WATER POLICIES: REGIONS WITH INTENSE AGRICULTURE (INTRODUCTION TO THE IIASA STUDY)

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PREFACE

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

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

This differentiation is reflected in the ongoing studies based on "experimental" regions. One of them is the Southern Peel region in the Netherlands, where agriculture is the dominating activity. Another region in the GDR is a typical open-cast mining area. This paper is concerned with the first study and the research on this study is a collaborative effort of the IIASA project team and of the Institute for Land and Water Management Research (ICW) in Wageningen, NL. It is not a final report, rather it should be viewed as an outline of the approaches and models that are planned for the future development and implementation.

CONTENTS

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1. INTRODUCTION

Intense socio-economic development in many regions of the world puts an increasing pressure on the environment both by consuming natural resources and by discharging pollutants that are hazardous to the population and to natural ecosystems. A substantial part of these impacts takes place through regional natural water systems. Apart from 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.

In different regions different types of economic activities can vary in degrees of their influence on water systems. Here we consider regions where agriculture is the dominating activity both in its economic value and in the degree of its impacts on the regional surface and groundwater systems and through them on the whole regional environment as well as on other activities. If a sustainable coevolution between socio-economic and environmental

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subsystems can be achieved in such a region, it can be achieved to a major extent by changing the structure of agriculture in the region. Therefore, we should look into this structure to greater detail in our analysis.

Clearly, other water-users in an agricultural region, like industry, the population at large, etc., should also be considered. But rather than going into their structural details, it suffices to consider them only in terms of demands that they make on the quantity and quality of water resources, assuming these demands as exogenously fixed.

The impacts of agriculture on the natural water system can, 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 two general aspects of these impacts are probably common to all types of regions.

The first aspect is that agriculture uses water as the resource needed to sustain its development. In many regions this negatively affects the availability of water for natural ecosystems, as well as for other regional economic activities. Depending on the region these effects are pronounced as the depletion of groundwater and surface water levels or flows, and, frequently, as a combination of both these factors.

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

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 natural water system, and in particular, on the relative influence of its surface water and groundwater parts.

An important aspect of a region is its socio-economic structure, that may include besides farmers also water supply companies, industrial enterprises, etc. It also includes various governmental and regional agencies and commissions, which may possess some degrees of regulatory powers to influence regional development. All these elements of the socio-economic structure have different preferences and possibilities for action, and they interact with each other in a complex way. This structure determines to a great extent the possibilities for directing the regional development towards achieving a proper balance between economic welfare and the state of the environment, and should, therefore, be considered in our study.

This study is based on the example of an agricultural region Southern Peel in the Netherlands, where the groundwater system plays an important role. Problems characteristic of this type of regions are looked at from the viewpoint of systems analysts who see their goal as the elaboration of a methodology, approaches and systems of mathematical models which together with other approaches can be used in addressing this type of problems.

The paper consists of 5 major sections. In the following Section 2 we describe a conceptual and methodological approach to the analyses of regional regulation policies capable of achieving a sustainable coevolution of regional socio-economic and environmental subsystems. We also sketch in that Section our general analytical approach based on a two-stage decomposition, and discuss briefly a suitable structure of the necessary system of mathematical models.

Section 3 outlines some specifics of the Southern Peel region important for this study, and Section 4 describes mathematical models of various regional processes and aspects which are linked together to form a system of models for the first-stage scenario analysis. This stage is to be used for screening analyses using automated computerized methods, and therefore, the models introduced in that section are of a simplified type.

We should remark here that in a certain sense this paper finalizes the feasibility study stage, and should, therefore, be viewed as a preliminary description of those aspects of our study which are to be elaborated by the "Regional Water Policies" project of IIASA.

Many methodological and modeling aspects outlined in this paper are the results of fruitful discussions with scientists from our principal collaborating Institutions:

- Institute for Land and Water Management Research (ICW), Wageningen, The Netherlands,

- Computing Center of the USSR Academy of Sciences (CCUAS), Moscow, USSR.

The ICW research group participated and is currently participating in practically all stages of the elaboration of models for the processes considered in the Southern Peel study.

The CCUAS group is effectively contributing to the development of the methodological basis of this study.

We would also like to acknowledge the contributions of our colleague Dr. Stefan Kaden to the discussions leading up to the simplified model of the water quantity processes in regions with shallow groundwater tables.

2. CONCEPTUAL AND METHODOLOGICAL FRAMEWORK

This study addresses the general question of how can the socio-economic development of a region be directed towards a sustainable coevolution with the environment which in many cases functions over the limit of its capacity both in the quantity of natural resources used and/or level of pollution or other types of human interventions it can endure on the long-term basis.

To the same degree of generality the goal of this study can be described as that of elaborating system-analytical tools to help obtain answers to the above question. To be able to give a more concrete description of this goal we present in the next section an outline of a conceptual framework which underlines this study and provides us with a language for describing the study more precisely. It is worth noting here, however, that the reader should not expect that we capture in this framework all aspects specific to regional systems of our interest. The following conceptualization is an abstraction that necessarily omits many of the regional aspects and emphasizes only those of them which to our understanding and knowledge are highly relevant for most regional systems on the one hand, and can be accounted for in practice-oriented methodology and analysis, on the other.

2.1. Hierarchical institutional structure of a regional socio-economic subsystem

We view a regional system under study a consisting of two major parts: the environmental subsystem and the socio-economic subsystem. These subsystems interact with each other in a variety of ways, and in the majority of real systems these interactions lead to the deterioration of the environmental subsystem which is potentially dangerous for the existence of the whole socio-economic-environmental system in the long run. Therefore, the analysis of the regional means and possibilities of controlling these interactions to provide for a sustainable long-term coevolution of the regional subsystems is an important task and is the focal orientation of the study.

Typically, regional socio-economic subsystems are of a complex hierarchical structure. They include interdependent elements (producers-users of the environmental resources, various legislative agencies, governmental and regional commissions, etc.). Each of these elements has its own preferences and possibilities for action to influence the evolution of the whole system.

The lower-level elements (users of the environment) of this subsystem are those directly interacting with the environment. These interactions depend upon the production technologies (or, generally, the environment use technologies) implemented by the users, and they use these technologies according to their preferences. Depending on the region, the use of these technologies may involve land-use practices, irrigation and other water-use practices, waste-disposal practices, and many others. The major fact is that in regional systems these local interactions are often focused on local goals and are not coordinated with each other.

On the other hand, the upper-level elements of the socio-economic subsystem (governmental, regional agencies, etc.) have preferences more closely reflecting the regional perspectives. These preferences may be related to various aspects of the regional development and reflect the goals of different agencies and regional interest groups. One important component of such preferences should also reflect concerns and interests of the regional population at large. The latter may be related to such aspects as the distribution of income among different groups of population, stability of income, the rate of unemployment, and also the quality of the environment in various parts of the region.

The upper-level elements of the socio-economic subsystem do not directly control the interactions of lower level-users with the environment, but may have varying degrees of regulation power (depending on the particular region or problem) for influencing their behavior indirectly using economic, legislative and/or other types of policies or mechanisms. These policies may include imposing constraints on the use of surface water and groundwater, on the amounts of fertilizers used in different parts of the region, various economic measures like pricing, taxing, subsidizing and others. The feasibility of various regulation policies depends on the structure of the particular socio-economic subsystem considered and therefore adequate understanding is needed of this structure and also of the preferences and possibilities of its interacting elements.

One of the major problems in this setting is which of these policies to use and to what extent to apply them in order to direct the regional development towards achieving a proper balance between its economic and social needs and the preservation of the environment.

No formal description can encompass all the aspects of a real socio-economic subsystem. The goal of an analysis based on the use of specific instruments like mathematical modeling is not to determine final solutions to a scope of real problems under study, but rather to elaborate supplementary tools that can effectively be used together with other, probably less formal approaches to obtain insights that can be of help to regional policy-makers. Any model structure chosen for the analysis should be fairly simple and yet include essential characteristic features of the real system in question. In this study we use a simplified two-level representation of the socio-economic subsystem of the form shown in Fig. 2.1.

We assume that the upper-level element of this structure (regional policy-making authority, RPMA) represents the regional perspectives and has at its disposal policies capable of influencing to a certain extent interactions of the lower level elements (producers-users) with the environmental subsystem. It is the presence of this upper-level element with a certain degree of regulation power that distinguishes regional systems of our interest.

Clearly, the above schematization appears to attribute powers to the RPMA that probably no single agency will ever possess. The reason for this apparent naivety is that the term RPMA as used here is not a single agency but rather a surrogate for a number of agencies at national, regional or district

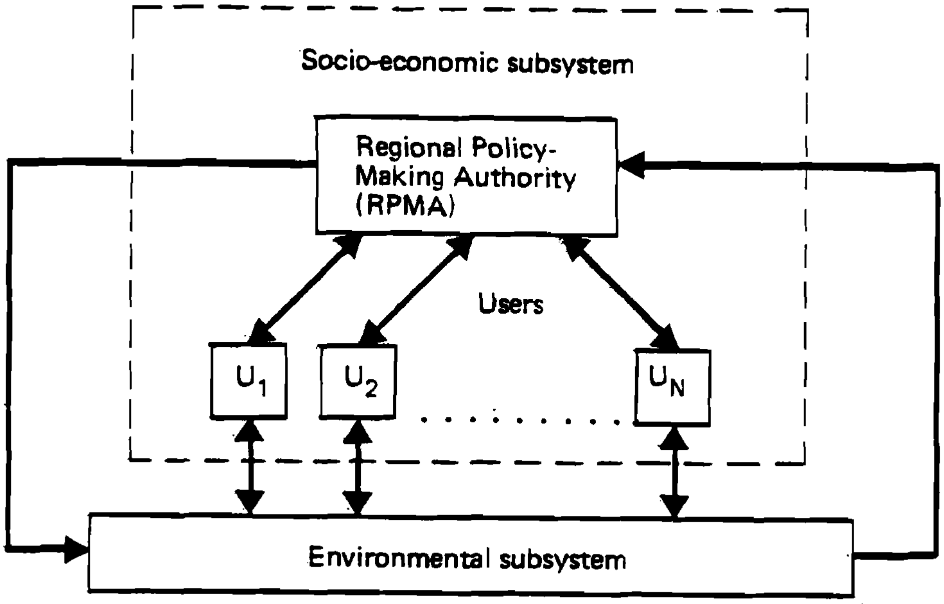

Fig. 2.1. Scheme of regional structure

level which: (1) have an interest in the development of the region in question and: (2) have regulatory powers which can influence this development. Of course, these agencies do not have the same objectives, therefore, the single RPMA concept is an obvious first approximation. But, nevertheless, this approximation can be a useful starting point for further research in this direction using more comprehensive institutional models and analytical procedures.

2.2. Decomposition analytical approach

Apparently, an accurate formalization and analysis of the above two-level structure of the socio-economic subsystem requires simultaneous consideration of preferences and actions (and reactions) of all of its interrelated elements. This formalization based on the concepts of the hierarchical game theory (see Ereshko and Vatel, 1977; Germeyer, 1976) helps conceptualize and understand the nature of regulation policies and decision processes in systems of this type, and also indicate the lines of the analysis. After having elaborated this framework for the context of the present study, we will present it in a separate publication.

But being certainly useful conceptually and methodologically this formalization is often too complex for its straightforward computational implementation. Recognizing this, we use in this study a heuristic approach based on what may be referred to as two-stage decomposition of the analysis. This approach facilitates qualitative analyses of various types of regulation policies, and is also suitable for the implementation of interactive analytical means.

The first stage of the analysis using this approach is directed towards generating trajectories of the potentially rational development of the system under study. At this stage the analysis aims at the evaluation (based on the preferences of the RPMA) of the possibilities of the regional development in terms of the regional indicators of effectiveness. No behavioral aspects of the lower-level elements are considered explicitly at this stage, and the analysis results in generating in some sense a reference trajectory of regional development. This trajectory is based on trade-offs among goals of different regional interest groups. We call this trajectory a reference scenario of regional development. This scenario is described in terms of the essential parameters of the socio-economic and/or of the environmental structure of the system. Various approaches to regional planning with the explicit consideration of the environmental processes may be used for this analysis.

After having determined a reference scenario, the second stage of analysis is concerned with the search for those feasible regulation policies that influence the behavior of the users and by doing that can direct the development of the whole system along the lines specified by the reference scenario obtained at the first stage.

Since the first stage of the analysis is performed without explicitly considering feasible regulation policies, the scenario obtained at the first stage may be practically unattainable, or, in other words, no one of the feasible policies may provide for the realization of this scenario. In such cases, the analyst will have to come back to the first stage and search for another "less ideal" scenario that is attainable using some of the feasible regulation policies. Moreover, feasible policies may differ from each other in their "degree of feasibility" (for an example, two policies may differ from each other by the public reaction to their implementation). Recognizing this factor, an environmentally and/or economically less effective scenario may have to be considered that may be achieved using those "more popular" regulation policies.

Schematically, this decomposition analytical procedure is illustrated in Fig. 2.2.

The scenario module is designed for the analysis and generation of trajectories of future regional development which are potentially rational from the viewpoint of the overall regional perspectives. A concrete realization of this module can be different for different regions and we will outline here only some general principles that should be followed in this study. We leave its more detailed description for the subsequent sections where we discuss a concrete realization of this module for the Southern Peel region of the Netherlands:

- The module should have the form of a hierarchically structured system of mathematical models embedded in a computer software facilitating the analysis.
- The first level of this structure should be based on simplified agregated models of the relevant interrelated economic and environmental regional processes. These models are designed for screening analyses using optimization procedures and interactive techniques for multiobjective choice.
- The second level should include more detailed models of the processes under consideration and their interelations. These models are designed for simulation runs to verify and to estimate more accurately the scenarios (trajectories of regional development) obtained at the first level.
- Both levels should be used as repetitive iteration steps in an integrated analytical procedure which should be highly interactive and reasonably fast.

A scope of related problems here includes choices of adequate and analytically convenient spatial and temporal scales for models at both the levels of the system, organization of an iterative analytical procedure based on this hierarchy, adequate formalization of the preferences of the RPMA (for example, in the form of multiple objective functions), adequate use of available information about uncertain factors in the analytical procedure and in the

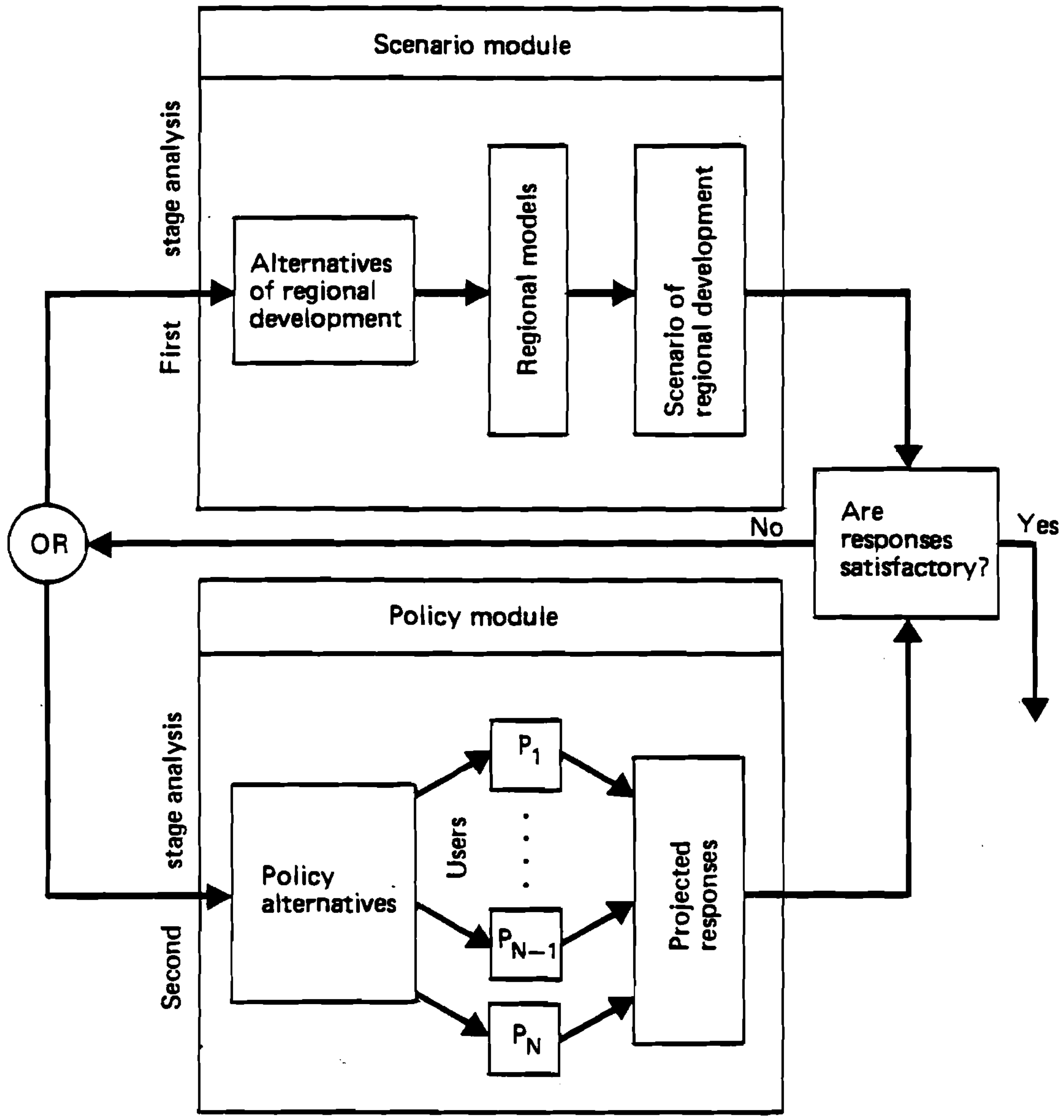

Fig. 2.2. Schematic of decomposition approach.

interpretation of the results, and of course, problems of technical computer implementation of the system.

The policy module is designed for the second-stage analysis of the reactions of the lower-level elements to various policy options considered by the RPMA. It is important to note here that the whole analysis is performed "on behalf" of the RPMA (or by the RPMA itself), therefore, its second stage depends strongly on the knowledge that the RPMA has (or can obtain) about the behavior of the lower-level elements, since this knowledge is used to project possible reactions of these elements to choices of various policies by the RPMA. And it is apparent that besides using more or less formal mathematical descriptions of this behavior, less formal approaches should be applied including discussions with experts, with representatives of the respective interest groups, gaming approaches, and other methods. This latter aspect necessitates the elaboration of interactive analytical methodologies and procedures and also their incorporation into the computer software supporting the analysis.

2.3. Aspects of scenario analysis

Models of the scenario module represent a formal description of the regional system under analysis characterized by state variables (e.g. yearly incomes of the farmers, seasonal average groundwater tables, etc.), by control variables* (e.g. yearly crop allocation patterns, irrigation rates, etc.), and also by parameters which can not be controlled and are "chosen by nature" (e.g. yearly precipitations, temperatures, etc.).

We can understand the state variables as components of the state vector of the system considered. The state variables can roughly be classified into those related to economic aspects and those describing the state of the environment or the impacts on it from the socio-economic subsystem. Using this classification we can distinguish between state vectors of the system having various degrees of trade-offs among their economic and environmental components. And on the basis of the regional preferences (of the RPMA) we can speak about state vectors having more preferable trade-offs than the others.

* We should remind here that at this first stage of analysis the RPMA (or the analyst on its behalf) performs the analysis without considering behavioral aspects of the lower-level elements of the region and, therefore, can to a certain extent "play" freely with the control variables many of which are in reality controlled by the lower level elements of the socio-economic subsystem.

Furthermore, we can speak about a subset S of such preferable state vectors in the set of all possible state vectors. Let us now view any pattern of regional development as a trajectory in this latter set of all state vectors.

Using this language, we can say that the scenario analysis aims at the determination of values of the control variables which can provide for the system's transition from its current state into the set S. But some components of the state vector can be changed only gradually in time due, for instance, to the specific characteristic times of the respective processes. This means that the transition of the system from its current state into the set S would require a certain time period. We refer to this period as the transition period and view it as one of the unknowns of the system that is to be estimated in the course of the analysis.

To obviate the analytical and computational difficulties associated, among other things, with the explicit description of the subset S of preferable state vectors the following procedure can be sugested. At first we determine some state of the system that belongs to the set of preferable states S. This state, that we refer to as a target state, should firstly be characterized by acceptable trade-offs among its economic and environmental components, and secondly, ensure that there exists a trajectory that originates from this state and does not leave the set S in the future.

Then we look for trajectories of the system's transition from its current state which either pass through this state or through some state close to it. In case such a trajectory does not exist, the state found is not reachable and we should look for another target state in S, and repeat the analysis until a reachable state in S is found together with a trajectory leading from the current state to this target state, or at least passing in its acceptable vicinity. Two important aspects of scenario analysis should be considered.

The first aspect is the multiobjective nature of the problems involved. As has already been discussed in the previous sections, the interlinked first-level regional models are designed for fast generation of reference scenarios which are potentially rational, or more precisely, which do not appear very irrational and are, therefore, worth analyzing further using more detailed second-level models of the scenario module. Regional preferences of the RPMA are described in these models in terms of a number of indicators, and therefore, choices of rational scenarios can only be based on the determination of Pareto nondominated alternatives for these indicators. The common nonuniqueness of such alternatives in multiobjective choice problems necessitates the use of interactive analytical procedures through which additional preferences of the RPMA can be taken into account which have not been formalized in the model. Various procedures and elaborated software systems can be used for this purpose. We can mention DIDASS - a system developed by the SDS Program of IIASA [Grauer et al., 1982], and The Generalized Reachable Sets System developed at the Computing Center of the USSR Academy of Sciences [Lotov, 1982].

The second aspect is the presence in the models of parameters which are not controlled by the RPMA and the future values of which are not known to RPMA (e.g. meteorological conditions, prices and other economic parameters, etc.) Only some information about these parameters based on past observations of their values or on experts' judgements can be used in the analysis but this information is not sufficient for the description of the future states of the system unambiguously. This fact should be taken into consideration both in the mathematical formulations of the problems to be solved using the scenario module, in the solution procedures themselves, and also in the interpretation of the analytical results. In real problems, uncertain factors can often be adequately modeled as stochastic variables and the available information about their values can be interpreted in probabilistic terms. In such cases any solution to the problem considered should also be interpreted in probabilistic terms since no alternative can unambiguously guarantee any particular future performance of the system under analysis.

As has been said in the Introduction, the Southern Peel region in the Netherlands is used as an experimental basis for this study. Therefore, we use the remaining part of this paper to outline aspects of this region related to this study, and also to formulate mathematical first-level models of the basic processes which we plan to include into the scenario module for this study.

3. THE SOUTHERN PEEL REGION

Environmental setting

The Southern Peel is an undulating area, of about 30,000 ha in the south of the Netherlands (Fig. 3.1). The lie of the land varies in altitude between 17 and 35 m above sea level.

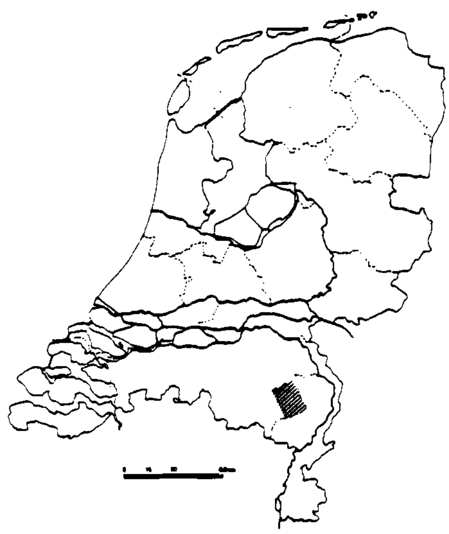

Fig. 3.1 Location of the Southern Peel Region in the Netherlands

A major feature of the hydrogeology (for a schematic representation see Fig. 3.2) is the presence of a fault that divides the area into a Western part — the "Slenk" — which has a deep hydrological basis at 300-500 m below ground level, and an Eastern part — the "Horst" — which has a shallow hydrological basis at 8-36 m. Geologic formations that were deposited after the main period of faulting (and the concurrent erosion of the higher land, the Eastern part) are present in the whole region. These are the Nuenen group, which reaches to a depth of 15-20 m in the Slenk area and to 5-10 m in the Horst area, and the Veghel-Sterksel formation, which in the Slenk area reaches to 50-70 m and to the hydrological basis at 8-36 m in the Horst area. The phreatic aquifer — the Nuenen group — consists of fine sand, sandy loam and loam, the Veghel Sterksel formation of coarse and sometimes gravel-bearing sand. In the Northern part of the Slenk, the clayey Kedichem/Techelen formation is at the base of the Veghel-Sterksel sands. In the Southern Slenk this clay, which forms a resistance to vertical flow, is absent, and the Veghel-Sterksel sands are directly underlain by the Kieselolite formation. This formation extends to the hydrological basis and consists of fine sand, coarse gravel-bearing sand and humic clay beds. Owing to the absence of the Kedichem/Techelen formation and the relatively high altitude, in the Southern Slenk there are more possibilities for percolation to the deep groundwater than in the Northern Slenk. In general, the land in the Southern Slenk has a good natural drainage, in contrast to the rest of the region.

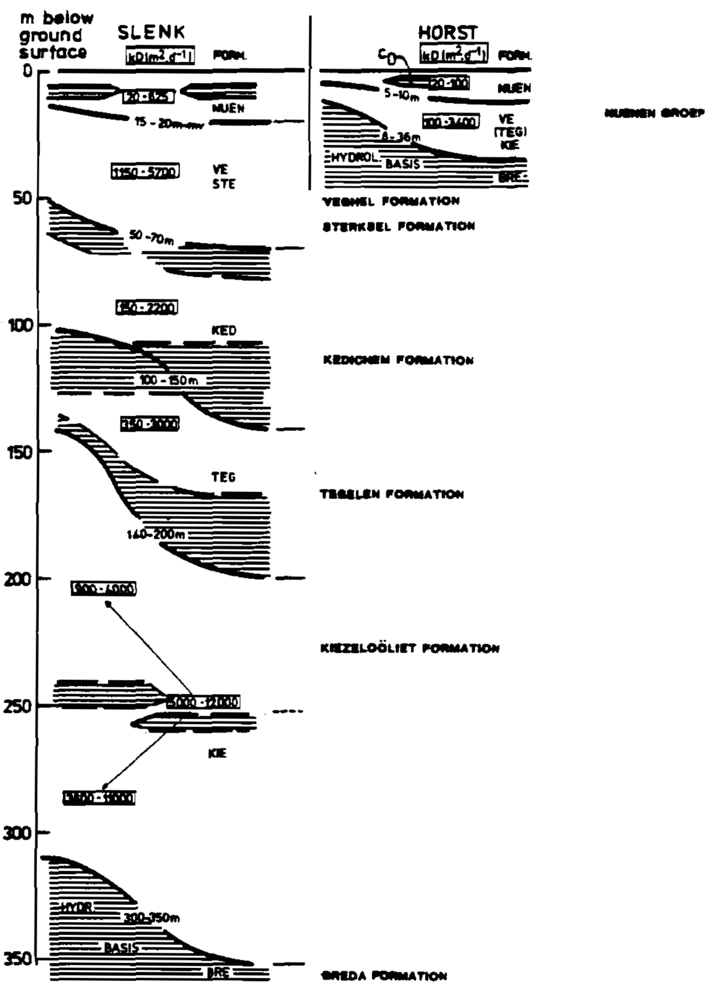

Fig. 3.2 Schematic representation of hydrogeology

A large part of the area used to be covered by a layer of peat, that grew as a consequence of extremely high groundwater levels. Most of the peat has been delved and used as fuel for heating. The remaining peat areas are now protected from exploitation, because of their value as recreation or nature areas. The nature areas can only keep their value if high enough groundwater levels are maintained. This is because the vegetation has a high water demand that is partly supplied by capillary rise of moisture from the groundwater to the rootzone; a groundwater level lowering would reduce the capillary rise, and the vegetation would suffer from water deficits in dry years. A groundwater level lowering would also increase the soil aeration, causing oxidation of peat, thereby releasing mineralized forms of nitrogen and phosphorus. This eutrophication would improve circumstances for the introduction of species with a high nutrient demand, thus endangering the continued presence of the "natural" species. Eutrophication can also take place by upward seepage of nutrient-rich groundwater.

Human activities and their impacts

Roughly half of the agricultural land is used as pasture for dairy cattle; the remaining area is used for growing a variety of crops, of which maize is the most important one, followed by sugarbeets, potatoes and cereals. The agricultural productivity is influenced by many factors. Here we will only consider those that are of principal importance for this study, i.e. the moisture and nutrient supply of crops.

Due to the shallowness of the groundwater tables, which in the Southern Peel are mostly between 1 and 2 *m* below ground level, a substantial part (up to one third) of the moisture required for crop growth can be supplied by capillary rise of moisture from the subsoil to the rootzone. The other "natural" sources of moisture are soil storage (which is filled by the winter precipitation) and precipitation during the growing season. The availability of moisture for crop growth is evidently influenced by meteorological conditions, and therefore varies from year to year. Depending on the soil type, the groundwater conditions, and to a certain extent on the type of crop, in a certain percentage of years there is a moisture deficit, which causes a crop production loss. Of special interest for this study is that activities in other parts of the region can have an impact on crop productivity through influencing the groundwater conditions, by for instance pumping water from a well.

Farmers try to reduce moisture deficits by water conservation, subirrigation, and sprinkler irrigation. The practised water conservation consists of raising water levels in drainage ditches at the end of spring, to reduce the outflow of groundwater; this increases the availability of moisture for capillary rise to the rootzone of crops. The same is achieved by subirrigation, which is the infiltration of imported surface water in the bottoms of ditches, thereby raising groundwater levels in neighboring fields. Sprinkling is a more direct way of supplying water to the soil. Water for sprinkling is pumped from the groundwater or taken from the surface water supply system. This pumping from groundwater affects agricultural production in other parts of the region and also the conditions in nature areas. In the Southern peel, the surface water supply system coincides with the drainage system. It consists of some larger canals and a network of ditches and brooks with a varying density (Fig.3.3).

As is characteristic of all regions with intense agriculture, farmers in the Southern Peel attempt to optimize the nutrient supply conditions of their crops. Both chemical fertilizers and animal slurries are used for this purpose. The urge to heavily fertilize agricultural land stems, however, not only from considerations of optimizing the nutrient supply of crops, but also from the circumstance that in the Southern Peel there is a tradition of factory farming. This factory farming produces large quantities of slurry from cattle, pigs and chickens. These quantities cannot be disposed of by fertilization at the optimal level. This has resulted in heavy over-fertilization of maize fields and dumping of slurry on fallow pieces of land. (Over-fertilization normally causes a decrease in crop production, but maize is not so sensitive to it.) The soils in the Southern Peel are sandy and therefore have poor purification and fixation capabilities. So the excess nitrate is easily leached, thus increasing the nitrogen load on groundwater. The soils contain enough iron to fix the excess phosphate for still quite a number of years, but not forever. After the saturation point has been reached, the phosphorus load on groundwater will also increase. The pollution by nitrate and phosphate lowers the value of groundwater as a resource for use as drinking water and can cause eutrophication of nature areas. Indirectly it also causes additional pollution of surface water by drainage of nutrient-rich groundwater to ditches.

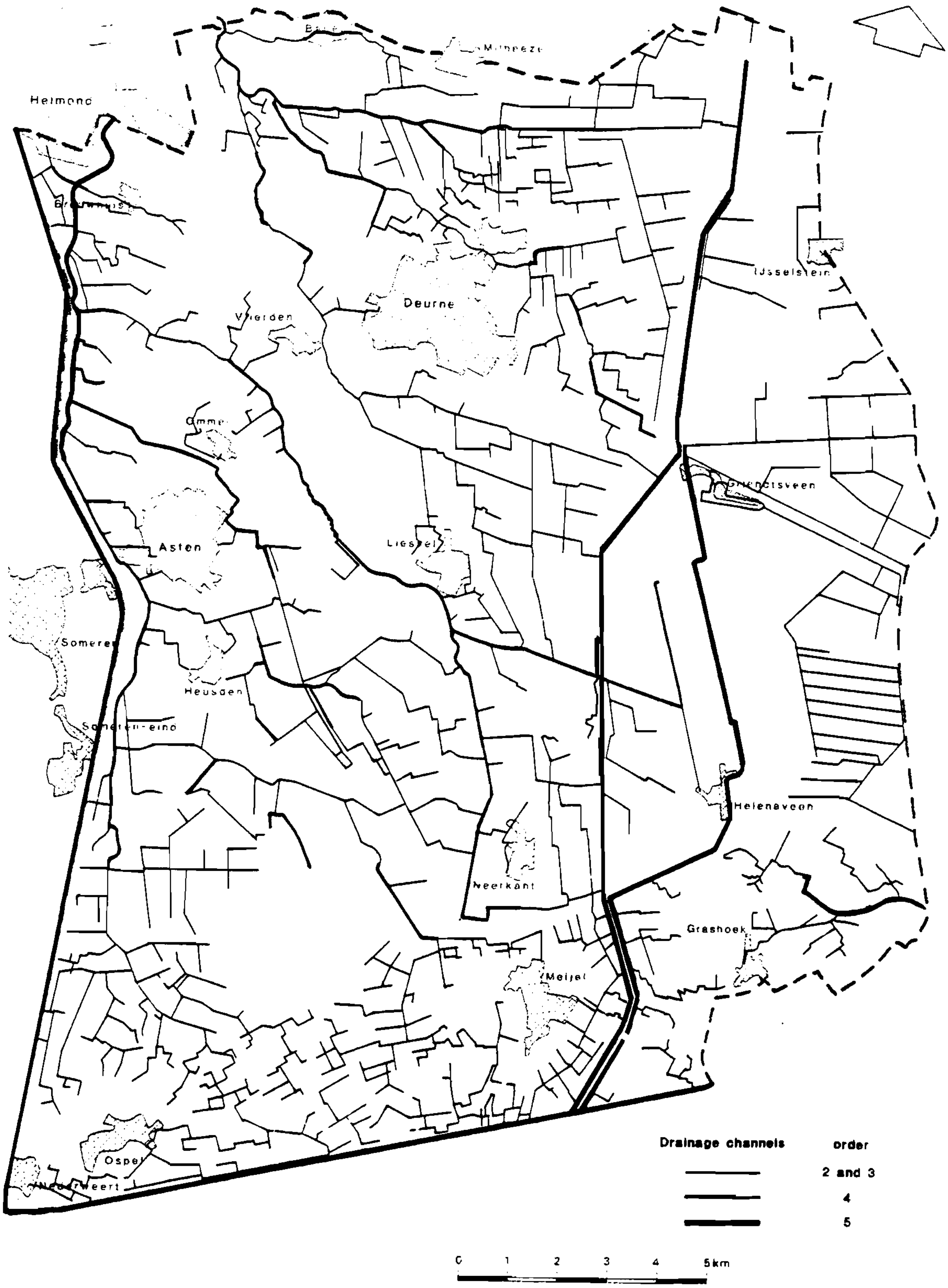

Fig. 3.3 Surface water system

Most of the surface-water pollution by agriculture is, however, through surface runoff that has high concentrations of nutrients. The factory farming produces slurry continuously throughout the year. In order to avoid the costs of storage, farmers not only spread slurry on fields during spring but also during autumn. This greatly increases the concentrations of nutrients in the surface runoff that is caused by the winter rains. (In the Southern Peel surface runoff only occurs as a consequence of waterlogging during the winter.)

The population, industry, and factory farming need in total about 10 million m^3/p.a. of high quantity water for their use. This water is extracted from the aquifers in the Slenk area by public water supply companies. The mentioned amount represents roughly 20% of the precipitation surplus (i.e. precipitation minus evapotranspiration) of the Slenk area. The resulting lowering of groundwater tables reduces the capillary rise of moisture from groundwater to the rootzone, thereby decreasing the productivity of agriculture and deteriorating conditions in nature areas. Apart from reducing the moisture supply to the vegetation, lowering of groundwater levels that are within 1 *m* of the ground surface increases the nitrogen load on groundwater, as evidenced by Verdonschot(1981).

The quality of the extracted groundwater 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, and that action to curb the nitrate pollution of groundwater is urgently needed.

A schematic diagram of the main impacts of human activities in the Southern Peel is given in Fig. 3.4 .

Institutional aspects and their formal outline

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

*The European Economic Community has stipulated that 50 mg/l is the highest nitrate level that is acceptable. Also, it has prohibited the mixing of low-concentration with high concentration water. (This makes it easier to check on the compliance with the stipulated maximum level.)

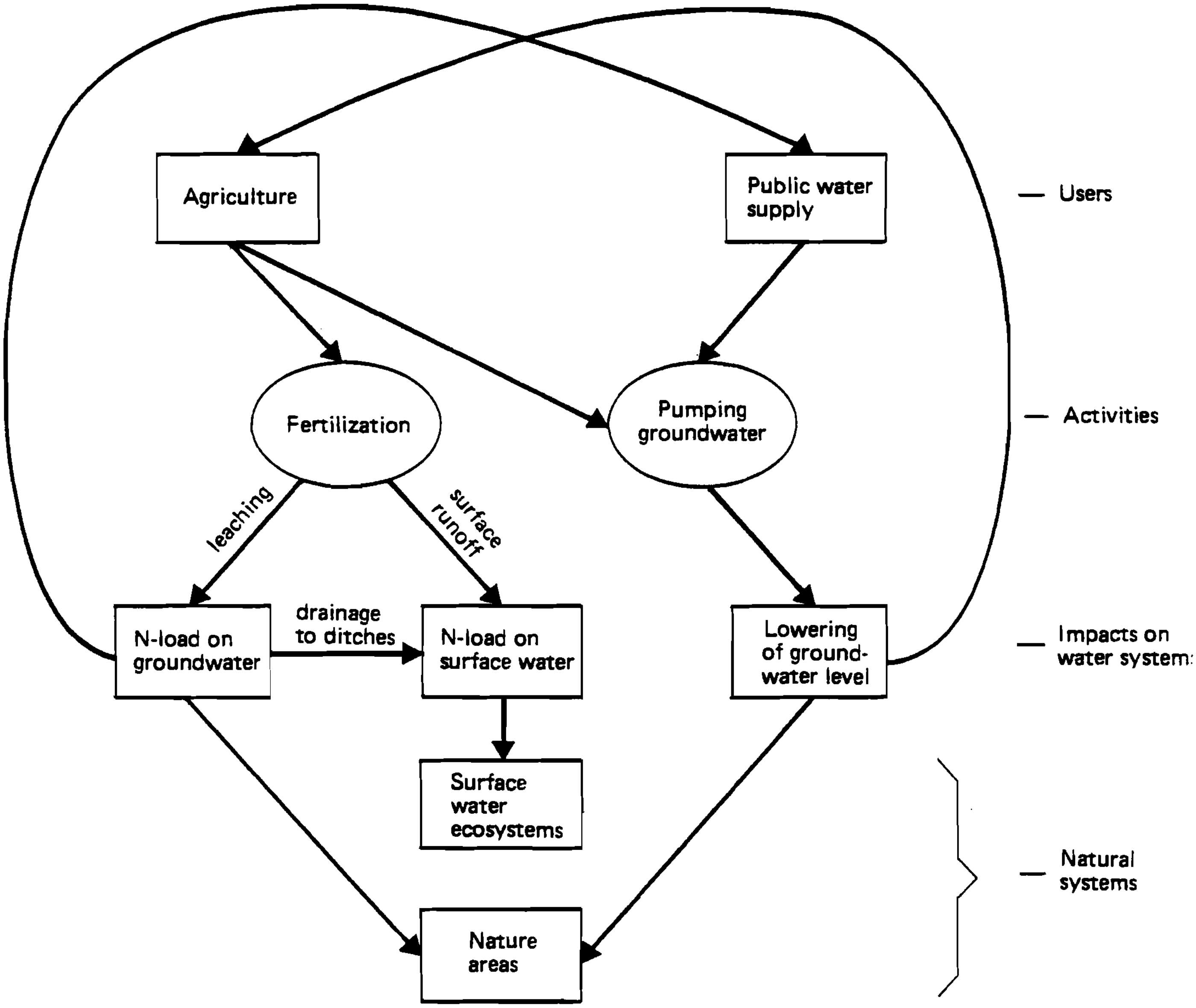

Fig. 3.4 Main impacts of human activities

- the Ministry of Public Works;

- the Ministry of Agriculture and Fisheries;

- the Ministry of Welfare, Health and Cultural Affairs;

- the Ministry of Housing, Physical Planning and Environment.

Each of these ministries have their own organizations for guarding their interests and performing their 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 in summer are used for importing surface water. 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 the conceptual and methodological framework of this study we will use the concept of the RPMA as a surrogate for the institutions mentioned above. We assume that the preferences of the RPMA are related to the region as a whole and therefore reflect preferences of all regional interest groups. We describe these preferences in terms of indicators of regional development. In this study the following interest groups are considered:

- farmers,

- public water supply companies,

- nature conservation groups.

Reflecting preferences of farmers we consider the following types of indicators:

- 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 also consider two types of indicators reflecting RPMA's expenditures for changing the infrastructure of the region:

- costs of infrastructure for surface water supply.

- costs of water purification plants,

The RPMA is in the special position of being able to impose restrictions on the other interest groups, albeit that it can not completely control their behavior. In view of its concern for the well-being of the region as a whole, the RPMA 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 RPMA considered are 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 the 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,

- subsidizing investments of farmers,

- 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 the cropping pattern,

- investing in water conservation and irrigation technologies,

- changing the fertilization practices,

- changing the intensity of factory farming.

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

- investing in new wells.

According to our decomposition scheme, at the first stage of the analysis (scenario analysis) the RPMA performs the analysis without explicitly considering behavioral aspects of farmers and drinking water supply companies. Therefore we assume that the RPMA can at this stage play "freely" with the actions of these interest groups, whereas in reality many of these actions are controlled by the farmers and drinking water supply companies themselves.

The stage of scenario analysis is based on the use of a system of models constituting the scenario module. As was outlined in Section 2 of this paper this system of models should have a hierarchical structure with simplified models for screening analyses on the first level. These first level-models are described in the remaining part of this paper.

4. SCENARIO MODULE (First-level models)

4.1. Introduction

The scenario-module takes into account the following interrelated processes:

1. Agricultural production, economic development of agriculture in terms of incomes, consumptions, savings, investments, changes in land use, changes in factory farming, 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 slurries, nitrogen mineralization of slurries, leaching of nitrate to groundwater, and denitrification processes.

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

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 the models existed already, some have been developed specially for the purpose of this study, and some are still in the process of being developed, meaning that changes in model structure are likely.

Common to all the proposed first-level models is that they use a time-step of ***half*** a year; "summer" starts on April 1, "winter" on October 1. The hydrological year has been taken from the beginning of *winter*.

The spatial resolution for the models is provided by a division into 31 subregions (Fig. 4.1), based mainly on classes of groundwater conditions.
These classes range from "I" for extremely high groundwater levels to "VII" for relatively deep groundwater levels (Table 4.1). In Fig. 4.1 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.

Table 4.1 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 groundlevel*.

4.2. Technologies

We use the term technology for a combination of agricultural activities involved in growing and processing of a certain crop and/or livestock. We assume that technologies differ from each other by their outputs and also by the inputs required to produce these outputs. For convenience, we will distinguish between agricultural technologies that use land and those that do not. The set of the former will be denoted by *JX*, the set of the latter by *JZ*. It will also be convenient to further subdivide the set *JX* into subset *JXL* of land-use technologies involving livestock, and the subset *JXD* of land-use technologies not involving livestock. We will make a similar subdivision of the set JZ into subsets *JZL* and *JZD*.

All technologies considered are explicitly characterized by the following types of inputs (resources): labour, capital, water. Land-use technologies of the set *JX* are additionally characterized by the input of nitrogen supplied by fertilization*.

* 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.

ANNEX A

SUBREGIONS IN THE SOUTHERN PEEL AREA

based on hydrological and soil physical characteristics

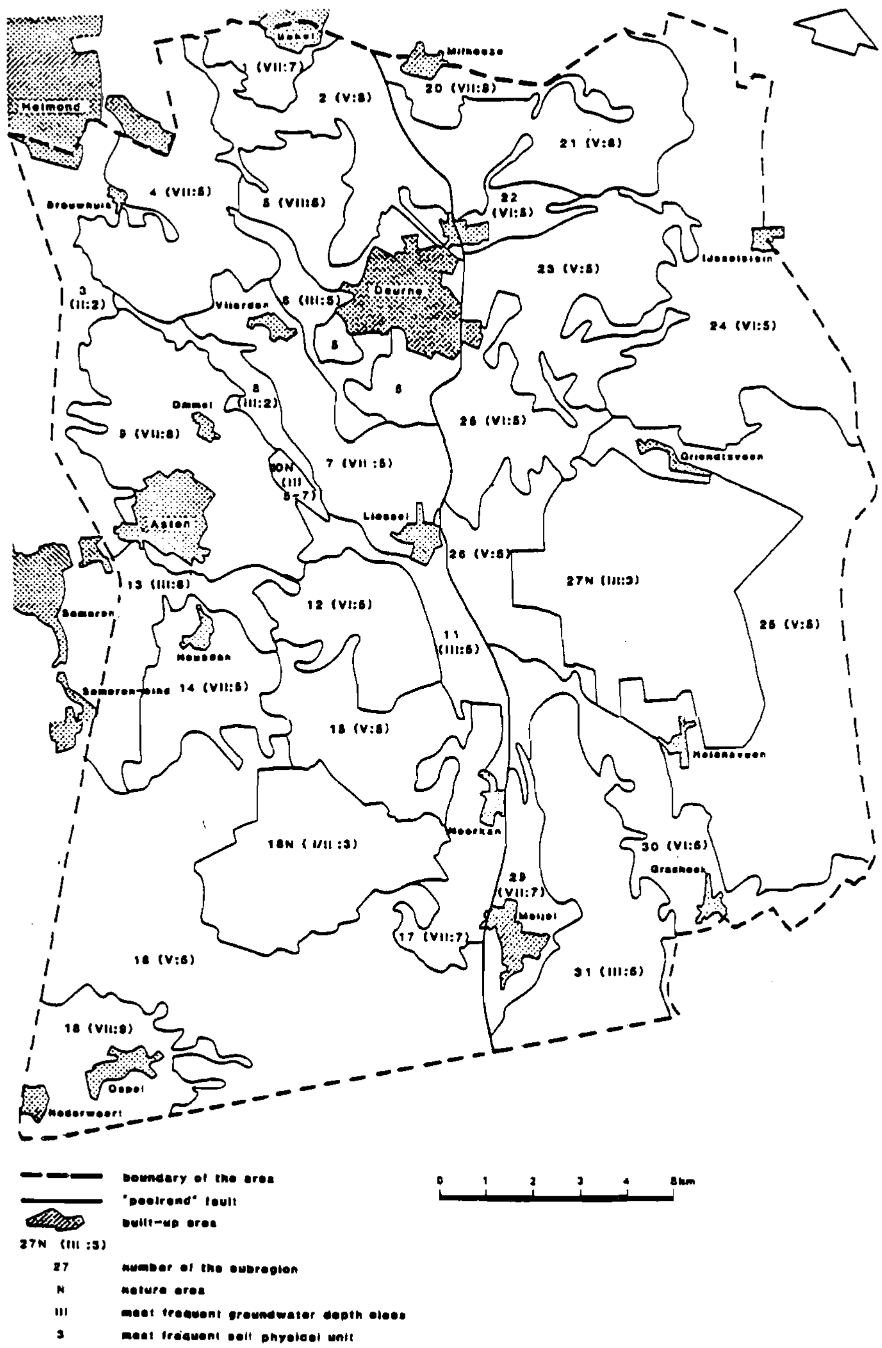

Fig. 4.1. Division into subregions.

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 slurries 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 (from set *JZL*) intensities have the meaning of a number of livestock-heads; for a technology from the set *JZD*, the intensity may have the meaning of for instance the amount of pig slurry transported to outside the region.

We assume that such inputs as labour and capital for every technology can be represented by corresponding quantities per unit of its intensity. (For example, amount of labour per unit area of land for a technology from set *JX*.) We can also quite adequately assume that the water inputs for technologies not using land can be quantified in the same normative way (amount per unit intensity).

But the situation is different with describing water inputs and the corresponding outputs for land-use technologies. One reason for this difference is that both the water availability and the output of land-use technologies depend on weather conditions. Another reason is that the availability of water is also influenced by activities in the region, especially pumping of groundwater. In order to take into account the respective possible variations in the performance of land-use technologies, we will consider a finite number of options for each such technology, which cover a suitable variety of typical water availability situations in each subregion. For the sake of brevity we will use the term subtechnology to refer to such an option.

Each of subtechnologies k is characterized by the crop productivity cp_k, by the corresponding seasonal averages of the soil moisture vr_k and of actual evapotranspiration ea_k, as well as by the total nitrogen requirement nr_k (all amounts per unit area of land). The value vr_k is treated in our model as the "demand" for soil moisture, the satisfaction of which (together with the satisfaction of the requirement for nitrogen) guarantees obtaining the crop productivity not lower than cp_k*. We should note here that the three interrelated

* We can also put this in the following way: the satisfaction of the demands vr_k and nr_k is the necessary condition for the implementation of subtechnology k.

parameters cp_k, vr_k, and ea_k are weather dependent, and therefore should be treated as uncertain parameters in the analyses.

In the remaining part of this section we describe those aspects of technologies that do not involve environmental processes. Those aspects that do involve environmental processes — the satisfaction of the moisture and the nitrogen requirements — are described in subsequent sections.

Intensities of technologies

We introduce the following notation for intensities of technologies and subtechnologies (r - subregion, j - technology, k - subtechnology, t - year):

$x(r,j,t)$ – area of land allocated to technology $j \in JX$,

$xw(r,j,k,t)$ – area of land allocated to subtechnology k of technology $j \in JX$,

$z(r,j,t)$ – intensity of technology $j \in JZ$.

Then we obviously have

$$x(r,j,t) = \sum_k xw(r,j,k,t). \tag{4.1}$$

for all r, $j \in JX$, t.

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

$$\sum_j x(r,j,t) \le xa(r), \tag{4.2}$$

Other areal 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. These constraints involve areas of land allocated to certain crops. For the purpose of describing the aforementioned constraints we group the technologies into subsets $C_1, C_2, \ldots, C_L$ for the respective crops. Then the area of land allocated for crop l is constrained as follows:

$$\sum_{j \in C_l} x(r,j,t) \le xmax(r,l), \tag{4.3}$$

where $C_l \supset JX$, and $xmax(r,l)$ is exogenously fixed.

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 we introduce the *increments* and *decrements* of intensities of certain technologies as (non-negative) variables:

$$x(r,j,t) = x(r,j,t-1) + x_i(r,j,t) - x_d(r,j,t), \quad (4.4)$$

$$z(r,j,t) = z(r,j,t-1) + z_i(r,j,t) - z_d(r,j,t), \quad (4.5)$$

where

i – suffix for increment,

d – suffix for decrement.

Sprinkling capacities

Implementation of land-use technologies in a subregion may be supported by sprinkling irrigation. The potential for this type of irrigation in a subregion is characterised by:

$sc(r,t)$ – capacity for sprinkling from surface water,

$gc(r,t)$ – capacity for sprinkling from groundwater.

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

$$sc(r,t) = sc(r,t-1) + sc_i(r,t) - sc_d(r,t), \quad (4.6)$$

$$gc(r,t) = gc(r,t-1) + gc_i(r,t) - gc_d(r,t), \quad (4.7)$$

where i and d are respectively suffices for increments and decrements of the corresponding capacities.

Animal slurry byproducts

The technologies that involve livestock produce animal slurries as byproducts. These slurries 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 slurry can temporarily be stored in tanks. From a water quality point of view, animal slurry that is produced during the summer can best be stored till the next spring and only then be applied to the land, because application of animal slurries in autumn increases the nitrogen and phosphorus content of surface runoff and the nitrogen content of the winter percolation to the groundwater. The storage at the end of winter, just before the spring application, must not exceed the slurry storage capacity. Assuming that after the spring application in the year before the tanks were empty, the constraint on the amount of slurry in storage at the end of winter is described by:

$$\sum_{j \in JZ} mz(j,m) \cdot [z(r,j,t-1) + z(r,j,t)] + \sum_{j \in JXL} mxw(j,m) \cdot x(r,j,t) - \sum_{j \in JX} ma(r,j,m,t) \le mc(r,m,t) \qquad (4.8)^*$$

where

$mz(j,m)$ – half-year production of slurry m per unit of technology $j \in JZ$,

$mxw(j,m)$ – winter production of slurry m per unit of technology $j \in JXL$,

$ma(r,j,m,t)$ – autumn application of slurry m to technology $j \in JX$

$mc(r,m,t)$ – storage capacity for slurry of type m.

The summer slurry production of land-use technologies that involve livestock (from set JXL) is not included in these equations because this slurry is in virtue of its nature inherently applied to land. Of the technologies that do not use land, some of them produce slurry (all technologies of the livestock set JZL), whereas others "consume" it (some of the technologies of the set JZD, e.g. transport to outside the region). In the latter case $mz(j,m)$ is negative. The assumption that after the spring application the tanks are empty, is only valid if the application in spring equals the slurry storage at the end of winter (cf. Eq. 4.8):

$$\sum_{j \in JZ} mz(j,m) \cdot [z(r,j,t-1) + z(r,j,t)] + \sum_{j \in JXL} mxw(j,m) \cdot x(r,j,t) - \sum_{j \in JX} ma(r,j,m,t) = \sum_{j \in JX} ms(r,j,m,t) \qquad (4.9)$$

where

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

$ms(r,j,m,t)$ – spring application of slurry m to technology $j \in JX$

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

$$mc(r,m,t) = mc(r,m,t-1) + mc_i(r,m,t) - mc_d(r,m,t). \qquad (4.10)$$

Labour requirements

An important aspect of the technologies is the amount of labour required for their implementation. Activities that involve employment of labour are cultivation of land (ploughing etc.), application of chemical fertilizer and animal slurry, sprinkling, factory farming and other technologies that do not use land. The total amount of labour required in the region is described by the following equation:

$$l(t) = \sum_r \{ \sum_j [lx(j) \cdot x(r,j,t) + lfs \cdot fs(r,j,t) +$$

$$\sum_m [lms(m) \cdot ms(r,j,m,t) + lma(m) \cdot ma(r,j,m,t)] + \qquad (4.11)$$

$$lis(r) \cdot is(r,t) + lig(r) \cdot ig(r,t) + \sum_j lz(j) \cdot z(r,j,t) \},$$

where

$l(t)$ – labour required in the region,

$lx(j)$ – labour requirement of technology $j \in JX$,

$lz(j)$ – labour requirement of technology $j \in JZ$,

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

lfs – labour requirement for application of chemical fertilizer,

$ma(r,j,m,t)$ – autumn application of slurry m to technology j,

$ms(r,j,m,t)$ – spring application of slurry m to technology j,

$lma(m)$ – labour requirement for autumn application of slurry,

$lms(m)$ – labour requirement for spring application of slurry,

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

$ig(r,t)$ – amount of sprinkling from groundwater,

$lis(r)$ – labour requirement for sprinkling from surface water,

$lig(r)$ – labour requirement for sprinkling from groundwater.

If the amount of required labour is less than the amount available, there is unemployment. If on the other hand, the former exceeds the latter, this means that additional labour is employed from outside the region. To take these factors into consideration, we introduce the following notation:

$lp(t)$ – amount of labour available in the region,

$lu(t)$ – amount of unemployed labour in the region,

$lh(t)$ – amount of labour hired from outside of the region.

Using these notations we can write:

$$lp(t) + lh(t) - lu(t) = l(t), \tag{4.12}$$

with $l(t)$ being defined by equation (4.11).

Constraints on the amounts of unemployed and hired labour are determined exogenously:

$$lu(t) \leq lumax(t), \tag{4.13a}$$

$$lh(t) \leq lhmax(t). \tag{4.13b}$$

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 apparatus, slurry storage tanks) the replacement costs should be included explicitly.

Let us introduce the following notation:

$y(t)$ – income from agriculture in the region,

$yx(r,j,k,t)$ – income per unit area of land for a subtechnology k,

$xw(r,j,k,t)$ – area of land for a subtechnology k,

$yz(r,j,t)$ – income per unit intensity of technology $j \in JZ$,

$peis(r,t)$ – energy cost of sprinkling from surface water,

$peig(r,t)$ – energy cost of sprinkling from groundwater,

pf – price of chemical fertilizer,

$fs(r,j,t)$ – amount of chemical fertilizer applied in spring,

$lh(t)$ – amount of hired labour used in the region,

$plh(t)$ – price of hired labour,

$rsc(r,t)$ – replacement cost of capacity for sprinkling from surface water,

$rgc(r,t)$ – replacement cost of capacity for sprinkling from groundwater,

$rmc(r,m,t)$ – replacement cost of slurry storage capacity.

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

$$y(t) = \sum_r y(r,t) = \sum_r [\sum_j \sum_k yx(r,j,k,t) \cdot xw(r,j,k,t) + \sum_j yz(r,j,t) \cdot z(r,j,t) -$$

$$peis(r,t) \cdot is(r,t) - peig(r,t) \cdot ig(r,t) - pf \cdot \sum_j fs(r,j,t) - \qquad (4.14)$$

$$rsc(r,t) \cdot sc(r,t) - rgc(r,t) \cdot gc(r,t) - \sum_m rmc(r,m,t) \cdot mc(r,m,t)] -$$

$$plh(t) \cdot lh(t).$$

Cumulative savings

We assume in our analyses that agricultural development of the region must be financed from its cumulative savings, and not by borrowing capital from outside the region. To write down the expression for cumulative savings we introduce the following additional notations:

$cs(t)$ – cumulative savings of the region,

$cl(t)$ – consumption per unit of available labour,

$px_i(r,j,t)$ – investment cost per unit of $x_i(r,j,t)$,

$px_d(r,j,t)$ – liquidation value per unit of $x_d(r,j,t)$.

Coefficients pz_i, pz_d, psc_i, psc_d, pgc_i, pgc_d, pmc_i, pmc_d have similar meanings.

Using these and previously introduced notations we can write the expression for the cumulative savings for the whole region as follows:

$$\begin{aligned} cs(t) = cs(t-1) + y(t) - lp(t)\cdot cl(t) - \\ \sum_r \{ \sum_j [px_i(r,j,t)\cdot x_i(r,j,t) - px_d(r,j,t)\cdot x_d(r,j,t)] + \\ \sum_j [pz_i(r,j,t)\cdot z_i(r,j,t) - pz_d(r,j,t)\cdot z_d(r,j,t)] + \\ psc_i(r,t)\cdot sc_i(r,t) - psc_d(r,t)\cdot sc_d(r,t) + \\ pgc_i(r,t)\cdot gc_i(r,t) - pgc_d(r,t)\cdot gc_d(r,t) + \\ \sum_m [pmc_i(r,m,t)\cdot mc_i(r,m,t) - pmc_d(r,m,t)\cdot mc_d(r,m,t)]\}. \end{aligned} \tag{4.15a}$$

Since borrowing is excluded from the model, we should have:

$$cs(t) \geq 0, \tag{4.15b}$$

We should note here that putting the cumulative savings on interest can make the real total income of the region greater than that defined using equations (4.14).

4.3. Water quantity processes

In the present conception, the dynamics of groundwater processes are described by equations that have a (stochastic) basic component related to the unperturbed state of the system and components for the influence of control variables (e.g. the groundwater extractions for public water supply). The basic component not only takes into account the influence of meteorological conditions but also the physical circumstances that are not influenced by the control variables.

Two key variables in the conceived water quantity equations are the groundwater level at the beginning of summer, $hs(r,t)$, and the level at the end of summer, $hw(r,t)$, where the index r stands for the subregion and t for the year considered*. The groundwater level at the beginning of summer has been assumed to depend only on the groundwater extractions and the weather conditions during the preceding winter. So the assumption is that the "memory" of the meteorological circumstances and the activities during the preceding summer is "wiped out" by the winter precipitation. (This is why we have chosen the hydrological year to start at the beginning of *winter*.) Furthermore, the assumption has been made that $hs(r,t)$ can be approximated by a linear function of the public water-supply extractions during winter, $qw(r,t), r=1,..n$, where n=31 for the Southern Peel. In vector notation this approximation reads

$$\overline{hs}(t) = \overline{hso}(t) - \mathbf{A}\cdot\overline{qw}(t) \qquad (4.16a)$$

where $\overline{hso}(t)=(hso(r,t), r=1,..n)$ are (stochastic) groundwater levels that would occur if there were no extractions; A is a $n \times n$ influence matrix with positive elements.

The groundwater level at the end of summer is assumed to depend on the extractions during the summer, $\overline{qs}(t)=(qs(r,t), r=1,...,n)$, on the extractions for sprinkling from groundwater, $\overline{ig}(t)=(ig(r,t), r=1,...,n)$, and on the amounts of subirrigation, $\overline{us}(t)=(us(r,t), r=1,...,n)$. Furthermore, the assumption has been made that the levels of groundwater at the end of summer $\overline{hw}(t)$ can be approximated by a linear equation (in vector notation):

$$\overline{hw}(t) = \overline{hwo}(t) - B\cdot\overline{qs}(t) - C\cdot\overline{ig}(t) + D\cdot\overline{us}(t) \qquad (4.16b)$$

where B, C, and D are $n \times n$ influence matrices similar to matrix A. These matrices are different from each other because the extractions for the public water supply are from the deep aquifers, the extractions for sprinkling from the bottom of the phreatic aquifer, and the subirrigation is to the top of the phreatic aquifer. (The phreatic aquifer is modeled as a so-called flow- resisting layer.)

* In the sequel we will also be using vector notations of the type $\overline{hs}(t)=(hs(1,t),...,hs(n,t))$ for all variables dependent on index r.

Deep percolation is the flow from a phreatic aquifer to the deep aquifers; The proposed way of computing amounts of deep percolation during winter is given by the equation

$$\overline{dw}(t) = \overline{dwo}(t) + E \cdot \overline{qw}(t) \qquad (4.17a)$$

where

$\overline{dw}(t)$—amounts of deep percolation during winter,

$\overline{dwo}(t)$—amounts of unperturbed (basic) deep percolation during winter,

$\overline{qw}(t)$—extractions of groundwater during winter,

E—$n \times n$ influence matrix.

The amount of deep percolation during summer in subregion r, $ds(r,t)$, is influenced by extractions for sprinkling, $ig(r,t)$, and for public water supply, $qs(r,t)$, as well as by the amount of subirrigation, $us(r,t)$. Using vector notation we formulate this dependence as follows:

$$\overline{ds}(t) = \overline{dso}(t) + F \cdot \overline{qs}(t) + G \cdot \overline{ig}(t) - H \cdot \overline{us}(t). \qquad (4.17b)$$

where F,G, and H are influence matrices.

The ***extractions for the public water supply*** can be subject to constraints imposed by hydrogeologic circumstances. This is described by

$$\overline{qs}(t) \le \overline{qmax}(t) \qquad (4.18a)$$

$$\overline{qw}(t) \le \overline{qmax}(t) \qquad (4.18b)$$

where $\overline{qmax}(t)=(qmax(r,t),\ r=1,\dots,n)$ is the vector of hydrogeologically imposed upper bounds on the extractions during summer, $qs(r,t)$, and those during winter, $qw(r,t)$.

We will now proceed by listing equations that only apply to the summer period, followed by a section with equations that only apply to the winter period.

Equations for summer period

In the first-level model the amount of subirrigation water $us(r,t)$ is treated as a control variable that is subject to a number of constraints. We define a maximum infiltration rate $usmax(r)$ that has to be estimated from the hydrologic characteristics of the respective subregions. In vector notation the corresponding constraints are:

$$\overline{us}(t) \le \overline{usmax}, \tag{4.19}$$

where

$\overline{us}(t)$ – vector of subirrigations in year t,

$\overline{usmax}$ – vector of maximum infiltration rates.

The supply of surface water to a subregion involves some infiltration in the bottoms of ditches, even if the purpose of the supply is only for sprinkling from surface water. We take this into account in a very simple manner by including the constraint

$$\overline{us}(t) \ge p \cdot \overline{is}(t) \tag{4.20}$$

where

p – a proportionality constant.

$\overline{is}(t)$ – amounts of sprinkling from surface water,

A number of subregions contain areas that can not be reached by the surface-water supply system. This leads to constraints on the amounts of water that can be used for sprinkling from surface water:

$$\overline{is}(t) \le \overline{ismax} \tag{4.21a}$$

Sprinkling from groundwater, $ig(r,t)$, is subject to constraints imposed by the local hydrogeologic circumstances. This leads to a set of upper bounds:

$$\overline{ig}(t) \le \overline{igmax} \tag{4.21b}$$

Sprinkling is also subject to constraints imposed by the amount of sprinklers in a subregion. This is described by

$$\overline{is}(t) \le \overline{sc}(t) \tag{4.22a}$$

$$\overline{ig}(t) \le \overline{gc}(t) \tag{4.22b}$$

where

$\overline{sc}(t)$ – capacity of sprinkling from surface water,

$\overline{gc}(t)$ – capacity of sprinkling from groundwater.

The differentiation between sprinkling from surface water and that from groundwater is made because they require different auxiliary equipment.

The surface-water supply capacity for a subregion can be limiting; so the amount of subirrigation water and water used for sprinkling from surface water must not exceed this capacity $smax(r,t)$:

$$\overline{us}(t) + \overline{is}(t) \leq \overline{smax}(t) \tag{4.23}$$

The supply capacity for the whole region, $stmax$, can also be limiting; so the total amount of subirrigation water and of surface water used for sprinkling can not exceed this capacity:

$$\sum_{r}[us(r,t) + is(r,t)] \leq stmax(t) \tag{4.24}$$

Both the surface water supply capacities to subregions and the supply capacity to the whole region can be increased by investments in infrastructure by the RPMA.

For the purpose of discarding "scenarios" that are not feasible due to limitations set by the availability of soil moisture for crop growth, we need a simplified description of water quantity processes in the unsaturated zone.

The moisture content of the rootzone at the beginning of summer, $vs(r,t)$, depends on the soil type and the groundwater level $hs(r,t)$ as indicated in an approximate manner by Fig. 4.2 .
This graph reflects that for groundwater levels above a certain threshold $he(r)$, the soil moisture is in equilibrium with the water table. Below $he(r)$, the moisture content at the beginning of summer is equal to "field capacity", i.e. the amount of moisture that can not be drained (at an appreciable rate) by the force of gravity. The moisture content $vs(r,t)$ could be written as $\max\{vsmin(r);\ L_r[hs(r,t)]\}$*. To avoid analytical difficulties associated with the nonlinearity of this function, we decided to classify the subregions into those where $vs(r,t)$ is equal to $vsmin(r)$ and those where $vs(r,t)$ is equal to $L_r[hs(r,t)]$. If necessary this classification can be corrected so that it agrees with the computed results. Initially we will base the subdivision on $hso(r,t)$, because $hs(r,t) \leq hso(r,t)$:

* Here and in the following, $L_r[\cdot]$ denotes a subregion-specific linear function of the respective variable.

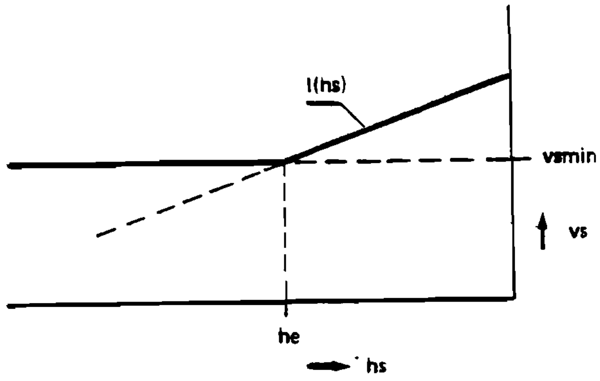

Fig. 4.2 The moisture content of the rootzone at the beginning of summer, *vs*, approximated by a piece-wise linear function of the groundwater level at the beginning of summer, *hs*.

$$vs(r,t) = \begin{cases} vsmin(r), & \text{if } hso(r,t) \le he(r) \\ l_r[hs(r,t)], & \text{if } hso(r,t) \ge he(r) \end{cases} \qquad (4.25)$$

Capillary rise of moisture to the rootzone is a complex process. It is one of the processes that are hard to model in a simplified way. Pending further research, we will base the computation of the capillary rise on the the weighted mean of the groundwater level at the beginning of summer, $hs(r,t)$ and the level at the end of summer, $hw(r,t)$. The proposed function is given in Fig. 4.3 .

The parameter $vzmax(r)$ of this function reflects that when the groundwater table rises above a certain level, the soil physical characteristics are no longer limiting for the capillary rise. The used formal description of the amount of capillary rise in subregion r, $vz(r,t)$, is as follows:

$$vz(r,t) = \min \{vzmax(r,t);\ l_r[\alpha \cdot hs(r,t) + (1-\alpha) \cdot hw(r,t)]\} \qquad (4.26)$$

(One of the possible pitfalls of this representation is that it does not guard against the computation of a negative capillary rise — see dashed line in Fig. 4.3.)

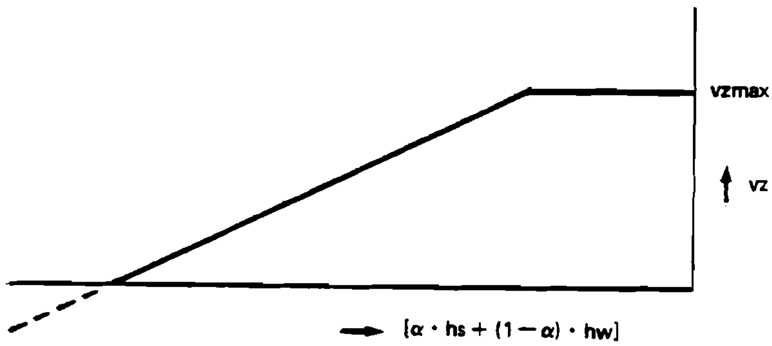

Fig. 4.3 Proposed graph for the capillary rise as a function of the weighted mean of $hs(r,t)$ and $hw(r,t)$.

Using this function we have the following equation for the soil moisture contents at the end of summer:

$$vw(r,t) = \min \{vs(r,t);\ vs(r,t) + ps(t)\cdot xa(r) + ig(r,t) + is(r,t) + vz(r,t) - \sum_j \sum_k ea(r,j,k,t)\cdot xw(r,j,k,t)\} \quad (4.27)$$

where

$vs(r,t)$–moisture contents of the rootzone at the beginning of summer,

$vw(r,t)$– moisture contents of the rootzone at the end of summer,

$ps(t)$– precipitation during summer, per unit area,

$xa(r)$– area of agricultural land in subregion r,

$ea(r,j,k,t)$– evapotranspiration for subtechnology k,

$xw(r,j,k,t)$– area of land for subtechnology k.

The term $\min\{vs(r,t);...\}$ is used here to ensure that the value of $vw(r,t)$ is not greater then $vs(r,t)$: when there is a lot of precipitation the excess moisture percolates to the groundwater. The evapotranspiration values correspond to a mean moisture content in the rootzone during the growing season, $vr(r,j,k,t)$, "required" by the respective subtechnology k (see Section 4.2). The values of $vs(r,t)$ and $vw(r,t)$ must be consistent with these values of $vr(r,j,k,t)$. As a selection principle for discarding sets of subtechnologies that are not feasible owing to the limited availability of moisture in the rootzone, the following equation involving the weighted mean of $vs(r,t)$ and $vw(r,t)$ can be proposed (moisture demand satisfaction):

$$\beta \cdot vw(r,t) + (1-\beta) \cdot vs(r,t) \geq \sum_j \sum_k vr(r,j,k,t) \cdot xw(r,j,k,t). \qquad (4.28)$$

The equation states that the weighted mean of $vs(r,t)$ and $vw(r,t)$ must be greater or equal to the total moisture contents required by subtechnologies implemented in a subregion.

Combination of Eqs. 4.27 and 4.28 yields after some rearranging

$$\min\{\frac{1}{\beta} vs(r,t);\ \frac{1}{\beta} vs(r,t) + ps(t) \cdot xa(r) + ig(r,t) + is(r,t) + vz(r,t) - \sum_j \sum_k ea(r,j,k,t) \cdot xw(r,j,k,t)\} \geq \frac{1}{\beta} \sum_j \sum_k vr(r,j,k,t) \cdot xw(r,j,k,t). \qquad (4.29)$$

As can easily be seen this inequality combined with Eq. 4.26 for $vz(r,t)$ can be replaced by the following set of three inequalities:

$$vs(r,t) \geq \sum_j \sum_k vr(r,j,k,t) \cdot xw(r,j,k,t) \qquad (4.30a)$$

$$\frac{1}{\beta} vs(r,t) + ps(t) \cdot xa(r) + ig(r,t) + is(r,t) + vzmax(r,t) - \sum_j \sum_k ea(r,j,k,t) \cdot xw(r,j,k,t) \geq \frac{1}{\beta} \sum_j \sum_k vr(r,j,k,t) \cdot xw(r,j,k,t), \qquad (4.30b)$$

$$\frac{1}{\beta} vs(r,t) + ps(t) \cdot xa(r) + ig(r,t) + is(r,t) +$$

$$l_2[\alpha \cdot hs(r,t) + (1-\alpha) \cdot hw(r,t)] - \sum_j \sum_k ea(r,j,k,t) \cdot xw(r,j,k,t) \qquad (4.30c)$$

$$\geq \frac{1}{\beta} \sum_j \sum_k vr(r,j,k,t) \cdot xw(r,j,k,t),$$

Eq. 4.30a does not have to be included in the model, however, because this constraint will always be satisfied in reality.

Equations for winter period

Flow processes that usually only occur during the winter period are ***surface runoff*** and ***drainage of phreatic groundwater to ditches***. In this context, these processes are of interest because of the water quality aspects that are involved.

The proposed way of describing the surface runoff is with a function of the type

$$sw(r,t) = f_{r,t}\ [hw(r,t-1), hs(r,t)] \qquad (4.31)$$

where

$hw(r,t-1)$ – groundwater level at the end of summer in year $t-1$,

$hs(r,t)$ – groundwater level at the beginning of summer in year t.

The function $f_{r,t}[\cdot,\cdot]$ depends on the meteorological circumstances, owing to variations in the precipitation pattern.

The drainage to the ditches will be described by

$$uw(r,t) = \max\ \{l_r^1[hw(r,t-1), hs(r,t)];\ l_r^2[hw(r,t-1), hs(r,t)]\} \qquad (4.32)$$

This function reflects that there are ditches with different drainage base levels: when the groundwater level rises above a threshold h_1 the first class of ditches starts to operate; above a threshold h_2 a second class of ditches also becomes active (Fig. 4.4).

The surface-water flow will simply be described as sum of the surface runoff and drainage to ditches upstream of certain points in the channel system. These points will be chosen in such manner that the water quality computations have enough spatial resolution to indicate which parts of the region pollute surface water more than others.

Let the set of summation points be given by $p = 1,..P$, and the set of subregions upstream of a point p by $\mathbf{R}(p)$; then the summation for the throughflow at a point p reads

$$rw(p,t) = \sum_{r \in R(p)} [sw(r,t) + uw(r,t)] \tag{4.33}$$

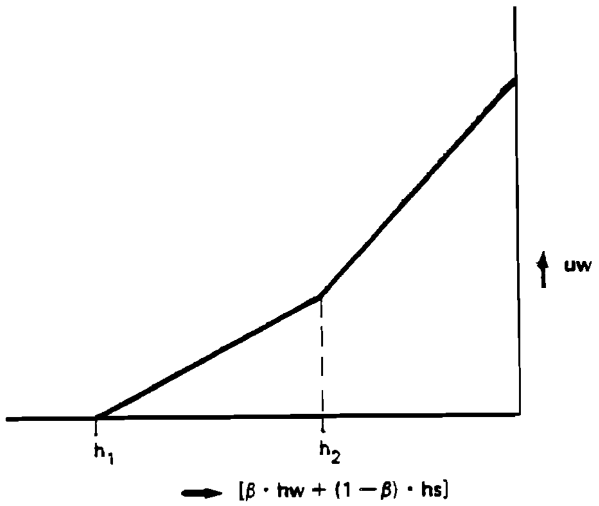

Fig. 4.4 Function for the drainage to ditches during the winter period.

4.4. Nitrogen processes in the soil

Fertilization, mineralization of organic-N

Each technology that uses land ($j \in JX$) has a specified level of the amount of nitrogen that is required for crop growth $nr(r,j)$. This nitrogen can come from different sources, i.e. chemical fertilizer and various types of animal slurries. The nitrogen in slurry 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 slurry, 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 slurry 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 slurry. As described by Lammers (1983), it is then possible to compute the amount of nitrogen available for crop growth by simply multiplying the slurry 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 (the effectivity of nitrogen in applied chemical fertilizer is assumed to be 1.0)

$$\sum_{m} [ema(j,m) \cdot ma(r,j,m,t) + ems(j,m) \cdot ms(r,j,m,t)] + \qquad (4.34)$$

$$fs(r,j,t) = nr(r,j) \cdot x(r,j,t)$$

where

$ma(r,j,m,t)$ – amount of slurry k applied in autumn,

$ms(r,j,m,t)$ – amount of slurry k applied in spring,

$ema(j,m)$ – nitrogen effectivity coefficient, autumn application,

$ems(j,m)$ – nitrogen effectivity coefficient, spring application,

$fs(r,j,t)$ – amount of nitrogen in applied chemical fertilizer,

$nr(r,j)$ – nitrogen requirement (per unit area) of technology j,

$x(r,j,t)$ – area of land allocated to technology j.

Livestock technologies that use land (from set JXL) inherently ***involve*** the application of slurry to land, i.e. grassland with cattle involves "natural" application of cattle slurry. This natural application is ***not*** included in the application $ma(r,j,k,t)$; the nitrogen requirement of technologies from set JXL is taken as the ***extra*** nitrogen requirement above the amount that is supplied by "recycling".

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

$$fs(r,j,t) \geq rfs(j) \cdot x(r,j,t) \tag{4.35}$$

where

$fs(r,j,t)$ – amount of nitrogen in applied chemical fertilizer,

$rfs(j)$ – requirement (per unit area) of chemical fertilizer N.

Application of animal slurries must not exceed maximum tolerance levels, because of the high content of certain mineral components, e.g. chloride and potassium:

$$ma(r,j,m,t) \leq mma(r,j,m) \cdot x(r,j,t), \tag{4.36a}$$

$$ms(r,j,m,t) \leq mms(r,j,m) \cdot x(r,j,t), \tag{4.36b}$$

where

$mma(r,j,k)$ – maximum amount of slurry application in autumn,

$mms(r,j,k)$ – maximum amount of slurry application in spring.

Leaching of nitrate to groundwater; denitrification

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

$$np(r,t) = f_1 \cdot f_2 \tag{4.37}$$

where

$np(r,t)$ –nitrate load on phreatic water,

f_1 –nitrate leaching,

f_2 –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 *JXL*)* differ from those of variables that pertain to arable land technologies (from set *JXD*). The function f_1 is of the form

$$f_1 = c_1 \sum_{j \in JXL} x(r,j,t) + c_2 \sum_{j \in JXD} x(r,j,t) + c_3 \sum_{j \in JXL} fs(r,j,t) + c_4 \sum_{j \in JXD} fs(r,j,t) +$$

* In the Southern Peel "winter" crops are not sown.

* The use of grassland for haymaking is not practised in the Southern Peel.

$$\sum_m c_5(m) \cdot \sum_{j \in JXL} [ma(r,j,m,t) + mxs(j,m) \cdot x(r,j,t) + c_6(m) \cdot ms(r,j,m,t)] +$$

$$\sum_m c_7(m) \cdot \sum_{j \in JXD} [ma(r,j,m,t) + c_8(m) \cdot ms(r,j,m,t)] + \qquad (4.38)$$

$$c_9 \cdot [xf(r) + xn(r)]$$

where

$x(r,j,t)$ – area allocated to a technology j,

$fs(r,j,t)$ – amount of nitrogen in applied chemical fertilizer,

$ma(r,j,m,t)$ – application of slurry m in autumn,

$ms(r,j,m,t)$ – application of slurry m in spring,

$mxs(j,m)$ – summer production of slurry m per unit area of technology j,

$xf(r)$ – area of forest in subregion r,

$xn(r)$ – area of nature reserves in subregion r.

The values of the coefficients $c_1, \ldots, c_7$ given in Lammers(1983) have been derived 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. An adequate way of taking into account the nitrate leaching reduction by sprinkling has yet to be found.

As evidenced by Verdonschot(1981), in sandy regions with shallow groundwater tables the groundwater level has an influence on the amount of nitrate that enters the groundwater system. In our model a groundwater level reduction function of the following form will be used:

$$f_2 = \frac{1}{1+e^{-c_{10} \cdot [hsc(r,t) - c_{11}]}} \qquad (4.39)$$

where $hsc(r,t)$ is the groundwater level in spring in m below groundlevel.

4.5. Water quality processes

Groundwater quality

For the moment, pending further research, we will be using a very crude first-level model for groundwater quality processes. The assumptions the model is based on are:

1. All deep aquifers over the whole (Slenk) region can be regarded as one mixing cell. The phreatic aquifers are separate mixing cells that overlie the deep aquifers.
2. Decomposition of nitrate in the deep aquifers can be taken into account by a factor α (that depends on the organic matter content of the subsoil).
3. Adsorption and dispersion can be neglected.
4. The volume of water in the aquifers does not change.

The time step used for the computations is one year. This is a very short interval in comparison to the time lag of the system; so an "explicit" computation scheme can be used, meaning that fluxes during the year t can be assumed to have concentrations as computed for the beginning of that year. Deep percolation, $d(r,t)$, is taken positive downwards. So if $d(r,t) \geq 0$ then there is a transport of solutes from the phreatic aquifer in subregion r to the deep aquifers, and inversely so if $d(r,t) \leq 0$. For the phreatic aquifers the equations are (terms for $ig(r,t)$ and $vz(r,t)$ are not included because of their negligible influence)

$$\begin{aligned} cp(r,t+1) \cdot vp(r) &= \alpha \cdot cp(r,t) \cdot vp(r) \\ &+ np(r,t) - uw(r,t) \cdot cp(r,t) - \\ &\mathbf{max}\{0;dw(r,t)\} \cdot cp(r,t) - \mathbf{min}\{0;dw(r,t)\} \cdot cd(t) - \\ &\mathbf{max}\{0;ds(r,t)\} \cdot cp(r,t) - \mathbf{min}\{0;ds(r,t)\} \cdot cd(t) \end{aligned} \tag{4.40}$$

where

$cp(r,t)$–nitrate concentration in phreatic aquifer r at the beginning of year t,

$vp(r)$–volume of water in phreatic aquifer r

$cd(t)$–nitrate concentration in the deep aquifer

vd–volume of water in the deep aquifer,

α–decomposition factor,

$np(r,t)$–nitrate load on phreatic groundwater,

$uw(i,t)$–drainage of phreatic groundwater to ditches during winter,

$dw(r,t)$–deep percolation during winter,

$ds(r,t)$–deep percolation during summer,

The equation for the deep aquifer is

$$cd(t+1)\cdot vd = \alpha\cdot cd(t)\cdot vd - cd(t)\cdot \sum_r [qw(r,t) + qs(r,t)] +$$
$$\sum_r [\mathbf{max}\,\{0;dw(r,t)\}\cdot cp(r,t) + \mathbf{min}\{0;dw(r,t)\}\cdot cd(t)] + \tag{4.41}$$
$$\sum_r [\mathbf{max}\,\{0;ds(r,t)\}\cdot cp(r,t) + \mathbf{min}\{0;ds(r,t)\}\cdot cd(t)]$$

where $qw(r,t)$ and $qs(r,t)$ are extractions for the public water supply during winter and summer respectively.

Surface water quality

In summer, surface-water quality is hardly influenced by fertilization practices, because in most subregions there is no drainage of phreatic groundwater to the ditches and there is no surface runoff. (In the Southern Peel there are no steep slopes, and the topsoil has a large infiltration capacity; so even heavy rainstorms cause hardly any surface runoff.) So in the summer surface water quality is mainly influenced by the quality of water that is imported from outside the region and by the discharge of waste waters from households, dairies and sewage plants. Owing to the long residence time of surface water in the summer, it is extremely difficult to model water quality processes in that period. This, and in view of the fact that fertilization practices are not of much influence on surface water quality during the summer has led us to for the moment exclude attempts at modelling the latter.

During the winter period, residence times are rather short, owing to the substantial outflow of drainage water and surface runoff. (it is in the winter that surface runoff can occur at places where the groundwater level reaches the soil surface.) So the concentrations as computed by simply taking the quotient of the N-load on surface water and the corresponding throughflow give a good indication of the surface water quality. Field measurements have shown that the concentration of nitrogen in various forms in surface runoff, $cns(r,t)$, does not depend on the amount of surface runoff itself (Steenvoorden, 1983), and that the following linear function of manure applications is valid.

$$cns(r,t) = cb(r) + cw(t) \cdot \sum_{j} \sum_{m} nf(k) \cdot ma(r,j,m,t) \qquad (4.42)$$

where

$cns(r,t)$ – nitrogen concentration of surface runoff,

$cb(r)$ – base concentration,

$cw(t)$ – coefficient that depends on the type of winter,

$nc(k)$ – nitrogen fraction of slurry m,

$ma(r,j,m,t)$ – slurry application in autumn.

The N-load on surface water due to surface runoff is equal to the product of the concentration of nitrogen in surface runoff and the amount of surface runoff itself, that due to drainage of phreatic groundwater to ditches to the product of the nitrogen concentration in the phreatic aquifer and the amount of drainage. At a point p in the surface water system (see also Section 4.3), the predicted N-concentration is given by

$$cn(p,t) = \frac{\sum_{r \in R(p)} [cns(r,t) \cdot srw(r,t) + cp(r,t) \cdot uw(r,t)]}{\sum_{r \in R(p)} [sw(r,t) + uw(r,t)]} \qquad (4.43)$$

where

$cn(p,t)$ – N-concentration at point p in the surface water system,

$R(p)$ – set of subregions upstream of point p,

$cns(r,t)$ – N-concentration of surface runoff,

$sw(r,t)$ – amount of surface runoff during winter,

$cp(r,t)$ – N-concentration of phreatic groundwater,

$uw(r,t)$ – amount of drainage of phreatic groundwater to ditches.

4.6. Public water supply

If the demands of public water supply are given, then the total of the extractions in the subregions must satisfy respectively for the winter and summer period

$$\sum_r qw(r,t) \geq qpw(t) + \sum_r [\sum_{j \in JXL} wxw(j) \cdot x(r,j,t) + \sum_{j \in JZ} wzw(j) \cdot z(r,j,t)], \quad (4.44a)$$

$$\sum_r qs(r,t) \geq qps(t) + \sum_r [\sum_{j \in JXL} wxs(j) \cdot x(r,j,t) + \sum_{j \in JZ} wzs(j) \cdot z(r,j,t)], \quad (4.44b)$$

where

$qw(r,t)$ – public water supply extractions during winter,

$qs(r,t)$ – public water supply extractions during summer,

$qpw(t)$ – total demand for public water supply during winter,

$qps(t)$ – total demand for public water supply during summer,

$x(r,j,t)$ – area for a technology $j \in JX$,

$wxw(j)$ – water use per unit of $x(r,j,t)$ during winter,

$wxs(j)$ – water use per unit of $x(r,j,t)$ during summer,

$z(r,j,t)$ – intensity of a technology that does not use land,

$wzs(j)$ – water use per unit of $z(r,j,t)$ during summer,

$wzw(j)$ – water use per unit of $z(r,j,t)$ during winter.

If a certain water quality $cdmax$ of the extracted groundwater is demanded, the nitrate concentration in the deep aquifer $cd(t)$ must satisfy

$$cd(t) \leq cdmax \quad (4.45)$$

4.7. Natural ecosystems

Ecological processes in nature areas are influenced in a complex way by the groundwater regime. We do not attempt to describe the dynamics of these processes. Instead, we assume that the conditions in "critical" years, e.g. years with a "dryness" that on average occurs only once per decade, are good indicators for the level of satisfaction of water demand of nature areas. Details of ongoing research regarding the influence of the groundwater regime on natural vegetations are given in Kemmers (1983) and Jansen (1983).

The concentration of nitrogen compounds in surface water has a great influence on surface water ecosystems. So if a certain "value" of surface water ecosystems is demanded, the nitrate concentration must meet certain water quality standards, which are given by

$$cn(p,t) \leq cnmax(p) \tag{4.46}$$

Since agriculture is not the only source of pollution by nitrogen compounds, the values of $cnmax(p,t)$ used in the model allow for an exogenously "fixed" amount of pollution by for instance households. Since investment in water purification plants is one of the options of the RPMA, the values of $cnmax(p,t)$ can be increased, meaning that a higher N-load on surface water is allowed.

5. CONCLUDING REMARKS

This paper outlines the methodological and conceptual framework for the analysis of regional policies providing for a balanced socio-economic development and evolution of natural ecosystems.

Analytically the paper focuses more on the first stage analysis that is concerned with the generation of potentially satisfactory scenarios of regional development. An important part of this stage is based on the use of relatively simple mathematical models designed for the first level screening analyses. This initial versions of these models related to various processes and aspects of the region under study are described in the previous sections.

The screening analyses of scenarios in this study using these models are to be based on the iterative use of various techniques like multiobjective programming using algorithms coupled with simulation runs and also with statistical and other, less formal, procedures for the evaluation of the results at various steps of the analysis. And rather than involving all the above models in each of these analytical steps, we will more flexibly use only some of them with optimization or more generally multiobjective programming algorithms, leaving the others for subsequent simulation runs. The major concern here is that the structure of the analytical procedures involved should enable the analyst to obtain meaningful results in a relatively short time. And as is common to all systems analytical studies the final structure of such workable procedures will emerge in the course of the experimental work with the models outlined in the paper.

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