a policy analysis would support the selection of proper policy instruments applicable on a wider scale.







Variant	β_i [Mark/m^3]	Reference points Cost – mi	Cost – i
1	0,16	utopia	nadir
2	0,16	nadir	utopia
3	0,32	utopia	nadir
4	0,32	nadir	utopia
5	0,08	utopia	nadir



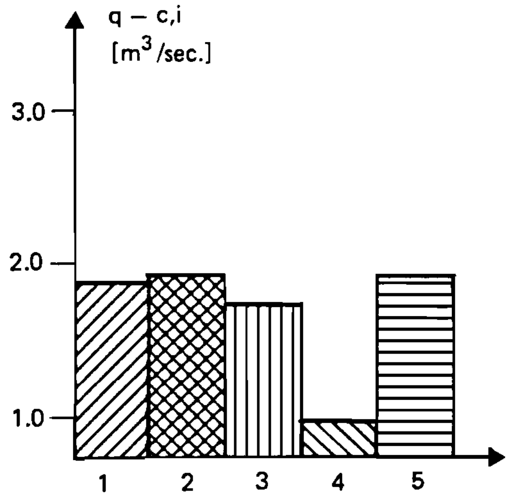


Figure 3.6.11: Example for policy analysis

3.6.3.4 The game MINE

In the past, gaming approaches have been widely studied also at IIASA. The major advantage of these approaches is the direct involvement of the players (decision makers), and by this the consideration of behavioural aspects. And this is what made gaming also of interest for our study, especially with regard to the policy analysis as discussed above. In general the following subdivisions of gaming can be distinguished:

(1) *Training*: to illustrate some aspects without going into conceptual details

(2) *Teaching*: to get across concepts and abstracts

(3) *Operational gaming*: (a) policy formulation, (b) dress rehearsals, (c) gaming for sensitivity analysis and commentary on plans

(4) *Experimentation*: (a) theory validation and (b) theory generation

(5) *Future studies*: i.e. structural brain storming

The game MINE is designed above all for decision makers in open-pit mining areas to find good long-term strategies for regional development. It should be played by the policy makers or the representatives of the different interest groups that are concerned. The game MINE should help to choose a policy in consideration of every interest group in the area, and, beyond that, of the desire to preserve natural ecosystems and recreational areas.

The players should learn:

- the interdependency between the different elements of the area,
- the consequences of the actions and decisions of the policy makers and the interest groups,
- all the different circumstances of a chosen policy,
- the necessary coordination of the demands and actions,
- to pay attention also to the long-term consequences, to the global goal, to the reason of activities of other groups.

Consequently, MINE is first of all a *teaching game*. Its extension to an *operational game* will be decided based on practical experiences playing the game with decision makers. Other purposes of the game, with regard to the game operator and the scientists have been:

- test, validation, verification of the model,
- new aspects on the decision making process: there may be elements that are not considered in the model, as well as psychological, social and subjective aspects that are difficult to quantify.

With this respect MINE may be viewed as an *experimental game*.

The first version of the game – MINE 1 – was implemented in BASIC on an APPLE IIe. This version also has been implemented on a portable computer NEC/PC 8201A. A playing board with appropriate pieces is associated to the game. During the game, the players are sitting around the board, filling out different forms with their decisions. The computer with the model is running in the background, the input of the decisions is made by the game operator. The communication between model and decision makers is realized by pieces moved on the board. All model outputs as allocation and quality of water, etc., are printed on an additional printer.

The second version – MINE 2 – was implemented in FORTRAN 77 on the VAX and the ALTOS. A graphic terminal can be associated to the VAX that corresponds to the board in MINE 1. The input of the decisions is made by the players or by the game operator on the computer.

The gaming board for MINE 1 and the graphic schema for MINE 2 represent a schematical map of the test area similar to Figure 3.2.2 as depicted in Figure 3.6.12.

From experience in running the game it was learned that the simpler version of the game being implemented for small microcomputers is more favourable due to its communicative character. Above all the game should be portable as easily as possible. Therefore it was decided to improve the NEC version of the game. Details on the different versions of the game MINE is available in Weigkricht and Kaden 1985, Kaden and Varis 1986. The first gaming sessions indicate that it is very useful in order to get a better understanding of the complex interrelated socio-economic processes in

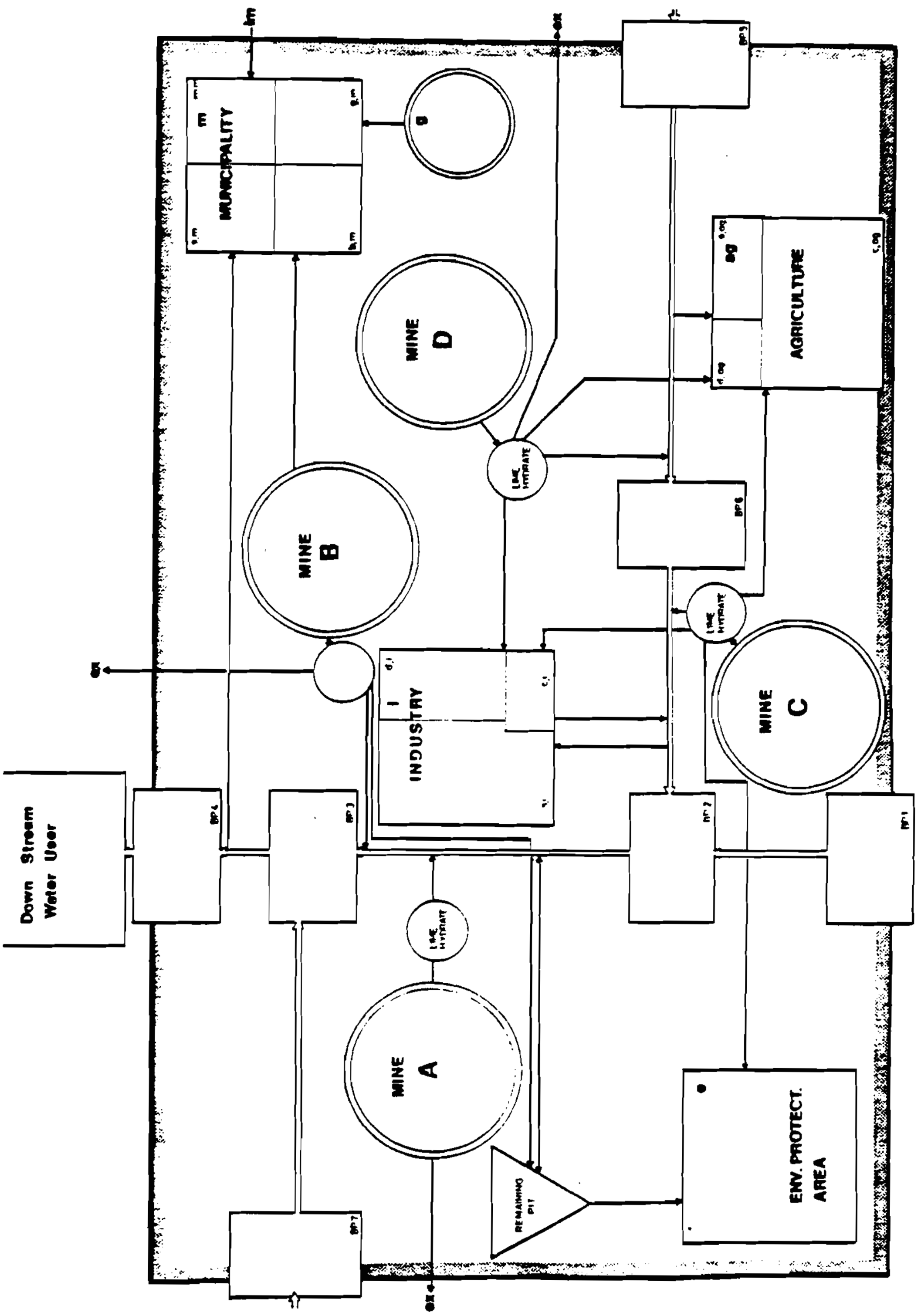


Figure 3.6.12: Board of the game MINE

lignite mining regions for decision makers and their staff. In analysing such gaming sessions behavioural aspects become obvious which hardly can be formalized.

3.7 Conclusions

With the DSS MINE a helpful tool for the analysis of regional water policies in lignite mining areas has been developed. During its presentation to international scientific audience at numerous conferences and workshops as well as its demonstration for high level decision makers of the GDR the research results were highly evaluated. In the GDR, the system will be applied in a number of regions. Applications of our methodology and models in other countries are under discussion. Nevertheless, it would be naive to assume that with the DSS MINE any related research is finished. Its application to different practical problems will reveal further research needs. According to our present knowledge the following topics seems to be of major interest.

Application of fuzzy sets

Water resources management and planning takes place in an environment in which the basic input information, the goals, constraints, and consequences of possible actions are not known precisely (Kindler et al. 1985). This is also very typical of the water policies in mining regions that are studied. Examples for such imprecise informations are environmental objectives and constraints (water quality, water demand, economic coefficients, parameters in submodels, e.g. for water quality, etc. With the fuzzy sets method a possibility is given to deal with such imprecisions due to insufficient and imperfect informations. A first attempt to combine fuzzy sets with nonlinear multiobjective optimization for water allocation problems in mining areas has been made by Kindler et al. 1985. The promising results emphasize the need for future research and practical tests. Besides theoretical problems in applying the method the interpretation of imprecise results emerging from imprecise informations and its presentation to the decision makers have to be analysed.

Integration of integer programming methods

Presently the DSS considers only continuous decisions (control variables). Discrete decisions (construction of a treatment plant, size of pipelines, etc.) have either to be fixed in different scenarios or smoothed. Solutions can only be found in an interactive procedure. In order to automatize this, integer programming methods (e.g. branch and bound method) could be included.

Application of random search methods

As it was discussed in Section 3.4.5.2 for the nonlinear optimization problems to be solved in the DSS MINE it cannot be ensured to obtain ***global optimal solutions***. In order to test the behaviour of the mathematical model and to get starting points for optimization close to global optima random search methods, e.g. Born 1985 should be studied.

Improvement of water quality submodels

The submodels for groundwater quality have to be improved (presently simple trend models). Besides the considered components Fe^{2+} and H^{+} additional relevant water quality problems as the salt water intrusion have to be analysed.

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