COMMISSIE VOOR HYDROLOGISCH ONDERZOEK TNO

COMMITTEE FOR HYDROLOGICAL RESEARCH TNO

Verslagen en Mededelingen No. 27

Proceedings and Informations No. 27

WATER RESOURCES MANAGEMENT ON A REGIONAL SCALE

TNO

WATER RESOURCES MANAGEMENT ON A REGIONAL SCALE

E R R A T A

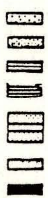
Proceedings and Informations No. 27 :

' WATER RESOURCES MANAGEMENT ON A REGIONAL SCALE '

Pag. 103, section 3.1. 2nd line: macro-invertebrates in stead of macro-inertebrates.

Pag. 117, fig. 4 : the shade column under the heading 'Shade' in the LEGEND has been printed upside down (in the figure the darkest shade represents the type code Vb, etc.)
The LEGEND must be:

LEGEND and Ellenberg indication (Wetness, Acidity and Mineral N)



Shade	Code	Type	Indication
	I	wet heath	W7,7 A1,5 N2,1
	II	heath edge	W7,9 A3,0 N2,3
	IIIa	poor open fen	W8,3 A3,8 N2,4
	IIIb	rich open fen	W8,4 A3,8 N3,4
	IVab	wooded heath edge	W7,3 A3,9 N3,9
	IVc	wooded open fen	W7,8 A3,3 N2,7
	Va	poor carr	W7,4 A4,4 N3,9
	Vb	rich carr	W7,7 A4,6 N4,4

Symbol	Explanation
	forested (Populus)
	forested (Pinus)
•x	sample station (fig. 5, table 2)
	supposed direction of flow of ground and surface water
---	parallel to MLL: indicates pass frequence threshold level of regional water table

COMMISSIE VOOR HYDROLOGISCH ONDERZOEK TNO
COMMITTEE FOR HYDROLOGICAL RESEARCH TNO

Verslagen en Mededelingen No. 27
Proceedings and Informations No. 27

WATER RESOURCES MANAGEMENT ON A REGIONAL SCALE

PROCEEDINGS OF
TECHNICAL MEETING 37
(November, 1980)

VERSL. MEDED. COMM. HYDROL. ONDERZ. TNO 27 – THE HAGUE – 1981

CONTENTS

AUTHORS

Dr. ir. Th.J. VAN DE NES	Provincial Waterboard of Gelderland, Arnhem
Dr. ir. P.J.M. DE LAAT	International Institute for Hydraulic and Environmental Engineering, Delft
Ir. R.H.C.M. AWATER	Rijkswaterstaat, Data Processing Division, Rijswijk
Ir. P.J.T. VAN BAKEL	Institute for Land and Water Management Research, Wageningen
Ir. K. KOVAR	National Institute for Water Supply, Leidschendam
Ir. H.L.M. ROLF	National Institute for Water Supply, Leidschendam
Dr. ir. J. BOUMA	Soil Survey Institute "Stiboka", Wageningen
Ir. A.F. VAN HOLST	Soil Survey Institute "Stiboka", Wageningen
Drs. J.J.P. GARDENIERS	Nature Conservation Department of the Agriculture University, Wageningen
Drs. G. VAN WIRDUM	Research Institute for Nature Management, Leersum
Drs. J.P. ANCOT	Netherlands Economic Institute and Erasmus University, Rotterdam
Drs. E. ROMIJN	Provincial Waterboard of Gelderland, Arnhem

ACKNOWLEDGEMENT

I would like to take the opportunity to thank the Committee for Hydrological Research TNO for the readiness to organize a symposium on the results of the research programme of the CWG.

Also, I like to mention the very pleasant co-operation of the many institutes that participated in this meeting.

Last but not least I thank the Provincial Waterboard of Gelderland, and especially its former director, Ir. C.C.M. Baron van Hövell tot Westerflier, for the continuous assistance to complete the research programme and to publish the results of CWG.

E. ROMIJN
Secretary of the Committee for the Study of the Water Resources Management in Gelderland (CWG)

INTRODUCTION TO A SYSTEM APPROACH FOR WATER MANAGEMENT IN GELDERLAND, NETHERLANDS

TH. J. VAN DE NES

SUMMARY

In the 1971-1979 period, a first attempt was made in the (Dutch) province of Gelderland to analyse the management system for water resources on a regional scale. The complex character and the large scale of the system necessitated the involvement of many disciplines in the study.

On the one hand, this caused problems of communication between the various disciplines and on the other hand, problems of transfer of knowledge to the management concerned.

These problems have meanwhile been solved with the aid of systems theory, where the theory concerning hierarchical systems offers perspectives. In this approach, the water resources management system is divided into a number of levels that are studied with the aid of mathematical models and computer science. Special attention has been given to the development of a methodology, forming the scientific base for an integral approach to water management. In future the results thus obtained can be used in the planning of water resources management.

The present paper gives the framework for the various topics which will be offered for discussion at this meeting.

1. INTRODUCTION

In 1970 it was felt in the province of Gelderland that the many research activities in the field of water management, with their different goals, should be integrated. The reason was that in our present-day society, which is becoming more and more complicated, with its increased demand for water and rapidly deteriorating water quality, the water problem, as a whole, has become highly complex. There is no longer the freedom to consider one single facet separately and then propose improvements for this facet. Again and again the policy-makers or action groups will ask for the consequences of suggested measures upon other interests. So, often one is forced to view the water problem as a whole and, consequently, an integral approach to inherent problems is an abolute must.

In November 1970, the Provincial Government installed the "Commissie Bestudering Waterhuishouding Gelderland" ("Committee for the Study of Water Resources Management in Gelderland") with the following instruction: creation of a scientific base for an optimal management of the surface water and groundwater available in Gelderland with regard to their quantity and quality, including all interests. The research should result in a water management model, which can serve as a means for weighing alternative uses of water. Water policy relates to national, provincial, regional and local levels. Each unit of decision makers tries to realize, with optimal means, the objectives set at its level. As a result, the question arises via what kind of mechanism, the various decision-making authorities can be induced to take the very measures that result in a solution that, upon the whole, is satisfactory.

That is the reason why 30 representatives of the various agencies, but also universities, participate in the Committee mentioned above, which has delegated the execution of a research program to a working group. The working group had the supervision of 16 research groups, with a total research budget during the 1971-1979 period of 2, 3 million guilders and an extra contribution of manpower from the various research institutes. The number of specialists in the various scientific fields increased from 20 in 1972 till about 80 in 1979.

The studies have been published in some 115 reports and papers, on which the final report of the Committee is based (Commissie Bestudering Waterhuishouding Gelderland, 1980).

2. OBJECTIVES OF THE STUDY

The formulation of the Committee's general objective reads: "creation of a scientific base for an optimal management of the surface water and groundwater in Gelderland with regard of their quantity and quality". It has over the years been elaborated in terms of the following sub-objectives:

- Analyze the water problems on provincial and regional levels in relation to national water management.
- Develop a related set of technical-scientific instruments as a tool for solving provincial and regional water problems.
- Study the accuracy of the technical-scientific instruments by making sensitivity analyses.
- Afford insight into the necessary data and their accuracy.
- Give recommendations as to the use and management of the technical-scientific instruments, and as to the management of the relevant data.
- Analyze the applicability of the technical-scientific instruments for the policy-making on provincial and regional levels.
- Indicate the lag in knowledge of the water management system.

3. SYSTEM APPROACH

3.1. *Description of the management system for water resources*

In view of the complexity of the water resources management system, and the necessary planning in this field, there is a great need for intensive participation and integration of various disciplines in the decision-making process. With the aid of mathematical models, a systems theory approach tries to describe the various elements of the water resources management system and their mutual dependence. In this way, the results of the measures to be taken can be predicted, so that alternative plans can be evaluated and mutually compared. In the water management system, three types of elements can be distinguished:

- social elements (demand of water for various purposes);
- natural elements (the various natural water supplies with their physical, chemical and biological characteristics);
- artificial elements (technical and administrative measures).

The pertinent management policy must promote an adequate cooperation among the elements.

The social elements are the driving force for the water resources management, from which the management policy must be derived. The following needs are to be distinguished:

- domestic water;
- water for agriculture (sprinkling, level control);
- processing and cooling water for industry;
- nature and landscape conservation;
- outdoor recreation;
- shipping; transport and conservation (decomposition) of waste products;
- water level control for the benefit of urban areas.

Natural elements are potential sources to meet those needs. These sources comprise: rainfall, evaporation, water present in the soil and surface water. The water in the soil can be distinguished in terms of water above groundwater level (soil moisture) and water below the groundwater level (groundwater). This distinction is important because a great part of the soil moisture can be extracted by the local vegetation only (agriculture, and nature). A remarkable relation between these elements is found to apply. It appears, for instance, how evaporation, which is also a control for agricultural production and natural vegetation, depends on the soil moisture content. The latter, however, is related to the groundwater level, which in turn is coupled with the surface water. Control of the level of surface water can affect agricultural production and natural vegetation. Conversely, via a certain selection of vegetation within agriculture and forest culture, one can influence evaporation, so that either more or less groundwater and surface water remains for other interests. Draining solid and liquid wastes on to the soil, or directly on to the surface water, obviously affects the quality of soil and surface water. Extracting groundwater for the benefit of the population and industry lowers the groundwater level and this may well do harm to agriculture and nature. The characteristic feature here, too, is that the conditions of the natural elements vary largely with location and time.

The artificial elements (technical and management measures) form the expedients available to management for balancing pertinent supplies and demands. Selection of measures, and the handling of these selected measures, form the crux for decision making in management. A complete and consistent aggregate of measures is a plan.

The artificial elements can be distinguished as measures that either try to affect the demands, such as information, permits, regulations and price policy, or try to affect the supplies, such as the construction of technical works or operation rules. Four types of elements, indicated as management sub-systems, may be distinguished:
- water supply (ground and surface water extractions, permits);
- water quantity management (level management and water distribution by means of dike building, brook improvements, weirs, etc.);
- water quality management (purification plants, draining permits, etc.);
- nature conservation (conservation and restoration of natural resources).

The description of the water resources managing system just given cannot be handled irrespectively of the size of the area considered, nor of the period over which the measures extend. The strong relationship between the natural elements makes it necessary to coordinate the measures of the four management sub-systems.

The functioning of the large-scale complex water resources management system can be improved by application of the theory of hierarchical multilevel systems (Mesarović et al., 1970). Then, basically, it is assumed that the overall system considered is built up hierarchically from a number of sub-systems. This hierarchy is characterized by two factors: the right of intervention of the higher level, and the mutual dependence between levels. The behaviour of a sub-system at every level is directly and explicitly prescribed by the higher levels. This influence expresses a priority in the objectives at the higher levels; this influence will be indicated as the right of intervention. It is directed downward in a command fashion; the success of the total system performance depends on the activities of the lower levels. In theory, three types of hierarchical systems are distinguished:
- description hierarchy: levels of description or abstraction (strata);
- decision hierarchy: levels of decision complexity (layers);
- organization hierarchy: levels of organization (echelons).

3.2. *Description hierarchy*

Levels of description are mostly necessary because complex systems make it impossible to describe the system fully and in detail. The general characteristics of a hierarchical description can be summarized as follows:

At a lower level, one concentrates on the performance of the sub-systems whereas the interactions between the various sub-systems are studied at a higher level.

Knowledge of a subsystem increases upon passing levels: in the downward direction of the hierarchy, a more detailed description and explanation are obtained, whereas in the upward direction of the hierarchy a better insight is obtained into the meaning of the sub-systems within the total system.

In describing the water resources management system four layers (see fig. 1.) are distinguished:

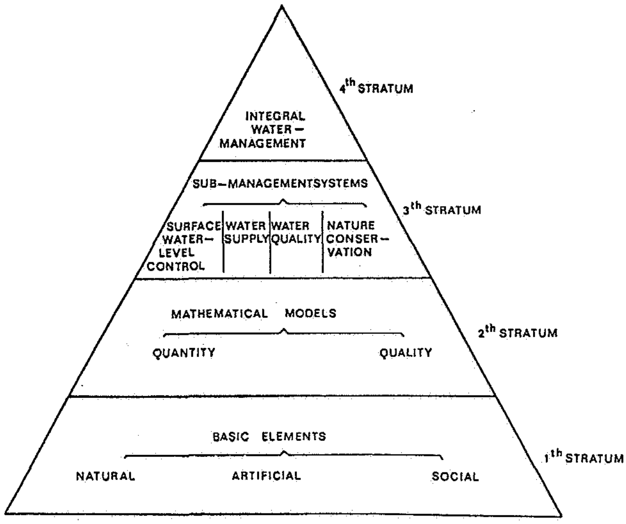


Fig. 1. Description hierarchy of the water resources management system

- within the first stratum, the individual basic elements of the water resources management system are described.
- within the second stratum, the physical and artificial elements are studied in their mutual coherence, with the aid of mathematical simulation models.
- within the third stratum (sub-management systems), the physical system is studied in mutual dependence upon a number of social elements.
  Multicriteria decision models are important tools for optimization.
- within the fourth stratum, reaching an integral model for water resources management will be tried. Here, too, multicriteria decision models may be very helpful.

Between the strata, there is a flow of information in upward as well as in downward direction.

3.3. *Decision hierarchy or decision process*

Another important hierarchical system approach is needed, if the decision process within the system is very complex. There are two utterly trivial, but very important characteristics in almost any real life decision-making situation:

a. When the time for decision has come, making and carrying out the decision cannot be delayed: for every delay implies that "no decision" has been selected as the most preferable among the alternatives.
b. The uncertainties concerning the consequences of implementing alternative decisions and the lack of knowledge of the various relations involved, often make a rational decision impossible.
   These two factors result in the fundamental dilemma of "deciding or not deciding";

on the one hand is a necessity to act without delay and, on the other hand, there is the necessity to understand the system better.

In the hierarchical system approach, formulating a structure is tried in which the solutions of decision problems are sought at different layers successively.

The solution of the original decision problem is completed if all decisional sub-problems have been solved at the various layers. In theory, three layers are distinguished:

– the selection from strategies for the solution of the complex decision problem (planning procedure, formulation of objectives, conditions and constraints, etc.);
– the reduction or elimination of uncertainties within the decisionmaking process (the acquisition of knowledge by means of model investigation within various strata);
– the investigation of optimal or acceptable decisions within prescribed conditions or restrictions (optimization with the aid of the models developed).

The general objective of water resources management. i.e. the maximization of the social utility of water resources management, can be subdivided between maximizing the social utility of water supply, water level control, water purification and nature conservation. These sub-objectives, each in turn, can be divided into regional development, retention of environmental quality and economic efficiency. These divisions can also be divided in turn. In this manner, a properly defined hierarchy of objectives is produced. Every objective at the lowest level can be expressed as an elementary objective function of some effects, provided the latter are quantifiable. If the preferences of the population can be quantified in collective weights, with sufficient objectivity, the elementary objective functions can be combined to higher objective functions with the aid of these weights.

In this manner, the hierarchy of objectives can be followed upwards, until the general objective function is formulated. Then the selection procedure is an "uni-criterion" optimization without constraining criteria.

If the weights are not known a priori, the elementary objective functions can only be combined as far as certain levels of the hierarchy of objectives. Then various objective functions coexist. However, the selection procedures, wich will be discussed below, offer oportunities for solving the inherent decision problematics.

– A multicriteria procedure without constraining criteria calculates, for each plan, the values of the various objective functions; only in the decision phase does it grant ranks or weights to these functions. These ranks and weights are considerably more subjective than the weights that have already been incorporated in the objective functions.
– A uni-criterion procedure with constraining criteria enables application of one optimization criterion by converting the other ones into constraining criteria. The pertinent objective functions are subjected to a lower or upper limit; they thus become constraining functions. The determination of these limits (standards) is implemented in an

evaluation of interests at a higher level. The standards can be made variable so that the effect of the standards on the optimal value of the remaining objective function can be quantified. The result is the optimal behaviour of a lower level system, as a function of the standards. Then, in turn, the result can serve as a basis for the evaluation of interests at a higher level.

3.4. *Organization hierarchy*

For this hierarchy it is necessary that a number of sub-systems are decision-making units. These systems are indicated as multilevel, multigoal systems, because in general the various decision-making units will strive after contrary purposes. An important feature of these systems is that the decision-making units at a higher level condition the goal-seeking activities of the lower level units, but do not control them completely. The latter is essential for the hierarchical structure.

In designing a hierarchical organization, the distribution of tasks to various decision-making units at various echelons, and the coordination between the decision-making units are the most important problems.

3.5. *Decomposition and integration*

The description hierarchy, the decision hierarchy and the organization hierarchy make it possible to decompose the complex water-management system to time horizon (short-term and long-term problems), location (local, regional and provincial, etc.) and functions (the various interests), without losing sight of their mutual dependence.

The common characteristics of the three hierarchies can be summarized as follows:

- a higher level considers a large proportion of the total system behaviour, where more aspects are considered;
- the period of decision or the time needed to reach a decision, is longer at a higher level than at a lower level;
- a higher level considers the more gradually changing aspects of the total system behaviour;
- the description of the system and the decision problem at the higher level are less structured, more difficult to formulate quantitatively and contain more uncertainties;
- the application of a certain combination of these three hierarchical systems will depend on the nature of the system considered, the available knowledge and the organization already present.

4 SIMULATION MODELS AND OPTIMIZATION TECHNIQUES

Figure 2 presents a more detailed hierarchical presentation of the water management system, showing the role of mathematical models as tools for water management. The

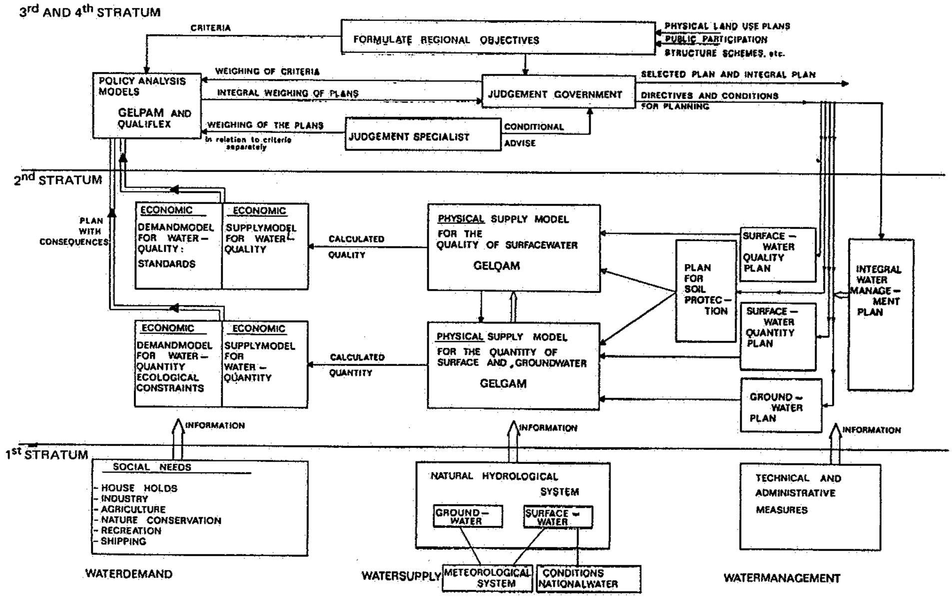


Fig. 2. Description and optimization regional watermanagement.

figure shows the importance of basic data, concerning water needs, water supply and the sub-management systems.

4.1. *Hydrological water-supply models*

The coherence between the natural elements is being studied with the objective of establishing the interactions of measures of the various management sub-systems. Models have been developed for the determination of the flow of groundwater and surface water (quantity models) and for the description of the oxygen dynamics of brooks (chemico-biological quality models). A coupling enables the integration of quantity and quality aspects.

GELGAM (Gelderland Groundwater Analysis Models)

A model was developed in which the sub-systems that had been described within the first layer, such as rainfall, evaporation, soil moisture, groundwater and surface water, are now described in their mutual coherence. The model can be applied for every random inhomogeneous area. It actually consists of a grid of squares with an arbitrarily chosen magnitude; it describes, for every nodal point, the condition of the various sub-systems.

The description of the processes is as much as possible based on physical laws and supplemented with data from empirical knowledge. The relation between groundwater on the one hand and soil moisture and surface water on the other, is established on the nodal points of the network.

Hydrogeological data on the deep sub soil, physical data on the upper soil and data on the vegetation must be put in each square of the grid. Every arbitrary operation of groundwater extraction, infiltration and brook level regulation has effects on the groundwater level soil moisture, the actual evaporation and the runoff in the remaining nodal points, as functions of time and place. The effects can be calculated per nodal point.

GELQAM (Gelderland surface water Quality Analysis Model)

In describing water quality, the problem arises that it cannot be characterized by one specific variable, since various decomposable and non-decomposable substances finally determine the water quality. An important variable in evaluating this quality is dissolved oxygen. So as to calculate the oxygen concentration it is necessary to characterize the pollution that consumes oxygen or biological oxidation by micro-organisms (BOD) and algae growth. Apart from the model for oxygen, models for BOD and algae growth must be developed. In the model, the river is divided into a number of sections, thus enabling the calculation of oxygen content, the BOD and algae concentration as average values per section.

The effects of water quality measures as primary, secondary and tertiary treatment of waste water can be calculated. The same can be done for quantity measures, as low flow argumentation.

In conclusion it can be stated that GELGAM is an important tool for the integration of the water-supply sub-system, water quantity management sub-system and the nature conservation sub-system. GELQAM is an important tool for the integration of the water quantity management sub-system, the water quality management sub-system and the nature conservation sub-system.

The two models together form the physical base of integral water management.

For a complete description of the hydrological system (water supply system) it is necessary to also develop a model for the groundwater quality. Because of a lag of data, the development of a groundwater quality model has been delayed.

Figure 2 shows that GELGAM and GELQAM produce only the physical consequences of measures or water-plans.

These physical consequences have to be translated into a socio-economic water supply. This means that costs and benefits of alternative plans, expressed, if necessary, in various units have to be determined.

4.2. *Econometric water-demand models*

For the water-demand by the various sectors, too, a distinction can be made between water quality and water quantity.

For the water quality no models have been developed. It is assumed that standards are essential.

For the water quantity, 3 simulation models can be distinguished:

HUISIM (demand model for household)

A number of models have been developed, and tested, to describe the use of water by households. They describe the yearly use per capita as a function of the price of water, the income per capita, the household size, the change in mentality of the population, the growing wealth of the population, the effect of installing meters, the degree of urbanization, and the climate.

The aggregation level chosen is the municipality. These models have a macro-economic character and are of the type called "Black box regression models". Based on economic and statistical criteria, one model has been preferred.

AQUSIM (demand model for industry)

In its final specification, the industrial demand model consists of eight submodels, one for each of eight broad sectors into which the industrial activity has been classified. Each submodel describes the yearly water use as a function of the price of water, the origin of water (privately extracted groundwater or tapwater), the function in the production process, a trend factor in relation to innovation, the levy on effluent discharge and the gross value added at factor costs.

The aggregation level chosen depends on the availability of data. In general the municipality is too small, so that a whole region has to be taken.

These models also have a macro-economic character and are of the type known as "Black box regression models".

UNSAT (demand model for agriculture)

One part of the GELGAM model is called UNSAT. It describes the meteorological system and the soil moisture system. The demand of water by agriculture as a function of crop, soil, climate and groundwater regime can be predicted by the model.

These three types of demand models make it possible to predict the use of water by the various categories for alternative water management scenarios. Water demand by nature has be taken into account as a boundary condition.

4.3. *Optimization techniques*

The physical and social consequences of alternative measures or water-plans can be described, if possible, by the mathematical simulation models for water supply and water demand. These consequences have to be tested against the policy criteria, upon which the optimal management plan can be selected.

The rise in interactions between the public and private sectors, as well as the presence of many intangible effects of water-plans, imply that an unambiguous evaluation of water-plans on the basis of their social utility is, in general, very difficult. The main reason for this difficulty is the fact that the various aspects of a water-plan are very hard to convert into the same dimension; particularly into the monetary dimension.

Therefore, the water resource planning profession is currently engrossed in a period of reformulation of its project evaluation procedures and development of corresponding mathematical techniques. The ongoing transformation is from traditional benefit-cost-analysis, and its associated uni-objective planning models, to multi-objective analysis; this has promoted two fields of decision models:
(A) the mathematical programming models with more than a single objective function;
(B) the multicriteria decision models.

With these two types of decision models, many attempts have been made to develop new evaluation methods which are based more adequately on the multi-dimensionality of a decision problem (including the intangibles). The general feature of these methods, which are based on weighing systems for the decision criteria, is that the plan impacts are not necessarily transformed into monetary units. Instead, a weighing scheme is developed which reflects the relative importance of each of the decision criteria.

The models of group A, which have been developed since 1950, consider the objective functions as continuous functions of the decision variables, while the decision variables are also continuous.

For their application in complex water resources systems it is very often necessary to simplify the description of the system or to split up the system in simple sub-systems in a hierarchical structure. The disadvantage of all these techniques is that the social aspects of planning, the decision and the decision-making process have been neglected.

The models of group B, whose development was started in 1970, consider the objective functions as discrete functions of the decision variables, while the decision variables are also discrete. In this case, there are a number of distinct alternatives, while further more the methods are closer to the decision-making process.

In practice, a combination of both types of decision models is possible and necessary. Another possibility is the combination of complex simulation models (hydrological supply models and econometric spatial demand models) for the water resources management system with the multicriteria decision models. In this case, the consequences of a number of alternative plans or measures, will be calculated by the simulation models. The evaluation of the consequences can be done by the multicriteria decision model. We have followed this approach in Gelderland. In Gelderland, 2 multicriteria decision models or policy analysis models have been used and compared with each other.

QUALIFLEX and GELPAM (Gelderland Policy Analysis Model).

Both mathematical optimization techniques form an important tool for decision problems of a complex nature. The complex character has been determined by the number of alternatives, the number of criteria and the number of persons, who are involved in the decision-making process.

As final results, both models produce a ranking of the alternative plans with their integral weights. These integral weights depend on the weight of the alternative water-plan for every criteria separately, the weight of the criteria and the weight of the decision makers.

The techniques make it possible to split decision making and planning, without losing the feedback between them.

Accordingly, the results obtained with the aid of these techniques can give rise to a reconsideration of the alternative plans and/or policy criteria. This is due to a growing insight into the decision problem, which is the final goal of policy analysis.

In Figure 2 it is shown that from the water management objectives the policy criteria have to be derived. The weighing of the criteria is a task of the Government. The weighing of the alternative water-plans in relation to the criteria separately is a task of the engineer or system analyst. The integral weighing implies teamwork for planners and decisionmakers.

5 CONCLUSIONS

Based on the research results, many conclusions can be drawn. However only some of the main conclusions will here be given:

- The theory of hierarchical systems, applied to the regional water management system, may be helpful for the integration of research (description hierarchy), water management (decision hierarchy) and organizational structure (organization hierarchy). This approach offers the possibility to coordinate research and water policy on the various levels.
- The mathematical simulation models for the water supply in relation to quantity (GELGAM) and in relation to quality (GELQAM) are important technical-scientific instruments for integral water management.
- The mathematical simulation models for the water demand by households (HUISIM),

by industry (AQUSIM) and agriculture (UNSAT) give important directives about the water-use in the future.

- The multicriteria decision models, QUALIFLEX and GELPAM, are important tools for policy analysis. The results of simulation models and other information can be integrated in this way. They also offer the possibility of direct teamwork between decision-makers and planners.
- The reliability of model calculations is dependent on the accuracy of the model itself and on the basic data. In general it is necessary to focus attention on the acquisition and availability of data. This is especially valid for regional data in relation to the demand of water, geohydrology, the quantity and quality of surface water, the quality of groundwater and nature conservation.
- The water-need of agriculture has increased, because of the high requirements in relation to drainage. Therefore, an adequate surface water level control is of great importance.
- The quality of extracted groundwater shows, on several locations, a gradual decline. The cause has to be sought in a changing flow pattern of groundwater, a more intensive land use and in the pollution of the rainfall. In relation to this aspect, groundwater quality management of surface water also to consider the protection of groundwater
- The relationship between groundwater and surface water makes it necessary for the quality management of surface water also to consider the protection of groundwater against pollution.
- For a number of small nature reserves, the relationship between water management and natural vegetation has been studied. However, more knowledge is necessary for a nature conservation oriented water management.
- The research results show that water of a good quality has become scarce. Optimal water allocation is, therefore, also a political problem.

REFERENCES

COMMISSIE BESTUDERING WATERHUISHOUDING GELDERLAND (1980) – Een systeembenadering voor het waterbeheer van Gelderland (A system approach of the water management in Gelderland); abbreviated version of the final report, pp. 88. Provincial Waterboard, Arnhem. (in Dutch)

MESAROVIC, M.D. et al. (1970) – Theory of hierarchical, multilevel systems. Academic Press, New York.

GELGAM – A MODEL FOR REGIONAL WATER MANAGEMENT

P.J.M. DE LAAT, R.H.C.M. AWATER AND P.J.T. VAN BAKEL

SUMMARY

The structure of the quasi three-dimensional mathematical model GELGAM is described and the applicability for solving regional water management problems is discussed. A comprehensive sensitivity analysis has been carried out with both the combined model and the model for the vertical flow system only. Some results obtained with GELGAM for a large area are given.

1. MODEL DESCRIPTION

1.1. *Structure of GELGAM*

GELGAM (Gelderland Groundwater Analysis Model) is a distributed deterministic hydrological model for the simulation of groundwater flow and evapotranspiration in large, non-homogeneous areas. GELGAM is developed from equations for mass and energy transfer, supplemented with empirical relations and conceptual elements. In the construction of the model some delicate decisions had to be made with regard to the conflicting interests between physical-mathematical rigor on the one hand and program efficiency on the other. In the present version of GELGAM the compromise settled in favour of the efficiency, which limits the applicability of the model.

Assuming that the Dupuit-Forchheimer assumptions are approximately valid, the three-dimensional sub-surface flow system is rationally schematized into horizontal flow in the saturated and vertical flow in the unsaturated region. If the fluctuations of the water table are small as compared with the total saturated thickness D of the aquifer, the latter may be taken as a constant. The value of D is chosen such that the upper boundary of the saturated zone is just beneath the lowest phreatic level occurring in the period considered. Water and soil are assumed incompressible, so that changes in storage are restricted to the unsaturated zone. Taking into account groundwater extraction q_e and interaction with both the overlying unsaturated zone q_w and the surface water system q_o, the equation for horizontal saturated flow may be written as

$$\frac{\partial}{\partial x}(T(x,y)\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T(x,y)\frac{\partial h}{\partial y}) = q_e(x,y,t) + q_w(x,y,h,t) + q_o(x,y,h,t) \qquad (1)$$

where x and y are horizontal space coordinates, h is the hydraulic head or water-table elevation, t is time and T is the transmissibility of the saturated aquifer. Positive values for terms on the right-hand side of equation (1) represent sinks, negative values source functions. If R is the region for which equation (1) holds and S_1 and S_2 constitute the boundary of R, the conditions valid along the boundary may be formulated as

$$\text{along } S_1: \; h = h^*(x, y, t) \tag{2a}$$

$$\text{along } S_2: \; \frac{\partial h}{\partial n} = 0 \tag{2b}$$

where the phreatic level h^* on S_1 is supposed to be given and n is the direction normal to the boundary. For the solution of equation (1) a square grid is used of which the mesh width is usually taken between 100 and 1000 m.

Vertical unsaturated flow is simulated in each node of the horizontal grid. In GELGAM the unsaturated region extends from the upper boundary of the saturated zone to the soil surface (fig. 1). The region is schematized into a root zone and a subsoil. Transient unsaturated flow is simulated by a succession of steady-state situations. The procedure is efficient in terms of computer costs as it does not require the two-dimensional grid to be expanded in the vertical direction and it allows for the use of time increments in the order of days.

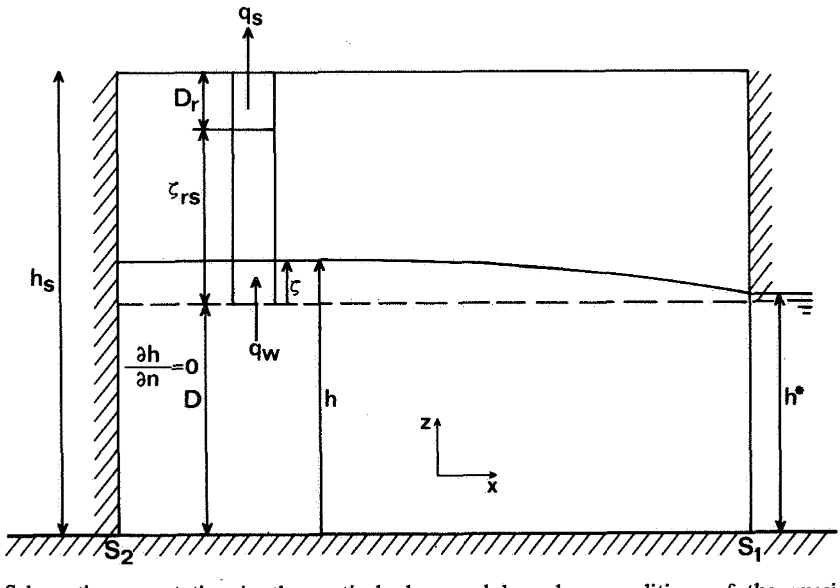


Fig. 1 Schematic presentation in the vertical plane and boundary conditions of the quasi three-dimensional approach to saturated-unsaturated flow.

D	thickness of saturated zone	cm
D_r	thickness of root zone	cm
h	water-table elevation	cm
h_s	soil surface elevation	cm
h*	water-table elevation at boundary S_1	cm
q_s	flux across soil surface	$cm \cdot d^{-1}$
q_w	flux across interface saturated-unsaturated region	$cm \cdot d^{-1}$
t	time	d
T	transmissivity of aquifer	$cm^2 \cdot d^{-1}$
x, y, z	space coordinates	
ζ	water-table elevation in the model for unsaturated flow	cm
ζ_{rs}	height interface root zone – subsoil in the model for unsaturated flow	cm

The surface water system is included in GELGAM in order to improve the simulation of the sub-surface flow system, rather than to predict water discharges. A detailed simulation of surface water runoff is of course impossible in view of the length of the time increments used. As the model does not consider overland flow all rainfall excess is assumed to infiltrate.

The model for evapotranspiration is based on the formula of Penman, which has been adapted to cropped surfaces. Interception and snow melt are not taken into consideration.

A short description of the different components of GELGAM is given below.

1.2. *Saturated flow system*

It is assumed that the unconfined aquifer is resting on an impermeable basis. If the lower boundary is semi-permeable, flow into or out of the underlying semi-confined aquifer(s) must be considered. For the simultaneous solution of flow in a multi-aquifer system the reader is referred to De Laat and Awater (1978).

GELGAM uses a finite element method, based on the variational principle to approach the solution of equation (1). The horizontal x, y grid divides the region R into a number of sub-areas, the elements. Within each element (indicated by a letter in figure 2) the transmissivity T is assumed to be constant. For a mesh width $\ell = \Delta x = \Delta y$, the equation for node i, j at time $n + \frac{1}{2}$ is written as (Van den Akker, 1972)

$$\begin{aligned} &\tfrac{2}{3}(T_C + T_D + T_P + T_Q)h_{i,j}^{n+\frac{1}{2}} - \tfrac{1}{6}\,[T_C(2h_{i-1,j+1}^{n+\frac{1}{2}} + h_{i,j+1}^{n+\frac{1}{2}} + h_{i-1,j}^{n+\frac{1}{2}}) + \\ &+ T_D(h_{i,j+1}^{n+\frac{1}{2}} + 2h_{i+1,j+1}^{n+\frac{1}{2}} + h_{i+1,j}^{n+\frac{1}{2}}) + T_P(h_{i-1,j}^{n+\frac{1}{2}} + 2h_{i-1,j-1}^{n+\frac{1}{2}} + h_{i,j-1}^{n+\frac{1}{2}}) + \\ &+ T_Q(h_{i+1,j}^{n+\frac{1}{2}} + h_{i,j-1}^{n+\frac{1}{2}} + 2h_{i+1,j-1}^{n+\frac{1}{2}})] = \ell^2\,(q_w)_{i,j}^{n+\frac{1}{2}} + \ell^2\,(q_e)_{i,j}^{n+\frac{1}{2}} + \ell^2\,(q_o)_{i,j}^{n+\frac{1}{2}} \end{aligned} \quad (3)$$

Application of equation (3) to each of the nodes for which h has to be calculated yields a set of equations which is solved by using a Gauss-Seidel iterative procedure. The solution

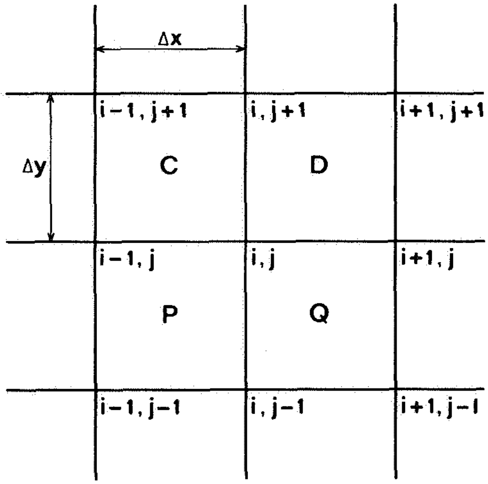


Fig. 2 Grid configuration for two-dimensional horizontal flow.

requires that q_e is given for nodes in which groundwater is extracted and that q_w and q_o are replaced by linear(ized) relations in terms of the unknown $h_{i,j}^{n+\frac{1}{2}}$.

1.3. *Unsaturated flow system*

For a shallow water-table in a sandy aquifer the characteristic time of the flow system is in the order of days (De Laat, 1980). Using these, relatively large, time increments, transient unsaturated flow can be described by a succession of steady-state situations. To facilitate simulation techniques, saturation deficits are introduced (fig. 3), defined as the amounts of water required for complete saturation of the profile. As flow in the upper layers of the soil is largely governed by the water uptake of the roots, the hydraulic gradient in the root zone is taken equal to zero. Given the soil moisture characteristic and depth D_r of the root zone, the saturation deficit S_r may be computed for pressure p_{rs} at the interface root zone – subsoil. The root zone is thus considered as a reservoir, characterized by the relation $S_r(p_{rs})$.

Using Darcy's law, moisture- and pressure profiles may be computed for any steady vertical flux $\overline{q}$, given the soil moisture- and hydraulic conductivity characteristics of the subsoil. Integration of the saturation deficit of the subsoil S_s for a number of values of $\overline{q}$ yields relations between S_s and p_{rs}. The assumed steady flow situation during time increment Δt is fully determined by only two parameters, the saturation deficit of the root zone S_r and the steady flux $\overline{q}$ in the subsoil. The use of saturation deficit relations reduces the solution of the steady-state flow situation for given boundary conditions $q_s^{n+\frac{1}{2}}$ and $q_w^{n+\frac{1}{2}}$ to a problem of two relations with two unknowns. The solution is known as upper boundary solution, since the assumed steady flow situation corresponds

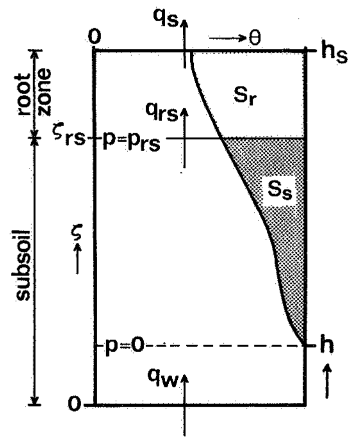


Fig. 3 Schematic presentation of the unsaturated flow system.

p	matric pressure, relative to atmospheric pressure	mbar
p_{rs}	matric pressure at interface root zone – subsoil	mbar
S_r	saturation deficit of root zone	cm
S_s	saturation deficit of subsoil	cm
q_{rs}	flux across interface root zone – subsoil	$cm \cdot d^{-1}$
θ	volumetric moisture content	—

to the flux across the upper boundary of the subsoil. Special procedures are developed to treat periods with alternatively rainfall- and evapotranspiration excess, taking into account hysteresis. The flux $q_s^{n+\frac{1}{2}}$ is the maximum possible flux across the soil surface. If the root zone dessicates to wilting point (p_{rs} = –16000 mbar), the calculation procedure yields furthermore the actual flux across the soil surface.

If the flow rate at the lower boundary of the subsoil is large and in downward direction, the upper boundary solution is unsuitable for computing the water-table depth. For a downward lower boundary flux condition the position of the phreatic level is therefore simulated by a pseudo steady-state approach corresponding to the (negative) flux q_w across the lower boundary. This approach is known as the lower boundary solution.

If the upper boundary solution is used to compute h for different q_w values an approximate linear relation is found. This allows the flux $(q_w)_{i,j}^{n+\frac{1}{2}}$ in equation (3) to be replaced by

$$(q_w)_{i,j}^{n+\frac{1}{2}} = a_{i,j}\, h_{i,j}^{n+\frac{1}{2}} + b_{i,j} \tag{4}$$

where a and b are constants to be determined for each time step. For the lower boundary solution an implicit non-linear expression for q_w may be derived which is also time-variant. The linear equation (4) and non-linear relation intersect for $q_w = q_w^*$. Hence, for $q_w < q_w^*$ the flux $(q_w)_{i,j}^{n+\frac{1}{2}}$ in equation (3) should be replaced by a non-linear relation, but to maintain linearity the tangent to the non-linear relation is used. If the tangent is written as equation 4 the coefficients a and b may vary during the iterative solution of equation (3).

1.4. *Surface water system*

Large open water courses (rivers, canals) are schematized to follow the nodes. The discharge of groundwater into open water courses depends on the drainage resistance, the open water level and the water-table elevation in the surrounding aquifer. For a negligibly small drainage resistance the open water course is said to belong to the primary drainage system. In these nodes the water-table elevation is set equal to the prescribed open water level. Other open water courses schematized in nearby nodes belong to the secondary drainage system. The drainage resistance is derived from geohydrological data, the river morphology and the presence of a silt layer at the river bed. Flow into or out of the secondary drainage system is proportional to the difference in the prescribed open water level h_o and the water-table elevation h in the surrounding aquifer.

Only part of the total groundwater discharge into the surface water system is drained directly by the large open water courses which are included in the model. The remaining part is drained by small rivers, streams, ditches, etc. This detailed surface water system is termed the tertiary drainage system. The grid configuration is too coarse to describe the tertiary system. Moreover, data on open water levels and drainage resistance are usually not available. Therefore, groundwater discharge into the tertiary drainage system is not described in detail, but with empirical relations between groundwater discharge and water-table depth. In nodes for which h has to be calculated the relation between groundwater and surface water is time-variant and non-linear. However, for different ranges of the water-table depth $(q_o)_{i,j}^{n+\frac{1}{2}}$ in equation (3) may be replaced by

$$(q_o)_{i,j}^{n+\frac{1}{2}} = (a^k)_{i,j}^{n+\frac{1}{2}} \{h_{i,j}^{n+\frac{1}{2}} - (h_o)_{i,j}^{n+\frac{1}{2}}\} + (b^k)_{i,j}^{n+\frac{1}{2}} \qquad (5)$$

where a^k and b^k represent parameters of range k for which $h_{i,j}^k \geqslant h_{i,j} > h_{i,j}^{k+1}$. If in node i, j the secondary drainage system is schematized, the parameters a and b depend on the drainage resistance of the open water course and the relation for the tertiary system. The open water level h_o is prescribed for each time increment. For other nodes h_o in equation (5) equals zero and a and b represent parameters of the empirical relation for the tertiary drainage system.

1.5. *Soil-plant-atmosphere system*

The upper boundary condition at soil surface for the unsaturated flow model may be written as

$$q_s^{n+\frac{1}{2}} = E_{re}^{n+\frac{1}{2}} - P^{n+\frac{1}{2}} \qquad (6)$$

where $E_{re}^{n+\frac{1}{2}}$ and $P^{n+\frac{1}{2}}$ are the real evapotranspiration rate, respectively precipitation rate during the considered time increment in $cm \cdot d^{-1}$. Real evapotranspiration is calculated with the following formula (Monteith, 1965; Rijtema, 1965)

$$E_{re} = \frac{s + \gamma}{s + \gamma(1 + r_s/r_a)} E_{wet} \qquad (7)$$

where s ($bar \cdot K^{-1}$) is the slope of the temperature-saturated vapour pressure curve, γ ($bar \cdot K^{-1}$) is the psychrometric constant, r_s ($s \cdot m^{-1}$) is the diffusion resistance of both crop and soil, r_a ($s \cdot m^{-1}$) is the diffusion resistance of water vapour in the air and E_{wet} ($cm \cdot d^{-1}$) is the evaporation flux of a wet cropped surface. The calculation of E_{wet} is based on the formula of Penman. It requires data on net radiation or relative sunshine duration, wind velocity, relative humidity and temperature. Values for the resistance r_a in relation to crop height and wind velocity are tabulated by Feddes (1971). Following Rijtema (1965) the diffusion resistance r_s is expressed as

$$r_s = r_c + S_c(r_\ell + r_p) \qquad (8)$$

where r_c ($s \cdot m^{-1}$) is the diffusion resistance depending on the fraction of soil covered, r_ℓ ($s \cdot m^{-1}$) is the resistance depending on light intensity, r_p ($s \cdot m^{-1}$) is the resistance depending on soil moisture conditions and flow in the plant while S_c is the fraction of soil covered by the crop. For a crop with ample water supply $r_p = 0$ and it follows for the potential evapotranspiration

$$E_{pot} = \frac{s + \gamma}{s + \gamma(1 + (r_c + S_c r_\ell)/r_a)} E_{wet} \qquad (9)$$

The expression proposed by Rijtema (1965) for the resistance r_p of the soil plant system and values for r_c and r_ℓ as functions of S_c and mean short wave radiation respectively can be found from Feddes (1971) and Van Bakel (1979). As the value of r_p depends on the pressure p_{rs} in the root zone, an iterative calculation of the models for evapotranspiration and unsaturated flow is necessary to solve $E_{re}^{n+\frac{1}{2}}$.

1.6. *Linking*

The calculation procedure for each time increment may be summarized as follows:

- Use the model for unsaturated flow to calculate for each node the coefficients of the (partly non-linear) relation between q_w and h.
- Solve the set of equations generated with equation (3) where q_w and q_o are replaced

by the equations (4) and (5) respectively. Use the latter equations and the computed water-table elevation to determine in each node the fluxes q_w and q_o.

– Use the flux q_w to find with an iterative computation from the models for evapotranspiration and unsaturated flow the actual evapotranspiration and the steady-state unsaturated flow situation.

The computer program GELGAM has a frame structure which is responsible for the linking procedure, the control of the water balances, data storage and retrieval, and the preparation of external boundary conditions. It furthermore includes procedures for initialization, computation of saturation deficit curves, hysteresis phenomena and the output of data and results. A dump procedure provides the possibility to store the internal state of GELGAM at prescribed time intervals. At these intervals the simulation may later be restarted. Additional computer programs were developed to process time-variant meteorological and geohydrological data for use in GELGAM.

1.7. *Applicability*

It was already mentioned that the emphasis in the construction of GELGAM was directed towards the efficiency of the model. This limits its applicability. The quasi three-dimensional approach to saturated-unsaturated flow restricts application to relatively flat areas. As overland flow is neglected, the model is not suitable for soils with a low infiltration capacity and for periods with high rainfall intensities. The pseudo steady-state solution for flow in the unsaturated zone only applies for rigid soils above a shallow water-table, while the large time increments of one day or more and the absence of overland flow and channel flow components do not allow a detailed simulation of surface water discharge. Moreover, empirical crop-dependent relations for the calculation of evapotranspiration are only available for certain crops which limits the choice in the types of land use. GELGAM is, therefore, particularly suited for relatively flat and sandy areas with high water-tables and a moderate climate. It predicts effects of groundwater extraction on surface water runoff, water-table elevation, evapotranspiration and crop production. Similarly consequences of artificial infiltration, crop irrigation and changes in open water level or land use can be predicted.

The sub-systems of GELGAM for the simulation of unsaturated flow and evapotranspiration are also applied separately for a variety of purposes. The computer program for this subset was adapted in order to allow as a lower boundary condition a prescribed water-table depth, a prescribed flux or a relation between these two. The latter boundary condition and actual meteorological data were used for an extensive sensitivity analysis, discussed in the next section. The unsaturated flow sub-system is furthermore used to predict yield depressions as a function of the drawdown of the water table, using statistically derived meteorological data (De Laat, 1979; Bouma et al., 1980).

2. SENSITIVITY ANALYSIS

For the verification of GELGAM a study area was selected around the pumping site "'t Klooster" near Hengelo (Gld) in the east of The Netherlands. The area is 6 × 6 km^2 and described by means of a square grid with a mesh width of 500 m. The pumping station is situated exactly in the middle. Most of the area is farmland, and grass is the principal crop grown. The mean annual rainfall and evapotranspiration are about 75 cm and 45 cm respectively. The region is geohydrologically characterized by a thick coarse sandy aquifer, overlying a more or less impermeable layer of fine silty sand at a depth of about 35 m, and covered on top by a few metres of aeolian loamy sand. The surface elevation shows a difference between the highest and lowest grid point of only 7 m. Almost six years were simulated (1971-1976) using time increments of ten days.

The simulation results described by De Laat (1980) show a close agreement with observed water-table elevations. As an example the simulated levels for a node 1000 m north of the pumping station and the observed values in a nearby well are plotted in figure 4.

A comprehensive sensitivity analysis was carried out in the study area. The analysis comprises three different parts. In one part the combined saturated-unsaturated flow system is used to investigate the effect of a variation in the values of several input parameters. In another part a similar analysis was carried out but only with the sub-systems for evapotranspiration and unsaturated flow. The third part was carried out in a less conventional way by Bouma et al, (1980) and will not be discussed here. In their analysis the combined model is used to study the effect of the different ways of collecting soil physical data on the simulation results. The investigations are important as the cost of simulating regional, saturated-unsaturated flow problems largely depends on the degree of detail to which soil physical data need to be measured.

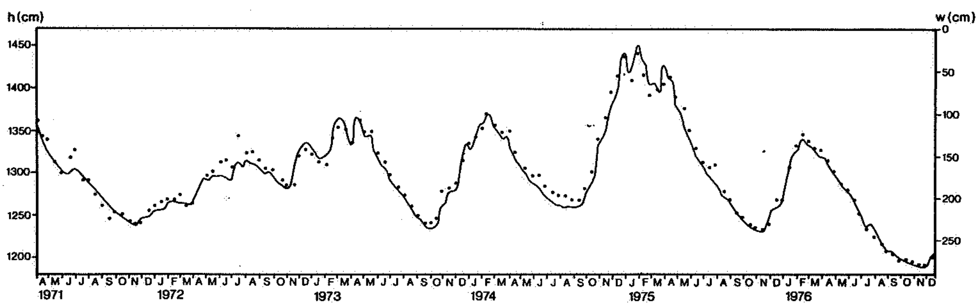


Fig. 4 Computed (——) and observed (•) water-table elevations for the study area "'t Klooster".

2.1. *Combined system*

The combined model was used to study the effect of a variation in the values of seven parameters on the simulation results. The sensitivity analysis is restricted to results obtained for a period of one year (37 time increments of 10 days each) starting at the beginning of April 1973. First a run of the model was made with the parameters set equal to their original values. This run was then repeated with nothing changed except the value of the parameter under consideration. The effect of parameter variation on the simulated water-table elevation and the calculated real evapotranspiration was investigated. A first impression of the influence of the various parameters may be obtained by comparing average values. To reduce the effect of the prescribed phreatic levels at the boundary, simulated water-table elevations and real evapotranspiration values were averaged over the interior of the model area only. The interior comprises 49 nodes located in the centre at a distance of more than 1000 m from the model boundary. Results are summarized in table 1 and elucidated below.

Neglecting hysteresis results in a delayed response of the water table to rainfall excess at the end of the summer while the effect on the calculated real evapotranspiration is small.

The vertical hydraulic conductivity of the unsaturated zone in the study area is described by three different relations which characterize the capillary properties as "poor", "medium" and "good". The relation characterized as "poor" applies to only eight nodes. For the sensitivy analysis these nodes were left unchanged while nodes initially characterized as "good" became "medium" and those intially "medium" became "poor". The calculated real evapotranspiration proves to be sensitive to a variation in the hydraulic conductivity relation. The underestimation of evapotranspiration results in higher water-table elevations.

The originally used linear relation for the tertiary drainage system with $q_o = 0.2$ $cm \cdot d^{-1}$ for the water table at soil surface and $q_o = 0$ for a depth $w = 150$ cm was changed to $q_o = 0.3$ $cm \cdot d^{-1}$ for $w = 0$ and $q_o = 0$ for $w = 200$ cm. The change means an improvement of the drainage situation. Because the relations primarily affect the shallower water-tables, the effect of the change on the deeper levels is almost negligible. Calculated real evapotranspiration values are lower due to a drawdown of the water table.

A large change in the transmissivity values has little effect on the water-table elevations and calculated evapotranspiration rates.

The phreatic level at the boundary primarily affects the lower water-table elevations. Due to the large water-table depth (the average depth for 1973 in the interior is 190 cm) the calculated real evapotranspiration is not very sensitive to a change in the prescribed levels at the boundary.

The storage coefficient μ_q defined as

$$\mu_q = q_w \cdot \Delta t / \Delta h \qquad (10)$$

Table 1 Summary of sensitivity analysis results (combined system).

Parameter	Change	Effect of changing parameter value on	
		water-table elevation	real evapotranspiration
Hysteresis	No hysteresis	At the beginning of the second half year 12 cm lower, thereafter 2 cm higher.	Overestimated by 0.3 cm, but locally more than 1 cm.
Hydraulic conductivity	"good" → "medium" "medium" → "poor"	In the first half year 2 cm higher. In the second half year, at first more than 10 cm higher, later decreasing to no change.	Underestimated by 1.8 cm, but locally more than 5 cm.
Groundwater discharge relation $q_o(h)$	Drainage system improved	Varying from 20 cm lower for the highest levels to 2 cm lower for the lowest levels.	Underestimated by 0.6 cm, but locally more than 4 cm.
Transmissivity T	Increased by 25%	High levels 2 cm lower. Local effect (except for the well site) ranges from +3 to −8 cm.	Underestimated by 0.1 cm.
Prescribed phreatic levels at the boundary	Raised by 5 cm	High levels 2 cm and low levels 4 cm higher.	Overestimated by 0.1. cm, but locally almost 1 cm.
Storage coefficient μ_q	Increased by 0.03	Up to 10 cm higher in summer and 10 cm lower in winter.	Underestimated by 0.4 cm (at some locations by 1 cm but also overestimated by 1 cm).
Depth of root zone D_r	Decreased by 10 cm	In the second half year (when the water table is rising) 10 to 15 cm higher.	Underestimated by almost 2.8 cm. (The local effect ranges from 2 to 5 cm.)

is determined by the slope of the relation between q_w and h (section 1.3). For $q_w < q_w^*$ the storage coefficient μ_q is a function of q_w and depending on the soil physical parameters of the lower part of the unsaturated zone. These parameters were changed so that the storage coefficient (fraction) is effectively increased by 0.03. The change has two effects acting in opposite directions on the real evapotranspiration. On the one hand capillary rise benefits from the higher phreatic levels in the growing season, while on the other hand less moisture is available in the subsoil due to a larger downward flux across the lower boundary of the unsaturated zone.

Decreasing the depth of the root zone results in an underestimation of E_{re} as there is less water available initially and less water is retained in the root zone during periods with rainfall excess, while capillary rise is hampered due to a larger depth to the water table.

The results of the sensitivity analysis with the combined model may be summarized as follows. The fluctuation of the water-table elevation depends largely on the relation between μ_q and q_w which is derived from soil physical data applying to the lower part of the unsaturated zone. The average water-table height in summer is predominantly governed by the prescribed phreatic levels at the boundary, while in winter the empirical relation between q_o and h appears to prevail.

The calculated real evapotranspiration is sensitive to the water-table elevation at the beginning of the growing season, the hydraulic conductivity relation and the depth of the root zone D_r. The sensitivity to the parameter D_r is most pronounced as it directly affects the amount of water available for the crop.

2.2. *Vertical flow system*

As simulation with the combined model is relatively expensive, part of the model for unsaturated flow and evapotranspiration was used separately to study the effect of a variation in the values of input parameters on the simulated evapotranspiration rates and water-table depths. The use of the disconnected model requires the lower boundary condition to be specified. For this purpose the results described in the previous section were used to derive a relation between the water-table depth w and the flux q_w across the lower boundary of the unsaturated zone for a node 1000 m north of the pumping station. By using the derived (quasi-linear) relation between q_w and w, simulation of evapotranspiration and unsaturated flow for this node yields values that compare favourable with the results obtained with the combined system. The disconnected model was then used for this single node to carry out a similar sensitivity analysis as with the combined system, except that now the entire period (April 1971 – December 1976) is simulated.

A summary of the sensitivity analysis as described by Van Bakel (1979) is given in table 2 and discussed below.

Values for ΣE_{pot} and ΣE_{re} (cm) represent averages for the total potential and real evapotranspiration respectively calculated for each hydrological year (note that for the last year only 270 days are considered). The water-table depth refers to the average depth over the entire simulation period.

Table 2 shows that the effect of a change in the standard meteorological data, which are often used for the calculation of evapo(transpi)ration with the Penman formula, is most pronounced for relative humidity. The effect on real evapotranspiration is less than on potential evapotranspiration. Particularly during dry summers, when the demand for evapotranspiration as expressed by its potential value cannot be met, real evapotranspiration is largely governed by the availibility of moisture.

For the original situation a grass crop is considered with a constant height of 10 cm during the growing season. A change in crop height has a considerable effect on the calculated potential evapotranspiration. When compared to E_o as defined by Penman, it was found that for a height of 10 cm the crop factor f in $E_{pot} = fE_o$ equals 0.8 in very

Table 2 Summary of sensitivity analysis results (vertical flow system)

Parameter	Change	ΣE_{pot} (cm)	ΣE_{re} (cm)	Mean water-table depth (cm)
	Original situation	57.7	41.2	178
Windspeed	Increased by 5%	58.5	41.5	178
Relative sunshine duration	Increased by 5%	58.9	41.7	179
Relative humidity	Increased by 5%	53.4	39.2	170
Temperature	Increased by 5%	59.2	41.7	179
Crop height	Increased by 5 cm	61.2	41.9	180
Moisture characteristic root zone	Improved		42.2	179
Capillary properties subsoil	Improved		41.3	176
Hysteresis	No hysteresis		41.6	181
Depth of root zone D_r	Increased by 10 cm		43.5	185
Storage coefficient μ_q	Increased by 0.035		40.7	164

wet years and approaches 1.0 in extremely dry years. For a crop height of 5 cm the relation $E_{pot} = 0.8\ E_o$ appears to be approximately valid.

In the second half of table 2 the sensitivity to a variation of soil physical parameters is presented. A change in the value of these parameters does not affect the potential evapotranspiration E_{pot}.

The capillary properties of the subsoil include the soil moisture and hydraulic conductivity relations for the upper boundary solution. The hydraulic conductivity and moisture content values in the relations for both the subsoil and the root zone were increased by an amount approximately equal to their standard deviation. The resulting shift in the soil moisture and hydraulic conductivity relations means an improvement of the capillary properties. The changed relations are approximately equidistant to the original ones. This could explain why the changes have little effect on the simulation results. It appears furthermore that the influence of hysteresis is small.

Finally, it is found that changing the storage coefficient and increasing the depth of the root zone from 30 to 40 cm have similar effects as found with the combined model.

To study the influence of the water-table depth on the calculated real evapotranspiration 17 additional runs were made using a large variety of relations between q_w and w. The calculated evapotranspiration ΣE_{re} and corresponding average water-table depth for each run are plotted in figure 5. It shows that ΣE_{re} depends strongly on the water-table depth, while the effect of the shape of the relation between q_w and w on the calculated real evapotranspiration is small.

From the sensitivity analysis it may be concluded that the calculated real evapotranspiration largely depends on the water-table depth and the parameters characterizing the reservoir properties of the unsaturated zone. The calculated potential evapotranspiration is sensitive to most parameters, but especially to relative humidity and crop height. The

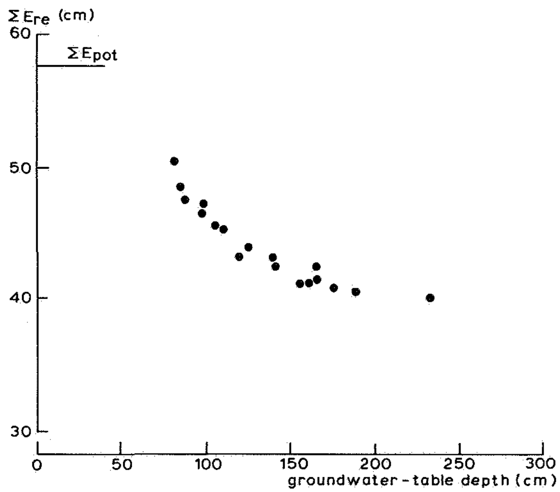


Fig. 5 Simulated average total real evapotranspiration ΣE_{re} and corresponding average water-table depth resulting from a variation in the relation for the lower boundary condition of the model for unsaturated flow.

calculated real evapotranspiration during dry summers depends on the availibility of moisture rather than on the evaporative demand.

When evaluating the sensitivity analyses, it should be realized that the results apply for this particular situation. For other periods or regions for which conditions differ significantly from those considered here, the foregoing conclusions may not be valid.

3. APPLICATION AND USE

3.1. *Study area "de Achterhoek"*

One of the larger regions to which GELGAM was applied is known as "de Achterhoek". The region is situated in the east of The Netherlands, north of the river Rhine and east of the river IJssel, and it includes the small study area "'t Klooster" (fig. 6). The rivers Oude IJssel, IJssel and Berkel constitute respectively the south, west and north boundaries of the model area. The east boundary coincides approximately with the line on which deposits constituting the impermeable base of the aquifer are cropping out at the soil surface.

The area can be framed in a rectangle measuring 32 km from west to east and 33 km from north to south. The rectangle is divided into square elements of 1 × 1 km^2 each. The effective model region being 701 km^2 covers only part of the rectangular area.

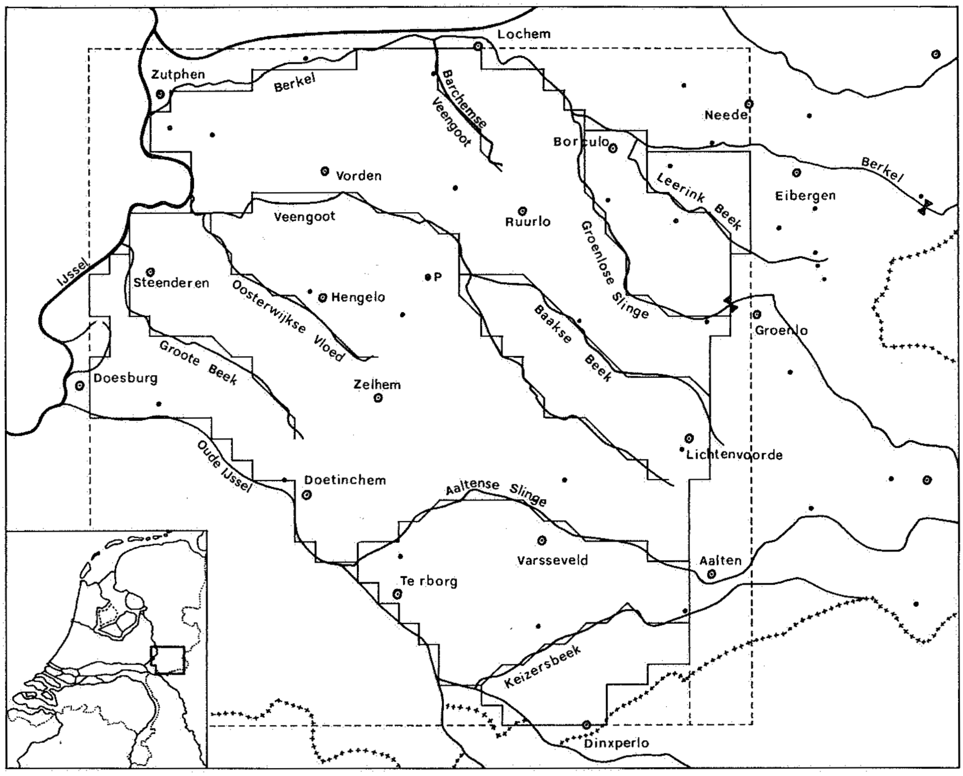


Fig. 6 Location of the study area "de Achterhoek".

For the greater part the area is relatively flat though at some locations hills formed during the Saalien glacial period are found (fig. 7). The aquifer consists of coarse sands. The depth of the aquifer base (tertiary deposits) varies strongly from almost zero at the east boundary down to locally 75 m below the soil surface. Figure 8 shows the distribution of the transmissivity of the aquifer. The figures north-west of the dotted line, where a two-aquifer system is found, refer to the lower aquifer. For the greater part the aquifer is covered on top by a layer of aeolian sands. Most of the land in the area is used for farming (fig. 9).

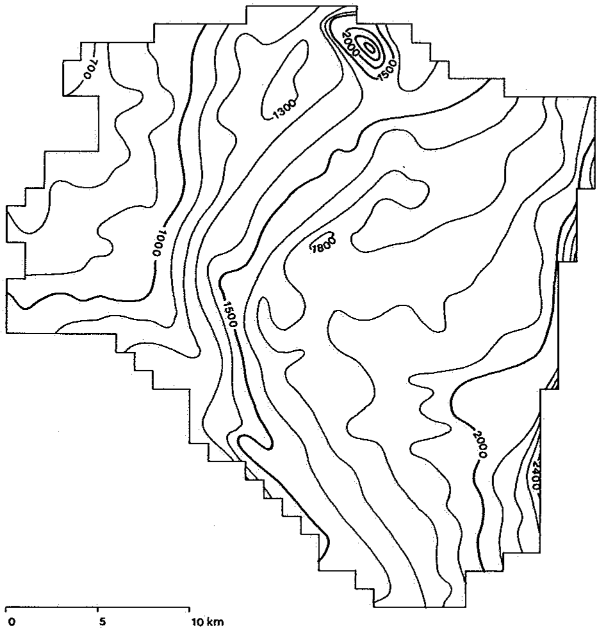


Fig. 7 Soil surface elevation (cm) in the study area "de Achterhoek".

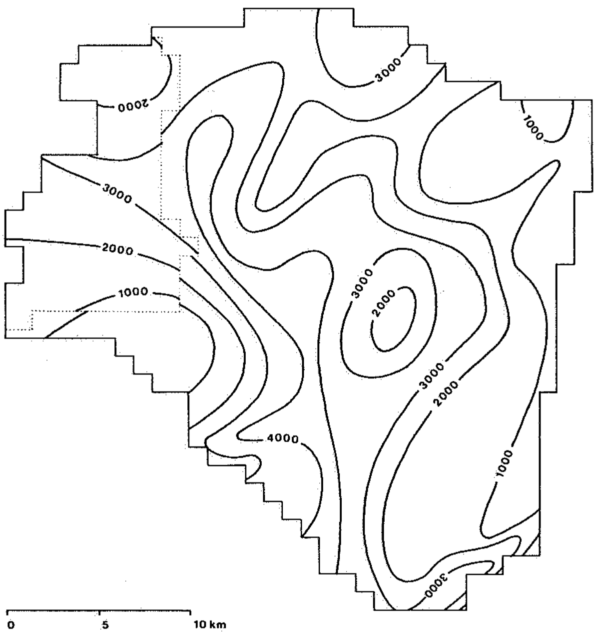


Fig. 8 Transmissivity of the aquifer ($m^2 \cdot d^{-1}$) in the study area "de Achterhoek".

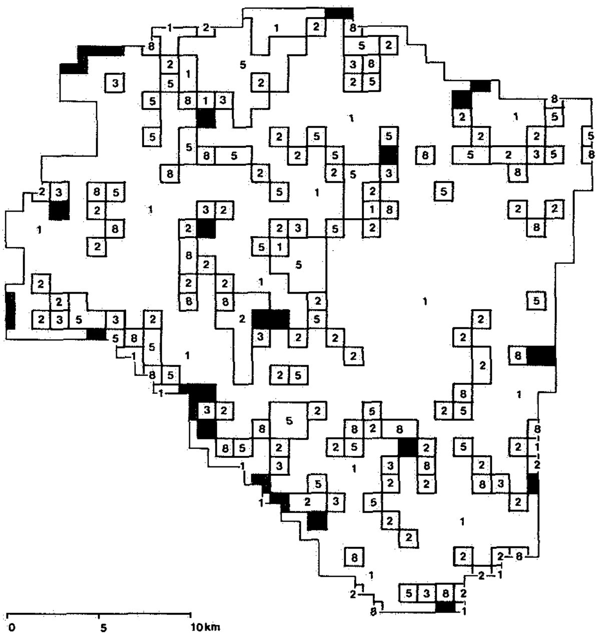


Fig. 9 Land use in the study area "de Achterhoek".
Key: 1 grass
2 cereals
3 potatoes
5 coniferous forest
8 maize
black urban area

3.2. *Simulations*

All simulations cover a three year period and refer to the climatological conditions in the years 1971-1973. Time is discretized into steps of 10 days each. Apart from the situation without groundwater extraction which serves as a reference (simulation 1), the following simulations were carried out to study the consequences of groundwater extraction.

Simulation 2 – Actual groundwater extractions (domestic and industrial) during the years 1971, 1972 and 1973. ("Actual extractions")

Simulation 3 – Domestic groundwater extractions expected in the year 1990 and industrial extractions being the same as for simulation 2. ("Extractions 1990")

Simulation 4 – Same as simulation 3 but in addition groundwater is extracted for sprinkler irrigation by farmers to decrease the precipitation deficit during dry periods. Sprinkler irrigation is applied on farmland only with the following strategy: Half of the difference between potential and real evapotranspiration during a time step is extracted from the aquifer during the next time step and added to the natural precipitation.

Next to these simulations a special application is presented to study the areal distribution of the sensitivity to groundwater extraction. Results of this study known as the "Wandering Well" are presented separately at the end of this chapter.

3.3. *Results*

In this study the year 1971 will be emphasized when presenting the results. More extensive information is given by Awater and De Laat (1980).

To illustrate the character of the flow pattern in the area, contours of the water-table elevation at the end of the growing season of 1971 for simulation 2 are shown in figure *10*. The growing season extends from the middle of April until the middle of September. If crop production is not restricted by water supply, the total actual evapotranspiration of the growing season ΣE_{re} equals the total potential evapotranspiration ΣE_{pot}. The production capacity of the crop is often expressed in terms of the relative evapotranspiration, defined as $(\Sigma E_{re}/\Sigma E_{pot}) \cdot 100\%$. The areal distribution of the relative evapotranspiration for the growing season of 1971 for simulation 1 is found in figure *11*.

For each time step of simulation 2 the terms of the water balance of the area are presented in figure *12*. Table *3* presents the terms of the water balance for each of the simulations for both the hydrological year 1971 (710401-720331) and the growing season of 1971 (710421-710917). From table 3 the contribution of terms of the water balance to groundwater extraction for the hydrological year 1971 can be derived as shown in figure *13* where also the contribution of terms of the water balance to groundwater extraction for the hydrological years 1972 and 1973 is presented.

A comparison of simulations in terms of the water-table elevation at the end of the growing season of 1971 is presented in figure 14 as follows:

Simulations compared	Figure
1 and 2	14a
1 and 3	14b
3 and 4	14c

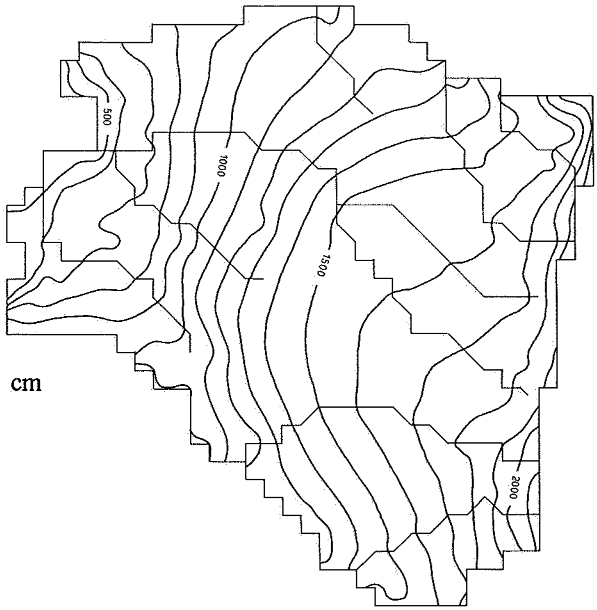


Fig. 10 Water-table elevation contour map at the end of the growing season of 1971 for simulation 2 ("de Achterhoek").

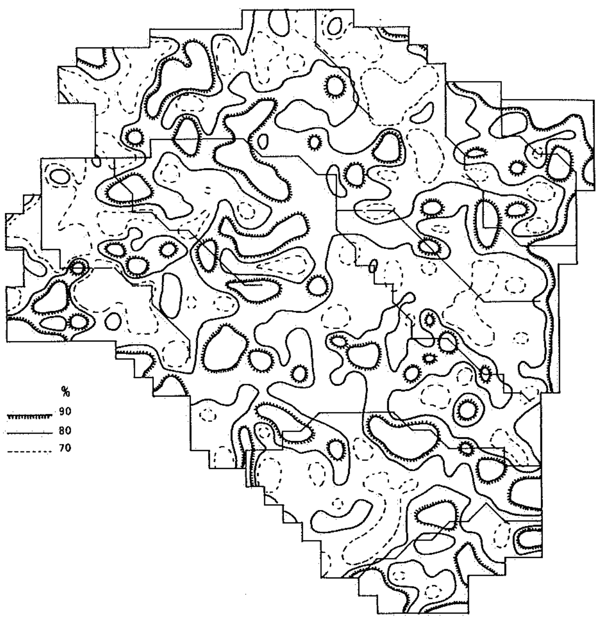


Fig. 11 Contour map of the relative evapotranspiration of the growing season of 1971 for simulation 1 ("de Achterhoek").

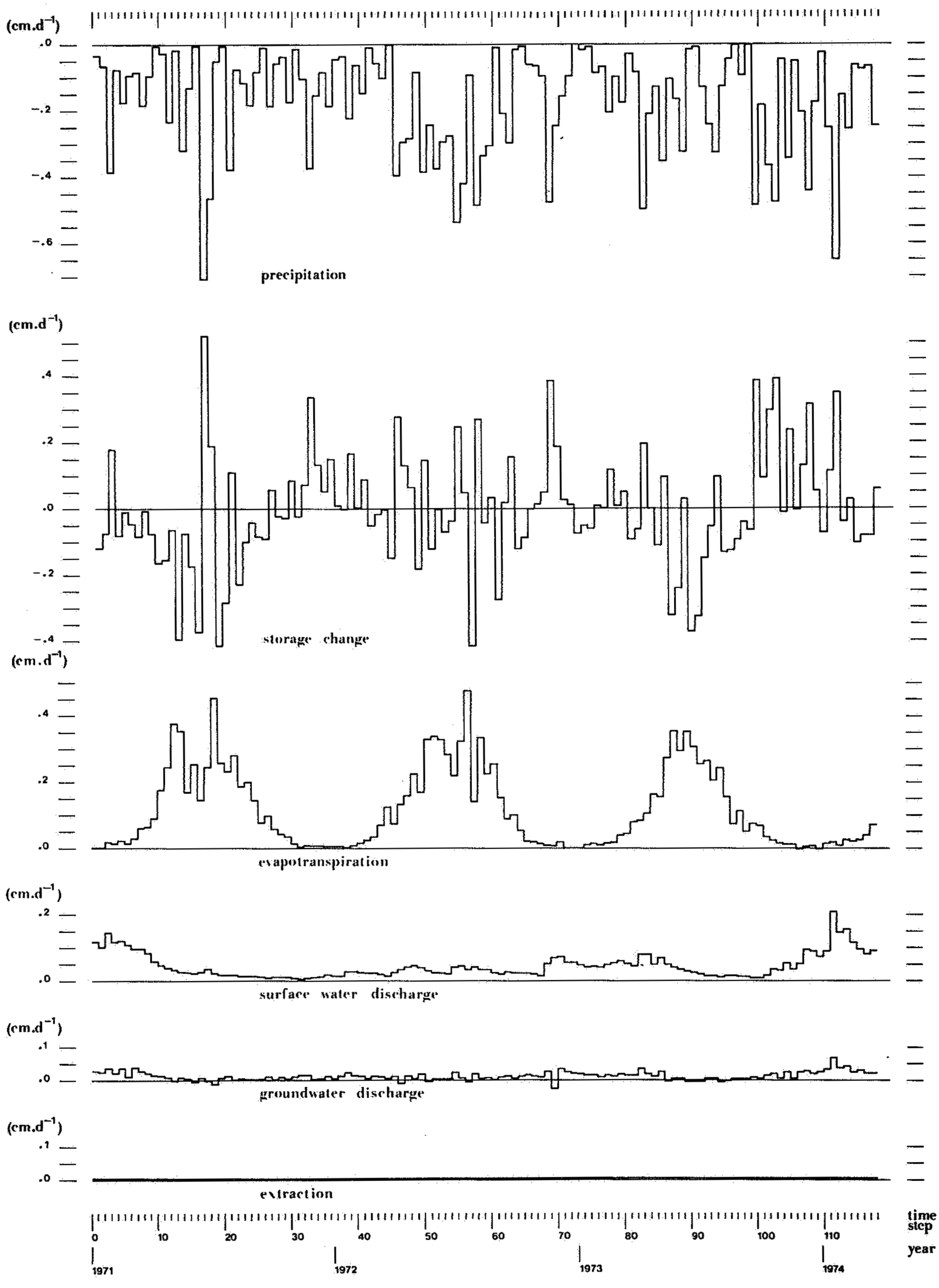


Fig. 12 The variation of terms of the water balance for simulation 2 during the considered three year period ("de Achterhoek").

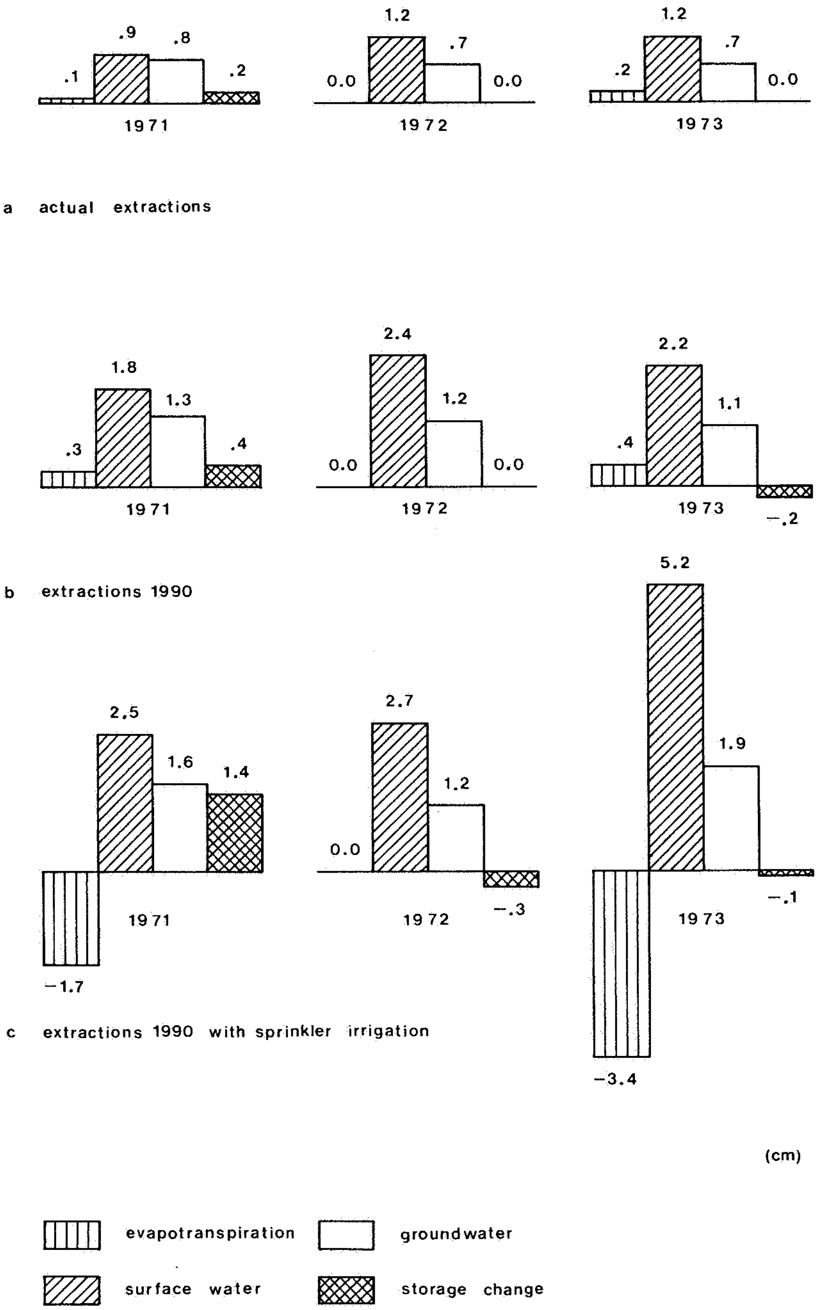


Fig. 13 Annual contribution (cm) of the different sources to groundwater extraction ("de Achterhoek").

Table 3 Water balances for 1971. Quantities are expressed in cm and positive when leaving the system.

hydrological year 1971 (370 days)	simulation			
	1	2	3	4
precipitation	–52.3	–52.3	–52.3	–52.3
sprinkler irrigation	.0	.0	.0	– 3.8
evapotranspiration	46.5	46.4	46.2	48.2
storage change	– 6.3	– 6.5	– 6.7	– 7.7
groundwater discharge	3.6	2.8	2.3	2.0
surface water discharge	8.6	7.7	6.8	6.1
extraction	.0	1.9	3.7	3.7
extraction on behalf of irrigation	.0	.0	.0	3.8
growing season 1971 (150 days)	simulation			
	1	2	3	4
precipitation	–27.7	–27.7	–27.7	–27.7
sprinkler irrigation	.0	.0	.0	– 3.4
evapotranspiration	37.4	37.3	37.1	39.1
storage change	–14.1	–14.2	–14.2	–15.3
groundwater discharge	.8	.5	.3	.0
surface water discharge	3.7	3.3	3.0	2.4
extraction	.0	.8	1.5	1.5
extraction on behalf of irrigation	.0	.0	.0	3.4

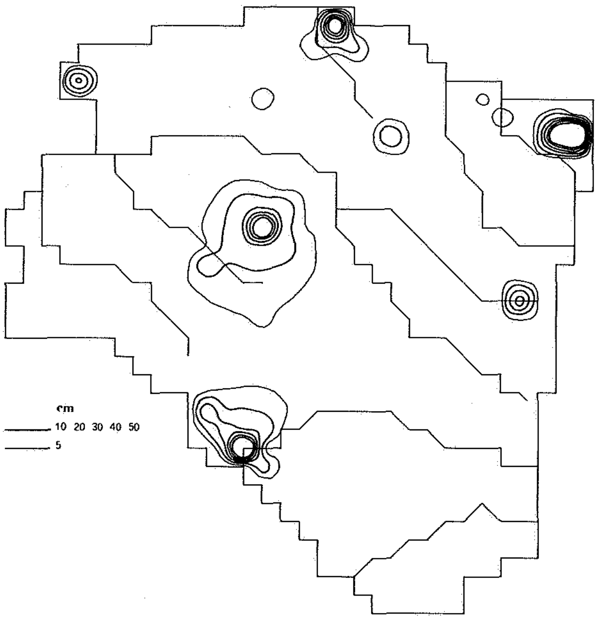


Fig. 14a Contour map of the difference in water-table elevation for the simulations 1 and 2 at the end of the growing season of 1971 ("de Achterhoek").

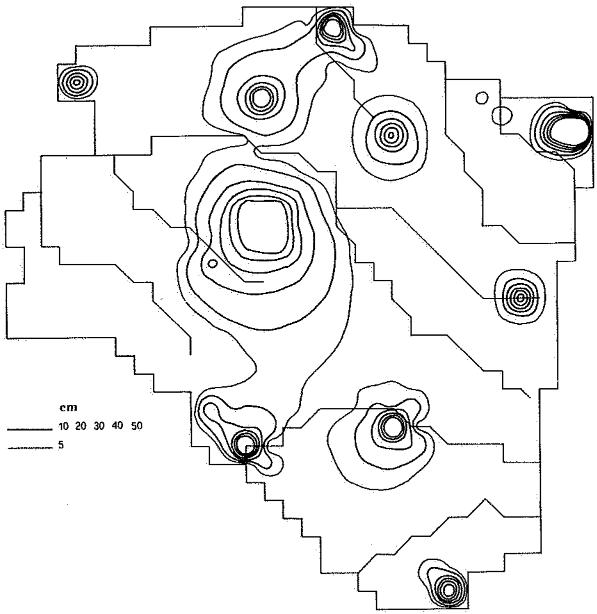


Fig. 14b Contour map of the difference in water-table elevation for the simulations 1 and 3 at the end of the growing season of 1971 ("de Achterhoek").

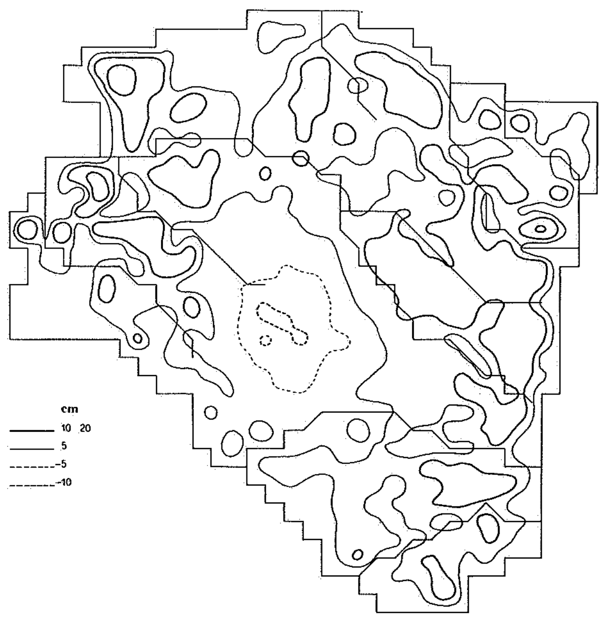


Fig. 14c Contour map of the difference in water-table elevation for the simulations 3 and 4 at the end of the growing season of 1971 ("de Achterhoek").

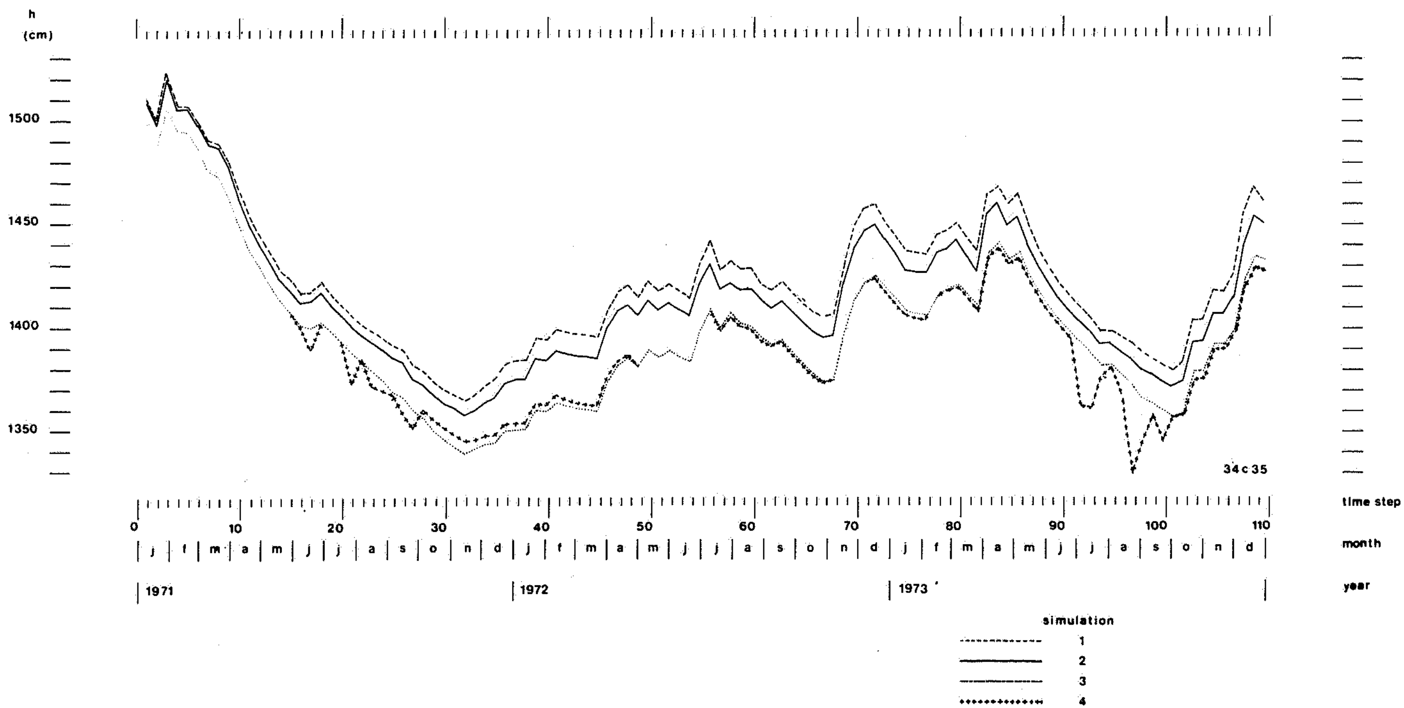


Fig. 15 Comparison of computed water-table elevations in location P (fig. 6) for the simulations 1, 2, 3 and 4 ("de Achterhoek").

To illustrate the transient behaviour of the water-table elevation at a certain location, the behaviour at location P as indicated in figure 6 is plotted for each of the simulations in figure 15.

A comparison of simulations in terms of the relative evapotranspiration for the growing season of 1971 is presented in figure 16 as stated below.

Simulations compared	Figure
1 and 2	16a
1 and 3	16b
3 and 4	16c

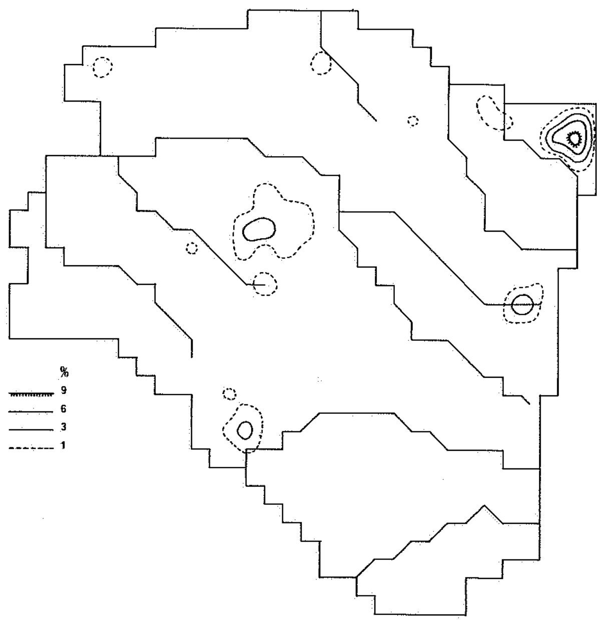


Fig. 16a Contour map of the difference in relative evapotranspiration for the simulations 1 and 2 for the growing season of 1971 ("de Achterhoek").

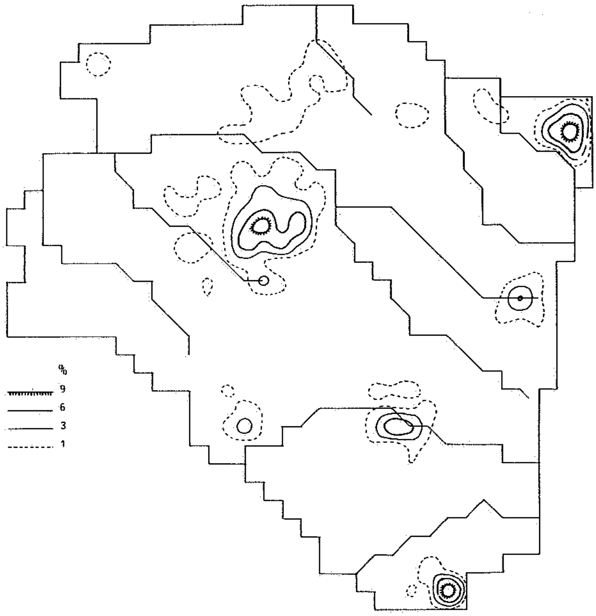


Fig. 16b Contour map of the difference in relative evapotranspiration for the simulations 1 and 3 for the growing season of 1971 ("de Achterhoek").

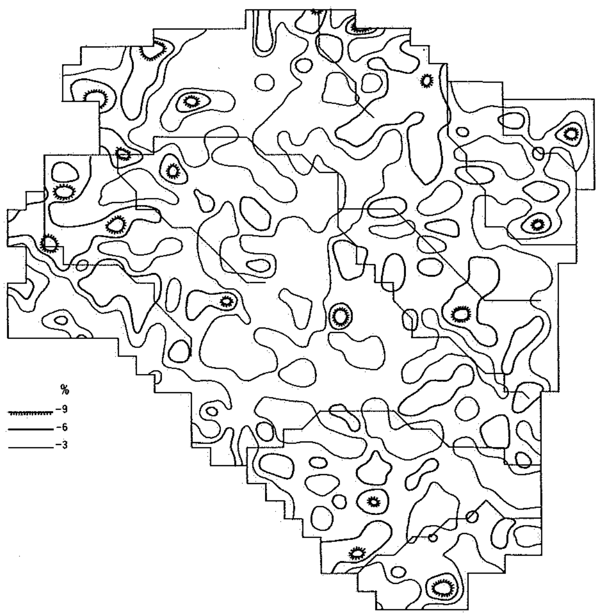


Fig. 16c Contour map of the difference in relative evapotranspiration for the simulations 3 and 4 for the growing season of 1971 ("de Achterhoek").

3.4. *Discussion*

Evaluation of results involves the comparison of various simulations. As prescribed hydraulic heads at the boundaries of the study area and prescribed surface water levels for each simulation are assumed to be equal; this comparison is only allowed when the interventions in the hydrological system do not affect these levels. Therefore the comparison of simulations is invalid for extractions located along the eastern boundary of the study area. Along the north, west and south boundaries hydraulic heads are expected not to change as they equal the open water levels of the rivers Berkel, IJssel and Oude IJssel. The assumption that water levels of brooks inside the study area do not change, becomes more questionable if groundwater extraction increases. In particular this assumption is violated in simulation 4 (added sprinkler irrigation). However, a correct interpretation of the results is obtained when surface water levels can be maintained by an intake of water from the rivers Berkel, IJssel and Oude IJssel, this assuming an ample supply of surface water.

Comparison of simulations 1 and 2 allows conclusions with regard to the consequences of the actual groundwater extractions. The drawdown of the water table (fig. 14a) is found to be rather constant in time (see also figure 15). From figure 13 it is seen that surface water and groundwater flow across the boundary are the main sources of the groundwater extracted. The actual groundwater extractions reduce the evapotranspiration during 1971 with 0.1 cm and during 1973 with 0.2 cm. No reduction is found for 1972. The areal distribution of the reduction in relative evapotranspiration for the growing season of 1971 as caused by the actual extractions is found in figure 16a.

Comparison of simulations 1 and 3 allows conclusions with regard to the consequences of groundwater extraction as expected for the year 1990. Though the amount of groundwater extracted roughly doubles for the situation "Extractions 1990" as compared to "Actual extractions", drawdowns caused by the extractions of 1990 (fig. 14b) appear to be more than twice as large. From figure 13 it is seen that the extracted groundwater is again mainly supplied by surface water and groundwater flow across the boundaries. The evapotranspiration is reduced during 1971 with 0.3 cm and during 1973 with 0.4 cm. Again no reduction is found for the relatively wet year 1972. For this area and for this simulation period a doubling of the strength of the extractions roughly causes a twice as high reduction in real evapotranspiration. The areal distribution of the reduction in evapotranspiration for the growing season of 1971 as caused by the extractions of 1990 is presented in figure 16b.

Comparison of simulations 3 and 4 allows conclusions with regard to the consequences of sprinkler irrigation when groundwater extractions as expected for the year 1990 are active. The drawdowns at the end of the growing season of 1971 caused by sprinkler irrigation (fig. 14c) are spread over the area. The same holds for the end of the growing season 1973 while for 1972 drawdowns are negligible, as practically no irrigation occurs (1972 and 1973 are not presented here). The sources of the additional amount of evapotranspiration as a result of sprinkler irrigation can be derived from figure 13 and are presented separately in figure 17 for both the hydrological year and the growing season of 1971 and 1973. In addition the amount of sprinkler irrigation is indicated. It is seen that the increase of evapotranspiration due to sprinkling originates from both storage decrease, surface water and groundwater flow across the boundary. The increase of evapotranspiration is completely achieved during the growing season, whereas especially in 1973 the recharge of the aquifer by surface water and groundwater flow across the boundary partly takes place after the growing season. With the adopted strategy during the year 1971 60% and during 1973 70% of the amount of groundwater extracted for

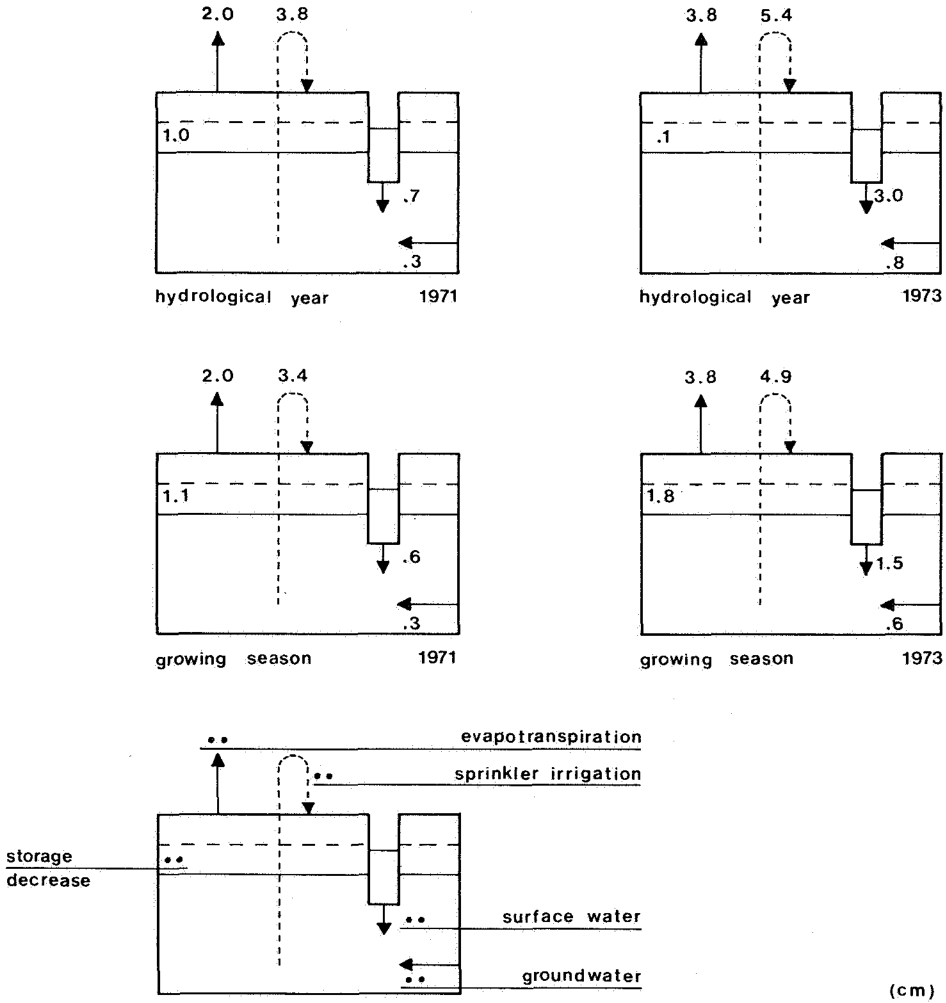


Fig. 17 The effect of sprinkler irrigation on terms of the water balance ("de Achterhoek").

sprinkling appears to benefit the real evapotranspiration. Contour plots of the difference in relative evapotranspiration caused by sprinkler irrigation (fig. 16c) show the areal distribution of the increase of the relative evapotranspiration. Striking are the terrace shaped areas with large effects, indicating that areas with an increased relative evapotranspiration are alternated with areas where no increase is found. Low increases are especially found in wooded areas (see figure 9) and in parts where values for the relative evapotranspiration are high already without sprinkler irrigation (a comparison is possible with figure 11 although this figure applies for simulation 1 where groundwater extractions are not included). In these areas indeed no or only little irrigation water has been added because of the adopted strategy for sprinkler irrigation.

3.5. *Wandering Well*

To indicate the sensitivity of a certain location to groundwater extraction one could extract a certain amount of groundwater at that location and determine with GELGAM the consequences of the extraction in the surroundings. The information for a great number of locations in an area can be used to produce a map indicating the distribution of the sensitivity to groundwater extraction within the area.

This idea has been practised in the area "de Achterhoek" (fig. 6). A well extracting 4.10^6 $m^3 \cdot year^{-1}$ is successively located at 134 different nodal points (fig. 18). Around

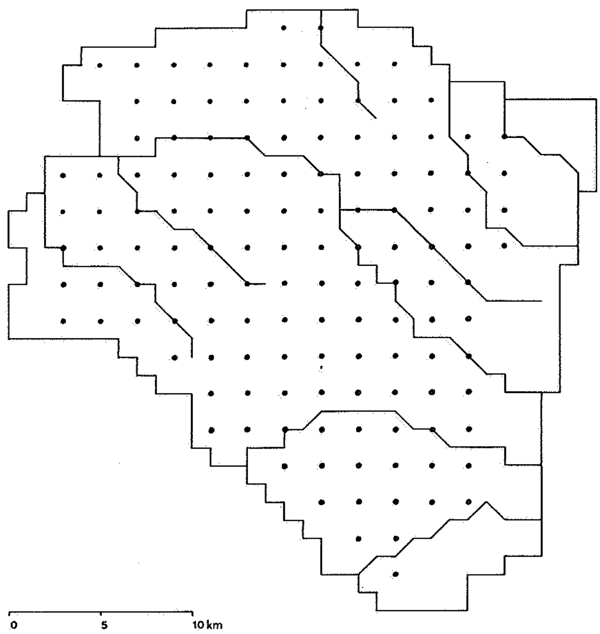


Fig. 18 Locations of the Wandering Well in the study area "de Achterhoek".

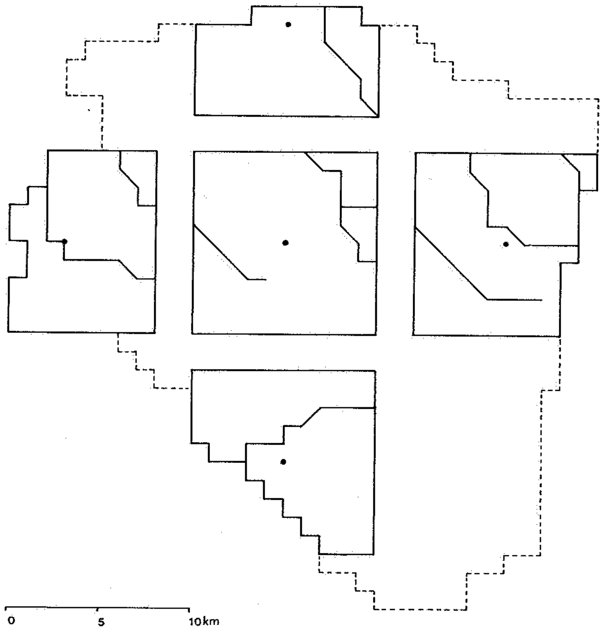


Fig. 19 Examples of the configuration of the model area for some of the locations for the Wandering Well in the study area "de Achterhoek".

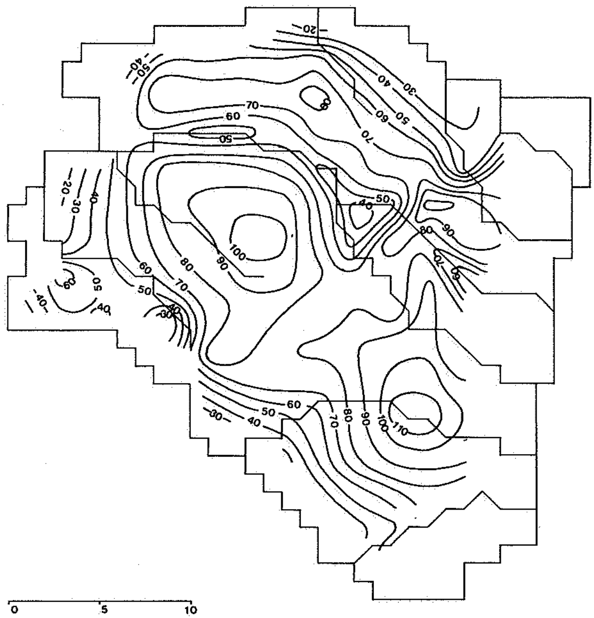


Fig. 20 Contour map of the sensitivity to groundwater extraction for the study area "de Achterhoek".

each location a square area of 10×10 km^2 is considered for simulation, an example of which for some locations is shown in figure 19. Both the situations with and without groundwater extraction are simulated for climatological conditions in the growing season of 1973 (730421-730917). When comparing the simulations, the reduction in relative evapotranspiration caused by the extraction in the surrounding of the well can be derived. The reductions for farmland are accumulated into one parameter R. Contours of the value of R are shown in figure 20. The value of R can be related to the reduction in agricultural crop production, where high values of R indicate a large reduction.

REFERENCES

AKKER, C. VAN DEN (1972) – A mathematical model to calculate consequences of groundwater extraction for a situation with two aquifers separated by a semi-permeable layer. Delft University of Technology, Department of Civil Engineering, pp. 59. (in Dutch)

AWATER, R.H.C.M. and P.J.M. DE LAAT (1980) – Groundwater flow and evapotranspiration; A simulation model. Part 2: Applications. Report Comm. Study Water Res. Man. Gelderland, Arnhem.

BAKEL, P.J.T. VAN (1979) – Evaporation and crop yield. Part 2: Evaporation in relation to soil and crop. Report Comm. Study Water Res. Man. Gelderland, Arnhem, pp. 49. (in Dutch)

BOUMA, J., P.J.M. DE LAAT, A.F. VAN HOLST and TH.J. VAN DE NES (1980) – Predicting the effects of changing water-table levels and associated soil moisture regimes for soil survey interpretations. Soil. Sci. Soc. Am. J. 44: 797–802.

FEDDES, R.A. (1971) – Water, heat and crop growth. Thesis Comm. Agric. Univ. Wageningen 71-12, pp. 184.

LAAT, P.J.M. DE (1979) – Calculations of the moisture supply capacity. In: Overzicht kaarten met betrekking tot een aantal aspecten van de waterhuishouding in Gelderland (Maps showing aspects of the water regime in the Province of Gelderland) (Ed. J. Bouma). Basis rapport Commissie Waterhuishouding Gelderland Arnhem. Also Report Soil Survey Inst. Wageningen, no. 1434. pp. 23-28. (in Dutch)

LAAT, P.J.M. DE (1980) – Model for unsaturated flow above a shallow water-table, applied to a regional sub-surface flow problem. Thesis Agric. Res. Rep. 895, Pudoc, Wageningen, pp. 126.

LAAT, P.J.M. DE and R.H.C.M. AWATER (1978) – Groundwater flow and evapotranspiration; A simulation model. Part 1: Theory. Report Comm. Study Water Res. Man. Gelderland, Arnhem, pp. 64.

MONTEITH, J.L. (1965) – Evaporation and environment. Proc. Symp. Soc. Exp. Biol. 19: 205-234.

RIJTEMA, P.E. (1965) – An analysis of actual evapotranspiration. Thesis Agric. Res. Rep. 659, Pudoc, Wageningen, pp. 107.

APPLICATION OF THE MODEL OVER-BETUWE; COMPLEXITY OF THE MODEL IN RELATION TO THE OBJECTIVE OF THE HYDROLOGICAL STUDY

K. KOVAR, H.L.M. ROLF

SUMMARY

This paper reviews the development and application of a simulation model for groundwater flow and evapotranspiration for the area of the Over-Betuwe. The emphasis is put on the relation between the objective of a hydrological study and the complexity of the model needed for the problem.

A fairly common hydrological problem in The Netherlands is the prediction of the hydrological effects of groundwater extraction. For the Over-Betuwe it is shown that this problem can be solved adequately by a model of much lower sophistication than the model Over-Betuwe.

1. INTRODUCTION

Within the framework of activities of the Commissie Bestudering Waterhuishouding Gelderland (CWG; Committee for the Study of Water Resources Management in Gelderland) a simulation model for groundwater flow and evapotranspiration was developed and applied for the area of the Over-Betuwe. The model area consists mostly of clayey soils. The groundwater flow is strongly affected by a drainage system of ditches. The most important task of the study, which has been carried out by the Rijksinstituut voor Drinkwatervoorziening (National Institute for Water Supply), was to investigate the possibility of simulation of groundwater flow in this kind of complex area. The following aspects were of particular importance:

- the unsaturated groundwater flow in clayey soils;
- the relations for flow between groundwater and surface water.

The model Over-Betuwe is a finite element quasi three-dimensional model. The elements are quadrangles and squares. The model is suitable for simultaneous simulation of the following time-dependent processes:

- groundwater flow in the saturated zone;
- soil water flow in the unsaturated zone;
- actual evapotranspiration.

The total simulation period is to be subdivided into a number of time-steps of equal length. For the study Over-Betuwe the simulation period involved two calender years (1974 and 1975), subdivided into 73 time-steps of 10 days each.

The computer code of model Over-Betuwe has been used as the prototype for the operational computer program of the CWG, GELGAM (Gelderland Groundwater Analysis Model).

This paper reviews only a small part of the total study. Thereby, the emphasis is put on the relation between the objective of a hydrological study and the complexity of the model needed for the solution of the problem.

2. HYDROLOGICAL CONDITIONS IN THE MODEL AREA

The location of the model area is given schematically in figure 1. In the section north of the river Nederrijn two hilly areas can be distinguished, of which the largest area is the Zuidelijke Veluwezoom. In the latter area maximum elevations are about N.A.P. +60 m (N.A.P. = reference level ≈ mean sea level). The river Nederrijn forms a rather abrupt boundary between the undulated northern part and the flat southern part of the model area, the latter area with elevations varying between N.A.P. +8 m and N.A.P. +10 m. The modelling activities discussed in this paper were primarily focused on the southern part of the model area, i.e. the area of the Over-Betuwe.

In figure 2 the cross-section A-B is given as indicated in figure 1. The geohydrological system consists of two aquifers. The base of the deep aquifer is supposed to be impermeable. Between the aquifers a semi-permeable layer is situated, of which the thickness varies strongly between 0 and 30 metres. In the area of the Over-Betuwe clayey soils are found overlying the shallow aquifer. The maximum thickness of these clayey soils is about 5 metres. At some places, within the clayey soils a clay layer of significantly low permeability can be distinguished, to be referred to as "shallow semi-permeable layer".

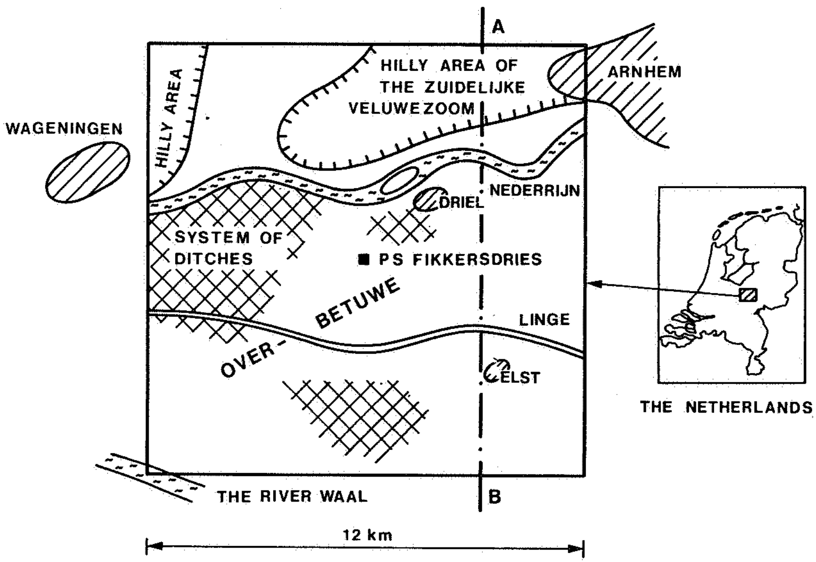


Fig. 1 Location of the model area.

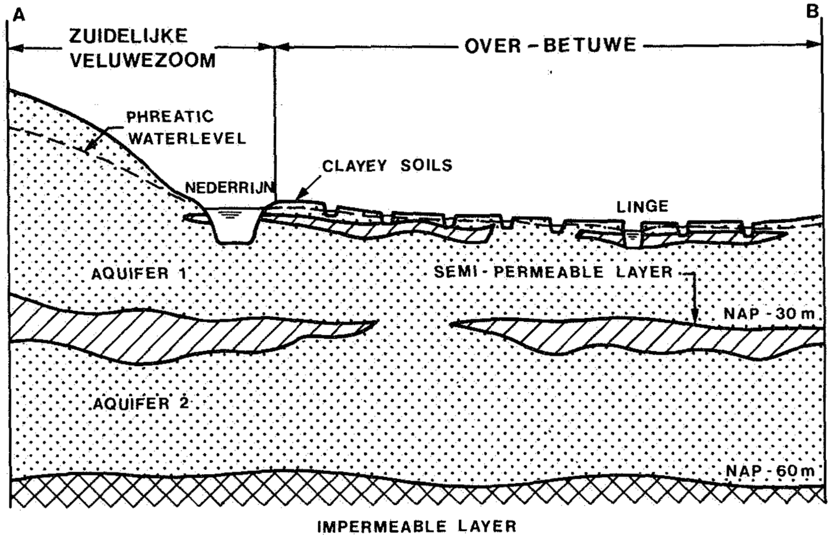


Fig. 2 Cross-section of the geohydrological system.

While in the area of the Over-Betuwe the unsaturated zone consists of clayey soils, in the area of the Zuidelijke Veluwezoom sandy soils are found.

In the area of the Over-Betuwe the phreatic water table is situated at about 1 metre below soils surface. Discharge of groundwater takes place by means of a dense system of small ditches. Depending on the season the water level in the ditches can either be fixed at a certain level or is not prescribed. The latter results in a discharge from groundwater to the ditches when the groundwater level is higher than a certain depth below soil surface. The discharge is zero for groundwater levels below that depth which implies that the ditches are dry. When the water level in the ditches is fixed at a certain level, both discharge from groundwater to the ditches and recharge from the ditches to groundwater can occur, depending on groundwater level. The relation between groundwater and surface water in the ditches is elaborated in detail in chapter 4. Besides the drainage system of small ditches, there are also large and relatively deep water courses in the model area, i.e. the Nederrijn and the Linge.

Henceforth, the part of the geohydrological system located between groundwater and the top of the shallow aquifer will be denoted as "top-system". The shallow semi-permeable layer, if present, forms part of the top-system, being its lower boundary. In the area of the Over-Betuwe the top system consists of clayey material. Due to the complex genetic conditions (river basin area) the clayey material is strongly anisotropic and heterogeneous in both local and regional sense. Existing maps show well-developed areas of basin clay separated by (partially) clay-covered sand ridges.

To model the saturated groundwater flow the complex reality in the topsystem was schematized for the local variation of the hydraulic conductivity with respect to the depth below groundlevel. The top-system was schematized into a sequence of sublayers, assumed to be homogeneous and isotropic. Where the shallow semi-permeable layer is present, this layer was represented by means of a separate sublayer.

An important feature of the physical behaviour of clay soils in the model area are the heterogeneities in soil moisture flow. These heterogeneities are strongly related to the phenomena of shrinkage and swelling which depends on the time varying soil moisture contents. The swelling and shrinkage result in a variability of soil properties (e.g. storage capacity and hydraulic conductivity) both with respect to depth and time. Thereby the shrinkage cracks, both vertical and horizontal, play an important role. The modelling approach to the heterogeneities, namely the approximation to the effect of horizontal shrinkage cracks, will be discussed briefly in chapter 6.

In the middle of the model area the groundwater pumping station Fikkersdries is situated. Groundwater flow in the Over-Betuwe is affected by this groundwater extraction in the deep aquifer. Simulation of the hydrological effects of this groundwater extraction is taken as the main issue for this paper.

3. SCHEMATIZATION OF THE GEOHYDROLOGICAL SYSTEM

Due to the complexity of physical processes the geohydrological system is too complicated to be accurately described by means of a model. In order to ensure the mathematical tractability of the problem various simplifications have to be introduced, resulting in a so-called "conceptual model" of the reality. After the conceptual model is set up, it is translated into mathematical terms, in this case resulting in a formulation of the problem by means of the finite element method. The application of the finite element method to the model area, implying another series of simplifications, is treated in detail by Kovar (1982). A wide range of practice-oriented, generally applicable aspects of the application of the finite element method to the saturated groundwater flow is presented by Leijnse and Kovar (1981). Within the context of this paper it is sufficient to know that the finite element grid applied consists of quadrangles (mostly squares) of which the size varies between 0.5 km × 0.5 km and 1 km × 1 km.

In this chapter only the construction of the conceptual model for the area of the Over-Betuwe will be dealt with, i.e. the hydrological schematizations. The simplification of the reality for the purpose of modelling implies the choice of the most appropriate conceptual model for a *given geohydrological system* and for a *given management problem* (Bear, 1979). In this study the latter aspect was not taken into account. The reason for neglecting this important consideration has to do with the nature of the study reported here. The task given to the authors was namely not to solve a specific management problem, but to develop a model generally applicable in areas with geohydrological conditions similar to those in the area of the Over-Betuwe. In order to test the applicability of the model, a more or less common, arbitrary chosen management problem was considered after the model was completed. The problem chosen by the authors was to study the effect of an increase of groundwater extraction at an existing groundwater pumping site (Fikkersdries), expressed in terms of lowering of hydraulic heads and a decrease of evapotranspiration. The results of this hypothetical study are discussed in chapters 8 till 10. Thereby the question is put forward whether it is desirable to develop very sophisticated *generally applicable* models which may yield very accurate results, but whose development and operation are costly and time consuming, or to apply a set of models of lower sophistication, each of them treating a clearly delineated small-size problem. The type of the latter models strongly depends on *the nature of the management problem on hand*.

The schematizations related to the construction of the conceptual model can be carried out with respect to the following two aspects (Kovar, 1979):
- a selection of subsystems;
- a selection of relations interlinking the subsystems.

In this paper only the conceptual model of the saturated zone will be considered, the model of the unsaturated zone is discussed elsewhere, e.g. De Laat and Awater (1978).

Within the conceptual model of the saturated zone the following three subsystems are distinguished:
- the top-system, characterized by the phreatic water level φ;
- the shallow aquifer, characterized by the piezometric head φ_1;
- the deep aquifer, characterized by, the piezometric head φ_2.

These subsystems are illustrated in figure 3, in which also an indication of scales is given.

The assumption was done that groundwater flow in both aquifers is predominantly

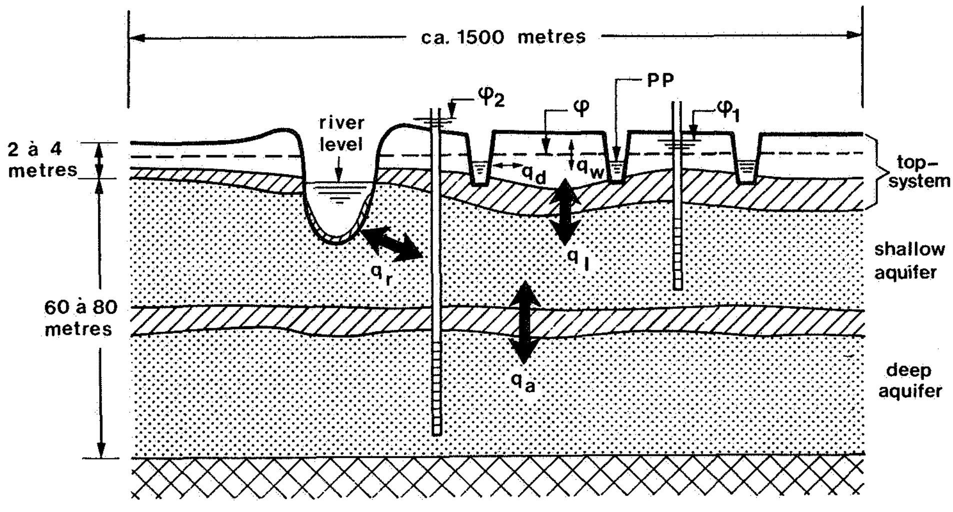


Fig. 3 Illustration of the conceptual model for the saturated zone.

horizontal, the vertical flow component in the aquifers being negligible. The effect of (elastic) storage in the aquifers was neglected. The aquifers are assumed to be isotropic and non-homogeneous, i.e. with respect to the transmissivity.

The groundwater flow through semi-permeable layers is assumed to be vertically oriented and storage within these layers is neglected. The storage effects are taken into account only with respect to the variation of the phreatic water level.

At the boundary of the model area the values of piezometric heads φ_1 and φ_2 are prescribed (boundary conditions). The second type of "boundary conditions", valid within the model area, are water levels in the ditches and rivers. In figure 3 the water levels in ditches are denoted by PP.

Within the conceptual model the following relations interlinking the subsystems are distinguished (see figure 3):

- the flux (q_a) between the deep aquifer and the shallow aquifer;
- the flux (q_1) between the shallow aquifer and the top-system;
- the groundwater flow (Q_r) between the river and the shallow aquifer;
- the flux (q_d) between the top-system and the system of deep and shallow ditches;
- the flux (q_w) across the interface between the saturated zone and the unsaturated zone. For simplicity, the position of the interface can be viewed as coinciding with the phreatic water level φ.

On the fluxes q_d and q_w will be elaborated further in chapters 4 and 5 respectively.

4. RELATIONS BETWEEN GROUNDWATER AND SURFACE WATER IN THE DITCHES

In this chapter the relations for the flux q_d between groundwater in the top-system and surface water in the ditches are considered. The top-system is shown schematically in figure 4. The drainage system was schematized into two types of ditches of various

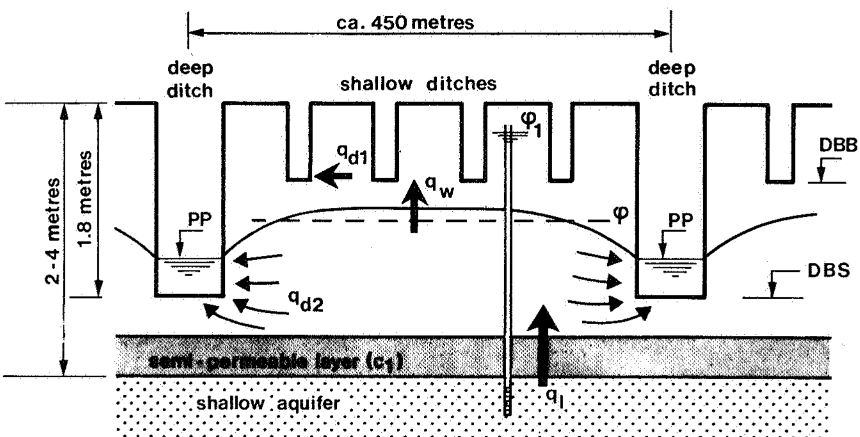


Fig. 4 Flux components within the top-system.

depth, referred to as "shallow ditches" and "deep ditches". The total flux q_d into the drainage-system is assumed to be the sum of fluxes into the shallow ditches (q_{d1}) and deep ditches (q_{d2}). Both the magnitude and the direction of q_d depend on the phreatic water level φ. For the purpose of calculation the phreatic water level stands for the average value of the actual phreatic water level between the ditches. The averaged φ is indicated by means of a dashed line.

In the system of shallow ditches the water level is not controlled. Thereby, due to the rapid surface water discharge, only small water depth can occur in the ditches. The flux q_{d1} into shallow ditches is assumed to be a linear function of φ, the flux also depends on the drainage resistance of shallow ditches. The flux q_{d1} occurs only for φ above the bottom level (DBB) of shallow ditches. For φ below DBB flux q_{d1} is zero, this situation is depicted in figure 4.

In the system of deep ditches either the water level can be maintained at the level PP or the water level is not controlled (also small water depth in the ditches). In figure 4 only the former case is illustrated, whereby the flux q_{d2} is assumed to be a linear function of φ. The flux q_{d2} also depends on the drainage resistance of deep ditches. If the water level in deep ditches is not controlled, the assumption was done of the top-system dewatering with respect to a fixed level DBS. The level DBS may be viewed at as the bottom level of deep ditches. For φ below DBS the flux q_{d2} is zero.

The relation between φ and the flux q_d, i.e. the total discharge to both shallow and deep ditches, is illustrated in figure 5.

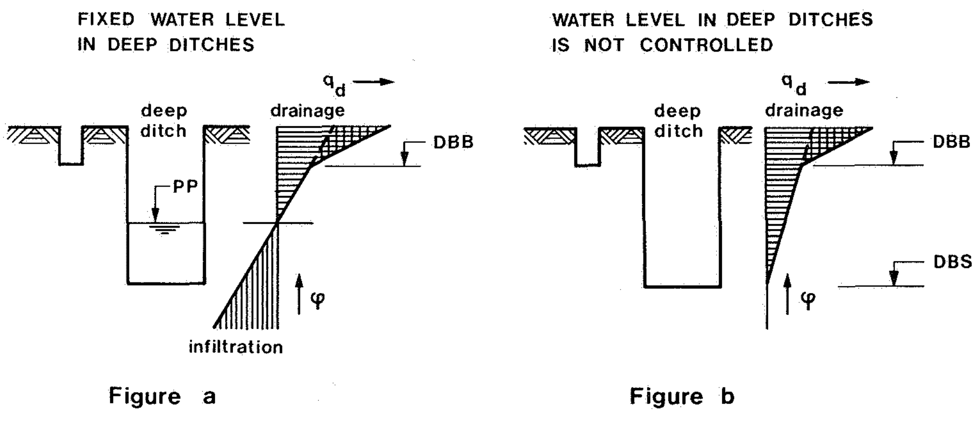


Fig. 5 Relation between phreatic water level φ and total discharge to the ditches q_d.

Figure 5a: both drainage of and the infiltration to the top-system can be realized. This type of relation is valid in areas where water level (PP) in the deep ditches is maintained.

Figure 5b: only drainage of the top-system can occur. This type of relation is suitable for simulation of areas where water level in the deep ditches is not controlled, in combination with small water depth in the ditches.

At each location of the model area only one of the two relations given above can be introduced.

5. RELATION BETWEEN THE SATURATED ZONE AND THE UNSATÚRATED ZONE

In this chapter the flux q_w occuring between the saturated part of the top-system and the unsaturated zone (i.e. unsaturated part of the top-system) will briefly be discussed. The flux relation will be dealt with in so far as it is necessary for the understanding of the modelling approach to the saturated zone.

In case of a shallow phreatic water level capillary rise of soil moisture from groundwater to the roots may contribute considerably to the water supply (evapotranspiration) for the crop. The lowering of the phreatic water level (e.g. caused by groundwater extraction) will reduce the rate of capillary rise. Depending on meteorological parameters such as rainfall and solar radiation this may lead to a reduction of evapotranspiration, which will affect the yield of the crop.

A change in the rate of capillary rise also implies a change in the soil moisture conditions in the unsaturated zone and vice versa. Obviously, there is a relationship between the phreatic water level, the soil moisture conditions in the unsaturated zone and the flux occuring between the unsaturated zone and the saturated zone, of which the phreatic water level is the upper boundary. The principles of the relation have been developed by De Laat and Van den Akker (1976). Lateron the relation has been improved by De Laat (De Laat and Awater, 1978).

In figure 6 the usual form of the relation is shown. The flux q_w across the interface of the saturated-unsaturated subsystem is taken positive in upward direction. The meaning of the interface within the concept of the model is described in detail by De Laat and Awater (1978). Here, for simplicity, the interface may be assumed to be equal to the phreatic water level.

The phreatic water level is symbolized by φ, while φ^* denotes the phreatic level calculated in the previous time-step. Thus the difference (taken positive) represents the rise of the phreatic water level with respect to the phreatic water level calculated in the previous time-step.

The relation is determined for each time-step by the model itself applying the meteorological boundary conditions, the soil moisture conditions in the unsaturated zone and the phreatic water level, the soil moisture conditions in the unsaturated zone and the flux small in downward direction, q_w is expressed by a linear relation in $\Delta\varphi$. In the remaining section of the relation, q_w is defined by a complex non-linear implicit relation in q_w and $\Delta\varphi$.

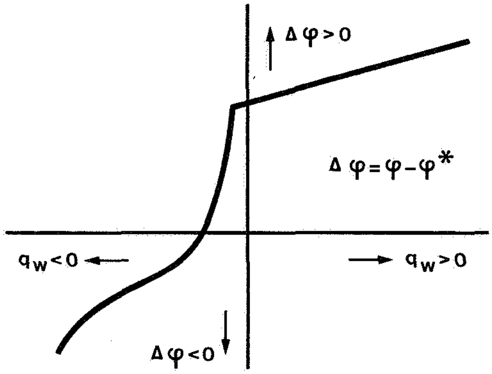


Fig. 6 The relation between the change in the phreatic water level and the flux q_w across the interface saturated-unsaturated subsystem.

6. HETEROGENEITIES IN SOIL MOISTURE FLOW

Soil moisture flow in clay soils is essentially less homogeneous than soil moisture flow in e.g. sand soils. Various aspects of heterogeneities related to clay soils, among these also the phenomena of shrinkage and swelling, are treated elsewhere, e.g. Bouma and Wösten (1979) and Stoffelsen and Bouma (1979). It is beyond both the subject of this study and the qualification of the authors to deal with the heterogeneities in soil moisture flow extensively. These heterogeneities and, in particular, an extension of the initial modelling concept to the heterogeneities as presented in this paper, are discussed by Bouma and De Laat (1981).

For the purpose of the model study in the area of the Over-Betuwe an attempt was made to incorporate approximately the effect of heterogeneities in the model concept. In order to enable the mathematical tractability of the problem, for clay soils the theory of one-dimensional homogeneous soil moisture flow was applied. This theory assumes constant values of the soil moisture content at horizontal planes, implying vertically homogeneous movement of soil moisture fronts. However, this flow theory is not valid for clay soils.

Because this flow theory is not valid for swelling and shrinking clay soils, obviously the model adaption to the heterogeneities (maintaining the homogeneity concept) is a very crude one. Moreover the modelling approach includes only the effect of horizontal shrinkage cracks.

Due to the shrinking both vertical and horizontal cracks play an important role in the unsaturated groundwater flow.

- *Vertical shrinkage cracks* result in a rapid transport of water from precipitation to groundwater, thus bypassing clay soil in the upper section of the unsaturated zone. This type of transport is referred to as "short-circuiting", Bouma and Dekker (1978). Due to the low infiltration capacity at the groundlevel and due to the short-circuiting, soil moisture deficits may occur in the upper sections of the unsaturated zone, primarily in the root zone, while the saturated groundwater is recharged with the short-circuited precipitation. For several reasons in the model no provisions were taken to incorporate the effect of vertical cracks.

Horizontal shrinkage cracks result in a significant decrease of the flux from the saturated zone into the unsaturated zone, which may lead to soil moisture deficits in the root zone. In the model the effect of horizontal cracks was approximately approached by means of adaption of the relation between hydraulic conductivity k and moisture tension Ψ. The principles of this adaption were set up in co-operation with Bouma and De Laat. The adaption is schematically illustrated in figure 7. The adapted relation is characterized by a strong decrease in (unsaturated) hydraulic conductivity for values

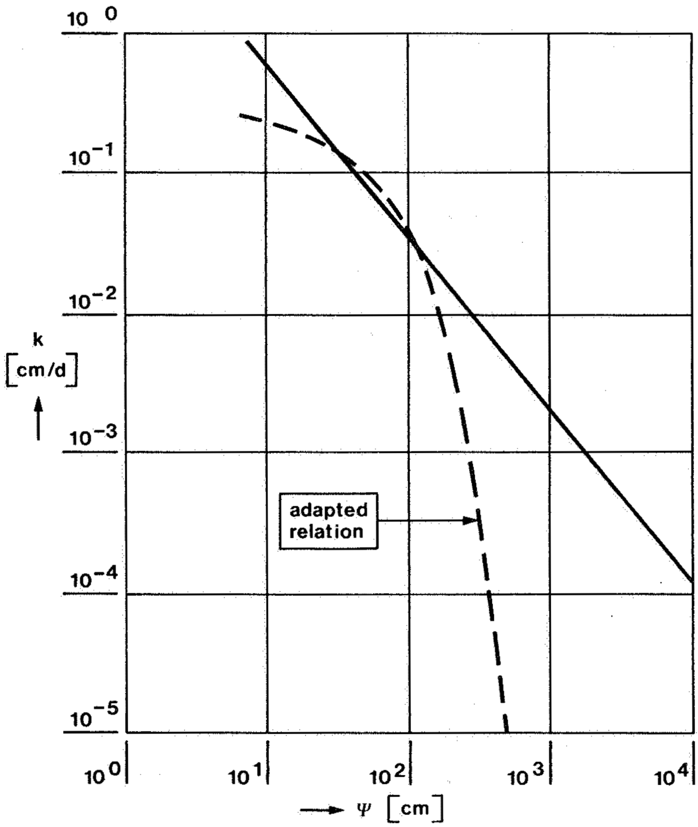


Fig. 7 Effect of horizontal cracks: adapted relation between hydraulic conductivity (k) and moisture tension (Ψ) (see also Bouma and De Laat, 1981, for a measured version of this curve).

of moisture tension higher than about 100 cm. The modelling approach to horizontal cracks presented here is essentially a first approximation to the phenomenon.

In chapter 9 (sensivity analysis) the effect of the adaption of the model structure (horizontal cracks) on the results is discussed. Although the effect of vertical cracks was not encountered, it may be assumed that the approximative approach with respect to horizontal cracks yields results in the direction and the order of magnitute of the overall effect of heterogeneities.

As mentioned before, an extension of the model concept to the heterogeneities has already been done (Bouma and De Laat, 1981). This extension also includes the effect of vertical cracks, i.e. short-circuiting.

7. VERIFICATION OF THE MODEL

The verification of the model is the final step in the process of model building. This process consists of the three basic steps (e.g. Young, 1978):

- model structure identification (the construction of the conceptual model and relevant mathematical formulations, see chapter 3);
- model parameter estimation (also referred to the "calibration", "inverse" or "parameter identification" problem);
- *model verification* (also referred to as "model validation").

According to Matalas and Maddock (1976) the term verification should rather be replaced by the term *acceptance* in order to express the true capabilities of this part of the modelling process. The essential activity of the verification is namely to answer the question whether the model can be accepted for the simulation of the behaviour of the geohydrological system in relation to the given management problem. If the performance of the model in the verification period is unacceptably poor the model has to be rejected. In the latter case the model structure can be refined or more reliable input data can be applied in order to improve the performance of the model.

The model Over-Betuwe was verified by means of the visual matching of the calculated groundwater heads to the observed groundwater heads. The verification period involved two calendar years (1974, 1975). The approach to the question whether the model should be accepted or not was in our case strongly influenced by the arbitrary nature of the management problem to which the model was to be applied. As set out in chapter 3 the management problem was chosen arbitrarily by the authors (simulation of the effect of groundwater extraction). Thereby, however, no requirements on the reliability of model results were defined. Such requirements would also apply on the performance of the model in the verification period. The reason for disregarding the requirements on the reliability of performance of the model is, among others, that there are no suitable mathematical techniques to handle such requirements. Obviously, because of the lack of these requirements, in principle any degree of model performance can be accepted for our hypothetical problem.

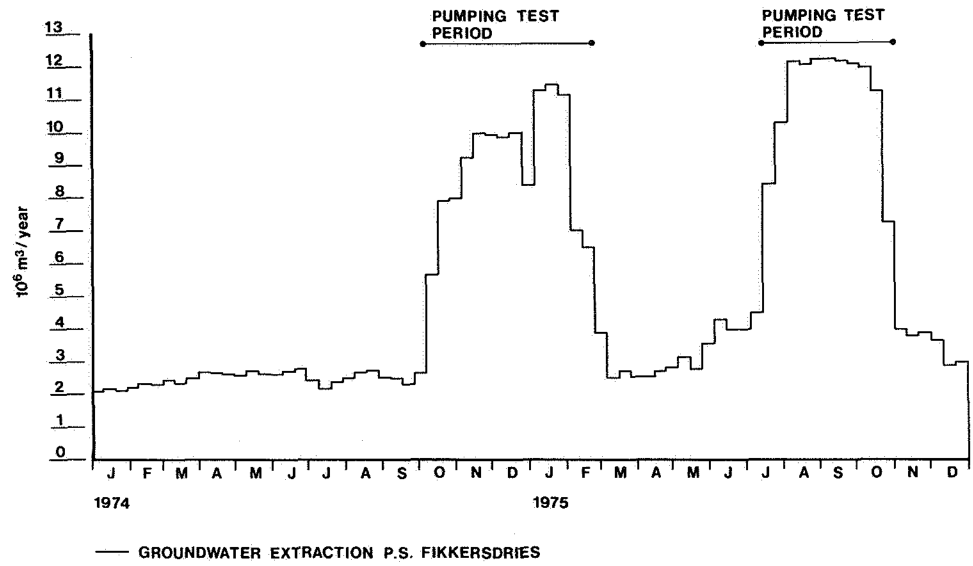


Fig. 8 Extraction rate pumping station Fikkersdries, 1974-1975.

In this chapter a number of aspects characterizing the model behaviour in the verification period will be considered. First the model input will be reviewed. Secondly the model output (groundwater heads and evapotranspiration) will be treated.

The input for the model can be divided into two groups, namely the time-invariant data and the time-variant data. The time-invariant data concerns transmissivity of the aquifers, hudraulic resistance of semi-permeable layers, drainage resistance of rivers and ditches, bottom level of ditches, groundlevel and parameters characterizing the unsaturated zone (thickness of the rootzone, relation between hydraulic conductivity and moisture tension, etc.).

The time-variant input concerns groundwater levels on the model boundary, water level in ditches and rivers, meteorological data (precipitation, air temperature, solar radiation, humidity and wind speed) and the variation in agricultural crop. Finally, the time-variant input also includes groundwater extractions. Especially the extractions from the deep aquifer at the pumping station Fikkersdries strongly affect the groundwater flow regime. The extraction rate at Fikkersdries is shown in figure 8. Within the verification period (1974-1975) two subperiods of high extraction rate can be distinguished, representing two pumping tests.

It should be stressed that all input data represent the estimated "best possible" values of parameters derived from maps, extrapolated from pumping tests and other local field studies. The parameter values were not assessed by means of the calibration of the model. The model could not be calibrated due to the high complexity of the model structure and (in relation to the latter) because no consistent calibration technique is available. Moreover, without regard to the availability of a calibration technique, the calibration of the complex model Over-Betuwe against a limited amount of field data would be meaningless, resulting in unreliable and/or ambiguous parameter values.

In the remaining part of this chapter the model output in the verification period are considered. The results are illustrated by the model output at a restricted number of nodes of the model grid. The water mass balance for the model area is not treated in this paper. The model results in the verification period are considered in more detail by Rolf (1981).

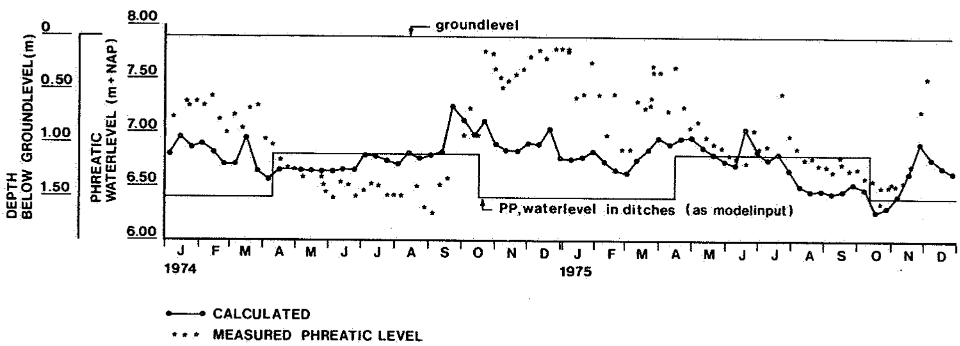


Fig. 9a Verification of the phreatic water level for node 146.

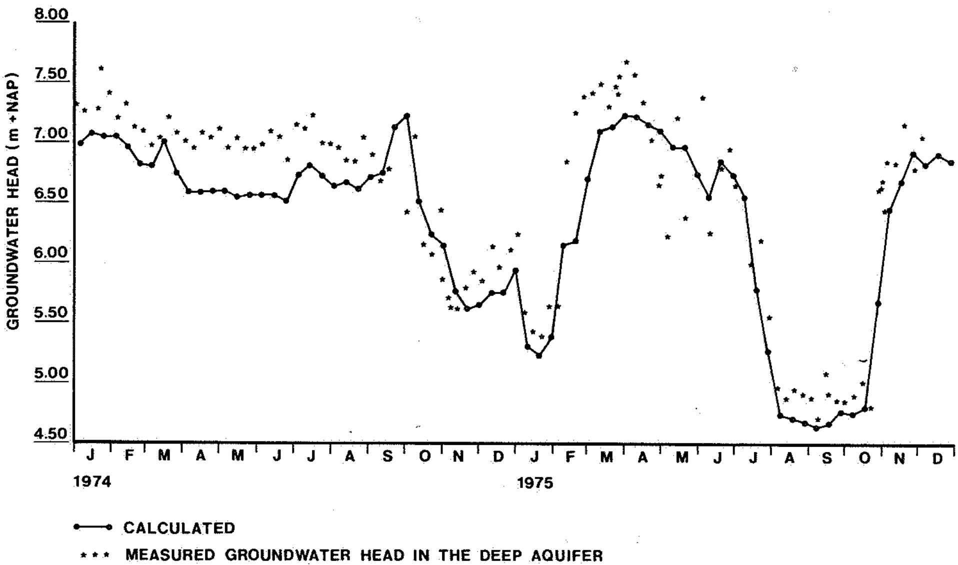


Fig. 9b Verification of the groundwater head in the deep aquifer for node 146.

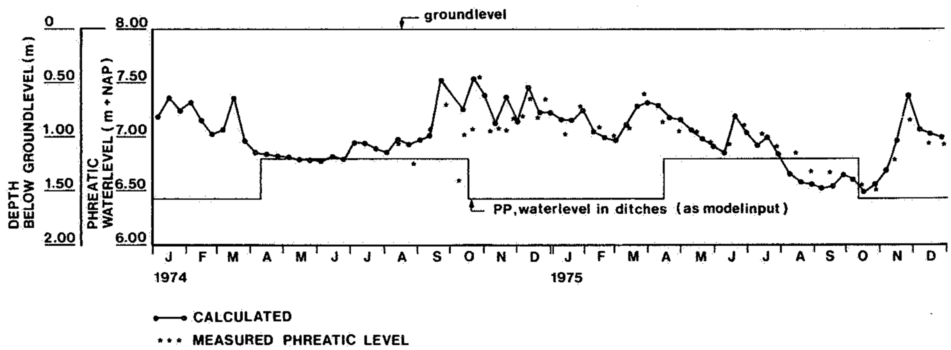


Fig. 10 Verification of the phreatic water level for node 147.

For node 146 phreatic water level and groundwater head in the deep aquifer are given in figure 9a en 9b, respectively.

Figure 9b shows the strong influence of the two pumping test periods on the variation in groundwater heads in the deep aquifer. In general, the calculated heads fairly closely follow the trend in the observed groundwater heads. The maximum deviation between observed and calculated heads are about 50 cm. The calculated heads are on average 22 cm below the observed heads. The standard deviation of the deviations between observed and calculated heads is 35 cm.

Figure 9a shows that in node 146 the calculated phreatic water level is significantly lower than the observed level in the winter season 1974-1975. The phreatic water level calculated in this very wet season is only slightly higher than the summer levels. Several reasons were given to explain the bad performance of the model during the winter season 1974-1975.

Figure 10 shows the calculated and observed phreatic water level in node 147. In this node the calculated levels match the observed levels significantly better than in node 146. The averaged deviation between calculated and observed level is 5 cm, the relevant standard deviation is 14 cm.

For node 146 the cumulated values of the calculated actual and potential evapotranspiration are given in figure 11. The difference between the potential and the actual evapotranspiration is referred to as moisture deficit. The gross moisture deficit for growing seasons 1974 and 1975 is 190 mm and 220 mm, respectively. The variation in the moisture deficit in time is given in figure 12. In a number of time-steps no moisture deficit occurs, i.e. in these time-steps the actual evapotranspiration equals the potential evapotranspiration.

In this chapter model input and model output were considered. The calculated groundwater heads were visually matched to the observed groundwater heads in order to obtain information about the validity of the model for prediction purposes. However, the verification based on groundwater heads alone, does not provide adequate information on

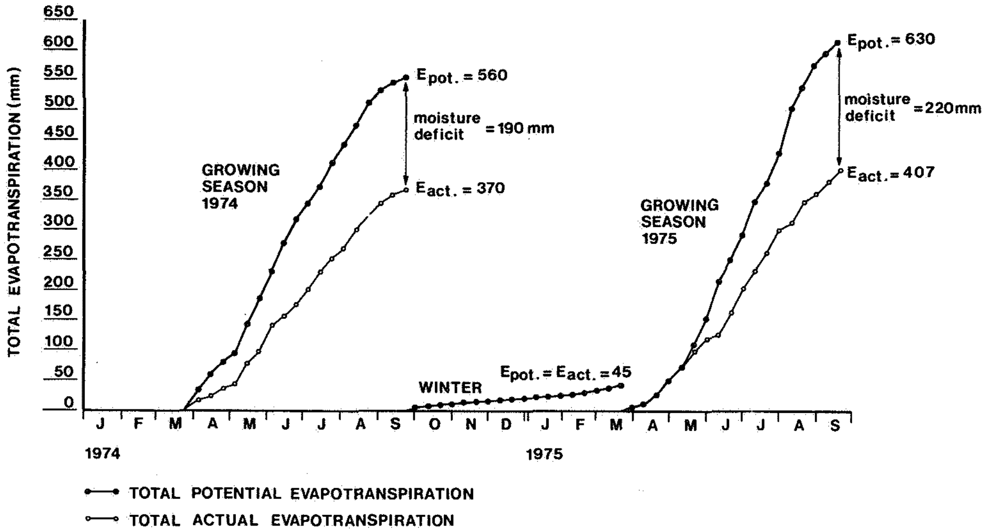


Fig. 11 Calculated actual and potential evapotranspiration for node 146.

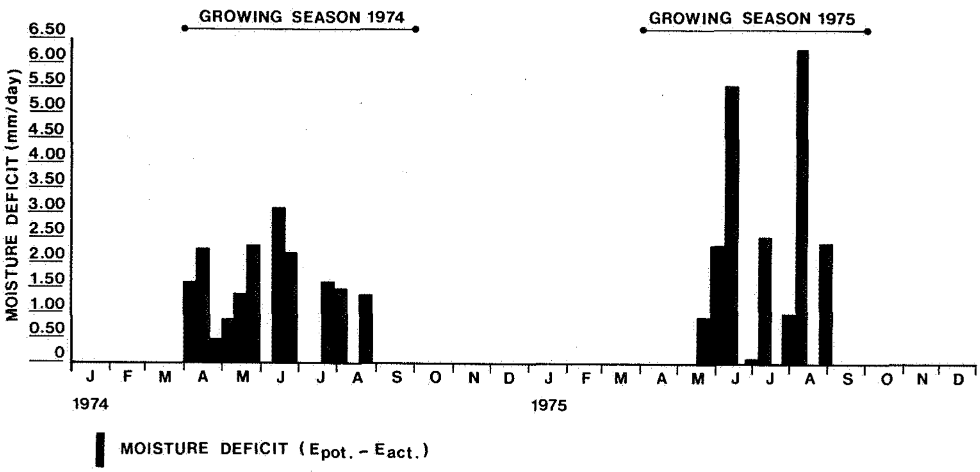


Fig. 12 Calculated moisture deficit for node 146.

the capabilities of the model, especially concerning the ability to simulate both the evapotranspiration and the soil moisture conditions in the unsaturated zone. Unfortunately no observations were available of either evapotranspiration or the soil moisture content.

In relation to the arbitrary character of the problem to which the model was to be applied, no requirements were set up on the degree of performance of the model, i.e.

the reliability of model predictions. Because of the lack of such requirements the model verification resulted in an unconditional acceptance of the model. The application of the model to a hypothetical problem is considered in the next chapter.

8. SIMULATION OF THE EFFECT OF GROUNDWATER EXTRACTION

In order to test the applicability of the model, a fairly common, arbitrary chosen management problem was considered after the model was completed. In this sense the problem was a hypothetical one.

The model was applied to simulate the effect of the existing extraction at the location Fikkersdries on the geohydrological system. The simulation period involved two calender years, namely 1974 and 1975. The variation in the rate of groundwater extraction from the deep aquifer is presented in figure 8. The effect of groundwater extraction was chosen to be expressed in the following two terms:
– the lowering of groundwater heads;
– the decrease of the actual evapotranspiration.

The required lowering of groundwater heads can be obtained as the difference between groundwater heads not affected by the extraction, and the groundwater heads affected by the extraction. Similarly, the decrease of the evapotranspiration can be calculated. The hydrological situation affected by the groundwater extraction was already considered for the purposes of the verification of the model (see chapter 7). In order to obtain the situation not affected by the extraction the calculation was repeated with the extraction reduced to zero within the total period 1974-1975. The time-dependent variation in lowering of groundwater heads is illustrated in figure 13. The figure involves the lowering of the phreatic water level and the lowering of the piezometric head in the deep (pumped) aquifer for grid node 146. The lowering of the piezometric head is about 1 metre in times of regular extraction, while during the two pumping test periods the lowering reaches 3 to 3.5. metres. Analogically, the lowering of the phreatic water level is 0.1 to 0.15 metres in times of regular extraction, and 0.5 to 0.6 metres during the pumping test periods. The average lowering of the phreatic water level for growing seasons 1974 and 1975 is 13 cm and 25 cm respectively.

The magnitude of the actual evapotranspiration is often supposed to be a measure for the crop production. In general, with increasing actual evapotranspiration a higher yield of the crop may be expected. Therefore, from the viewpoint of agricultural water demand, the difference between the potential evapotranspiration and the actual evapotranspiration is referred to as moisture *deficit*. The potential evapotranspiration represents the rate of evapotranspiration that should occur under conditions of optimal water supply. If the actual evapotranspiration equals the potential evapotranspiration (e.g. during winter season) the moisture deficit is zero. The lowering of the phreatic water level affects the soil moisture conditions in the unsaturated zone, resulting in the reduction of the actual evapotranspiration. Due to this reduction the moisture deficit increases in

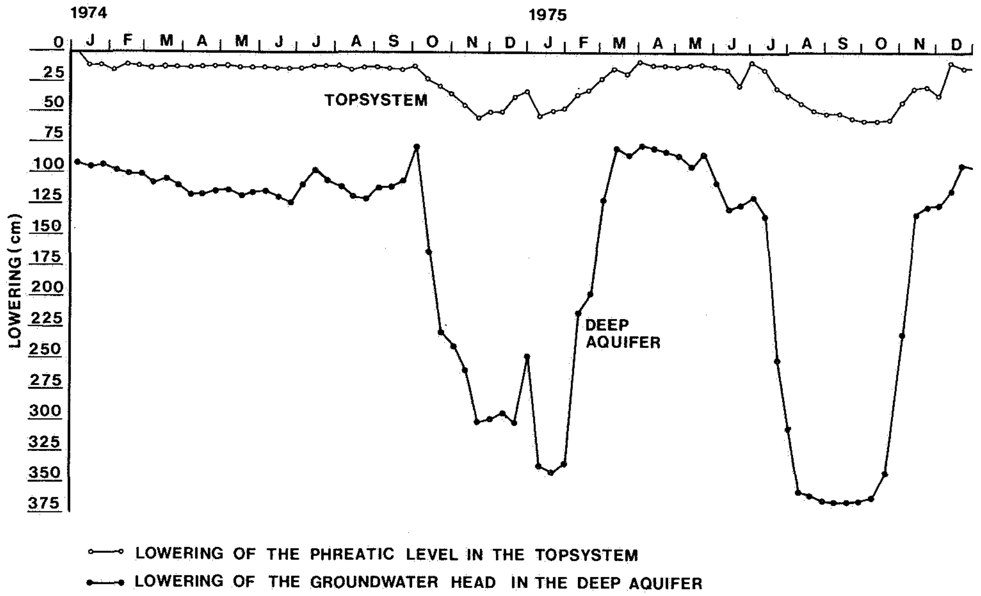
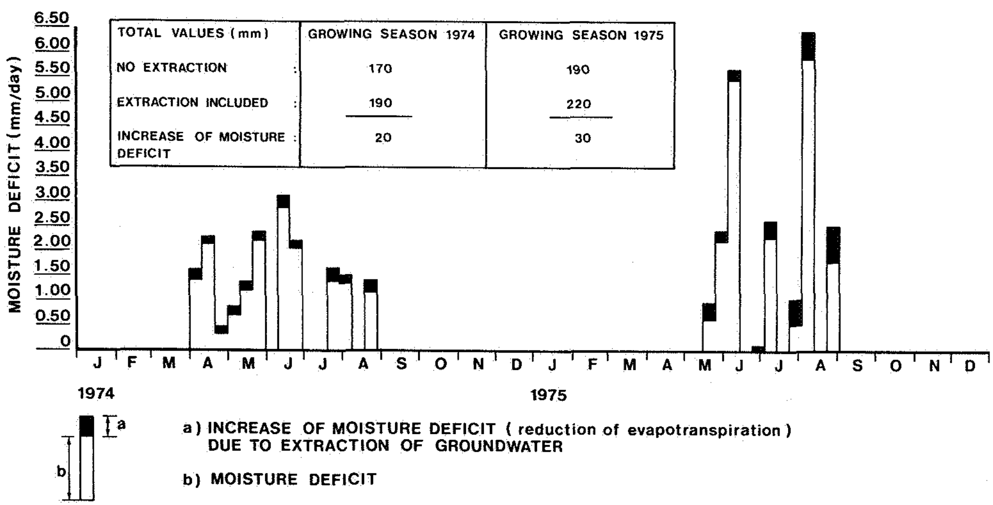


Fig. 13 Calculated lowering of groundwater heads for node 146 (due to groundwater extraction).

periods where non-zero moisture deficit existed before the lowering of the phreatic water level occured. The increase of the moisture deficit due to the groundwater extraction is illustrated in figure 14. This figure is based on the model results for grid node 146. In the table included in figure 14 the gross moisture deficits are presented for the growing



TOTAL VALUES (mm)	GROWING SEASON 1974	GROWING SEASON 1975
NO EXTRACTION :	170	190
EXTRACTION INCLUDED :	190	220
INCREASE OF MOISTURE : DEFICIT	20	30

Fig. 14 Calculated effect of groundwater extraction on evapotranspiration for node 146.

seasons 1974 and 1975. In the situation with no groundwater extraction the gross moisture deficits in the growing seasons 1974 and 1975 are calculated to be 170 mm and 190 mm respectively. Due to groundwater extraction the calculated gross moisture deficit increases to 190 mm and 220 mm respectively. In other words, the reduction of the actual evapotranspiration is 20 mm and 30 mm respectively.

9. SENSITIVITY ANALYSIS

The results of the sensitivity analysis are presented in table 1. The sensitivity analysis was carried out to assess the relative influence of six various model input data on four model output data. The sensitivity analysis of the output data to particular input data was obtained by altering the magnitude of the relevant input data, while all remaining input data were kept unchanged. The following six alterations in model input were considered:

a) the omission of model adaption for cracks in the unsaturated zone. This model adaption is considered in chapter 6;
b) lowered water level in the ditches (–30 cm);
c) reduced drainage resistance of the ditches and hydraulic resistance of the shallow semi-permeable layer, decrease is 50% of the initial values;
d) reduced transmissivity of the shallow aquifer, decrease is 25% of the initial value;

	SIMULATION OF PHREATIC WATER LEVELS AND EVAPOTRANSPIRATION		SIMULATION OF THE EFFECTS OF GROUNDWATER EXTRACTION	
	evapotranspiration (mm)	phreatic water level (cm-ground level)	reduction of evapotranspiration (mm)	lowering of phreatic water level (cm)
RESULTS OF THE "BASIC" CALCULATIONS →	407	110	30	25
"SENSITIVITY" CALCULATIONS:				
a) omitting the model adaption for CRACKS in the unsaturated zone	562 (+155)	123 (+13)	34 (+4)	25 0)
b) lowered WATER LEVEL IN THE DITCHES (-30cm)	393 (-14)	127 (+17)	21 (-9)	26 (+1)
c) reduced DRAINAGE RESISTANCE and HYDRAULIC RESISTANCE OF THE SHALLOW SEMI-PERMEABLE LAYER (-50%)	409 (+2)	109 (-1)	22 (-8)	16 (-9)
d) reduced TRANSMISSIVITY OF THE SHALLOW AQUIFER (-25%)	406 (-1)	112 (+2)	31 (+1)	27 (+2)
e) reduced HYDRAULIC RESISTANCE OF THE DEEP SEMI-PERMEABLE LAYER (-50%)	405 (-2)	115 (+5)	33 (+3)	37 (+12)
f) reduced TRANSMISSIVITY OF THE DEEP AQUIFER (-25%)	405 (-2)	115 (+5)	31 (+1)	30 (+5)

Table 1 Results of the sensitivity analysis for node 146 for the growing season 1975.

e) reduced hydraulic resistance of the deep semi-permeable layer, decrease is 50% of the initial value;

f) reduced transmissivity of the deep aquifer, decrease is 25% of the initial value.

The sensitivity analysis is given on four selected output data, each of these existing in node 146. Though each sensitivity computer run comprised a period of two years (1974-1975), the results of the sensitivity analysis presented in table 1 are restricted to the growing season 1975 only.

The first two output data are related to the verification period. In this period the hydrological situation was simulated, related to the groundwater extraction at Fikkersdries during 1974-1975. The two output data, including the results of the relevant basic computer calculations presented in chapter 7, are as follows:

– the gross actual evapotranspiration. For the growing season 1975 the calculated value is 407 mm;
– the averaged depth of the phreatic water level below ground level. For the growing season 1975 the calculated average depth is 110 cm.

The remaining two output data concern the effect of the existing groundwater extraction with respect to zero extraction. The two output data, including the results of the relevant basic computer calculations presented in chapter 8, are as follows:

– the reduction of the actual evapotranspiration. For the growing season 1975 the calculated reduction due to groundwater extraction is 30 mm;
– the average lowering of the phreatic water level. For the growing season 1975 the calculated average lowering due to groundwater extraction is 25 cm.

The figures put in brackets in table 1 represent the difference between the so-called "sensitivity" calculations and the so-called "basic" calculations. The results of the six sensitivity calculations, labelled from a) through f) are discussed below.

The first sensitivity calculation a) concerns the model adaption for cracks in the unsaturated zone. The adaption was used in the basic calculations but was omitted in sensitivity calculations, thus disregarding the effect of cracks. From the sensitivity calculations it follows that the actual evapotranspiration increases enormously. If the effect of cracks would not have been accounted for by means of the adaption, then the calculated actual evapotranspiration would be 155 mm higher. The time-varying effect of cracks on the actual evapotranspiration in node 146 is illustrated in figure 15.

If a reliable simulation of the evapotranspiration is required from the sensitivity analyses it may be concluded that it is absolutely necessary to correctly model the effect of cracks in clay soils. If, on the other hand, the objective of the hydrological study is e.g. the simulation of lowering of the phreatic water level, it follows that modelling of the effect of cracks is not important. The magnitude of the lowering both affected and not-affected by cracks is the same (25 cm). The time-varying effect of cracks on the lowering of the phreatic water level in node 146 is illustrated in figure 16.

The second sensitivity calculation (b) concerns the effect of lowering the water level in the ditches by 30 cm. Due to this lowering the depth of the phreatic water level below

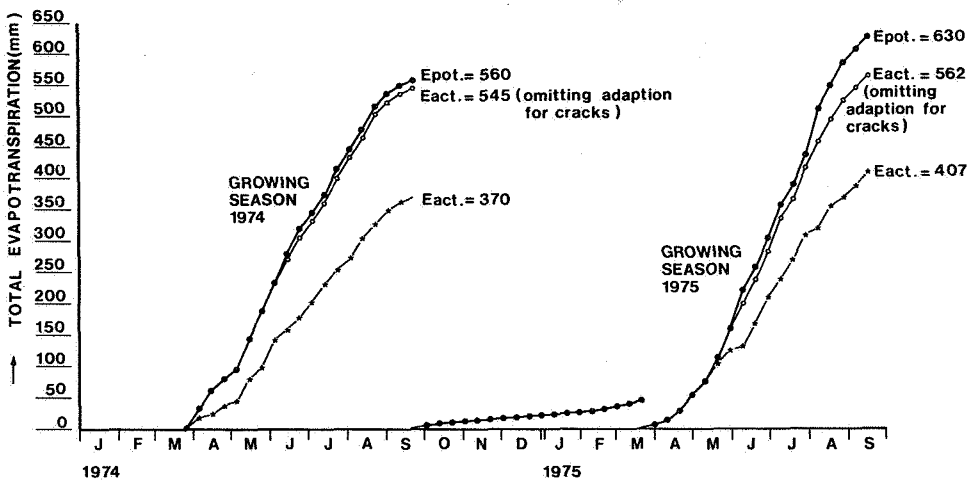


Fig. 15 The effect of cracks on the evapotranspiration.

ground level increases by 17 cm. However, similar to the effect of cracks, the lowering of the phreatic water level does not change (the increase by 1 cm is negligible with respect to the basic value of 25 cm).

The remaining sensitivity calculations, labelled c) through f) concern the parameters of the saturated zone. Due to the reduced drainage resistance of the ditches and the hydraulic resistance of the shallow semi-permeable layer, the lowering of the phreatic water level decreases by 9 cm. This decrease is not negligible with respect to the basic lowering of 25 cm. Finally, from the sensitivity analysis of the transmissivity of the shallow aquifer, the hydraulic resistance of the deep semi-permeable layer and the transmissivity of the deep aquifer, it follows that the lowering of the phreatic water level is most strongly affected by the deep semi-permeable layer.

From the wide range of physical phenomena affecting the soil moisture flow in the unsaturated zone, the cracks are likely to have a dominant influence. From the sensitivity analysis it follows that the lowering of the phreatic water level is only very slightly

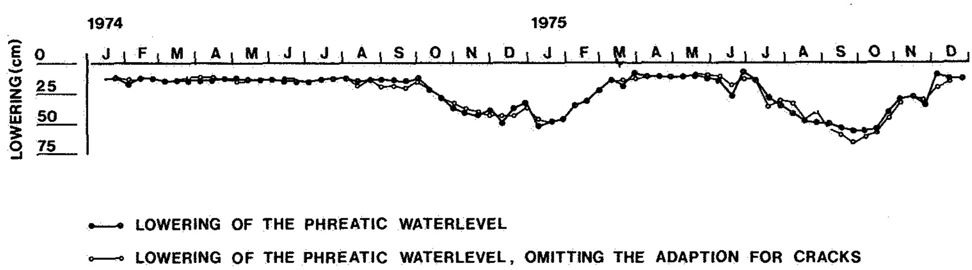


Fig. 16 The effect of cracks on the lowering of phreatic water level.

affected by the occurence of cracks in the unsaturated zone. It may therefore be expected that the effect of the whole system of the unsaturated zone on the lowering of the phreatic water level is so small that the unsaturated zone may conveniently be neglected for the calculation of this lowering.

The lowering of the phreatic water level is predominantly affected by the flow within the saturated zone. As indicated by the sensitivity analysis the following parameters of the saturated system most strongly affect the lowering of the phreatic water level:

- the hydraulic resistance of the deep semi-permeable layer;
- the combination of the drainage resistance of the ditches and the hydraulic resistance of the shallow semi-permeable layer.

Locally, primarily in the vicinity of the pumping site, the transmissivity of the deep (pumped) aquifer may also be important. The relative contribution of the above mentioned parameters to the regional variation in the lowering in the phreatic water level depends on the regional variation in the magnitude of these parameters.

In course of hydrological studies, often the question is put foward whether the lowering of groundwater levels due to a constant rate of groundwater extraction can be expected to be (more or less) constant throughout the calculation period. The answer to this question can be given through the sensitivity analysis of the lowering of groundwater levels with respect to the time-variant data.

In the Over-Betuwe, the time-variant input data that could affect the lowering of the phreatic water level are water levels in ditches and meteorological data (precipitation, air temperature, solar radiation, humidity and wind speed). The effect of the remaining time-variant input data, i.e. groundwater levels on the model boundary and water levels in rivers, is restricted to narrow sections alongside the model boundary and rivers respectively. The sensitivity analysis for water levels in ditches already showed that these water levels would only slightly affect the lowering. The meteorological data affect the lowering indirectly via the unsaturated zone. However, from the sensitivity analysis it follows that the impact of the unsaturated zone on the lowering of the phreatic water level may conveniently be neglected. Hence meteorological data are not important in this context. Therefore, in case of a constant rate of groundwater extraction, the lowering of the phreatic water level is expected to be a more or less constant value in time.

The expectation of a constant lowering was verified by means of a model calculation, in which constant groundwater extraction was introduced. The relevant lowering of the phreatic water level (with respect to the situation with zero extraction) for grid node 146 is presented in figure 17. The sudden jumps in the graphs are caused by conceptual inadequaces of the model section for the unsaturated zone (when the phreatic water level reaches the root zone). Figure 17 shows that the lowering is more or less constant throughout the whole calculation period. There are no significant differences between the lowering in winter and the lowering in the summer periods.

The conclusion to be drawn from the sensitivity analysis is that the lowering of the phreatic water level due to a constant rate of groundwater extraction can conveniently be treated as a steady-state saturated groundwater flow problem.

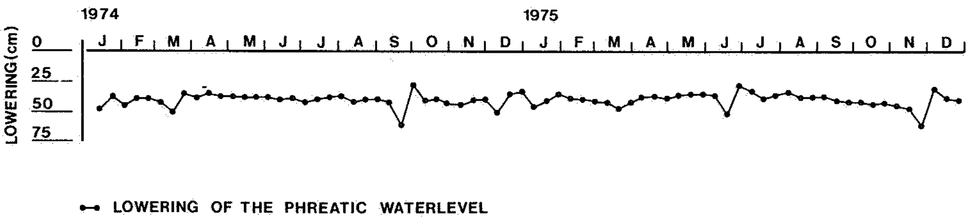


Fig. 17 The lowering of the phreatic water level due to constant groundwater extraction ($10 \cdot 10^6$ m³/ year).

10. COMPARISON OF VARIOUS MODELLING APPROACHES

In the past ten years several model investigations have been made concerning the effects of groundwater extraction at the pumping station Fikkersdries. These effects were expressed in terms of lowering of groundwater heads.

In the foregoing chapter is was suggested that the lowering of groundwater heads due to groundwater extraction can be approximated by means of a relatively simple modelling approach, i.e. a model for steady-state groundwater flow in the saturated part of the geohydrological system. According to these conclusions the model Over-Betuwe is unnecessary complex for the defined groundwater extraction problem.

In this chapter various simple model approaches used for the same problem in the past will be compared with the underlying model results. This will be done from the calculated lowering of groundwater heads due to a constant extraction of 10 million m^3/year at the pumping station Fikkersdries.

The calculated lowering-pattern (model Over-Betuwe) of groundwater heads in the shallow aquifer is given at figure 18. The figure also shows the lines of equal thickness of the semi-permeable layer between the deep and the shallow aquifer. South-east of the pumping station there is a buried glacial basin where the thickness of this layer is strongly decreased and is zero at some places. Adjacent to this basin the thickness of this layer is 10 to 20 metres and therefore the hydraulic resistance of the deep semi-permeable layer will be relatively large.

In chapter 9 it was demonstrated that the calculated lowering of groundwater heads are very sensitive to the value of the deep hydraulic resistance. Figure 18 shows the excentric pattern of calculated lowering of the groundwater heads in the shallow aquifer with respect to the location of the pumping station. The largest lowerings are calculated in the centre of the glacial basin where deep hydraulic resistance is small.

In figure 19 the results of the various model approaches in the past are given in a vertical cross section through the middle of the lowering pattern. The location of this cross section is shown at figure 18.

The first model approach for the same problem was done in 1973. Using an analytical formula (Bruggeman, 1972) the lowerings were calculated in the two aquifer system. However, the analytical approach required fully homogeneous conditions and an infinite

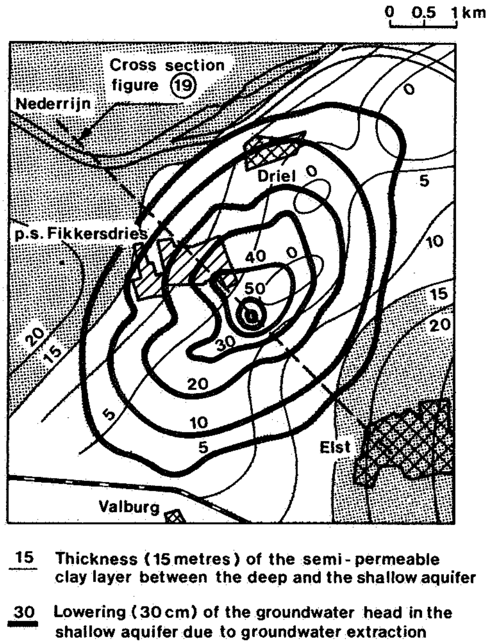


Fig. 18 Thickness of the deep semi-permeable layer and the calculated lowering pattern (model Over-Betuwe) in the shallow aquifer due to a constant groundwater extraction of 10 million m^3/year.

extent for the aquifers and semi-permeable layers. The results (fig. 19) show a fully symmetric lowering pattern in the shallow aquifer around the pumping station.

To take into account the heterogeneities of the geohydrological system, in 1977 the same problem was approached by means of a relatively simple numerical model for steady-state groundwater flow in the two aquifer system. The resulting lowerings of the groundwater head in the shallow aquifer show the difference between this numerical approach and the analytical approach. In the area of the basin with thin or missing clay layers between the two aquifers, relatively large lowerings are calculated. Near the river Rhine, as a hydrological boundary, the lowering are close to zero.

The results of the complex model Over-Betuwe show the fully excentric lowering pattern as given in figure 18. The centre of greatest lowerings is no longer calculated near the pumping station but about 1000 metres south-east, in the area with thin clay layers.

In the last step there have been two important changes. The model Over-Betuwe is a lot more complex and the knowledge on the geohydrological input has increased significantly between 1977 and 1980.

To see whether the differences in the model results are due to one or both of these two reasons, the calculation with the relatively simple model concept of 1977 has been repeated with the more recent geohydrological input data from the model Ovèr-Betuwe.

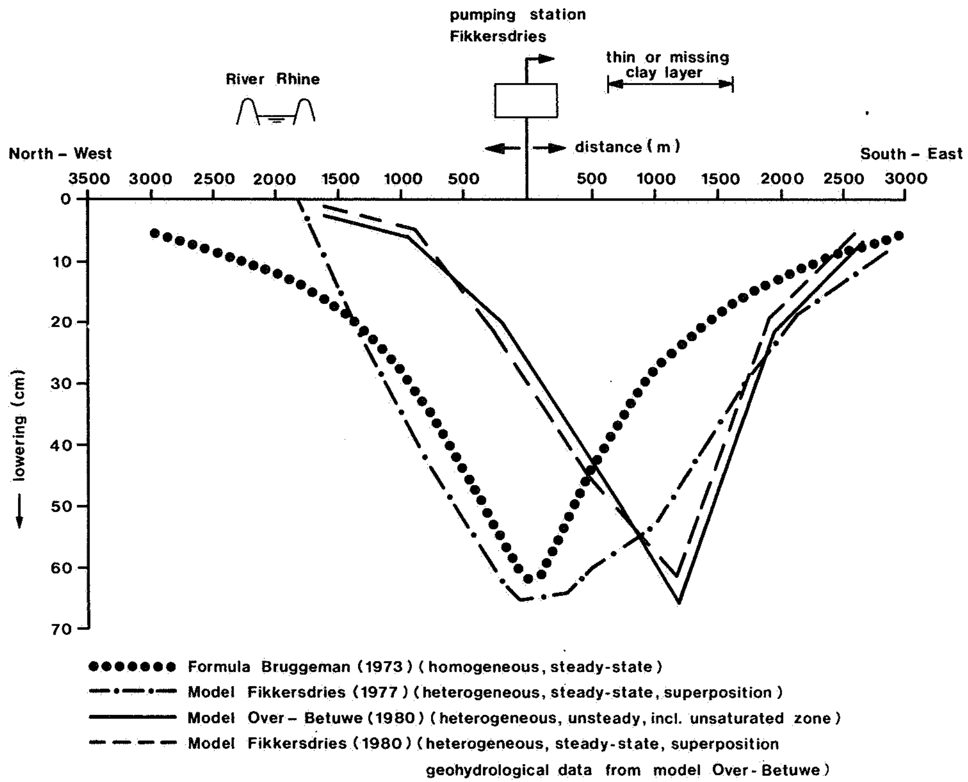


Fig. 19 Calculated lowering of the groundwater heads in the shallow aquifer due to groundwater extraction. The results are given for various model approaches and presented in a nort-west to south-east cross section.

In this way the difference of geohydrological knowledge is excluded. Only the significant difference in the complexity of the model concept remains.

Figure 19 shows the results of the latter model approach which are practically identical to the results of the model Over-Betuwe.

The comparison of various modelling approaches confirms the suggestions from the sensitivity analysis that the model Over-Betuwe is unnecessary complex for calculating the lowering of groundwater heads due to extraction of groundwater in the Over-Betuwe. It shows that practically the same results can be calculated by means of a relatively simple numerical model for saturated flow. Moreover, the simple model used contains linear equations only, so that the principle of superposition can be used.

11. CONCLUSIONS

The object of this paper was to investigate whether it is necessary to use very sophisticated generally applicable models, such as the model Over-Betuwe to simulate the hydrological effects of groundwater extraction in the area of the Over-Betuwe. These effects are commonly expressed in terms of lowering of groundwater heads and a decrease of evapotranspiration.

Based on the sensitivity analysis and comparison of various modelling approaches, it can be concluded that the lowering of groundwater heads by good approximation can be simulated by means of a relatively simple numerical model for saturated groundwater flow. If the variations of the extraction rate are sufficiently small it may be treated as a steady-state flow problem. Moreover, it has been shown that superposition can be applied. The resulting lowering of groundwater heads and thereby the reliability of these values are particularly sensitive to the hydraulic resistances in the system, i.e. the hydraulic resistance of the deep and the shallow semi-permeable layer and the drainage resistance of the surface water system.

Compared to the use of the model Over-Betuwe the simple model approach has a number of advantages. Less input data is required and results are quickly obtained. The calculation problem is fairly clear and manageable. All these advantages help to reduce total costs.

After the lowerings of the groundwater heads have been calculated the effects on the unsaturated groundwater and particularly the evapotranspiration can be calculated separately with a model for the unsaturated system. Thereby the initial phreatic water level (no groundwater extraction) and the lowering of this water level due to the extraction (calculated by the saturated model) can be used as boundary conditions in the separate model for the unsaturated zone.

The conclusions are in principle only valid for the limited problem of simulating the hydrological effects of groundwater extraction in the area of the Over-Betuwe. Because this kind of problem is fairly common in The Netherlands an important question is whether the same conclusions hold for other areas and which are the main hydrological reasons that allow the separate, more simple model approach.

Although it is not the purpose of this paper to discuss this subject in detail it is particularly the ratio between the contributions of the surface water system (reduction of drainage) and the unsaturated system (decrease of evapotranspiration) to the groundwater extraction flow problem that is decisive for treating the unsaturated system separately. In the Over-Betuwe area the contribution of the surface water system (the ditches) is relatively higher then the contribution of the unsaturated system.

Whether the extraction problem in case of a constant extraction rate can be treated as a steady-state flow problem depends mainly on the variability in the total contribution of the top-system (the surface water system and the unsaturated system) in wet or dry hydrological conditions. If for instance, a lot of ditches are dry in summer periods (large variability), the lowering of groundwater heads in winter can differ significantly from the lowering of groundwater heads in summer. In the latter case it should be the storage capacity of the system that decides whether the problem must be treated as a not-stationary flow problem. Obviously in the Over-Betuwe the variability of the total contribution of the topsystem is so small that the problem can be treated under steady-state conditions.

The validity of these conclusions and thereby the most appropriate construction of the conceptual model should be investigated in relation to the hydrological characteristics of each area. The main criteria are given hereabove. For instance, the separate simple model approach for the same kind of extraction problem is in principle not applicable to sandy areas with little effect of surface water. On the other hand the conclusions for the Over-Betuwe are certainly valid for the "polder" areas in the West and North of The Netherlands. These clay or peat areas are characterized by a dense drainage system.

Studies such as described in this paper, whereby a sophisticated model was applied, give a lot of insight into the problem of modelling in relation to the demands of the management problem and the hydrological characteristics of the area.

It was certainly not the intension of the authors to question the practical value of the concept underlying the model Over-Betuwe. The sophisticated concept should be used whenever this use is justified by the management problem. However this paper shows that it is worth-while to strive for simplicity, by always looking for the most appropriate conceptual model in relation to the management problem.

To find the best model demands good and intensive consultation between the hydrologists and all other parties concerned in the management problem. A clear and precise formulation of the hydrological demands from the management problem is also very important.

This paper does not discuss the reliability of model results. However the authors would like to state that the reliability aspect should be one of the most important decision standards for searching the optimal model approach and for collecting the input data. In their opinion the development of mathematical techniques to handle the reliability problem and also consistent calibration techniques for the assessment of model parameters should receive more attention in the hydrological research in The Netherlands.

REFERENCES

BEAR, J. (1979) – Hydraulics of groundwater. McGraw-Hill Inc. London.

BOUMA, J. and L.W. DEKKER (1978) – A case study on infiltration into dry clay soil. I. Morphological observations. Geoderma, 20: 27-40.

BOUMA, J. and J.H.M. WOSTEN (1979) – Flow patterns during extended saturated flow in two, undisturbed swelling clay soils with different macrostructures. Soil Sci. Soc. Am. J., 43: 16-22.

BOUMA, J. and P.J.M. DE LAAT (1981, in press) – Estimation of the moisture supply capacity of some swelling clay soils in The Netherlands. J. of Hydrology.

BRUGGEMAN, G.A. (1972) – Fundamentals of transport phenomena in porous media. Development in Soil Science 2. IAHR.

DE LAAT, P.J.M. and C. VAN DEN AKKER (1976) – Simulatiemodel voor grondwaterstroming en verdamping. In: modelonderzoek 1971-1974, Th. v.d. Nes (ed.), Commissie Bestudering Waterhuishouding Gelderland, Arnhem.

DE LAAT, P.J.M. and R.H.C.M. AWATER (1978) – Groundwater flow and evapotranspiration. A simulation model Part 1. Theory Report Comm. Study. Water Res. Man. Gelderland, Arnhem.

KOVAR, K. (1979) – Gebruik van numerieke modellen. In: Cursus Geohydrologische systemen en exploratietechnieken van de Stichting Postakademische Vorming Gezondheidstechniek, Delft.

KOVAR, K. (1981) – Model description, Model for saturated groundwater flow. In: Model study Over-Betuwe, Deel 2, Report, Comm. Study Water Res. Man. Gelderland, Arnhem.

LEIJNSE, A. and K. KOVAR (1982) – Schematiseringen bij het gebruik van eindige elementen modellen voor grondwaterstroming. RID-Mededeling, Voorburg. (in press)

MATALAS, N.C. and Th. MADDOCK III (1976) – Hydrologic semantics. Water Resources Research, 12 (1): 123.

ROLF, H.L.M. (1981) – Modeltoepassing voor de Over-Betuwe. In: Modelonderzoek Over-Betuwe, Deel 3, Basisrapport Commissie Bestudering Waterhuishouding Gelderland, Arnhem. (in press)

STOFFELSEN, G.H. and J. BOUMA (1979) – Waterwingebied Over-Betuwe (Toelichting op en verwerking van bodemkundige gegevens). Basisrapport. Commissie Bestudering Waterhuishouding Gelderland, Stichting voor Bodemkartering, Wageningen.

YOUNG, P. (1978) – General theory of modelling for badly defined systems. In: Modelling, identification and control in environmental systems, Vansteenkiste (ed.). IFIP, North-Holland Publishing Company, Amsterdam.

USE OF SOIL-SURVEY DATA FOR HYDROLOGICAL SIMULATION MODELS

J. BOUMA, P.J.M. DE LAAT AND A.F. VAN HOLST

SUMMARY

Computer simulation of soil-moisture regimes and associated crop productions within a region requires the use of basic soil data. Basic data are difficult to obtain by measurement due to the high cost involved. Existing soil-survey data, such as soil texture, structure, bulk density, organic matter content and horizon designations, allow satisfactory estimates of basic soil data, as is demonstrated. However, additional field work is needed to obtain data on rooting depth and on properties of the deeper subsoil. In addition, the soil map is indispensable to select the most dominant soil type within each nodal area.

Simulation is not successful in swelling clay soils because the underlying physical theory does not apply. Some soil morphological procedures are discussed which allow a successful application of the existing simulation model in clay soils.

Calculations of productions for varying soil types, which are considered representative for mapping units of the soil map, can be used to demonstrate the effects on production of lowering of the water table within a region. Calculations for a grass crop are made for actual and for lowered water-table levels and they result in many data for varying climatic conditions. Actual water-table fluctuations are estimated from soil-survey data (Gt). Interpretive maps are prepared using the SYMAP computer mapping program. Such maps are helpful for regional planning purposes. Not only agricultural but also ecological effects of lowering of the water table can be considered. Aspects of the physical availability of water, as governed by geohydrological conditions, can also be expressed. Separate SYMAP maps are prepared for each aspect.

In all studies point data have been considered representative for areas of land. A discussion of soil variability demonstrates the feasibility of this approach which uses soil mapping units as "carriers" of physical information, as obtained for representative soil types. But the variability within the mapping units is high.

1. INTRODUCTION

Characterization of natural soil-moisture regimes has always been a central theme in soil survey. Classes of water-table fluctuations (Gt) are being used in the Netherlands (Van Heesen, 1970). Descriptive drainage classes (Soil Survey Staff, 1951) and better defined soil-moisture regimes (Soil Survey Staff, 1975) have been essential ingredients for soil-survey interpretation in the United States.

Adequate characterization of natural soil-moisture regimes is difficult and costly as it requires monitoring over preferably long periods.

Computer-simulation techniques are therefore increasingly used for predictive purposes (e.g. Hillel, 1977; Feddes et al., 1978; De Laat, 1980).

As described in the previous chapters, physical input data such as hydraulic conductivity and moisture-retention curves and data on rooting depth, are used to simulate soil moisture regimes and crop development.

Obtaining input data to characterize the soils in an area is quite laborious because extensive field and laboratory work may be involved. The availability of soil maps provides in principle the opportunity to limit field work by deriving data from soil descriptions but only, of course, if these descriptions contain relevant information. The first purpose of this study was therefore to test the latter aspect by evaluating the usefulness of current soil-survey data for use in simulation models such as GELGAM. An operational sensitivity analysis was performed that implied repeated use of GELGAM in four successive phases, characterized by increasingly quantitative input data. Simulation of the soil-moisture regimes by GELGAM is based on physical laws which describe movement of water in porous media which are stable and homogeneous with respect to the hydraulic properties. Most natural soils in the field do not satisfy these requirements due to stratification, the occurrence of continuous larger pores or to swelling phenomena in clay soils. The *second* purpose of this study was therefore to test the suitability of the existing flow theory for describing moisture regimes of heterogeneous swelling soils and to develop alternative procedures.

The availability of maps which show the regional variation of soil properties and expected soil behaviour is crucial for demonstration and for planning purposes. Traditionally, delineated areas, as shown on the soil map, have been used widely for this purpose (Haans and Westerveld, 1970). Computer techniques are now available to produce various types of maps and the *third* purpose of this study was therefore to demonstrate the use of the SYMAP package for producing various interpretive maps to be derived from the soil map. Use of simulation techniques for the soil-moisture regime and crop production allows generation of quantitative data from which a specific choice can be made. Emphasis will be on the use of these maps for planning purposes.

So far, only point data have been considered as derived for a particular type of soil at a given location. GELGAM requires soil data which should be representative for areas of land, which are also being considered by regional planning. Soil maps contain delineated areas (in mapping units) which are named for a particular type of soil as defined by the map legend. The latter is based on pedological criteria (Schelling, 1970). Soil boundaries are drawn by the soil surveyor and they are based on a from necessity limited number of observation.

It is generally assumed that soils within a delineated area are of the same type and that they behave identically, even though it is recognized that perhaps up to 30% of the area may contain other soil types ("impurities") that may conceivably act differently. An additional complication is introduced by the fact that some soils that are identical from a pedological point of view may act differently in terms of physical behaviour. On the other hand some soils that are different from a pedological point of view may act identically in terms of physical behaviour. The assumption that mapping units are suitable carriers for soil physical data needs therefore to be analysed. This analysis constitutes the *fourth* purpose of this study.

2. BASIC SOIL DATA

As discussed by De Laat (1980), different input data are needed for the simulation model. Many methods are available to measure hydraulic conductivity (K-h) and moisture retention (θ-h) curves. Comprehensive reviews for hydraulic conductivity are presented by Klute (1972) and by Bouma et al. (1980[a]). Many laboratory measurements have been made in the past using columns with sieved aggregates. Unfortunately, data thus obtained are not always representative for field soils. Currently, methods are applied preferably in situ or they are used to measure undisturbed soil cores in the laboratory. Either way, procedures are costly and time consuming. Possibilities have therefore been explored for calculating hydraulic conductivity using moisture-retention data or easily available characteristics (e.g. Bloemen, 1980). These methods yield good results for sandy soils (Dana, 1980), but results for clayey soils are often disappointing (Denning et al., 1974). The best future course would perhaps be to measure directly as many K-h curves as possible and to express their shape afterwards by regression analysis as a function of easily available soil characteristics, such as texture, bulk density and organic matter content. The latter procedure has been followed successfully for moisture-retention data (Poelman and Van Egmond, 1979).

Different methods are available to determine rooting patterns in the soil. Counts on vertical profile walls can be made (Reymerink, 1964) and special augers can be used.

When simulating water extraction from the soil by the crop it is assumed in GELGAM that the rooting density in the root zone is sufficiently high to allow complete lateral extraction of moisture. In practice this may only occur in a strict sense if the lower side of the root zone is bounded by a layer which is impermeable for root penetration. In general the rooting density decreases with depth. In order to use the model conception for the extraction of water by the crop the rooting depth is defined as the level above which 80% of all roots are present (Rijtema, 1971).

As with the physical methods, direct measurement of rooting patterns is time consuming and costly. Soil-profile descriptions as made during soil survey can be used to obtain estimates of rooting depths which are often limited to one or more surface horizons. Use of this procedure as well as the use of estimates for physical data will be evaluated in the next section.

3. OBTAINING BASIC SOIL DATA IN A REGION WITH SANDY SOILS

3.1. *Procedures*

The grid configuration used by the simulation model GELGAM is superimposed on a simplified soil map of the study area 't Klooster in figure 1. Data and simulated values at a particular node are representative for a small square sub-region, the nodal area. The size of the nodal area of the internal mesh points is 25 ha. Basic soil data for each of the 169

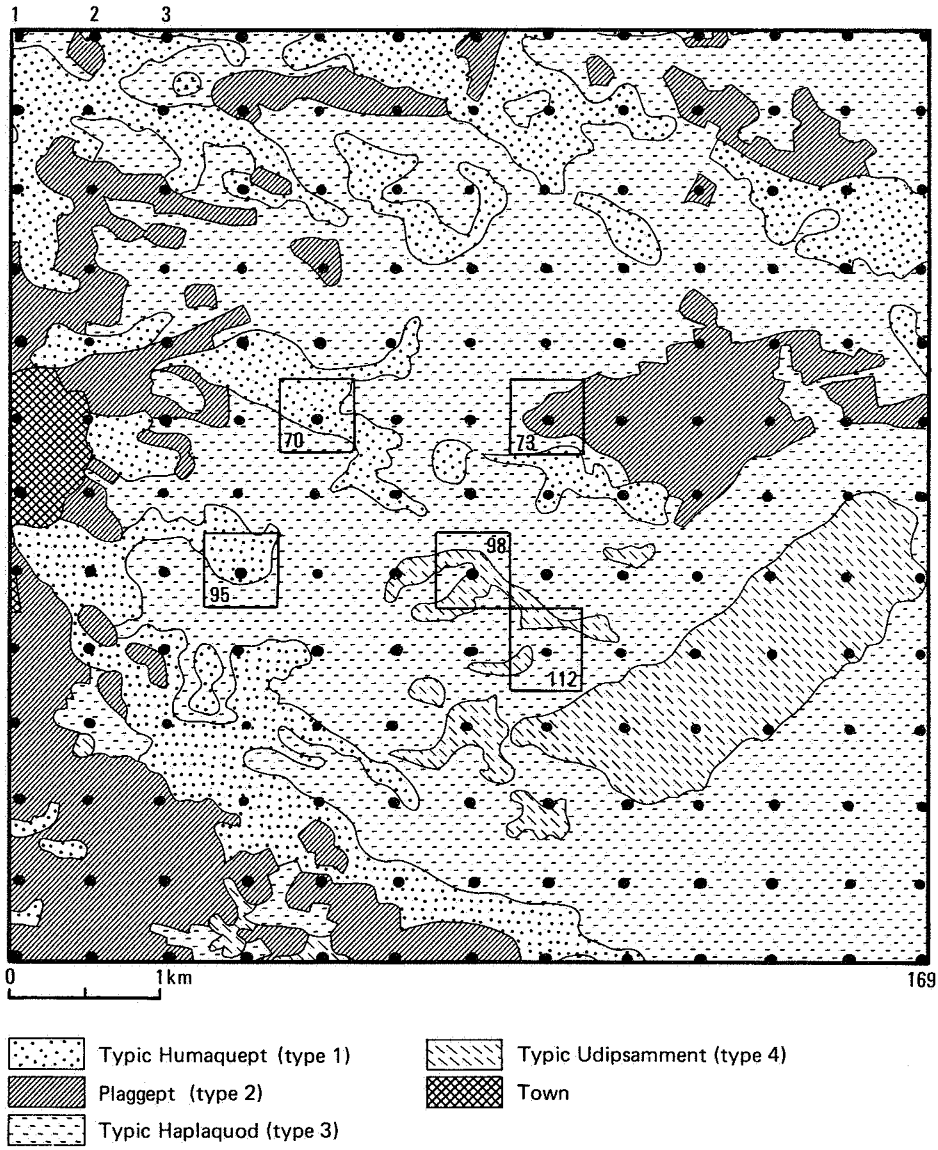


Fig. 1 Simplified soil map showing four major types of soil in the study area 't Klooster (3600 ha). The points constitute the grid used for the simulation model. For the five nodes considered, (numbers 70, 73, 95, 98 and 112) the corresponding nodal area is indicated. Basic soil data for each nodal area are derived for the soil type which occupies the largest region within each nodal area.

nodal areas were derived in terms of the properties of the soil type occupying the largest region within the respective nodal area. The average elevation of each nodal area with respect to sea level was determined using topographic maps. For this paper five nodal areas were selected, as indicated in figure 1, representing four major types of (sandy) soils in the study area. Type 1, representative for nodal area 70 and 95, is classified as a Typic Humaquept (Beekeerdgrond). Type 2 for nodal area 73 is a Plaggept (Enkeerdgrond) en type 3 for nodal area 112 is a Typic Haplaquod (Veldpodzolgrond) and type 4 for nodal 98 is a Typic Udipsamment (Duinvaaggrond). All soils belong to sandy, siliceous and mesic families (Soil Survey Staff, 1975). Detailed profile descriptions are provided by De Bakker (1979). An existing detailed soil map (scale 1:25000) was used to determine the most dominant soil type within each nodal area of 25 ha. Four successive procedures, which constitute an operational sensitivity analysis focused on the use of soil survey data in computer simulation, were followed to collect basic data for the GELGAM model as discussed by De Laat (1980).

The operational sensitivity analysis involves the following four phases. *Phase 1*: An identical soil is used for all nodal areas. Soil type 3 was chosen since it occurs most widely in the study area. Estimates of physical data for soil type 3 were obtained as in phase 2. *Phase 2*: Basic data are derived from the soil map (and accompanying report) by estimates based on detailed profile descriptions for each soil type. Estimates of physical data are based on measurement results obtained elsewhere in comparable soils by empirical extrapolation using soil texture, organic matter content and bulk density data as discussed by Bouma et al. (1980[b]).

In contrast to the first two phases, for which no field work is involved, one boring is made in the largest mapping unit within each nodal area in *phase 3* to allow a more reliable estimate of basic physical data (using better values for texture, organic matter content and bulk density because the soil is observed in situ). Observations of rooting depth are also made. Physical data, as discussed, are finally measured in *phase 4* in the field and the laboratory.

Soil-survey data are gathered by the soil surveyor who makes many borings as he walks through the field. His description of soil variability within given mapping units of the soil map may be more realistic than a description of a single boring as made in the context of phase 3. This aspect was investigated (at the end of the original study) by making at least ten borings in the area occupied by the representative soil in each of the five nodal areas. Boring were made in a square grid pattern (100 m x 100 m) to ensure at random observations. Procedures for making estimates for basic physical data and rooting depth were identical to those described earlier for phase 3.

The sequence for phase 1 through phase 4 obviously implies a strong increase of costs as more procedures become involved. Relative costs in relation to those of phase 1 are indicated in table 1. The costs of collecting data, using the complete phase 4 approach, could well be prohibitive for routine use of the simulation model. Development of simpler, yet still acceptable procedures is therefore of practical significance. The comparison of the different phases constitutes an operational sensitivity analysis, which differs from a conventional one where only one parameter is changed at a time while all

Table 1. Summary of the four phases of data gathering discussed in this paper including an estimate of relative costs (for 169 nodal areas)

Phase	Work type	Rooting depth	Physical data	Relative cost
1	Office (identical soil for each nodal area	estimate	estimate	1
2	Office (use of soil map)	estimate	estimate	30
3	Office + field (one boring per nodal area)	observation	estimate	400
4	Office + field + lab. (one set of measurements per nodal area)	observation	measurement	1000

other parameters remain constant. In the operational sensitivity analysis more than one parameter may differ when two phases are compared. The conventional analysis is still needed if the specific effect of single factors has to be known (see De Laat, 1980).

3.2. *Results*

As demonstrated by De Laat et al. in this issue, the soil moisture regime of sandy soils can be analysed and predicted quite satisfactory using the GELGAM simulation program. Detailed results of the study on using soil survey data for GELGAM are presented by Bouma et al. (1980[b]). They can be summarized as follows:

- Soil-survey descriptions of surface-soil horizons allow accurate predictions of textures, bulk densities and organic matter contents and therefore of h-θ (moisture retention) curves.
- Estimates of h-θ and K-h relations for the upper part of the subsoil demonstrate variable conditions within the mapping units considered. However, estimates of phase 2 agree, without exception, better with the observed population of ten borings than those based on the one boring in phase 3.
- Rooting depth varies considerably within each nodal area. The observed average depth among the borings are close to the estimates of phase 2 and these, in turn, are as good as the observed values based on one boring in phase 3 (table 2). However, the observed variation among the borings in each mapping unit is significantly larger than the differences between the original phase 2 and 3.

Use of soil-survey data in this study was useful for two reasons:

- Use of soil maps was essential to obtain representative soils for each nodal area (fig. 1).
- Realistic estimates for physical data and rooting depth were obtained.

But estimates for physical data proved to be inadequate for the deeper subsoil which is largerly beyond the solum, which extends to about 80 cm below surface in many soils. Future soil-survey studies should therefore include a more complete characterization of subsoils, at least to the depth of fluctuation of the water table.

Table 2. Observed and estimated thicknesses of root zones using at random borings within representative mapping units and the phase 2 and phase 3 approaches

Nodal area	Number of borings	Root zone (cm)		
		thickness (average + range)	phase 2	phase 3
70	19	29 (22-50)	30	30
73	8	84 (60-120)	100	90
95	11	29 (25-59)	30	20
98	9	23 (15-65)	20	20
112	13	40 (30-50)	40	40

Rooting depth proved to be a very important feature due to the character of the simulation model. As such, rooting is not discussed extensively in soil survey reports. However, correlation with depths of soil horizons, as derived from profile descriptions, provides reasonable estimates when compared with field observation. But even small differences of ten centimeters yield significant differences in evapotranspiration of 30 to 40 mm water (Bouma et al., 1980^{b}). Increased emphasis on the observation of rooting patterns in major soils will be necessary in future soil-survey research. However, when considering field variability (table 2) one can hardly expect that such studies would allow more "exact" estimates for large-size nodal areas than the ones obtained in this study using soil survey data. The particular aim to obtain representative data for mapping units requires therefore a special approach which establishes the degree of variability observed. *Conclusions and classifications to be derived should not exceed the level of generalization to be dictated by the natural variability of the unit of study*. Data gathering for the particular study discussed here would, in retrospect, have been most efficient by using the phase 2 approach for all nodal areas and by selective use of the phase 3 and 4 approach in major mapping units. This procedure would involve a saving of an estimated 50% as compared with a systematic phase 3 approach with one boring in each nodal area and some selected physical measurements.

The study reported here is based on the availability of a detailed soil map and many soil physical data. Often less data will be available. In that case a detailed soil survey can be made in which rooting depth and subsoil properties receive attention.

4. CHARACTERIZING SWELLING CLAY SOILS

Flow theory on which GELGAM is based, assumes that soils are rigid and homogeneous with respect to the hydraulic properties. These conditions are closely satisfied in sandy soils where GELGAM produced good results. Clayey soils swell upon wetting and shrink upon drying. They consist of large natural aggregates ("peds") which are mutually seperated by cracks with ever changing dimensions. Part of the natural precipitation flows

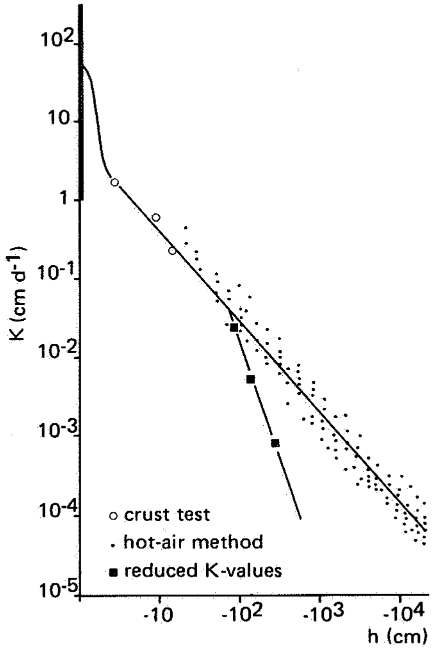


Fig. 2 Hydraulic conductivity (K) data, measured with the column method (K_{sat}), the crust test and the hot-air method. The indicated range for K_{sat} is based on some 80 measurements with the column method. The reduced K values are due to the formation of horizontal cracks upon drying of the clay soil. Reduced values were determined with a new staining technique (Bouma and De Laat, 1980).

rapidly downwards along the vertical cracks without moistening the interior of the peds ("short-circuiting") (Bouma and Dekker, 1978; Hoogmoed and Bouma, 1980). Horizontal cracks will not allow upward movement of water from the water table to the rootzone.

The soil-moisture regime of a heavy clay soil was simulated to investigate these processes. Measured physical data were used (phase 4 approach, see section 3.1) Recorded levels of the water table in the summer of 1979 were used as the lower boundary condition. The model for unsaturated flow, which is part of GELGAM, was applied to simulate the moisture regime (see next section). Validation was based on the comparison of calculated and measured moisture contents and pressure potentials as reported by Bouma and De Laat (1980). Results, as shown in table 3, were poor when applying the standard model. Calculated moisture contents were much higher than the measured ones. Techniques were developed to express the effects of vertical and horizontal cracking. A summary will be presented here. The reader is referred to Bouma and De Laat (1980) for details. The amount of short-circuiting was estimated by considering the occurrence of heavy and very heavy rains in proportion to total rainfall. Heavy and very heavy rains are most likely to short-circuit and thus they do not contribute to the moisture supply for plants. A field procedure was developed to stain horizontal cracks. The stained area

Table 3. Validation of the simulation model for water movement in clay soil. The standard simulation model uses first a measured K curve and measured precipitation and evaporation data for 1979. The reduced K represents the effect of horizontal cracking (fig. 2) and short-circuiting represents the effect of vertical cracking (see text). The values represent the result of simulation and field measurement in the test soil at a depth of 20 cm below surface, which is the lower boundary of the root zone.

	Calculations				Field measurement	
Date (1979)	measured K no short-circuiting		reduced K short circuiting			
	h(-cm)	θ (cm^3 cm^{-3})	h	θ	h	θ
26-6	34	0,52	120	0,50	100	0,50
19-7	50	0,51	2400	0,43	8000	0,41
1-8	320	0,48	16000	0,38	10000	0,40
13-8	60	0,51	2000	0,43	2000	0,43
30-8	160	0,49	2600	0,43	2000	0,43

increases with decreasing moisture content and pressure head due to progressive cracking. A number of measurements of different moisture contents are made and these allow a modification of the measured K curve. The latter is still valid for the peds, while the reduced K must be used to calculated upward flow of water (fig. 2). Good simulation results are obtained with the modified model (table 3).

Flow through swelling porous media is the subject of many theoretical investigations which show little promise so far for practical application. The procedure developed here is attractive because the conventional simulation model can still be used while input data are modified according to independent, specifically defined procedures. These involve staining of pores and their observation. This aspect is essential. Descriptions of soil structure, as provided by the soil-survey report are *not* informative enough to be used for modification of the traditional simulation model.

5. SHOWING REGIONAL DIFFERENCES IN SOIL MOISTURE REGIMES FOR PLANNING PURPOSES

5.1. *Introduction*

Regional differences in soil-moisture regimes and associated crop productions must be known to allow planning of good water management practices. Simulation programs, as discussed in this issue, can help to specifically define those regimes. In addition, they have particular value for predicting the effects of changing regimes, for example, following groundwater extraction. This may result in reduced crop yields due to reduced flow of water from the water table to the rootzone. Different soil types are bound to react differently to a receding water table, due to differences in rootzone thickness, and in soil physical characteristics. Specific knowledge about these reactions is essential for planners who have, for example, to select future locations of pumping stations for potable water supply. Such locations should preferably result in relatively little yield reductions for agriculture. Of course, other considerations regarding the ecological vulnerability of an area and the geohydrological availability of the water should also be part of the decision process. All three aspects mentioned require means to show regional distribution patterns. Delineations on the soil map are particularly suitable to show at least some of these patterns as will now be discussed. A more detailed account is presented by Bouma (1979) and Bouma et al. (1980[c]).

5.2. *Calculation procedures*

The part of GELGAM concerning unsaturated flow is used to simulate the soil-moisture regime. It describes vertical flow in the subsoil by a combination of steady-state situations corresponding to the upper and lower boundary flux q_c and q_w respectively. For prescribed boundary flux conditions (q_s at soil surface and q_w from below the water table) transient unsaturated flow is simulated by a sequence of steady-state situations, yielding the flux q_c and the water-table depth w.

The upper boundary flux condition q_s is given by

$$q_s = E_{pot} - R \qquad (1)$$

where E_{pot} is the potential evapotranspiration and R the rainfall rate. It is assumed that the actual flow across the soil surface $q_s{}^*$ equals q_s until the rootzone desiccates to wilting point (h = –16000 cm). For the latter situation $q_s{}^* = q_c$ so that the actual evapotranspiration rate E_{act} follows from

$$E_{act} = R + q_s{}^* \qquad (2)$$

For the simulation of the actual situation in the growing season of 1979 (Bouma and De Laat, 1980), recorded water-table depths were used to serve as the lower boundary condition, while at the soil surface daily q_s values were computed from measured rainfall and evaporation data. When using statistically derived climatic data, actual evapotranspiration rates are calculated for a growing season of 150 days, starting at April 15. The initial condition in the unsaturated zone corresponds with an equilibrium situation. The growing period is divided into 10 time steps of 15 days each. From an analysis of potential evapotranspiration and rainfall data q_s values are derived for the following frequency of occurrence per 100 years: 1, 10, 20, 50, and 90. A set of ten q_s values derived for a frequency of once in 100 years is said to represent a 1% dry year, as the probability that these values are exceeded is only 1%.

Average depths to water table at the beginning and end of the growing season (w_b and w_e respectively) are obtained from soil-survey data (e.g. Van Heesen, 1970).

The lower boundary flux condition q_w is assumed a constant during the considered period. An iterative application of the simulation model, subject to the set of q_s values for a 50% dry year, allows q_w to be solved so that the simulated water-table depth equals w_e at the end of the growing season.

If crop production is not restricted by water supply, the total actual evapotranspiration at the end of the growing season (ΣE_{act}) equals the total potential evapotranspiration (ΣE_{pot}). From data presented by Rijtema (1971) the following expression is derived for the relative fractional production P of a grass crop:

$$P = (\Sigma E_{act}/\Sigma E_{pot})^2 \qquad (3)$$

The average production $\overline{P}$ (%) is computed as follows (Rijtema, 1971). The simulation model is applied subject to appropriate boundary conditions to compute for the 1, 10, 20, and 50% dry year ΣE_{act}, which is used to calculate P with (3). It is found that no large errors are introduced if the lower boundary flux condition q_w as derived for the average year is also used for years with a different frequency of occurrence. In a 90% dry year (wet conditions) potential production is assumed (P = 1). The average production $\overline{P}$ is then found by integrating P over the frequency of years.

The above procedure is repeated for the following set of water-table drawdowns: 10, 25, 50, 75, 100, 150, 200 and 300 cm. Each drawdown applies to both w_b and w_e. As a result a relation is obtained between the average production $\overline{P}$ and the drawdown of the water table (see fig. 3).

5.3. *The effects of lowering of the water table in different soils*

Six soil types with a wide range of soil-moisture regimes and physical properties were selected from a larger series which was used for the general study. Some major data are summarized in table 4. Physical characteristics have been generalized in terms of poor, medium and good. The terms for the K curves refer to the potential for upward flow of water from the water table to the root zone. Exact data are presented by the two papers cited in section 5.1. Simulation involves the calculation of relative transpiration and production for actual water-table fluctuations (table 4) and for a series of lowered levels. It is assumed that the drawdown at the beginning of the growing season equals the drawdown at the end of the growing season.

The simulated average production is expressed as a percentage of the potential production which can be achieved when water availability is not limiting. Actual conditions are characterized as well as those resulting from lowering of the water table (fig. 3). Average productions for actual conditions of water-table fluctuations decrease from high to low in the following sequence: Soil 2 (100%), 4 (98%), 3 (97%), 5 (94%), 6 (93%) and 1 (67%). Exact verification with measured yields is not possible because results of well controlled experiments on the different soils are not available and different yields on different farms, as such, are not only determined by differences in soil moisture regimes

Table 4. Six soil types with associated water-table fluctuations which are used to calculate the moisture supply capacity for natural conditions and for lowered levels of the water table (see fig. 3)

Soil	Classification	Root-zone (cm)	Moisture retention surface soil	K curve (upward flow) subsoil	Water-table fluctuation (cm – surface)
1	Typic Udipsamment (sandy) (Duinvaaggrond)	20	poor	poor	130 to 200
2	Typic Fluvaquent (fine loamy) (Ooivaaggrond)	40	good	good	60 to 140
3	Plaggept (sandy) (Enkeerdgrond)	80	medium	poor	130 to 200
4	Typic Humaquept (sandy) (Beekeerdgrond)	30	medium	medium	50 to 110
5	Typic Haplaquod (sandy) (Veldpodzol)	40	poor	medium	60 to 140
6	Typic Haplaquept (fine loamy) (Poldervaaggrond)	40	good	poor	50 to 110

but also strongly by the farmer's management. Besides, reliable records for many years would be needed to allow an estimate of yields in an "average" year. However, the sequence observed is in agreement with practical field experience.

Lowering of the water table has little effect in soils 1 and 2 for quite different reasons. Initially there is already little upward flow to the shallow root zone in soil 1 with a deep water table. Upward flow is higher in soil 2 which has a higher water table and a "good" K curve for the subsoil. The upward flow rate remains high, even when the level of the water table is lowered.

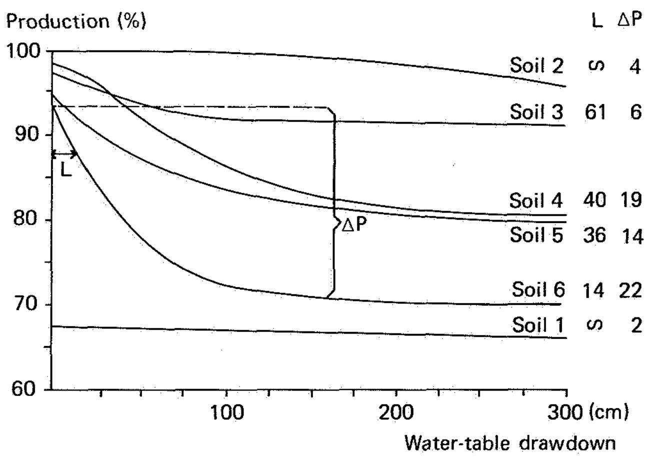


Fig. 3 Relative productions for six soils at natural depths to water table and following drawdown to a maximum of 3 m. The curves are characterized by L and ΔP values as defined in text.

Average productions drop most strongly in soil 6, followed by soils 4, 5 and 3 respectively. These four soils have about the same fluctuations of the water table during the growing season. One reason for the pronounced drop in soil 6 is the relatively "poor" K curve of the subsoil which allows little upward flow at lower depths to water table. Besides, the limited volume of water which is initially available in the soil surface results in a rapid depletion and increases the relative importance of upward flow from the water table.

The drop in production in soils 4 and 5 is less than in soil 6 because there is more water available in the root zone at the beginning of the growing season and the K of the subsoil is "better". Production for soil 3 is rather insensitive to lowering of the water table due to the relatively deep root zone which has much available water. Upward flow of water from the water table is less important here. The reaction of the different soils to lowering of the water table has been discussed so far in a qualitative manner. A classification system was devised to allow a quantitative expression of the phenomena observed.

5.4. *A soil-sensitivity classification*

The graphs for the average production (fig. 3) are used to derive two criteria:

- the distance L by which the water table must be lowered to produce an absolute production loss of 5% and
- the maximum loss of production (ΔP) which can occur as a result of lowering of the water table (see example for soil 6 in fig. 3).

Small L and large ΔP values are indicative for a relatively high sensitivity for lowering of the water table. Values derived for the six soils, which are considered here, show very high L and low ΔP values for soils 1 and 2 and increasing L and decreasing ΔP values for the sequence: soil 6, 4, 5 and 3 (the criteria are close for soils 4 and 5). The trends observed correspond with the visual evaluation discussed earlier. A classification can be made using the defined L and ΔP criteria. Maps can be made then which show the relative impact on production of drawdown of the water table in a number of arbitrarily selected classes. The use of storage and retrieval facilities of computers for producing such maps is particularly advantageous because all basic data for the soils and the associated calculations for evapotranspiration and equivalent productions can be manipulated at will. An example of such a map, which was prepared using the SYMAP program (SYMAP, 1975), is shown in figure 4. The most dominant soil type is square elements of 1 km^2 each within the area to be investigated was determined using a soil map. Basic data in terms of h-θ and K-h and rooting depths were assigned to each soil type and the average fluctuation of the water table during the growing season was estimated, as already discussed. Identical soils usually occur in several elements in a large area of land. The number of calculations is therefore much less than the number of elements.

Simulation results obtained with the unsaturated flow model for a series of water-table drawdowns (fig. 3) are used to derive values of L and ΔP for each of the elements.

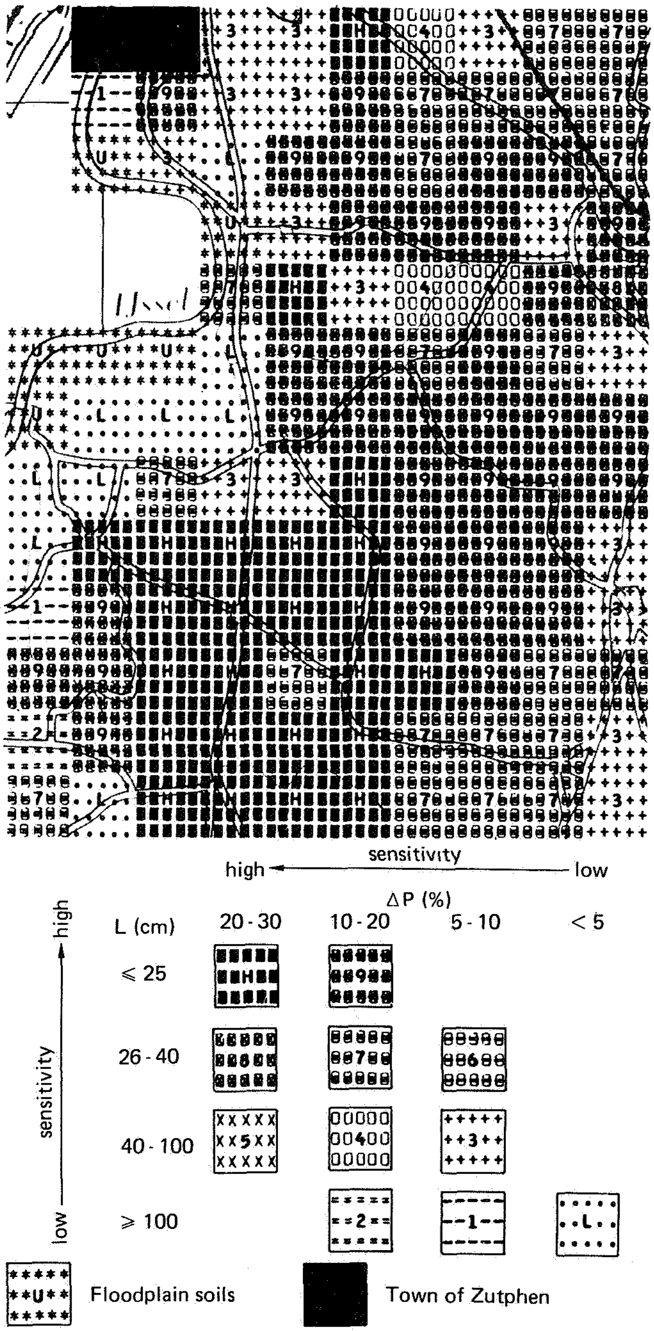


Fig. 4 SYMAP computer map of an area of 119 km² (each block is 1 km²) which shows relative soil sensitivity to water-table drawdown, expressed in eleven classes based on L and ΔP values. Use potential for groundwater extraction (considering agricultural production only) is relatively high when the sensitivity is relatively low.

The map fragment in fig. 4 distinguishes eleven degrees of soil sensitivity for drawdown of the water table. The six soil types discussed, or strongly related types, appear in the area shown. Their classification can be derived from their L and ΔP values (fig. 3) and the legend of (fig. 4). Use of computer facilities allows preperation of large maps. For example in a recent project maps were made (scale 1:100 000) for a 5 000 km^2 area (Bouma, 1979). Such large maps are suitable for broad land use planning purposes.

The selection of the L and ΔP criteria, as defined, was arbitrary. Many other differentiating criteria could have been selected using the basic data of the dominant soil in each element and the calculation results which are readily accessible by computer. The present system is therefore more flexible than the traditional system for soil-survey interpretation, as it does not result in a single judgement but, rather, in the possible listing of a wide variety of possibilities which are all based on quantitative and reproducible calculations. The user is given a choice rather than a judgement.

The overall purpose of this study is to define the locations of areas where extraction of water is expected to cause little agricultural damage. Maps are prepared in cooperation with specialists of other disciplines to show the technical availability of water (which is determined by geohydrological conditions) and the ecological vulnerability of the land in the different elements (see Bouma, 1979). Modern decision making procedures can be used then by planners to arrive at final plans or a series of alternative plans, which always represent some compromise among conflicting interests.

5.5. *The soil-variability problem*

In the examples discussed so far certain soils types are considered to be representative for areas of land as delineated on a soil map. The discussion in section 3.2 demonstrated a high variability within a mapping unit, but also that the descriptions of the mapping unit, as provided by the survey report, were satisfactory as "carriers" of basic data for simulation. A more fundamental evaluation of the aspect of soil variability would still seem to be necessary. This is particularly true because of newly developed statistical interpolation techniques which use point data, to be derived from soil borings, to predict spatial variability (e.g. Nielsen et al., 1980). Three interpolation techniques were applied in a recent study (Van Kuilenburg et al., 1981). Three interpolation techniques were applied for predicting the soil moisture supply capacity. Standard deviations were high, due to the natural variability of relevant soil characteristics. In fact, use of soil mapping units as "carriers" of this type of information, resulted in identical standard deviations. At least in this study, interpolation techniques did not allow better estimates of the spatial variability than those obtained by using the mapping units of the soil map. More studies of this type are needed to further evaluate soil variability aspects.

REFERENCES

BAKKER, H. de (1979) – Major soils and soil regions in The Netherlands. Pudoc, Wageningen/Junk, Den Haag. pp. 203.

BLOEMEN, G.W. (1980) – Determination of unsaturated flow properties of soils from texture and organic matter content. I Calculation of hydraulic conductivity. Instituut voor Cultuurtechniek en Waterhuishouding, Wageningen.

BOUMA, J. (ed.) (1979) – Overzichtskaarten betreffende aspecten van de waterhuishouding in Gelderland. Rapport nr. 1434. Stichting voor Bodemkartering, Wageningen. pp. 36.

BOUMA, J. and L.W. DEKKER (1978) – A case study on infiltration into dry clay soil. I Morphological observations. Geoderma 20: 27-40.

BOUMA, J. and P.J.M. DE LAAT (1980) – Estimation of the moisture supply capacity of some swelling clay soils in The Netherlands. J. of Hydrology.

BOUMA, J., R.F. PEATZHOLD and R.B. GROSSMAN (1980a) – Application of hydraulic conductivity measurements in soil survey. Soil Cons. Service USDA. Soil Survey Investigation Report (in press).

BOUMA, J., P.J.M. DE LAAT, R.C.H.M. AWATER, A.F. VAN HOLST, H.C. VAN HEESEN and Th.J.M. VAN DE NES (1980b) – Use of soil survey data in a simulation model for predicting regional soil moisture regimes. Soil Sci. Soc. Amer. J. 44: 808-814.

BOUMA, J., P.J.M. DE LAAT, A.F. VAN HOLST and Th. J.M. VAN DE NES (1980c) – Predicting the effects of changing water table levels and associated soil moisture regimes for soil survey interpretations. Soil Sci. Soc. Amer. J. 44: 797-802.

DANE, J.H. (1980) – Comparison of field and laboratory determined hydraulic conductivity values. Soil Sci. Soc. Amer. J. 44: 228-232.

DENNING, J.L., J. BOUMA, O. FALAYI and D.J. VAN ROOYEN (1974) – Calculation of hydraulic conductivities of horizons in some major soils in Wisconsin. Geoderma. 11: 1-16.

FEDDES, R.A., P.J. KOWALIK and H. ZARADNY (1978) – Simulation of field water use and crop field. Simulation monograph. Pudoc, Wageningen. pp. 189.

HAANS, J.C.F.M. and G.J.W. WESTERVELD (1970) – The application of soils survey in The Netherlands. Geoderma 4: 279-311.

HEESEN, H.C. VAN (1970) – Presentation of the seasonal fluctuation of the water table on soil maps. Geoderma 4: 257-279.

HILLEL, D.I. (1977) – Computer simulation of soil water dynamics. Int. Development Res. Centre, Ottawa. pp. 320.

HOOGMOED, W.B., and J. BOUMA (1980) – A simulation model for predicting infiltration into cracked soil. Soil Sci. Soc. Amer. J. 44: 458-462.

KLUTE, A. (1972) – The determination of the hydraulic conductivity and diffusivity of unsaturated soils. Soil Science 113: 264-276.

KUILENBURG, J. VAN, J.J. DE GRUYTER, B.A. MARSMAN and J. BOUMA (1981) – Obtaining regional estimates of the soil moisture supply capacity from point data. Geoderma (in prep.).

LAAT, P.J.M. DE (1980) – Model for unsaturated flow above a shallow water table, applied to a regional sub-surface flow problem. Agric. Res. Rep. 895. Pudoc, Wageningen. pp. 126.

NIELSEN, D.R., J. METTHEY and J.W. BIGGAR (1980) – Soil hydraulic properties, spatial variability and soil water movement. Chapter 3 in: Simulating nutrient transformation and transport during land treatment of waste water. John Wiley, New York (in press).

POELMAN, J.N.B. and Th. VAN EGMOND (1979) – Uit eenvoudige grootheden af te leiden pF-waarden voor de zee- en rivierkleigronden. Stiboka rapport 1492.

REYMERINK, A. (1964) – Een verbeterde methode voor bewortelingsonderzoek. Meded. Dir. Tuinb. 27: 42-49.

RIJTEMA, P.E. (1971) – Een berekeningsmethode voor de benadering van de landbouwschade ten gevolge van grondwateronttrekking. Nota 587. Instituut voor Cultuurtechniek en Waterhuishouding, Wageningen. pp. 46.

SCHELLING, J. (1970) – Soil genesis, soil classification and soil survey. Geoderma 4: 165-195.
SOIL SURVEY STAFF (1951) – Soil Survey Manual. USDA Handbook no. 18 Wash. D.C. pp. 593.
SOIL SURVEY STAFF (1975) – Soil Taxonomy. A basic system of soil classification for making and interpreting soil survey. SCS-USDA. Agr. Handbook no. 436, pp. 750.
SYMAP (1975) – SYMAP user's reference manual. Laboratory for computer graphics and spatial analysis. Cambridge Mass. USA.

THE IMPACT OF REGULATION ON THE NATURAL CHARACTERISTICS OF DUTCH LOWLAND STREAMS

J.J.P. GARDENIERS

SUMMARY

A survey is given of the condition of the dutch lowland streams regarding their natural stream character that is destroyed by stream regulation. To assess this condition an assessment method is used, that measures the stream character by means of the composition of the macrofauna community.

The results of the survey give a rather negative picture of the condition of the streams of The Netherlands. Only about 5% of the streams has a (semi) natural stream character and even these 5% of the streams are threatened by regulation works.

1. INTRODUCTION

In the northern, eastern and southern parts of the Netherlands lowland streams are an important and characteristic element of the landscape.

Nearly all the streams flow through agricultural districts. To keep streams from flooding and to lower the groundwater level in marshy areas many streams have been regulated.

A survey will be given of the effects of regulation on the macrofauna in the streams. Further the present condition of the lowland streams in The Netherlands will be evaluated.

2. LOWLAND STREAMS

2.1. *Characteristics*

The greater part of the running waters in The Netherlands belongs to the lowland stream-type. Compared with mountain streams they have a smaller slope and a lower current velocity. The discharge fluctuates strongly with precipitation because the lowland streams for the greater part are fed by superficial groundwater.

In summer current velocity varies from 5 to 20 cm/s and in winter from 30 to 60 cm/s, with peaks up to 100 cm/s after heavy rainfall (Moller Pillot, 1971; Tolkamp, 1980). Differences in current velocity in the cross section of the stream give rise to meandering. The streambed becomes asymmetrical, one bank is gently sloping, the other one steep or even undercut.

The composition of the bottom substrate is directly dependent on this dynamic flow pattern. The sorting activity of the current brings about a continually changing mosaic pattern of substrate types. The grain size composition may vary from gravel and coarse sand in places with a strong current, to fine sand, silt and detritus in more quiet places.

The unstability of the bottom and the interception of the sunlight by the shrubs and trees along the banks, prevent the aquatic plants from forming a dense vegetation.

The present aspect of the lowland streams in The Netherlands is the result of management by man for centuries: aquatic plants were cut a few times a year, caved-in banks were repaired, sandbanks and fallen trees were removed. In many streams water-mills were built. These management operations were small-scaled. Every time the stream could recover from the man-made disturbances.

2.2. *Regulation*

Since the thirties of this century the lowland streams of The Netherlands have been regulated on an ever bigger scale to improve drainage in connection with re-allotment of agricultural land.

The regulation of the streams does mean a straightening, widening and deepening of the streambed. Sometimes a complete new canal is dug and the old stream is filled in (figures 1, 2, 3, 4 and 5).

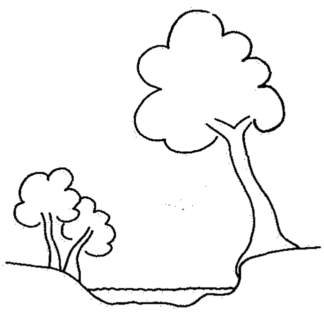


Fig. 1 A. Cross section of a natural unregulated lowland stream. The width is about 5 m.

Fig. 1 B. Natural unregulated lowland stream, view from above.

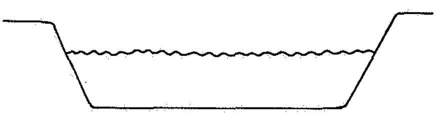


Fig. 2 A. Cross section of a regulated lowland stream. The width is about 10 m.

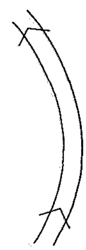


Fig. 2 B. Regulated lowland stream with weirs, view from above.

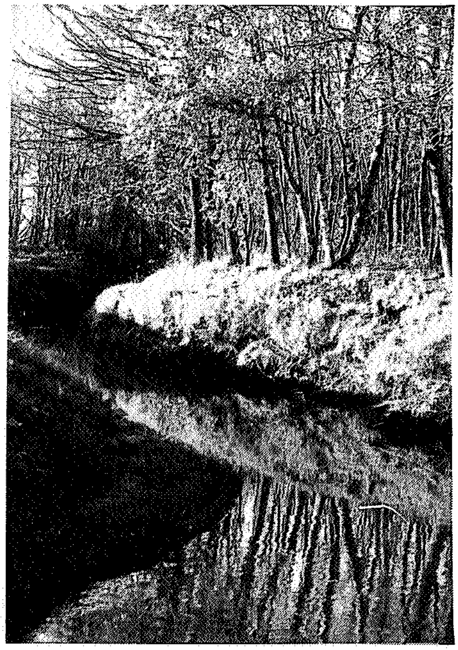


Fig. 3 A natural unregulated lowland stream.
photo by C. de Pater

Fig. 4 A regulated lowland stream.
photo by H.H. Tolkamp

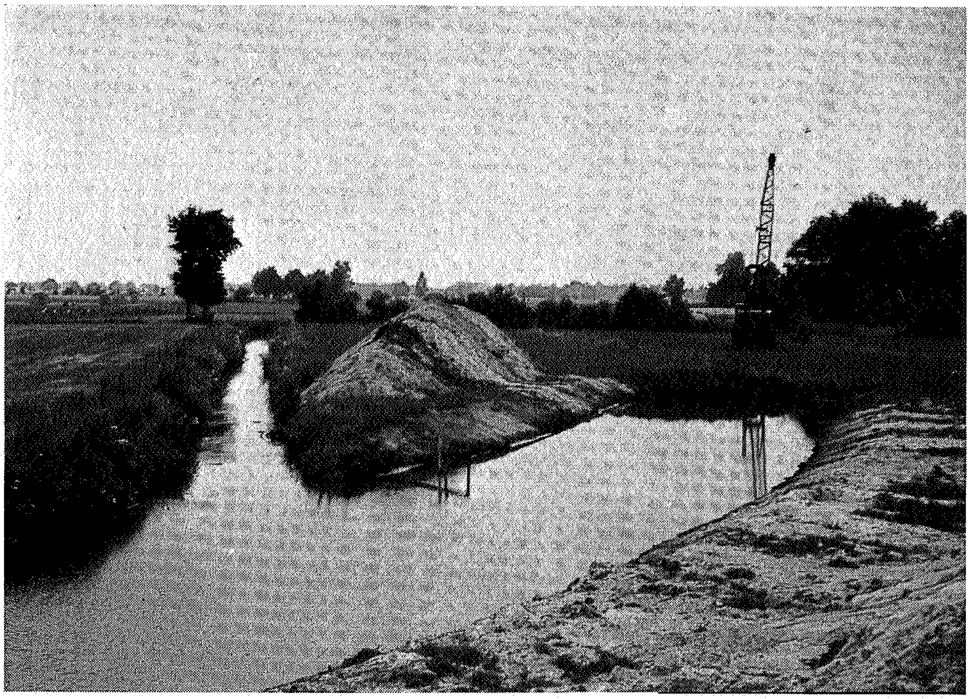


Fig. 5 Regulation in action. To the left the original lowland stream De Beerze (province of Noord Brabant), to the right the new "stream". After completion of the regulation the old stream was filled in.
photo by J.J.P. Gardeniers

The demands made upon a regulated stream are:

- a straight course with standardized slope of the banks, sometimes reinforced with nylon matting or concrete blocks, to assure an unhampered discharge;
- a low current velocity even at times when the discharge is high, to prevent sand transport and undercutting of the banks;
- the possibility to hold the water by weirs in times of low discharge;
- removal of the vegetation along the banks for the construction of "inspection-paths" to facilitate the mechanical cutting of the aquatic plants.

These demands are the reverse of the main characteristics of a typical lowland stream. Most factors are changed in dimension, some are even changed on the main point. The disappearance of meandering and the reduction of fluctuations of the water level and the current velocity lead to a uniform and mostly muddy bottom.

The greater part of the year the current velocity is below the level needed for a lasting running water community. The stable bottom, the better light conditions and the rather constant water level give rise to dense growths of aquatic plants. In summer the photo-synthetic activity and the respiration of these plant-masses lead to big fluctuations of the oxygen content of the water. During the day the water becomes supersaturated with oxygen, while at night the values are very low.

3. STREAM FAUNA

3.1. *The macrofauna community*

The macrofauna forms a characteristic and important part of the animal community of a lowland stream. Macrofauna is defined as the benthic macro-inertebrates living on or in the bottom and on aquatic plants. Their size is from one millimeter to a few centimeters. The macrofauna community may consist of a few hundreds of species, belonging to the following taxa: *Tricladida* (flatworms), *Oligochaeta* (worms), *Hirudinea* (leeches), *Crustacea* (freshwater shrimps), *Diptera* (fly- and midgelarvae), *Ephemeroptera* (mayflies), *Plecoptera* (stoneflies), *Odonata* (dragonflies), *Trichoptera* (caddis larvae), *Coleoptera* (beetles), *Heteroptera* (waterbugs), *Megaloptera* (alder flies), *Gastropoda* (snails) and *Bivalvia* (mussels). This macrofauna community with its many species is made possible by the diversity of habitats and food in the dynamic environment of the natural lowland stream. Particularly the temporal and spatial variation in substrate composition is an important prerequisite made by the macrofauna (Tolkamp, 1980).

3.2. *The assessment of the impact of stream regulation by means of the macrofauna*

When the factors characteristic for lowland streams are changed by regulation, the composition of the macrofauna community alters also. Knowledge of this alteration gives the possibility to evaluate the degree of regulation of a stream.

Numerous methods are available to assess the effects of pollution on the aquatic community. Parallel to these methods a stream-character-index is developed to evaluate the change of the physical factors (the stream character) of a stream after regulation. (Gardeniers and Tolkamp, 1976; Tolkamp and Gardeniers, 1977).

To each macrofauna-species a stream factor is given according to the following criteria:

- factor 1 for taxa which are not or only exceptionally present in running water;
- factor 2 for taxa which prefer stagnant water to running water;
- factor 3 for taxa which are indifferent to current velocity;
- factor 4 for taxa which prefer running water to stagnant water;
- factor 5 for taxa which are only found in running water.

The percentage occurrence of each species is multiplied by its stream factor. These numbers are added up and the sum represents the stream-character-index. The index varies from 100 (100% organisms of species with factor 1) in a strongly regulated stream, to 500 (100% organisms of species with factor 5) in an undisturbed, meandering and shaded lowland stream.

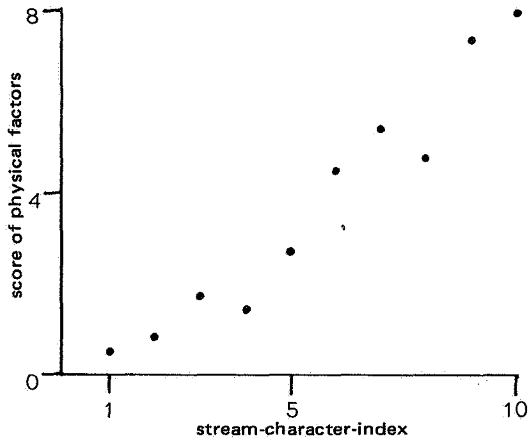


Fig. 6 Relationship between stream-character-index (x-axis) and score of physical factors (y-axis) for the streams in the Twente region. The range of the index (100-500) is divided in ten equal classes. Explanation of score in text (see section 3.2.).

The stream factors are based on the known preference of species for running water and on the actual distribution of the species over the different watertypes in The Netherlands. A check on the validity of the stream factors to evaluate the changes when a stream has been regulated, was made in the Twente region (province of Overijssel) (Heydeman and Van 't Oever, 1979). For 170 sampling stations in the streams of Twente a two-point score was used with respect to the type of substrate, the current velocity, the type of cross section and the degree of shading.

The results of this score have been plotted against the stream-character-index given by the macrofauna at the same sampling stations (figure 6). A high correlation can be observed between the assessment of the stream character by means of physical and faunistic parameters.

In the next section a survey will be given of the condition of the lowland streams in the Achterhoek (province of Gelderland) by means of the above mentioned assessment method.

4. THE CONDITION OF THE LOWLAND STREAMS IN THE ACHTERHOEK

An assessment of the condition of the streams in the Achterhoek region was made by sampling the streams at 175 sampling stations in the summer of 1973. According to their stream-character-index, only 16% of the streams is in a (semi)natural condition (represented by the classes 7, 8, 9 and 10, when the range of the stream-character-index from 100 to 500 is divided into 10 equal classes). About 65% of the streams is only inhabited by very common species of stagnant waters (the classes 1, 2, 3 and 4). In fact only the streams belonging to the classes 9 and 10 (6% of the streams) can be considered as representative for the original type of a lowland stream (figure 7).

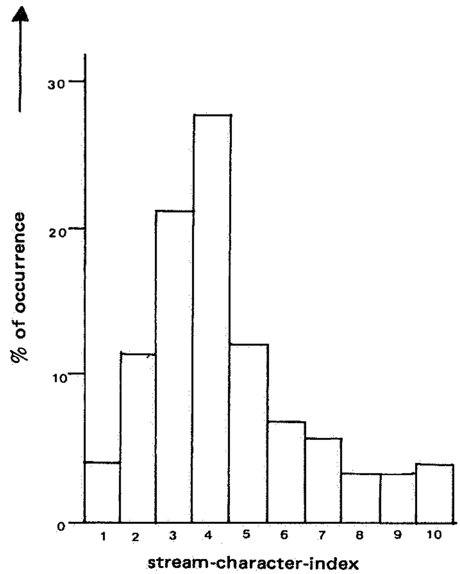


Fig. 7 Distribution of the sampling stations in the Achterhoek region over the stream character classes. x-axis: stream-character-index (100-500) divided in 10 equal classes (1-10); y-axis: percentage occurrence of the sampling stations in the 10 index-classes.

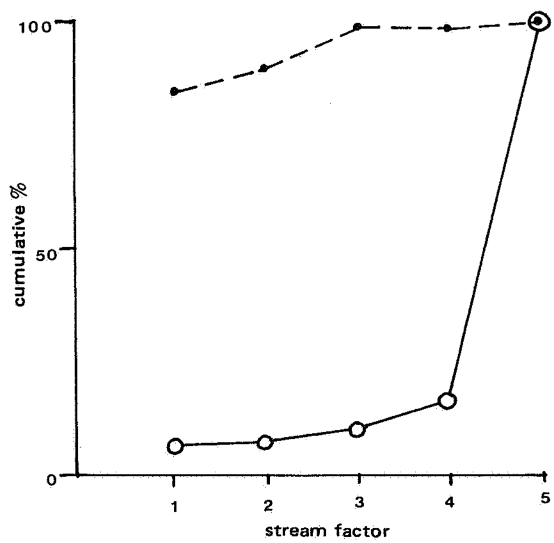


Fig. 8 Species composition at two sampling stations in the Stuwbeek (Achterhoek) as measured by their cumulative percentage distribution over the 5 stream factors (see section 3.2.). x-axis: stream factor; y-asis: cumulative percentage. Open circles: the natural section of the stream; closed circles: the regulated section.

The complete change of the stream environment after regulation can be illustrated by the difference in species composition between two sampling stations in the same stream (the Stuwbeek, Achterhoek). One sampling station is situated in a still natural section of the stream, the other one is situated in a downstream regulated section. In figure 8 the distribution of the fauna species over the different stream factors (see section 3.2.) for these two stream sections is illustrated by means of curves indicating the cumulative percentages.

In the natural stream section the greater part of the macrofauna consists of species with a preference for running water. In the regulated section, most species are inhabitants of stagnant water.

5. THE CONDITION OF THE LOWLAND STREAMS IN OTHER REGIONS OF THE NETHERLANDS

The negative picture of the condition of the streams in the Achterhoek region is also characteristic for other regions in The Netherlands. In the province of Drenthe, in the Twente region, in the Gelderse Vallei region, in the province of Noord Brabant and in the northern and middle part of the province of Limburg most streams have been regulated. A recent study of the streams of the Twente region showed that of a total length of the streams in this region of 1940 km, only 95 km (= 5%) has a natural stream character (Heydeman and Peters, in print).

6. CONCLUSION

These results emphasize the importance of the conservation and restoration of those streams that still possess lowland stream characteristics. When we have to take the governmental policy regarding the conservation of the typical dutch lowland streams seriously, we have to realize that at this very moment even our last natural streams are threatened by regulation for land re-allotment and lowering of the groundwater level.

REFERENCES

GARDENIERS, J.J.P. and H.H. TOLKAMP (1976) – Hydrobiological survey of the streams of the Achterhoek. In: Th.v.d. Nes (ed.) Modelresearch 1971-1974, Arnhem: pp. 26-29, 106-114, 294-296. (in Dutch)

HEYDEMAN, B. and E. VAN 'T OEVER (1979) – Twente, a hydrobiological examination of the streams I. Report Nat. Cons. Dept. Agric. Univ. Wageningen no. 409: pp. 52. + appendices. (in Dutch)

HEYDEMAN B. and A. PETERS (in print) – Twente, a hydrobiological examination of the streams IV. Report Prov. Plan. Serv. Overijssel, Zwolle. (in Dutch)

MOLLER PILLOT, H.K.M. (1971) – Assessment of the pollution of lowland streams by means of the fauna. Thesis, Pillot Standaardboekhandel, Tilburg: pp. 286. (in Dutch)

TOLKAMP, H.H. (1980) – Organism-substrate relationships in lowland streams. Nat. Cons. Dept. Agric. Univ. Wageningen, Thesis. (XI) + pp. 211.
TOLKAMP, H.H. and J.J.P. GARDENIERS (1977) – Hydrobiological survey of lowland streams in the Achterhoek (The Netherlands) by means of a system for the assessment of waterquality and stream character based on macro-invertebrates. Mitt. Inst. Wasserwirtschaft, Hydrologie u. Landwirtsch. Wasserbau, T.U. Hannover, Heft 41, pp. 215-235.

LINKING UP THE NATEC SUBSYSTEM IN MODELS FOR THE WATER MANAGEMENT

G. VAN WIRDUM

SUMMARY

This contribution deals with the problem of emphasizing nature protection in models for the water management. The problem is conceived as a driving forces – phenomenological coefficients – generalized fluxes system, in which any area, purposefully used by Man for its habitat function, is looked upon as an (eco)device. An ecodevice for nature protection is called a natec. Driving forces are defined in a structure, named an ecological field.

Some reconnoitring case studies indicate that measures of water management do not only alter the quantitative water aspect of an ecological field, but also, for instance, macro-ionic concentrations. The reaction of a natec may be primarily by the production of a changed nutrient flux in both cases.

Only for some of the processes "microscopic" models are available. Moreover, defining which processes are decisive in any case, and coupling models for the transport of different physical quantities, calls for a macroscopic superstructure.

This is provided by a conceptual model of independent state factors. The initial state of a landscape column is considered a memory structure now, ruling conditional feedback on change processes. The evaluation of change is thought to be possible by emphasizing ecological preference of species known to be indicative of natec quality. Thus, the decisive change agent is related to physically defined factors by a characteristic vector and transport models could be formulated.

1. INTRODUCTION

In the preparation of measures of water management, information is desired on demands and sensitivity of nature protection and other interests. Since economic evaluation can be regarded as the outcome of social appreciation, and since nature protection as a recognized social aim is subject to the latter, multicriteria simulation of social appreciation could be a more direct help in decision making than the conflictuous matter of weighing against monetary standards (a unicriterion method). Economic tactics can now be tried out as steering mechanisms in the execution of a strategy. The input needs of multicriteria methods as outlined by Ancot and Van de Nes (1981) are met by just ranking the utility of plans or variants for each interest. The scientific approach of the forthcoming demand for a ranking criterion (*ranker*) and its application, involves modelling of the relation between realization of plans and the *habitat function* of any influenced area for the user organisms.

If such an area is purposefully used by Man for its habitat function, it is named an *ecodevice* (Both and Van Wirdum, 1979; Van Leeuwen, 1979; Van Wirdum, 1979b). If it is tailored to the immediate needs of Man himself, it is an ecodevice for direct human profit, called *humec* for short, whereas a *natec* is an ecodevice for nature protection (whatever reason one may have to protect nature). Ultimately Man is the driver and end user in both cases, but spontaneous organisms are intermediate users in the natec one. Avoiding the discussion whether all natecs are nature reserves or not, it can be concluded that at least all nature reserves are natecs, producing the *juste milieu* required by organisms (in particular threatened ones) to survive. Or, consequently: producing the survival of threatened organisms. As ecodevices do not reflect closed systems [I adhere the notion of a system being a mental abstraction of reality we are capable to understand and denote as its organization], they produce out of their surrounding environment. It is for this very reason that environmental changes affect natec performance. Using a time span of considerable length, a physical approach might say the environment provides a generalized driving force and the ecodevice embodies an aggregation of phenomenological transport coefficients, leaving a generalized flux for the product. The latter candidates to be a ranker for natec utility.

The driving force an ecodevice is exposed to, is said to depend on its *position* in an *ecological field*, and is characterized by the local gradient of this field. According to this conversational agreement, the position of an object can be altered by physical translocation in the unaltered field as well as by variation of the local field gradient. The ecodevice itself is *conditional* between the general environment and the produced fluxes or *operational* processes. All this holds for humecs as well as for natecs. Looking at nature protection, it is clear that, when humec functions are (intentionally) changed, the ecological field surrounding a humec may be subject to a resulting change. On its turn, a natec in such a field may show a behavioural reaction. For practical purposes, it is recommended to choose the conceptual boundaries of ecodevices under study so, that no competition of functions is encountered within the ecodevices. By this schematization, humecs and natecs are separate also if they occupy the same physical space, and can only compete on sources and sinks of the union of their ecological fields. The ideas to be presented are not only suited to predict possible natec malfunction, since they can be used just as well to find out which places in a region are best suited for natec applications and to develop strategies to obtain more and better natecs.

This contribution is meant to summarize some recent attacks at the problem of making nature protection a bit more wieldy in policy analysis. It is more detailed in the analysis of possible effects of measures of water economy and real examples are drawn from the participation of the Research Institute for Nature Management (RIN) in the project of the Committee for the Study of Water Resources Management in Gelderland as reported by the Comm. Bestudering Waterhuishouding Gelderland (CWG) (1980) and sources to be mentioned. The conceptual area of the problem thus introduced is depicted in figure 1. In this figure the ecological field appears split up in several *aspects*, each referring to a different physical quantity transferred. If transport of water were the only thing to occur, the area of interest would reduce to the hatched part of this figure, a direct cause-effect *channel*, namely the water-water-water one. If water is withdrawn in a humec, e.g. for drinking water, one just has to study the fall of the hydraulic head where a natec is situated and to calculate the decrease of water supply to the natec vegetation, to see this channel at work. However, a measure that has an impact on the water

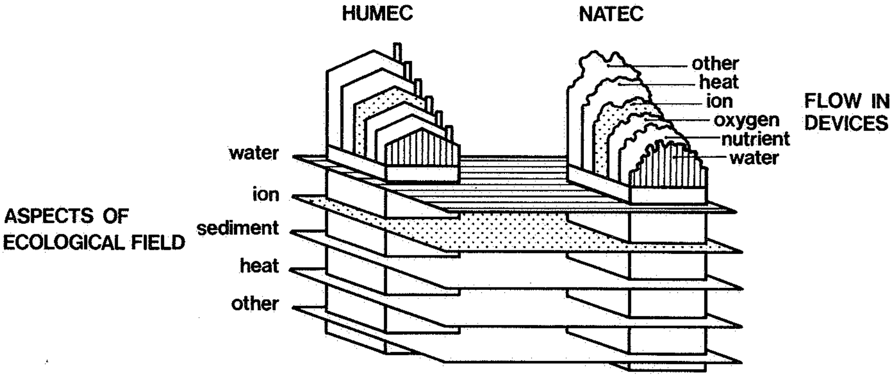


Fig. 1 The direct channel of water (hatched) through an ecological field from man in a humec to nature in a natec. The direct ion channel has been indicated by dotting.

balance sheet of a region, generally also alters solute and, if surface water is concerned, sediment budgets, since water acts as a carrier of these physical quantities. The ecological position of a natec is thus changed in more than just the water aspect. At second, all aspects of an ecological field actually changing may interfere with the transfer of other quantities from the internal stores of a natec or from external sources to organisms to be safeguarded. At third, and out of the realm of pure science now, agreement shall have to be reached upon a technical principle (the ranker) to evaluate natec utility, i.e. to decide which state of a natec is best. Probably this ranker will not be mere water consumption of the local vegetation.

2. A RECONNOITRING APPROACH OF THE IMPACT OF WATER MANAGEMENT

Ecological meddling in nature protection mainly deals with the first and second of the introductory remarks above: positional changes of a natec in its ecological field caused by measures of quantitative water economy, and conditional changes of a natec, resulting from the former. Reconnoitring examples of both will be given, starting with the latter, as ruled by the water aspect of the ecological field.

2.1. *The direct channel of water*

The direct channel of water (water-water-water) as highlighted in figure 1 relates a water economy measure in a humec to plant water use in a natec. This channel has got quite a bit of attention since it is very important agriculturally, determining crop water use in humecs for food production. Moreover, direct channels are easier to handle than others. In the CWG project, GELGAM was developed as a tool for the calculation of flow in this channel (De Laat et al., 1981). Simulation of unsaturated flow and related

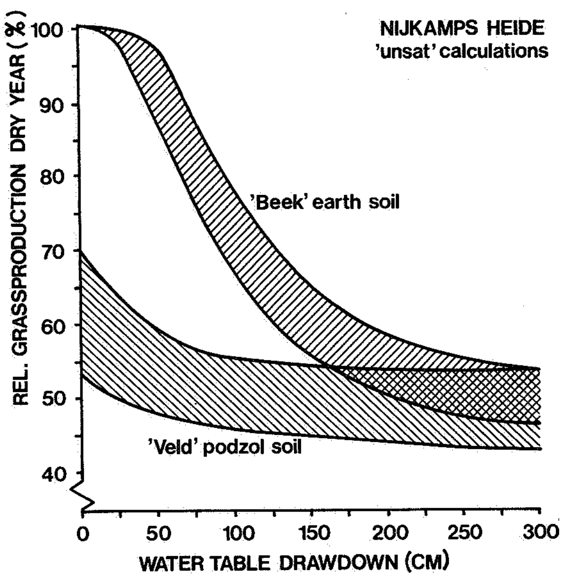


Fig. 2 Relative grass production in a dry year, related to depth of water table drawdown (UNSAT calculations, from Bannink and Pape, 1979) in Nijkampsheide nature reserve.

crop production is realized in the UNSAT module (De Laat et al., 1981). UNSAT has been applied to data of two experimental plots in the nature reserve Nijkampsheide (Bannink and Pape, 1979) as part of ecological research in this reserve (Both and Van Wirdum, 1981).

For this purpose, part of the model, relating a measure to local hydraulic heads, was passed by, assuming a variable value for the lowering of the march of the groundwater table in the experimental plots. As the model was used in its original, "agricultural" form, the predicted response of nature has been given as a percentage of the biomass production of grass with optimal supply of water, occurring if grass would be grown at the experimental sites. All calculations have been done for

- different values for soil data, as actually observed at the plots,
- different values for the lowering of the water table, and
- a year with normal weather as well as a dry year with a treshold frequency of 10%

The results for the dry year and those for the normal year exhibit the same trends, although absolute values differ. Figure 2 gives the dry year results. The width of both bands in the graph reflects heterogeneity of the results, caused by the observed variation of soil data, mainly the thickness of the root zone. Obviously, this variation prohibits any precise forecast.

From figure 2, it is clear that even the slightest drawdown of the groundwater table in this reserve may shorten the supply of water to the heathland vegetation of the "*veld*"-*podzol* soil. [For definitions and descriptions of dutch soil types, see De Bakker and

Schelling (1966)]. This might ultimately lead to a change in floristic composition and other properties of the site. At only 50 m distance, in a "*beek"earth* soil (see also De Bakker and Schelling, 1966), water supply is not reduced before the drawdown of the water table exceeds 25 cm or so. This profile has a vegetation of a "litter" community indicating rather nutrient poor and acid circumstances, with the rare *Cirsium dissectum* as a striking species. People concerned with nature conservation have numerous indications of vegetation on this soil type showing a really explosive reaction to drawdowns, without water supply becoming critical. It is therefore believed, no important information on natec performance is obtained just from the direct channel in the "beek"earth case. Here, vegetation might rather explore the indirect water-water-nutrient channel.

Most plant species characteristic for degrading earth soils are known to be nitrophilous and have a very high productivity: mineralization from the soil organic store can presumably be used by the vegetation for the very reason water supply is not yet hampered.

Some minor remarks on the applicability of models are added here:

- GELGAM and related models will need excessively many real data to provide reliable and precise information on small areas that contrast with the general idea of their surroundings (like nature reserves tend to do).
- UNSAT is restricted to the effect of water supply in well aerated root zones. Effects of water logged conditions are not predicted. This model also needs much information and many runs to cope with heterogeneity as it is met with in many nature reserves.
- Typical applications of the model with non-rigid soils, like peat or clay ones, will not give satisfactory results, unless skilful formulation of the physical behaviour of the transport medium is allowed for, as done by Bouma et al. (1981).

2.2. *The water-ion-nutrient channel*

A water economy measure in a humec will, as explained before, in many cases change other aspects of the ecological field of natecs. In this paragraph, macro-ionic composition of ground and surface water will be related to the hydrological cycle as well as to natec vegetation by an example concerning Empese en Tondense Heide (Both and Van Wirdum, 1979, 1981). The example is preceded by some explanatory remarks on criteria for the evaluation of macro-ionic composition and on possible mechanisms of natec response to it. The last subparagraph deals with a case of change.

2.2.1. *Macro-ionic composition of natural water*

Macro-ionic composition of natural water is ruled by reactions on its way from the atmosphere through the lithosphere to the ocean (Hem, 1970). These system compartments can thus be looked upon as reaction vessels in the hydrological cycle. The key idea is that percolating rainwater, acidified by the uptake of biologically produced CO_2

in the root zone, will solve calcium ions from calcareous minerals if residence time in the lithosphere is long enough. The sink of the hydrological cycle, the ocean, is characterized by high concentrations of Cl^- and Na^+. Where the hydrological cycle is interfaced with ecodevices (the active zone of life processes), waters of different stages in the hydrological cycle occur together and mixed, reflecting the influence of the pertinent reaction vessels by their chemical composition. Part of the concerned properties is certainly relevant to the development of nature and natec utility.

In search of a simple set of criteria out of many solute concentrations, the author (1980) has tried to diminish redundancy and to gain efficiency in field sampling, analysis and interpretation. In that publication, it is argued that electrical conductivity and a ionic ratio (IR)

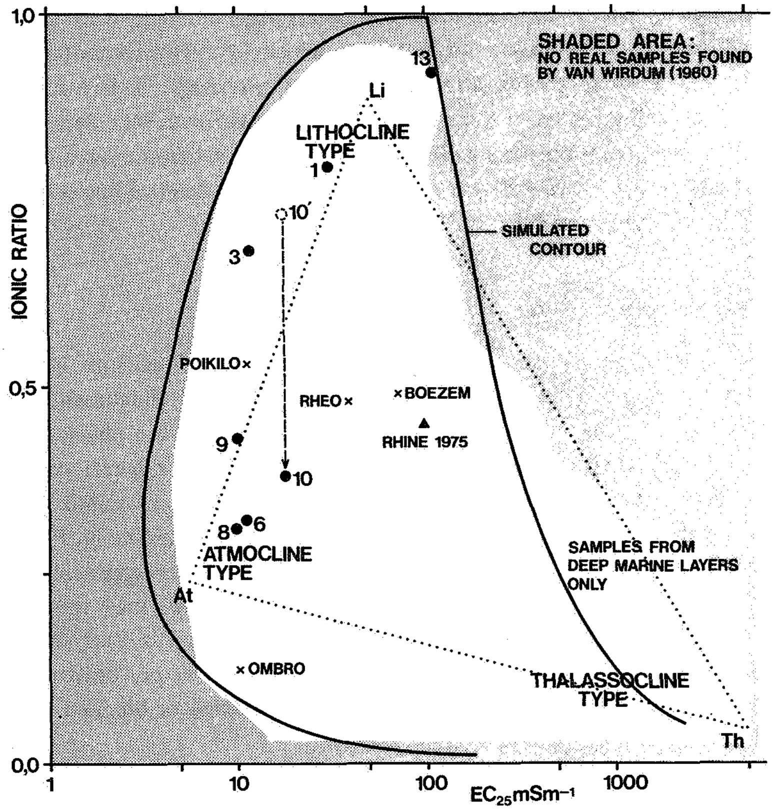


Fig. 3 IR-EC representation of the macro-ionic aspect of ecological field properties. Empese en Tondense Heide samples from table 2 have been indicated by station number. Mire samples from Van Wirdum (1979a) are added for reference. The river Rhine sample serves as a guide for artificial supply of surface water, as in "boezem". Sample 10 quality is thought to be derived from position 10' by the influence of a nearby draining ditch.

$$IR = \frac{[\frac{1}{2}Ca^{++}]}{[\frac{1}{2}Ca^{++}] + [Cl^{-}]}$$

are relevant to both the qualitative description of water in the hydrological cycle and its reactivity in biologically important processes [[X]: molar concentration of the X-ion, $[\frac{1}{2}Ca^{++}]$ having the same value as the SI abandoned equivalent concentration of Ca^{++}]. With a very rude model simulation and using a two years weighted mean composition of rainwater as a seed, it was possible to delineate the effective plotfield of some hundreds of Dutch water samples in a diagram of ionic ratio (IR) and electrical conductivity (EC). The major disagreement was shown to be limited to groundwater from very deep marine layers. In reproducing those results in figure 3, guiding plot positions for three main types of water are indicated by the set names *atmo-, litho- and thalassocline*. These names refer to the reaction vessels in the hydrological cycle (Gr. thalassa: sea, klino: to slope) and they typically, but certainly not necessarily, coincide with the physical type names rainwater, groundwater and seawater, which just refer to containers in the hydrological cycle, without paying attention to their reactivity. It is for this reason that no demarcation lines between the sets have been drawn here. Members of each set approaching the guiding plot position will be named after the set from now on. Moreover, it will be said that the relative influence of the mechanisms determining set properties decreases with increasing distance from the guiding plot position.

2.2.2. *Natec response mechanisms*

There is an enormous amount of literature on the role of calcium in soil plant relations, although many questions seem to be still unanswered (Buckman and Brady, 1969; Russell, 1973; Larcher 1980). Calcium is a very important ion physiologically, as it governs membrane functions and meristem growth processes. Operational problems related to calcium over- or underfeeding in plants seem to be of minor importance however, if compared with its impact on the economy of the nutrients N, P and K and the availability of iron in the soil plant system. Although plant response to all of the involved factors certainly is far from uniform, and different soils may show different reactions to a changing Ca status, the general impression in natecs is, that a high relative Ca status in the ecological field will maintain or even improve natec performance

- by exhaustion of nitrogen availability if biomass is removed or blocked in a tree or peat layer, and
- by cutting down irregularities in phosphorus availability.

Furthermore, the Ca system interferes with the Fe and Al systems in the soil and it influences soil structure and humus formation. All these themselves are buds from which systems of mainly indirect effects on plant life fan out. Thus a water economy measure taking hold of the ion aspect of the ecological field, may control physical soil properties in a natec, for example, and this may consequently alter the flux of water to the vegetation. It is an example of the water-ion-water channel in figure 1.

Up to now, just Ca has been taken into account in the ion aspect of the ecological field. It should be recalled however that this was, via IR, introduced as a mere criterion to evaluate an ensemble of properties, owned by most waters sharing any area in the IR-EC diagram. Other properties of members of the macro-ionic watertypes will be needed to provide miscroscopic explanations for corresponding natec behaviour in many cases, and other evaluating criteria might be more informative than IR and EC. Nature is not that simple to see all its features explained by two chemical figures! Sulphur, for instance, might sometimes explain much residual variation. Yet, a useful model of the interaction between humecs and natecs in water economy questions could presumably go without many details in the beginning.

Leaving natec response mechanisms to the macro-ionic ecological field status a grey or, admittedly, nearly black box, the present author (1979a) has drawn attention to empirical correlations under the heading of positional relationships. Although recent research in The Netherlands increases indications of the importance of the ion aspect of ecological fields (Grootjans, 1980; Kemmers and Jansen, 1980), a reliable inventory of mechanisms involved is still lacking, and so are actual proofs of selected mechanisms in case studies.

2.2.3. *Species distribution over a macro-ionic field gradient*

Empese en Tondense Heide is a small nature reserve on gently sloping terrain halfway the Veluwe glacial high and the river IJssel valley. In dry periods, the groundwater table under the reserve reflects this regional slope by a 1:1000 depth gradient, as indicated in figure 4. The highest water tables in contrast mirror the local relief. The effect is, that the lower parts of the reserve are largely under the influence of the chemical composition of the regional groundwater, whereas the higher parts are chemically controlled by locally percolating rainwater. Correspondingly, part of a hydrological (micro)sequence of soil types (Jenny, 1946) is found, going from imperfectly drained podzols down to poorly and very poorly drained earth and peat soils. If the Nijkampsheide "veld"podzol and "beek"earth soils are considered representative for the water supply to the root zone in the Empese en Tondense Heide soils of the same type, water supply to the root zone would range from 85% to 100% of cultivated grass demand under normal weather conditions, and from 60% to 100% under dry conditions as specified for figure 2. Obviously, differences in the availability of water for plant growth occur and presumably coregulate species distribution. This operational factor is interwoven with soil and water chemical factors in an intimate complex. It might therefore be expected that some of the occurring species are sensitive to these more than to the water factor, justifying the holistic approach of nature. A first impression of which are the main threads in this web is provided by an analysis of the indicative value of plant species for the water factor, pH and mineral nitrogen respectively (Ellenberg, 1974, 1978). The relevant Ellenberg indicatory scales are marked in table 1.

Table 1 Relevant marks on the Ellenberg indicatory scales with regard to wetness, acidity and mineral nitrogen.

	wetness		acidity		mineral N	
lowest value	W1:	very dry	A1:	very acid	N1:	very poor
	W7:	moist, not really wet	A7:	circum-neutral	N7:	intermediate
	W9:	wet, often devoid of air				
highest value	W12:	submerged	A9:	calcareous	N9:	excessively rich

Working with the classifying table in Both and Van Wirdum (1981), representative values for each type were calculated, taking into account the frequency of species in samples of the types. For this purpose (orientation), all tabled species occurring in 0-25% of the samples (exclusive) were counted once, the up to 50% group species twice, and the 50% or more ones three times. Forgetting all possible criticism concerning this data handling, the results have been entered in the legend of figure 4 and in figure 5. Obviously,

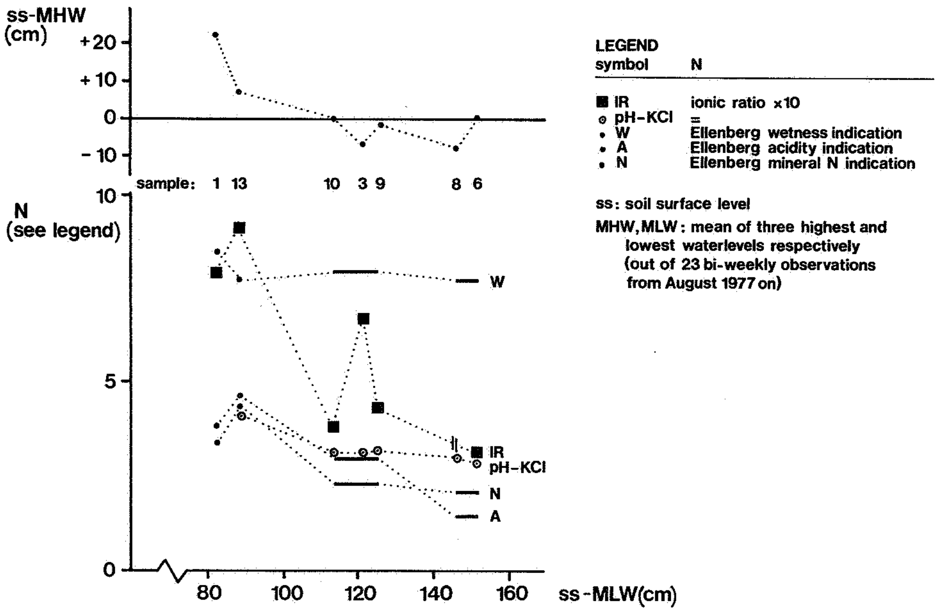


Fig. 5 Physico-chemical data and vegetation indication of samples from Empese en Tondense Heide nature reserve (compare figures 3 and 4 and table 2).

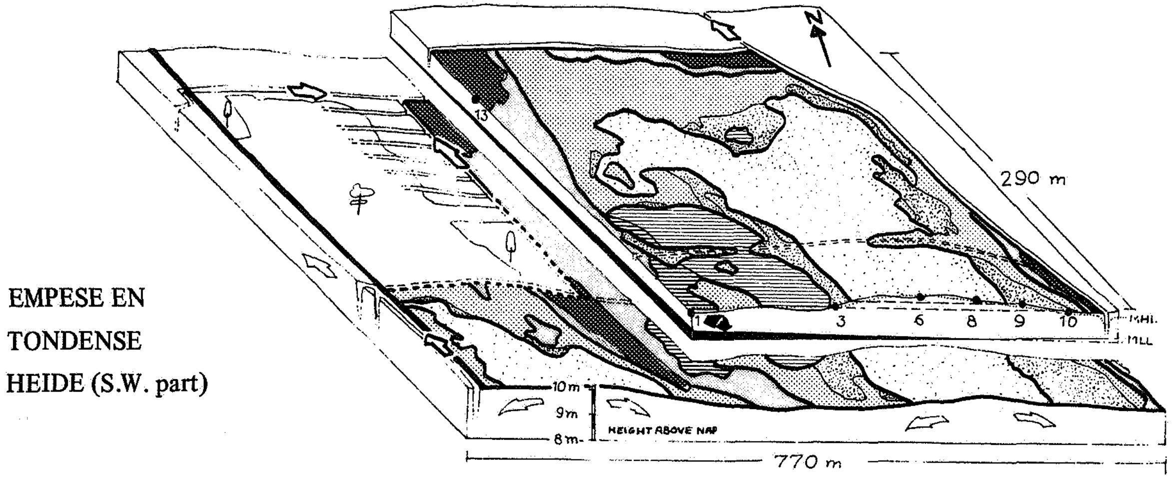


Fig. 4 Block diagram of Empese en Tondense Heide nature reserve. Numbers of sample stations refer to table 2 and figures 3 and 5. MLL, MHL: mean lowest and highest waterlevels, as defined in table 2. NAP: height reference (about sealevel). Vegetation type names (codes refer to Both and Van Wirdum, 1981) have been substituted by names of general types of landscape. Carr is a type of woodland on peaty soil.

LEGEND and Ellenberg indication (Wetness, Acidity and Mineral N)

Shade	Code	Type	Indication	Symbol	Explanation
	I	wet heath	W7,7 A1,5 N2,1		forested (Populus)
	II	heath edge	W7,9 A3,0 N2,3		forested (Pinus)
	IIIa	poor open fen	W8,3 A3,8 N2,4	•x	sample station (fig. 5, table 2)
	IIIb	rich open fen	W8,4 A3,8 N3,4		supposed direction of flow of ground and surface water
	IVab	wooded heath edge	W7,3 A3,9 N3,9	---	parallel to MLL: indicates pass frequence threshold level
	IVc	wooded open fen	W7,8 A3,3 N2,7		of regional water table
	Va	poor carr	W7,4 A4,4 N3,9		
	Vb	rich carr	W7,7 A4,6 N4,4		

the differences between the types are small, but, although they are not too reliable, they coincide more or less with environmental data given in table 2 and figure 5.

Allowing for the span width of the indicator scales, the vegetation would indicate a slightly greater importance of variation of pH than of mineral N and wetness respectively over the transect. This would stress the relative significance of the lithocline-atmocline balance, and set off my (1979a) mire poikilotrophic zone to advantage. It is interesting that some of the most characteristic species of the latter are seen again in the relevant part of the Empese en Tondense Heide transect in spite of the contrasting overall appearance. Effectively, some generalization and exaggeration would reduce figure 4 to figure 6, which is taken from the afore publication. For comparison, Empese en Tondense Heide vegetation types have been indicated next to this figure 6, stressing relevance to the terrestrial equivalent of mire zonation.

Table 2 Environmental data and plant indicated operational factors along a groundwater gradient at Empese en Tondense Heide nature reserve. Location of samples: see figure 4. Vegetation data are type (not sample) characteristics. Waterlevels: 23 bi-weekly data from August 1977 on. Soil and water samples: March 1977 (Laboratorium voor grond- en gewasonderzoek, Oosterbeek). Beek, broek, goor: "-"earth soils; veld "-"podzol soil. MLW, MHW: mean of three lowest and highest waterlevels respectively.

sample		13	1	3	6	8	9	10
distance (m)			250	172	97	63	49	50
soil surface (cm above NAP)		905	906	937	964	952	925	908
MLW (cm above NAP)		816	824	815	812	805	799	794
MHW (cm above NAP)		912	928	930	964	944	923	908
soil type		beek	broek	veld	veld	veld	goor	goor
vegetation type (fig. 4)		Vb	IIIb	II	I	I	II	II
wetness factor (Ellenberg	W	7.7	8.4	7.9	7.7	7.7	7.9	7.9
acidity factor (Ellenberg)	A	4.6	3.8	3.0	1.5	1.5	3.0	3.0
mineral N factor (Ellenberg)	N	4.4	3.4	2.3	2.1	2.1	2.3	2.3
groundwater IR		0.92	0.79	0.68	0.32		0.43	0.38
groundwater EC_{25} ($mS\ m^{-1}$)		110	31	12	11		10	18
soil pH-KCl		4.1		3.1	2.9	2.0	3.2	3.1
soil exchangeable bases (val kg^{-1})		90		33	22	19	10	13
soil Ca/exchangeable bases		0.88		0.70	0.64	0.53	0.40	0.23
soil mineral N (mg kg^{-1})		24		76	35	39	57	99

As only indicated for the highermost types of vegetation in figure 4, many species combinations and species show distributive limits at the intersections of planes parallel to the depicted drainage base or regional groundwater table, imagined to move up and down stochastically (compare Jenny (1946): geological groundwater table). These planes can be characterized by a certain frequency of being below the regional groundwater

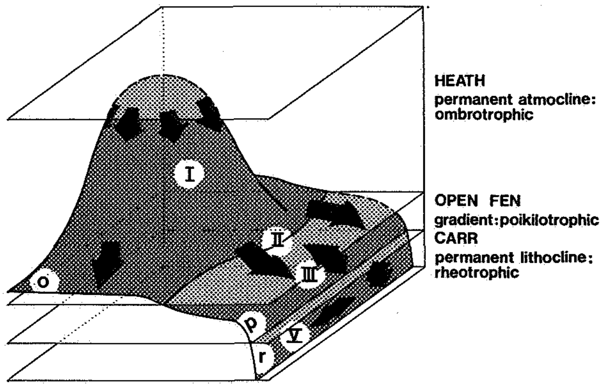


Fig. 6 Rheo-, poikilo- and ombrotrophic hydrological mire zones (defined by processes) compared with heathland-fen atmo-lithocline gradient (defined by properties). Codes indicate Empese en Tondense Heide vegetation types as in figure 4; their placing in the diagram is tentative. Trophic terminology also holds if the rheotrophic belt has thalassocline properties.

table. It suggests the importance of the regional groundwater table in lithocline control. From the point of view of this analysis, bare pH seems to be a rather clumsy variable and not too representative for lithocline influences. Many species behave indifferent to it: from the 49 ones in the table used, 8 are indicated indifferent to wetness, 11 to mineral nitrogen and 23 to pH. With respect to pH, it may be noted that natural acidity in the root zone will presumably go down to an Ellenberg indication A3 or less in the absence of calcareous matter or lithocline impact.

Summarizingly, if the question runs about the importance of water for the vegetation, it might be important to emphasize the role of water in the ecological field of the natec concerned, i.e. to take into account indirect effects.

2.2.4. *Succession in reaction to changed water management*

Empese en Tondense Heide, like most other nature reserves, is only a poor approximation of a steady state example of natec performance. In particular the poor carr reflects rather recent changes, partly explained by the management and partly by a lowering of the mean height of the regional groundwater table by some 2 or 3 dm. However, there is not enough data to quantify the reaction of the vegetation to this, and it seems to react very slowly moreover. In another of the reserves studied (Both and Van Wirdum, 1979, 1981), Koolmansdijk, actual lowering of the groundwater table proved to have been about 40 cm from 1970 on, natural causes excluded. For agricultural purposes, drainage conditions in the region had been improved already earlier in this century. The occurrence of plants in the grassland part of this reserve has been registered with a different degree of precision in 1952-'53, 1958, 196x and 1977-'78. 27 species were noted in the first three inventories only or notably more abundant than in the 1977-'78 one. Six of these clearly indicate ephemeral use of the terrain as arable land some years in advance of the first inventory and have not been taken into account in the present analysis. 20 species did not occur before 1977-'78 or clearly increased in numbers. Of these, 7 could have been easily overlooked by the earlier, more casual, visitors and are left out from calculations here. The same applies to another species, which is not reported in the earlier written data, but did occur according to personal information of the warden of the reserve.

In the absence of physical and chemical data, the species groups can be used to indicate which alterations occurred. This procedure has the advantage of using factor scales that are adjusted to what plants perceive, as shown in the Empese en Tondense Heide case. Mean indicatory values for both mentioned groups of species are listed in table 3, suggesting acidity change being dominant over changes in wetness and mineral N in the causal complex.

In studying Dutch grassland vegetation, mainly in the period 1934-'53, Kruijne et al. (1967) have worked out a method for the ecological assessment of edaphic factors by means of species indication. Except for wetness, this very reproducible and carefully

Table 3 Plant indicated operational factors after a drawdown of the water table at Koolmansdijk nature reserve (Ellenberg, 1974)

	wetness	acidity	mineral N
species disappeared or disappearing	W7,5	A5,5	N3,8
species coming in or increasing	W6,6	A3,6	N3,1

explained method even provides a translation into analytical quantities. As far as P and K are concerned, these are not reproduced in this text as they would call for a rather lengthy explanation of analytical methods. In both cases, methods strived at the evaluation of plant available amounts and are backed by a good deal of research. Nitrogen was not covered, but phosphorus and potassium were both in the study. As the grassland part of Koolmansdijk seems to be in the range of the Kruijne c.s. grasslands trajectory, application is considered justified. However, at this extreme wing of the ecological trajectory, one must be aware of reduced reliability of indications, as many of the encountered species were not too frequent in the study referred to. Plant indicated operational factors as obtained by the above method have been depicted in figure 7. Comparison of the present situation, according to species frequency in 30 equally spaced $2 \times 2\ m^2$ 1977 samples of the vegetation, and the group of decreasing or disappeared species with those increasing or newly appeared, reveals that the latter has

- its wetness maximum slightly less wet (though still in the highest class),
- its acidity maximum clearly in the lowest alkalinity class ($pH\text{-}H_2O < 5{,}05$), mainly

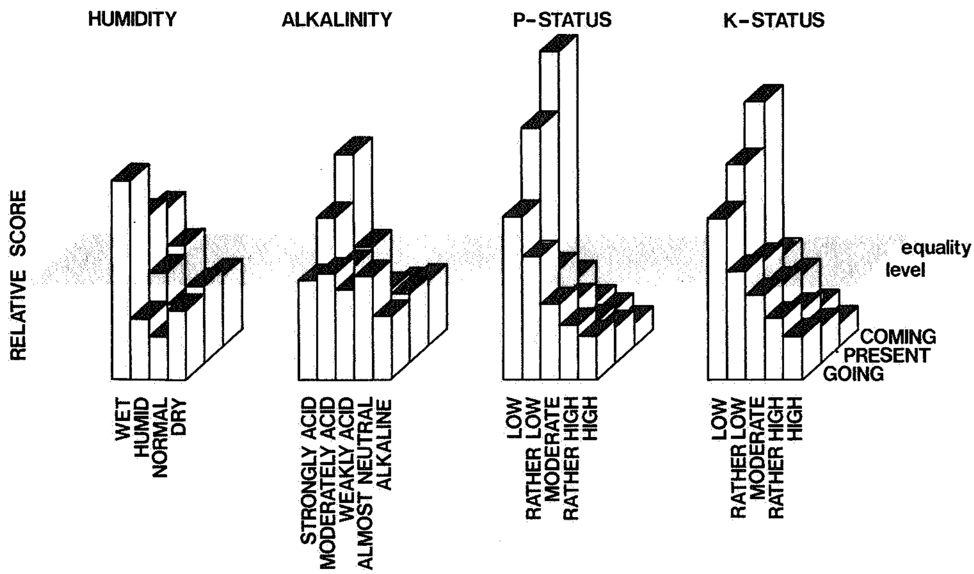


Fig. 7 Plant indicated operational factors after a drawdown of the water table at Koolmansdijk nature reserve. Obtained via the Kruijne et al. (1967) method.

at the cost of decreases in the weakly acid (5,55-6,00) and almost neutral (6,05-7,00) classes, and

– much more pronounced phosphorus and potassium maxima in the lowest out of five classes.

Far from being bright and sharp now, the picture of figure 7 seems to say water supply is not really hampered, but wetness impact on plant-soil-atmosphere gaseous exchange is released. Nutrient and organic material economy bear the stamp of increasing acidification, the higher initial availability perhaps (but not necessarily so) partly being due to some manuring in the past. N and K are probably largely lost by leaching and by the strict mowing regime. With P, fixation might be of major importance. As to acidity, P and K, diversity has decreased. Leaving the overall picture now to study a detail, it must be noted that the rarest of gone or going species, *Carex flacca* and *Parnassia palustris*, both prefer a low phosphorus status, but a high alkalinity in comparison to their group indication, suggesting some spots at Koolmansdijk were well below the average with respect to P availability. This could have been facilitated by their high base status and wetness. These places would be expected to show an increasing P flux when acidification proceeds, until fixation with Fe and Al becomes possible. The fact that some of the species coming in contrast with their group representative indication in higher P and base demands, tempts to hypothesize they might grow at the very places left by the mentioned gone or going ones.

Summarizing the Koolmansdijk case, it indicates water supply still being sufficient or nearly so, lithocline retreat in general motoring the pinch off of nutrient flux, and leading to a less varied edaphic picture. However, at particular places (presumably the lowest part of the terrain), the same general cause might have evoked the reverse result, leading to the loss of some particularly rare species.

Examples of vegetational succession in response to a changing macro-ionic position in the ecological field have also been found by the author in floating mires, excluding problems in the physical availability of water. A fine case to be studied might be Grootjans' (1980) *Ranunculus lingua* one, this species showing a dramatical decrease in numbers, two years after reallotment works. The accompanying measures of water management did not lead to an observably lower water table at the particular site, but Grootjans got indications that the macro-ionic position of the station had shifted from a more or less lithocline reigned one towards the atmocline domain. The Ellenberg scales assign 10 for wetness (periodically inundated stations), 6 for acidity and 7 for mineral N to *Ranunculus lingua*. As long as chemical factors are not impaired with, this species would therefore not be expected to be very sensitive to short lived drawdowns of the water level, its *juste milieu* being indeed characterized by fluctuations of that factor.

2.3. *Availability of models for the prediction of nutrient flux*

Reconnaissance data given in the afore paragraphs suggest direct relationship between quantitative aspects of water management and species composition in nature reserves may be often weak. Apparently, the water-water-water channel discussed in 2.1. is often dominated by indirect effects of humec water management on natec performance via the water-water-nutrient and water-ion-nutrient channels. A first improvement of informal systems for the prediction of natec damage could, for the time being, consist of considering just the processes dominant in the cases concerned, using quantitative computer models as far as these are available.

Although the main items to be incorporated in model formulation appear to be known scientifically (Van Dorp, 1977; Bolt and Bruggenwert, 1978; Rose, 1966), no universal model seems to be available for the prediction of nutrient flux in natecs. Viewed in the light of the complexity of the matter concerned and the amount of potentially relevant nutrient species, this might show quite a challenge indeed. Yet, if qualitative knowledge is available to make up what set of processes and nutrient species may be decisive to the result to be predicted, simpler computations may be used, of which at least some are, or will soon become, at hand.

Another desire concerns the macro-ionic aspects of the ecological field, requiring a coupled system of flow and chemical quality models. Water quality modeling in The Netherlands seems to be mainly inspired by aquatic, salt and terrestrial pollution problems (Comm. Hydr. Onderzoek TNO, 1980) justified by the severe environmental problems raised by the expanded use and abuse of chemicals. The detection of and solution to perhaps less obvious, but as severe, threats to natec performance, however, calls for reliable models of the geographical aspects of water quality generation. As work towards this is in good progress, RIN schedules the availability of such models before long.

3. A MACROSCOPIC SYSTEMS FRAMEWORK

Up to now, effectively some bolts and nuts of the problem stated have been discussed. To decide which microscopic processes will be considered in any case, or what qualitative reasoning will be used if no microscopic knowledge is available, a macroscopic systems framework has to be provided for the routing of change agents active after a humec water economy measure.

3.1. *The independent state factors*

At the ecological level of complexity, geography has a long tradition of systematic thought on processes that have lead to the existence of spatial variety, its subject. With respect to this, Jenny (1946, 1958) has given a scheme for the separation of conceptually independent *state factors* into *climate, topography* (including the depth of his "geological groundwater table"), the *biotic factor*, the *initial state* of the system (considered as parent material), and *time* (age of the system). In his 1958 publication, he introduced a *tessera* as an important conversational aid: a vertical column of soils with vegetation and fauna, historical processes crystallized in observable structure. Although this term has been overridden by U.S. Soil Survey Staff's *pedon* (see Cruickshank, 1972) in soil science, ecology might profit from its reintroduction, as advocated by Both and Van Wirdum (1979). There seems to be no objection to use the tessera as a critical sample to judge the state of a natec. If so, climate, topography and the biotic factor in the Jenny sense can be identified as principal components of the ecological field. The state factors being known, Jenny studied tesserae to trace the reaction (developmental cycle, succession) of nature into nearly steady states. Some comments on this equilibrium approach may serve as a stepping stone to the macroscopic analysis of change processes.

To be an independent factor, the biotic one should be interpreted as the frequency characteristics of the complete disseminule that reaches the selected area during its developmental cycle, largely differing in most cases from what actually grows there. Limiting this discussion to the plants part of the biotic factor, this set is called the *potential flora* (Jenny, 1958). The *actual flora* being dependent on the state factors, competition of species will never be a macroscopic cause of change, but a microscopic and unavoidable mechanism, contained in the relevant potential flora. Considering a period of some years or tens of years, the biotic factor, nor climate, will show any change of concern to the present question. Thus, water management in humecs will mainly result in a changing topography, in particular concerning the geological groundwater table. The present figure 1 could be said to illustrate physically defined interdependent factors, partially explained by the conceptual Jenny topography component of the ecological field. Once this change becomes effective, a new development cycle starts, the initial state being the final state of the passed cycle. The initial state of an ecodevice is therefore conditional to its sequentional development. Although a mere scientist might sometimes learn more from an analysis of the historical sequence of states than from a mysterious ecological code, it is formally desirable to separate the historical sequence in initial state information, which is in agreement with the foundations of modeling dynamic systems (Lewis, 1977).

3.2. *Intelligence of ecodevices*

Indicating the initial state factor information as contained in an ecological memory device, enables the devision into several degrees of softness, ruling reaction times of the device in question. Thus, hard, firm and soft memory layers have been distinguished (Both & Van Wirdum 1979), now augmented with a very soft one and named by their primary seats and the realm of processes involved: the *geomneme, pedomneme, biomneme* and *noomneme* (Gr. mneme: memory, remembrance). The hardest mneme needs the greatest environmental change to show a clear reaction and it will take a very long time to reach a new equilibrium. For this reason, it is often concerned fixed data in change analysis, as in the paragraph 2.1. models. On that occasion, it was noticed already the pedomneme might cause troubles if dealt with in the same way (non-rigid soils problems in UNSAT applications). It will be really very important if nutrient flux in natecs is to be concerned, as in 2.2. and 2.3.

Reaction time lengths connected with the biomneme are largely determined by the age organisms present will reach. If trees and large mammals are involved, this will lead to reaction times of several centuries, in contrast to the much faster response of unicellular algae dominated devices. With respect to this, it is important to draw attention to interlocking of memory layers. Growing vegetation influences soils conditions and therefore alters the pedomneme, which will in turn partly determine the actual flora for a next generation of the biocoenosis, and so on. It is this type of things which makes ecodevices intelligent devices, seeming to have a will of their own and making game of scientific care.

More in particular still, this holds true for the noomneme, connected with the minds of organisms, especially Man. It has the fastest response of all and, as its functioning is scientifically least unravelled, it is typically dealt with stochastically and empirically. When the noomneme becomes important, science tends to give the floor to policy, like in agricultural forecasts based on standard crops and cropping tactics. In this example,

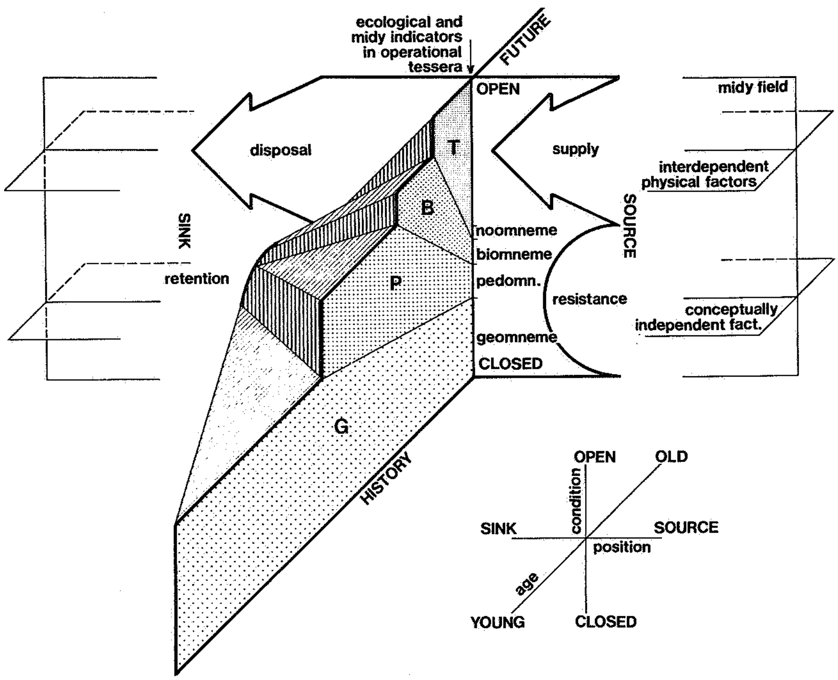


Fig. 8 Schematic representation of an ecodevice in its ecological field. T(echnological), B(iological), P(edological) and G(eological) processes in the past are projected into the mnemes to determine the conditional value of the Jenny initial state. Field analysis is alternatively by Jenny's conceptually independent climate, topography and biotic factor, by interdependent physical aspects, or by their midy component. The latter might be found by factorial analysis of midy indicators in a sample tessera, informative of operational factors.

the biomneme is largely passed by as crops can be renewed and pig-headed pedomneme is called to order by manuring tactics for nutrient supply. Natec ecology, however, is seriously concerned with those conditional problems, dealt with in cybernetics as feedback mechanisms and embodied in the retention compartment of ecodevices (Both and Van Wirdum, 1979). Highlighting the ecodevice functions, another representation of the figure 1 natec has been prepared in figure 8.

A further exploration of macroscopic feedback mechanisms will be needed to fully profit from the systems structure developed. In doing so, considering a generalized flux may show helpful and mark the transition to an approximation of the evaluation procedure. Interesting exercises are by Van Leeuwen (1979) in teaching the foundations of ecology and nature management, in Terweij (1980) in the analysis of humec planning problems, and in Kemmers (1980) in studying the relation between hydrological factors and spontaneous vegetation.

4. THE EVALUATION OF CHANGE

If it is possible to precisely predict future states of natecs, this will not yet be enough to feed a multicriteria policy analysis. For this purpose, it is necessary to evaluate predicted states by ranking. Although a fundamental discussion of the matter involved and the mathematical technics to be used is thought to be too far out of the scope of this contribution, some remarks on it should complete this introduction to a systems approach to the natec subsystem in models for the water management.

4.1. *Generalized fluxes and indicator organisms*

Experienced workers in nature protection in The Netherlands have adopted a certain way of looking at flora and fauna of natecs by which organisms are made indicators for natec quality (Westhoff et al., 1970; Dirkse, 1977; Oosterveld, 1978). As a scale reference for this indication a hypothetical or abstract factor is used, named *milieudynamiek* (Van Leeuwen, 1966), abbreviated in this text to *midy* to minimize misinterpretation of the verbal meaning. The roots of the introduction of midy as an environmental factor governing natec quality are in Van Leeuwen's theory of relations, which is itself inspired by general systems theory. As a scientifically univalent definition of midy, which is in all details in agreement with the idea of its creator, seems not yet to exist, guessing levels of midy by straight-forward studies of ecology, as done by Strijbosch (1976) and suggested by Van der Maarel and Dauvellier (1978), is rather tricky. Nevertheless, it has become a central item in nature conservation in The Netherlands (Bakker, 1979) and initiates get very good results with its application. Although Van Leeuwen (s.d.) gave some hints on the relation of midy with physically defined factors, an embarkation on this problem with empirical data is preferred at this stage. It uses the happy coincidence many midy indicators are in the Ellenberg and Kruijne c.s. schemes too. Furthermore, rareness of species could, in a less rigorous approach, serve as a substitute for midy preference, as species, which are sensitive to midy according to the mentioned authors will become or be rare. An important contribution could be to calculate the main ecological axis of variance in species-indication matrices and to check their relevance to rareness and midy preference.

If midy has a physical meaning not restricted to the perceptive peculiarities of organisms, it is to be foreseen the midy component of generalized natec flux can be computed from the physical fluxes vector and it seems an interesting challenge to check this with ecological field aspect vectors, as suggested in figure 8. Natec phenomenological coefficient vectors should then bridge the gap to the formulation of transport laws for midy in the humec-ecological-field-natec system, giving the mnemes their right places as feedback mechanisms.

REFERENCES

ANCOT, J.P. and Th. VAN DE NES (1981) – Integral evaluations of alternative water management scenarios in East-Gelderland. Comm. Hydr. Onderzoek TNO, Den Haag. Versl. en Meded. 27: 129-164.

BAKKER, P.A. (1979) – Vegetation science and nature conservation. In: M.J.A. WERGER: The study of vegetation, pp. 247-288. Junk, The Hague.

BAKKER, H. DE and J. SCHELLING (1966) – Systeem van bodemclassificatie voor Nederland (A system of soil classification for The Netherlands). Pudoc. Wageningen.

BANNINK, J.F. and J.C. PAPE (1979) – Enige gegevens betreffende de bodemgesteldheid van de natuurterreinen Empese en Tondense Heide, Koolmansdijk en Nijkampsheide, Stiboka, Wageningen, report.

BOLT, G.H. and M.G.M. BRUGGENWERT (1978) – Soil chemistry. Elsevier, Amsterdam.

BOTH, J.C. and G. VAN WIRDUM (1979) – Sensitivity of spontaneous vegetation to variation of water regime. In: Models for the water management II, pp. 191-211. Provincial Waterboard, Arnhem.

BOTH, J.C. and G. VAN WIRDUM (1981, in press) – Waterhuishouding, bodem en vegetatie van enkele Gelderse natuurgebieden. RIN, Leersum, report.

BOUMA, J., P.J.M. DE LAAT and A.F. VAN HOLST (1981) – Use of soil survey data for hydrological simulation models. Comm. Hydr. Onderzoek TNO, Den Haag. Versl. en Meded. 27: 81-97.

BUCKMAN, H.O. and N.C. BRADY (1969) – The nature and properties of soils. Collier-Macmillan, London.

COMMISSIE VOOR HYDROLOGISCH ONDERZOEK TNO, (1980) – In: Waterkwaliteit in grondwaterstromingsstelsels. Rapporten en Nota's no. 5, Comm. Hydr. Research TNO, Den Haag.

COMMISSIE BESTUDERING WATERHUISHOUDING GELDERLAND (1980) – Een systeembenadering voor het waterbeheer van Gelderland. (A system approach of the water management in Gelderland); abbreviated version of final report, pp. 88 Provinciale Waterstaat, Arnhem. (in Dutch)

CRUICKSHANK, J.C. (1972) – Soil geography. David & Charles, Newton Abbot.

DIRKSE, G. (1977) – Opmerkingen over milieudynamiek. RIN, Leersum, manuscript.

DORP, F. VAN (1977) – Simulatie van veranderingen in concentraties van voedingselementen rond plantewortels (with summary). Pudoc, Wageningen.

ELLENBERG, H. (1974) – Zeigerwerte der Gefässpflanzen Mitteleuropas. Scripta Geobotanica 9. Erich Goltze, Göttingen.

ELLENBERG, H. (1978) – Vegetation Mitteleuropas mit den Alphen. Eugen Ulmer, Stuttgart.

GROOTJANS, A.P. (1980) Distribution of plant communities along rivulets in relation to hydrology and management. In: O. Wilmanns and R. Tüxen: Epharmonie, pp. 143-170. Cramer, Vaduz.

HEM, J.D. (1970) – Study and interpretation of the chemical characteristics of natural water. U.S.D.I., Washington.

JENNY, H. (1946) – Arrrangement of soil series and types according to soil forming factors. Soil Science 61: 375-391.

JENNY, H. (1958) – Role of the plant factor in pedogenic functions. Ecology 39: 5-16.

KEMMERS, R.H. (1980) – Systems approach in terrestrial ecosystems. In: E.W. Schierbeek: Research digest, pp. 70-77. ICW, Wageningen.

KEMMERS, R.H. and P.C. JANSEN (1980) – De invloed van chemische factoren in grondwater en bodem op enkele vegatatietypen van het CRM-reservaat "Groot Zandbrink". ICW, Wageningen, report.

KRUIJNE, A.A., D.M. DE VRIES and H. MOOI (1967) – Bijdrage tot de oecologie van de Nederlandse graslandplanten (Contribution to the ecology of the Dutch grassland plants). Pudoc, Wageningen.

LAAT, P.J.M. DE, R.H.C.M. AWATER and P.J.T. VAN BAKEL (1981) – GELGAM. A model for regional water management. Comm. Hydr. Onderzoek TNO, Den Haag. Versl. en Meded. 27: 23-53.

LARCHER, W. (1980) – Physiological plant ecology, Springer, Berlin.

LEEUWEN, C.G. VAN (1966) – A relation theoretical approach to pattern and process in vegetation. Wentia 15: 25-46.

LEEUWEN, C.G. VAN (1978) – Ekologie I. T.H., Delft (Bouwkunde), syllabus 1979-1980.

LEEUWEN, C.G. VAN (undated) – Ekologie I. T.H. Delft (Bouwkunde), syllabus ca. 1975.

LEWIS, E.R. (1977) – Network models in population biology. Springer, Berlin.

MAAREL, E. VAN DER and P.L. DAUVELLIER (1978) – Naar een globaal ecologisch model voor de ruimtelijke ontwikkeling van Nederland. Staatsuitgeverij, 's Gravenhage.

OOSTERVELD, P. (1978) – De indicatiewaarde van het genus *Taraxacum* voor het beheer van graslanden (with summary). Gorteria 9 (5): 188-193.

ROSE, C.W. (1966) – Agricultural physics. Pergamon, Oxford.

RUSSELL, E.W. (1973) – Soil conditions and plant growth. Longman, London.

STRIJBOSCH, H. (1976) – Een vergelijkend syntaxonomische en synoecologische studie in de Overasseltse en Hatertse vennen bij Nijmegen. K.U., Nijmegen, thesis.

TERWEIJ, H.J. (1980) – Zuid-Holland West, een poging tot "ecologisering" van de planningspraktijk. T.H., Delft (Bouwkunde), report.

WESTHOFF, V., P.A. BAKKER, C.G. VAN LEEUWEN and E.E. VAN DER VOO (1970) – Wilde planten I. Natuurmonumenten, Amsterdam.

WIRDUM, G. VAN (1979a) – Dynamic aspects of trophic gradients in a mire complex. Comm. Hydr. Onderzoek TNO, Den Haag, Versl. en Meded. 25: 66-82.

WIRDUM, G. VAN (1979b) – Ecoterminologie en grondwaterregime. WLO-mededelingen 6 (3): 19-24.

WIRDUM, G. VAN (1980) – Eenvoudige beschrijving van de waterkwaliteitsverandering gedurende de hydrologische kringloop ten behoeve van de natuurbescherming. In: Waterkwaliteit in grondwaterstromingsstelsels, Rapporten en Nota's no 5: 118-143, Comm. Hydr. Onderzoek TNO, Den Haag.

INTEGRAL EVALUATIONS OF ALTERNATIVE WATER MANAGEMENT SCENARIOS IN EAST-GELDERLAND

J.P. ANCOT AND Th.J. VAN DE NES

SUMMARY

Hydrological studies of the water supply with the aid of physical-mathematical simulation models have been complemented by a more integral socio-economic approach by including the water demands of agriculture, households, industry, waste water control and conservation of nature reserve. In order to develop and to test a methodology for integral water management a case study for the region East-Gelderland was carried out.

The study can be divided into two parts. The first part describes the development of a number of econometric models for the water demand by various sectors. The objectives of these models are to examine the forecasts of the impacts of policy instruments on water consumption. In the second part the results of these forecasts are used together with water management scenarios and policy criteria to prepare the political decision process, by means of multicriteria decision models, in a very explicit way.

A comparison of two multicriteria decision models have been made. From the preliminary results no practical conclusions can be drawn, because the given policy analysis was not fully completed.

However, the developed methodology seems to be a very powerful tool for policy analysis.

1. INTRODUCTION

In the course of the C.W.G.-study it was recognised that the physical models had to be complemented by a more integral socio-economic approach to study the relations between water demands of agriculture, households, industry, waste water control, conservation of nature reserves, etc. and the available water supply. In order to tackle these problems a case study for the region East-Gelderland was carried out in cooperation with the Netherlands Economic Institute (Nederlands Economisch Instituut, 1979).

This study can be divided into two parts. The aim of the first part is to develop a certain number of econometric models and to use these models to prepare medium-term forecast and simulation exercises to examine the (quantitative and qualitative) impact of policy instruments on water consumption. The water quality aspects, however, have been treated less extensively than the water quantity aspects. In the second part the results of these forecasts are used together with water management scenarios and management criteria to prepare the political decision process, by means of a multicriteria methodology, in a very explicit way.

Although the emphasis of this paper is on the second part of the study, the content and the results of the first part will briefly by exposed in section 2. In section 3 the specification of the alternative scenarios and the selection of the policy decision criteria will be presented. The primary evaluation of the scenarios with respect to the criteria is discussed in section 4. Section 5 deals with the results of the multicriteria analysis, achieved by means of two alternative multicriteria methods: the QUALIFLEX method developed at the Netherlands Economic Institute and the method of Saaty, developed at the University of Pennsylvania, U.S.A. In Gelderland this method get the name GELPAM (Gelderland Policy Analyse Model). In the final section some concluding remarks are made.

It is important to stress from the outset that the results presented in this paper should be interpreted as the illustration of a methodology with respect to water management decision processes rather than as a concrete preparation of a specific decision. The scenarios which are presented and the criteria which are selected correspond to hypothetical strategies and constitute only a very arbitrary selection amongst many other possible and feasible alternatives.

2. THE DEMAND MODELS

In the demand models which constitute the specific subject of one part of the study three main sectors are distinguished: the demand for water by households, the industrial demand for water and the agricultural demand for water. The purpose of the demand models is twofold. Firstly, they are designed to estimate certain major economic parameters, from cross-section and time-series data, such as direct and cross price elasticities, income elasticities, etc., which should allow the decision maker to evaluate the impact on the demand for water (of different categories) of changes in the structure and levels of these variables. Secondly, they should also lead to projections about water requirements during the planning period.

As a compromise between data availability constraints and the desirability of linking the economic models with the physical ones (which operate at a very fine level of disaggregation), the chosen level of aggregation is the division of the region into municipalities. Although at that level time-series for many of the relevant variables could be made available, considerable data problems (missing data, inconsistent and hetoregeneous series, etc.) constantly had to be tackled.

2.1. *The water demand of households*

The first demand model concerns the demand for water by the households. Apart from the specific influence of prices and income on the demand for water, the following other explanatory variables have been introduced into the model: the growing wealth of the population (implying better housing conditions, with more extensive sanitary and other water consuming facilities), the household size, the change in the mentality of the population, the effect of installing meters, the degree of urbanisation and the climate. The dependent variable is the water consumption per head. The effect of installing meters is introduced as a dummy variable, equal to one in the years and municipalities where water consumption is metered, and equal to zero otherwise. Three alternative variables were considered to represent climate: temperature, average rainfall, and number of hours sunshine, in each case averaged over the summer months. The price structure of the drinking watersupply companies consists of a variable rate per m^3 and a fixed rate; for the price variable, an average price per m^3 was used, including a percentage of the fixed rate. Price and income variables ware deflated by means of the national index of consumption prices (base 1970). Concerning the urbanisation element three effects are distinguished: a neutral effect, an effect resulting from a high level of urbanisation and one resulting from a low level of urbanisation.

A large number of different specifications of this demand equation were tested and a selection of six models was made on the basis of economic and statistical criteria combined. As a sample of the outcomes the following results were obtained for one of these models.

$$\ln \frac{q_{rt}}{pop_{rt}} = -\underset{(.65)}{3.56} - \underset{(.63)}{2.13}\frac{p_t}{P_t} - \underset{(.0038)}{.0071}\left(\frac{Y_{rt}}{pop_{rt}}\frac{1}{P_t}\right)^{-1} - \underset{(.039)}{.15}\, d_{rt} + \qquad (1)$$

$$+ \underset{(.11)}{.18}\ln k_t + \underset{(.0179)}{.0068}\, t + \underset{(.10)}{.17}\ln g_{rt} + \underset{(.072)}{.056}\, v_{rt},\; R^2 = .95$$

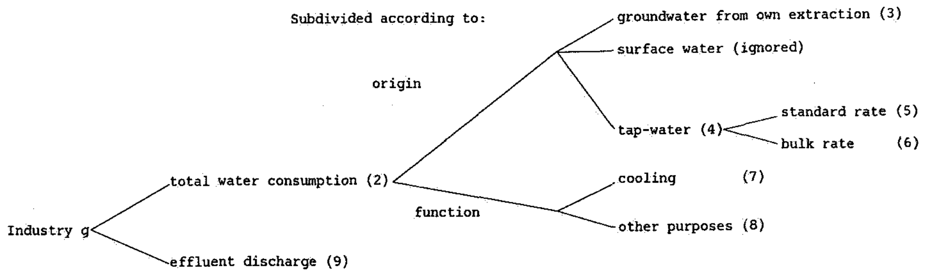
In this equation the symbols are defined as follows: q is the yearly consumption of water by the households, pop is population on June 30th, p is the unit price of water paid by households, P is the price deflator, Y is the yearly gross nominal income, d is a dummy variable equal to one where and when meters are installed and to zero otherwise, k is the average number of hours of sunshine during the period May to September, t is a time-trend, g is the household size and v is the percentage users in the core area of the corresponding municipality; the subscripts r and t refer to the rth municipality and to year t. R^2 is the coefficient of determination [The value of R^2 always lies between 0 and 1. The higher R^2 the greater the percentage of the variation of the dependent variable explained by the estimated equation, that is, the better the "goodness of fit" of the estimated model to the sample observations. The closer R^2 to zero, the worse the fit.]

For each variable, the first number is the estimated coefficient and the second (in brackets) the estimated corresponding standard error.

The estimated average price elasticities vary between –0.63 and –0.88. [The elasticity of a variable y with respect to a variable x is defined as the percentage change in y resulting from a one per cent change in x; formally, $E = (dy/y)/(dx/x)$. As a reference frame the following indications may be useful. In an extensive international study (about 30 countries), H.S. Houthakker (1957), obtained ranges for elasticities for food, clothing, housing and miscellaneous items with respect to total expenditure (roughly income) and family size. The income elasticities ranged from 0.34 to 0.73 for food, from 1.00 to 1.50 for clothing, for housing generally below one (largest for suburbs and smallest in large cities), for the residual category well above one. The elasticities with respect to family size ranged between 0.2 and 0.35 for food; for clothing and housing the effect is positive (more strongly for clothing than for housing) and for the miscellaneous expenditures the effect is unclear (negative for items like entertainment and domestic help, but positive for items like domestic appliances, furniture, transportation). In a detailed study of 37 commodity groups, A. Deaton (1975), finds income elasticities ranging from 0.52, for food, to 1.55 for transport and communication and nominal price elasticities ranging from –0.24 for housing to –0.51 also for transport and communications.] Although this seems to be rather high (in absolute values), it must be stressed that prices are expressed in relative terms with respect to a general price index. The average income elasticities are highest in municipalities with a high degree of urbanisation (between 0.21 and 0.30) and lowest in municipalities with an average degree of urbanisation (between 0.08 and 0.13). The interpretation is complicated by the fact that it was not possible to completely disentangle specific household consumption from some commercial and agricultural consumption. For this reason, the income effect and the urbanisation effect were treated independently in two of the six models. In these models, the general income effect becomes significant and the income elasticity varies between 0.12 and 0.16. On the other hand, the degree of urbanisation still remains insignificant, with a very low elasticity, between 0.04 and 0.06. The estimated elasticities for the climate variable vary from 0.15 to 0.22 and for the household size from 0.12 to 0.19.

2.2. *The water demand of industry*

In its final specification, the industrial demand model consists of eight submodels, one for each of eight broad sectors into which the industrial activity has been partitioned. Those sectors are: food, drink and tobacco; textiles; leather and rubber; paper; chemicals and allied industries; building materials; metal; other manufacturing. Each submodel, schematically presented in figure 1, contains, in principle, eight equations: a sectoral total demand equation for water (2); this total demand is then subdivided according to the origin of the water, into demand for "own" groundwater (3) (this is groundwater abstracted by the firm for its own use) and demand for drinking water (4); the latter demand is further subdivided according to the two different rates applied by the drinking-water companies: the standard rate (5) and the bulk rate (6). On the other hand, total sectoral water consumption is also subdivided according to the function which the water fulfills in the production process, into cooling water and water consumption for other purposes (mainly, of course as process water); these are the relations (7) and (8). A last equation (9) is a supply function of industrial effluent discharge. Given that the consumption of surface water is negligeable in East-Gelderland, this aspect of the problem has been ignored in the final specification [in 1976, only two firms were using surface water: a textile firm in Eibergen (consuming 550,000 m^3 from the Berkel) and a dairy in Lochem (consuming 850,000 m^3 from the Twente canal)]. In other words, the model is confined to the description of the industrial demand for groundwater.



$$\frac{p_E Q_E + p_L Q_L}{pQ} = a_0 + a_1 p_{AF} + a_2 \Delta_{prod} + a_3/t \qquad (2)$$

$$\frac{p_E Q_E}{pQ} = b_0 + b_1 p_E + b_2 p_L \qquad (3)$$

$$\frac{p_L Q_L}{pQ} = c_0 + c_1 p_E + c_2 p_L \qquad (4)$$

$$\frac{p_{LK} Q_{LK}}{pQ} = c_0^1 + c_1^1 p_{LK} + c_2^1 p_{LG} + c_3^1 \frac{p_L Q_L}{pQ} + c_4^1/t \qquad (5)$$

$$\frac{p_{LG} Q_{LG}}{pQ} = c_0^2 + c_1^2 p_{LK} + c_2^2 p_{LG} + c_3^2 \frac{p_L Q_L}{pQ} + c_4^2/t \qquad (6)$$

$$Q_K = d_0^1 + d_1^1 \Delta_{prod} + d_2^1/t + d_3^1 (Q_K + Q_A) \qquad (7)$$

$$Q_A = d_0^2 + d_1^2 \Delta_{prod} + d_2^2/t + d_3^2 (Q_K + Q_A) \qquad (8)$$

$$\frac{Q_{AF}}{pQ} = f_0 + f_1 p_{AF} \qquad (9)$$

Meaning of the symbols

- Q_E total yearly consumption in volume of "own" groundwater of the sector, in the region;
- Q_L total yearly consumption in volume of tap-water of the sector, in the region;
- p_E unit cost of extraction for "own" groundwater;
- p_L average price of tap-water;
- Q yearly volume of production of the sector, in the region;
- p average price of the product of the sector;
- p_{AF} unit levy on effluent discharge;
- Δ_{prod} yearly changes in production in the sector;
- t time trend;
- Q_{LK} total yearly consumption in volume of tap-water in the sector according the basic rate;
- Q_{LG} total yearly consumption in volume of tap-water in the sector according to the bulk-rate;
- p_{LK} price of tap-water according to the standard rate;
- p_{LG} price of tap-water according to the bulk-rate;
- Q_K total yearly consumption, in volume, of water used in the sector, for cooling purposes;
- Q_A total yearly consumption, in volume, of water used in the sector, for purposes other than cooling;
- Q_{AF} total yearly effluent discharge, of the sector, in accounting units.

coll.
code: sm/D14/M

Fig. 1 Structure of the typical submodel for the industrial demand for water

As it can be seen from figure 1, the main explanatory variables are cost elements, price variables, levies, production fluctuations and a time trend. Because of the lack of space the complete results are not reproduced here. From these results it can be concluded that, generally speaking, the different price effects are statistically not very significant, even if the absolute values of the elasticities are high (in the region of 0.3 to 0.4, on average, for the direct price elasticities). The costs of "own" abstraction of groundwater seem to be more important than the average price of drinking water to explain the gradual substitution of drinking water for "own" groundwater. The introduction of a levy on effluent discharges seems to have had a favourable influence on the pollution of surface water, but has had no significant impact on the total industrial water consumption (at least, in the short run). If it is accepted that the trend variable can be interpreted as an indicator for the technological evolution, it has been found that the latter has had a saving influence on total water consumption in the food, drink, and tobacco industry, in the textile industry and in the chemical industry, whereas the opposite holds for the metal industry. This is consistent with the observation that the most water dependent industries (per unit product) are the first ones to take measures to economise on the corresponding input. The short-term production fluctuations only have a small, generally saving, influence on total water consumption and on the consumption of drinking water. Concerning the relationships existing between the consumption of "own" groundwater and that of drinking water, it can be said that firms tend more and more to switch from the first to the latter. Concerning the partitioning of drinking water consumption according to the two-tier price system, it has been seen that this relation remains very stable during the sample period with a small tendency to increased consumption of the more favourably priced water; this is probably more a consequence of the changing structure of the industry in East-Gelderland than of the changes in relative prices. The model has little to say about the partitioning of water consumption into water for cooling and water for other purposes, most probably because of the unsatisfactory character of the available data. Figures 2 to 9 give a graphical representation of the estimated total water consumption, "own" groundwater consumption and drinking water consumption per industry, compared with the corresponding observed series. It appears from these figures, that, although the value of the determination coefficient was sometimes rather low, the fits are fairly satisfactory; not only is the trend well predicted by the model, but the deviations from the trend and/or the turning points are, in many cases correctly identified.

FOOD, DRINK and TOBACCO

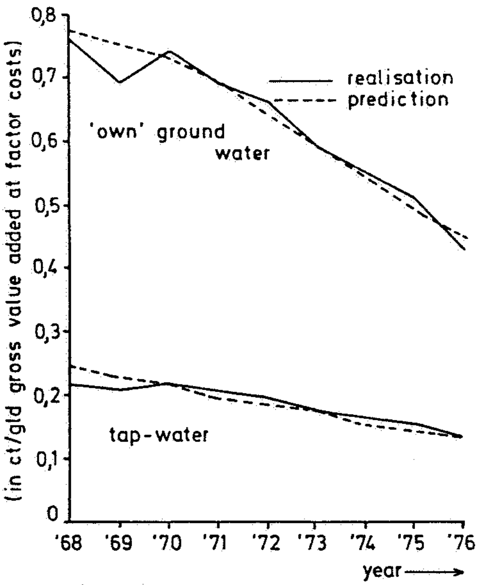


Figure 2

TEXTILE

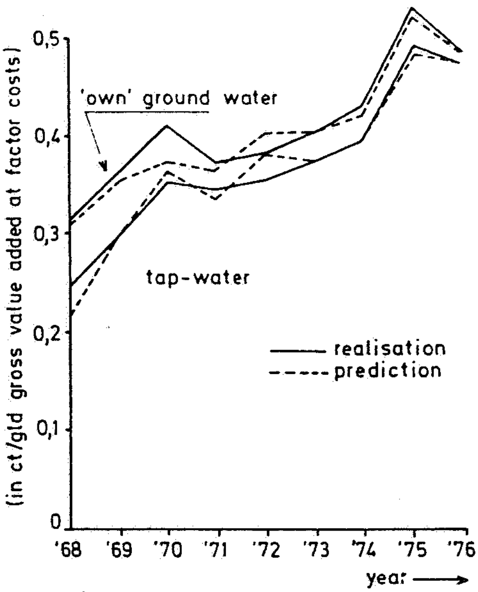


Figure 3

LEATHER AND RUBBER

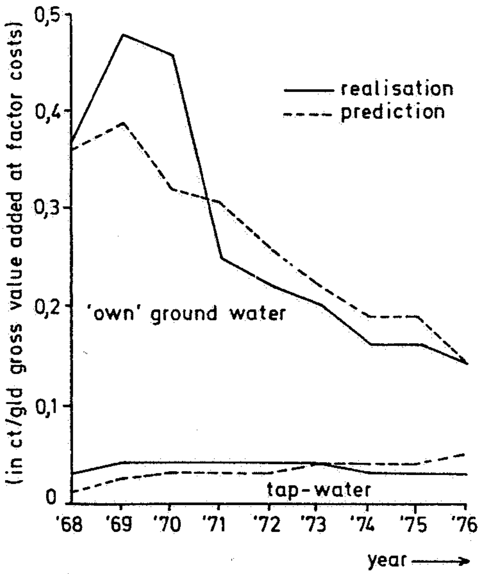


Figure 4

PAPER

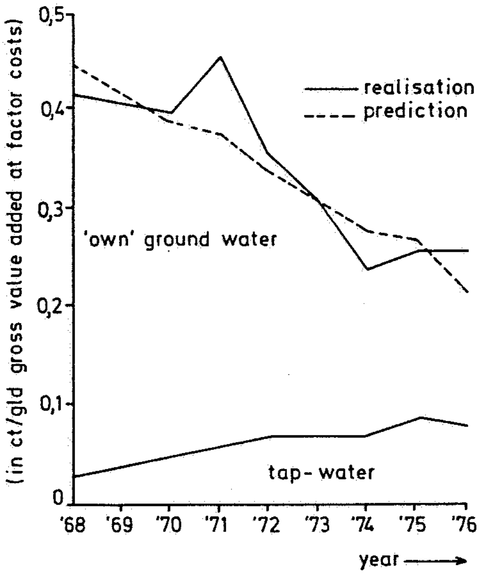


Figure 5

Fig. 2 – Fig. 9 Measured and calculated values of the water consumption per industry for the years 1968–1976.

CHEMICALS

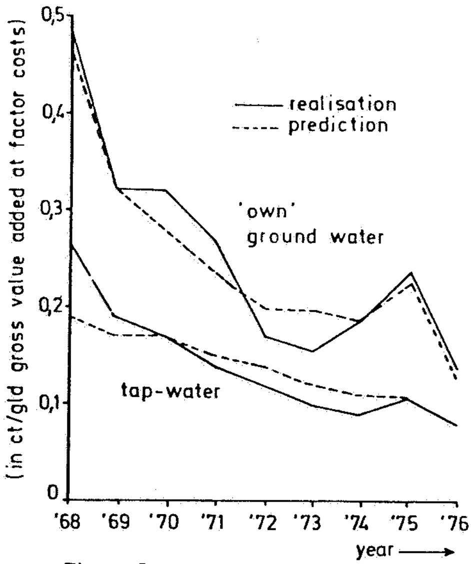


Figure 6

BUILDING MATERIALS

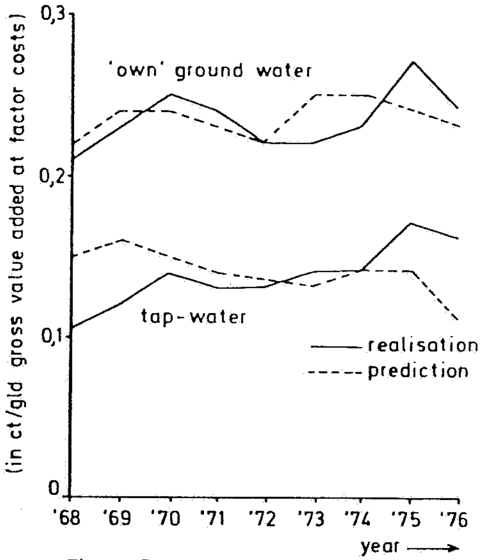


Figure 7

METAL

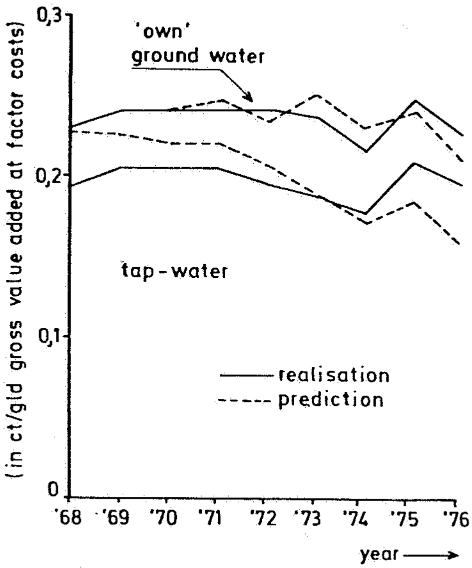


Figure 8

OTHER MANUFACTURING INDUSTRIES

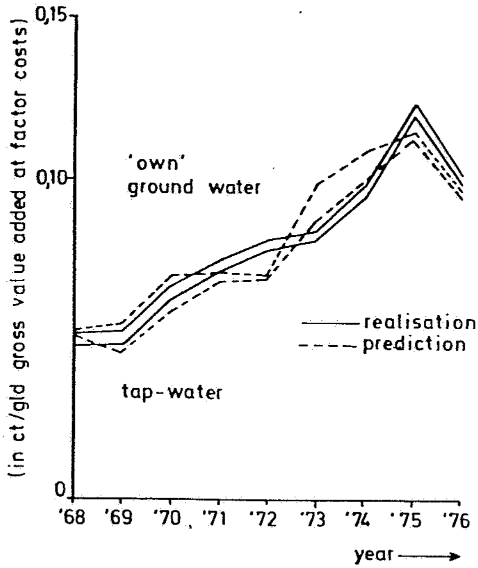


Figure 9

2.3. *The water demand of agriculture*

The agricultural aspects will very briefly be mentioned here, mainly to complete the picture. Given the nature of the problems, the treatment of the agricultural demand for water is heavily based on straightforward agricultural data and on the results of the physical based groundwater model GELGAM (see P.J.M. de Laat and R.H.C.M. Awater, 1978, 1980). As a result of the time- and other constraints the economic content of the approach is, in this case, very much lower than in the previous ones.

The computations for the demand for water in the agricultural sector are exclusively concerned with predictions of the water needs in 1990. Predictions for the water consumption in the stock-breeding sector, per municipality and per type of stock, are obtained as the product between predicted number of animals and the water requirements per animal. This includes water from own abstraction as well as drinking water and water for consumption by the animals as well as water for cleaning and other purposes.

Projections concerning the water requirements of the plants have been confined to grass. The reason is that, from the agricultural point of view, it only makes sense to artificially sprinkle grass and potatoes (apart from horticulture) and potatoes constitute a very marginal crop in the study region. The starting point is the calculation of the average moisture deficit for grassland per municipality for different alternative climatological situations, given data on the potential evapotranspiration, the results of the physical model GELGAM concerning relative evapotranspiration per soil profile and the soil configuration of the municipalities. This was done for two groundwater levels at the beginning of the season (the definition of the season which was used in from 15th April to 15th September, i.e. 150 days): no reduction with respect to an average groundwater level at the beginning of the growth season and 25 cm groundwater level reduction, which could be the consequence of a dry winter. These calculated moisture deficits were then used to compute relative yields and absolute yields (in ton dry material (DM)/ha), yield depression (in ton/ha and in guilders/ha), averaged for the different municipalities and for the various climatological alternatives (J. Bouma et al., 1980). These calculations were made using an empirical linear relationship between relative evapotranspiration and relative yield, for alternative assumptions concerning the potential yield (in ton DM/ha) and the average price of DM. Finally, and this was the main purpose of the exercise, we computed per municipality and per climatological hypothetical situation the quantities of water which, given the previous results and predictions concerning the acreage of grassland in 1990, would be necessary to artificially sprinkle 50 per cent of the grassland in that year. This percentage was chosen as a compromise based on economic considerations and physical constraints to represent a maximum objective. In order to complete the picture a very brief analysis has also been made, per municipality, of the needs for water discharge in order to improve the agricultural situations in certain areas. (C.R. Jurgens, 1979). To illustrate the computations of water demand a sample of results in given in tabel 1.

Table 1 Water demand (in 100.000 m^3) of the crops in 1990 per municipality for a situation with 50% sprinkling-irrigation of the agricultural area and a 25 cm reduction of groundwaterlevel in spring.

Exceedence Frequency (%)	AVERAGE	1 0/0	10 0/0	20 0/0	50 0/0	90 0/0	AREA (in ha)
ANG	2.37	13.94	5.77	3.68	1.20	0.00	1460.
DID	4.74	21.76	11.45	7.59	3.14	0.00	1520.
DUI	2.21	13.67	6.06	3.62	.79	0.00	1200.
HER	1.23	7.78	2.51	1.86	.67	0.00	1130.
PAN	1.05	5.00	2.66	1.89	.54	0.00	410.
WEH	4.26	19.65	10.94	7.25	2.42	0.00	1260.
WES	.30	1.89	.70	.46	.14	0.00	260.
ZEV	1.74	10.51	4.53	2.76	.79	0.00	1000.
BER	13.03	51.89	30.51	21.46	9.60	0.00	3050.
DIN	.98	7.86	3.28	1.34	.08	0.00	670.
DOE	.18	1.74	.37	.24	.05	0.00	380.
DOT	2.06	15.03	6.11	2.90	.55	0.00	1400.
GEN	6.66	40.55	19.39	10.50	2.33	0.00	3200.
HUM	6.86	28.94	16.41	11.64	4.55	0.00	2300.
WIS	5.97	45.62	20.00	9.24	.22	0.00	3750.
AAL	7.20	53.64	23.17	10.38	1.06	0.00	4430.
EIB	12.21	82.76	35.75	16.66	4.36	0.00	7200.
GRO	.42	4.68	1.50	.25	0.00	0.00	540.
LIC	7.55	53.34	23.38	10.76	1.79	0.00	4350.
NEE	4.54	27.19	12.61	6.79	1.96	0.00	2150.
BOR	8.50	42.20	21.89	13.27	5.04	0.00	3300.
GOR	9.18	53.14	26.71	15.39	3.05	0.00	3900.
HEN	3.41	26.49	11.12	4.72	.43	0.00	2250.
LAR	13.54	83.43	39.90	21.86	4.07	0.00	6450.
RUU	4.91	40.51	16.22	6.49	.39	0.00	3800.
STE	9.44	38.72	21.29	15.60	6.95	0.00	2900.
VOR	3.72	27.89	11.80	5.42	.54	0.00	2460.
WAR	4.71	26.93	13.34	7.68	1.81	0.00	2000.
ZEL	6.54	47.48	19.21	9.31	1.63	0.00	4200.
ZUT	.63	2.92	1.64	1.15	.32	0.00	210.
WIN	10.52	80.44	35.03	15.86	.51	0.00	6600.
O-G	160.65	977.58	455.25	248.01	60.95	0.00	79730.

3. DESCRIPTION OF THE ALTERNATIVE SCENARIOS AND THE POLICY DECISION CRITERIA

The progress of the second part of the study closely follows the sequence of steps involved by the multicriteria methodology. Initially, alternative scenarios must be formulated and decision criteria must be selected. Then primary evaluations of each of the scenarios must be made with respect to each of the criteria: these primary evaluations constitute the input for the multicriteria analysis. The final step is the multicriteria analysis itself. These three stages are successively discussed in this and the following two sections, with reference to the application of the methodology to water management in East-Gelderland.

3.1. *The basic assumptions*

First of all a relational scheme between the regional interest spheres was constructed. With the aid of this information, six alternative scenarios P_1 ... P_6 were derived and water demand predictions for the different sectors in a 10%-year in 1990 were calculated. The following assumptions were made:

improvement works

a. the total area of pasture in Eastern Gelderland is about 80,000 ha. Diminishing of water excess is needed urgently for about 46,000 ha, the net profit of these works being estimated at Dfl 30 per ha on the average (costs of improvement works included). Whenever within the improvement area nature reserves (wetlands) have to be protected by compensatory works, the net profit becomes negative (about (–) Dfl 100 per ha);
b. alternatives are formulated for 50% (40,000 ha), 25% or 13% (situation 1976) sprinkling of the pasture land. The net profit for replenishment by sprinkling with groundwater is estimated at Dfl 130 per ha on the average, for sprinkling with surface water at Dfl 85 per ha (assuming low costs of water supply which apply to only 10% of the total pasture area) or (–) Dfl 20 per ha (high costs of supply, canals having to be dug and pumping works being needed). The surface water is taken from the rivers Rhine and IJssel. It is interesting to compare the results with those of the Tielerwaard and Leerinkbeek reports. The water needs are less than the evapotranspiration excess as a result of the water content of the soil and the capillary rise.

drinking water

a. the tariff for drinking water is Dfl 1.– per m^3 according to the basic rate (small users) and Dfl 0.50 per m^3 according to bulk rate (big users); all the water supplied by water supply companies is exclusively ground water;
b. the available ground water is estimated to be around 70.10^6 m^3 per year in a 10% dry year;
c. the location of new pumping stations are taken from the 10-years master plan of the water companies or determined according to the criterion of minimal damage to agriculture (model GELGAM);
d. the water-supply by drinking-water companies was in 1976 about 27.10^6 m^3, the groundwater abstraction by industry about 13.10^6 m^3. The water-supply companies delivered 13% to the industry.

nature conservation

a. a map was prepared with indication of every km^2 where wetlands of high ecological value are present (often in only a small part of this km^2);
b. five municipalities have so many wetlands of ecological value that they were given a special status and called "nature-municipalities" (these contain in total 13,000 ha pasture). In some scenarios no technical works are undertaken in these municipalities.

waste-water treatment

a. The cost of removal of phosphates from the effluent of the "nature-municipality" Winterswijk are estimated to be Dfl 100,000.– per year (the effluent is about 4.10^6 m^3 per year).

3.2. *The alternative scenarios*

The different scenarios P_1 ... P_6 are summarized in table 2.

P_1 (reference scenario): a more or less equilibrated distribution of the available water is aimed at. There is a shortage of sprinkling water of 19.10^6 m^3 in a 10% dry year;

P_2 (nature friendly scenario): the water demand is compressed by a tax of Df. 0.25 per m^3 on ground water abstraction by industry and by an increase of 20% of the drinking water tariff, sprinkling is restricted to 25% of the pasture land. Because of protection of wetlands, the costs of improvement works are increased by 50%;

P_3 (scenario with emphasis on agricultural and nature conservation): compensation works for nature protection lead to rises in the costs of improvements, farmers have priority over drinking water companies with respect to ground water abstractions, and, as a consequence, the water supply companies have to abstract about 19.10^6 m^3 per year surface water from the big rivers Rhine and IJssel;

P_4 (groundwater economy scenario): groundwater is saved by a tax on groundwater abstraction (Dfl 0.25 per m^3) to be payed by industry and farmers; sprinkling is restricted to the areas of 1976 (13% of pasture land);

P_5 (minimum scenario): minimum predictions for water demand and minimum change with respect to the existing situation;

P_6 (maximum scenario): maximum predictions for water demand and maximum change (within the feasibility domain) with respect to the existing; in order to remain within the feasible constraints water prices are raised.

Table 2 Alternative schemes

Plan Characteristic	P_1 Reference (r)	P_2 Nature friendly (n)	P_3 Agriculture favouring (1)	P_4 Ground-water economy (g)	P_5 Minimum plan (a)	P_6 Maximum plan (z)
A. Agriculture A 1 Drainage	high and average priority regions see B	as P_1, see B	as P_1, Winterswijk is drained	as P_3	as P_1	as P_1, see B
A 2 Sprinkling	50% of pasture (10%-drought)	25% of pasture (10%-drought)	as P_1	13% of pasture (10%-drought)	as P_4	as P_1
A 3 Ground/ Surface water	ground w. and paying surface w., see C_4	as P_1	ground w. priority, see C_4	as P_1	ground w. see C_4	as P_1, also expensive surface water
B. Nature conservation	no works in "nature-municipalities"*)	as P_1, in other municip. drainage costs are risen to protect nature	as P_2 plus drainage of Winsterswijk	as P_3	as P_1	drainage of all nature municip. plus risen costs
C. Watersupply C 1 Quantity	mean prognosis	as P_1	as P_1	as P_1	min. prognosis	max. prognosis
C 2 Tariff	no change	tax on ground water (industry); drinkw. tariff plus 20%	as P_1	tax on ground water (industry & agriculture)	as P_1	as P_2
C 3 Situation pumping stations	10-years master plan,**) see B	min. damage to agriculture see B	as P_2	as P_2	as P_1	as P_2
C 4 Ground/ Surface water	ground water priority over agriculture	as P_1	ground w. and surface water	as P_1	as P_1	as P_1
D. Environmental hygiene D 1 Quality	plan of Water Board**) (biol. treatm.)	as P_1 plus phosphate removal in Winterswijk	as P_1	as P_1	as P_1	as P_1
D 2 Situation water treatment plants	plan of Water Board**)	as P_1	as P_1	as P_1	as P_1	as P_2 plus reuse of waste water

* Winterswijk, Vorden, Herwen-Aeardt, Pannerden, Hummelo-Keppel
** existing plans

In tabel 3 the water allocation schemes for the six scenarios are given

Table 3 Water allocation schemes (in 10^6 m^3 per year) for the six scenarios

Scenario	Category	Ground water	Surface water	Total
r	sprinkling	17.3	9.5	26.8
79.5. 10^6 m^3	ind. own abstr.	20.4	–	20.4
	water comp.	32.3	–	32.3
n	sprinkling	22.8	–	22.8
57.5. 10^6 m^3	ind. own abstr.	1.0	–	1.0
	water comp.	33.7	–	33.7
1	sprinkling	36.0	9.5	45.5
98.3. 10^6 m^3	ind. own abstr.	20.4	–	20.4
	water comp.	13.6	18.7	32.3
g	sprinkling	11.8	–	11.8
50.5. 10^6 m^3	ind. own abstr.	1.0	–	1.0
	water comp.	37.8	–	37.8
a	sprinkling	11.8	–	11.8
52.6. 10^6 m^3	ind. own abstr.	16.9	–	16.9
	water comp.	23.9	–	23.9
z	sprinkling	23.5	22.0	45.5
92.0. 10^6 m^3	ind. own abstr.	1.2	–	1.2
	water comp.	45.3	–	45.3

3.3. *The policy decision criteria*

The following six policy decision criteria emerged from discussions with the experts:

1. the conservation of nature (N);
2. the interests of agriculture (L);
3. the satisfaction of the demand for drinking and industrial water (V);
4. global costs and benefits of the water management system (K);
5. aspects of environmental hygiene (M); and
6. the groundwater reserves (G).

Further, a certain hierarchy between these criteria obtains from the outset in the sense that the first four criteria must be considered as being relatively more important than the last two. Justification for this is as follows. In the case of environmental hygiene, the different scenarios leave little scope for variation because water quality aspects have been treated less fully than water quantity aspects; as a result of this lack of detailed analysis rating this criterion higher than the first four might be misleading. As to the groundwater reserve, it would be difficult to argue that this criterion could be an aim in itself in view of the very important other regional interests; it is a secondary criterion which should be used to restrain decisions implied by the first four.

3.4. *Evaluations of the scenarios with respect to the criteria*

Given the formulation of the alternative scenarios and the definition of the criteria, the evaluations of the six scenarios have to be made in relation to the six criteria. As far as nature and environmental hygiene are concerned, these evaluations were of an ordinal nature; with the other criteria there was in principle sufficient information available to establish cardinal or quantitative measures. Regarding the criteria agriculture and costs/benefits, these measures could in the first instance be expressed in net yields in guilders per year; watersupply and groundwater reserves could be measured in cubic metres per year. The quantitative evaluations are based on published sources as well as on expert's advice; medium-term forecasts of water demands were computed by means of the demand models developed in the first part of the study and in function of the specific assumptions concerning the values of the explanatory variables and policy instruments as specified by the alternative scenarios. The results of the computations, which in certain instances correspond to fairly sophisticated evaluation processes, are summarised in tabel 4. All these computations were made under the restriction that the physical limit of the ground water supply does not exceed 70.10^6 m^3 per year.

The evaluations with respect to the cost/benefit criterion as represented in table 4 are expressed with respect to the reference plan as a basis.

Table 4 Evaluations of the scenarios with respect to the criteria

Scenarios Criteria		r	n	l	g	a	z
agriculture	(L)	3850	1688	3392	(–) 3027	2421	1514
nature	(N)	+++	++++	++	++	+++	+
water supply	(V)	52.8	34.7	52.8	38.7	40.8	46.5
environment	(M)	+	++	+	+	+	++
costs	(K)	0	(–)9717	(–) 458	(–)20297	2046	(–)23052
groundwater reserve	(G)	0	12.5	0	19.4	17.4	0

4. THE MULTICRITERIA ANALYSIS

The purpose of multicriteria analysis is the determination of the optimal ranking of alternative scenarios for any weighted combination of given policy decision criteria.

In the present study two different multicriteria methods were used to conduct the analysis: the QUALIFLEX method and GELPAM (the method of Saaty). These methods and the results obtained are briefly presented hereafter.

In contrast to unicriterion methods, the evaluations of the alternatives with respect to the criteria in the multicriteria situation can be expressed in "natural" units of measurement so that they must not be reduced to a common dimension such as money. Water consumption can be expressed in m^3 per year, noise nuisance in decibels, water quality aspects in equivalents, etc. Further, both methods used here are such that these evaluations must not necessarily be made along a cardinal scale so that whenever accurate quantative information is lacking, a simple ordinal ranking is sufficient. Once these evaluations have been made, the technique can then be used to determine the optimal ranking of the alternative scenarios for any weight combination of the policy decision criteria.

4.1. *The multicriteria method QUALIFLEX*

The QUALIFLEX multicriteria method used in this application has been developed to deal with very broad categories of problems including those for which only very meagre information is available. [The QUALIFLEX method was designed to provide a FLEXible method to deal with QUALItative as well as with quantitative information. The technical aspects of the method have been developed in several papers. For a general introduction see, e.g. J.H.P. Paelinck, (1978) and J.P. Ancot and J.H.P. Pealinck, (1979).]

4.1.1. *The concept of decision space*

Before briefly describing the method it is useful to introduce the concepts of decision space and decision subspaces which constitute the framework for the implementation of the method. The decision space is defined by the set of all possible combinations of weights which can be associated with the policy criteria. This decision space is then divided in subspaces corresponding to all possible weight combinations respecting a particular priority ranking of the criteria. For example, with three criteria, the decision space consists of all the points corresponding to all the possible values of the triplet (w_1, w_2, w_3) such that $w_1 + w_2 + w_3 = 1$ and w_1, w_2 and w_3 are non-negative values. A particular subspace can then be defined as the set of all points where, e.g., $w_1 \geqslant w_2 \geqslant w_3$, meaning that within that subspace criterion number one is always more important than criterion number two, and that criterion number two is always more important than criterion number three. With three criteria, one obtains six (3!) such subspaces. This situation is illustrated in figure 10.

This division of the decision space into subspaces is useful for the organisation of the study of the optimal solutions to the decision problems corresponding to all possible priority rankings of the policy criteria. Indeed, especially when the number of criteria increases, it may become extremely laborious to investigate in detail all possible choice situations. Although it is not the role of the researcher to determine the specific weights

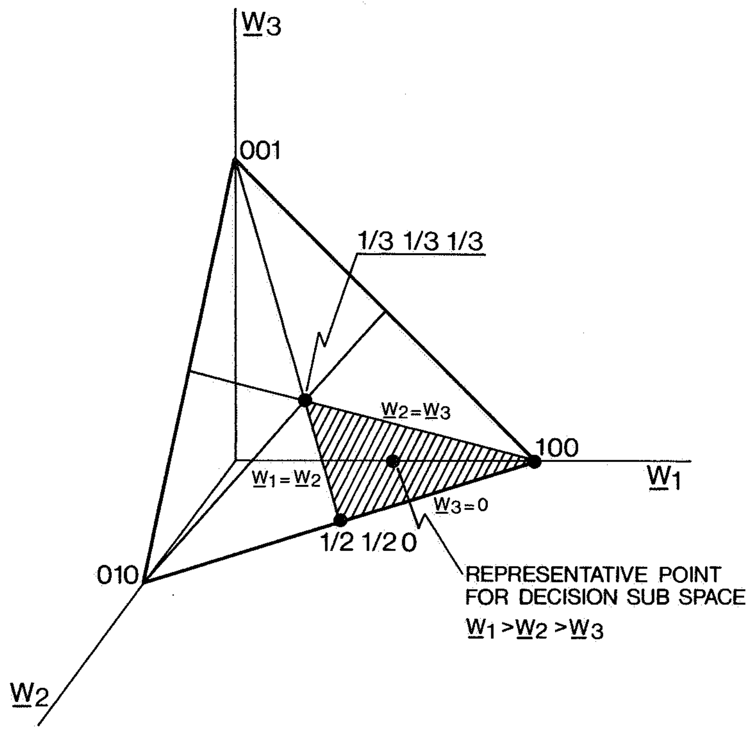


Fig. 10 Decision space *W*1 *W*2 *W*3

which should be associated with the criteria (and not even their priority ranking), he may like to make a more detailed examination of certain parts of the decision space, because they may appear to be particularly sensitive to marginal variations in the relative values of the weights or because they correspond to typical "political" profiles. This partitioning of the decision space into subspaces, leads to two types of multicriteria analyses: a general study of the whole space or of a very large part of that space to obtain a general picture of the variety and of the occurrence frequencies of the optimal decision possibilities as a function of the possible priority rankings of the criteria and a much more detailed study of the local structure of any selected subspace.

4.1.2. *The matrix of score values*

The starting point for the method is a matrix of score values, represented in table 5, derived by means of normalisation operations from the primary evaluations of the scenarios (table 4).

The evaluations presented in table 4 were in the present application normalised by

Table 5 Matrix of score values (QUALIFLEX)

Scenarios Criteria		r	n	l	g	a	z
agriculture	(L)	25	17	23	0	19	16
nature	(N)	15	37	12	12	15	9
water supply	(V)	20	13	20	15	15	17
environment	(M)	11	28	11	11	11	28
costs	(K)	28	16	27	3	26	0
ground water reserve	(G)	0	28	0	41	31	0

translating the quantitative information into percentages; those with respect to the criteria agriculture and costs/benefits were transformed in a simple way to ensure non-negative values for all quantities. When only ordinal information with respect to a specific criterion is available for $P_1 \ldots P_6$, the most representative point of the subspace for this criterion is used, e.g. the centre of gravity. This results in a set of (cardinal) weights for the different scenarios with respect to this criterion (fig. 10, for example $w_1 > w_2 > w_3$ gives $w_1 = 0.58$; $w_2 = 0.24$; $w_3 = 0.18$).

4.1.3. *General outline of the QUALIFLEX method*

The QUALIFLEX method is basically a permutation type multicriteria algorithm. Given the normalised evaluations of the scenarios with respect to the criteria, as presented in table 5, the basic principle of the method consists in considering all possible rankings of the scenarios and, for a given weight combination of the policy decision criteria, to obtain a total score for each of these rankings so that the ranking with the highest total score is the most attractive one in that point of the decision space.

The total score for each ranking ultimately rests on information of the type contained in table 5. For each criterion the information of table 5 defines a cardinal order relation between the scenarios, in the sense that any row of that table not only defines an optimal preferences ordering of the scenarios with respect to the corresponding criterion, but also indicates the relative "distances" between scenarios within that ranking. As a result, it is possible to use that information to obtain scores for each of the possible rankings with respect to each criterion. If only qualitative information was available, table 5 would define purely ordinal relations. The principle of the method however, would remain the same in this case, except that, of course, the scores obtained for each ranking would not include information about relative distances between scenarios.

These scores which reflect the only common dimension of the evaluations presented in a table like table 5, i.e. the order relations existing between the scenarios for each criterion, are then standardised to assure comparability across criteria. Given a weight set for these criteria these standardised scores are further aggregated in a weighted average fashion to yield the total score for each of all possible rankings of the scenarios.

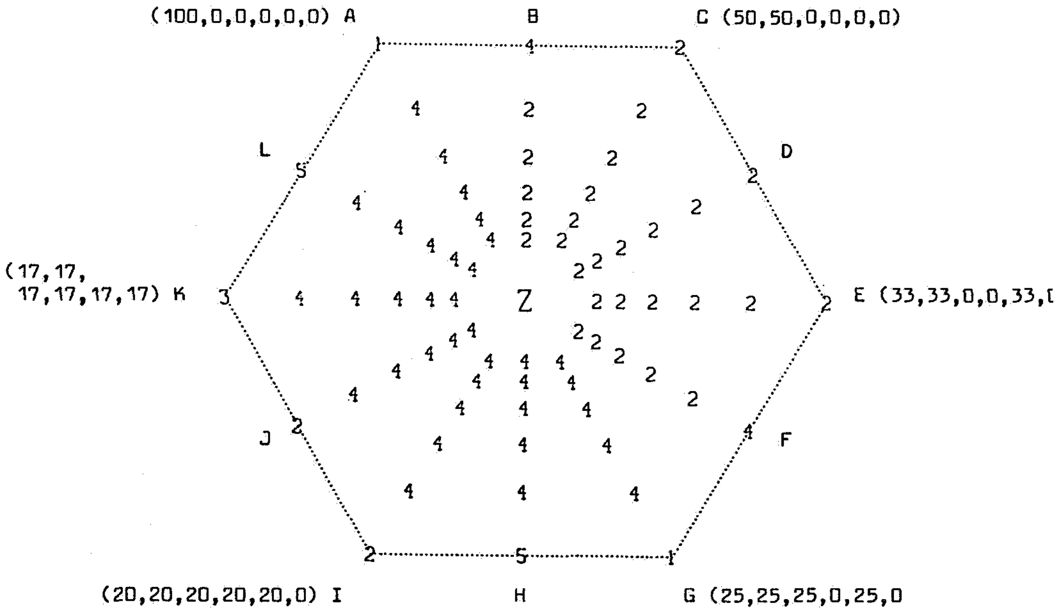
The number of different rankings to be compared very rapidly increases with the number of scenarios (this number of rankings is exactly equal to n!, where n is the number of scenarios). Therefore efficient algorithms were developed to maintain tractability of problems involving a relatively high number of scenarios. In the case of quantitative or semi-quantitative information (such as the information contained in table 5) it can be shown that the procedure can be reduced to a very simple algorithm. In the more difficult case of purely qualitative information it has been shown that an approximate solution can be found be means of a linear programme. These proofs are based on the fact that the solution procedure, which belongs to the combinatorial methods, in a special case of the quadratic assignment problem (J.P. Ancot and J. Paelinck, 1979). This formalisation is further useful because as a result of the reduction of the problem to a constrained maximisation of an objective function, it can be exploited to guide the analysis for the comparison of suboptimal solutions with respect to the optimal one. This constitutes the basis for the sensitivity analysis presented in subsection 4.1.4. with the aid of figure 12.

4.1.4. *A detailed analysis of a decision subspace*

In order to illustrate the technique a fairly detailed analysis of a subspace with a simple structure will first be presented; the subspace selected corresponds to that part of the decision space in which the weights of the criteria obey the following (decreasing) priority ranking: agriculture, nature, costs, water supply, environmental hygiene and finally ground water reserves.

Figure 11 represents the results of scanning the subspace studied. A direct graphic reproduction of these results is not possible, because six criteria imply a five-dimensional subspace. The graph is a hexagon of which the corner represent the extreme combinations of the weights, given the ranking chosen. In point A the first criterion, agriculture, gets all the weight, the others playing no part there; in the next vertex, C, the first two criteria, agriculture and nature, get equal weights, the other being left out of consideration; in that way more criteria are gradually introduced until, in point K, all criteria play their part, all having the same weight. The other points investigated are then generated as follows. In five-dimensional space, schematically represented in figure 11 by the hexagon, every pair of successive vertices are linked by straight lines, producing the segments AC, CE, EG, etc., in the graph; of each such segment the middle is determined, which produces points B, D, F, etc. Still in five-dimensional space, these points are again connected pairwise by straight-line segments, and the middles of the segments found, and so on. The procedure has several advantages: it permits simply and systematically to generate points within the five-dimensional subspace; it leads to a well-ordered and clear graphical representation, and it allows the generated points to converge to the point of gravity of the five-dimensional figure.

AQUAFLEX



Number	Optimal ranking	Number	Optimal ranking
1	r l a n z g	4	r n l a z g
2	n r l a z g	5	r l n a z g
3	n r a l z g		

Legend

Alternative schemes:

r: reference plan
n: nature favouring plan
l: agriculture favouring plan
g: ground-water economy plan
a: minimum plan
z: maximum plan

Criteria:

N: nature
L: agriculture
V: water supply
K: costs
M: environment

Fig. 11 The optimum permutations in a decision subspace
Ranking of the weights L-N-K-V-M-G

For each point examined, figure 11 indicates the optimum ranking of the alternative scenarios by the integers from one to five; the corresponding rankings are defined in the accompanying table. In point A, e.g., where agriculture is given weight 1 and where the other criteria are left out, the optimum ranking of the plans is ranking number 1, with the reference scenario in the lead, followed by the agriculture-favouring scenario, the minimum scenario, the nature-favouring scenario, the maximum scenario, and with the groundwater saving scenario bringing up the rear. In point C, where the criteria agriculture and nature both get weight ½, the nature-favouring scenario takes pride of place (as a result of bringing in the criterion nature), while the agriculture-favouring and the minimum scenario drop back in respect of the optimum ranking of point A. In the next vertex, point E, where the third criterion, that of costs, is introduced with a weight equal to 1/3, the optimal ranking remains unchanged compared with the situation in point C. In the fourth vertex, point G, the optimal ranking is the same as in point A: introduction of the fourth criterion, water supply, with a weight equal to ¼, has neutralized the impact of the previous two criteria.

The most important conclusion arising from the study of figure 11 is the division in about equal parts of the largest part of the subspace into two areas where rankings number two, four respectively are found to be optimal; the only difference between these two rankings is the relative ranking of the first two plans. When nature and costs are rated to be relatively important criteria, the nature-favouring scenario is the winner and in the other cases the reference scenario is the preferred alternative.

Although figure 11 already indicates clearly how the policy subspace can be studied with respect to the calculated optimum rankings of the scenarios and their dispersion in decision space, it is even more important to have an evaluation of the relative position of the alternatives within the ranking that has been found optimal for a certain point. The question can be asked, for example, whether the first two scenarios in point A within ranking 1 are clearly separated or, on the contrary, hardly distinguishable from each other; this question is answered in figure 12 for some selected points. It emerges from this graph that in point A, where the criterion agriculture is the only one that counts, the reference scenario occupies a first place, closely followed by the agriculture-favouring scenario the ground water saving scenario a clear last one; the other three scenarios form a cluster in the middle of the interval. It is interesting to find out what happens when, starting from point A, one moves along the segment AC to C and next from C to E, nature being introduced as a new criterion, as yet with a low weight, at point B. The new ranking that comes into being as a result, number 2, is easy to interpret with the help of figure 12: in comparison with the situation in point A, scenario n advances, showing an inclination to take the first position, whereas the positions of the other scenarios remain practically unchanged. The moves become much more pronounced when, as in point C, the weight of a new criterion increases relatively: scenario n takes the first place and pushes scenario r clearly to the second one; the scenarios 1, a and z fall back significantly and 1 and a are hardly distinguishable. In the next two points, points D and

E, this configuration remains practically unaltered. In these points the scenarios r, 1 and a become again somewhat more attractive and scenario z gets steadily worse. The improved performance of r, 1 and a relatively to n and the deterioration in the position of z are the consequence of the cost implications for households and industry of the price policies implied by scenarios n and z.

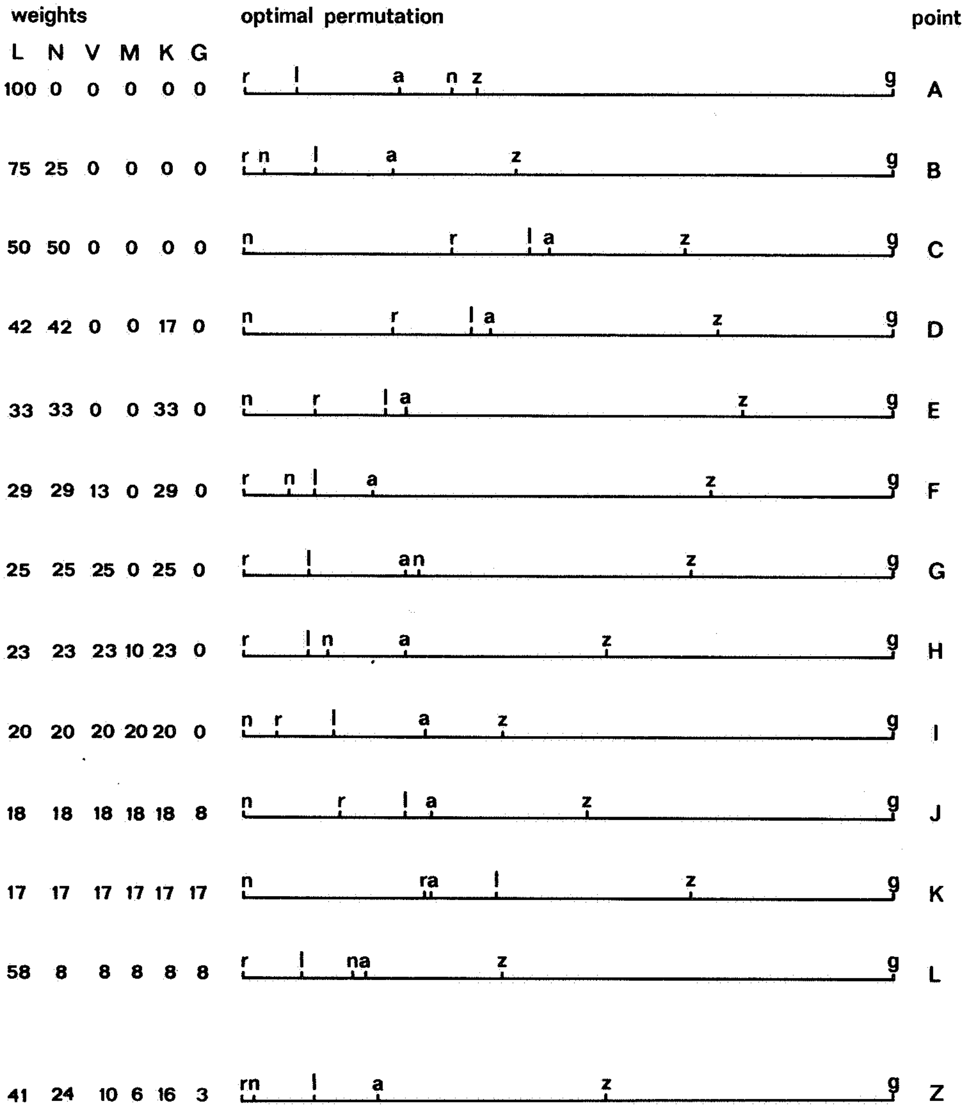


Fig. 12 Relative position of the plans within a number of selected optimal permutations

The points with the greatest stability in respect of the optimum ranking of the alternative scenarios are those that in figure 11 are nearest to the centre of the hexagon, or, in five-dimensional space, near to the point of gravity. It is evident from figure 12 that in the centre of gravity, Z, scenarios r and n practically share the first place, followed by the scenarios 1 and a, while the scenarios z and g clearly take up the last but one and the last place, respectively. Presumably this ranking and the relative distances between the scenarios within it are most representative of the ranking of weights studied here. The study of figure 12 inspires two further remarks. One regards the "strictness" with which the groundwater saving scenario is consistently treated; even if all criteria are given equal weights (in point K), this scenario very clearly brings up the rear in the optimum ranking. It follows from the fact that this scenario does not defend any one of the large interests, and is rather costly into the bargain. The second remark concerns the optimum permutation in point K, which is to be considered the most neutral point in policy space, because it is there that all criteria take the same weight. In this point the nature favouring scenario is preferred to the hardly distinguishable reference and minimum scenarios; these are followed by scenario 1, next comes scenario z and finally scenario g.

4.1.5. *Four decision priority rankings*

In order to illustrate the detailed analysis presented in the previous subsection figures 13 to 16 represent the results of scanning four subspaces which could correspond to relevant profiles in a policy decision situation with respect to water management. In order to preserve legibility the graphical representations which are analoguous to that of figure 11, are limited to the rankings of the three most attractive scenarios in each point studied.

The first subspace (fig. 13) is characterised by heavy weights for agricultural interests and cost elements; this priority ranking could be interpreted as corresponding to the preferences of the agricultural representative. From this figure it appears clearly that, as long as the first three or four criteria dominate (L, K, V and M), the optimal ranking of the scenarios is $r \geqslant 1 \geqslant a$; when the last two criteria, N and G, are introduced with steadily higher weights, the nature favouring scenario becomes gradually more attractive: it first takes third place ($r \geqslant 1 \geqslant n$), then second place ($r \geqslant n \geqslant 1$) and finally even first place ($n \geqslant r \geqslant a$ and $n \geqslant r \geqslant 1$). The most typical ranking for this agricultural "profile" probably corresponds to the north eastern part of the hexagon, so that, in this case, ranking $r \geqslant 1 \geqslant a$ would be chosen.

The second case (fig. 14) where nature, environmental hygiene and groundwater reserves are the priority objectives could be typical for the ecological "profile". In this subspace the nature favouring scenario always takes the lead. The rankings of the other scenarios are rather variable. When M, G and L are relatively important (eastern part of the figure) the maximum and the minimum scenarios take up second and third place. In the western part of the figure, where criteria V, K and N carry relatively higher weights, these two scenarios lose their respective positions in favour of the reference scenario, which scores favourably with respect to these criteria.

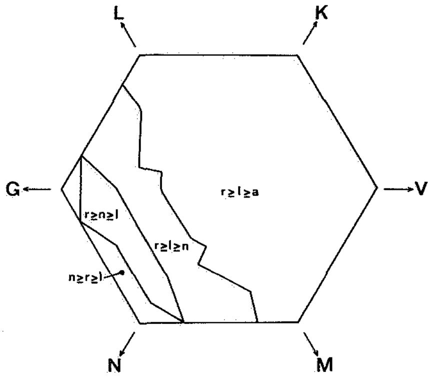


Figure 13 Agriculture profile
(L≥K≥V≥M≥N≥G)

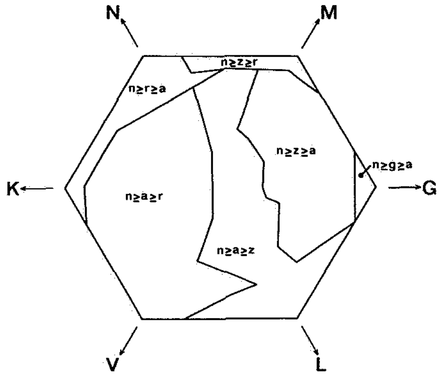


Figure 14 Ecological profile
(N≥M≥G≥L≥V≥K)

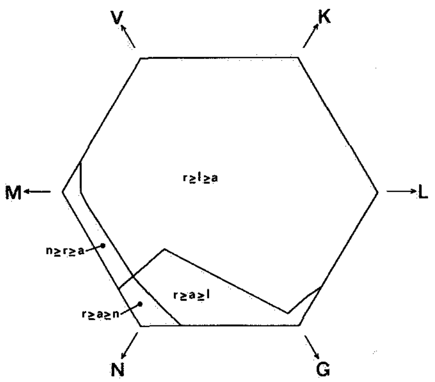


Figure 15 Watercompany profile
(V≥K≥L≥G≥N≥M)

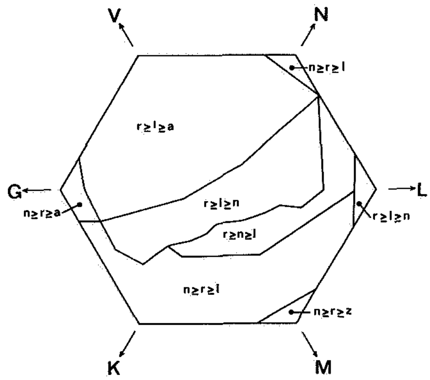


Figure 16 Profile of the provincial anthorities
(V≥N≥L≥M≥K≥G)

The situation of figure 15 could be typical for the representative of the drinking-water supply companies: high priorities to V, K and L. In this subspace the configuration is particularly simple: practically the whole subspace is dominated by the ranking r ⩾ 1 ⩾ a; only in the extreme south western boundary some changes occur in favour of scenarios n and a.

The last case (fig. 16) assumes that the satisfaction of demand for water by households and industry, agricultural interests and nature conservation are the primary objectives and that the other criteria are relatively unimportant. This "profile" which could be representative of the preference of the local authorities specially refers to the south eastern part of the hexagon, where the rankings r ⩾ 1 ⩾ n, n ⩾ r ⩾ 1 and r ⩾ n ⩾ 1 dominate. This subspace has a more complicated structure; nevertheless the reference scenario nearly always takes up the lead often followed by the agriculture favouring scenario, especially when criterion V carries a large weight. In the south western part of the hexagon the nature favouring scenario is the most attractive one as a result of the combined action of the environmental hygiene, costs and groundwater reserves criteria.

From the study of these profiles it is clear that an aggregation of figures 13 to 16 would lead to the choice of the reference scenario. Only if the ecological priorities of figure 16 were very dominant, the nature favouring scenario would be chosen. It is however, relevant to point out in this context that, if all criteria are given equal weights (the extreme eastern vertex of the hexagon) the most attractive scenario is the nature favouring one, followed by the reference scenario.

4.1.6. *General analysis of the decision space*

The detailed study of a certain number of particularly relevant subspaces can be completed by a general study of the whole decision space. Indeed, as soon as the number of criteria is larger than 3 to 4, the number of subspaces increases so quickly that it becomes impractical to study all of them in detail. On the other hand some of these subspaces will be of particular interest to the researcher and to the decision maker because they correspond to weight combinations which are realistic and relevant with respect to the specific situation at hand, but other subspaces will obviously have a very much more marginal character, so that detailed analysis of these is not really required. Nevertheless, in order to get an overall picture of all possible solutions (e.g. to examine the robustness of the solutions or to arrive at a small number of synthetic statistics for the complete set of optimal solutions) one may wish to add to the detailed studies a general study, or at least a study covering a larger part of the possible source of variations than any of the detailed studies.

This possibility is briefly illustrated hereafter. All 24 possible priority rankings of the criteria obtained when groundwater and environment are always given respectively the lowest and the second lowest priorities, are studied globally. [The reasons why the criteria groundwater and environment are held on the two lower rankings are the lack of variability of the scenarios with respect to waste water treatment and the nature of the groundwater criteria which could be seen as a consequence of other criteria such as nature, agriculture, water-supply and even costs.] For each of the 24 selected subspaces 50 points or weight combinations were examined; these points were largely chosen in the more excentric parts of the subspaces (or near the boundary of the hexagon in figure 11), in order to allow for maximal variability in the corresponding rankings of the scenarios in those points.

The results of this general study can be summarised in the form of a frequency distribution. Given that there are six scenarios the maximum number of different rankings is $6! = 720$. Analysis of the frequency distribution has shown that, although 1200 points were examined, only 15 different rankings were found, and that for individual subspaces that number is even lower: between 5 in the cases $L \geqslant N \geqslant V \geqslant K \geqslant M \geqslant G$, $L \geqslant N \geqslant$

K$\geqslant$V$\geqslant$M$\geqslant$G and L$\geqslant$K$\geqslant$N$\geqslant$V$\geqslant$M$\geqslant$G, and 12 in the case K$\geqslant$N$\geqslant$V$\geqslant$L$\geqslant$M $\geqslant$G. Since the generation of points was concentrated in the more excentric parts of the subspaces (where, as can be seen from figure 11 the variability of the optimal permutations is much higher than in the region around the centre of gravity) one can already conclude that the results are fairly stable with respect to changes in the priority rankings of the criteria. This conclusion is confirmed when one studies the distribution in detail. It appears from this study that only four rankings cover 73% of the examined points: ranking rlangz (meaning, by decreasing order of attractiveness, the reference scenario, the agriculture favouring scenario, the minimum scenario, the nature favouring scenario, the maximum scenario and the groundwater saving scenario) in 24% of the points, ranking rlnazg in 18% of the points, ranking rnlazg in 16% of the points (this is ranking 4 in figure 11) and ranking nrlazg in 15% of the points (this is ranking 2 in figure 11). In a further 19% of the points two additional rankings hold: nralzg and rlazng. The main information contained in the frequency distribution is presented, in an aggregate way, in table 6. This table presents a cross-classification in percentages of the scenarios and the frequency of occurrence of their rankings (r comes in 72 of 100 cases on the first place). From table 6 an average picture emerges. The best scenario is undoubtedly the reference scenario; the second place, on an average, is taken by the agriculture-favouring scenario, the last but one and last places are taken, respectively, by the maximum and groundwater saving scenarios. The nature favouring scenario shows a wide spread among the first four rankings; it is handicapped in several instances by the high drinking water prices it implies.

Table 6 Frequency distribution of the scenarios and the rankings for 1200 different weight combinations of the criteria

Scenario Ranking	r	n	l	g	a	z
1st	72	28	–	–	–	–
2nd	28	17	54	–	1	–
3rd	–	18	33	–	49	–
4th	–	25	13	–	50	12
5th	–	10	–	8	–	82
6th	–	2	–	92	–	6
Average ranking	1.28	2.78	2.59	5.92	3.49	4.94
Variance	0.20	2.07	0.50	0.01	0.47	0.18

4.2. *The multicriteria method GELPAM.*

4.2.1. *General outline of the method*

The general principle of the method differs from that of the QUALIFLEX method [for details, see T.L. Saaty (1978), J.G. de Graan (1978), Th. J. van de Nes (1980) and Th.J. van de Nes and E.P. van Lohuizen (1978)] and the interaction between systems analysts and technicians on the one hand and the decision-makers on the other hand is more direct. As with the QUALIFLEX method one starts from a decision problem where a number n of alternative scenarios are compared in relation to a number m of criteria.

For a given weight distribution of the criteria one is looking for the best project, a so-called multicriteria decision. First one looks at every criterion separately and compares the projects in relation to this criterion one by one. For the calculation of the score values of the projects for every criterion one constructs a matrix of pair-wise comparisons. Suppose a vector w of score values for n projects and define a matrix A, with elements

$$a_{ij} = \frac{w_i}{w_j} \tag{10}$$

A is a so-called reciprocal matrix, meaning that

$$a_{ij} = \frac{1}{a_{ji}} \text{ and } a_{ii} = 1 \tag{11}$$

It can be proved easily that $A\,w = n\,w$.

This is a well-known linear algebra problem, where n is called the eigenvalue and w the eigenvector of the matrix A. If A is known, n and w can be calculated. Matrix A satisfies the cardinal consistency property $a_{ij} \cdot a_{jk} = a_{ik}$, and we call A therefore consistent.

It can be proved easily that if A is consistent there is only one eigenvalue $\lambda = n$, while all other eigenvalues are zero, and the corresponding eigenvector w is the weight vector we are looking for; this vector is unique. In practice however, we have to make estimates of the relative weights

$$a_{ij} = \frac{w_i}{w_j} \tag{12}$$

If the information is rather soft, subjective judgment and feelings of people are not always consistent, specially if a large number of projects must be compared. Therefore the matrix A will not be consistent and the eigenvalue λ will deviate from n. Moreover the other eigenvalues are not zero. It can be proved that we have to look for the largest eigenvalue and the corresponding eigenvector. As a measure for the consistency of the matrix A the following relation can be derived:

$$\mu = \frac{\lambda - n}{n-1} \tag{3}$$

It is clear that if $\mu = 0$ the matrix A is consistent; further the larger μ the larger the inconsistency of A. In the latter case this calls for revising the matrix.

Scale For the estimation of the values w_i/w_j in matrix A, Saaty uses a scale from 1 to 9. From experience he has shown that this gives the best results. At a finer scale (for example 1 to 25) the matrix becomes rapidly less consistent, whereas with a grosser scale, (for example 1 to 5) the differences in judgment give difficulties. Saaty explains that the scale 1 to 9 represents judgment entries as follows:

1: equally important;
3: weakly more important;
5: strongly more important;
7: demonstratedly more important;
9: absolutely more important.

The values 2, 4, 6 and 8 are a compromise in judgment of importance between 1 and 3, 3 and 5, 5 and 7, 7 and 9 respectively. Given a_{ij} one enters the reciprocal value $a_{ji} = 1/a_{ij}$. Thus one always has $a_{ii} = 1$ and only the relative weights below the diagonal of the matrix have to be estimated.

It is thus clear that more information is necessary than only a ranking of the projects.

Hierarchy. In this way one can find for every criterion a vector of score values of the projects. This vector of score values has been normalised, which means that $w_{1,j} + w_{2,j} \ldots\ldots w_{n,j} = 1$ for $j = 1, 2 \ldots\ldots m$. This results for m criteria in m (normalized) score values vectors, which can be collected in one matrix C of order (n x m) with w_{ij} = score value of scenario i with respect to criterion j.

If the information on scenarios with respect to some criterion is cardinal (for example monetary values), then the score values of the scenarios can be directly calculated without using the relative weights of the matrix A. However, in this application the evaluations according to the scale of Saaty have been used.

Now one wants to know for a given weight distribution of the criteria, which is the best project. Therefore, it is necessary first that the absolute weights (also normalised) of the criteria will be fixed. In the same way as for matrix A, a matrix B has to be estimated, which gives the relative weights of the criteria. This has to be done by the decision maker with the help of the system analyst, who has to provide the necessary information on which the matrix B is based.

The elements v_i/v_j of the matrix B, of order m are determined in the same way as the elements of matrix A: namely by means of a pairwise comparison and evaluation of the criteria.

From the matrix B, one can derive the normalised eigenvector v, which represents the absolute weights of the criteria. The total scores of the scenarios for a given weight distribution v of the criteria, can be calculated by multiplying the matrix C with the vector v:

$$Cv = g \text{ or}$$

$$g_i = \sum_{j=1}^{m} v_j w_{ij} \quad \text{for } i = 1, 2 \ldots\ldots n \tag{14}$$

From the vector g, which is also normalised, one can see which project has the largest total score, one can see which scenarios have the same total score, or which scenarios perform very badly.

For different weight distributions of the criteria, there are in general different optimal scenarios. However, these "best" scenarios are always pareto-optimal or non-inferior. A solution is pareto-optimal if an improvement with respect to one criterion only can be reached by a deterioration with respect to another criterion.

4.2.2. *The matrix of score values*

Based on the primary evaluations of the scenarios, given in table 4, the matrix of score values (in percentages) is presented in table 7. This matrix of score values differs from the already presented matrix of score values, used in the QUALIFLEX method, which was based on the objective cardinal evaluation of the various scenarios, without any interpretative content. However, in both cases the ranking of the scenarios with respect to each criterion is of course the same.

Table 7 Matrix of score values (Saaty-De Graan)

Scenarios Criteria		r	n	l	g	a	z
agriculture	(L)	37	8	29	2	16	8
nature	(N)	18	50	6	6	18	2
water supply	(V)	34	2	34	5	9	15
environment	(M)	7	36	7	7	7	36
costs	(K)	34	9	23	3	28	2
ground water reserve	(G)	4	17	5	46	24	4

4.2.3. *The weighing of the policy decision criteria*

As it has been stated earlier, for the weighing of the policy decision criteria a direct interaction with decision makers is necessary. Every decision maker has to fill in matrix B, which gives the relative weights of the criteria.

In this case the primary evaluations of the scenarios and the interpretation by the systems analysts or technicians offers very important information for the decision maker in establishing the relative weights of the criteria.

In most cases the decision maker is interested in the influence of the weighing of the policy decision criteria on the total score of the alternative projects of scenarios. For the decision maker this information may be very helpful if he is not very sure about his weighing of the criteria. For this purpose De Graan (1978) introduced the concordancy coefficient, which will be presented in the next section.

4.2.4. *The concordancy coefficient*

This coefficient can be used for two different purposes: firstly, for every decision maker it gives a measure of the agreement between the total scores of the scenarios with respect to the criteria. The concordancy coefficient for project i is defined as follows:

$$c_i = \sqrt{\frac{(g_i - 1/_n)^2}{\sum\limits_{j=1}^{m} v_j (w_{ij} - 1/_n)^2}}, \qquad (15)$$

where n is the number of scenarios, g_i the total score of the scenario i, v_j the weight of criterion j and w_{ij} the score value of scenario i in relation to criterion j. If there is complete agreement ($g_i = w_{ij}$ for $j = 1, \ldots\ldots, m$) then $c_i = 1$ and if the total score of the scenario is equal to the average score ($g_i = 1/_n$) then $c_i = 0$. In the last case no information is available to distinguish between different scenarios. In the first case the ranking of the scenario is not sensitive to a change in the weight distribution of the criteria. Secondly, we can also say that c_i is a measure for the variation of w_{ij} around g_i. In conclusion one may state that if a senario has a high total score and a high concordancy coefficient, the scenario is robust. However, if the concordancy coefficient is low, then the scenario is rather sensitive to a change in the weight distribution of the criteria. For the overall concordancy coefficient of all scenarios the following definition holds:

$$c = \sqrt{\frac{\sum\limits_{i=1}^{n} (g_i - 1/_n)^2}{\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{m} v_j (w_{ij} - 1/_n)^2}} \qquad (16)$$

This coefficient, also between 0 and 1, gives the robustness of the total score of the various scenarios. If the coefficient is 1, then the total score of the scenarios is insensitive to a change in the weight distribution of the criteria. If the coefficient is 0, then the total score is very sensitive to a change in the weight distribution of the criteria.

In the case of many decision makers the concordancy coefficient can be used as measure for the agreement between the various decision makers. The following definition then holds:

$$c_i = \sqrt{\frac{(g_i^o - 1/_n)^2}{\sum_{k=1}^{o} p_k (g_{ik} - 1/_n)^2}}, \tag{17}$$

where g_i^o is the overall total score of the scenario by all decision makers (1, 2 ....., 0); p_k is the weight of the decision maker k and g_{ik} is the total score of scenario i for decision maker k. In this case the following equation holds:

$$g_i^o = \sum_{k=1}^{o} p_k\, g_{ik}\,. \tag{18}$$

If all decision makers have the same weight, $p_k = 1/0$.

If there is complete agreement between the decision makers, so $g_i^o = g_{jk}$ for k = 1, ... 0, then $c_i = 1$, if g_i^o is equal to the "average" project (1/n) then $c_i = 0$. We can also say that c_i in this case is a measure for the variation of g_{ik} around g_i^o. It is also possible in this case to formulate the overall concordancy coefficient for all scenarios. In conclusion one may state that if a scenario has a high overall total score and a high concordancy coefficient, the project is robust for the whole team of decision makers. However, if the concordancy coefficient is low, then the project is rather sensitive to a change in the weight distribution of the decision makers. The same holds for the overall concordancy coefficient for all projects. Namely, if this coefficient is low the overall ranking of the scenarios is very sensitive for the weight distribution of the decision makers.

4.2.5. *The four decision priority rankings revisited*

In this section the example of the four policy profiles presented in section 4.1.5. will be handled by the method of Saaty-De Graan. In this case however, a ranking of the policy decision criteria is not sufficient, because it is necessary to fill in matrix B of the reative weights of the criteria, so that a concrete weight distribution *v* of the criteria can be derived. In the following the results for the various policy profiles will be presented.

Agricultural profile. The weight distribution of the criteria is as follows:

Ranking	L	>	K	>	V	>	M	>	N	>	G
Weight	0.45		0.29		0.13		0.06		0.04		0.03

This weight distribution of the policy decision criteria results in the following ranking, total scores, concordancy coefficients and overall concordancy coefficient of the projects.

From these results it can be concluded that the reference scenario and the agriculture favouring scenario are the best and the most robust scenarios. The other four scenarios are unattractive, because of the low total score and/or low concordancy coefficient. Also from the overall concordancy coefficient it can be concluded that this ranking of scenarios

Ranking	Scenario	Total score	Concordancy coefficient	Overall concordancy coefficient
1	r	0.33	0.86	
2	l	0.25	0.70	
3	a	0.18	0.24	0.75
4	n	0.11	0.43	
5	z	0.09	0.70	
6	g	0.04	0.87	

is rather stable. These results are in agreement with the analyses of the decision space for the "agricultural" profile by the QUALIFLEX method.

Ecological profile. The weight distribution of the criteria is as follows:

Ranking	N	>	M	>	G	>	L	>	V	>	K
Weight	0.45		0.25		0.16		0.08		0.04		0.02

This weight distribution of the policy decision criteria results now is the following:

Ranking	Scenario	Total score	Concordancy coefficient	Overall concordancy coefficient
1	n	0.35	0.75	
2	a	0.16	0.11	
3	r	0.15	0.09	
4	z	0.12	0.32	0.57
5	g	0.12	0.30	
6	l	0.09	0.66	

In this case there is only one attractive scenario, the nature favouring scenario. The other ones have low total scores or low concordancy coefficients. The relative low value of the overall concordancy coefficient indicates that the rankings of the scenarios a to g are rather sensitive to a change in the weight distribution of the criteria. Also this result is in agreement with the analyses of the decision space of the "ecological" profile by the QUALIFLEX method.

Water company profile. The weight distribution of the criteria is as follows:

Ranking	V	>	K	>	L	>	G	>	N	>	M
Weight	0.46		0.27		0.13		0.08		0.04		0.02

This weight distribution of the policy decision criteria results now in the following:

Ranking	Scenario	Total score	Concordancy coefficient	Overall concordancy coefficient
1	r	0.31	0.84	
2	l	0.26	0.71	
3	a	0.17	0.02	0.70
4	z	0.10	0.71	
5	n	0.09	0.61	
6	g	0.07	0.64	

In this case the reference scenario and the agriculture favouring scenario are attractive. The other ones have low scores or low concordancy coefficients. The overall ranking of the scenarios is rather stable. These results are in agreement with the analyses of the decision space for the water company profile by the QUALIFLEX method.

Profile of the Provincial authorities. The weight distribution of the policy decision criteria is as follows:

Ranking	V	>	N	>	L	>	M	>	K	>	G
Weight	0.48		0.24		0.14		0.07		0.04		0.02

This weight distribution of the criteria results now in the following:

Ranking	Scenario	Total score	Concordancy coefficient	Overall concordancy coefficient
1	r	0.28	0.75	
2	l	0.24	0.47	
3	n	0.18	0.06	0.54
4	a	0.13	0.53	
5	z	0.11	0.51	
6	g	0.06	0.86	

In this case the reference scenario and the agriculture favouring scenario are preferred. The other ones have low total scores or low concordancy coefficients. The overall ranking of the scenarios is not very stable. This picture is in agreement with the analysis of the decision space for the provincial authority.

Collective profile of the 4 decision makers. If the four decision makers carry the same weight in the final decision the following results are obtained:

Ranking	Scenario	Overall total score	Concordancy coefficient	Overall concordancy coefficient
1	r	0.27	0.84	
2	l	0.21	0.53	
3	n	0.18	0.16	0.73
4	a	0.16	0.27	
5	z	0.10	0.98	
6	g	0.07	0.96	

This shows that the reference and agriculture favouring scenarios have been preferred by the group decision. Concerning the position of the nature favouring scenario there is a low concordancy in the group decision. Concerning the maximum and the groundwater saving scenario there is general agreement that they are unattractive scenarios. Further there is a rather large agreement about the ranking of the scenarios. These results are in full agreement with the general analyses of the decision space, represented by a percentage distribution of the rankings among alternative scenarios (see table 6). The calculations were also repeated for the case in which the provincial authorities carry relatively much more weight. The total scores were nearly the same, only the concordancy coefficients increased. This means that the stability of the ranking has been improved.

5. CONCLUDING REMARKS

Given that the present application is to be seen as an illustration of a methodology rather than as the concrete preparation of a specific decision, the empirical conclusions are less important than the methodological ones.

Therefore, the empirical conclusions can be dealt with very briefly. The results shown indicate that, in the present application, the multicriteria analyses have produced rather robust solutions, in which the reference plan is clearly the most attractive scenario, the agriculture favouring scenario takes the second place and the last but one and last scenarios are the maximum and the groundwater saving scenarios respectively. The nature favouring scenario shows a high degree of variability with respect to its ranking as a function of varying weight combinations.

Concerning the methodological aspects, one can certainly conclude that the multicriteria approach has provided a clearer understanding of the choice problem because it expresses the explicit relations between decision criteria, weights of these criteria and scenarios and because all the results have always been consistent and have lead to straightforward interpretations. With respect to these methodological aspects one can ask three important questions: how sensitive are the results with respect to the choice of the method, how sensitive are they with respect to changes or measurement errors in the basic evaluations of the scenarios and what is their sensitivity with respect to changes in the weights of the criteria? The examples presented in this paper indicate that the results are quite robust as well with respect to the choice of the method as with respect to the initial evaluations of the basic input data. It has been demonstrated that the GELPAM method leads to nearly identical results as the QUALIFLEX method. This illustrates not only the robustness of the results with respect to the choice of the method but also with respect to the accuracy of the evaluations of the scenarios, given that the two methods start from two slightly different data sets. On the other hand, the examples presented in the previous sections indicate that the results can be sensitive to changes in the weights of the criteria. This was the case for the nature favouring plan, as a result of the specific content of that plan and of the evaluations of this scenario with respect to the various criteria. The ranking of the other scenarios were however rather robust to changes in the weights: the QUALIFLEX application has shown that 73% of the 1200 studied weight combinations were explained by only 4 different rankings (out of a maximum number of 6! = 720 permutations).

REFERENCES

ANCOT, J.P. (1980) – An econometric spatial demand model for water with an application to the demand for water in East-Gelderland. Seminar on economic instruments for rational utilization of water resources. Committee on Water Problems of the Economic Commission for Europe, United Nations; Veldhoven.

ANCOT, J.P. and J.H.P. PAELINCK (1979) – *Multicriteria analysis, combinatorial mathematics and* zero-one programming, foundations of empirical economic research. 1979/16, Netherlands Economic Institute, Rotterdam.

ANCOT, J.P. and E. ROMIJN (1980) – Design and economic evaluation of alternative schemes for combined use of groundwater and surface water in Eastern-Gelderland (The Netherlands) with the use of the multicriteria method QUALIFLEX. Seminar on economic instruments for rational utilization of water resources. Committee on Water Problems of the Economic Commission for Europe, United Nations; Veldhoven.

BOUMA, J. (ed.) (1979) – Overzichtskaarten betreffende aspecten van de waterhuishouding in Gelderland. Rapport no. 1434; STIBOKA, Wageningen.

BOUMA, J., P.J.M. DE LAAT, A.F. VAN HOLST and Th.J. VAN DE NES (1980) – Predicting the effects of changing water-table levels and associated soil moisture regimes for soil survey interpretations. Soil. Sci. Soc. Amer. J. 44: 797-802.

DEATON, A. (1975) – Models and projections of demand in Post-War Britain. Chapman and Hall, London.

GRAAN, J.G. DE (1978) – Enkele uitbreidingen van het beslismodel van Saaty. Een aanvulling op het onderzoek naar de toepasbaarheid van multicriteria-afwegingsmodellen ten behoeve van de waterhuishouding in Gelderland, Rijksinstituut voor Drinkwatervoorziening, Voorburg.

HOUTHAKKER, H.S. (1957) – An international comparison of household expenditure patterns, Commemorating the Centenary of Engel's Law, Econometrica, 25: 522-551.

JURGENS, C.R. (1979) – Enkele aspecten betreffende de waterbeheersing en landbouw in Oost-Gelderland. Deel 1 Inventarisatie waterbeheersing. Deel 2 Kosten van waterbeheersing (ontwatering en afwatering) ten behoeve van de landbouw. Basis rapport Commissie Bestudering Waterhuishouding, Gelderland, Arnhem.

LAAT, P.J.M. DE and R.H.C.M. AWATER (1978) – Groundwater flow and evapotranspiration. A simulation model. Part 1 Theory. Commissie Bestudering Waterhuishouding Gelderland, Arnhem.

LAAT, P.J.M. DE and R.H.C.M. AWATER (1980) – Groundwater flow and evapotranspiration. A simulation model, Part 2. Practical application in East-Gelderland. Basis rapport. Commissie Bestudering Waterhuishouding Gelderland, Arnhem.

NES, TH.J. VAN DE (1980) – Applicability of multicriteria decision models with multiple decision makers in water-resources systems. Seminar on economic instruments for rational utilization of water resources, Committee on Water Problems of the Economic Commission for Europe, United Nations; Veldhoven.

NES, Th. J. VAN DE and E.P. VAN LOHUIZEN (1978) – Onderzoek naar de toepasbaarheid van multicriteria-afwegingsmodellen ten behoeve van de waterhuishouding in Gelderland. Basisrapport Commissie Bestudering Waterhuishouding Gelderland, Arnhem.

NEDERLANDS ECONOMISCH INSTITUUT (1979) – QUALIFLEX, een modelmatige aanpak ter voorbereiding van beslissingen met betrekking tot de waterhuishouding in Gelderland. Basisrapport Commissie Waterhuishouding Gelderland, Rotterdam.

PAELINCK, J.H.P. (1978) – QUALIFLEX, a flexible multiple-criteria method. Economics Letters, 3: 193-197.

SAATY, T.L. (1978) – Exploring the interface between hierarchies, multiple objective and fuzzy sets. Fuzzy sets and systems, 1: 57-68.

SYSTEMS ANALYSIS AND WATER MANAGEMENT. SOME CONSIDERATIONS WITH RESPECT TO DEVELOPMENT AND USE OF MODELS

E. ROMIJN

SUMMARY

After an introduction to the concepts of a system and of water management some remarks about systems terminology follow. The notion of a model and the use of models in decision – making is explained. A classification of models is illustrated with examples from the research programme of the *Committee for the Study of the Water Resources Management in Gelderland* (CWG). A more co-ordinated use of models for water management is recommended. To realize this co-ordination, a close co-operation between all the national institutes that develop or use mathematical models for water management is needed.

1. INTRODUCTION

Systems analysis (or systems approach) and *water management* have been the subject of discussion at a meeting of the Committee for hydrological research TNO some five years ago. At that time, only preliminary results of the research programme of the Committee for the Study of the Water Management in Gelderland (CWG) could be published. Studies on water quality were partly published during the 35th meeting of the Committee (Commissie Hydrol. Onderzoek TNO 1979). Now the research programme of the CWG is completed and the moment has come to look back and to look forward.

Concepts as "system" and "water management" are at the base of the research programme of the CWG. Basic concepts are very often more easily defined implicite than explicite and their meaning only becomes clear as one works with them for some time.

In a report of the Committee on Water Problems of the E.C.E. (1979) is pithily said that "appliqué à la gestion des ressources en eau, l'analyse de système est une technique d'aide à la *décision* et d'aide à la *connaissance*." Both aspects of decision and knowledge will be explained furtheron, but the *instrumental* character of systems analysis (or systems approach) is obvious.

As was stated by Van de Nes (1981) *water management* can be considered as an interaction of natural, social and artificial elements which represent resp. the (natural) supply of water (quantity and quality), the water demand and – as artificial elements – the technical works and the administrative measures (such as legislation, taxes and fees etc.) In the texts of the previous authors (De Laat et al., Kovar et al., Bouma et al., Van Wirdum, Gardeniers, Ancot et al., 1981) application of the systems approach to water management has been illustrated. Here follow some comments on these systems and models.

2. SYSTEMS

A *system* is a whole that can be separated more or less from its surroundings and that consists of a set of elements and of a set of relations between these elements. Forrester (1968) calls a system a "grouping of parts that operate together for a common purpose" (e.g. an autocar). In symbols – with a glance at graph theory

$$\Sigma \triangleq \langle B, C, g \rangle$$

with
- Σ for system
- B for set of elements
- C for set of relations (connections) between elements
- g for function; prescribes how relations of C are attributed to elements of B

If the relation (connection) has a direction (is a digraph) it is attributed to an ordered pair $\langle u, v \rangle$ of B

A picture of a system could be as in figure 1, with elements as rectangles and relations (connections) as lines or arrows (digraphs). In hydrological systems the elements are often reservoirs and the connections the flows between the reservoirs (fig. 2).

In general flows refer to mass, energy and information. Information flows are essential in control systems.

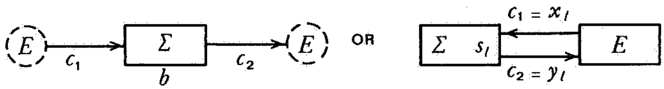
These consist of at least a controller (CR) and a controlled system (CS) which are connected by information flows (or signals).

CS gives information about its performance and CR about the objectives or commands. The interaction between CR en CS in order to get a prescribed systems behaviour is called feed back. A very well known example is the thermostat. The person who commands the thermostat is a controller on a "higher" level. This serves as an example of hierarchy in systems (Hanken and Reuver, 1977; Kickert, 1980). See figure 3.

Systems terminology is still in development. For an important class of systems, the *dynamic* systems, an adequate terminology is present (Zadeh and Desoer, 1966). Dynamic systems are characterized by having *state variables*, a concept introduced by Turing in 1935. They describe the relevant history of the system completely and they are often called the memory of the system. For a moving object (e.g. a rocket) the state is described by position (x, y, z) and velocity (v) of the object at the corresponding time. Every next timestep the system performance (*output*) depends on the state and the (new) influences (*input*) on the system. Hydrological sciences can now reap the fruits of many developments in control theory as applied in for example the conquest of the space.

Systems analysis obtains its significance from its explanatory value. Explanation means the possibility of prediction and afterwards of control and management. Explanation (Nagel, 1979) deals with

1 PICTORIAL PRESENTATION OF A SYSTEM



Σ SYSTEM

E ENVIRONMENT OF THE SYSTEM

b ELEMENT (box), $b \in B$

c RELATION (connection), $c \in C$

x_l INPUT

y_l OUTPUT

s_l STATE

2 MATHEMATICAL PRESENTATION OF A SYSTEM

$$\Sigma \begin{cases} \phi : T \times T \times S \times \Omega \rightarrow S & \text{STATE EQUATION} \\ \eta : T \times S \rightarrow Y & \text{OUTPUT EQUATION} \end{cases}$$

$$\Omega \triangleq \{ \omega : T \rightarrow X \}, \quad \omega \quad \text{INPUT FUNCTION}$$

$$\Gamma \triangleq \{ \gamma : T \rightarrow Y \}, \quad \gamma \quad \text{OUTPUT FUNCTION}$$

$$T \times S \quad \text{PHASE}$$

WITH SPACES T (time), S (state), X (input), Y (output), Ω AND Γ

$\phi, \eta, \omega, \gamma$ ARE FUNCTIONS WITH VARIABLES AND PARAMETERS

Fig. 1 Example of a system.

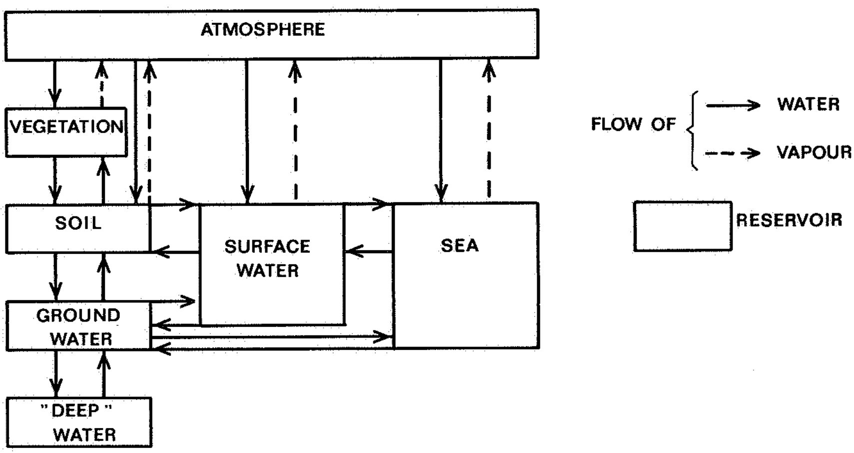


Fig. 2 A hydrological system

– the structure of the system (division in elements, hierarchy);
– the working of the system (goal directed behaviour, dynamics, causality).

As to causality, difference is made between a deterministic element with an input-output function (or impuls respons) of the kind "if-then ... at all times", and a probabilistic element with an input-output function of the kind "if-then ... sometimes".

Most usefull is explanation in mathematical form because the system can then be simulated with a computer (the computer being itself a system). Here we come to the subject of mathematical models.

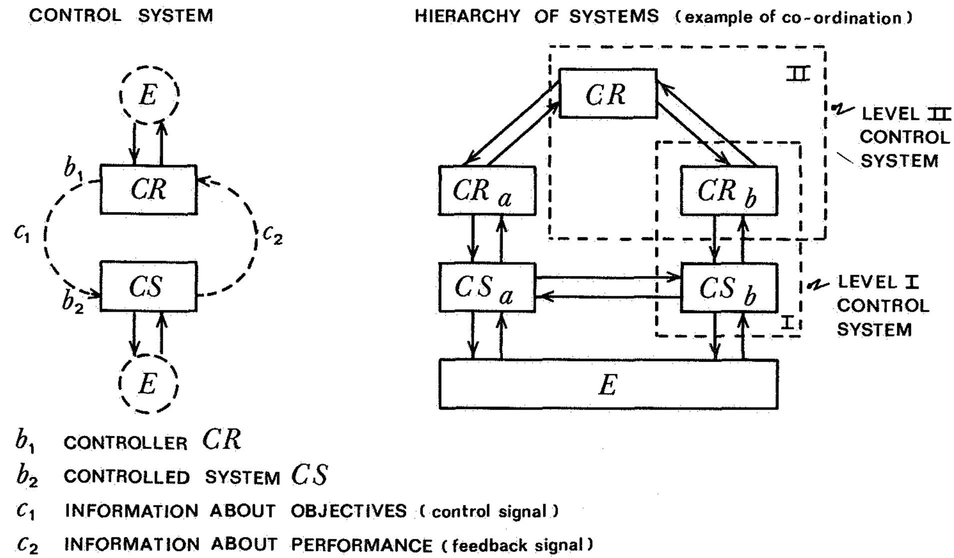


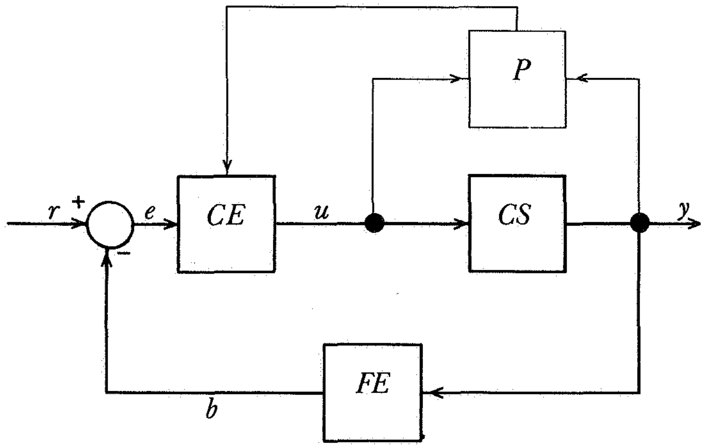
Fig. 3 Example of hierarchy within a system.

3. MODELS

A *model* is an appropriate simplification of reality. For reason of efficiency we only deal in our model with matters in which we are interested with respect to the objective of our research. The word model is used in many ways (e.g. scale model, examplary model, analog model, logical model, numerical model, pictorial model etc.) Within the CWG the notion model was restricted to a *mathematical system*, in symbols:

$$M \triangleq < \Sigma_m, R >$$

with
M for model
Σ_m for system of mathematical equations
R for set of rules of correspondence between mathematical equations and reality.



CS	CONTROLLED SYSTEM
FE	FEEDBACK ELEMENT } CONTROLLER *CR*
CE	CONTROL ELEMENT } CONTROLLER *CR*
P	IDENTIFICATION AND PARAMETER ADJUSTMENT
b	FEEDBACK SIGNAL
r	REFERENCE (set point)
e	ACTUATING SIGNAL (error), $e = r - b$.
u	CONTROL SIGNAL
y	CONTROLLED OUTPUT (criterion variable)

Fig. 4 An adaptive model.

The mathematical model is fitted to the real system (reality) by means of model identification (what type of model) and parameter estimation. If model identification can be (partly) accomplished by automation, the model is called *adaptive* (fig. 4).

4. SYSTEMS ANALYSIS AND DECISIONS

Hanken and Reuver (1977) compared our own process of learning with the process of model identification and parameter estimation. I am not sure that even scientists always work so systematically, not to speak of "decision-makers". Nevertheless, decision-making should relie on systematic thinking in spite of the truth of Pascals pensée nr. 277 that "le coeur a ses raisons que la raison ne connaît pas".

To decide is to choose out of different *known* possibilities. But systems analysis is quite suitable for preparation of decision-making. With the "if-then functions" the consequences of different strategies or plans can be surveyed. As was illustrated by Ancot et al., (1981) the *constraints* (e.g. available groundwater, available canals and waterways) and the choice of the type of decision variables or *criteria* (e.g. cost-benefit, ecological value, quality standards) in general restrict the set of feasable plans very much. Therefore decision making requires close co-operation between system analists and decision-makers.

5. CLASSIFICATION OF MODELS

From the previous considerations follows a classification of models with respect to structure and mechanism of the system. The latter divides the model set in

- descriptive and prescriptive models (goal directed behaviour of the system);
- static and dynamic models (memory);
- deterministic and probabilistic models (causality).

As to structure, one can distinguish

- simple and complex models (number of elements);
- non hierarchical and hierarchical models (number of levels).

Each model can further be characterized by the mathematical properties of the input-output function (e.g. linearity, time variance) and of the spaces of variables and parameters (e.g. continuous or discrete, constraints).

As to structural complexity in descriptive hydrological models difference is made between "black-box" like, simple, input-output models (e.g. for rainfall-runoff relations) and more complex "physical" models which are "internally descriptive" (e.g. hydraulic models in difference equation form). The "conceptual" models are somewhat in between (e.g. rainfall-runoff models consisting of a number of elements like linear reservoirs and channels).

The prescriptive models can be divided into instrumental and normative models. They differ in complexity of the objective function. The more simple instrumental models are the ones of control engineering with a "set point" as objective (e.g. the fixed temperature of the thermostat) and the more complex normative models are those from operations research techniques (e.g. programming methods).

In the report of the CWG the following models amongst others are described.

I *Descriptive models*

A *Static-deterministic*: correlation (black-box) models for the relation between evapotranspiration and crop yield; HUISIM and AQUSIM (water demand).

B *Dynamic-deterministic* (most of the hydrological models belong to this group): UNSAT (unsaturated flow & evapotranspiration); GELGAM (groundwater flow & evapotranspiration); Conceptual rainfall-runoff models; GELQAM (phyto plankton, phosphate & oxygen).

C *Static-probabilistic* (stationary): generation of random numbers (synthetic hydrology).

D *Dynamic-probabilistic*: Markov chains (river flow).

II *Prescriptive models*

A *Static-deterministic:* linear programming (transport problems); multicriteria decision models like GELPAM and QUALIFLEX.
(No dynamic or stochastic models were considered).

6. UNCERTAINTY

Usefulness of models depends of course on the reliability of the (calculated) results. This reliability depends on the model itself in relation to the structure and mechanism of the simulated system *and* on the accuracy of the inputdata. As inputdata are often measured in the field, the whole problem of measurement and data processing is involved, but this problem is beyond the scope of this paper.

During the calibration of the model an impression of the reliability of the model is obtained. As to the more simple correlation models (like HUISIM) the parameter estimation techniques give automatically information about the reliability of the input-output functions. (Ancot et al., 1981). More complicated models like GELGAM and GELQAM cannot be used for parameter estimation (Kovar et al., 1981). Parameters must be obtained in the field or in the laboratory (pumping tests, dark and light bottle experiments, tests with soil samples etc.). This is of course only possible if the parameters have a physical meaning. At last there is the possibility of sensitivity analysis in order to get an estimate of the reliability of the model (De Laat et al., Kovar et al., Bouma et al., 1981).

Most interesting is the way in which Ancot et al. (1981) use the sensitivity analysis in decision problems.

In the last few years there is a tendency to simplify hydrological models and to enhance their reliability by making them *adaptive* (O'Connell, 1980).

7. RECOMMENDATIONS

Looking forward we can start with the recommendations of the report of CWG (1980). They are as follows (somewhat abridged).

1 The results of the research programme of CWG must be applied to the *planning* of the water management in Gelderland.
2 For the application of the results of the research programme of CWG *fundamental* research remains of importance.
3 Further development of models and techniques with respect to water management has to be co-ordinated on the national level (and not on the provincial level) because of its great interest for the whole country.
4 National and regional *networks* for the measurement of data needed for water management have to be reorganized. The availability of existing data has to be improved.
5 *Regional* measurement networks (e.g. hydrological networks) have to be controlled by regional Waterboards.

6 Special attention has to be paid to *research* in
   - economic aspects of water demand;
   - economic and hydrological aspects of water use in agriculture;
   - ecological aspects of water management.
7 The *connection* between models for water quantity and water quality must be improved (both for surface water and groundwater). Special attention must be paid to models for *groundwater quality*.

The recommendations of the CWG can be illustrated with some remarks.

The research programme of CWG was only possible through the co-operation of many national research institutes. Such a co-operation can be better controlled on a national level than by an arbitrary province like Gelderland.

The effectiveness of the data collections was very unsatisfactory during the research period. Much time was lost with data collection and processing and with filling up the gaps in time series.

In order to tackle some of these problems, the Committee for Hydrological Research TNO and the Organization for co-operation on automation within "Waterstaat" (Samenwerkingsorgaan Automatisering Waterstaat) SAW have installed working groups to work out proposals for co-operation with respect to the development and use of models.

The "Contactgroep Grondwatermodellen" (Working group Groundwater models) of the Committee for Hydrological Research TNO has as objective "the promotion of the co-operation with respect to the development and application of groundwater models on behalf of the groundwater management as a whole". The Working group has as tasks a contact function, a stimulating function and an informative function.

The Working group promotes the contacts between model specialists and users, advises about new developments and promotes standardisation of the documentation of computer programmes.

Besides this TNO Working group, special advisory groups have been established with reference to GELGAM and GELQAM

Within SAW the possibility is studied for a co-ordinated management of the hydrological and water management models themselves, that is to say the maintenance and improvement of existing computer programmes.

These models will be very usefull for the *waterplanning* which will be prescribed in the very near future by legislation on groundwater, surface water quantity and quality and water management in general.

Much will depend on the willingness of the institutes in The Netherlands which develop and use models, to co-operate in order to obtain the required tools for the water planning as will be prescribed by legislation.

Last but not least I want to discuss the education of hydrologists. Although the computer is now a common tool to many hydrologists (contrary to some ten years ago) abuse of computerprogrammes is not at all excluded if one does not realize that a model is only a crude *approximation* of reality. The choice of the approximation depends on the common sense of the hydrologist. Only through a combined knowledge of both hydrology and systems approach progress in water sciences will be made.

REFERENCES

ANCOT, J.P. and Th.J. VAN DE NES (1981) – Integral evaluations of alternative water management scenarios in East-Gelderland. Comm. Hydr. Onderzoek TNO, Den Haag; Versl. en Meded: 27: 129-164.

BOUMA, J., P.J.M. DE LAAT and A.F. VAN HOLST (1981) – Use of soil-survey data for hydrological simulation models. Comm. Hydrol. Onderzoek TNO, Den Haag; Versl. en Meded. 27: 81-97.

COMM. HYDROL. ONDERZOEK TNO (1976) – Systems approach to the management of water resources. Versl. en Meded. 22. Den Haag. pp. 98. (in Dutch)

COMM. HYDROL. ONDERZOEK TNO (1979) – The relation between water quantity and water quality in studies of surface waters. Versl. en Meded. 25, Den Haag. pp. 98.

COMM. ON WATER PROBLEMS E.C.E. (1979) – Application de l'analyse des systemes a la gestion des ressources en eau.

COMMISSIE BESTUDERING WATERHUISHOUDING GELDERLAND – (Comm. for the Study for the Water Resources Management in Gelderland – CWG) (1980) – Een systeembenadering voor de waterhuishouding van Gelderland. Provincial Waterboard of Gelderland, Arnhem.

FORRESTER, J.W. (1976) – Principles of systems. MIT Press., Cambridge Mass. USA.

GARDENIERS, J.J.P. (1981) – The impact of regulation on the natural characteristics of Dutch lowland streams. Comm. Hydrol. Onderzoek TNO, Den Haag; Versl. en Meded. 27: 99-107.

HANKEN, A.F.G. and H.A. REUVER (1977) – Sociale systemen en lerende systemen. Stenfert Kroese, Leiden.

KICKERT, W.J.M. (1980) – Organisation of decision-making. North-Holland. Publishing Company, Amsterdam.

KOVAR, K. and H.L.M. ROLF (1981) – Application of the model Over-Betuwe; complexity of the model in relation to the objective of the hydrological study. Comm. Hydrol. Onderzoek TNO, Den Haag; Versl. en Meded. 27: 54-80.

LAAT, P.J.M. de, R.H.C.M. AWATER and P.J.T. VAN BAKEL (1981) – GELGAM. A model for regional water management. Comm. Hydrol. Onderzoek TNO, Den Haag; Versl. en Meded. 27: 23- 53.

NAGEL, E. (1979) – The structure of science. Routledge & Kegan Paul, London & Henley

NES, Th.J. VAN DE (1981) – Introduction to a system approach for water management in Gelderland. Comm. Hydrol. Onderzoek TNO, Den Haag; Versl. en Meded. 27: 9-21.

O'CONNEL, P.E. ed. (1980) – Real-time hydrological forecasting and control, Proc. 1 st. Int. Workshop Inst. of Hydrology July, 1977.

WIRDUM, G. VAN (1981) – Linking up the natec subsystem in models for the water management. Comm. Hydrol. Onderzoek TNO, Den Haag; Versl. en Meded. 27: 108-128.

ZADEH, L.A. and C.A. DESOER (1963) – Linear system theory McGraw-Hill, New York.

COMMITTEE FOR HYDROLOGICAL RESEARCH T.N.O.

Proceedings and Informations

No. 1. Proceedings of Technical Meetings 1–6 (with summaries in English), 1952.

1. Investigations into the Water Balance of the Rottegatspolder
2. The Water Supply for Crops I
3. Observations of Groundwater Levels
4. Investigations by Drain gauges in the Netherlands
5. The Water Supply for Crops II
6. The Problem of the increasing Salinity of Ground and Surface Water in the Netherlands

No. 2. Proceedings of Technical Meeting 7–10 and Report on the evaporation research in the Rottegatspolder 1947-1952 (with summaries in English), 1955.

7. The Study of Precipitation Data
8. Model Research on Groundwater Flows
9. Measurements and improvement Works in Basin of Brooks
10. Geo-electrical Research

No. 3. Proceedings of Technical Meetings 11–12 (with summaries in English) and Report on the Lysimeters in the Netherlands (in English), 1958.

11. The Water Supply of Sandy Soils
12. Quality Requirements for Surface Waters

No. 4. Evaporation Synposium and Report on the Lysimeters in the Netherlands II (with summaries in English), 1959.

No. 5. Proceedings of Technical Meetings 13–14 (with summaries in English), 1960.

13. Groundwater Levels and Groundwater Movement in the Sandy Areas of the Netherlands
14. Water in unsaturated Soil

No. 6. Proceeding of Technical Meeting 15 (with summaries in English and French), 1961.

The Regime of the Rhine, the Ysselmeer and Zeeland Lake

No. 7. Proceeding of Technical Meeting 16 (with summaries in English), 1962.
The dry Year 1959

No. 8. Proceeding of Technical Meeting 17 (with summaries in English), 1963.
The Laws of Groundwater flow and their Application in Practice

No. 9. Proceeding of Technical Meeting 18 (with summaries in English), 1963.
Water Nuisance

No. 10. Steady Flow of Ground Water towards Wells, compiled by the Hydrologisch Colloquium (in English), 1964.

No. 11. Proceeding of Technical Meeting 19 (with summaries in French and German), 1964.
Geo-hydrological Cartography

No. 12. Proceeding of Technical Meeting 20 (in English), 1966.
Water Balance Studies

No. 13. Proceeding of Technical Meeting 21 (in English), 1966.
Recent Trends in Hydrograph Synthesis

No. 14. Proceeding of Technical Meeting 22, 1968.
Precipitation Data (II) and
Report on the Lysimeters in the Netherlands (III) (both with summaries in English)

No. 15. Proceedings and Informations no. 15 (in English), 1969.
Soil – Water – Plant

Proceeding of Technical Meeting 23, 1968.
Seepage
(Will not be published).

Proceeding of Technical Meeting 24, 1970.
Flow in the unsaturated Zone
(Will not be published).

No. 16. Proceeding of Technical Meeting 29 (with summaries in English), 1975.
Hydrological Investigations for Masterplan for the future Watersupply in the Netherlands

No. 17. Proceeding of Technical Meeting 25 (in English), 1973.
Automatic Processing of Hydrological Data

No. 18. Proceeding of Technical Meeting 26 (in English), 1974.
Hydraulic Research for Water Management

No. 19. Proceeding of Technical Meeting 27 (in English), 1974.
The Hydrological Investigation Programme in Salland (The Netherlands)

Proceeding of Technical Meeting 28, 1973.
Water Quality of Dutch Rivers with respect to Water Management
(Will not be published).

No. 20. Proceeding of Technical Meeting 30 (in English). 1976.
Salt distribution in Estuaries

No. 21. Proceeding of Technical Meeting 31 (in English), 1976.
Groundwater Pollution

No. 22. Proceeding of Technical Meeting 32 (with summaries in English), 1976.
Systems Approach to the Management of Water Resources

No. 23. Proceeding of Technical Meeting 33 (in English), 1977.
Precipitation and Measurements of Precipitation

No. 24. Proceeding of Technical Meeting 34 (in English), 1978.
Urbanization and Water Management

No. 25. Proceeding of Technical Meeting 35 (in English), 1979.
The Relation between Water Quantity and Water Quality in Studies of Surface Waters

No. 26. Proceeding of Technical Meeting 36 (in English), 1980.
Research on possible Changes in the Distribution of saline Seepage in The Netherlands

No. 27. Proceeding of Technical Meeting 37 (in English), 1981.
Water Resources Management on a Regional Scale