Optimization of water management in regions with conflicting interests

Simplified models

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Report 15

The WINAND STARING CENTRE, Wageningen, (The NETHERLANDS), 1991

ABSTRACT

Walsum, P.E.V. van, 1991. Optimization of water management in regions with conflicting interests; simplified models. Wageningen (the Netherlands), The Winand Staring Centre. Report 15, 95 pp., 5 Tables, 8 Figs., 8 Refs.

Authorities in the Netherlands realize that measures are needed for protecting the environment in regions with intensive livestock breeding and with high-intensity land cultivation. Nitrate leaching and phosphate accumulation need to be controlled, as well as the lowering of groundwater levels. A scenario generating system has been developed for aiding the design and evaluation of control measures. An integrated approach has been followed. Scenarios can be generated by setting requirements on the indicators for the 'well-being' of the various water users. One of the indicators is left free and gets optimized using simplified models that have been implemented in the form of an integrated linear programming (LP) model. Comprehensive models can then be used for verifying and more accurately estimating scenarios that seem promising.

Keywords: livestock breeding, high-intensity agriculture, nitrate pollution, groundwater, integrated water management, linear programming

ISSN 0924-3070

This report has earlier been announced as Report 30 (1988) of the Institute for Land and Water Management Research, Wageningen, the Netherlands, entitled: "Decision support system for regions with intensive agriculture: simplified models".

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The WINAND STARING CENTRE is continuing the research of: Institute for Land and Water Management Research (ICW), Institute for Pesticide Research, Environment Division (IOB), Dorschkamp Research Institute for Forestry and Landscape Planning, Division of Landscape Planning (LB), and Soil Survey Institute (STIBOKA).

Project 100.21 [010.bw]

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PREFACE

The models described in this report were initially developed in the course of the 'Regional Water Policies Project' at the International Institute for Applied Systems Analysis (IIASA, Laxenburg, Austria) in the period 1984-1985. Their finalization took place at the (former) Institute for Land and Water Management Research (ICW), which is now part of the Winand Staring Centre. The finalization activity formed part of the project 'Optimization of Water Management in Regions with Conflicting Interests'.

I am indebted towards B. Wennekes for her diligence in doing the type-setting.

SUMMARY

Introduction
In an environment like in the Netherlands both groundwater and surface water have an integrating role. Groundwater and surface water interact through drainage of groundwater to surface water and through infiltration of surface water to groundwater. Combined groundwater and surface water subsystems thus form a complex medium through which local human interventions can have impacts in other parts of a region. This can lead to conflicts between the various water users. In the Netherlands such conflicts have become especially apparent in regions with a sandy soil and a tradition of factory farming.

The amount of animal wastes produced in regions like this cannot be disposed of by fertilization at the optimal level. Over-fertilization of maize fields and dumping of slurry on fallow pieces of land is currently common practice. Most soils in sand regions have poor retention capacities for minerals. Excess nitrate, for example, is easily leached, increasing the nitrogen concentration of groundwater.

In dry periods with an evapotranspiration surplus, soil water is supplemented by sprinkling and subsurface irrigation. The lowering of groundwater levels that results from extractions by farmers for sprinkling, by public water supply companies for consumption and by industry causes conditions in nature areas to deteriorate.

Another problem in the regions concerned is surface water pollution through surface runoff, especially if spreading of slurries continues in autumn and winter when there is a precipitation surplus. A schematic diagram of interactions of water users is given in Figure 1.

Central governments and regional authorities realize that measures are needed for attaining a balance between economic developments and long-term environmental conditions. The complexity of relations between water users and water subsystems, as well as the large number of possible water management alternatives, make it hard to design policies for the efficient control of quantity and quality of water. For aiding this design a scenario generating system (SGS) has been developed.

Scenario generating system
For reasons of simplicity, it is assumed that regional water management is in the hands of one (imaginary) regional authority. With the developed scenario generating system (SGS) the regional authority can generate scenarios that can be seen as reference states of future regional development, that could be reached if the water users would behave in the way the authority wants. By this is meant that the users behave in a way that makes full use of the physical possibilities of the regional environmental system.

The SGS itself is a module of a two-stage procedure involving also a policy analysis system for predicting the behavioral responses of water users to measures taken by the regional authority. The two-stage procedure as a whole is described in Drent (1989) and Orlovski et al. (1986).

Comprehensive models

Basic to the SGS is the use of the available knowledge about the relevant processes. This knowledge should preferably be in a form that facilitates the performing of (reproducible) 'experiments on paper', since the regional systems concerned do not allow the making of large-scale real-life experiments. The best answer on this requirement is a computer model, although not all types of knowledge can be converted into a model. For the simulation of the regional hydrologic system and its interactions with the water users, five models have been developed.

A concept of a model has been developed for describing the development of agriculture (Vreke, 1981). The model requires that farms in a region are classified into a number of farm types with an imaginary representative farm for each farm type. The activities on a farm are described by intensities of technologies, which are agricultural activities that can have labour, water, fertilizers, etc, as input and can have crop yield, milk, meat, manure, etc. as output. The technologies are grouped into soil-use technologies (cereals, grassland with dairy cattle, etc) and non soil-use technologies (pigs for breeding, mushrooms, manure processing, etc.).

The model SWAFLO (Soil WAter in relation to FLOra) has been developed to evaluate loss of nature 'performance' after lowering of the groundwater level. SWAFLO takes into account four environmental factors that are related to groundwater:
- reliability of site factors (N, P, water);
- nitrogen supply;
- soil aeration;
- soil moisture supply.

Loss of nature performance is given in terms of a composite species-rareness indicator. Application of SWAFLO to a nature area yields a diagram that shows what the upper limits are for the lowerings of the groundwater level, for a sequence of values of the species-rareness indicator (Kemmers and Jansen, 1988).

Public water supply is simply modelled in the form of a demand requirement that specifies the total need for groundwater. The model SIMGRO (SIMulation of GROundwater flow) has been developed for simulating the flow of water in the saturated and unsaturated zone on a regional scale. The interaction between groundwater and surface water is also modelled. SIMGRO contains operational rules for sprinkling and the manipulation of the surface water level. Amounts of sprinkling and subirrigation are calculated, as well as groundwater depths and crop evapotranspirations (Querner and Van Bakel, 1989).

With the model SIMCROP (SIMulation of CROp Production) the effects of changes in water management on the crop production in a region can be calculated. SIMCROP uses evapotranspiration data that are calculated in SIMGRO. The actual production can be calculated for both optimal and suboptimal nitrogen fertilization (Querner and Feddes, 1989).

The model ANIMO (Agricultural NItrogen MOdel) is used to predict the long-term nitrate contamination of groundwater and surface water as a function of soil type, soil use, water management, weather conditions, fertilizer use and cropping history. For use on a regional scale ANIMO has been coupled to SIMGRO (Drent, 1989).

Simplified models

With the exception of SWAFLO, the above comprehensive models are not suitable for a quick generation of scenarios that are to be analyzed by the authority - for this their mathematical form is too complex and the computational effort required to run them is too high. Models that have a simple mathematical form are more suitable for scenario generation because they allow the use of highly developed mathematical programming algorithms. The choice was made to keep the simple models linear as much as possible. The simplicity of such models entails, however, that they use a relatively crude approximation of reality. The comprehensive models will therefore always be needed for verification and more accurate estimation of scenarios that seem promising.

The agricultural model is simplified by assuming that the region will not receive external funding (Vreke and Locht, 1983). This means that investments in agriculture have to be earned in agriculture itself. The simplified model is further based on the following three assumptions concerning the behaviour of farmers in the region.

- The income of agriculture is maximized. This assumption simplifies the behaviour of the farmers with respect to change of farm type and investments. Changes are assumed to be made when the expected revenues exceed the costs and if there are funds to finance them. Personal preferences of farmers are left out.
- The conditions posed by the regional authority are met. These conditions are introduced in the model as constraints.
- No differences in efficiency between the farmers exist. This implies that the yield per unit of a technology is equal for all farms in the region.

The diagram that is obtained by applying SWAFLO to a nature area can be used directly in the combined set of simplified models, because it can be represented by two constraints. One of the constraints is on the lowering of the groundwater level at the beginning of winter; the other is on the lowering at the beginning of summer.

A simplified model for crop production in relation to water quantity is obtained by first making a reference run with SIMGRO-SIMCROP. Then, various perturbations (extractions of groundwater, surface water supply) are introduced during successive runs. The reference results are subtracted from the perturbed results which yields 'responses'. The responses are then collected into a matrix which is used as a linear approximation of the effects of perturbations. The response matrix approach is also used for modelling the surface water - groundwater interaction : a response matrix is derived for approximating the induced infiltration caused by the extractions of groundwater for sprinkling and for public water supply. Though the model has linear components, multiplication of crop production by the area of a soil-use technology yields a (weakly) non-linear function.

In the simple model for groundwater quality, the leaching of nitrate to groundwater is computed with leaching factors that are derived from the comprehensive model ANIMO. Also a groundwater-level reduction factor is derived from this model; this factor takes into account the denitrification in the vicinity of the water table. A steady-state approach is used for the calculation of the nitrate content: the nitrate concentrations are computed which are reached if application of animal slurries, as described in a certain scenario, were repeated each year, for an infinite number of years. For the transport of nitrate a mixing-cell approximation is used, based on the principle of conservation of mass. Each subregion has mixing cells for the phreatic layer and for the aquifers directly underneath. In the mass-balance equations of mixing cells the left-hand sides contain the yearly decompositions of the nitrate and the right-hand sides the net influxes of nitrate. The steady-state is reached when the decompositions become exactly equal to the net influxes.

Implementation of models

Implementation of the simplified models in the form of an integrated linear programming model (LP) has been done with the cross-compiler GEMINI (Lebedev, 1984) and the software package MINOS (Murtagh and Saunders, 1983). The non-linearity in the computation of income from agriculture is dealt with by means of successive LP.

Of prime interest to the regional authority are the indicators of well-being of the water users. Since well-being can have various aspects that cannot quantified in a commensurable manner, there can be more than one indicator of well-being per group of users. Increase of well-being can either be associated with 'maximization' or with 'minimization' of the respective indicator values; in the following list the former is designated by 'max', the latter by 'min':

- income from agriculture (max);
- labour demand of agriculture (max);
- extraction of groundwater for public water supply (max);
- maximum concentration of nitrogen in the phreatic layer (min);
- maximum concentration of nitrogen in the first aquifer (min);
- loss of species rareness in nature areas (min);

The above indicators can be seen as the multi-objectives of the regional development. For handling the multi-objectivity a simple constraint method is used. This means that questions can be answered of the type: what maximum agricultural income per year can be attained under the conditions that the maximum nitrogen concentration of phreatic groundwater should not exceed 11.2 $mg.l^{-1}$ NO_3-N?

This is just one example of numerous questions that can be 'answered'. Each of such questions is formulated by fixing desired values for the indicators considered and by treating one of the indicators 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 human activities in the region that facilitates the achievements of these values.

Preferably, answers to the questions should be forthcoming after some 'on-line' computing. However, it was found that certainly for the type of problems addressed in this context it is not possible to simplify the models to such an extent that the computation time becomes acceptable for interactive running and at the same time to maintain credibility of the system. But for easy user access and interpretation of results an interactive system with colour graphics has indeed been developed. So the procedure as a whole is 'off-line', but the interpretation of results is 'on-line' (Fig.7).

After a scenario has been generated, runs can be made with the comprehensive models in order to verify and more accurately estimate scenarios that seem promising. Also, runs with the comprehensive models for a number of different weather years can provide data for the statistical evaluation of scenarios.

Conclusions

The described scenario generating system can be used for generating scenarios that comply with certain requirements set by the user. These requirements are on the values of 'indicators' that serve as quantifications of the well-being of the various water users. One of the indicator values is left free by the user and gets optimized by the system.

With the interactive display system the authority can analyze generated scenarios and can evaluate them in terms of his own preferences and judgements. No doubt he will require additional scenarios to be generated on the basis of his analysis of the ones that are initially presented to him. Only after this cycle has been gone through several times, and also additional sources of information have been accessed, will the time have come that the decision-making process concerning a region can be finalized.

The operational status of the scenario generating system is that of a working prototype. It can be used as a starting point for further model development (e.g. Van Walsum, 1990). The formulation of the simplified models in terms of constraints and state equations of a linear programming problem makes it easy to apply only a certain part, e.g. only the part involving water quantity. This is simply done by deleting the non-relevant equations from the computer code.

For actual results obtained from running the prototype system the reader is referred to Drent (1989).

1 INTRODUCTION

In an environment like in the Netherlands both groundwater and surface water have an integrating role. Groundwater and surface water interact through drainage of groundwater to surface water and through infiltration of surface water to groundwater. Combined groundwater and surface water subsystems thus form a complex medium through which local human interventions can have impacts in other parts of a region. This can lead to conflicts that have become especially apparent in regions with a sandy soil and a tradition of factory farming.

The amount of animal wastes produced in these regions cannot be disposed of by fertilization at the optimal level. Over-fertilization of maize fields and dumping of slurry on fallow pieces of land is therefore currently common practice. Since most soils in sand regions have poor retention capacities for minerals, excess nitrate, for example, is easily leached, thus increasing the nitrogen concentration of groundwater.

In dry periods with an evapotranspiration surplus, soil water is supplemented by sprinkling and surface water infiltration (to raise the groundwater level and thereby increase the capillary rise of moisture to the root zone). The lowering of groundwater levels that results from extractions by farmers (for sprinkling) and by public water supply companies causes conditions in nature areas to deteriorate. Also the productivity of farmland is impaired due to the reduction of capillary rise.

Another problem in the regions concerned is surface water pollution through surface runoff, especially if spreading of animal wastes continues in autumn and winter when there is a precipitation surplus. A schematic diagram of interactions of water users is given in Figure 1.

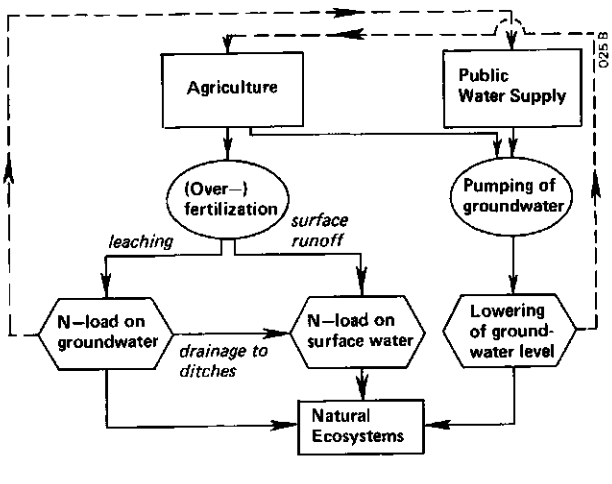

Fig. 1 Some interactions of agriculture, public water supply, and natural ecosystems through the regional hydrologic system

Central governments and regional authorities realize that measures are needed for attaining a balance between economic developments and long-term environmental conditions. The complexity of relations between water users and water subsystems, as well as the large number of possible water management alternatives, make it hard to design policies for the efficient control of quantity and quality of water. For aiding this design a scenario generating system (SGS) has been developed.

In the subsequent chapter a brief description is given of the general idea behind the SGS. This is followed by an overview of the comprehensive models for describing the interactions between the various water users through the regional hydrologic system. After explaining the need for also having simplified models. These models are described in chapters 3 till 7. In chapter 8 a description is given of how the simplified models have been implemented and the way they are used as part of the scenario generating system. Furthermore, the way in which the input data can be obtained is described. In chapter 9 some conclusive remarks are made, among other things about the operational status of the scenario generating system. For actual results obtained from running the models the reader is referred to Drent (1989).

2 SCENARIO GENERATING SYSTEM

For reasons of simplicity, it is assumed that regional water management is in the hands of one (imaginary) regional authority. With the developed scenario generating system (SGS) the regional authority can generate scenarios that can be seen as reference states of future regional development, that could be reached if the water users would behave in the way the authority wants. By this is meant that the users behave in a way that makes full use of the physical possibilities of the regional environmental system.

The SGS itself is a module of a two-stage procedure involving also a policy analysis system for predicting the behavioral responses of water users to measures taken by the regional authority. The two-stage procedure as a whole is described in Drent (1989) and Orlovski et al. (1986).

2.1 Overview of comprehensive models

Basic to the SGS is the use of the available knowledge about the relevant processes. This knowledge should preferably be in a form that facilitates the performing of (reproducible) 'experiments on paper', since the regional systems concerned do not allow the making of large-scale real-life experiments. The best answer on this requirement is a computer model, although not all types of knowledge can be converted into a model. For the simulation of the regional hydrologic system and its interactions with the water users, five models have been developed. These models are more fully described in Drent (1989). Here only a brief summary is given:

A concept of a model has been developed for describing the development of agriculture (Vreke, 1981). The model requires that farms in a region are classified into a number of farm types with an imaginary representative farm for each farm type. The activities on a farm are described by intensities of technologies, which are agricultural activities that can have labour, water, fertilizers, etc. as input and can have crop yield, milk, meat, manure, etc. as output. The technologies are grouped into soil-use technologies (cereals, grassland with dairy cattle, etc.) and nonsoil-use technologies (pigs for breeding, mushrooms, manure processing, etc.).

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- nitrogen supply;
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With the model SIMCROP (SIMulation of CROP Production) the effects of changes in water management on the crop production in a region can be calculated. SIMCROP uses evapotranspiration data obtained from SIMGRO. The actual production can be calculated for both optimal and suboptimal soil-nitrogen conditions (Querner and Feddes, 1989).

The model ANIMO (Agricultural NItrogen MOdel) can be used to predict the long-term nitrate contamination of groundwater and surface water as a function of soil type, soil use, water management, weather conditions, fertilizer use and cropping history. For use on a regional scale ANIMO has been coupled to SIMGRO (Drent, 1989).

Application of the models requires a spatial resolution by means of a division into subregions. For the case study on which the development of the models was based this was done in the manner indicated in Figure 2. The division is on the basis of classes of groundwater conditions and soil physical units. Concerning this division into subregions it should be remarked that for the groundwater modelling with SIMGRO subregions with a much more regular shape have been used.

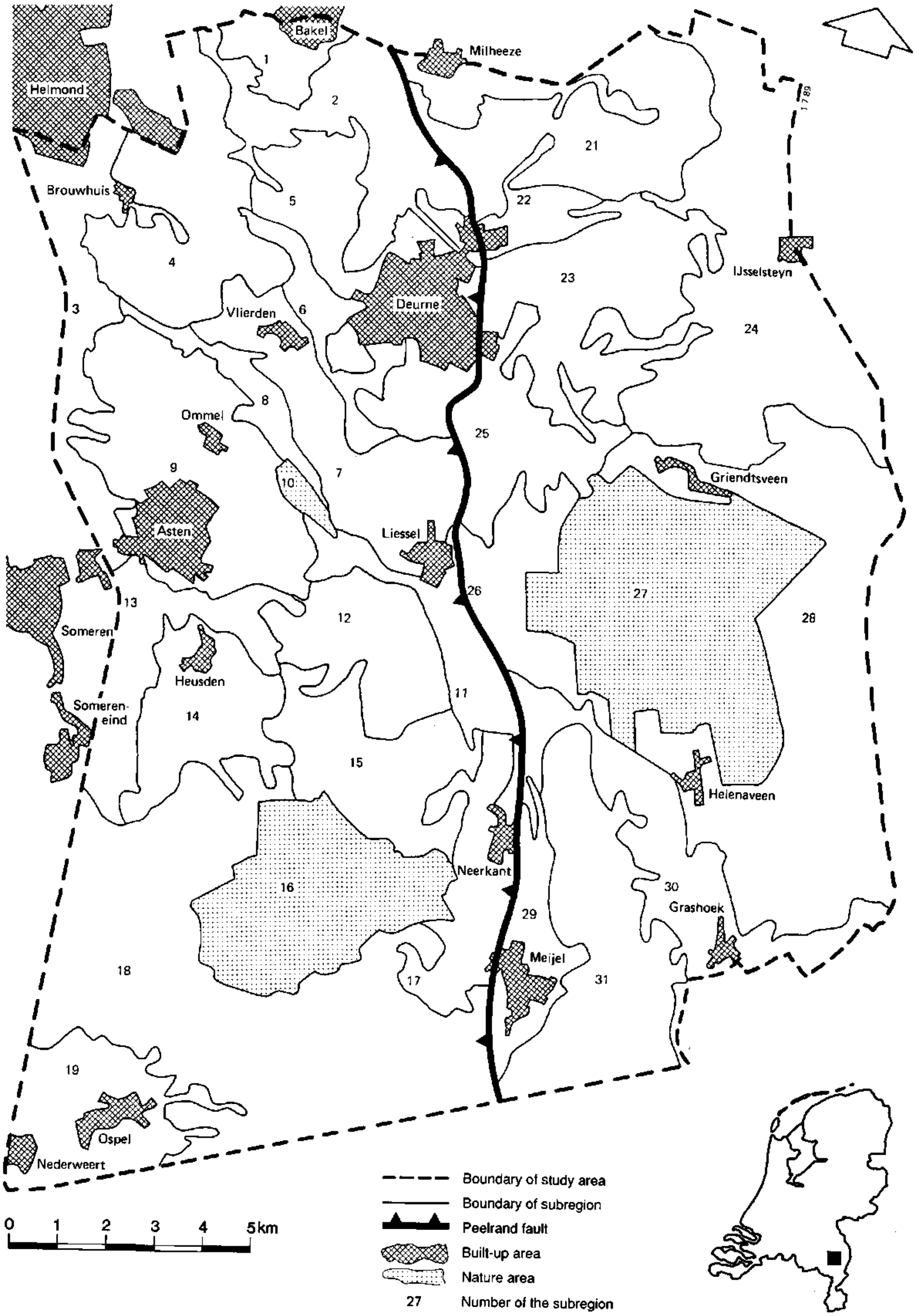

Fig. 2 Division of the Southern Peel region into subregions

2.2 Simplified models

With the exception of SWAFLO, the above 'comprehensive' models are not suitable for a quick generation of scenarios that are to be analyzed by the authority - for this their mathematical form is too complex and the computational effort required to run them is too high. Models that have a simple mathematical form are more suitable for scenario generation because they allow the use of mathematical programming algorithms. The choice was therefore made to keep these models linear wherever possible. The simplicity of such models entails, however, that they use a relatively crude approximation of reality. The comprehensive models will therefore always be needed for verification and more accurate estimation of scenarios that seem promising.

The various simplified models that together form an integrated system each consist of a number of mathematical relations. In the terminology used in Operations Research these relations are called *constraints*. The unknowns in the constraints are (by convention) termed *decision variables*. If not otherwise indicated these variables are in the remainder of this text taken to be *non-negative*. Variables for which there exist expressions relating them directly to the decision variables are termed *state variables*. A set of values attributed to the decision variables, together with the set of state variables that can be derived from them, is termed a *scenario*.

An *indicator* is a special type of state variable that is a measure of 'goodness' of a scenario, as seen from a certain viewpoint. Since the regional systems concerned involve diverse groups of water users with conflicting interests, there are several such indicators, in some cases even more than one per group of water users. This is because 'well-being' can have various non-commensurable aspects, which can lead to multiple indicators even per group of water users.

In the description of the models there is a strict adherence to the classification of variables into decision variables, state variables and parameters. Typographically the class to which a variable belongs is made clear in the following manner:

- decision variables are printed in bold face, e.g. $\boldsymbol{x_w(i, j, k, n)}$;
- state variables are printed in normal face, with the first letter underlined, e.g. $\underline{v}_n(i, l)$;
- parameters are printed in normal face, e.g. p_{fs}.

In view of their importance the 'indicators of well-being' of water users are typographically distinguished in a special manner. This is done by means of one- or two-letter symbols, that are printed in bold face and also have the first letter underlined, e.g. $\boldsymbol{\underline{Y}_T}$. Use of this typography is independent of whether an indicator is implemented as a decision variable or as a state variable; this deviates from the convention followed for the 'ordinary' variables. The latter are only indicated to be decision variables or state variables if they are actually *implemented* as such in the *computer code*. Implementation as a state variable involves replacement of the variable by the expression relating it to decision variables. Implementation as a decision variable involves including an extra equality constraint for the expression. Whether a variable is made into a decision or a state variable is not only based on mathematical considerations but also on practical grounds: A substantial number of the variables that could have been implemented as state variables have actually been implemented as decision variables. Computationally this is not the most efficient, but it does contribute to the tractability of the computer code; thus it is efficient from another point of view than that of 'computational demand'.

The strict adherence to the classification into types of variables is also followed concerning the distinction between state variables and parameters. For instance, the 'duration of the sprinkling period' in a subregion, $P_s(i,k)$, can be seen as a state variable (Eq. 43). It is not implemented as such, however, because this would have lead to a non-linearity in the model (see also Section 8.1). In the pre-processing section of the computer code it is therefore computed as a function of the decision variables obtained from the *preceding* run, and then further treated as a parameter in the model.

3 SIMPLIFIED MODEL OF AGRICULTURE

The agricultural model has been simplified by assuming that the region will not receive external funding (Vreke and Locht, 1983). This means that investments in agriculture have to be earned in agriculture itself. The simplified model is further based on the following three assumptions concerning the behaviour of farmers in the region:
- The income of agriculture is maximized. This assumption simplifies the behaviour of the farmers with respect to change of farm type and investments. Changes are assumed to be made when the expected revenues exceed the costs and if there are funds to finance them. Personal preferences of farmers are left out.
- The conditions posed by the regional authority are met. These conditions are introduced in the model as constraints.
- No differences in efficiency between the farmers exist. This implies that the yield per unit of a technology is equal for all farms in the region.

3.1 Technologies

3.1.1 Definition

The term technology is used for a specific combination of agricultural activities. It is convenient to group the technologies into three sets:
- technologies that make use of the soil as a production factor;
- technologies that do not make use of the soil, but do generate income;
- technologies that support the others by providing 'input' or by dealing with the 'output' especially with output in the form of byproducts like animal wastes.

For the sake of brevity the first two will be called 'income generating technologies', the third 'auxiliary technologies'. Furthermore, the first set will be referred to with 'soil-use technologies' or just 'set J_x', the second set with 'miscellaneous technologies' or just 'set J_z'; the third set is sometimes referred to with 'set J_a'.
The set of soil-use technologies is divided into four subsets:
- $J_x(1)$: arable land technologies, excluding maize;
- $J_x(2)$: (silage) maize technologies;
- $J_x(3)$: grassland technologies;
- $J_x(4)$: 'new forest' technologies.

Lists of technologies considered in the case study that the development of the models was based on are given in Tables 1, 2 and 3. As can be seen from the lists, the technologies in sets J_x and J_z are numbered. In the mathematical notations the symbol 'j' is used for indicating the index number of a technology. If it is necessary to make clear whether a technology of set J_x or of set J_z is meant, this is done by means of

'$j \in J_x$' and '$j \in J_z$' respectively. The auxiliary technologies each have a separate symbol. The sets of technologies with which the model can be implemented are flexible; the given sets of technologies only serve as examples.

Table 1 Soil-use technologies (set J_x)

Index	Technology	Subset
1	Glasshouse horticulture	$J_x(1)$
2	Asparagus & orchards	$J_x(1)$
3	Small scale horticulture	$J_x(1)$
4	Large scale horticulture	$J_x(1)$
5	Row crops	$J_x(1)$
6	Cereals	$J_x(1)$
7	Maize	$J_x(2)$
8	Grassland with 3.0-4.0 LSU*.ha^{-1} ('dairy cattle')	$J_x(3)$
9	Grassland with 2.0 LSU.ha^{-1} ('rearing cattle')	$J_x(3)$
10	New forest	$J_x(4)$

*see List of Symbols

Table 2 Miscellaneous technologies (set J_z)

Index	Technology
1	Calves for feeding
2	Pigs for feeding
3	Pigs for breeding
4	Laying hens
5	Broilers
6	Mushrooms

Table 3 Auxiliary technologies (set J_a)

Symbol	Technology
f_s	Application of chemical fertilizer nitrogen to the soil
m_w	Application of animal wastes to the soil during autumn and winter
m_s	Application of animal wastes to the soil during spring
m_t	Transport of animal wastes inside the considered region
m_e	Export of animal wastes to outside the region
m_c, m_b	Storage capacity for animal wastes, actual amount of animal wastes in storage
s_c, i_s	Capacity of sprinkling from surface water, actual volume of sprinkling from surface water
g_c, i_g	Capacity of sprinkling from groundwater, actual volume of sprinkling from groundwater

All technologies are explicitly characterized by inputs of labour and capital. Auxiliary technologies involve a certain amount of costs and do not generate (in a direct manner) any income. Income generating technologies also involve (direct) costs but these costs are more than compensated by the benefits in the form of income. In the model these costs are mostly left implicit and are assumed to have been subtracted from the (gross) income to yield nett income. Apart from inputs of labour and capital, soil-use technologies are additionally characterized by 'inputs' of soil area, water, nitrogen, phosphorus, and other nutrients. In the model, for each soil-use technology a number of options concerning combinations of water and nitrogen inputs have been taken into consideration. The index k (k=0,1 or 2) is used for indicating the water supply option; the index n (n=1 or 2) is used for indicating the nitrogen supply option. The options for water are:
- k=0 : no sprinkling;
- k=1 : sprinkling with a maximum intensity of 25 mm per 14 days;
- k=2 : sprinkling with a maximum intensity of 25 mm per 7 days;

and for nitrogen:
- n=1 : low nitrogen supply;
- n=2 : high nitrogen supply.

For phosphorus, potassium and other nutrients the supply is always assumed to be optimal. (This is only from the point of view of crop growth; the overdosage of phosphorus that is very common in regions with a sandy soil is assumed to not harm the productivity.) The choice of the above options is based on expert judgements of what is relevant for the type of application that is envisaged for the models. Combination of the water and the nitrogen options yields in total six so-called subtechnologies k,n of each soil-use technology.

Except for maize, n=2 corresponds to 'optimal' nitrogen supply. Maize is an exception because in practice maize it is used for 'disposal' of animal wastes, involving high overdosage of nitrogen. For maize n=1 is therefore taken to represent the 'optimal' nitrogen supply, and n=2 the highest level of nitrogen overdosage that it can take. For the grassland technologies, a suboptimal nitrogen supply also involves a lower cattle stocking density: the grass production under suboptimal nitrogen conditions can support less cattle than under optimal conditions.

Technologies that involve livestock are additionally characterized by outputs of animal wastes produced as byproducts. In the example lists given in Tables 1 and 2 this concerns j=8 and j=9 of the soil-use technologies and all of the miscellaneous technologies except for mushrooms.

The use of agricultural technologies is described in terms of their intensities. For technologies of set J_x, intensities have the meaning of areas of soil allocated to them. For technologies of set J_z that involve livestock, intensities have the meaning of a number of livestock places. (The area of land that is required for these technologies is left out of consideration.) For the remaining technologies of set J_z intensities are measured in diverse units; e.g. for mushrooms in m^2. In the explanations of variables the units of miscellaneous technologies are left undefined and are simply indicated by the symbol '#'. For auxiliary technologies intensities also have various meanings and therefore have their intensities measured in various units. Because the knowing of these units is important for obtaining a clear understanding of the model, all of them are specified explicitly. For instance the capacity of sprinkling from surface water has the intensity measured in $m^3.d^{-1}$.

Before proceeding to further introduce notations and to describe the models, the following remark should be made. All agricultural activities and aspects of water and nitrogen processes are related to time and, therefore, the corresponding variables introduced in the following should in principle have the time parameter t as one of the indices. However, implementation of the models in a dynamic form, incorporating year-to-year changes of agricultural activities, is computationally not feasible. The 'problems' that are solved using the system of models are thus essentially 'one-year' and for this reason the index t is omitted from the notations. (See also Section 8.2).

3.1.2 Intensities

The following notations for intensities of technologies and subtechnologies are used:

$\underline{x}(i, j)$	- area of soil allocated to a soil-use technology j of set J_x, in subregion i	(ha);
$x_w(i, j, k, n)$	- area of soil allocated to a subtechnology of a soil-use technology	(ha);
$z\ (i, j)$	- intensity of a miscellaneous technology j of set J_z	(#) .

Obviously, the area allocated to subtechnologies k,n of a soil-use technology must add up to the total area allocated to the technology:

$$\underline{x}(i,j) = \sum_k \sum_n x_w(i,j,k,n) \tag{1}$$

for all i and $j \in J_x$.

If the total area of agricultural land in a subregion is denoted by $x_a(i)$, then the total of the areas allocated to the technologies should add up to this amount:

$$\sum_{j \in J_x} \underline{x}(i,j) = x_a(i) \tag{2}$$

for all i.

Other area constraints on (groups of) technologies follow for instance from the diversity that is required for a crop rotation scheme and for reducing the risks due to pests. The total area $\underline{x}_r(i)$ involved in a crop rotation scheme is given by

$$\underline{x}_r(i) = \sum_{j \in J_r} \underline{x}(i,j) \tag{3}$$

for all i, where J_r is the subset of J_x that is involved in the rotation. The flexibility limits of the separate technologies are given by:

$$\underline{x}(i,j) \leq r_x(j) \cdot \underline{x}_r(i) \tag{4}$$

for all i and $j \in J_r$, where $r_x(j)$ is the maximum fraction that a technology j is allowed to cover of the total area involved in the crop rotation.

The stocking of dairy cattle (j=8 of Table 1) is related to that of rearing cattle (j=9 of Table 1) and of calves for feeding. A dairy cow normally gives birth to one calf per year. One hectare with a stocking of 4 LSU involves 3 dairy cows (see Table 1 and Reinds, 1985). Of the 3 calves produced per year by these cows one calf has to be kept for replacement of the cows; the remaining two can be used as calves for feeding. 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 six months. So one hectare of grassland with 4 $LSU.ha^{-1}$, which yields 2 calves for feeding per year, can only support one permanent place for a calf.

The assumption is made that it is not possible to import from outside the region more calves for feeding than those produced inside the region. The reason for making this assumption is simply that if no upper bound is set on the import 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. So a second place can be occupied by calves imported from outside the region, based on the assumption described above. In the constraint reflecting the given considerations, the fact is also taken into account that grassland with a suboptimal nitrogen supply supports a lower stocking density than grassland with an optimal supply:

$$\sum_{i} z(i,j_{cf}) \leq 2 \cdot 1/4 \cdot \sum_{i} \sum_{k} \sum_{n} n_x\,(j_{dc},n) \cdot x_w(i,j_{dc},k,n) \tag{5}$$

where:

$z\,(i, j_{cf})$	-intensity of calves for feeding (j=1 of Table 2)	(#)
"$2 \cdot {}^1/_4$"	-amount of calves for feeding per LSU of cattle	($\#.LSU^{-1}$)
$n_x\,(j_{dc}, n)$	-stocking density of grassland with dairy cattle (j=8 of Table 1)	($LSU.ha^{-1}$)
$x_w\,(i, j_{dc}, k, n)$	- area allocated to a subtechnology k, n of grassland with dairy cattle	(ha)

A similar kind of reasoning can be followed with regard to the relation between dairy cattle and rearing cattle. This leads to the following constraint:

$$\sum_{i} \sum_{k} \sum_{n} x_w(i,j_{rc},k,n) \leq 1/16 \cdot \sum_{i} \sum_{k} \sum_{n} n_x(j_{dc},n) \cdot x_w(i,j_{dc},k,n) \tag{6}$$

where:

$x_w\,(i, j_{rc}, k, n)$ - area allocated to subtechnology k, n of grassland with rearing cattle (j=9 of Table 1) (ha)

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 in the region the ratio is lower than 6 to 1, there must be a continuous export of surplus young pigs. Conversely, if the ratio is higher than 6 to 1, there must be a continuous import of young pigs to sustain this 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 equation is introduced:

$$\sum_{i} [6 \cdot z(i,j_{op}) - z(i,j_{yp})] = z_s(j_{yp}) - z_d(j_{yp}) \tag{7}$$

where:

$z\,(i, j_{op})$	-intensity of pigs for breeding ('old pigs' ; j=3 of Table 2)	(#)
$z\,(i, j_{yp})$	-intensity of pigs for feeding ('young pigs' ; j=2 of Table 2)	(#)
$z_s\,(j_{yp})$	-regional surplus (farm economic) of pigs for feeding	(#)
$z_d\,(j_{yp})$	-regional deficit (farm economic) of pigs for feeding	(#)

Both z_s (j_{yp}) and z_d (j_{yp}) are non-negative variables, and of course always one of them should be equal to zero, because it does not make sense (from a regional point of view) to export and import simultaneously.

In order to avoid the generation of scenarios that are not realistic on a national scale, constraints are imposed on the ratio between young pigs and old ones. This is done by introducing the following relation:

$$1/9 \cdot \sum_i z(i,j_{yp}) \leq \sum_i z(i,j_{op}) \leq 1/4 \cdot \sum_i z(i,j_{yp}) \tag{8}$$

In the type of regions considered, maize is produced as foodstuff for the cattle during the winter period. The area of maize of which the crop production can be consumed by the cattle in a region is taken as 0.1 ha per livestock unit (Reinds, 1985). Maize produced in excess of the amount that can be consumed has to be sold to farmers outside the region. The nett income from this maize is lower than the yield of the maize that is consumed within the region (owing to costs of transport and functioning of the market). To be able to take this into account in the calculation of the income from agriculture, the following equation is introduced:

$$\begin{aligned} &\sum_i \underline{x}(i,j_{sm}) + x_d(j_{sm}) - x_s(j_{sm}) = \\ &0.1 \cdot \sum_i \sum_{j \in J_x(3)} \sum_k \sum_n n_x(j,n) \cdot x_w(i,j,k,n) \end{aligned} \tag{9}$$

where:

$\underline{x}$ (i, j_{sm})	- area of soil allocated to maize (j=7 of Table 1)	(ha),
x_d (j_{sm})	- regional deficit (farm economic) of maize	(ha),
x_s (j_{sm})	- regional surplus (farm economic) of maize	(ha),
J_x (3)	- subset of grassland technologies	(-),
n_x (j, n)	- stocking density of a grassland technology	(LSU.ha^{-1}).

In order to avoid the generation of scenarios that involve unrealistic increases of certain technologies, constraints of the following type are introduced:

$$\underline{x}(i,j) \leq f_x(j) \cdot x_o\,(i,j) \tag{10a}$$

$$z(i,j) \leq f_z(j) \cdot z_o(i,j) \tag{10b}$$

where:

$x_o\ (i, j)$ - area allocated to a soil-use technology in the current state (ha)

$z_o\ (i, j)$ - intensity of a miscellaneous technology in the current state (#)

$f_x\ (j)$ - flexibility parameter of a soil-use technology (-)

$f_z\ (j)$ - flexibility parameter of a miscellaneous technology (-)

For the 'auxiliary technologies' only a constraint on the export of animal wastes was deemed relevant:

$$\sum_i \sum_m m_e(i,m) \le \hat{m}_e \tag{10c}$$

where:

$\hat{m}_e$ - upper bound on animal wastes export ($t.yr^{-1}$)

3.1.3 Sprinkling

Implementation of soil-use technologies can be supported by sprinkling irrigation. This option is embodied by the subtechnologies that involve sprinkling (see also Section 3.1.1). Sprinkling can either be from surface water or from groundwater. The sprinkling capacity in a subregion is determined by the total capacity of sprinkler canons and the accompanying equipment. In the model the capacity of sprinkling for k=1 subtechnologies is kept separate from that for the k=2 subtechnologies. For the k=1 subtechnologies the total sprinkling capacity in a subregion should comply with:

$$s_c(i,1) + g_c(i,1) = C_u \cdot \sum_{j \in J_x} \sum_n x_w(i,j,1,n) \cdot 25/14 \tag{11a}$$

and for the k=2 subtechnologies:

$$s_c(i,2) + g_c(i,2) = C_u \cdot \sum_{j \in J_x} \sum_n x_n(i,j,2,n) \cdot 25/7 \tag{11b}$$

where:

$s_c\ (i, k)$ - capacity of sprinkling from surface water ($m^3.d^{-1}$),

$g_c\ (i, k)$ - capacity of sprinkling from groundwater ($m^3.d^{-1}$),

x_w *(i, j, k, n)* - area allocated to a subtechnology with a maximum sprinkling intensity of 25 mm/14 d (*k*=1) or 25 mm/7 d (*k*=2) (ha),

C_u - unit conversion factor (numerical value = 10) ($m^3.(mm.ha)^{-1}$).

3.1.4 Soil fertilization

In the model, fertilisation is considered in a selective manner. Only those nutrients are considered that are abundantly present in the locally produced animal wastes and that form a threat to the soil productivity and/or to the quality of the environment. Considered are only nitrogen and phosphorus. (The model is easily extendable to other elements like potassium.) The crop requirements of these nutrients are calculated on the aggregation level of the subsets of set J_x, which are:

- arable land technologies, excluding maize;
- (silage) maize technologies;
- grassland technologies;
- 'new forest' technologies.

The justification for choosing this aggregation level is given in Section 7.1.1

For nitrogen the following equations give the totalized requirement per category of soil use, per subregion:

$$\underline{v}_r(i,l) = \sum_{j \in J_x(l)} \sum_k \sum_n n_r(j,n) \cdot x_w(i,j,k,n) \qquad (12)$$

for all *i* and *l* (except *l*=4 for new forest technologies), where:

$\underline{v}_r$ *(i, l)* - total nitrogen requirement of technologies in soil-use category *l* (i.e. technologies of subset $J_x(l)$) ($t.yr^{-1}$)

n_r *(j, n)* - nitrogen requirement of a soil-use subtechnology ($t.ha^{-1}.yr^{-1}$)

For phosphorus (and other nutrients) a similar equation applies.

3.1.5 Crop production

A great many factors determine the yield of a crop. Here the focus is on the influence of soil moisture and of soil nitrogen. The computation of the crop production is done in two steps:

- computation of the crop production under optimal nitrogen conditions;
- multiplication of the crop production by a reduction factor for suboptimal nitrogen conditions (if applicable).

This scheme is the same as that followed in the coupled models SIMGRO-SIMCROP. Since the first step is performed in a manner that is completely analogous the computation of the evapotranspiration, these calculations are given in Section 6.5.

The second step of the computation is done with (Feddes & Rijtema, 1983):

$$c_q(i,j,k,n) = n_{red}(j,n) \cdot c_{qw}(i,j,k) \tag{13}$$

where:

$c_q\ (i,j,k,n)$	- actual crop production	$(t.ha^{-1}.yr^{-1})$
$c_{qw}\ (i,j,k)$	- crop production under optimal conditions of nitrogen supply	$(t.ha^{-1}.yr^{-1})$
$n_{red}\ (j,n)$	- reduction factor for suboptimal conditions of nitrogen supply	(-)

3.1.6 Animal wastes byproducts

The technologies that involve livestock produce animal wastes as byproducts. These wastes can be used as soil fertilizers in the region itself, or can be transported to outside the region, where they can also be used as fertilizers or be 'destructed' in a processing plant. Excess animal wastes can temporarily be stored in tanks; from a water quality point of view, animal wastes that are produced during the summer, autumn and winter can best be stored until the next spring and only then be applied to the soil.

The temporal cycle of applying animal wastes to soil is schematized into a number of periods. The schematization is based on practical considerations at the farm level and on considerations deriving from developments at the national policy making level. The practical considerations are that
- from January 1 1988 there will be enforced a prohibition of animal wastes application to arable land (with a sandy subsoil) during the autumn, till November 1; for pasture land this will be till December 1;
- roughly from the year 2000 there will also be a general application prohibition during autumn and winter till February 15.

The measures that are planned for enforcement as of January 1 1988 have been implemented. Therefore, these measures have not been included as 'options' of the models, but as unmodifiable reality. In order to avoid having two dates for the ending of the prohibition period (November 1 and December 1), a single date has been taken:

November 15. A further simplification is that the wastes produced by dairy cattle in the period leading up to November 15 all get applied to land, either during grazing or through spreading by farmers. In view of the long-term policy goal of implementing a general winter prohibition till February 15, the period of winter application is in the model taken as November 15 - February 15.

Summarizing, the schematized annual cycle involves three distinct periods of application:

1. April 15 - November 15: *summer period*
2. November 15 - February 15: *autumn/winter period*
3. February 15 - April 15: *spring period*

In the model, the decision variables for the application of animal wastes to the soil are on the aggregation level of 'categories of soil use' - there is only one composite application variable per category of the soil-use technologies that were defined in Section 3.1.1:

- arable land technologies;
- maize technologies;
- grassland technologies;

('New forest' is not included here, because spreading of slurry in forests is ruled out.)

The reasons for introducing the animal wastes application variables on this level of aggregation are that

- none of the constraints in which they are involved are on a lower level of aggregation;
- the available data of nitrogen effectivity and nitrogen leaching are also only available on this level (see Section 7.1.1).

Combination of the two application periods with the three categories of soil use gives six decision variables for the applications (per type of animal wastes and per subregion). The notation used for these applications is:

- $m_w(i, l, m)$ - autumn/winter application of animal wastes type m in subregion i to soil with technologies of subset $J_x(l)$;
- $m_s(i, l, m)$ - spring application of animal wastes.

Costs of transporting animal wastes on a local scale are derived from the following type of equation (Limpens, 1985):

$$C_t = m_t \cdot (c_f + L_t \cdot c_v) \tag{14}$$

where:

C_t - total costs of transport (fl.yr^{-1})
m_t - transport of animal wastes (t.yr^{-1})
c_f - fixed costs (fl.t^{-1})
c_v - variable costs (fl.t^{-1}.km^{-1})
L_t - distance (km)

For export to outside the region a representative distance is taken (e.g. 160 km); the variable costs are lower than for transport on a local scale.

For the purpose of formulating the mathematical relations pertaining to the transport of animal wastes on a local scale the following variables are introduced:

$m_q\ (i, 1, m)$ - deficit of wastes of type m in subregion i, i.e. the total (local) application minus the total (local) production (t.yr^{-1});
$m_q\ (i, 2, m)$ - part of the surplus of wastes that gets disposed of by means of transport to another subregion inside the region considered (t.yr^{-1});
$m_e\ (i, m)$ - part of the surplus of wastes that gets disposed of by means of transport to outside the region (t.yr^{-1});
$n_t\ (i)$ - number of subregions that neighbour a subregion i;
i_t - local index of a subregion neighbouring subregion i (i_t ranges from 1 to $n_t\ (i)$)
$n_{sub}\ (i, i_t)$ - index of a subregion neighbouring subregion i;
$m_t\ (i, i_t, m)$ - transport of wastes from subregion i to subregion $n_{sub}\ (i, i_t)$ (t.yr^{-1}).

The transport network that was implemented for the study region is given in Figure 3. In the model the transports are assumed to take place continuously through time, with a constant intensity. The exception to this is the transport of animal wastes produced by dairy cattle: only the wastes produced during the period November 15 - April 15 can potentially be transported. (The rest is applied to the soil during grazing). So the transport of dairy manure is assumed to be constant during this period, and zero during the rest of the year.

The fixed costs of transport on a local scale are proportional to $m_q\ (i, 2, m)$, being the amount of the local production that gets disposed of by means of transport to another subregion. The variable costs are related to $m_t\ (i, i_t, m)$, proportional to the distance between subregion i and subregion $n_{sub}\ (i, i_t)$.

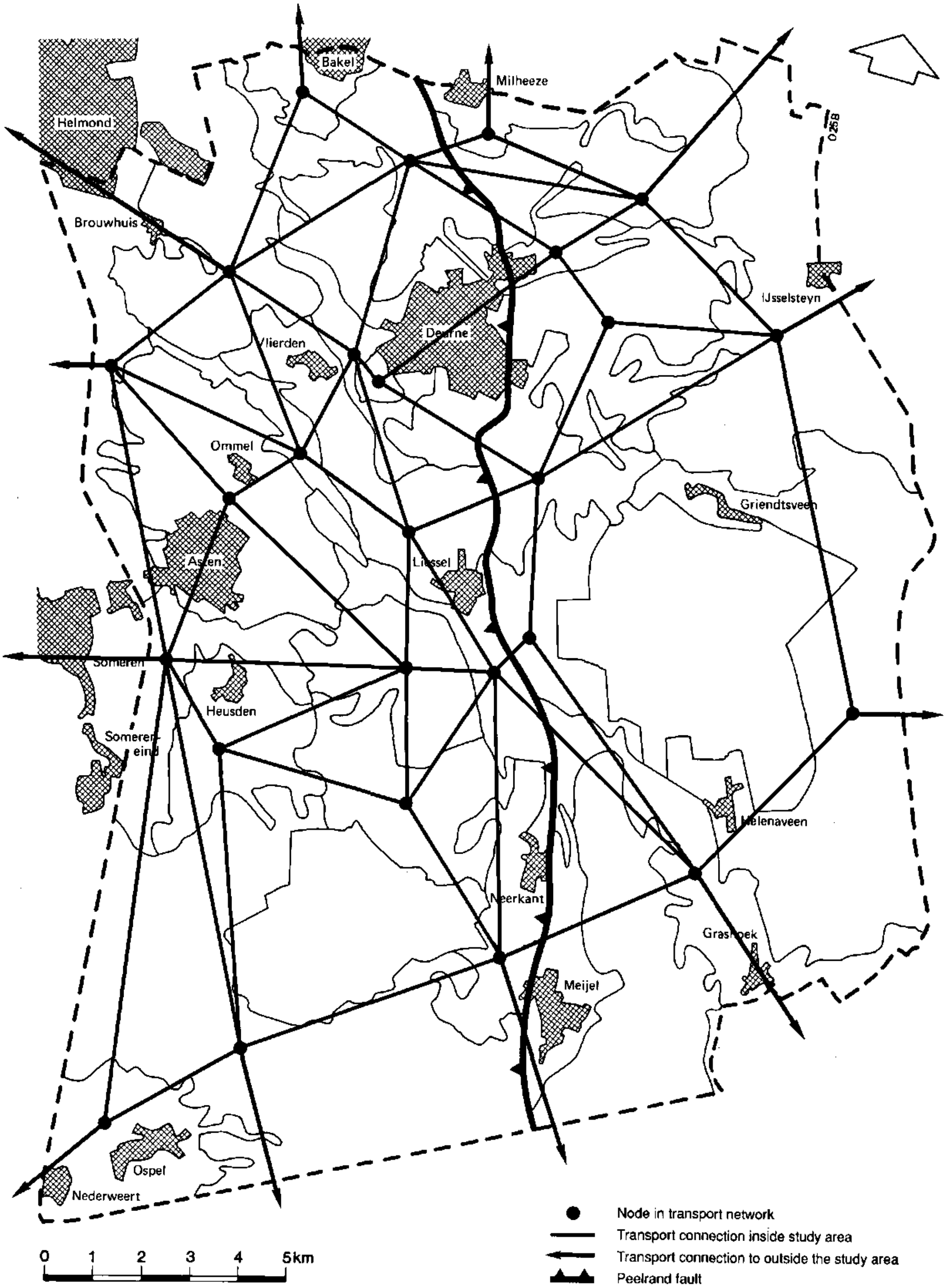

Fig. 3 Animal wastes transport network for the Southern Peel region

The local transports from and to a certain subregion should comply with:

$$m_q(i,2,m) - m_q(i,1,m) =$$

$$\sum_{i_t=1}^{n_t(i)} m_t(i,i_t,m) - \sum_{(i_2,i_t),\ n_{sub}(i_2,i_t) = i} m_t(i_2,i_t,m) \tag{15}$$

where the notation below the second summation symbol indicates that all combinations of (i_2, i_t) are relevant of which n_{sub} (i_2, i_t) is equal to the number of the subregion for which the balance holds.

Though the model assumes that there is no accumulation of wastes over the years, accumulation within a year is allowed for. This accumulation occurs during the summer period; and if there is a winter prohibition of animal wastes spreading, accumulation continues throughout the winter. By the end of the spring period, however, the wastes in storage are assumed to all have been disposed of in order to make space for the wastes produced during the next year. The required storage capacity for accommodating this annual cycle is determined by the *peak* amount of wastes in storage. Since the soil applications and also the transports are assumed to be of constant intensity during the model application periods, the amount in storage as a function of time follows a linear trajectory between the transition dates (see also Table 4). So the peak amount can simply be derived from the values on the transition dates.

For the sake of convenience the transition dates of the storage trajectory are associated with values of the index *t*. The index value *t*=0 is taken at the beginning of the summer accumulation period, i.e. April 15. The tanks are assumed to be empty on this date, which is in line with the assumption of there not being any accumulation of wastes over the years.

***Table 4** Transition dates of 'storage trajectory' of animal wastes*

t	Date	Length of preceding period (d)
0	April 15	59
1	November 15	214
2	February 15	92

In the following, the storages on the dates given in Table 4 are computed. These storages are in the model treated as decision variables that of themselves are non-negative; so it is not necessary to include constraints specifying their non-negativity.

As already stated, the storage is taken to be zero on April 15 (t=0); thus we have for the storage of wastes type m in subregion i:

$$m_b\ (0,\ i,\ m) = 0 \tag{16}$$

for all i and m.

During the period between April 15 and November 15 (which has a length of 214 days) spreading of wastes is not possible. It is, however, assumed that all the wastes produced by cattle are applied to the grassland during grazing. So for the wastes from cattle (m=1) we have for November 15 (t=1):

$$m_b\ (1,\ i,\ 1) = 0 \tag{17}$$

For $m \geq 2$ we have:

$$m_b(1,i,m) = (214/365) \cdot \{ \sum_{j \in J_z} m_z(j,m) \cdot z(i,j) + m_q(i,1,m) - m_q(i,2,m) - m_e(i,m)\} \tag{18}$$

where:

$m_z\ (j,\ m)$ - yearly production of animal wastes type m per unit of $z\ (i,\ j)$ (t.#$^{-1}$.yr^{-1})

Dairy cattle are assumed to be kept indoors between November 15 (t=1) and April 15 (t=0), which is for a period of 151 days (92+59). So the amount of cattle wastes in storage on February 15 (t=2) is given by

$$m_b(2,i,1) = (92/151) \cdot \{ \sum_{j \in J_x(3)} \sum_k \sum_n m_x(j,n,1) \cdot x_w(i,j,k,n) + m_q(i,1,1) - m_q(i,2,1) - m_e(i,1)\} - \sum_l m_w(i,l,1) \tag{19}$$

where:

$m_x\ (j,\ n,\ 1)$ - half-yearly production (November 15 - April 15) of cattle wastes per unit of $x_w\ (i,\ j,\ k,\ n)$ (t.ha^{-1}.yr^{-1})

For the other types of wastes ($m \geq 2$) the amount in storage on February 15 is given by:

$$m_b(2,i,m) = ((214 + 92)/365) \cdot \{ \sum_{j \in J_z} m_z(j,m) \cdot z(i,j) + m_q(i,1,m) - m_q(i,2,m) - m_e(i,m)\} - \sum_l m_w(i,l,m) \tag{20}$$

On April 15 the tanks should be empty again so that there is space for the summer accumulation. For animal wastes produced by cattle this is ensured by the equation (m=1):

$$\sum_{j \in J_x(3)} \sum_k \sum_n m_x(j,n,1) \cdot x_w(i,j,k,n) + m_q(i,1,1) - m_q(i,2,1) - m_e(i,1) = \sum_l \{m_s(i,l,1) + m_w(i,l,1)\} \tag{21}$$

and for the other types of animal wastes ($m \geq 2$):

$$\sum_{j \in J_z} m_z(j,m) \cdot z(i,j) + m_q(i,1,m) - m_q(i,2,m) - m_e(i,m) = \sum_l \{m_s(i,l,m) + m_w(i,l,m)\} \tag{22}$$

The peak value of the amount of wastes in storage, which determines the required storage capacity, is in the model reached on either November 15 or on February 15. So we have:

$$m_c(i) = MAX \{\sum_m m_b(1,i,m); \sum_m m_b(2,i,m)\} \tag{23}$$

for all i, where $m_c\ (i)$ is the required storage capacity. In the model the MAX operator is implemented by introducing the following pair of constraints:

$$m_c(i) \geq \sum_m m_b(1,i,m) \tag{24}$$

$$m_c(i) \geq \sum_m m_b(2,i,m) \tag{25}$$

The storage tanks involve costs which are subtracted from the gross income, thus yielding nett income from agriculture. Maximization of nett income from agriculture is one of the objectives of the regional development. The way in which the model is used therefore leads to the elimination of unnecessary costs, meaning that the chosen value of a decision variable m_c (i) will be such that it just fulfils both of the above constraints. This outcome is identical to the sought MAX-value. Figure 4 shows typical trajectories of animal wastes storage during a year.

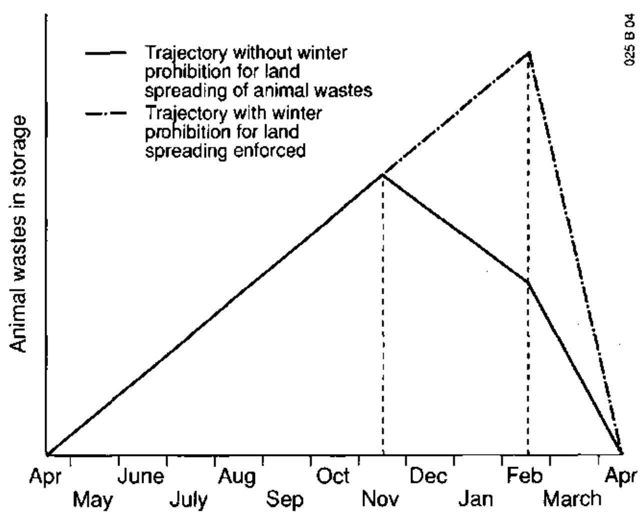

Fig. 4 Typical trajectories of storage of animal wastes (other than that of cattle)

3.2 Economic aspects

3.2.1 Labour

Due to the differences between local and hired workers, both types are introduced into the model. By local workers are meant people that own capital goods and sometimes even land, i.e. the farmers and their families. Local workers differ from hired workers in their mobility and 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 also requires 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 towards income is relatively flexible: in many situations a reduction of income can be acceptable as long as other forms of remuneration remain intact or are increased.

The amount of employed workers clearly depends on the technologies that are implemented. Expressed in terms of 'man year', the labour balance equation reads:

$$
\begin{aligned}
l_a(i) + l_h(i) = & \sum_{j \in J_x} \sum_k \sum_n l_x(j,n) \cdot x_w(i,j,k,n) + \\
& \sum_{j \in J_z} l_z(j) \cdot z(i,j) + \sum_l l_{fs} \cdot f_s(i,l) + \\
& \sum_l \sum_m \{ l_{mw}(m) \cdot m_w(i,l,m) + l_{ms}(m) \cdot m_s(i,l,m) \} + \\
& \sum_k \{ l_{is} \cdot i_s(i,k) + l_{ig} \cdot i_g(i,k) \}
\end{aligned}
\qquad (26)
$$

where:

$l_a(i)$	- amount of labour done by local workers	(myr.yr^{-1})
$l_h(i)$	- amount of labour done by hired workers	(myr.yr^{-1})
$l_x(j, n)$	- labour requirement per unit of $x_w(i, j, k, n)$	(myr.ha^{-1}.yr^{-1})
$l_z(j)$	- labour requirement per unit of $z(i, j)$	(myr.#$^{-1}$.yr^{-1})
$f_s(i, l)$	- application of chemical fertilizer N to subset $J_x(l)$ of J_x	(t.yr^{-1})
l_{fs}	- labour requirement per unit of chemical fertilizer application $f_s(i, l)$	(myr. t^{-1})
$m_w(i, l, m)$	- autumn/winter application of animal wastes type m on subset $J_x(l)$ of J_x	(t.yr^{-1})
$l_{mw}(m)$	- labour requirements per unit of $m_w(i, l, m)$	(myr.t^{-1})
$m_s(i, l, m)$	- spring application of animal wastes type m on subset $J_x(l)$ of J_x	(t.yr^{-1})
$l_{ms}(m)$	- labour requirement per unit of $m_s(i, l, m)$	(myr.t^{-1})
$i_s(i, k)$	- volume of sprinkling from surface water	(m^3.yr^{-1})
l_{is}	- labour requirement per unit of $i_s(i, k)$	(myr.m^{-3})
$i_g(i, k)$	- volume of sprinkling from groundwater	(m^3.yr^{-1})
l_{ig}	- labour requirement per unit of $i_g(i, k)$	(myr. m^{-3})

The respective labour requirement data are given by Reinds (1985).

The amount of workers that are employed in agriculture is of special interest to the regional authority, because it serves as one of the indicators of well-being of the agricultural population:

$$\underline{L}_T = \sum_i \{ l_a(i) + l_h(i) \} \tag{27}$$

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

$$\check{l}_a (i) \leq l_a (i) \leq \hat{l}_a (i) \tag{28}$$

where:
$\check{l}_a$ - lower bound on total labour done by local workers $(myr.yr^{-1})$,
$\hat{l}_a$ - upper bound on total labour done by local workers $(myr.yr^{-1})$.

Constraints that are useful for avoiding the generation of scenarios which are not realistic from the employment point of view are included in the form of lower and upper bounds on labour used in the whole region. For the local labour this is

$$\check{l}_l \leq \Sigma\, l_a (i) \leq \hat{l}_l \tag{29a}$$

where:
$\check{l}_l$ - lower bound on labour done by local workers in the region $(myr.yr^{-1})$
$\hat{l}_l$ - upper bound on labour done by local workers in the region $(myr.yr^{-1})$

And for the total labour (i.e. the sum of local and hired labour) such constraints are:

$$\check{l}_t \leq \underline{L}_T \leq \hat{l}_t \tag{29b}$$

where:
$\check{l}_t$ - lower bound on total labour done in the region $(myr.yr^{-1})$
$\hat{l}_t$ - upper bound on total labour done in the region $(myr.yr^{-1})$

3.2.2 Income

The regional annual income from agriculture is of special interest because it is one of the indicators of well-being of agriculture. In the computation of the nett income

a number of costs are included in the income coefficients of technologies. Others are included explicitly; these are:
- costs of hired labour;
- costs ('variable' and 'fixed') of auxiliary technologies;
- extra costs due to imbalance between technologies (like between silage maize and cattle).

Implicit is left for instance the costs of feedstuff concentrates that are required for the technologies of set J_z that involve livestock. The following equation for the regional annual income is used:

$$
\begin{aligned}
\underline{Y}_T &= \sum_i \underline{y}(i) = \\
&\sum_i \Big[\sum_{j \in J_x} \sum_k \sum_n \{c_q(i,j,k,n) \cdot y_x(j) - p_x(j)\} \cdot x_w(i,j,k,n) + \\
&\sum_{j \in J_z} y_z(j) \cdot z(i,j) - p_{lh} \cdot l_h(i) - \sum_l p_{fs} \cdot f_s(i,l) - \\
&\sum_l \sum_m \{p_{mw}(m) \cdot m_w(i,l,m) + p_{ms}(m) \cdot m_s(i,l,m)\} - p_{mc} \cdot m_c(i) - \\
&\sum_m \{p_{me}(m) \cdot m_e(i,m) + p_{mq}(m) \cdot m_q(i,2,m)\} - \\
&\sum_m \sum_{i_t} p_{mt}(i,i_t,m) \cdot m_t(i,i_t,m) - \\
&\sum_k \{p_{sc}(k) \cdot s_c(i,k) + p_{gc}(k) \cdot g_c(i,k)\} - \\
&\sum_k \{p_{is}(k) \cdot i_s(i,k) + p_{ig}(k) \cdot i_g(i,k)\}\Big] - p_{xs}(j_{sm}) \cdot x_s(j_{sm}) - \\
&p_{zs}(j_{yp}) \cdot z_s(j_{yp}) - p_{zd}(j_{yp}) \cdot z_d(j_{yp})
\end{aligned}
\qquad (30)
$$

where:

$\underline{Y}_T$	- total income from agriculture in the region	(fl.yr^{-1})
$\underline{y}(i)$	- income from agriculture in subregion i	(fl.yr.$^{-1}$)
$c_q(i, j, k, n)$	- crop production per unit of $x_w(i, j, k, n)$	(t.ha^{-1}.yr^{-1})
$y_x(j)$	- income per unit of crop production	(fl.t^{-1})
$p_x(j)$	- fixed costs per unit of $x_w(i, j, k, n)$	(fl.ha^{-1}.yr^{-1})
$y_z(j)$	- income per unit of $z(i, j)$	(fl.#$^{-1}$.yr

l_h *(i)*	- amount of labour done by hired workers	$(myr.yr^{-1})$
p_{lh}	- price of hired labour	$(fl.myr^{-1})$
f_s *(i, l)*	- amount of chemical fertilizer nitrogen applied to subset J_x *(l)* of set J_x	$(t.yr^{-1})$
p_{fs}	- price of chemical fertilizer nitrogen	$(fl.t^{-1})$
m_s *(i, l, m)*	- spring application of animal wastes	$(t.yr^{-1})$
p_{ms} *(m)*	- costs per unit of m_s *(i, l, m)*	$(fl.t^{-1})$
m_w *(i, l, m)*	- autumn/winter application of animal wastes	$(t.yr^{-1})$
p_{mw} *(m)*	- costs per unit of m_w *(i, l, m)*	$(fl.t^{-1})$
m_c *(i)*	- total animal wastes storage capacity	(t)
p_{mc}	- annual costs per unit of m_c *(i)*	$(fl.t^{-1}.yr^{-1})$
m_e *(i, m)*	- export of animal wastes to outside the region	$(t.\ yr^{-1})$
p_{me} *(m)*	- cost per unit of m_e *(i, m)*	$(fl.t^{-1})$
m_q *(i, 2, m)*	- part of the surplus of animal wastes that gets disposed of by local transport to another subregion within the region	$(t.yr^{-1})$
p_{mq} *(m)*	- fixed costs of animal wastes transport within the region	$(fl.t^{-1})$
m_t (i, i_t, m)	- transport of animal wastes type *m* from subregion *i* to the i_t-th neigbouring subregion, subregion n_{sub} (i, i_t)	$(t.yr^{-1})$
p_{mt} (i, i_t, m)	- variable costs of animal wastes transport from subregion *i* to the i_t-th neighbouring subregion, subregion n_{sub} (i, i_t)	$(fl.t^{-1}.yr^{-1})$
s_c *(i, k)*	- capacity of sprinkling from surface water	$(m^3.d^{-1})$
p_{sc} *(k)*	- annual costs per unit of s_c *(i, k)*	$(fl.yr^{-1}.(m^3.d^{-1})^{-1})$
g_c *(i, k)*	- capacity of sprinkling from groundwater	$(m^3.d^{-1})$
p_{gc} *(k)*	- annual costs per unit of g_c *(i, k)*	$(fl.yr^{-1}.(m^3.d^{-1})^{-1})$
i_s *(i, k)*	- volume of sprinkling from surface water	$(m^3.yr^{-1})$
p_{is} *(i, k)*	- costs per unit of sprinkling i_s *(i, k)*	$(fl.m^{-3})$
i_g *(i, k)*	- volume of sprinkling from groundwater	$(m^3.yr^{-1})$
p_{ig} *(k)*	- costs per unit of sprinkling i_g *(i, k)*	$(fl.m^{-3})$
x_s (j_{sm})	- regional surplus (farm economic) of area allocated to maize	(ha)
p_{xs} (j_{sm})	- extra costs per unit of x_s (j_{sm})	$(fl.ha^{-1}.yr^{-1})$
z_s (j_{yp})	- regional surplus (farm economic) of pigs for feeding	(#)
p_{zs} (j_{yp})	- extra costs per unit of z_s (j_{yp})	$(fl.\#^{-1}.yr^{-1})$
z_d (j_{yp})	- regional deficit (farm economic) of pigs for feeding	(#)
p_{zd} (j_{yp})	- extra costs per unit of z_d (j_{yp})	$(fl.\#^{-1}.yr^{-1})$

Local transport of animal wastes *into* a subregion is not included in the above equation because that would cause double counting of this transport. The values of parameters in the income equation are given in Reinds (1985).

3.2.3 Capital

Expansion of certain technologies is related to increase in capital goods, i.e. investments. In the theoretical model of agriculture (Vreke, 1981) the assumption is made that the required investment must be financed from savings of the farmers, and therefore not from borrowed capital. The savings are what is left of the income after the 'consumption' of income by the local workers has been subtracted. In the simplified model of agriculture it is not possible to capture the dynamics of savings in relation to investments. A very simple approach is followed:

- per subregion the requirement is made that the income is not less than the consumption by local workers;
- for the region as a whole the total of the capital goods in the generated scenario must not exceed the amount present in the current state by more than a certain factor.

The constraint on the income per subregion reads:

$$\underline{y}\,(i) \geq c_o \cdot l_a\,(i) \tag{31}$$

for all i, where:

$\underline{y}\,(i)$ - subregional income from agriculture (fl.yr^{-1})
l_a - labour done by local workers (myr.yr^{-1})
c_o - consumption per unit of $l_a\,(i)$ (fl.myr^{-1}.yr^{-1})

The constraint on the total amount of capital goods reads:

$$\sum_i \Big[\sum_{j \in J_x} \sum_k \sum_n p_{xi}(j,n) \cdot x_w(i,j,k,n) + \sum_{j \in J_z} p_{zi}(j) \cdot z(i,j) + \sum_k \{p_{sci}(k) \cdot s_c(i,k) + p_{gci}(k) \cdot g_c(i,k)\} + p_{mci} \cdot m_c(i) \Big] \leq c_f \cdot K_o \tag{32}$$

where:

p_{xi} *(j, n)*	- amount of capital per unit of $\boldsymbol{x_w}$ *(i, j, k, n)*	(fl.ha^{-1})
p_{zi} *(j)*	- amount of capital per unit of *z (i, j)*	(fl.$\#^{-1}$)
p_{sci} *(k)*	- amount of capital per unit of $\boldsymbol{s_c}$ *(i, k)*	(fl.$(m^3.d^{-1})^{-1}$)
p_{gci} *(k)*	- amount of capital per unit of $\boldsymbol{g_c}$ *i, k)*	(fl.$(m^3.d^{-1})^{-1}$)
p_{mci}	- amount of capital per unit of $\boldsymbol{m_c}$ *(i)*	(fl.t^{-1})
c_f	- flexibility parameter of capital	(-)
K_o	- capital goods in the current state	(fl)

Application of SWAFLO (Kemmers & Jansen, 1988) to a nature area yields a simple relation between the loss of species rareness and the lowering of the groundwater level due to extractions of groundwater for sprinkling and for public water supply. This loss of species rareness $\underline{W}$ is the used indicator of well-being for nature areas. Clearly, the lower the value of $\underline{W}$, the better it is. Typical results of computations with the SWAFLO model are given in Fig. 5. The horizontal axis is for the lowering at the beginning of summer (h_s), the vertical axis for the lowering at the beginning of winter (h_w). For a number of $\underline{W}$-values the envelope line indicating the limiting combinations of h_s and h_w is drawn.

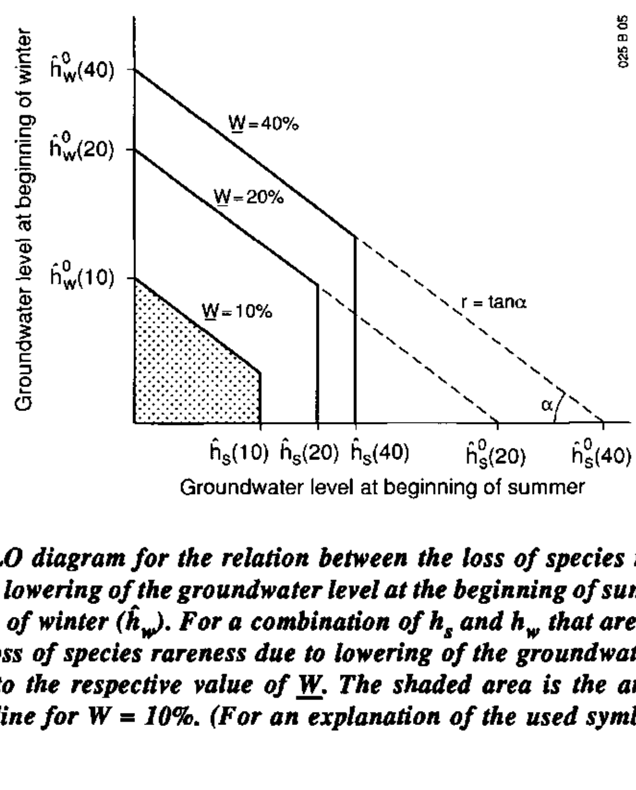

***Fig. 5** A SWAFLO diagram for the relation between the loss of species rareness $\underline{W}$ and the maximum lowering of the groundwater level at the beginning of summer ($\hat{h}_s$) and at the beginning of winter ($\hat{h}_w$). For a combination of h_s and h_w that are within an envelope line the loss of species rareness due to lowering of the groundwater level is less than or equal to the respective value of $\underline{W}$. The shaded area is the area enclosed by the envelope line for W = 10%. (For an explanation of the used symbols see Eqs. 33, 34 and 35).*

For reasons given in Kemmers & Jansen (1988) the lowering at the beginning of summer pertains to the lowering in an 'average' meteorological year, whereas the lowering at the beginning of winter refers to a '10% dry year', i.e. a year with an evapotranspiration surplus (over precipitation) that has an exceedance probability of 10%. The vertical section of a $\underline{W}$-line corresponds with the constraint:

$$\underline{h}_s(i) \leq \hat{h}_s(i, \underline{W}) \tag{33}$$

for all i that are nature areas, where:

$\underline{W}$	- allowed loss of species rareness	(%)
$\underline{h}_s\ (i)$	- lowering of the groundwater level at the beginning of summer in an 'average' year	(cm)
$\hat{h}_s\ (i, \underline{W})$	- maximum lowering at the beginning of summer	(cm)

(The allowed loss of species rareness can be specified differently for different nature areas, and should therefore actually be written as $\underline{W}\ (i)$. This is, however, avoided, in order to not clutter up the notations).

The slope of the remaining part of the envelope line means that there is a relation between the bounds on the lowerings and the *actual* values of the lowerings: the bound on the lowering at the beginning of winter is a function of the actual lowering at the beginning of summer. This is reflected by the constraint:

$$\underline{h}_w\ (i) \le \hat{h}_w^{\,o}\ (i, \underline{W}) - \underline{h}_s\ (i) \cdot r\ (i, \underline{W}) \tag{34}$$

for all i that are nature areas, where:

$\underline{h}_w\ (i)$	- lowering of the groundwater level in a '10% dry year'	(cm)
$\hat{h}_w^{\,o}\ (i, \underline{W})$	- intercept term (see Fig. 5)	(cm)
$r\ (i, \underline{W})$	- slope of the envelope line	(-)

An alternative way of formulating the above constraint is:

$$\underline{h}_s\ (i) \le \hat{h}_s^{\,o}\ (i, \underline{W}) - \underline{h}_w\ (i)\ /\ r\ (i, \underline{W}) \tag{35}$$

The manner in which the actual lowerings are computed is given in Section 6.6.

5 SIMPLIFIED MODEL OF PUBLIC WATER SUPPLY

Public water supply is here defined to include the supply of water for domestic use, for use by industry, and for providing livestock with drinking water. As a water resource groundwater is preferable to surface water in view of its constant high quality, at least, as long as it is not too heavily contaminated by nitrate.

In the model, the total amount of groundwater that can be extracted for satisfying the needs of households and of industry is treated as an 'indicator', i.e. a quantification of 'well-being' of public water supply. In this manner the need for quantifying the benefits that derive from the availability of groundwater for public water supply is circumvented: this quantification is made external to the model. In the model there is also no attempt at quantifying the costs of making new wells and connecting them to the existing distribution network. The only relation pertaining to the quantitative aspect of 'public water supply' is the constraint that relates the sum of the extractions to the value of the public water supply indicator $\underline{Q}_T$:

$$\sum_i q(i) \geq \underline{Q}_T + \sum_i \{ \sum_{j \in J_x(3)} \sum_k \sum_n w_x(j,n) \cdot x_w(i,j,k,n) + \sum_{j \in J_z} w_z(j) \cdot z(i,j) \} \tag{36}$$

where:

$q\ (i)$	- extraction of groundwater for public water supply	($m^3.yr^{-1}$)
$\underline{Q}_T$	- total amount of groundwater available for households and industry	($m^3.yr^{-1}$)
$J_x\ (3)$	- subset of grassland technologies	(-)
$w_x\ (j, n)$	- drinking water requirement per unit of $x_w\ (i, j, k, n)$	($m^3.ha^{-1}.yr^{-1}$)
$w_z\ (i, j)$	- drinking water requirement per unit of $z\ (i, j)$	($m^3.\#^{-1}.yr^{-1}$)

A second indicator for the well-being of public water supply is the concentration of nitrate in the extracted groundwater. The value of this indicator serves as an upper bound of the concentrations in the aquifer from which the extractions take place (see also $\underline{\hat{C}}_d$ in Eq. 71).

6 SIMPLIFIED MODEL OF THE REGIONAL HYDROLOGY AND CROP PRODUCTION

The water users interact with the regional water system in a complex manner. The interactions that are of interest for the present study are:
- supply of surface water from an external source;
- raising of surface water levels to increase the infiltration to groundwater ('subirrigation');
- withdrawal of surface water for sprinkling of crops;
- extraction of groundwater for public water supply;
- evapotranspiration of crops;
- impact of hydrological conditions on the vegetation in nature areas.

Seen from a systems viewpoint, these interactions can be grouped into the following four categories:
- input;
- throughput;
- output;
- state.

Only one interaction fits the first category, being the supply of surface water from an external source. Evapotranspiration of crops and extraction of groundwater for public water supply fit the third. The 'state' of the system affects the vegetation in nature areas: the groundwater regime has a strong influence on the aeration; groundwater level lowerings therefore have an impact on the biochemical and microbial processes in the soil.

The remaining interactions are what can be called 'modifications of the throughput'. Such modifications can, characteristically, give rise to closed circles of causes and effects. For example, the extraction of groundwater and subsequent use for sprinkling can cause a lowering of groundwater levels, thus leading to a reduction of capillary rise, which in turn leads to a deficit of soil moisture supply to crops; this deficit prompts extra extractions of groundwater for sprinkling. Such 'feedback loops' add special problems to the task of simplified modelling. But it is not only the feedback that is induced by human intervention that causes the difficulties. Feedback is a mechanism that is omnipresent in the hydrosphere. In order to capture some of this feedback in the simplified model, heavy use has to be made of results obtained with the comprehensive model SIMGRO-SIMCROP.

Since the credibility of the simplified model largely depends on the technique of obtaining certain data from running SIMGRO-SIMCROP, the model description given in the following includes indications of how this is accomplished. Because of the interdependent nature of the diverse relations that the simplified model consists of, it is not possible to order the relations in such a manner that the introduction of (state) variables in the text is immediately followed by a description of how they are computed. Thus, only after having gone through the whole of Chapter 6 will the reader be able to grasp how the relations together form a coherent model.

6.1 Sprinkling of crops

For the purpose of constructing a simplified model, a discrete number of sprinkling options have been introduced (see also Section 3.1.3):
- no sprinkling (index value k=0);
- sprinkling with a maximum intensity of 25 mm per 14 days (k=1);
- sprinkling with a maximum intensity of 25 mm per 7 days (k=2).

It is of course possible to expand the number of options, but this has the drawback of increasing the computational burden. For the above set of options, a convenient expression for the respective sprinkling intensity is given by ' $\frac{25k}{14}$ mm/d'.

For being able to compute the 'variable costs' of sprinkling (and also for some other purposes) it is necessary to know the total volume of water that is sprinkled. In order to obtain an estimate of this volume one must make assumptions with respect to the operational rule with which sprinkler apparatus is used. Such a rule is contained in SIMGRO. This rule consists simply of a root-zone soil-moisture criterium for turning on the sprinklers. For k=2 an amount of 25 mm is applied during the ensuing week before making the next check of the soil moisture content. For k=1 the next check is made after a week of sprinkling with an intensity of $\frac{25}{14}$ mm/d, i.e. after a total sprinkling of 12.5 mm. The soil moisture criterium has not been subjected to a formal optimization: values obtained from 'expert judgements' were considered to suffice - it was also found that the outcome of the model was not very sensitive to variation of the criterium. As already brought forward in the introduction, the amount of sprinkling is influenced by the extractions of groundwater. To take this into account the following relation is introduced:

$$s_w\,(i,j,k) = s_w^{\,o}\,(i,j,k) + s_w^{\,g}\,(i,j,k) \qquad (37)$$

for all i, j, and k=1 and 2, where:

$s_w\,(i,k,k)$	- total amount of sprinkling of a subtechnology k, n of technology j (of set J_x)	($mm.yr^{-1}$)
$s_w^{\,o}\,(i,j,k)$	- basic amount of sprinkling	($mm.yr^{-1}$)
$s_w^{\,g}\,(i,j,k)$	- extra amount of sprinkling due to the influence of groundwater extractions	($mm.yr^{-1}$)

The data for $s_w^{\,o}\,(i,j,k)$ are obtained by running a modified version of SIMGRO in which the sprinkling water 'appears out of nowhere'. This 'appearing out of nowhere' is purposely done in order to obtain the separate effects of activities that impact the system. An estimate of $s_w^{\,g}\,(i,j,k)$ is made by assuming that all of the evapotranspiration reduction that would occur if a crop were not sprinkled is compensated by extra sprinkling. The efficiency of the extra sprinkling is assumed to be the same as that for the 'basic' sprinkling. This leads to the following expression for $s_w^g\ (i, j, k)$:

$$s_w^g\ (i, j, k) = \frac{s_w^o\ (i, j, k)}{e_a^o\ (i, j, k) - e_a^o\ (i, j, 0)} \cdot e_a^g\ (i, j) \tag{38}$$

where:

$e_a^o\ (i, j, k)$	- actual evapotranspiration of a sprinkled subtechnology	(mm.yr^{-1})
$e_a^o\ (i, j, 0)$	- actual evapotranspiration of a non-sprinkled subtechnology	(mm.yr^{-1})
$e_a^g\ (i, j)$	- reduction of evapotranspiration of a non-sprinkled subtechnology, due to groundwater extractions	(mm.yr^{-1})

The computation of $e_a^g\ (i, j)$ is given in Section 6.5.

The total volume of sprinkling with an intensity k is given by:

$$i_s(i,k) + i_g(i,k) = C_u \cdot \sum_k \sum_n s_w(i,j,k) \cdot x_w\ (i,j,k,n) \tag{39}$$

where:

$i_s\ (i, k)$	- volume of sprinkling from surface water, of subtechnologies with sprinkling intensity k	(m^3 .yr^{-1})
$i_g\ (i, k)$	- volume of sprinkling from groundwater	(m^3.yr^{-1})
C_u	- unit conversion factor	(m^3.(mm.ha)$^{-1}$)

In the model it is assumed that there are no preferences for sprinkling a certain subtechnology from surface water or from groundwater. So each subtechnology is assumed to get the same percentage of its sprinkling from surface water and groundwater in the following manner:

$$i_s\ (i, k) = \frac{s_c\ (i, k)}{s_c\ (i, k) + g_c\ (i, k)} \cdot C_u \cdot \sum_j \sum_n s_w\ (i, j, k) \cdot x_w\ (i, j, k, n) \tag{40}$$

and

$$i_g\,(i,k) = \frac{g_c\,(i,k)}{s_c\,(i,k) + g_c\,(i,k)} \cdot C_u \cdot \sum_j \sum_n s_w\,(i,j,k) \cdot x_w\,(i,j,k,n) \quad (41)$$

By substituting the expression given by Eq. 11 (in the generalized form, using the expression $(\frac{25k}{14})$ for the sprinkling intensity) and rearranging, the expression for sprinkling from surface water becomes:

$$i_s\,(i,k) = \frac{\sum_j \sum_n x_w\,(i,j,k,n) \cdot s_w\,(i,j,k)/(\frac{25k}{14})}{\sum_j \sum_n x_w\,(i,j,k,n)}\, s_c\,(i,k) \qquad (42)$$

A similar expression can be given for the sprinkling from groundwater. The (same) factor with which both $s_c\,(i,k)$ and $g_c\,(i,k)$ are multiplied has the dimension of time; it can be interpreted as the average duration $P_s\,(i,k)$ of the period that the sprinklers are actually operative. It can further be seen as the weighted mean of the durations $p_s\,(i,j,k,)$ of periods that the sprinkler outlays for the separate subtechnologies are operative:

$$P_s\,(i,k) = \frac{\sum_j \sum_n x_w\,(i,j,k,n) \cdot p_s\,(i,j,k)}{\sum_j \sum_n x_w\,(i,j,k,n)} \qquad (43)$$

with

$$p_s\,(i,j,k) = s_w\,(i,j,k)/(\frac{25k}{14}) \qquad (44)$$

A substantial part of the sprinkling water does not get absorbed by the topsoil but percolates through cracks and large pores directly to the groundwater. Irregularity of sprinkling application (e.g. through the overlapping of the areas sprinkled from two sprinkler locations) leading to local oversaturation also causes percolation. Indirectly this water does, however, influence the moisture supply to crops through raising the groundwater level. In SIMGRO the percolation of sprinkling water is simply calculated to be 10% of the amount that is sprinkled. Here the same approximation is used:

$$p_e(i) = 0.1 \cdot \sum_k \{ i_s(i,k) + i_g(i,k) \} \qquad (45)$$

where:

$p_e(i)$ - percolation of sprinkling water to groundwater ($m^3.yr^{-1}$).

The way in which the influence of sprinkling on the evapotranspiration is calculated is described in Section 6.5.

6.2 Surface water management

Supply of surface water to a region involves the use of scarce resources that could also be used for other regions. So the simplified model should include a mechanism for ensuring the optimal allocation of the available supply. In the Netherlands the constraint is usually on the supply rate, because the main canals are the bottleneck in the system. The allocation problem (both on the regional and the provincial scale) therefore pertains to the *peak* demand time.

In the present model, the network of surface water channels is not considered explicitly. Instead, the surface water supply is modeled as if there are aqueduct connections between the external source and the subregions. So the decision variables are not the throughflows of 'links' in the network, but the *peak rates* that actually get used in the subregions, either for surface water infiltration or for sprinkling. The constraint on the total supply to the region is accordingly formulated as:

$$\sum_i S_c(i) \leq S_T \qquad (46)$$

where:

$S_c(i)$ - peak demand of surface water supply to a subregion ($m^3.d^{-1}$)

S_T - total available rate of surface water supply ($m^3.d^{-1}$)

This constraint is somewhat on the safe side: in reality the times of peak demand of the various subregions do not have to coincide; this leads to a slightly higher availability of water supply to the subregions than follows from Eq. 46. The constraints reflecting the limitations of the infrastructure are simply:

$$S_c\ (i) \leq \hat{S}_c\ (i) \tag{47}$$

where:

$\hat{S}_c\ (i)$ - capacity of infrastructure for surface water supply ('aqueduct connection') ($m^3.d^{-1}$)

These upper bounds are obtained by 'expert judgement' after analysis of the regional supply network.

For modeling purposes, the peak supply to a subregion is decomposed into components for subirrigation and for sprinkling:

$$S_c\ (i) = \underline{u}_c\ (i) + \sum_k s_c\ (i,\ k) \tag{48}$$

where:

$\underline{u}_c\ (i)$ - total surface water supply rate required for surface water level management (= peak infiltration rate) ($m^3.d^{-1}$)

$s_c\ (i,\ k)$ - capacity of sprinkling from surface water, with intensity of $\frac{25k}{14}$mm/d ($m^3.d^{-1}$)

Just like Eq. 46 the above equation can lead to a slight underestimation of the actual availability of surface water supply, owing to the non-coincidence of peak demands.

The availability of surface water for sprinkling can locally be limited by the density of the ditch network. For sprinkling from surface water to remain practically feasible the distance to a ditch must not be greater than say 200-300 m. This reachability constraint is given by:

$$\sum_k s_c\ (i,\ k)/(\frac{25k}{14}) \leq C_u \cdot \hat{s}_c\ (i) \tag{49}$$

where:

$\hat{s}_c\ (i)$ - area that is reachable for sprinkling from surface water (ha)

C_u - unit conversion factor ($m^3.(mm.ha)^{-1}$)

The unit conversion in this equation is the same as in the equations given in Section 3.1.3 and 6.1.

6.3 Groundwater management

Extraction of groundwater for sprinkling and for public water supply can be subjected to constraints that derive either from local or from regional conditions. By the latter are meant the impacts that are transmitted by the regional flow system; an example of such an impact is the lowering of groundwater levels in nature areas. These regional impacts are dealt with in subsequent sections; here the focus is on constraints that are a consequence of local conditions.

Extraction of groundwater for sprinkling usually takes place by drawing water from shallow well. In order to avoid having to transport water over large distances, each well only supplies water to a few hectares. This leads to a large number of wells. Extraction of groundwater for sprinkling has therefore a rather 'diffuse' nature. By contrast, extraction for public water supply usually takes place from a small number of deep wells. This is because at greater depth the quality of the water is usually better, especially in regions where there is heavy pollution of groundwater by excessive nitrate leaching. Since the cost of making deep wells is relatively high, the tendency is to construct as few of them as possible.

Another difference between the two types is that extraction for public water supply is continuous throughout the year, without much variation: during summer the extraction rate is normally about 20% higher than during winter, owing to higher demand as a consequence of watering of gardens, etc. Extraction for sprinkling, on the other hand, only takes place during the summer months, and then only if the soil moisture content in the rootzone drops below a certain level.

Local conditions that can hamper the extraction of groundwater are the permeability and porosity of the aquifer that is being tapped. A high enough permeability is important for all types of extractions. Porosity is especially of importance in the case of non-steady extraction, like for sprinkling. The binding physical constraint on this type of extraction can either be on the peak rate or on the volume, or even on both. Since it does not make sense to install more sprinkling capacity than the upper bound on the peak rate, the following constraint is introduced:

$$\sum_k g_c\,(i,\,k) \leq \hat{g}_c\,(i) \qquad (50a)$$

where:

$g_c\,(i,\,k)$	- capacity of sprinkling from groundwater with an intensity of $\frac{25k}{14}$ mm/d	$(m^3.d^{-1})$
$\hat{g}_c\,(i)$	- upper bound on peak rate of groundwater extraction for sprinkling	$(m^3.d^{-1})$

The bound on the volume of water that can be extracted is given by:

$$\sum_k i_g\,(i,\,k) \leq \hat{i}_g(i) \qquad (50b)$$

for all i, where:

$i_g\,(i,\,k)$	- volume of sprinkling from groundwater with an intensity of $\frac{25k}{14}$ mm/d	$(m^3.yr^{-1})$
$\hat{i}_g\,(i)$	- upper bound on volume of groundwater extracted for sprinkling	$(m^3.yr^{-1})$

Extraction of groundwater for public water supply is virtually steady; thus one type of constraint can suffice to reflect the limitation posed by local geohydrological conditions:

$$q\,(i) \leq \hat{q}\,(i) \qquad (51)$$

where:

$q\,(i)$	- extraction bound on extraction for public water supply	$(m^3.yr^{-1})$
$\hat{q}\,(i)$	- upper bound on extraction for public water supply	$(m^3.yr^{-1})$

6.4 Conjunctive management of surface water and groundwater

Surface water management cannot be seen separately from groundwater management. This is due to the strong interaction between groundwater and surface water - especially the infiltration of surface water is of interest here. Extraction of groundwater leads to a lowering of the hydraulic head in the aquifer. This induces a downward flow of phreatic groundwater, which leads to an increase of the surface water infiltration. The percolation caused by sprinkling has the opposite effect. Whereas the extractions of groundwater for public water supply are from the aquifer, extractions for sprinkling and percolation due to sprinkling directly impact the phreatic layer. Induced infiltration can of course only taken place if there is enough surface water available. In the simplified model it is assumed that this is indeed the case, as long as the capacity of the supply infrastructure is not limiting (cf. Eq. 47).

For computing the induced infiltration, use is made of the so-called response matrix approach, involving linear response functions:

$$u_c^i(i) = \sum_{i_2} \{ a(i, i_2) \cdot q(i_2) + b(i, i_2) \cdot \{ \sum_k i_g(i_2, k) - p_e(i_2)\} \qquad (52)$$

where:

$u_c^i\ (i)$	- peak rate of induced infiltration	$(m^3.d^{-1})$
$a\ (i, i_2)$	- element of response matrix A: the extra induced infiltration in subregion i per unit of groundwater extraction $q\ (i_2)$	$(m^3.d^{-1}.(m^3.yr^{-1})^{-1})$
$b\ (i, i_2)$	- element of response matrix B	$(m^3.d^{-1}.(m^3.yr^{-1})^{-1})$

The matrices of coefficients are obtained by performing a sequence of simulations with SIMGRO. The reference run for this sequence of simulations is for the situation in which
- all extractions of groundwater are zero;
- just enough supply of surface water takes place for maintaining 'winter level' in the ditches during the whole summer; this supply is, however, not allowed to exceed the supply capacity of the infrastructure.

In the sequence of simulations unit groundwater extractions are introduced in the subregions, one at the time. For each position of the extraction the increase of the infiltration is computed and stored as a column of the response matrix. The described reference run is also used for other applications of the response matrix method.

For modelling the effect of subirrigation on the regional system it would seem appropriate to introduce the 'summer level' of surface water as a decision variable, or even a strategy for manipulating the level as a function of the prevailing groundwater conditions. Such a strategy is included in the simulation model SIMGRO. To attempt to introduce such a level or strategy in the simplified model would, however, be futile. This is because in the real system there are strong feedback mechanisms. And due to the varying meteorological conditions a steady state is rarely reached. Such a complex system defies being 'modeled' in a simple manner without the aid of results obtained from a comprehensive model.

So instead of introducing the water level as a decision variable, the available surface water supply for implementing a management strategy is introduced as such. The strategy itself is left implicit - it implicitly is included in the results of simulation runs with SIMGRO that are used as coefficients in the simplified model. In the simulation runs, a 'maximum strategy' is implemented: within the limits posed by the supply capacity of the infrastructure, an abundant supply of surface water is assumed. The peak rate of *extra* infiltration - as compared to the amount in the reference run - is subsequently used in the simplified model as an upper bound on the decision variable that represents the amount of surface water supply that is made available for water level management:

$$u_c^z(i) \leq \hat{u}_c^z(i) \qquad (53)$$

where:

$u_c^z(i)$	- extra surface water supply rate required for implementing surface water level management	$(m^3.d^{-1})$
$\hat{u}_c^z(i)$	- extra surface water supply rate required for implementing the 'maximum strategy' of surface water level management	$(m^3.d^{-1})$

For values of $u_c^z(i)$ that are between zero and the upper bound, the effects of subirrigation on the evapotranspiration of crops and the groundwater levels in nature areas are computed by means of linear interpolation (see also Sections 6.5 and 6.6).

The total rate of surface water supply $\underline{u}_c(i)$ that infiltrates to groundwater (see also Eq. 48) is computed as the simple sum of three components:

$$\underline{u}_c(i) = u_c^o(i) + u_c^i(i) + u_c^z(i) \qquad (54)$$

where:

$u_c^o(i)$	- basic surface water supply rate for surface water management (= peak infiltration rate in the reference run)	$(m^3.d^{-1})$
$u_c^i(i)$	- induced infiltration due to groundwater extractions	$(m^3.d^{-1})$
$u_c^z(i)$	- extra surface water supply required for implementing surface water level management strategy	$(m^3.d^{-1})$

This summation is of course a simplification - in reality there is a degree of interdependence between the three components.

6.5 Evapotranspiration and production of crops

As was already stated in Section 2.4.1 the assumption is made that for sprinkled subtechnologies the reduction of evapotranspiration due to groundwater extractions is compensated by extra sprinkling. So the evapotranspirations of sprinkled technologies are set equal to the values obtained with the 'sprinkling out of nowhere' version of SIMGRO (see Section 6.1).

The evapotranspiration reduction of non-sprinkled crops is, just like the peak infiltration rate, computed with the response matrix method:

$$e_a^g(i,j) = \sum_{i_2} [\ c(i,i_2,j) \cdot q(i_2) + d(i,i_2,j) \cdot \{\sum_k i_g(i_2,k) - p_e(i_2)\} - e(i,i_2,j) \cdot u_c^z(i_2)\ ] \tag{55a}$$

and

$$e_a(i,j,0) = e_a^o(i,j,0) - e_a^g(i,j) \tag{55b}$$

for all i (except nature areas) and j, where:

$e_a\ (i, j, 0)$	- actual evapotranspiration of a non-sprinkled subtechnology	($mm.yr^{-1}$)
$e_a^g\ (i, j)$	- reduction of evapotranspiration due to groundwater extractions	($mm.yr^{-1}$)
$e_a^o\ (i, j, 0)$	- actual evapotranspiration in the reference run	($mm.yr^{-1}$)
c, d and e	- coefficients of response matrices C, D and E	($mm.yr^{-1}.\#^{-1}$)

All the coefficients in the above equation are obtained by making sequences of simulation runs with SIMGRO.

The computed (total) evapotranspirations do not form an essential link in the model, because the crop productions are computed in a direct manner without the evapotranspiration as an intermediate variable (see below). However, the evapotranspirations are indeed of interest for the verification of the simplified model by means of comparing the results with those produced by the comprehensive model: judgement of the validity of the simplified model is easiest when the comparison is in terms of mm's evapotranspiration, because this is a unit with which people are well acquainted.

Moisture supply is one of the most important factors that determine the production of a crop. The other factor that is of interest for the present study is availability of nitrogen (see Section 7.1.1). The influence of regional water management on the crop production is computed in a manner that is completely analogous to Eqs. 55a and 55b:

$$c_{qw}(i,j,0) = c_{qw}^o(i,j,0) - \sum_{i_2} [\ c(i,i_2,j) \cdot q(i_2) + d(i,i_2,j) \cdot \{\sum_k i_g(i_2,k) - p_e(i_2)\} - e(i,i_2,j) \cdot u_c^z(i_2)\ ] \tag{56}$$

for all i (except nature areas) and j, where:

c_{qw} *(i, j, 0)* - actual crop production, under optimal conditions of nitrogen supply (t.ha^{-1}.yr^{-1})
$c_{qw}{}^{o}$ *(i, j, 0)* - actual crop production in the reference run, under conditions of optimal nitrogen supply (t.ha^{-1}.yr^{-1})
c, d and *e* - coefficients of response matrices C, D and E (t.ha^{-1}.yr^{-1}.#$^{-1}$)

Just like is done with the evapotranspiration, the crop productions of sprinkled subtechnologies (*k*=1 and 2) are set equal to the ones obtained with the 'sprinkling out of nowhere' version of SIMGRO.

6.6 Groundwater level lowering in nature areas

For the computation of the impact of regional water management on the vegetation in nature areas (see Chapter 4) it is necessary to know the effects on the groundwater regime in these areas. Specifically, it is necessary to know the lowering at the beginning of summer and at the beginning of winter. In the model, it is assumed that at the beginning of summer the impacts of agricultural activities during the summer in the preceding year have been 'erased' by the winter rain. That leaves only the extractions for public water supply to cause the lowering at the beginning of summer; thus this lowering is computed with:

$$\underline{h}_s(i) = \sum_{i_2} f(i,i_2) \cdot q(i_2) \tag{57}$$

for all *i* that are nature areas, where:
$\underline{h}_s$ *(i)* - lowering of the groundwater level at the beginning of summer (cm)
f - coefficient of response matrix F (cm.m^{-3}.yr^{-1})

The lowering at the beginning of winter is of course also influenced by the agricultural activities during the summer; the lowering is computed accordingly:

$$\underline{h}_w(i) = \sum_{i_2} [\, r(i,i_2) \cdot q(i_2) + s(i,i_2) \cdot \{\sum_k i_g(i_2,k) - p_e(i_2)\} - t(i,i_2) \cdot \underline{u}_c(i_2) \,] \tag{58}$$

for all *i* that are nature areas, where:
$\underline{h}_w$ *(i)* - lowering of the groundwater level at the beginning of winter (cm)
r, s, t - coefficients of response matrices R, S and T (cm.#$^{-1}$)

In a SWAFLO-diagram the lowering at the beginning of summer is thought to be the lowering in an 'average' meteorological year. The lowering at the beginning of winter is thought to be the lowering in a so-called 10% dry year, i.e. a year with an evapotranspiration surplus (over precipitation) with an exceedance probability of 10%.

The values of the response coefficients in Eqs. 57 and 58 differ for different meteorological years. So for the computation of the lowerings the relevant coefficients are selected from the series of simulation runs made with SIMGRO. Concerning the extractions the assumption is made that the ones for public water supply do not differ from year to year, though in reality there will of course be a slightly increased demand in dry years, e.g. for the watering of gardens. With regard to the extractions for sprinkling the assumption is made that the capacity of the sprinkler outlays is the same as for the year that the optimization of agriculture is done (see also section 3.2). But for conversion of the capacity to the volume of water that is extracted, the duration of sprinkling in a '10% dry year' is used:

$$\underline{i}_g^{10}(i,k) = P_s^{10}(i,k) \cdot g_c(i,k) \tag{59}$$

for all i, and k=1 and 2, where:

$i_g^{10}(i, k)$	- extraction of groundwater for sprinkling in a '10% dry year'	($m^3.yr^{-1}$)
$P_s^{10}(i, k)$	- duration of sprinkling in a '10% dry year'	(d)

7 SIMPLIFIED MODELS OF NITROGEN AND PHOSPHORUS PROCESSES

7.1 Nitrogen

7.1.1 Nitrogen processes in the soil

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 in the course of the first year after application, and the third fraction only in subsequent years.

In the model the dynamics of the third fraction is not included. Instead, the assumption is made 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 is (yearly) 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 and the assumption that the effectivity of nitrogen applied in animal wastes from grazing cows is zero (due to the extremely local nature of the application), the amount of nitrogen available from application of animal wastes for crop growth can be calculated as:

$$\underline{v}_a(i,l) = f_s(i,l) + \sum_m \{e_{mw}(l,m) \cdot m_w(i,l,m) + e_{ms}(l,m) \cdot m_s(i,l,m)\} \tag{60}$$

for all i and l (except l=4 for new forest), where:

$f_s\ (i,l)$	- application chemical fertilizer nitrogen	$(t.yr^{-1})$
$e_{mw}\ (l,m)$	- nitrogen effectivity of animal wastes application in autumn/winter, $m_w\ (i,l,m)$	(-)
$e_{ms}\ (l,m)$	- nitrogen effectivity of animal wastes application in summer, $m_s\ (i,l,m)$	(-)

Each soil-use technology has a certain level of the amount of nitrogen that is required for crop growth $n_r\ (j,n)$. In Section 3.1.4 (Eq. 12) the calculation is given of the total requirement per category of soil use, $\underline{v}_n\ (i,l)$ (l=1 for arable land, l=2 for maize,

l=3 for grassland). This requirement must exactly be balanced by the supply - both too little and too much nitrogen can lead to a reduction of crop productivity. This balancing of demand and supply is in the model effectuated by setting $\underline{v}_a\ (i,l)$ equal to $\underline{v}_r\ (i,l)$:

$$\underline{v}_a(i,l) = \underline{v}_r(i,l) \tag{61}$$

for all i and l (except l=4, i.e. forest), where:

$\underline{v}_a\ (i,l)$	- amount of soil nitrogen available for crop growth	($t.yr^{-1}$)
$\underline{v}_r\ (i,l)$	- amount of soil nitrogen required for crop growth	($t.yr^{-1}$)

These balances are formulated on the aggregation level of 'categories of soil use' (i.e. subsets $J_x(l)$ listed in Table 1) for two main reasons:

- in the medium term there is a rotation of crops on the land allocated to these categories (and only in the long term does for instance grassland get converted to maize land and vice versa); it is also for the medium-term time-scale that the above-mentioned assumption concerning the 'steady state' of stable nitrogen compounds holds;
- the equations with which both supply and demand of soil nitrogen are computed are linear, thus allowing aggregation by means of summation of linear terms.

The nitrogen (NO_3-N) load on groundwater can approximately be described by a function of the form:

$$\underline{n}_p(i) = \underline{f}_1(i) \cdot f_2(i) \tag{62}$$

where:

$\underline{n}_p\ (i)$	- nitrogen (NO_3-N) load on phreatic groundwater	($t.yr^{-1}$)
$\underline{f}_1\ (i)$	- nitrogen (NO_3-N) leaching to phreatic groundwater	($t.yr^{-1}$)
$f_2\ (i)$	- groundwater level reduction factor	(-)

In the function f_1, the coefficients of variables that pertain to grassland technologies (subset $J_x\ (3)$) differ from those of variables that pertain to arable land and maize technologies ($J_x(1)$ and $J_x(2)$). To the applications in autumn are added the amounts that are applied during the grazing time of cattle. The function $\underline{f}_1\ (i)$ is of the form:

$$f_1(i) = \sum_l [c_1(l) \cdot \sum_{j \in J_x(l)} \underline{x}(i,j) + c_2(l) \cdot f_s(i,l) + \qquad (63)$$

$$\sum_l \sum_m c_3(l,m) \cdot \{m_w(i,l,m) + m_n(i,l,m) +$$

$$c_4(l,m) \cdot m_s(i,l,m)\}] + c_5 \cdot \{ \sum_{j \in J_x(4)} \underline{x}(i,j) + x_f(i) + x_n(i)\}$$

where:

$c_1(l)$	- basic NO_3-N leaching of soil-use type	($t.ha^{-1}.yr^{-1}$)
$c_2(l)$	- leaching coefficient of chemical fertilizer N	($t.t^{-1}$)
$c_3(m,l)$	- leaching of NO_3-N due to application of wastes in the autumn, $m_w(i,l,m)$ and $m_n(i,l,m)$	($t.t^{-1}$)
$c_4(l,m)$	- relative leaching (≤ 1.0) due to application in spring instead of in autumn	(-)
c_5	- basic NO_3-N leaching of forest and nature areas	($t.ha^{-1}$)
$m_n(i,l,m)$	- application of animal wastes during grazing	($t.yr^{-1}$)
$x_f(i)$	- area of existing forest	(ha)
$x_n(i)$	- area of 'nature'	(ha)

The amount of animal wastes that is applied during the grazing time of cows is computed with:

$$m_n(i,l,m) = \sum_{j \in J_x(1)} \sum_k \sum_n m_x(j,n,m) \cdot x_w(i,j,k,n) \qquad (64)$$

for all i, l=3 (grassland) and m=1 (cattle wastes), where:

$m_x(j,n,m)$	- half-yearly production of wastes type m per unit of $x_w(i,j,k,n)$	($t.ha^{-1}.yr^{-1}$)

7.1.2 Nitrogen processes in groundwater

In the simplified model for groundwater quality, a steady-state approach is used. By this is meant that the nitrogen concentrations are computed that would be reached if the animal wastes applications of a certain scenario would be repeated year after year, indefinitely. The choice of this approach is based on the following two considerations:

- on the policy level there is mainly an interest for the concentrations that are reached in the long run;

- the implementation of a 'dynamic' model would increase the computational burden manifoldly.

A further simplification is the use of a 'mixing-cell' approximation. Such an approach is reasonably acceptable here because it is applied in combination with steady-state computations. Thus one of the main drawbacks of using mixing-cells is to a large extent eliminated: When used in combination with a 'dynamic' model the mixing-cell method leads to the computation of a longitudinal propagation (through numerical dispersion) of pollutants that is totally unrealistic. In a steady-state approach the speed of propagation does not play a role; only the end-concentrations are relevant. Another justifying circumstance for using the mixing-cell approach is that a non-point source of pollution is being considered: the fact that through numerical dispersion the nitrate travels to nearly all corners of the regional system is not so unrealistic because of the diffuse nature of the source (i.e. the covering soil from which the leaching takes place).

Apart from the mixing-cell approximation itself, further simplifications are that
- decomposition of nitrate in the cells can be taken into account by means of decomposition factors;
- the nitrate concentration of water entering the region through a boundary section is equal to the concentration in the mixing cell to which the water goes to.

An appropriate scheme of mixing cells depends on the region that is being considered. For the Southern Peel region mixing cells have been taken for the phreatic groundwater in a subregion and for the first aquifer beneath (Fig. 6). In the 'Slenk' there is a second aquifer; for this aquifer only one mixing cell has been taken.

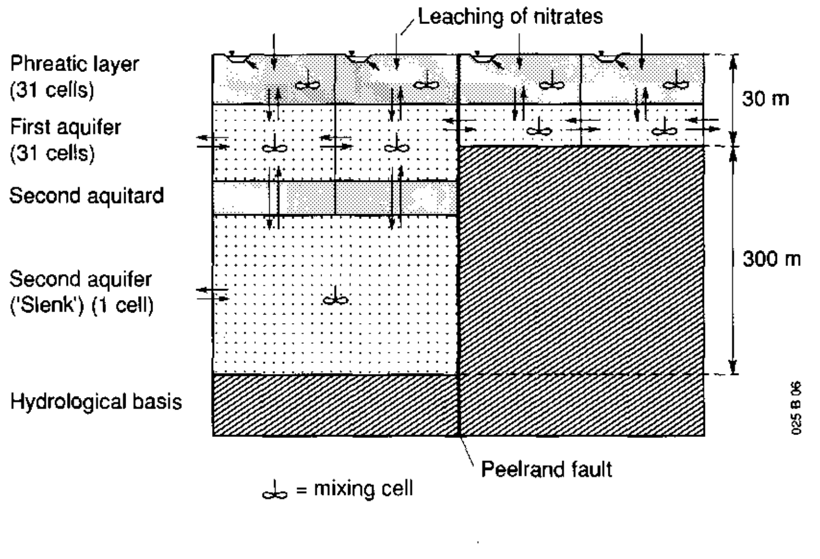

Fig. 6 Scheme of mixing cells for the Southern Peel region

The steady state is reached when the decomposition becomes exactly equal to the net influx. So in the mass balance equations of the mixing cells the left-hand sides contain the yearly decomposition of the nitrate and the right-hand sides the net influx of nitrate.

For the phreatic cells we have:

$$\alpha \cdot c_p(i) \cdot v_p(i) = \underline{n}_p(i) - u_w(i) \cdot c_p(i) - p_c(1,i) \cdot c_p(i) + s_p(1,i) \cdot c_d(i) \tag{65}$$

for all i, where:

α	- decomposition factor of nitrate in the phreatic aquifer	(yr^{-1})
$\underline{n}_p(i)$	- nitrogen (NO_3-N) load on phreatic groundwater	($t.yr^{-1}$)
$c_p(i)$	- nitrogen (NO_3-N) concentration of water in the phreatic layer	($t.m^{-3}$)
$c_d(i)$	- nitrogen (NO_3-N) concentration of water in the first aquifer	($t.m^{-3}$)
$v_p(i)$	- volume of water in cell i of the phreatic layer	(m^3)
$u_w(i)$	- drainage of water from the phreatic layer to surface water	($m^3.yr^{-1}$)
$p_c(1,i)$	- percolation of water from the phreatic layer to the first aquifer	($m^3.yr^{-1}$)
$s_p(1,i)$	- seepage of water from the first aquifer to the phreatic layer	($m^3.yr^{-1}$)

Depending on the direction of flow being downwards or upwards, the seepage $s_p(1,i)$ or deep percolation $p_c(1,i)$ is zero, respectively. In some subregions there is seepage during one part of the year and percolation during the rest - seepage at the end of the winter when the regional system is fully recharged by the winter rains, and a switch to percolation in the course of the summer. In such cases both $p_c(1,i)$ and $s_p(1,i)$ will have positive values. No horizontal flow terms are included on the above equation because in the considered region the phreatic aquifer is a 'flow resisting layer' in which only vertical flow is possible; for horizontal flow the resistance is too high.

The water quantity variables in the above equation (and in the other mass balance equations given below) are fixed, i.e. they enter as parameters into the model. If these variables had been described using relations involving decision variables that have an impact on them (e.g. groundwater extractions), then the model as a whole would have become non-linear, because the concentrations themselves are implemented as 'decision variables'. For the present study such a non-linear model was considered beyond bounds.

The values of water quantity parameters are obtained from a multi-year run with SIMGRO. The meteorological data for this run are taken from a real series that spans a period of 10 years; thus the influence of all types of weather conditions and their recurrence frequencies are implicitly taken into account. For the cells in the first aquifer the mass balances are given by:

$$\beta \cdot c_d(i) \cdot v_d(i) = p_c(1,i) \cdot c_p(i) - s_p(1,i) \cdot c_d(i) - p_c(2,i) \cdot c_d(i) + s_p(2,i) \cdot c_s + \sum_{i_2} \{f_h(i_2,i) \cdot c_d(i_2) - f_h(i,i_2) \cdot c_d(i)\} + \{f_h(n+1,i) - f_h(i,n+1)\} \cdot c_d(i) \quad (66)$$

where:

β	- decomposition factor of nitrate in first aquifer	(yr^{-1})
$c_p(i)$	- nitrogen (NO_3-N) concentration of water in the phreatic layer	($t.m^{-3}$)
$c_d(i)$	- nitrogen (NO_3-N) concentration of water in the first aquifer	($t.m^{-3}$)
c_s	- nitrogen (NO_3-N) concentration of water in the deep Slenk aquifer	($t.m^{-3}$)
$v_p(i)$	- volume of water in cell i of the phreatic layer	(m^3)
$p_c(1,i)$	- percolation from the phreatic layer to the first aquifer	($m^3.yr^{-1}$)
$p_c(2,i)$	- percolation from the first aquifer to the deep Slenk aquifer	($m^3.yr^{-1}$)
$s_p(1,i)$	- seepage from the first aquifer to the phreatic layer	($m^3.yr^{-1}$)
$s_p(2,i)$	- seepage from the deep Slenk aquifer to the first aquifer	($m^3.yr^{-1}$)
$f_h(i,i_2)$	- horizontal flow in the first aquifer from cell i to i_2	($m^3.yr^{-1}$)
$f_h(n+1,i)$	- horizontal flow in the first aquifer from outside the region to cell i	($m^3.yr^{-1}$)
$f_h(i,n+1)$	- horizontal flow in the first aquifer from cell i to outside the region	($m^3.yr^{-1}$)

In the above equation the flow from outside the region is set equal to the concentration of nitrogen in the cell that it goes to (see also the assumptions listed at the beginning of this section). For the single cell representing the Slenk the balance reads:

$$\gamma \cdot c_s \cdot v_s = \sum_{i} \{p_c(2,i) \cdot c_d(i) - s_p(2,i) \cdot c_s\} - f_{hd} \cdot c_s \quad (67)$$

where:

γ	- decomposition factor of nitrate in the Slenk	(yr^{-1})
c_s	- concentration of nitrogen (NO_3-N) in the deep Slenk aquifer	($t.m^{-3}$)
v_s	- volume of water in the deep Slenk aquifer	(m^3)
f_{hd}	- nett horizontal flow of water from the deep Slenk aquifer to outside the region	($m^3.yr^{-1}$)

In the above equation the term f_{hd} can either be positive or negative - the equation holds for both cases: the assumption that flow of water into the region has the same concentration as in the cell that it goes to, applies here as well. Assuming conservation of mass within the Slenk aquifer (and neglecting the extraction of deep groundwater for public water supply), the nett outflow f_{hd} follows simply from

$$f_{hd} = \sum_i \{p_c(2,i) - s_p(2,i)\} \qquad (68)$$

Substitution of this expression into Eq. 67 leads to the cancellation of the term involving $s_p\ (2,i)$:

$$\gamma \cdot c_s \cdot v_s = \sum_i p_c(2,i) \cdot \{c_d(i) - c_s\} \qquad (69)$$

This equation expresses that an amount of water $p_c(2,i)$ entering the Slenk with concentration $c_d(i)$ causes the leaving of a same amount (usually not the same water, however) with a concentration c_s; this can either be water leaving the system through seepage to the first aquifer or through horizontal flow to outside the region. Horizontal inflow of water from outside the region does not play a role in the above equation: this water is assumed to enter the system with a concentration that is the same as that of the water already present; and with this same concentration it again leaves the system, either through seepage to the first aquifer or through horizontal outflow.

With a view to maintaining the potability of groundwater (but also out of general environmental concern), constraints can be imposed on the nitrate concentration of groundwater (see also Chapter 5):

$$c_p(i) \leq \underline{\hat{C}}_p \qquad (70)$$

$$c_d(i) \leq \underline{\hat{C}}_d \qquad (71)$$

where:

$\underline{\hat{C}}_p$	- upper bound in nitrogen (NO_3-N) concentration of water in the phreatic aquifer	($t.m^{-3}$)
$\underline{\hat{C}}_d$	- upper bound on nitrogen (NO_3-N) concentration of water in the first aquifer	($t.m^{-3}$)

If both these constraints are met, a further constraint on the concentration in the deep Slenk aquifer is superfluous.

7.2 Phosphorus

Application of more phosphate (in animal wastes) to the soil than the amount that is required for crop growth causes a surplus. This surplus can be immobilized through precipitation with iron and aluminium ions, but only as long as the supply of such ions lasts. Heavy over-fertilization with phosphate inevitably leads to saturation of the available fixation capacity; this is then followed by sharply increased leaching to the groundwater.

In order to avoid such a course of events, the national government has implemented a regulation policy. This policy involves the enforcement of increasingly strict norms with respect to the application of phosphates in animal wastes. These norms are tabulated in Table 5.

Table 5 Phosphate norms of national regulation policy

Date of imple-mentation	**Phosphate norm ($kg.ha^{-1}.yr^{-1}$)**		
	arable land	**maize**	**grassland**
1/1/1987	**125**	**350**	**250**
1/1/1991	**125**	**250**	**200**
1/1/1995	**125**	**175**	**175**
1/1/2000	**70**	**75**	**110**

The fourth norm is the so-called 'crop uptake' norm: the application of phosphates must not exceed the amount that is used by crops. In the model, the enforcement of a norm is done with:

$$\sum_{m} \{m_s(i,l,m) + m_w(i,l,m)\} \cdot P_f(m) \leq P_n(l) \cdot \sum_{j \in J_x(l)} \sum_{k} \sum_{n} x_w(i,j,k,n) \tag{72}$$

For all i and l (except l=4 for new forest), where:

$P_f(m)$	-	phosphate content of animal wastes type m (kg.t^{-1})
$P_n(l)$	-	implemented phosphate norm for soil-use category l (kg.ha^{-1}.yr^{-1})

8 IMPLEMENTATION OF MODELS

The computer implementation of the simplified models should be done in such a manner that the models can be used with a maximum effectiveness for improving the quality of regional decision-making. One of the main factors determining this effectiveness is the type of 'questions' that the system can answer. The implementation should be flexible enough to allow for various types of questions to be asked without requiring time-consuming modification of the software.

A flexible implementation is achieved by using the system GEMINI (Lebedev, 1984) in combination with the linear programming modules of MINOS (Murtagh & Saunders, 1983). GEMINI is a cross compiler that not only recognizes formula-like descriptions of linear relations and translates them into 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 of the system can modify the mathematical programming problem that is to be solved in order to adapt it to a new type of question put to the system.

GEMINI has the further advantage that, in the hands of an expert, it is an effective tool for the fast implementation of constraints that for instance have become relevant due to developments on the policy-making level (e.g. phosphate norms).

8.1 Method for non-linearities

Not all the relations described in Chapters 3-7 are linear, however. Non-linear terms enter the calculation of the income from agriculture through the multiplication of areas x_w *(i,j,k,n)* and the influence of the groundwater extractions on the crop production per unit of area (Eqs. 13, 30 and 56). Non-linearities also enter the relations between the sprinkling capacity and the volume of water that actually is sprinkled (Eq. 42).

For the present, these non-linearities have been dealt with by means of *successive* linear programming. This method consists simply of linearizing the non-linearities by replacing *all but one* of the variables that are involved in a certain non-linearity by the values that were attributed to them at the end of the *preceding* LP-run. This yields a linear expression involving only the variable that has not been replaced by numerical values. Applied to problems with weakly non-linear relations, convergence is usually reached after repeating this procedure a few times. Some oscillation can remain due to the circumstance that the 'optimum' does not coincide with a 'corner' of the feasible region. Usually such oscillation is of minor importance, as in the present case.

The non-linearities in the income from agriculture (Eq. 30) are linearized by setting the variables x_w *(i,j,k,n)* to the values obtained in the preceding run. (Of course only where the variables x_w *(i,j,k,n)* form product terms with the groundwater extraction.) The non-linearities in Eq. 42 and its companion for i_g *(i,k)* are linearized by computing the parameters P_s *(i,k)* with Eq. 43 using the values of the decision variables obtained in the preceding run. Values of s_w *(i,j,k)* in Eq. 44 are obtained by inserting values obtained in the preceding run into Eqs. 37, 38, and 55a (in reversed order).

8.2 Scenario analysis procedure

Of prime interest to the regional authority are the indicators of well-being of the water users. Since well-being can have various aspects that cannot quantified in a commensurable manner, there can be more than one indicator of well-being per group of users. Increase of well-being can either be associated with 'maximization' or with 'minimization' of the respective indicator values; in the following list the former is designated by 'max', the latter by 'min':

- income from agriculture, $\underline{Y_T}$ (max);
- labour demand of agriculture, $\underline{L_T}$ (max);
- extraction of groundwater for public water supply, $\underline{Q_T}$ (max);
- maximum concentration of nitrogen in the phreatic layer, $\underline{\hat{C}_p}$ (min);
- maximum concentration of nitrogen in the first aquifer, $\underline{\hat{C}_d}$ (min);
- loss of species rareness in nature areas, $\underline{W(i)}$ (min).

The above indicators can be seen as the multi-objectives of the regional development. For handling the multi-objectivity a simple constraint method is used. This means that questions can be answered of the type:

- what maximum agricultural income per year can be attained under the conditions that the maximum nitrogen concentration of phreatic groundwater should not exceed 11.2 mg/l?
- what lowest nitrogen concentration of water in the first aquifer can be achieved if a reduction of income from agriculture by 10% is admissible?

These are just two examples of numerous questions that can be 'answered' with respect to the indicators. Each of such questions is formulated by fixing desired values for the indicators and by designating one of the indicators as the objective function*.

* The only indicator that does not, lend itself to being treated as an objective function, is the indicator for the loss of ecological value. This is because the relation between this indicator and the limiting lowerings of the groundwater levels are only available for a discrete set of indicator values (Ch.4).

The 'answer' is obtained by solving the corresponding linear programming problem as a step in the screening analysis. The solution (at least, if there is one at all that satisfies the constraints) represents an alternative (re)allocation of human activities that facilitates the achievement of these values.

As already remarked in the introduction to the model of agriculture (Chapter 3) the 'problems' that are solved using mathematical screening methods are essentially 'one-year'; by that is meant that the dynamics of agricultural development are not taken into account.

Questions of the above described type can be answered for various options with respect to *boundary conditions* and *data*. These options relate to factors that are controlled by decisions and processes that transcend the regional scale or that cannot be modelled.

Here only a selection is given of the *boundary conditions* that can be varied:
- maximum availability of 'local labour' in the region;
- maximum rate of surface water supply available to the region;
- maximum amount of animal wastes that can be disposed of by transport to outside the region;
- maximum phosphate application to the soil (see list of norms in Section 7.2)

The most important options with respect to the choice of *data* are:
- weather conditions used for modelling the regional hydrology and its interaction with agriculture;
- external economic conditions that determine prices of inputs and products.

Preferably the answers to questions should be forthcoming after some 'on-line' computing. However, it was found that for the type of problems addressed in this context it is not possible to simplify the models to such an extent that the computation time becomes acceptable for interactive running and to also maintain credibility of the system. But for easy user access and interpretation of results an interactive system with colour graphics has indeed been developed (Van Walsum, 1991). So the procedure as a whole is 'off-line', but the interpretation of results is 'on-line'.

The system is designed in such a way that the user can obtain a new scenario by setting a number of specially used option parameters that are contained on one small file of a disk storage system. After subsequent running of the system, the scenario data are automatically stored in a structured way for use by the interactive system. Apart from this form of output, a series of conventional tables is generated.

After a scenario has been generated, runs can be made with the comprehensive models in order to verify and more accurately estimate a scenario that seems promising. Also, runs with the comprehensive models for a number of different weather years can provide data for the statistical evaluation of scenarios. An overview

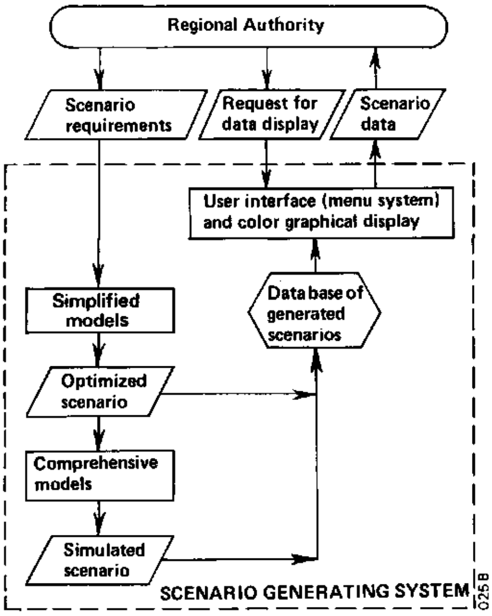

Fig. 7 ***Overview of the components of the Scenario Generating System and the way the regional authority can use them***

of the different components of the SGS and the way the regional authority can use them is given in Fig. 7.

A more detailed flowchart of how the comprehensive models are coupled to the simplified models is given in Fig. 8. For examples of numerical results, including a verification of the simplified hydrological model, the reader is referred to Drent (1989).

8.3 Input data requirements

Throughout the text some indications have been given about how certain input have been obtained for testing the system on a pilot region, the Southern Peel. By way of recapitulation an overview is given of these data. A fully detailed description of how the data should be organized in data files is not given, in view of the prototype nature of the developed system (see also the Preface) and the intermediate stage of development of certain submodels.

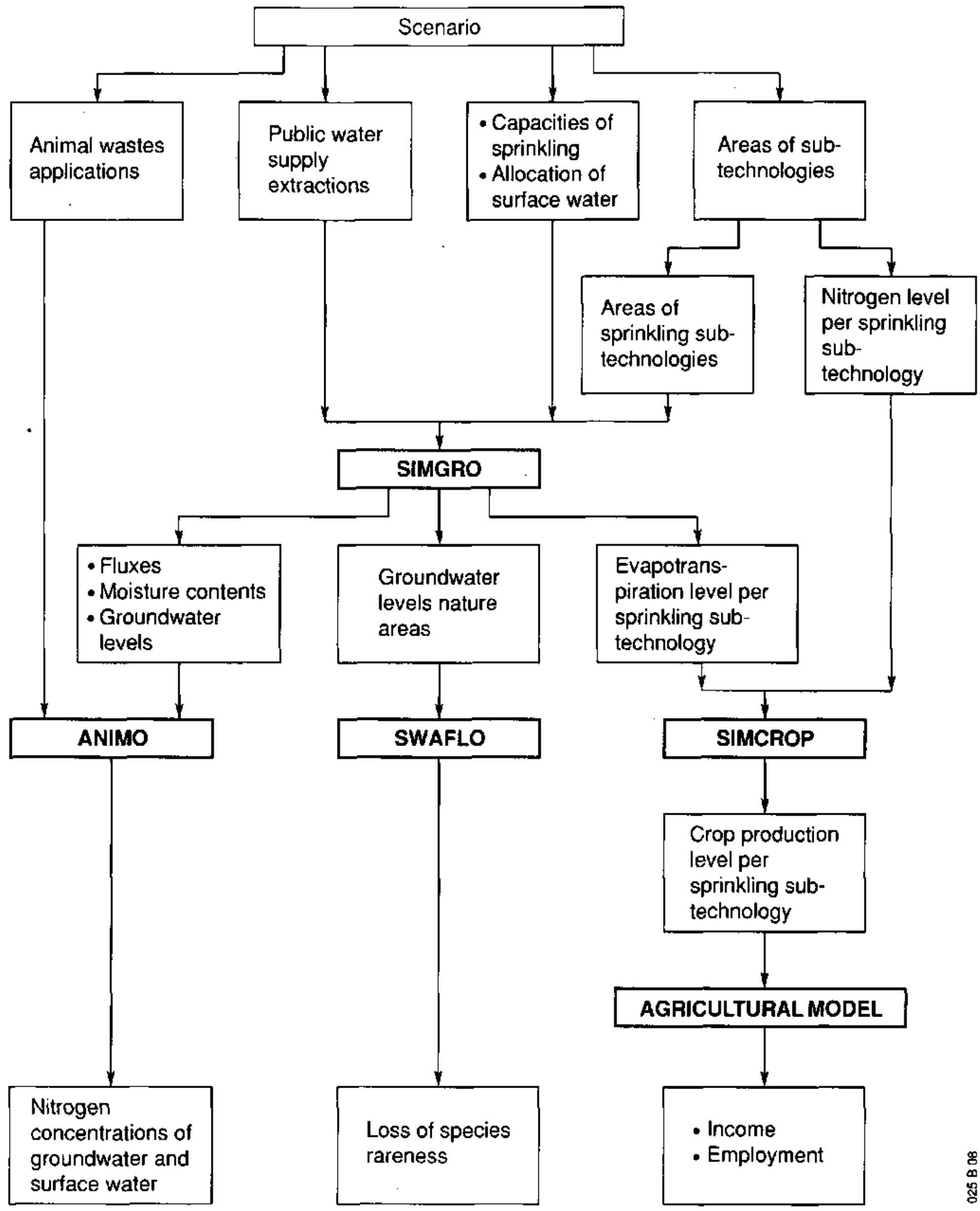

Fig. 8 Flowchart of verification of scenarios with comprehensive models

8.3.1 Agriculture

Prior to obtaining any other agronomic data, the relevant sets of technologies must be decided on (cf. Table 1 and 2). Implementation of the system with other 'auxiliary' technologies is in principle possible, but requires modifying the software. In many cases the modifications will not however require any drastic restructuring of the system, but indeed must be implemented by someone who is acquainted with 'GEMINI-language' (Lebedev, 1984).

After having settled on the sets of technologies that the system is to be implemented with, data have to be obtained about the intensities of these technologies in the 'current state'. In the Netherlands such data can be distilled from data banks that are maintained by the national bureau of statistics, CBS. Not all data on intensities of technologies can be obtained from this bureau though. This concerns especially the data on slurry application to land. For running the system these data are not essential, however. More important are the intensities of the technologies that produce the slurry. The system itself can then on the basis of these data and the soil-use data generate a scenario that very well can be seen as an estimation of what currently is applied to the various types of crop land.

Of the technologies the following data must further be obtained:
- maximum fraction of arable land that a technology can occupy (only relevant for technologies that are part of a rotation scheme);
- stocking densities of the grassland (sub)technologies;
- flexibility parameters of the soil-use and the miscellaneous technologies;
- nitrogen requirements of the soil-use (sub)technologies;
- labour requirements of all technologies;
- costs of implementing auxiliary technologies;
- nett income obtained from the miscellaneous technologies;
- income per unit of production by the soil-use technologies.

The productivities of the soil-use technologies are dependent on the hydrologic conditions. These data should therefore be obtained from a regional crop production model coupled to a regional hydrologic model. The production obtained from these coupled models may need to be corrected for 'suboptimal' nitrogen supply conditions. How the above listed data were obtained for the present study is described in Reinds (1985).

For the animal wastes transport model, the links in the network must be specified.

Concerning the use of local labour, bounds must be given on a sub-regional basis. For the total labour bounds must be specified on a regional basis. The consumption of income by local labour must also be given. For putting a bound on the increase of capital invested in goods a flexibility parameter must be estimated.

8.3.2 Nature areas

For the nature areas the envelope line for different levels of the 'loss of nature value' must be known. Such an envelope line specifies the limiting combinations of the groundwater level lowering at respectively the beginning of summer and the beginning of winter. They can be obtained by applying the method of Kemmers (1988).

8.3.3 Public water supply

Concerning the public water supply an estimate of current and future non-agricultural demands must be available. Often this will only be the case for the current situation. The system can then still be used for performing sensitivity analyses concerning this demand. Other parameters that must be known are the drinking water demand of the soil-use technologies (grassland with cattle) and the miscellaneous technologies.

8.3.4 Regional hydrology and crop production

Except for a number of parameters concerning the capacity of water supply to the subregions, the regional hydrologic data and the crop production (as far as it is dependent on soil moisture), are all obtained from runs with the coupled simulation models SIMGRO (regional hydrology) and SIMCROP (crop production). With these models first a so-called reference run is made, with no groundwater extractions of any sort, and no sprinkling of crops. The supply of surface water is kept to a minimum, just enough to ensure that the ditches in the subregions are water-bearing.

Then, for computing response matrices of deep groundwater extractions for public water supply, a unit extraction is subsequently introduced in the subregions, one by one. For each position of the unit extraction the reductions of the evapotranspiration and crop production (as compared to the values in the reference run) are computed and stored as a column of the response matrix. This is also done with the infiltrations of surface water ('induced infiltration') and the lowerings of the groundwater levels in the nature area (at the beginning of summer and at the beginning of winter). A similar procedure is followed for computing the response matrices of subirrigation, i.e. of the supply of surface water for increasing the infiltration in order to indirectly increase the production of crops and to raise the groundwater levels in nature areas.

For computing the response matrix of groundwater extraction for sprinkling, the temporal pattern of the water demand for sprinkling must be known. Therefore, first a simulation run is made in which the sprinkling 'comes out of nowhere'. The results of this run yields the above mentioned temporal pattern of the water demand, and also the crop productions of sprinkled subtechnologies. The response matrices of groundwater extractions of sprinkling are then obtained by using the water demand pattern as a flow of input data for the size of the extraction in a certain subregion. This is done, like with the deep extractions for public water supply, for each subregion in turn, each time yielding a column of the response matrix.

8.3.5 Nitrogen and phosphorus

For computing the contribution of animal wastes applications to the nitrogen supply of crops, the nitrogen effectivity coefficients must be known. For the present study the data of Lammers (1983) were used.

The nitrogen leaching coefficients and the groundwater level denitrification factor should preferably be obtained from performing experiments with a regional nitrogen model. For the present study, however, coefficients given in Lammers (1983) were used. For the groundwater level reduction factor the exponential relation given in Steenvoorden (1983) was used: the groundwater levels obtained from a ten-year run with SIMGRO were entered into this function; the mean function value was then used in the linear model. The same procedure was followed for obtaining the fluxes (vertical and horizontal ones) that are needed for the mixing-cell model. Only rough estimates of the decomposition factors (for computing the denitrification in the mixing cells due to presence of organic material in the subsoil) were available at the time of concluding the study (see also Drent et al., 1989).

9 CONCLUSIONS

The described scenario generating system can be used for generating scenarios that comply with certain requirements set by the user. These requirements are on the values of 'indicators' that serve as quantifications of the well-being of the various water users. One of the indicator values is left free by the user and gets optimized by the system.

With the interactive display system the authority can analyze generated scenarios and can evaluate them in terms of his own preferences and judgements. No doubt he will require additional scenarios to be generated on the basis of his analysis of the ones that are initially presented to him. Only after this cycle has been gone through several times, and also additional sources of information have been accessed, will the time have come that the decision-making process concerning a region can be finalized.

The operational status of the scenario generating system is that of a working prototype. It can be used as a starting point for further model development (e.g. Van Walsum, 1990). The formulation of the simplified models in terms of constraints and state equations of a linear programming problem makes it easy to apply only a certain part, e.g. only the part involving water quantity. This is simply done by deleting the non-relevant equations from the computer code.

For actual results obtained from running the prototype system the reader is referred to Drent (1989).

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LIST OF SYMBOLS

The various simplified models that together form an integrated system each consist of a number of mathematical relations. In the terminology used in Operations Research these relations are called *constraints*. The unknowns in the constraints are (by convention) termed *decision variables*. Variables for which there exist expressions relating them directly to the decision variables are termed *state variables*. An *indicator* is a special type of state variable that is a measure of 'goodness' of a scenario, as seen from a certain viewpoint.

In the description of the models there is a strict adherence to the classification of variables into decision variables, state variables and parameters. Typographically the class to which a variable belongs is made clear in the following manner:
- decision variables are printed in bold face, e.g. $\mathbf{x_w(i, j, k, n)}$;
- state variables are printed in normal face, with the first letter underlined, e.g. $\underline{v}_n(i, l)$;
- parameters are printed in normal face, e.g. p_{fs}.

In view of their importance the 'indicators of well-being' of water users are typographically distinguished in a special manner. This is done by means of one- or two-letter symbols, that are printed in bold face and also have the first letter underlined, e.g. $\underline{\mathbf{Y}}_{\mathbf{T}}$. Use of this typography is independent of whether an indicator is implemented as a decision variable or as a state variable; this deviates from the convention followed for the 'ordinary' variables. The latter are only indicated to be decision variables or state variables if they are actually *implemented* as such in the *computer code*. Implementation as a state variable involves replacement of the variable by the expression relating it to decision variables.

The used monetary unit is 'fl', for Dutch Guilder. However, this unit can be replaced by any other monetary unit. The used unit for 'human labour' is 'man year'; the abbreviation is 'myr'. Technologies included in the set of miscellaneous technologies (J_z) have their intensities measured in various units. Since it has no point to fully specify these units (which anyhow depend on the technologies with which the model is implemented) use is made of undefined units indicated by '#'. For quantifying the stocking density of grassland, use is made of the unit 'LSU', which stands for LiveStock Unit. One LSU represents one milking cow and enough offspring to supply the follow-up after three years of 'service'; thus one LSU represents one cow and 1/3 of a calf.

Integers

i, i_2	- indices for subregions
i_t	- index for neighbouring subregions (in network for transport of animal wastes)
j	- index for technologies (of both sets J_x and J_z)
j_{dc}	- index value of grassland with dairy cows ($\in J_x$)
j_{op}	- index value of pigs for breeding ($\in J_x$)
j_{rc}	- index value of grassland with rearing cattle ($\in J_x$)
j_{sm}	- index value of silage maize ($\in J_x$)
j_{yp}	- index value of pigs for feeding ($\in J_z$)
k	- index for sprinkling subtechnologies
l	- index for soil-use categories
m	- index for types of animal wastes
n	- index for nitrogen subtechnologies
$n_{sub}(i,i_t)$	- index for subregions that neighbour subregion i
$n_t(i)$	- number of subregions that neighbour a subregion i

Sets of technologies

J_a	- set of auxiliary technologies
J_r	- subset of soil-use technologies that is involved in a crop rotation scheme
J_x	- set of soil-use technologies
$J_x(1)$	- subset of arable land technologies, excluding maize;
$J_x(2)$	- subset of (silage) maize technologies;
$J_x(3)$	- subset of grassland technologies;
$J_x(4)$	- subset of 'new forest' technologies.
J_z	- set of miscellaneous technologies

Indicators of well-being

$\underline{\hat{C}_d}$	- maximum nitrogen (NO_3-N) concentration of water in the first aquifer	$t.m^{-3}$
$\underline{\hat{C}_p}$	- maximum nitrogen (NO_3-N) concentration of water in the phreatic layer of the subsoil	$t.m^{-3}$
$\underline{Q_T}$	- total amount of groundwater for households and industry	$m^3.yr^{-1}$

$\underline{W}(i)$	- loss of ecological value in nature area	%
$\underline{Y}_T$	- total income from agriculture in the region	$fl.yr^{-1}$
$\underline{L}_T$	- total demand of labour for agriculture	$myr.yr^{-1}$

Decision variables

$c_d(i)$	- nitrogen (NO_3-N) concentration of water in the first aquifer of the subsoil	$t.m^{-3}$
$c_p(i)$	- nitrogen (NO_3-N) concentration of water in the phreatic layer of the subsoil	$t.m^{-3}$
c_s	- nitrogen (NO_3-N) concentration of water in the deep Slenk aquifer	$t.m^{-3}$
$f_s(i,l)$	- application of chemical fertilizer nitrogen to soil used by technologies of subset $J_x(l)$	$t.yr^{-1}$
$g_c(i,k)$	- capacity of sprinkling from groundwater	$m^3.d^{-1}$
$i_g(i,k)$	- volume of sprinkling from groundwater	$m^3.yr^{-1}$
$i_s(i,k)$	- volume of sprinkling from surface water	$m^3.yr^{-1}$
$l_a(i)$	- amount of labour done by local workers	$myr.yr^{-1}$
$l_h(i)$	- amount of labour done by hired workers	$myr.yr^{-1}$
$m_c(i)$	- total animal wastes storage capacity	t
$m_b(t,i,m)$	- amount of animal wastes in storage at the end of period t (see Table 4)	t
$m_e(i,m)$	- part of the surplus of animal wastes that gets disposed of by means of transport to outside the region	$t.yr^{-1}$
$m_n(i,l,m)$	- application of animal wastes to soil-use category l during grazing (only relevant for l=3 and m=1)	$t.yr^{-1}$
$m_q(i,1,m)$	- deficit of animal wastes, i.e. the total (local) application minus the total (local) production	$t.yr^{-1}$
$m_q(i,2,m)$	- part of the surplus of animal wastes that gets disposed of by means of transport to another subregion within the considered region	$t.yr^{-1}$
$m_s(i,l,m)$	- spring application of animal wastes to soil used by technologies of subset $J_x(l)$	$t.yr^{-1}$

$m_t(i,i_t,m)$	- transport of animal wastes from subregion i to subregion $n_{sub}(i,i_t)$	$t.yr^{-1}$
$m_w(i,l,m)$	- autumn/winter application of animal wastes to soil used by technologies of subset $J_x(l)$	$t.yr^{-1}$
$p_e(i)$	- percolation of water from the unsaturated zone to the phreatic groundwater, due to sprinkling	$m^3.yr^{-1}$
$q(i)$	- extraction of groundwater for public water supply	$m^3.yr^{-1}$
$s_c(i,k)$	- capacity of sprinkling from surface water	$m^3.d^{-1}$
$S_c(i)$	- peak rate of surface water supply	$m^3.d^{-1}$
$u_c^z(i)$	- extra surface water supply rate required for implementing water level management (subirrigation)	$m^3.d^{-1}$
$x_d(j)$	- regional deficit (farm economic) of a soil-use technology	ha
$x_s(j)$	- regional surplus (farm economic) of a soil-use technology	ha
$x_w(i,j,k,n)$	- area of soil allocated to a subtechnology of a soil-use technology	ha
$z(i,j)$	- intensity of a miscellaneous technology (of set J_z)	#
$z_d(j)$	- regional deficit (farm economic) of a miscellaneous technology (of set J_z)	#
$z_s(j)$	- regional surplus (farm economic) of a miscellaneous technology (of set J_z)	#

State variables

$\underline{f}_l(i)$	- nitrogen (NO_3-N) leaching to phreatic groundwater	$t.yr^{-1}$
$\underline{h}_s(i)$	- lowering of the groundwater level at the beginning of summer	cm
$\underline{h}_w(i)$	- lowering of the groundwater level at the beginning of winter	cm
$\underline{n}_p(i)$	- nitrogen (NO_3-N) load on phreatic groundwater	$t.yr^{-1}$

$\underline{u}_c(i)$	- total surface water supply rate required for surface water level management (= peak infiltration rate)	$m^3.d^{-1}$
$\underline{v}_a(i,l)$	- soil nitrogen available for crop growth	$t.yr^{-1}$
$\underline{v}_r(i,l)$	- soil nitrogen required for crop growth	$t.yr^{-1}$
$\underline{x}(i,j)$	- area of soil allocated to a soil-use technology (of set J_x)	ha
$\underline{x}_r(i)$	- area involved in crop rotation	ha
$\underline{y}(i)$	- subregional income from agriculture	$fl.yr^{-1}$

Parameters

α	- decomposition factor of nitrate in the phreatic layer	yr^{-1}
β	- decomposition factor of nitrate in the first aquifer	yr^{-1}
γ	- decomposition factor of nitrate in the deep Slenk aquifer	yr^{-1}
c_o	- consumption per unit of $l_a(i)$	$fl.myr^{-1}.yr^{-1}$
$c_q(i,j,k,n)$	- actual crop production	$t.ha^{-1}.yr^{-1}$
$c_{qw}(i,j,k)$	- actual crop production under optimal conditions of nitrogen supply	$t.ha^{-1}.yr^{-1}$
$c_{qw}^o(i,j,k)$	- actual crop production in the reference run, under optimal conditions of nitrogen supply	$t.ha^{-1}.yr^{-1}$
C_u	- unit conversion factor (numerical value = 10)	$m^3.(mm.ha)^{-1}$
$c_1(l)$	- basic nitrogen (NO_3-N) leaching of soil with category of use l	$t.ha^{-1}.yr^{-1}$
$c_2(l)$	- leaching coefficient of chemical fertilizer nitrogen applied to soil with category of use l	$t.t^{-1}$
$c_3(m,l)$	- nitrogen (NO_3-N) leaching coefficient of animal wastes application in autumn/winter	$t.t^{-1}$
$c_4(l,m)$	- relative nitrogen (NO_3-N) leaching coefficient of animal wastes application in spring (in comparison to application in autumn/winter; the numerical value is less than unity)	1
c_5	- basic nitrogen (NO_3-N) leaching of soil in forest and nature areas	$t.ha^{-1}.yr^{-1}$

$e_a(i,j,0)$	- actual evapotranspiration of a non-sprinkled soil-use subtechnology	$mm.yr^{-1}$
$e_a(i,j,k)$	- actual evapotranspiration of a sprinkled subtechnology	$mm.yr^{-1}$
$e_a^g(i,j)$	- reduction of evapotranspiration of a non-sprinkled subtechnology, due to groundwater extractions	$mm.yr^{-1}$
$e_a^o(i,j,k)$	- actual evapotranspiration in the reference run	$mm.yr^{-1}$
$e_{ms}(l,m)$	- nitrogen effectivity of animal wastes application during spring, $m_s(i,l,m)$	1
$e_{mw}(l,m)$	- nitrogen effectivity of animal wastes application during autumn/winter, $m_w(i,l,m)$	1
$f_h(i,i_2)$	- horizontal flow in the first aquifer from cell i to cell i_2	$m^3.yr^{-1}$
$f_h(n+1,i)$	- horizontal flow in the first aquifer from outside the region to cell i	$m^3.yr^{-1}$
$f_h(i,n+1)$	- horizontal flow in the first aquifer from cell i to outside the region	$m^3.yr^{-1}$
f_{hd}	- nett horizontal flow of water from the deep Slenk aquifer to outside the region	$m^3.yr^{-1}$
$f_x(j)$	- flexibility parameter of a soil-use technology	1
$f_z(j)$	- flexibility parameter of a miscellaneous technology	1
$f_2(i)$	- groundwater level reduction factor of nitrogen load on groundwater	1
$\hat{g}_c(i)$	- upper bound on peak rate of groundwater extraction for sprinkling	$m^3.d^{-1}$
$\hat{h}_s(i,\underline{W})$	- upper bound on the lowering of the groundwater level at the beginning of summer (see Fig. 5)	cm
$\hat{h}_s^o(i,\underline{W})$	- intercept term (see Fig. 5)	cm
$\hat{h}_w^o(i,\underline{W})$	- intercept term (see Fig. 5)	cm
$\hat{i}_g(i)$	- upper bound on volume of groundwater extracted for sprinkling	$m^3.yr^{-1}$
K_o	- amount of capital goods in the current state	fl
$\check{l}_a(i)$	- lower bound on labour done by local workers in a subregion	$myr.yr^{-1}$

$\hat{l}_a(i)$	- upper bound on labour done by local workers in a subregion	$myr.yr^{-1}$
l_{fs}	- labour requirement per unit of chemical fertilizer (nitrogen) application	$myr.t^{-1}$
l_{ig}	- labour requirement per unit of $i_g(i,k)$	$myr.m^3$
l_{is}	- labour requirement per unit of $i_s(i,k)$	$myr.m^3$
$\check{l}_l$	- lower bound on labour done by local workers in the region	$myr.yr^{-1}$
$\hat{l}_l$	- upper bound on labour done by local workers in the region	$myr.yr^{-1}$
$l_{ms}(m)$	- labour requirement per unit of $m_w(i,l,m)$	$myr.t^{-1}$
$l_{mw}(m)$	- labour requirement per unit of $m_w(i,l,m)$	$myr.t^{-1}$
$\check{l}_t$	- lower bound on total labour done in the region	$myr.yr^{-1}$
$\hat{l}_t$	- upper bound on total labour done in the region	$myr.yr^{-1}$
$l_x(j,n)$	- labour requirement per unit of $x_w(i,j,k,n)$	$myr.ha^{-1}.yr^{-1}$
$l_z(j)$	- labour requirement per unit of $z(i,j)$	$myr.\#^{-1}.yr^{-1}$
$\hat{m}_e$	- upper bound on animal wastes export	$t.yr^{-1}$
$m_x(j,n,m)$	- half-yearly production of animal wastes per unit of $x_w(i,j,k,n)$	$t.ha^{-1}.yr^{-1}$
$m_z(j,m)$	- production of animal wastes per unit of $z(i,j)$	$t.\#^{-1}.yr^{-1}$
$n_r(j,n)$	- nitrogen requirement of a soil-use subtechnology	$t.ha^{-1}.yr^{-1}$
$n_{red}(j,n)$	- reduction factor for crop production under suboptimal soil nitrogen conditions	1
$n_x(j,n)$	- stocking density of a grassland technology, i.e. of a technology of subset $J_x(3)$	$LSU.ha^{-1}$
$P_f(m)$	- phosphate content of animal wastes	$kg.t^{-1}$
$P_n(l)$	- implemented phosphate norm for soil-use category l	$kg.ha^{-1}.yr^{-1}$
$P_s(i,k)$	- duration of sprinkling period	$d.yr^{-1}$
$P_s^{10}(i,k)$	- duration of sprinkling period in a '10% dry year'	$d.yr^{-1}$
$p_c(1,i)$	- percolation of water from the phreatic layer to the first aquifer	$m^3.yr^{-1}$
$p_c(2,i)$	- percolation of water from the first aquifer to the deep Slenk aquifer	$m^3.yr^{-1}$
p_{fs}	- price of chemical fertilizer nitrogen	$fl.t^{-1}$

$p_{gc}(k)$	- costs per unit of $g_c(i,k)$	$fl.yr^{-1}.(m^3.d^{-1})^{-1}$
$p_{gci}(k)$	- amount of capital per unit of $g_c(i,k)$	$fl.(m^3.d^{-1})^{-1}$
$p_{ig}(k)$	- costs per unit of sprinkling $i_g(i,k)$	$fl.m^{-3}$
$p_{is}(k)$	- costs per unit of sprinkling $i_s(i,k)$	$fl.m^{-3}$
p_{lh}	- price of hired labour	$fl.myr^{-1}$
p_{mc}	- costs per unit of $m_c(i)$	$fl.t.yr^{-1}$
p_{mci}	- amount of capital per unit of $m_c(i)$	$fl.t^{-1}$
$p_{me}(m)$	- cost per unit of $m_e(i,m)$	$fl.t^{-1}$
$p_{mq}(m)$	- fixed costs of local animal wastes transport	$fl.t^{-1}$
$p_{ms}(m)$	- costs per unit of $m_s(i,l,m)$	$fl.t^{-1}$
$p_{mt}(i,i_t,m)$	- variable costs of animal wastes transport from subregion i to the neighbouring subregion $n_{sub}(i,i_t)$	$fl.t.yr^{-1}$
$p_{mw}(m)$	- costs per unit of $m_w(i,l,m)$	$fl.t^{-1}$
$p_{sc}(k)$	- costs per unit of $s_c(i,k)$	$fl.yr^{-1}.(m^3.d^{-1})^{-1}$
$p_{sci}(k)$	- amount of capital per unit of $s_c(i,k)$	$fl.(m^3.d^{-1})^{-1}$
$p_x(j)$	- fixed costs per unit of $x_w(i,j,k,n)$	$fl.ha^{-1}.yr^{-1}$
$p_{xd}(j)$	- extra costs per unit of $x_d(j)$	$fl.ha^{-1}.yr^{-1}$
$p_{xi}(j,n)$	- amount of capital per unit of $x_w(i,j,k,n)$	$fl.h^{-1}$
$p_{xs}(j)$	- extra costs per unit of $x_s(j)$	$fl.ha^{-1}.yr^{-1}$
$p_{zd}(j)$	- extra costs per unit of $z_d(j)$	$fl.\#^{-1}.yr^{-1}$
$p_{zi}(j)$	- amount of capital per unit of $z(i,j)$	$fl.^{-1}$
$p_{zs}(j)$	- extra costs per unit of $z_s(j)$	$fl.\#^{-1}.yr^{-1}$
$\hat{q}(i)$	- upper bound on extraction of groundwater for public water supply	$m^3.yr^{-1}$
$r(i,\underline{W})$	- slope of an envelope line (Fig. 5)	1
$r_x(j)$	- maximum fraction of total area involved in a crop rotation scheme that technology j (of J_x) is allowed to be allocated	1
$\hat{S}_c(i)$	- capacity of infrastructure for surface water supply	$m^3.d^{-1}$
$\hat{s}_c(i)$	- area that is reachable for sprinkling from surface water	ha
$s_p(1,i)$	- seepage of water from the first aquifer to the phreatic layer	$m^3.yr^{-1}$
$s_p(2,i)$	- seepage of water from the deep Slenk aquifer to the first aquifer	$m^3.yr^{-1}$

$s_w(i,j,k)$	- total amount of sprinkling of a sub-technology k,n of a soil-use technology j	$mm.yr^{-1}$
$s_w^g(i,j,k)$	- extra amount of sprinkling due to the influence of groundwater extractions	$mm.yr^{-1}$
$s_w^o(i,j,k)$	- basic amount of sprinkling	$mm.yr^{-1}$
S_T	- total available supply rate of surface water	$m^3.d^{-1}$
$u_c^o(i)$	- basic surface water supply rate for surface water level management (= peak infiltration rate in the reference run)	$m^3.d^{-1}$
$\hat{u}_c^z(i)$	- extra surface water supply rate required for implementing the 'maximum strategy' of surface water level management	$m^3.d^{-1}$
$u_w(i)$	- drainage of groundwater from the phreatic layer of the subsoil to surface water (average over 10 years, for groundwater quality model)	$m^3.d^{-1}$
$v_d(i)$	- volume of water in the first aquifer of the subsoil (in cell i)	m^3
$v_p(i)$	- volume of water in the phreatic layer of the subsoil (in cell i)	m^3
v_s	- volume of water in the deep Slenk aquifer	m^3
$w_x(j,n)$	- drinking water requirement per unit of $x_w(i,j,k,n)$	$m^3.ha^{-1}.yr^{-1}$
$w_z(i,j)$	- drinking water requirement per unit of $z(i,j)$	$m^3.\#^{-1}.yr^{-1}$
$x_a(i)$	- area of agricultural land	ha
$x_f(i)$	- area of existing forest	ha
$x_n(i,j)$	- area of 'nature'	ha
$x_o(i,j)$	- area allocated to a soil-use technology in the current state	ha
$y_x(j)$	- income per unit of crop production	$fl.t^{-1}$
$y_z(j)$	- income per unit of $z(i,j)$	$fl.\#^{-1}.yr^{-1}$
$z_o(i,j)$	- intensity of a miscellaneous technology in the current state	#