PROBLEM-ORIENTED STUDIES ON PLANT-SOIL-WATER RELATIONS

cases:

SOWING STRATEGIES FOR MAIZE IN RAINFED AGRICULTURE
IN SOUTHERN MOZAMBIQUE

WATER MANAGEMENT IN BOG RELICTS IN THE NETHERLANDS

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Proefschrift
ter verkrijging van de graad van
doctor in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
dr. H.C. van der Plas, in het openbaar te verdedigen
op woensdag 13 juni 1990
des namiddags te vier uur in de aula
van de Landbouwuniversiteit te Wageningen

STELLINGEN

1. Alvorens te trachten om in een probleemgerichte hydrologische studie de fysische processen zo uitvoerig mogelijk te beschrijven is het nodig te verkennen welke mate van nauwkeurigheid op onderdelen gewenst is.

   Dit proefschrift

2. Voor veel probleemgericht onderzoek geldt dat het beter is te streven naar het minimaliseren van onzekerheden dan naar het maximaliseren van kennis.

   Dit proefschrift

3. In het landbouwkundig onderzoek naar risicomijdend handelen in semi-aride gebieden dient meer aandacht te worden gegeven aan de aspekten van het beheer van voedselvoorraden.

   Dit proefschrift

4. Een verandering van de politieke machtsverhoudingen in Zuid-Afrika zal meer invloed hebben op de landbouwproduktie in Mozambique dan faktoren van klimaat, bodem en water.

5. In Mozambique heeft de bevolking op grote schaal te maken met geweld en honger. In zo'n situatie is voor een studie naar zaaistrategieën veel fantasie vereist.

6. In veel hoogveenrestanten kunnen waterbeheersingsmaatregelen, gericht op het herstel van hoogveenvegetaties, beperkt blijven tot lokale ingrepen in het gebied zelf.

   Dit proefschrift

7. De aanwezigheid van hoogveenvegetaties is een voorwaarde voor het herstel van de hydrologische condities van hoogvenen.

   Dit proefschrift

8. Menselijke interventie ten behoeve van hoogveenregeneratie dient een tijdelijk karakter te hebben.

   Dit proefschrift

9. Natuurtechnici kunnen veel leren van de wijze waarop natuurlijke vegetaties hun leefmilieu gunstig beïnvloeden.

10. Het onderzoek ten behoeve van het Groote Peel gebied is een voorbeeld van de verwetenschappelijking van een maatschappelijk probleem.

11. Naast emissie-sanering spelen bij het waterkwaliteitsbeheer de inrichting en het kwantitatieve beheer een essentiële rol. Dit onderstreept de noodzaak voor cultuurtechnische opleidingen op wetenschappelijk nivo.

12. De uitspraak van een minister van Verkeer en Waterstaat, dat het met de Rijn weer bergopwaarts gaat, moet voor hydrologen tot wantrouwen aanleiding geven.

Minister Smit-Kroes, n.a.v. Overleg Rijnoeverstaten, 1988.

13. Het financieel beheer van de universiteiten gedurende de afgelopen jaren heeft ertoe geleid dat er steeds meer gezocht wordt en steeds minder onderzocht.

14. De vraag: "Aan wie moet de kunstenaar zijn kunstje kwijt?", is in gewijzigde vorm toepasbaar voor veel onderzoekers.

Freek de Jonge, cabaretier, 1981

15. Intolerantie t.a.v. asielzoekers met economische motieven verhoudt zich slecht tot de in Nederland aanwezige hoge waardering voor particulier initiatief en ondernemerszin.

Stellingen behorende bij het proefschrift van J.M. Schouwenaars:
Problem-oriented studies on plant-soil-water relations.

Wageningen, 13 juni 1990.

Aan Jelly
aan Nynke, Heinze en Atty

ABSTRACT

Schouwenaars, J.M., 1990. Problem-oriented studies on plant-soil-water relations. Doctoral thesis, Agricultural University Wageningen, The Netherlands. xiii + 175 p., 50 Figures and 37 Tables. English and Dutch summaries.

Plant-soil-water models are applied in two case studies. Attention is given to the desired level of accuracy in (agro-)hydrological research when applied in problem-oriented studies. In the case studies it is shown that when decision criteria are only roughly known and when only little information is available about the other aspects relevant to the problem, simple plant-soil-water models should be used.
A simple water balance and crop growth model was applied to simulate production of maize in southern Mozambique. For different sowing strategies, varying from a scattered one to sowing once a year, the available maize for consumption for an average family farming unit was determined. Different model parameters were varied to study their impact upon sowing strategies.
For maximizing yearly consumption the preferred strategy almost fully depended on losses by pests and diseases and post-harvest losses. However, regarding the decision criterion of minimizing the periods with food shortage the preferred sowing strategy greatly depended on water-availability and potential production levels.
Both field and model studies were carried out to study the water balance of bog relicts in the Netherlands. In the field experiments special attention was given to the hydrophysical properties of the upper peat layers and to the evapotranspiration of *Sphagnum papillosum* and *Molinia caerulea*.
A simple model was applied to simulate the water level fluctuations in a bog relict under different water management options. Both external measures (e.g. hydrological bufferzone's) and internal measures (water conservation) were analysed. Which option has to be preferred depends on the hydrological conditions in the bog relict and on the ecological constraints for bog regeneration, which are not fully known.
For an understanding of the hydrology of bogs and bog relicts detailed knowledge of the plant-soil-water relations is required. However, given the high spatial diversity in these areas, simple plant-soil-water models should be used.

keywords: plant-soil-water models, simulation, optimization
sowing strategies, maize, Mozambique
hydrology, water management, bogs, bog-regeneration

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It was Professor van Duin who learned me about the role of research in decision making. I expect that he will recognize important aspects of his ideas about research in this study.
It was Professor van der Molen who learned me to do research and in particular how to handle difficult subjects in field studies.His interest in the hydrology of nature reserves and in particular in water management for bog-regeneration has stimulated me to return to the wet bogs after a temporary stay in a dry region of Africa. His ability to give valuable suggestions and comments on both case-studies shows his wide experience. I am indebted for his willingness to be my promotor.
During the field work on the hydrology of bog-relicts I have had assistance from Roel Dijksma, who's enthousiasm to be a real digging bogman has not only resulted in nice photographs but was a highly appreciated support for the collection of field data.
Although it is in the interest of any department of a University to present results of research, part of the time which I have spend on it was only available because colleages took care of administrative matters. I greatly appreciate their willingness to do so.
Several students have participated in the case studies. Rudi Pelgrum and Jos Swennenhuis have given important contributions to the model studies on sowing strategies. Frans van Amerongen, Marian Booltink, Henk Eggink, Henk Nobbe en Jos Vink have been regular visitors in the Engbertsdijksvenen and have elaborated many of the collected data. Leon Schouten and Geert Sterk contributed to the model studies in bog relicts.
I very much appreciate the cooperation of Mr. R. Pereira, Dean of the Faculty of Agronomy in Maputo, who has given me the opportunity to work on the model studies in Mozambique. It was a very pleasant experience to work in Maputo with Jan van der Laan, who introduced me in many aspects related to agriculture in developing countries like Mozambique. In Wageningen, as a member of the UEM-LUW Steering Committee, I have had the opportunity to stay involved in the research carried out in Maputo.
The research carried out in the Dutch bog-relicts has always been very interesting and my enthousiasm for these areas certainly has been influenced by many persons. Here, I would like to mention Jan Streefkerk, Cor Beets and Hans Joosten. Also my regular visits to the Bodentechnologisches Institut in Bremen and the discussions and field visits with Prof. Kuntze, Prof. Eggelsmann and Dr. J. Blankenburg were very important.

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PART I

PROBLEM-ORIENTED STUDIES ON PLANT-SOIL-WATER RELATIONS

Far better an approximate answer to the right question,
which is often vague,
than an exact answer to the wrong question,
which can always be made precise.

(Turkey,J.W.(1962), quoted by Tarantola (1987))

1. Introduction

Plant-soil-water relations play an important role in a wide range of agronomical and environmental studies.
For the semi-arid region of southern Mozambique plant-soil-water models may serve to analyse sowing strategies. Schouwenaars et al(1988) applied them for maize, grown under rainfed conditions. Different factors, e.g. water use, pests and diseases and storage losses, which affect crop growth, production and consumption were quantified. An analysis of their relative impact as well as a selection of research priorities was made (Schouwenaars,1988a; Schouwenaars and Pelgrum,1990).
For the humid region of the Netherlands, Schouwenaars (1988b,c) incorporated the plant-soil-water relations in a water balance model for bog relicts. With this simulation model alternative water management options could be evaluated. To acquire the necessary data for model development, different terms of the water balance were studied in the Engbertsdijksvenen area (Netherlands), in particular evapotranspiration and downward seepage (Schouwenaars,1989,1990; Schouwenaars et al.,1990; Schouwenaars and Vink,1990).

Between the two case-studies, mentioned above, a great similarity exists in the problems related to the use of plant-soil-water models for the evaluation of alternative management options and for decision making. In both case-studies it is demonstrated that for the selection of management practices (sowing strategy, water management) quantitative information about many site specific characteristics is needed. It is difficult to obtain detailed information for an accurate quantitative analysis for both cases. Mostly, descriptions of site specific characteristics are global and values for certain model parameters can only be presented in terms of probability.
In either case it is questionable whether plant-soil-water relations, which are only part of the complex processes involved, should be studied in detail. It seems useful to define the desired level of knowledge of these plant-soil-water relations.

In this study attention is given to the application of research on plant-soil-water relations in decision-making. A research approach will be presented to develop criteria for desired levels of accuracy in describing plant-soil-water relations. It will be shown that for complex problems, as illustrated in the two cases, the objective of research should be to minimize uncertainty rather than to maximize knowledge.

2. The plant-soil-water system

For the objectives of this study it is important to describe the plant properties which influence and/or are influenced by water use. This also holds for the soil properties which influence e.g. the water content and the uptake of water by plants. These relations will not be treated completely or in any depth. Some main elements will only be discussed.

Terrestrial vegetation and agricultural crops depend for their water- and nutrient supply on soil properties like texture, organic matter content, porosity, permeability, cation exchange capacity etc.
Different parameters have been developed to describe these properties. The position of the phreatic level indicates the depth below which the pressure of the soil water is above atmospheric pressure. Above this phreatic level, soil water content and pressure head (now negative with respect to atmospheric pressure) are used to describe the moisture status in the unsaturated part of the soil. For a wide range of values for the soil water content (θ), the corresponding pressure head ($h(\theta)$) and hydraulic conductivity ($k(\theta)$) can be described.
In a mineral soil these hydrophysical properties largely depend on the texture of the soil and in a lesser degree on its organic matter content. The degree of humification is important for a peat soil.
The root development of the plant is largely dependant on the physical characteristics of the soil. Mechanical properties (e.g. penetration resistance) and hydrological properties (e.g. water availability) are of particular importance.
Under (semi-) natural conditions the development of the plant canopy and its structure depend on the competition between the different species within the plant community. In agriculture, human interference through management practices largely determines the canopy development. Water and nutrient conditions will also affect the growth of the vegetation canopy and influence its structure.
A scheme of the plant-soil-water system with its main elements is presented in Fig.1.

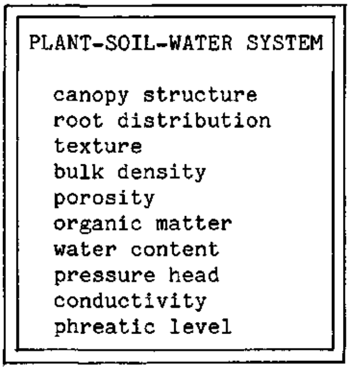

Fig.1 The main elements of the plant-soil-water system

3. Hydrological research on plant-soil-water relations

3.1 Modelling

There is a rich tradition in modelling various components of the plant-soil-water system, mostly interrelated with the atmospheric components (Fig.2).

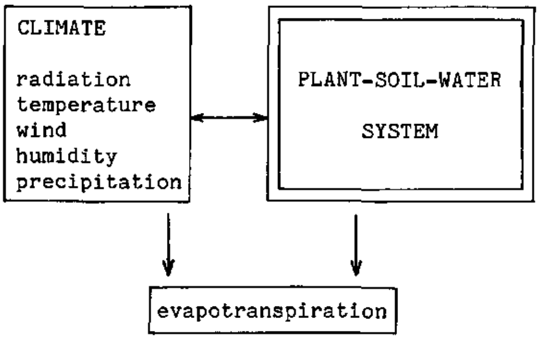

Fig.2 The plant-soil-water-atmosphere system
with its main elements

Numerous simulation models of this system have been developed. Feddes at al.(1988) quote Prickett (1975) who defines a simulation model as a system that can duplicate the response of a real system. Tarantola (1987) divides the scientific procedure for the modelling of a physical system into the following three steps:

- parametrization of the system
  discovery of a minimum set of model parameters whose values completely characterize the system
- forward modelling
  discovery of the physical laws allowing prediction of the values of some observable parameters
- inverse modelling
  use of the actual results of some measurements of the observable parameters to infer the actual values of the model parameters

The set of observed values normally overdetermines some model parameters while leaving others underdetermined. Underdetermination is a result of both experimental uncertainty and lack of data. The difficult task of the experimenter is to perform measurements as accurately as possible. He also has to imagine new experimental procedures which allow him to measure observable parameters carrying a maximum of information on model parameters (Tarantola,1987)

Sometimes a good resemblance of the real world can be obtained by physical models (e.g. lysimeters). Analogue models have been used based on the similarity between physical phenomena such as electrical flow and the processes under study (e.g. water dynamics) (Wind, 1979). Mathematical models are by far the most applied ones. These models usually have the form of a set of partial differential equations together with auxiliary conditons. The latter describe the system's geometry and its parameters, the boundary conditions and initial conditions. If the governing equations and auxiliary conditions are simple an exact analytical solution may be found, but this usually involves the introduction of several simplifying assumptions. Otherwise, a numerical approximation is applicable (Feddes et al., 1988).

The output of a simulation model can include such variables as soil water content, pressure head and water flux as a function of soil depth and time. In most studies the water balance terms are presented i.e. precipitation , actual evaporation, actual transpiration, infiltration, runoff, lateral and vertical subsurface fluxes and change in water storage.

3.2 Process-oriented studies

In many fundamental studies attention is given to the physical, chemical and biological processes which underly water flow, water use and plant growth (e.g. Taylor,1983). Knowledge of these processes is needed to construct the various modules of a simulation model. Here, some examples will be mentioned briefly.

The transport of water in the soil is often heterogeneous with part of the infiltrating water travelling faster than the average wetting front. This has important consequences for simulating the water balance. In some soils preferential flow occurs through large pores in an unsaturated soil matrix, a process known as bypass flow or shortcircuiting (Hoogmoed and Bouma (1980), Bronswijk(1988)). Hendrickx et al. (1988) describe the process of water repellency and its effect on water flow (wetting front instability). Most simulation models ignore the effect of preferential flow.
This also holds for the effect of hysteresis. When frequent changes from wetting to drying occur, hysteresis in the soil water retention curve influences the soil water movement (Mualem (1977),Hopmans and Dane (1986)). Much attention is being given to the consequences of spatial variability for soil water modelling. Hopmans and Stricker (1987) present an overview of techniques to describe the spatial variation in soil physical properties.
Spatial variation of rainfall may also pose problems for the reliability of model results. For example, Hromadka and McCuen (1988) argue that it is inappropriate to use a sophisticated runoff model to achieve a desired level of modelling accuracy if the spatial resolution of rain input is low. They found that with lack of precise rainfall data, simpler less data intensive models provided as good or better predictions than sophisticated ones.

Feddes et al.(1988) reviewed the principles underlying water dynamics in the unsaturated zone and gave an overview of simulation modelling of soil water flow in the unsaturated zone. They quote different authors who have shown that in arid and semi-arid regions with rapidly drying soils, the application of simultaneous soil water and heat flow principles is essential. A major problem in dealing with water flow in drying soils is the separation of vapour transport and liquid flow (Menenti,1984).

Simplifications are not only useful for an analytic approach (Schouwenaars,1987) but very often they are the consequence of insufficient knowledge. Mostly many assumptions have to be made in describing the relations within a system.
In studies on the plant-soil-water system one example is the way in which water uptake by the plants is described. Feddes et al. (1978) describe a 'sink'-term (S) representing water extraction by roots. In

this model the root system is assumed to have a homogeneous distribution and the extracted quantity of water S is expressed as volume of water per volume of soil per unit of time. For given soil moisture conditions, S is described semi-empirically as:

$$S(h) = a(h) \ . \ S_{max} \qquad (1)$$

where a(h) is a function of the pressure head h and S_{max} is the maximal possible water extraction by roots.

Eq.1 can be applied for the different nodes in a one-dimensional (vertical) soil water model. The integral of S_{max} over the different nodes in the rootzone is the potential transpiration rate (T_p). For most crops and especially when applied to (semi-)natural vegetation the reduction of water uptake under non-optimal conditions (i.e either too dry or too wet) is not well known and the shape of the a(h) function has been defined quite arbitrarily. For a homogeneous root distribution over the soil profile it can be assumed that S_{max} is equal to the ratio of potential transpiration rate (T_p) over the depth of the rootzone (z_r). In a study of Prasad (1988) it is taken into account that in a moist soil the roots principally extract water from the upper soil layers. The root water uptake at the bottom of the root zone equals zero and for the water extraction at a depth z the following equation is used:

$$S_{max}\ (z) = \frac{2.T_p}{z_r} \ . \ \left(1 - \frac{z}{z_r} \right)$$

In practice it is difficult to determine the depth of the active roots and it may be an important source of error when model results are very sensitive to minor changes in root depth. Also, root distribution is normally not homogeneous (e.g De Willigen and Noordwijk, 1987). In soils with a dry top soil it might even occur that a single deep root extracts most of the water used for transpiration.
When reliable and easily measurable field data such as water content and pressure head, etc., are available it is attractive to use inverse parametrization for the empirical determination of water uptake parameters.

3.2 Problem-oriented studies

The main purpose of studies on plant-soil-water relations is to obtain knowledge for the assessment of effects of alternative management options. Simulation models can be employed to evaluate different water management measures such as drainage, irrigation, soil improvement etc. Mostly the best option is searched among a limited number of tested

ones, but also more sophisticated optimization methods can be used (Orlovski et al.,1986).
For several decades much attention has been given to the integration of the various processes (sub-models) into dynamic crop growth and yield models (De Wit (1958), Van Keulen and Wolf (1986)).
In most of these studies attempts are made to describe the interaction (feedback) between plant (and crop-) development and water use. To do this, a profound knowledge of biological processes is required (e.g. Goudriaan,1982). Agronomical studies, in which plant-soil-water models are applied, do often necessitate the knowledge of processes and relations of another nature, e.g. cost-benefit analysis of water management measures. These economical aspects mostly determine the decision criteria.

When plant-soil-water models are applied in ecological and environmental studies it is evident that insight in the water balance of the system is not sufficient. Also here, for the selection of management alternatives it has to be clear which are the criteria to be decided upon. Often problems arise because ecological constraints are only roughly known. Several authors (Grootjans (1985), Van Wirdum (1981), Verhoeven et al.(1988)) show that nutrient budgets are closely interrelated with the water budget. Along this line attempts are made to develop simulation models which describe availability and uptake of the most important nutrients (Kemmers,1986). Due to limited knowledge of the biochemical and ecological processes involved in studies of this kind, mostly simple plant-soil-water models are used.

A good example of the relative role of detailed descriptions of plant-soil-water relations can be found in studies for water supply (e.g. irrigation). In the calculation of daily potential evapotranspiration values an accuracy of less than 0.1 mm is often reached. However, information about water losses as a result of leakage in the channels, deep percolation or surface runoff is mostly absent or they are only estimated very roughly.

When optimization models are used together with plant-soil-water models (Schweigman (1985), Hendrix (1989)) an improvement of mathematical methods might be irrelevant because of persisting uncertainties in the sub models describing the physical, biological and economical (decision-)environment.

In such real-world problems it is necessary to follow an integrated approach to all the relevant aspects involved in simulation studies. In an early stage a comprehensive analysis should be made of the relevancy of the different aspects for the decision to be made. An assessment should be made of the desired level of accuracy in the description of the processes involved (sub-models).
The two case studies given below, will be used to illustrate these points.

4. Examples of problem-oriented studies

4.1 Sowing strategies for maize in rainfed agriculture in southern Mozambique

Rainfed crop production in the coastal zone of southern Mozambique is mainly practised by small family farming units. Each family cultivates different fields (machambas) with a total area of 1 - 2 ha. Commonly mixed cropping is practised with low plant densities for maize, which is the most important cereal crop.
Rainfall is concentrated in the rainy period between October and April. It is very irregular and its yearly fluctuations are high. In the sandy soils capacity for water retention is extremely low (5-10% of its volumetric content). Here, the average production of maize is very low (less than 1000 $kg.ha^{-1}$) and yields vary with the amount and distribution of rainfall during the growing period. Although a concentration period can be distinguished, it seems a common practice to sow maize in small quantities throughout the whole year whenever rainfall is sufficient. The most important period for sowing however, is September-October. From an agrohydrological viewpoint this period is not the most favourable period . Risks for water deficiency are lower when one would start sowing in the period December-January. Probably earlier sowing can be explained by the almost permanent food shortage, inducing people to sow as early as possible and by the higher risks for damage caused by pests and diseases in later periods.

Schouwenaars and Pelgrum (1990) used a model approach to understand the logic of certain sowing strategies. A selection was made of some environmental factors which are expected to play a role in preferences for sowing strategies. Their impact upon these preferences was analysed in quantitative terms by using a simple water balance and crop growth model (Schouwenaars,1988c; Schouwenaars et al.,1988).
Available water for a maize crop depends on the amount and distribution of rainfall, water retention properties of the soil and of plant characteristics such as rooting depth, water uptake and plant-density. Water demand by the plant depends on climatic conditions and plant characteristics such as the length of the growing period, height of the crop and leaf area. Very important factors affecting the production of maize are the (low) soil fertility, damage by pests and diseases and losses caused by inadequate storage facilities. Different sowing strategies were analysed, varying from a very scattered strategy to sowing only once a year. Using simplifying assumptions, available maize for consumption per month for an average family farming unit was determined for a 28-year period.

In the studies mentioned above it was found that for the selection of an optimal strategy for a given site, it has to be well defined what the criteria are to decide upon. For instance, when alternative food is available during the whole year then preference might be given to the maximization of maize production. However, when this is not available, then preference might be given to the minimization of the length of the periods with shortage of maize.
The different interrelations in this decision problem are illustrated in Fig.3. It is clear that a description of the plant-soil-water system will only contribute partially to the understanding of the problem. In most cases much of the information about the different factors in Fig.3 will be only partially available, as was the case in Mozambique. Then also simple plant-soil-water models should be used, because a more detailed description of the water balance and corresponding yields does not substantially improve the analysis of sowing strategies (Pelgum and Schouwenaars, 1988).
An illustration of the desired level of accuracy in descriptions of the plant-soil-water system in relation to other factors affecting the sowing strategy, will be presented later.

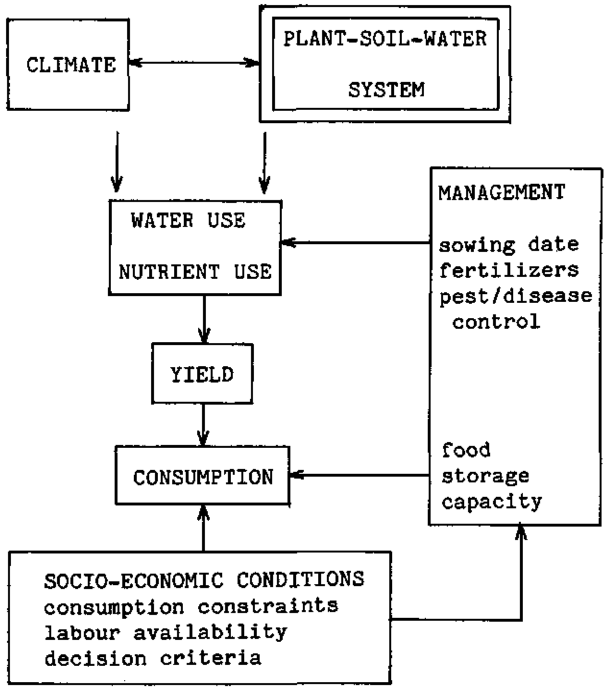

Fig.3 The main elements involved in the study on sowing strategies for maize in rainfed agriculture

4.2 Water Management in bog relicts in the Netherlands

In the Netherlands bog relicts cover about 9000 ha, which is only 5 % of the area occupied by bogs in the 17th century. In most of these relicts the upper peat layers have been cut away and the thickness of the remaining peat layers varies considerably. In the Netherlands as well as in the Federal Republic of Germany, most of these areas are managed as nature reserves or will be managed as such after the peat mining activities have ended. Because of the scarcity of oligotrophic wetlands in this part of northwestern Europe, the main objective for their management is the restoration of the original bog vegetation.
In bog relicts the hydrological conditions are different from those in undisturbed bogs. Vegetation indicates relatively drier conditions. In many relicts it can be observed that in summer the groundwater level drops below 40 cm depth, which is commonly accepted as the critical level for the growth of bog plant communities.
Hydro-physical properties of the upper peat layers play a dominant role in the groundwater fluctuation pattern. In an undisturbed bog the water storage capacity in the upper 20 cm is very high. Together with a reduced evapotranspiration of the dominant *Sphagnum* moss vegetation in dry periods, it results in limited fluctuations of the water table. In bog relicts with moderately to strongly humified peat at the surface, water storage coefficients of the soil are much lower (Schouwenaars and Vink(1990). In most bog relicts the vegetation is dominated by the grass species *Molinia caerulea* and evapotranspiration from these sites is hardly reduced is dry periods (Schouwenaars,1990).

During peat mining the bogs were drained and in many bog relicts deep open drains cut into the underlying sandy aquifer. As a consequence downward seepage from these areas has increased as compared to undisturbed bogs (Schouwenaars et al.,1990). In many bog relicts it is tried to reduce downward seepage by refilling the open drains reaching into the underlying aquifer and by diverting agricultural drainage channels that cross the area. For several bog relicts it is commonly believed that only the creation of hydrological bufferzones would reduce the losses to an acceptable level. These 'external' water management measures should limit the drop of the groundwater level in the summer period. Whether this is a feasible option depends on the hydrological characteristics of the bog relict and its environment. Another option is to increase the water storage capacity near the surface in the bog relict itself by so called 'internal' water management measures. The storage coefficient in open water is 100% and areas characterized by a high fraction occupied with permanently inundated sites (e.g. former drains after blocking with dams) show more limited water level fluctuations than areas without such sites (Schouwenaars, 1989).
The field conditions and processes leading to a high water storage capacity and limited water level fluctuations depend on areal characteristics such as the fraction open water and its distribution and

on the properties of the plant-soil-water system (e.g. soil water storage coefficient, evapotranspiration).
In the studies mentioned above it was found that also here well defined decision criteria are needed. For instance, when superficial runoff has to be guaranteed in order to remove sufficient nutrients from the bog-system (Streefkerk and Casparie, 1987), more emphasis should be laid on reduction of downward water losses. However, when one tries to minimize water level fluctuations preference might be given to other options, like the creation of more inundated sites within the bog relict.
The different interrelations of this decision problem are illustrated in Fig.4.

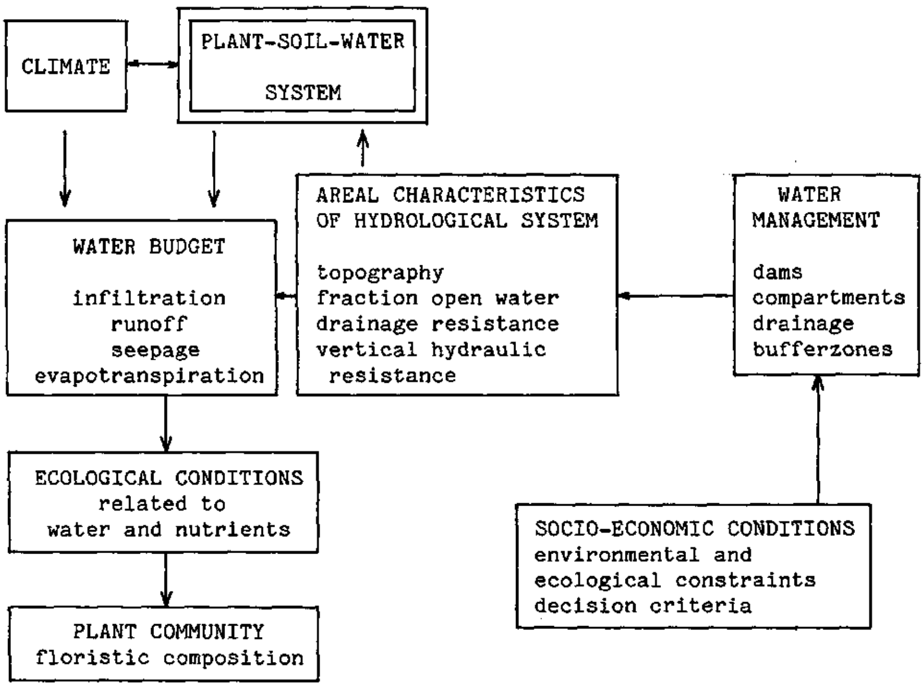

Fig. 4 The main elements involved in the study on water management in bog relicts

Also here, a description of the plant-soil-water system will only partially contribute to understand the problem. For many bog relicts the information about the different factors in Fig.4 will only be scarce or unavailable. In this case, like in the Mozambique case, also simple plant-soil-water models should be used. On the other hand, a good description of the water storage properties in the upper layers of the peat soil is essential for a correct analysis of water management options.
An illustration of the required attention to the different factors will be presented later.

5. A general outline of a problem-oriented approach

5.1 A Systems Approach

Between the two cases discussed above, differences exist in the subject and object of study, in means and medium of manipulation and in the decision-criteria. In Table 1 a summary of these characteristics is presented.

TABLE 1

Comparison of some features of the two case studies

	Case 1: Sowing strategies in southern Mozambique	Case 2: Water management in bog relicts
1. subject :	human population	plant population
2. object :	maize production and -consumption	water level and water balance
3. medium :	plant	water
4. human intervention:	sowing strategy	water management
5. decision criteria :	maximizing consumption and/or minimizing risks for shortage	maximizing water level and/or minimizing fluctuations and/or maximizing superficial discharge

Between both cases similarity exists in the role of the plant-soil-water system, where storage and transport of water occurs. Input and output of water is governed by upper boundary conditions (e.g. atmosphere), lower boundary conditions (e.g. underlying aquifer) and intrinsic regulation mechanisms (e.g. soil water storage, soil cover).
Storage can be regarded as a very important regulation mechanism. In the plant-soil-water system, the storage of water and its availability regulates the water use by plants. In case study 1, also the storage facilities for maize appeared to be of utmost importance for decisions on sowing strategies. In case study 2, it appeared that the water storage capacity in the peat relicts has a dominant impact upon the fluctuation pattern of the groundwater. In these areas infiltration from open water into peat relicts can be regarded as a mechanism to reduce the lowering of the water table when input from the atmosphere is insufficient or when output rates (evapotranspiration, seepage) are too high. In bog relicts the low vertical permeability and the thickness of the peat layers offer a resistance mechanism to limit downward water losses. It appeared that this mechanism is of great importance for the decisions on water management.
In the plant-soil-water system the plant canopy plays an important part in the rate of absorption and reflection of incoming solar radiation. In case study 1 a low plant density in combination with a mulched soil or dry top layer of the soil can be regarded as a mechanism to limit the conversion of incoming energy into latent heat. The same holds for sites in bog relicts (case study 2) where a high fraction of the soil is covered with the dead leaves of *Molinia*.

5.2 Sensitivity Analysis

Some of the above mentioned regulation mechanisms are selected for a further analysis.

The selected model parameters in case 1 are:

- water storage capacity of the soil
- availability of the soil water for the plant
- quality of storage facilities (post harvest losses)

The selected parameters in case 2 are:

- water storage capacity of the soil
- infiltration from open water into peat layers (drainage resistance)
- downward water losses (vertical hydraulic resistance)

Different sets of values for these parameters gave different results in production (case 1) and groundwater fluctuations (case 2). They lead to differences in decisions on sowing strategies (case 1) and water management (case 2). These decisions are strongly influenced by losses

of maize (case 1: poor storage facilities and yield reduction by pests and diseases (par.4.1)) and losses of water (case 2: downward seepage (par.4.2)).
As these losses can only be estimated in terms of probability (i.e. with a limited degree of accuracy) we need to define the desired level of accuracy for the parameters and variables governing the regulation mechanisms mentioned above. An outline for an approach is presented here.

In three-dimensional figures (Fig.5a,5b and 5c), values for the object of study (case 1: consumption , case 2: groundwater level) are presented on the vertical axis ($F=f(x_1,x_2)$). On horizontal axes values for the parameters describing the plant-soil-water system are presented. Sensitivity of model results (object-values F) for the parameter values x and y can be analysed. Of course in reality Fig.5 should be a n-dimensional figure ($F=f(x_1,\ldots,x_n)$).
It is possible to analyse the impact of differences in losses (e.g. storage losses, pests and diseases) by presenting the results of several model runs within the same figure, as was done in Fig.5a and 5b.
When this method is applied, it is possible to distinguish critical ranges for the values of the respective parameters. This is done by varying the values of one parameter (e.g. x_1) while keeping the values for the other parameters (e.g. x_2,x_3) constant. This is repeated for different sets of values for these other parameters (Fig.5c).
This sensitivity analysis serves to determine to which parts of the plant-soil-water system priority should be given in research.
In the study on sowing strategies for maize in Mozambique the mean annual consumption was determined over a 28 year period (for details see par 4.1). In Fig.6 results are presented for concentrated sowing (strategy 3: in December) and for a more distributed sowing (strategy 2: in September, December and March). In the case study also sowing throughout the whole year was examined (strategy 1) but this option is not regarded here. On the x-axis different sets for the two parameters describing water availability are presented. E.g. the figure 7.5 (25) indicates that maximum available soil water is 7.5 % of the volumetric soil content (equals 75 mm when the depth of the rootzone is 1 m.) and that 25% of it is easily available (no reduction in water uptake in this range). On the y-axis the monthly storage losses are presented.
For maximizing maize consumption preference should be given to strategy 3 when storage losses are limited. However, an increased water availability may lead to better results with strategy 2. The inclination of the planes in Fig.6 shows that storage losses have more effect on preferences for strategies than water availability. As a matter of fact, the impact of better storage facilities upon consumption levels is more pronounced when sowing is restricted to one period only.

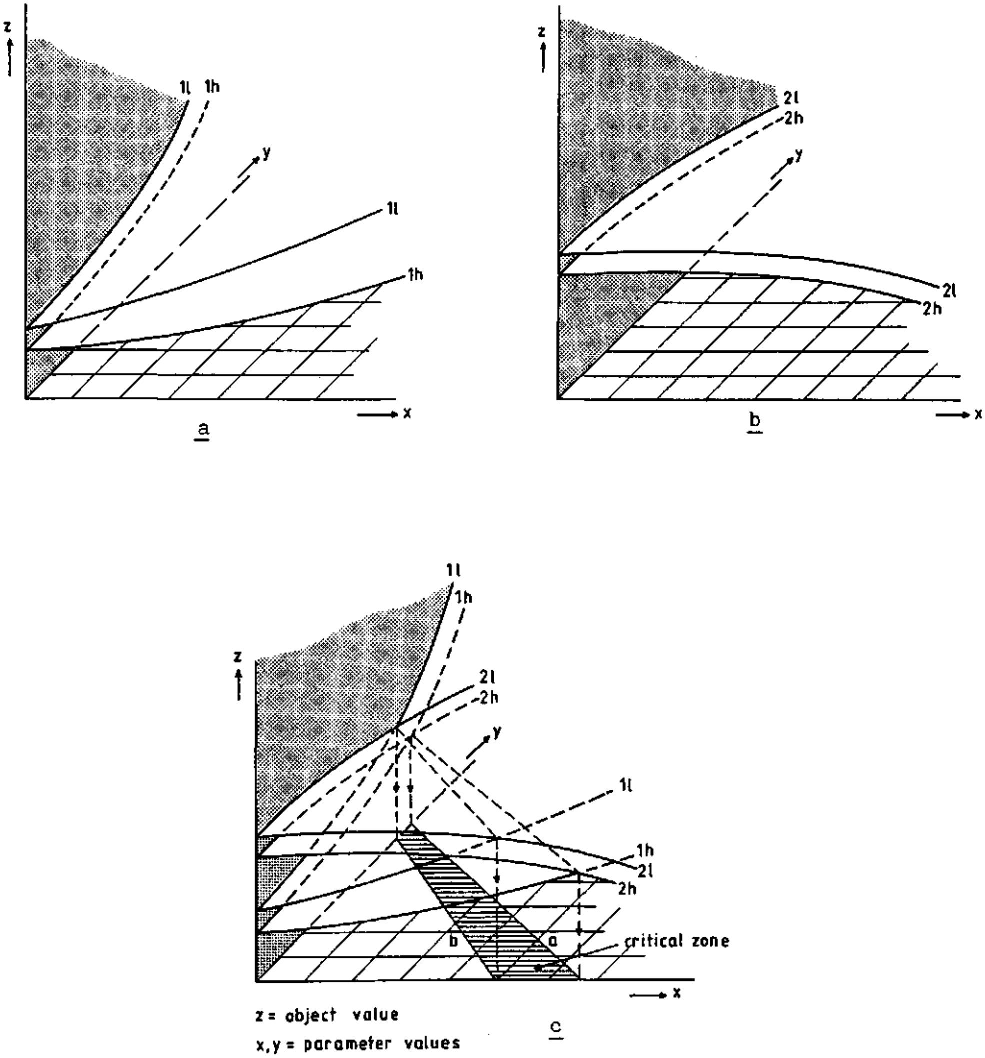

Fig.5 An illustration of the approach for sensitivity analyses
a: option 1, with high (1 h) and low (1 l) losses
b: option 2, idem
c: option 1 and 2 combined

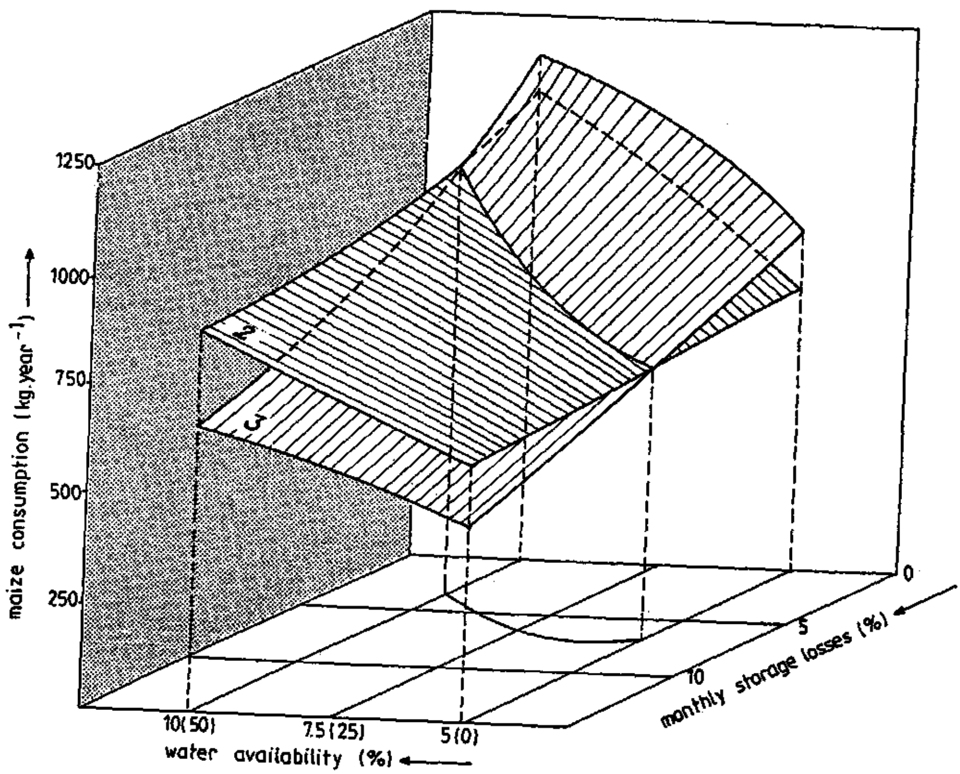

Fig.6 The effect of two sowing strategies on the mean annual maize consumption for different sets of values for water availability and monthly storage losses (Manhica, southern Mozambique)

strategy 2: 0.4 ha is sown in September, December and March
strategy 3: 1.2 ha is sown once a year (December)

The impact of a better water availability is more pronounced for low storage losses than for high storage losses. Measures to increase soil water availability will always result in higher production and consumption rates. However, optimal sowing strategies will only change when measures to increase soil water availability are combined with an improvement of storage facilities. More examples of other interrelated factors affecting preferences for sowing strategies are presented in chapter 2.

In the study on water management in bog relicts different alternatives were evaluated over a 30-year period. The frequency distribution of the groundwater depth can be used as a criterion. In Fig.7 the groundwater levels which are exceeded during 80% of the vegetation period (1 April - 15 October) are presented on the vertical axis.
In the actual situation 10% of the area is open water. In option 1 this fraction is maintained but downward seepage is reduced by 50%. In option 2 the fraction open water was increased to 50%, while there is no reduction in seepage.
On the horizontal axes the water storage coefficient (x) and the downward water losses in the actual situation (y) are indicated. For minimizing the groundwater depth preference should be given to option 2 when downward seepage is low. However, when the storage capacity is allready high, better results may be obtained with option 1 (i.c. bufferzones). The inclination of the planes show that both options have a similar relative impact upon the groundwater depth. Of course a combination of the reduction of seepage and the enlargement of the area with open water is possible. It is shown that both types of measures (external and internal) should be analysed and that a study involving only one of them is not sufficient (e.g. Poelman and Joosten, 1989).

5.3 Desired level of accuracy of data on plant-soil-water relations

When research priorities have been determined it is important to know how detailed the information about the selected model parameters should be and which level of accuracy is desired. When e.g. losses are estimated, it is possible to distinguish an upper and lower limit for its value, indicating the range with a given (e.g. 90%) probability that actual losses are within that range. The consequences of this uncertainty are illustrated in Fig.5. Upper and lower (probability-) limits for the rate of losses are distinguished (l and h respectively). Values for the object function (z) are determined as a function of x and y (z = f(x,y)). This is done for two management options.
In this way it is possible to determine critical trajectories for the x- and y-values. Outside this critical 'zone' preference for a certain option only depends on values for x and y.

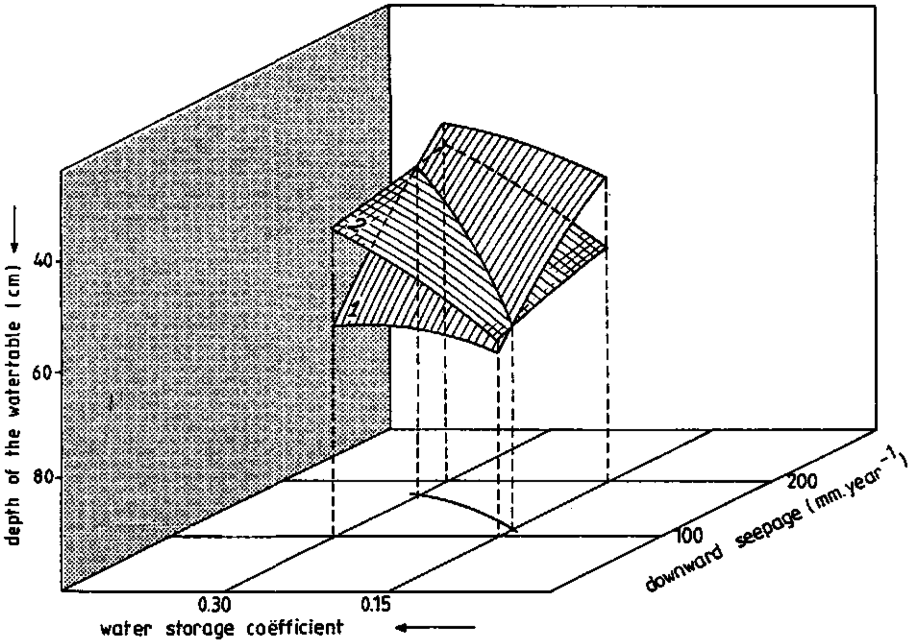

Fig.7 The effect of two water management options on the groundwater depth with 80% probability of exceedance (in vegetation period), for different sets of values for the soil water storage coefficient and downward seepage (Engbertsdijksvenen, Netherlands)

option 1 : downward seepage is reduced with 50%
option 2 : the fraction open water is enlarged to 50%

- in the actual situation the fraction open water is 10%
- the indicated values for downward seepage refer to the original situation and after realising option 1 values for seepage are only 50% of the indicated ones.
- the actual groundwater depth is not indicated
- only the results of the two options are indicated

Within this critical zone preference also depends on losses. Given the uncertainty in the estimation of these losses, an 'acceptable uncertainty' (or desired level of accuracy) for the values for x and y can be distinguished.

In Fig.8 another approach to analyse the consequences of uncertainty is visualized. On the vertical axis the rates of losses are presented (z), and on the horizontal axes the parameters describing the plant-soil-water system. For a given set of values for x,y and z it can be determined which option is preferred. A set of (x,y,z) values can be distinguished which form a 'boundary-plane', indicating when preference changes from one option to the other. In Fig.8 the lower and upper (probability-) limits for the rate of losses are indicated (z_1 and z_2, respectively). For a given uncertainty in z (i.c. z_2- z_1) a critical range for both x and y values can be distinguished. The width of this range can be regarded as the acceptable uncertainty (or desired level of accuracy) for the estimation of the values for the model parameters x and y.

In Fig.9 the above mentioned procedure is shown for the study on sowing strategies, using the criterion of maximizing average yearly maize consumption. Here, the dominant role of storage losses for preferences on strategies is clearly demonstrated by the wide ranges of the physical soil parameters that have an equivalent effect. Consequently, detailed studies on water availability and on the water uptake function of a maize crop are irrelevant for the analysis of sowing strategies as long as the storage facilities and -losses are not studied in detail.

In Fig.10 the procedure is illustrated for the study on bog relicts. Here, the criterion is to maximize the water level together with a minimization of its fluctuation. It is shown that the different factors affecting downward seepage, water storage and infiltration from open water are equally important. In studies where alternative water management options are evaluated these different factors (e.g. thickness of the peat layers, piezometric head difference with the underlying aquifer, vertical and horizontal permeability, water storage characteristics) need to be examined jointly. Given the difficulties in the correct assessment of downward seepage (where an error of 25% must be regarded as a minimum) the other aspects can be studied roughly.

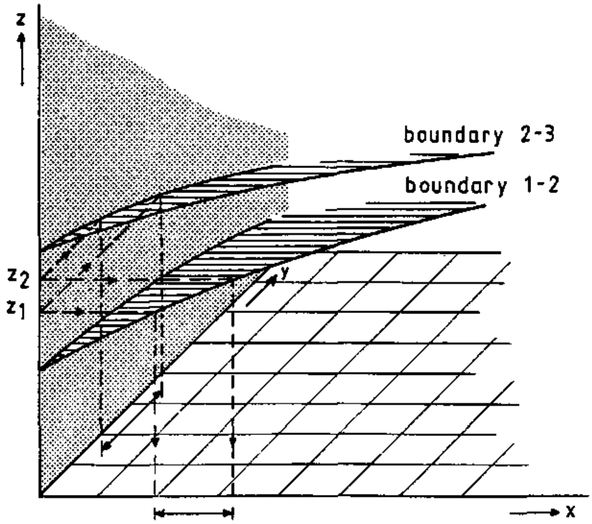

Fig.8 An illustration of the approach to define acceptable uncertainty or required degree of accuracy

- under boundary 1-2 option 1 is preferred
- above boundary 2-3 option 3 is preferred
- for a given uncertainty in z (z_2-z_1) a critical traject for x and y can be distinghuished. Its width is the acceptable uncertainty.
- in this example with this range of z-values preference for option 1 or 2 only depends on x

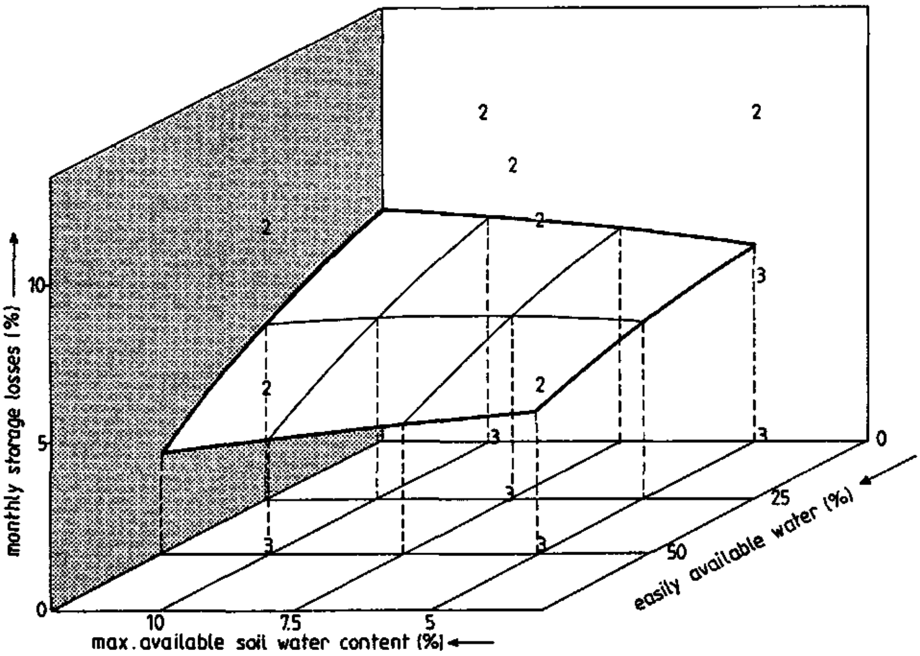

Fig. 9 Optimal sowing strategy for different sets of values for monthly storage losses and for the parameters describing soil water availability (Manhica, southern Mozambique)

strategy 2: 0.4 ha is sown in September, December and March
strategy 3: 1.2 ha is sown once a year (December)

- the plane is formed by sets of values where both strategies give equal results (indifferent)
- above the plane strategy 2 is preferred
- below the plane strategy 3 is preferred

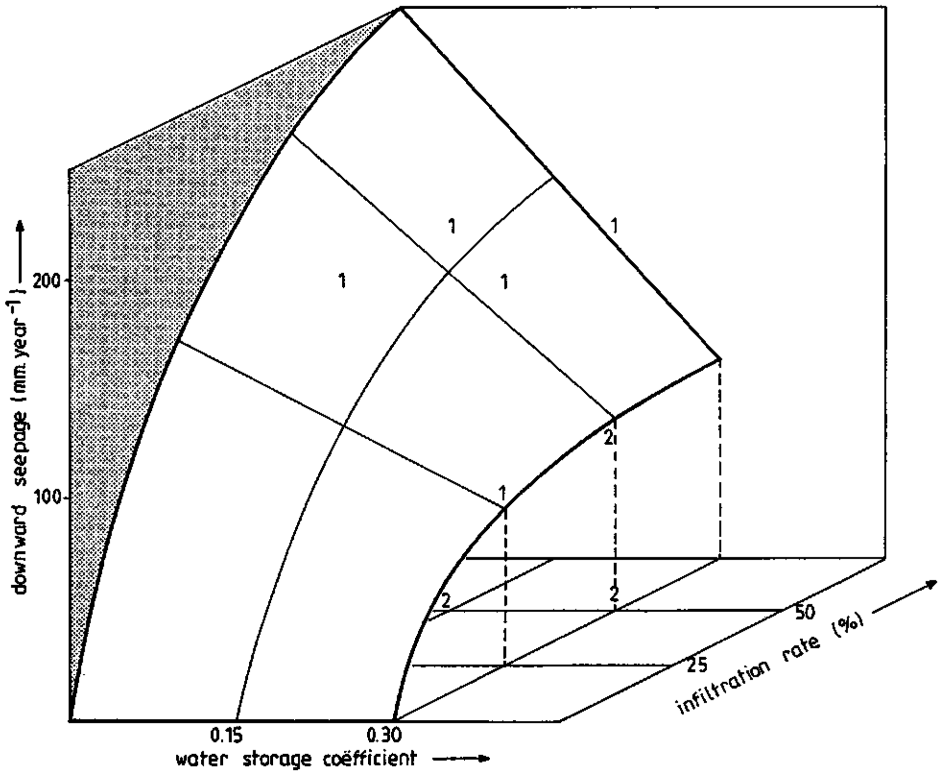

Fig.10 Optimal water management option for different sets of values for downward seepage, water storage and infiltration rate
(Engbertsdijksvenen, the Netherlands)

option 1 : downward seepage is reduced with 50%
option 2 : the fraction open water in the area is enlarged to 50%
- the plane is formed by sets of values where both options give equal results (indifferent)
- above the plane option 1 is preferred
- below the plane option 2 is preferred
- in the actual situation the fraction open water is 10%
- the indicated values for downward seepage refer to the original situation and after realizing option 1 values for seepage are only 50% of the indicated ones.

6. Discussion

In both case studies emphasis has been laid on (agro-)hydrological research. It is evident that the contribution of the (agro-)hydrologist to the understanding of the problems involved is limited. Certainly when decisions on management practices have to be prepared, the research should be interdisciplinary. In an early stage of the research the relative importance of the different disciplines should be analysed and consequences for the desired level of knowledge on the different aspects should be formulated.

In such analysis simple models serve to describe the different relations in a quantitative way. Only after a first, rough approach, as presented here, research priorities should be defined. It is shown that for a given decision problem, it is crucial to have well defined decision criteria. If they are not available main attention should be given to studies which focus on the problems related to the selection of these criteria (e.g. economy, ecology, sociology).

In more analytical studies, as on sowing strategies in southern Mozambique, a simple model approach on plant-soil-water relations may serve to distinghuish the probably relevant decision-criteria.

When in problem-oriented studies, meant to prepare decisions (e.g. on water management in bog relicts) the selection-criteria are not well defined and only little information is available about factors relevant to the problem, the (agro-)hydrologist focussing on plant-soil-water relations, should be well aware of his limited contribution.

References

Bronswijk, J.J.B., 1988. Modeling of water balance, cracking and subsidence of clay soils. J. of Hydrology 97: 199-212

De Willigen, P. and van Noordwijk, M., 1987. Roots, plant production and nutrient use efficiency. Ph.D. Thesis, Agricultural University Wageningen, 282 p.

De Wit, C.T., 1958. Transpiration and crop yields. Versl. Landbouwk. Onderz. 64.6 Inst. of Biol. and Chem. Res. on Field Crops and Herbage, Wageningen

Feddes, R.A., Kabat, P, van Bakel, P.J.T., Bronswijk, J.J.B. and Halbertsma, J. 1988. Modelling soil water dynamics in the unsaturated zone - state of the art. J. of Hydrology 100: 69-111

Feddes, R.A., Kowalik, P.J. and Zaradny, H., 1978. Simulation of field water use and crop yield. Pudoc, Wageningen, 189 p.

Goudriaan, J., 1982. Potential production processes. In: Penning de Vries, F.W.T. and Van Laar, H.H. (Eds.) Simulation of plant growth and crop production. Pudoc, Wageningen. pp. 98-113.

Grootjans, A.B., 1985. The impact of changes in the hydrology upon the presence of marsh- and grassland plants (in Dutch). PhD-thesis State University Groningen

Hendrix, E., 1989. Risk and uncertainty in operation research models which can be used in agriculture. Technical Note 89-01. Dept. of Mathematics, Agricultural University Wageningen, 24 pp.

Hendrickx, J.M.H., Dekker, L.W., Bannink, M.H. and Van Ommen, H.C., 1988. Significance of soil survey for agrohydrological studies. Agricultural Water Management 14: 195-208

Hoogmoed, W.B. and Bouma, J.,1980. A simulation model for predicting infiltration into cracked clay soil. Soil Sci. Soc. Am. J., 44: 458-461

Hopmans, J.W. and Dane, J.H., 1985. Effect of temperature dependent hydraulic properties on soil water movement. Soil Sci. Soc. Am. J., 49 : 51 - 58

Hopmans, J.W. and Stricker, J.N.M., 1987. Application and evaluation of techniques which describe the spatial variation in soil physical and hydrological variables: a final report. Publication 80 of the Dept. of Hydraulics and catchment hydrology, Agric. University, Wageningen, 16pp.

Hromadka, T.V. and McCuen, R.H., 1988. Uncertainty estimates for simple runoff-models. Adv. Water Resources, 11: 2-14

Kemmers, R.H., 1986. Perspectives in modeling of processes in the root zone of spontaneous vegetation at wet and damp sites in relation to regional water management. In: CHO/TNO Proceeding and informations 43: 91-116

Menenti, M., 1984. Physical aspects and determination of evaporation in deserts applying remote sensing techniques. Inst. Land and Water Management Research, Wageningen, Report 10: 202 p.

Mualem, Y., 1977 Extension of the similarity hypothesis used for modeling the soil water characteristics. Water Resources Research 13: 773-780

Orlovski, S., Kaden.S. and Van Walsum, P., 1986. Decision support systems for the analysis of regional water policies: final report of the collaborative IIASA 'Regional Water Policies' project. IIASA, 335 pp.

Pelgrum., G.H. and Schouwenaars, J.M.,1988 The importance of water-availability, pests and diseases and storage facilities for sowingstrategies in southern Mozambique - a sensitivity analysis for the waterbalance- and crop growth model SWETAM. UEM/LUW/PSW - project research report 2. Mededeling vakgroep Cultuurtechniek nr.121 29 p.

Poelman, A. and Joosten, J.H.J., 1989. On the identification of hydrological interaction zones for bog reserves. Symposium on Peatland ecosystems and man -an impact assessment. Dundee, Scotland (in prep)

Prasad, R., 1988. A linear root water uptake model. J. of Hydrology, 99: 297-306

Prickett, T.A., 1975. Modelling techniques for groundwater evaluation. Adv. Hydrosci., 10: 1-143 Schouwenaars, J.M., 1987. A simple method to estimate specific equilibrium soil water content in a uniform soil. J. of Hydrology, 95:13-17

Schouwenaars, J.M., 1988a. Rainfall irregularity and sowing strategies in southern Mozambique. Agricultural Water Management, 13 : 49-64.

Schouwenaars, J.M.,1988b. The impact of water management upon groundwaterfluctuations in a disturbed bog relict. Agricultural Water Management, 14: 439-449

Schouwenaars, J.M.,1988c. Hydrological Research in disturbed bogs and its role in decisions on water management in the Netherlands. Proceedings of the Symposium on the hydrology of wetlands in temperate and cold regions. vol 1. Joensuu, Finland, 6-8 june Publications of the Academy of Finland 4 (1988) 170-177

Schouwenaars, J.M., Pelgrum, R. and Swennenhuis, J.,1988. Research on Plant Soil Water Relations and its role in understanding sowing strategies in southern Mozambique. Proceedings of the International Symposium on water management for food production Athens, 14-16 december 1988. Water Resources Management 2 : 255-267

Schouwenaars, J.M., 1989. Hydrological characteristics of bog relicts in the Engbertsdijksvenen after peat cutting and rewetting Proceedings of the Symposium on Peatland ecosystems and Man - an impact assessment. Dundee, Scotland 11-15 Sept. 1989 (in press)

Schouwenaars, J.M., 1990. A study on the evapotranspiration of Molinia caerulea and Sphagnum papillosum, using small weighable lysimeters. Journal of Hydrology (in prep)

Schouwenaars, J.M.,Amerongen,F.v. and Booltink,M.,1990. Hydraulic resistance of peat layers and downward seepage in bog relicts. International Peat Journal 5 (in prep)

Schouwenaars, J.M. and Pelgrum, G.H., 1990. A model approach to analyse sowing strategies for maize in southern Mozambique. Netherlands Journal of Agricultural Sciences 38:9-20.

Schouwenaars, J.M. and Vink, J.P.M., 1990. Hydrophysical properties of peat relicts in a former bog and perspectives for Sphagnum regrowth. International Peat Journal 5 (in prep)

Schweigman, C., 1985. Operations research problems in agriculture in developing countries. University Press Groningen, 361 pp.

Streefkerk, J.G. and Casparie,W.A., 1987. The hydrology of bogsystems (in Dutch). National Forestry Service, Utrecht. 120pp.

Tarantola, A., 1987. Inverse Problem Theory. Elseviers Science Publishers, Amsterdam

Taylor, H.M., Jordan, W.R. and Sinclair, T.R. (Eds.), 1983. Limitations to efficient water use in crop production. Am. Soc. of Agronomy

Van Keulen, H. and Wolf, J., 1986. Modelling of agricultural production: Weather, Soils and Crops. Pudoc, Wageningen, 479 p.

Van Wirdum, G., 1981. Linking up the natec subsystem in models for the water management. CHO-TNO Proc. and Infor. 27: 108-128

Verhoeven, J.T.A., Koerselman, W. and Beltman, B., 1988. The vegetation of fens in relation to their hydrology and nutrient dynamics: a case study. In: Symoens, JJ.(ed.) Vegetation of inland waters. Kluwer, Dordrecht, pp. 249-282

Wind, G.P., 1979. Analog modeling of transient moisture flow in unsaturated soil. Agric.Reserch report 894: 123 p.

PART II

MODEL STUDIES ON SOWING STRATEGIES FOR MAIZE IN RAINFED AGRICULTURE IN SOUTHERN MOZAMBIQUE

2.1 Rainfall-irregularity and sowing strategies in southern Mozambique

published in:
Agricultural Water Management, 13 (1988) 49-64

2.2 Research on plant-soil-water relations and its role in understanding sowing strategies

published in:
Water Resources Management, 2 (1988) 255-267

2.3 A model approach to analyse sowing strategies for maize in southern Mozambique

published in:
Netherlands Journal of Agricultural Science 38 (1990) 9-20

Rainfall Irregularity and Sowing Strategies in Southern Mozambique

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ABSTRACT

Schouwenaars, J.M., 1988. Rainfall irregularity and sowing strategies in Southern Mozambique. *Agric. Water Manage.*, 13: 49–64.

Rainfed crop production in the sandy uplands of the coastal zone of Southern Mozambique is very risky. Year-by-year fluctuations of rainfall are extremely wide and rainfall is very irregular. Precipitation is concentrated in the rainy period between October and April. People tend to spread sowing over a long period.

This study aims to analyse yearly rainfall characteristics in the area in such a way that sowing strategies can be evaluated.

The model SWETAM was developed to simulate yields for maize (*Zea mays*) and sorghum (*Sorghum vulgare*) for two stations in Southern Mozambique over a period of about 30 years. For every year, each month with sufficient rainfall was considered to be a sowing period and for the subsequent growing period the water-balance terms of crop and soil were calculated. Yield reduction as a consequence of water deficit was analysed. Results of the simulation indicate that, for rainfed agriculture, the environmental conditions are very risky. For each station, yields vary greatly from year to year. Plant density and depth of root zone seem to be important characteristics that influence water deficit and yield reduction under the prevailing meteorological conditions.

From the subsistence farmer's point of view it seems rational to sow frequently over a long period. Their strategy for sowing is based upon a spreading of risks and short-term interests rather than upon maximizing production over a longer period. This may be the best way to secure the availability of a minimum of food every year, but it results in high losses of seeds.

INTRODUCTION

Rainfed crop production in the sandy uplands of the coastal zone in Southern Mozambique is mainly by small family-farming units. Cropping centres around the (marginal) production of foodcrops like cassava (*Manihot* sp.), maize (*Zea mays*), groundnut (*Arachis hypogea*), sweet potato (*Ipomea batatus*), cowpea (*Vigna* sp.) pigeonpea (*Cajanus cajan*) and vegetable crops

TABLE 1

Precipitation (mm) data for five stations in Southern Mozambique

Month	Salamanga			Boane			Manhica			Chinanguanine			Xai-Xai		
	26°28′S 32°39′E			26°04′S 32°18′E			25°24′S 32°48′E			25°18′S 32°31′E			25°02′S 33°38′E		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H[a]
Sep	8	21	54	4	18	45	9	24	45	0	19	40	6	18	66
Oct	27	43	97	20	29	70	38	59	73	13	35	49	31	56	81
Nov	28	60	116	31	59	108	48	65	101	22	31	63	27	56	112
Dec	36	63	108	33	66	107	57	78	150	34	62	98	70	108	151
Jan	45	91	180	52	106	186	73	116	217	42	75	122	57	113	223
Feb	57	95	188	34	65	154	47	132	234	44	100	132	66	119	198
Mar	37	64	127	35	50	92	57	100	132	37	52	95	61	94	152
Apr	23	35	75	12	41	71	41	58	111	23	43	56	45	73	179
May	8	17	31	0	10	47	15	31	87	0	9	28	25	66	140
Jun	4	13	20	2	6	19	10	19	39	0	7	20	27	48	93
Jul	2	8	20	0	1	19	0	14	34	0	3	12	18	41	66
Aug	5	10	29	0	6	28	3	16	33	0	2	27	7	17	52
Year	487	625	1030	435	559	813	726	932	1183	344	535	665	734	915	1222
Average		736			649			905			540			972	
Number of years		29			19			24			22			24	

[a]L, in 25%, M, in 50%, H, in 75% of the years precipitation is lower.

such as squashes, pumpkins (both *Cucurbita* sp.) and okra (*Hibiscus esculentus*).

From the coast towards the interior, mean annual rainfall decreases from 800–1000 mm to 550 mm. Rainfall is concentrated in the rainy period between October and April. Year-by-year fluctuations of rainfall are extremely wide, and rainfall is very erratic. Precipitation data for five stations are given in Table 1. Mean Penman-evaporation per month for five stations is listed in Table 2 (see also Fig. 1).

Average production is very low (for cereals less than 1000 kg/ha) and yields vary considerably. Irregularity of rainfall, even within the rainy period, has led to a strategy of minimising seasonal risks, rather than to one of maximizing production over a longer period.

Labour availability for land preparation and weeding is a limiting factor, whereas land availability is much less limiting (except in the suburban zones). Thus spreading of sowing seems a way to spread both labour demand and risks.

This study aims to analyse yearly rainfall characteristics in the area in such

TABLE 2

Penman evaporation (mm) for five stations in Southern Mozambique (mean monthly values over 20 years)

Month	Changalane	Umbeluzi	Maputo	Manhica	Xai-Xai
	26°27'S 32°15'E	26°18'S 32°11'E	25°53'S 32°36'E	25°24'S 32°48'E	25°03'S 33°38'E
Sep	116	122	117	119	107
Oct	131	139	136	150	137
Nov	142	151	147	158	148
Dec	155	162	166	170	161
Jan	157	164	163	167	160
Feb	133	140	138	138	139
Mar	114	121	131	127	125
Apr	93	100	97	100	92
May	77	81	74	76	68
Jun	60	62	57	59	49
Jul	67	67	62	64	55
Aug	90	98	87	86	80

Data from Mozambican Meteorological Service.
For net short-wave radiation the following equation was used:
$R_n = 0.75 R_{sa}\ (0.29 + 0.42\ n/N)$
where R_{sa} is short-wave radiation at top of atmosphere, and n/N sunshine (fraction).

a way that sowing strategies can be evaluated. This is done by analysing reduction of yields for maize and sorghum as a consequence of water deficit for various sowing periods.

METHODS

Determination of plant water use

Water storage in the soil is important in periods without rainfall. Thornthwaite and Mather (1954) suggested that plant water use decreases linearly from the upper to the lower limits of available soil water. Soil water content is maximal at field capacity, when (for sandy soils) pressure head (h) equals -30 kPa. Maximal extractable water is the difference in water content between 'field capacity' and 'wilting point'. Extractable water is zero at 'wilting point', when h equals -1.5 MPa.

Water content of the soil at a given time (V_t) can now be expressed as a function of accumulated potential water loss (A) and maximal extractable water content (V_{max}). Both can be expressed in mm. Water uptake from the soil in a given period equals ($V_{t-1} - V_t$).

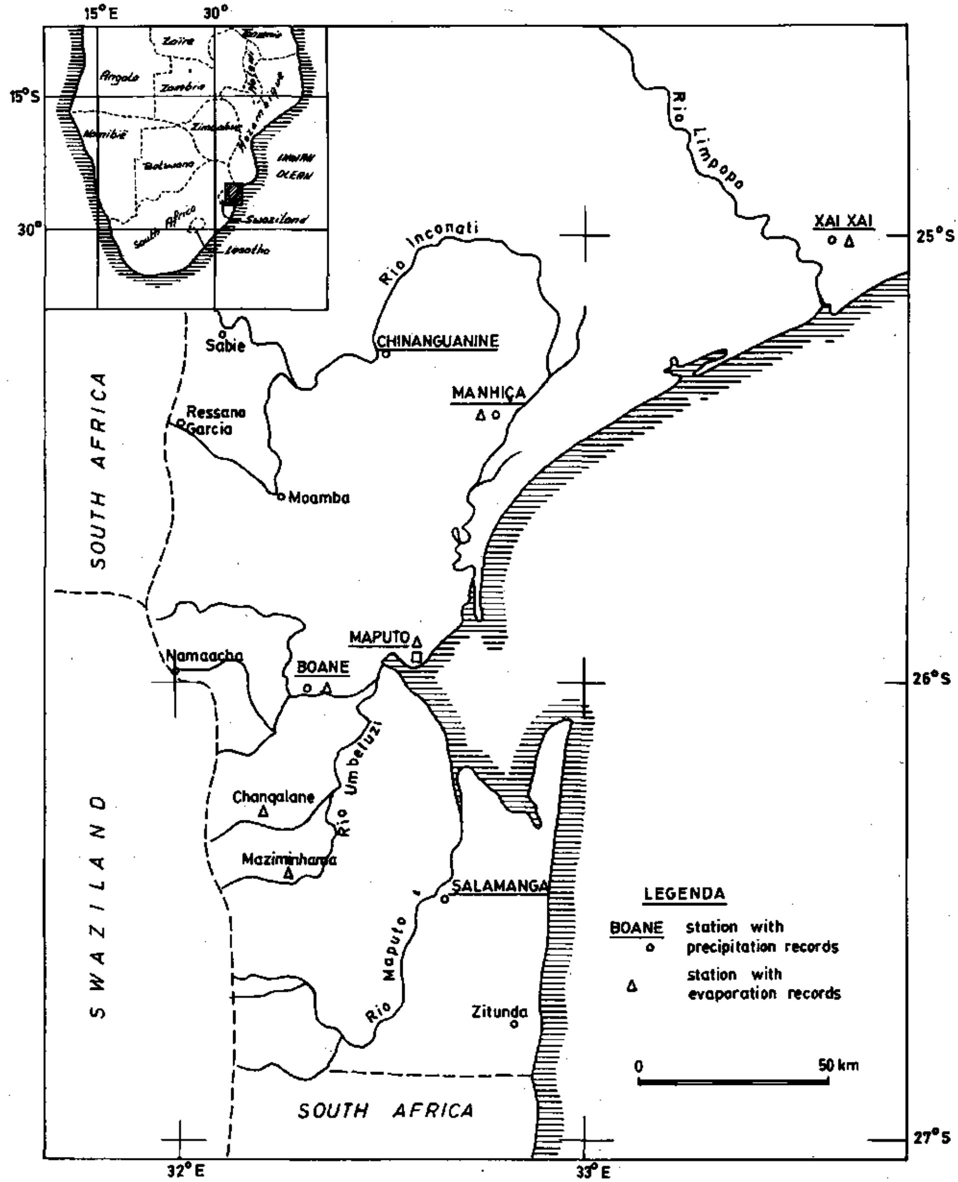

Fig. 1. Location of selected stations in Southern Mozambique.

The following notation is known as the Thornthwaite–Mather formula:

$$V_t = V_{max} \exp\,(-A/V_{max})$$

where

$$A = \sum_{i=o}^{i=n} T_{pot}\, dt_i \qquad (\text{at field capacity; } i=0)$$

This approach must be considered as a global model because water flow within the soil profile is disregarded and a uniform soil water distribution within the rootzone is supposed.

Many objections can be made to the approach of Thornthwaite and Mather. Nevertheless it may be 'the best practicable one' when detailed information, such as hydraulic conductivity in unsaturated conditions, is missing and if the relation between soil-water content and water-uptake by roots is unknown. Its application requires that the soil profile in the rootzone is uniform and capillary fluxes from the groundwater-table are negligible.

In this study the model SWETAM (Soil Water Extraction Thornthwaite And Mather) was developed. It simulates variations in soil water content within the root zone based upon simple concepts of water losses by evaporation from bare soil and through the crop canopy. A global scheme is given in Fig. 2.

Total precipitation (mm) and total (Penman) evaporation (mm) (for a short grass vegetation) per 5-day period are used as input. Total potential water losses (mm) from bare soil and through the crop are determined by using 'crop-factors', relating potential evaporation (E_{pot}) and Penman-evaporation (E_0):

$$E_{pot} = K_c\, E_0$$

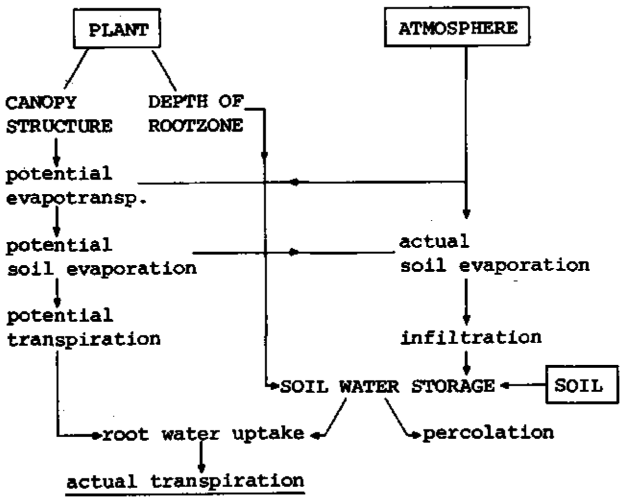

Fig. 2. Global scheme of the model SWETAM.

Values for K_c are given by many authors. Doorenbos and Pruitt (1977) summarize much of the work done on this subject.

The relationship between potential soil evaporation (S_{pot}) and potential transpiration (T_{pot}) is governed by the ratio between the amount of solar energy reaching the soil surface and the solar energy intercepted by the plant canopy. The ratio between S_{pot} and E_{pot} is a function of leaf-area index (L). Belmans et al. (1983) describe this function as:

$$(S_{pot}/E_{pot}) = 0.9 \exp(-0.6L)$$

Van Keulen (1975) gives:

$$(S_{pot}/E_{pot}) = 1.0 \exp(-0.5L)$$

Furthermore:

$$E_{pot} = S_{pot} + T_{pot}$$

In the study presented here it was supposed that a similar relationship can be used for maize and sorghum.

Belmans et al. (1983) give L as a function of soil cover fraction (C):

$$L = aC + bC^2 + dC^3 \tag{1}$$

where a, b and d are crop-specific parameters.

Soil cover (fraction) develops with time. For two different descriptions of soil cover as a function of time, an illustration of the estimation of ratio S_{pot}/E_{pot} is given in Fig. 3.

In this study values for a, b and d (in equation 1) are estimated at 2.6, 1.5 and 0.9, respectively.

In the model SWETAM a simplified approach was followed. From Fig. 3 it was concluded that, for the given soil cover development, the ratio S_{pot}/E_{pot} could be replaced by a linear function of time.

Other characteristics used as input are maximum extractable water content (%) and depth of root zone (mm).

Actual soil evaporation (S_{act}) was determined using the following assumptions:

(1) in a pentad without precipitation:

$$S_{act} = 0.1\, S_{pot}$$

(2) in a pentad with precipitation:

$$S_{act} = 0.25\, S_{pot}$$

with $S_{act} \leqslant$ precipitation. The latter assumption was made because it was found that for pentads with precipitation the mean number of days with rainfall was 2. We assume that on such a day S_{act} nearly equals S_{pot}. However, cloudiness

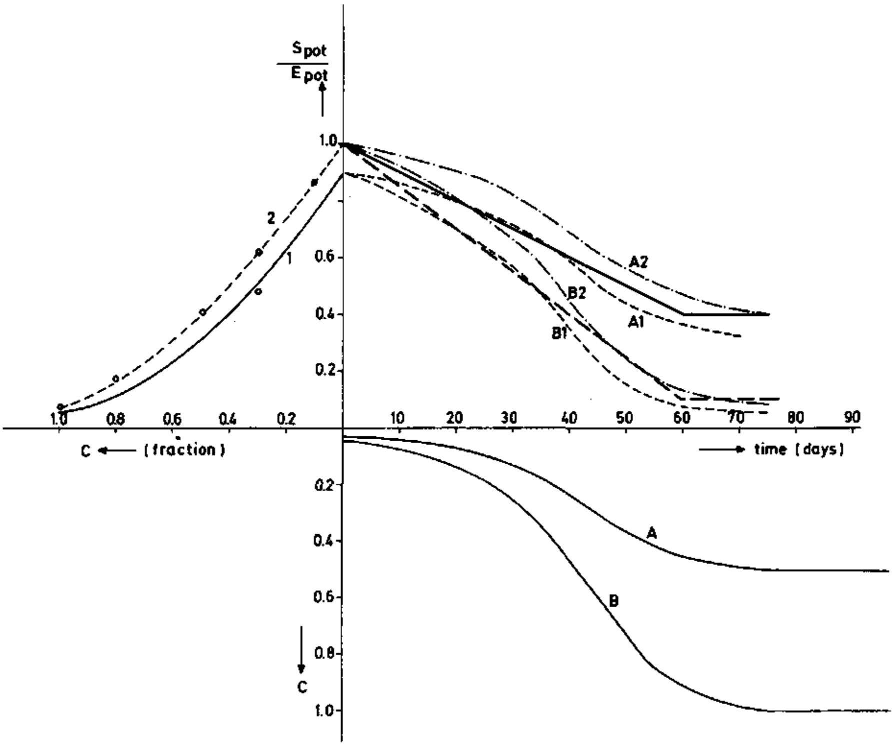

Fig. 3. Ratio S_{pot}/E_{pot} as a function of soil cover (C). A, maize, sorghum as estimated for low, and B, for high plant density. 1, according to Belmans et al. (1983), SWATRE model; and 2, to Van Keulen (1975).
———, relation assumed (SWETAM model) for low, and — — —, for high plant density.

on a rainy day makes S_{pot} for that day less than average, say 50% of the mean value for the pentad.

In the SWETAM model, interception of precipitation by crop and run-off are neglected. Infiltration equals precipitation minus water losses by soil evaporation.

Actual transpiration (T_{act}) is determined in the following way:

(1) When the amount of infiltrated rainwater in a given pentad exceeds T_{pot}, it is assumed that T_{act} equals T_{pot}. Extra water is stored in the root zone. When this storage exceeds maximum storage capacity, the surplus water infiltrates the soil layers below the actual root zone. In these layers, over a certain depth, soil water content will then equal maximum storage capacity. This storage is regarded as a 'buffer' which will be penetrated by roots later and used again. Water storage below the maximum rooting depth is regarded as percolation.

(2) When the amount of infiltrated rainwater is less than T_{pot}, the infiltrated quantity in a given pentad will be used for transpiration.

Transpiration demand that is not yet satisfied has to be taken up from the water stored in the root zone. Water extraction by the plant is calculated using the method of Thornthwaite and Mather. For a given pentad, the amount of available water in the root zone depends on rooting depth, soil characteristics and the prevailing meteorological conditions in earlier pentads.

For several growing periods of maize the results of the SWETAM model were compared with the results of the SWATRE model described by Feddes et al. (1978) and Belmans et al. (1983). Results from both models showed good agreement for the prevailing conditions in the high sandy soils near Maputo, especially for low plant densities. Plant density and depth of root zone seem to be important characteristics that influence water deficit under the prevailing meteorological conditions (see Schouwenaars, 1986).

Selected stations and crops

In this study, the stations Salamanga and Xai-Xai were selected because they represent respectively the most southern and the most northern part of the coastal zone in the study area. For these stations the SWETAM model was used to analyse yields of maize and sorghum as influenced by rainfall, soil physical characteristics, plant density and depth of root zone. Daily precipitation data were available. Penman evaporation per 5-day period was estimated, using (20-year) average values per decade.

Growing period — criteria

Field observations indicated that crops are sown when total precipitation within a 5-day period exceeds 20 mm. Each month in the subsequent years was analysed to find if conditions were suitable for sowing, and if so, the water balance terms were determined for the subsequent stages of crop development during the growing period. This is only done once a month. In reality there might be more periods within this month having favourable conditions for sowing.

Initial soil water storage was determined using precipitation data over the 30 days preceding the sowing date and taking into account the losses by evaporation during this period.

Soil and crop characteristics

In the sandy soils of the coastal zone, maximum available soil water content is about 5%. In this study only crops with a maximum soil cover of 50% are considered ($C_{max} = 0.5$). This value agrees well with the common agricultural practices in the study area.

Root penetration as a function of time is described as:

TABLE 3

Crop coefficients for maize and sorghum

Period (days)	K_c	
	Maize	Sorghum
0- 10	0.35	0.35
11- 20	0.50	0.45
21- 30	0.65	0.55
31- 40	0.75	0.70
41- 50	0.90	0.80
51- 60	1.00	0.90
61- 70	1.10	1.00
71- 80	1.00	1.10
81- 90	0.90	1.00
91-100	0.70	0.90
101-110	0.60	0.80
111-115	0.60	0.60

Length of growing period: 115 days. After Doorenbos and Pruitt, 1977.

$$D_t = D_{max}(t/G)^{0.5}$$

in which D_t rooting depth at time t (t in days), D_{max} maximum rooting depth (at the end of the growing period), and G length of growing period (days). Two alternatives were selected; $D_{max}=0.5$ m and $D_{max}=1.0$ m.

Crop coefficients used in this study are given in Table 3.

Water deficit and yield reduction

There has been little research on the impact of water deficit on yields in rainfed agriculture in Southern Mozambique. Traditional agriculture is based upon locally obtained knowledge and skills transferred from generation to generation. Local varieties of crops are grown, some of them highly adapted to water-stress conditions. Almost no research has been carried out on the different aspects of these farming systems.

Research on yield reduction by water deficit mostly concentrates on the effect of water stress under sub-optimal conditions and mainly focusses on the benefits of suplemental irrigation. Much of this work is summarized by Doorenbos and Kassam (1979). They proposed the following relation for various crops:

$$(1 - Y_{actual}/Y_{potential}) = f\ (1 - T_{actual}/T_{potential}) \quad (1)$$

in which Y is yield (kg/ha), and T transpiration (mm). The ratio Y_{act}/Y_{pot} is known as relative yield. The ratio T_{act}/T_{pot} is known as relative transpiration.

TABLE 4

Yield-reduction factors for water deficit for maize and sorghum

Growing stage	Period (days)	Maize	Period (days)	Sorghum
Vegetative	0- 50	0.4	0- 45	0.2
Flowering	51- 65	1.5	46- 60	0.55
Seed formation	66-105	0.5	61-100	0.45
Ripening	106-115	0.2	101-115	0.20

After Doorenbos and Kassam, 1979.

TABLE 5

Classification of relative yields

Class	Percent of maximum yield
1	0- 25
2	25- 37
3	38- 50
4	50- 62
5	63- 75
6	75-100

Equation (1) was applied. Values for the reduction factor f are given by Doorenbos and Kassam (1979) (see Table 4).

Another approach followed by many authors is to relate yield-reduction directly with the relative transpiration. This means that the reduction factor f is equal to 1.

It was decided to determine relative yield as the mean value of the relative yields calculated from the two approaches given above. The main objective of this study was to analyse the differences in yields that may be expected for the different stations and for the different periods. Therefore the assumptions made above are reasonable.

Finally the values for relative yields were grouped into six classes (see Table 5).

RESULTS

Probability distribution of yields for maize and sorghum

Results for Salamanga and Xai-Xai are given in Tables 6, 7, 8 and 9. The month refers to that of sowing.

TABLE 6

Frequency distribution (%) for relative yields of maize in Salamanga

Sowing in:	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	Max. root depth: 0.5 m											
No sowing	78.1	81.2	67.7	64.5	29.0	43.3	25.8	12.9	6.5	32.3	43.7	75.0
0.00-0.25	15.6	12.5	6.5	16.1	32.3	16.7	16.1	19.4	19.4	29.0	31.2	21.9
0.25-0.37	3.1	0.0	9.7	3.2	19.4	6.7	6.5	9.7	29.0	12.9	18.7	3.1
0.38-0.50	0.0	3.1	9.7	6.5	6.5	13.3	6.5	19.4	19.4	12.9	6.2	0.0
0.50-0.62	0.0	0.0	3.2	6.5	9.7	6.7	16.1	19.4	16.1	9.7	0.0	0.0
0.63-0.75	3.1	3.1	3.2	0.0	0.0	10.0	19.4	12.9	3.2	3.2	0.0	0.0
0.75-1.00	0.0	0.0	0.0	3.2	3.2	3.3	9.7	6.5	6.5	0.0	0.0	0.0
	Max. root depth: 1.0 m											
No sowing	78.1	81.2	67.7	64.5	29.0	43.3	25.8	12.9	6.5	32.3	43.7	75.0
0.00-0.25	12.5	6.2	3.2	6.5	9.7	6.7	6.5	3.2	12.9	6.5	6.2	6.2
0.25-0.37	0.0	6.2	3.2	6.5	29.0	10.0	6.5	12.9	6.5	16.1	21.9	12.5
0.38-0.50	6.2	0.0	6.5	3.2	12.9	6.7	9.7	12.9	22.6	12.9	18.7	6.2
0.50-0.62	0.0	3.1	12.9	9.7	3.2	13.3	9.7	22.6	22.6	16.1	9.4	0.0
0.63-0.75	0.0	0.0	3.2	6.5	12.9	6.7	12.9	16.1	19.4	12.9	0.0	0.0
0.75-1.00	3.1	3.1	3.2	3.2	3.2	13.3	29.0	19.4	9.7	3.2	0.0	0.0

33 years analysed, period: 1952–1984.

TABLE 7

Frequency distribution (%) for relative yields of sorghum in Salamanga

Sowing in:	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	Max. root depth: 0.5 m											
No sowing	78.1	81.2	67.7	64.5	29.0	43.3	25.8	12.9	6.5	32.3	43.7	75.0
0.00-0.25	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5	0.0	0.0	0.0
0.25-0.37	6.2	9.4	3.2	0.0	12.9	6.7	6.5	6.5	3.2	16.1	25.0	12.5
0.38-0.50	6.2	3.1	3.2	12.9	32.3	13.3	6.5	6.5	32.3	25.8	21.9	12.5
0.50-0.62	0.0	3.1	12.9	12.9	12.9	13.3	19.4	32.3	29.0	16.1	6.2	0.0
0.63-0.75	0.0	0.0	12.9	6.5	9.7	10.0	19.4	25.8	12.9	9.7	3.1	0.0
0.75-1.00	3.1	3.1	0.0	3.2	3.2	13.3	22.6	16.1	9.7	0.0	0.0	0.0
	Max. root depth: 1.0 m											
No sowing	78.1	81.2	67.7	64.5	29.0	43.3	25.8	12.9	6.5	32.3	43.7	75.0
0.00-0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.25-0.37	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	0.0	3.1	6.2
0.38-0.50	6.2	9.4	3.2	9.7	22.6	10.0	9.7	9.7	6.5	19.4	15.6	6.2
0.50-0.62	6.2	3.1	6.5	3.2	22.6	16.7	6.5	12.9	22.6	22.6	28.1	12.5
0.63-0.75	0.0	3.1	16.1	16.1	12.9	6.7	19.4	32.3	32.3	16.1	6.2	0.0
0.75-1.00	3.1	3.1	6.5	6.5	12.9	23.3	38.7	32.3	22.6	9.7	3.1	0.0

33 years analysed, period: 1952–1984.

TABLE 8

Frequency distribution (%) of relative yields for maize in Xai-Xai

Sowing in:	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	Max. root depth: 0.5 m											
No sowing	50.0	57.7	60.0	52.0	32.0	30.8	7.7	14.8	3.7	22.2	30.8	23.1
0.00-0.25	23.1	23.1	20.0	12.0	16.0	7.7	15.4	3.7	3.7	3.7	0.0	0.0
0.25-0.37	7.7	11.5	12.0	16.0	24.0	19.2	15.4	11.1	18.5	14.8	3.8	7.7
0.38-0.50	7.7	3.8	4.0	0.0	8.0	7.7	7.7	14.8	11.1	3.7	11.5	11.5
0.50-0.62	11.5	3.8	4.0	8.0	16.0	23.1	15.4	18.5	11.1	29.6	7.7	19.2
0.63-0.75	0.0	0.0	0.0	12.0	4.0	7.7	15.4	11.1	44.4	7.4	23.1	30.8
0.75-1.00	0.0	0.0	0.0	0.0	0.0	3.8	23.1	25.9	7.4	18.5	23.1	7.7
	Max. root depth: 1.0 m											
No sowing	50.0	57.7	60.0	52.0	32.0	30.8	7.7	14.8	3.7	22.2	30.8	23.1
0.00-0.25	3.8	11.5	12.0	8.0	8.0	0.0	11.5	0.0	0.0	0.0	0.0	0.0
0.25-0.37	11.5	11.5	4.0	8.0	8.0	7.7	3.8	3.7	0.0	3.7	0.0	0.0
0.38-0.50	15.4	7.7	16.0	12.0	24.0	19.2	15.4	11.1	18.5	11.1	0.0	7.7
0.50-0.62	7.7	11.5	4.0	0.0	12.0	7.7	7.7	14.8	11.1	7.4	11.5	3.8
0.63-0.75	11.5	0.0	4.0	12.0	12.0	26.9	15.4	18.5	22.2	29.6	7.7	26.9
0.75-1.00	0.0	0.0	0.0	8.0	4.0	7.7	38.5	37.0	44.4	25.9	50.0	38.5

28 years analysed, period: 1958–1985.

TABLE 9

Frequency distribution (%) of relative yields for sorghum in Xai-Xai

Sowing in:	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
	Max. root depth: 0.5 m											
No sowing	50.0	57.7	60.0	52.0	32.0	30.8	7.7	14.8	3.7	22.2	30.8	23.1
0.00-0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.25-0.37	15.4	19.2	4.0	8.0	12.0	3.8	7.7	0.0	0.0	0.0	0.0	0.0
0.38-0.50	15.4	15.4	28.0	4.0	16.0	0.0	11.5	3.7	7.4	3.7	0.0	7.7
0.50-0.62	15.4	3.8	4.0	16.0	20.0	26.9	15.4	29.6	18.5	14.8	0.0	15.4
0.63-0.75	3.8	3.8	4.0	16.0	16.0	26.9	19.2	14.8	37.0	22.2	30.8	42.3
0.75-1.00	0.0	0.0	0.0	4.0	4.0	11.5	38.5	37.0	33.3	37.0	38.5	11.5
	Max. root depth: 1.0 m											
No sowing	50.0	57.7	60.0	52.0	32.0	30.8	7.7	14.8	3.7	22.2	30.8	23.1
0.00-0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.25-0.37	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.38-0.50	11.5	19.2	8.0	12.0	12.0	3.8	7.7	0.0	0.0	0.0	0.0	0.0
0.50-0.62	15.4	15.4	24.0	4.0	16.0	7.7	11.5	7.4	11.1	3.7	0.0	7.7
0.63-0.75	15.4	7.7	4.0	16.0	24.0	26.9	23.1	29.6	14.8	14.8	3.8	15.4
0.75-1.00	3.8	0.0	4.0	16.0	16.0	30.8	50.0	48.1	70.4	59.3	65.4	53.8

28 years analysed, period: 1958–1985.

TABLE 10

Simulated yields for maize and sorghum at Salamanga

Sowing:	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S
52–53	- -	- -	- -	- -	5 6	5 5	4 5	2 3				
53–54		5 5	2 4	2 3			3 5		3 4	2 4		
54–55		3 5	5 6	6 6	6 6	6 6	4 5	4 5			1 2	
55–56			5 6	6 6	6 6	5 6	4 4	1 3				
56–57		1 4			5 6	6 6	6 6	5 5	4 5		6 6	6 6
57–58	6 6	2 3	2 3		6 6	5 6	4 5	3 4	1 2			
58–59		1 3			1 3	1 3	1 2			1 2		
59–60		2 3	2 3		3 4	4 5	5 5	4 4	2 3			
60–61	3 5	4 6		5 6	4 5	3 5	5 5	2 3	2 4			
61–62	4 4		1 3			2 5	3 5	2 4	4 4		1 3	
62–63	3 5		5 5	3 4	3 5		4 6		3 6		1 2	1 3
63–64			2 5		2 4	4 5	4 4		1 3			
64–65			2 3	2 4			4 5	3 4	3 4			
65–66	4 5		2 4			3 4	1 3		3 4			
66–67					6 6	6 6	5 6	5 5	2 3	2 3	1 3	
67–68			2 4	4 5	5 5	4 5	3 4	3 4				1 3
68–69				4 4		2 4	5 6	4 5		3 4		
69–70			3 4	1 3	1 3		1 2					
70–71			1 3			4 5			2 4			
71–72			3 5		6 6	6 6	6 6	6 6	3 4	2 3		
72–73			2 3	2 4	2 3	3 4		2 3				
73–74		6 6	6 6	6 6	5 5	2 3	2 3					
74–75				4 6	6 6	5 6	3 5		3 4	3 4		
75–76					6 6	6 6	6 6	5 6	4 5			
76–77			3 4		6 6	3 5	2 4	4 4	2 3			
77–78	4 5	5 5	1 4	3 4		5 6	3 4	2 3	2 4			2 4
78–79			3 4	1 3	3 5	4 5	3 4	3 4				
79–80	1 3		2 3			4 4	3 4			1 2		
80–81	- -	- -	- -	- -	- -	- -	5 6	5 6		2 4	3 4	
81–82	5 6	4 5	4 5	- -	- -	- -	- -	- -	2 3		3 4	
82–83				4 5	4 5	2 3	1 2	1 3			- -	2 3
83–84	2 4			6 6	6 6	6 6	5 5	4 5				4 5
84–85	4 5	4 5	5 6	5 6	4 6	4 5	- -	- -	- -	- -		- -

33 years analysed, period: 1952–1984. Explanation: M, Maize; S, Sorghum. **Classification:** blank, No sowing; -, No data; 1, 0.00-0.25, 2, 0.25-0.37, 3, 0.38-0.50, 4, 0.50-0.62, 5, 0.63-0.75, 6, 0.75-1.00 of maximum production.

Irregularity in production

Probability distributions do not give sufficient information for analysing the risks of failure. Therefore the regularity/irregularity of yields in subsequent

Simulated yields for maize and sorghum at Xai-Xai

Sowing:	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S	M/S
58–59	- -	- -	- -	5 6	4 6	6 6	6 6	5 6		6 6		
59–60	3 4	1 3	1 3		5 6	6 6	6 6	5 6	4 6			4 5
60–61		2 5	5 5	3 5	5 5	4 5	3 4	2 4			5 5	3 4
61–62	- -	- -	- -	- -	- -	5 6	6 6	6 6	6 6	3 4		
62–63	3 4		3 5	4 5	3 5		5 6	6 6	6 6	5 5	2 3	
63–64					3 4	3 5	3 5	5 5		5 6		2 3
64–65	1 3		3 4	3 4	1 4	4 5	5 6	4 6	6 6	3 4		
65–66	5 6	5 6	3 5	6 6	5 5	4 5	3 4			6 6	5 6	
66–67	2 4			5 6	6 6	6 6	5 6	6 6	6 6	6 6		1 3
67–68			1 3	2 4		3 4	3 6			5 5	3 3	
68–69		3 4		2 3	1 3			6 6	6 6	5 6		
69–70			2 3		1 3		4 5		5 5			
70–71					6 6	5 6	6 6	5 6	6 6	6 6	2 3	1 3
71–72			5 6	5 6	6 6	6 6	6 6	5 6		6 6	3 4	
72–73				3 5	4 6	5 6	5 6		4 6		3 4	2 5
73–74		5 5	4 5	3 5	6 6	6 6	6 6	6 6	6 6	5 5		2 3
74–75				5 6	6 6	6 6	6 6	3 5	5 6	4 5	1 2	
75–76				5 6	6 6	6 6	6 6	5 6	6 6	6 6	5 5	
76–77	1 3	1 3	3 4		6 6	4 5	3 4	3 5		5 6	4 5	
77–78	3 4	3 5	5 6		6 6	6 6	6 6	6 6	6 6		2 4	1 3
78–79		6 6	6 6	5 5	3 5	5 5	6 6	5 6	6 6	6 6	3 4	4 4
79–80	3 4		2 4		2 5		6 6	3 5	4 6			
80–81		6 6	3 5	3 5		5 5	4 5	6 6	6 6	6 6		
81–82	4 5	3 5	4 5	4 5	5 5	2 5	5 6		6 6	5 6		3 4
82–83		2 3	3 4		3 4	3 4	4 5			6 6		
83–84	1 4			5 6	6 6	6 6	5 6	5 6	6 6	6 6	4 5	4 4
84–85		5 6	4 6	6 6	6 6	6 6	6 6	4 6	- -	- -	- -	- -

28 years analysed, period: 1958–1985. Explanation: M, Maize; S, Sorghum. Classification: blank, No sowing; -, No data; 1, 0.00-0.25, 2, 0.25-0.37, 3, 0.38-0.50, 4, 0.50-0.62, 5, 0.63-0.75, 6, 0.75-1.00 of maximum production.

periods must be examined. Tables 10 and 11 contain the results for maize and sorghum when maximum rooting depth is 1.0 m.

DISCUSSION

Table 12 was derived from the probability distributions of yields. The term 'favourable sowing conditions' only refers to agro-hydrological conditions. No consideration was given to the reduction of yields by pests and diseases. In Southern Mozambique, crops growing in the months with the highest temperatures (November–February), which coincide with the rainy period, are the

TABLE 12

Summary of most favourable sowing periods

	Maximum root depth											
	0.5 m											
Month:	J	A	S	O	N	D	J	F	M	A	M	J
Salamanga	–	–	–	–	–	m	–	–	–	–	–	–
	–	s	s	–	s	s	s	s	–	–	–	–
Boane	–	–	–	–	–	m	–	–	–	–	–	–
	–	s	–	s	s	s	s	–	–	–	–	–
Chinanguanine	–	–	–	–	–	–	–	–	–	–	–	–
	–	–	–	–	–	s	s	s	–	–	–	–
Manhica	–	–	–	–	–	m	–	m	–	–	–	–
	–	–	s	s	s	s	s	s	s	–	–	–
Xai-Xai	–	–	–	–	m	m	m	m	m	m	m	–
	–	–	s	s	s	s	s	s	s	S	s	–
	Maximum root depth											
	1.0 m											
Month:	J	A	S	O	N	D	J	F	M	A	M	J
Salamanga	–	m	m	–	m	m	m	m	–	–	–	–
	s	s	s	s	s	S	s	s	s	s	s	–
Boane	–	m	–	–	m	m	m	–	–	–	–	–
	–	s	s	s	s	S	s	s	s	s	–	–
Chinanguanine	–	–	–	–	–	–	–	–	–	–	–	–
	–	–	s	s	s	s	s	s	s	–	s	–
Manhica	–	–	m	m	m	m	m	m	m	–	–	–
	s	s	s	s	s	S	S	S	s	s	s	–
Xai-Xai	–	–	–	–	m	m	m	m	m	M	M	–
	s	s	s	s	s	S	S	S	S	S	S	s

m, maize, s, sorghum. If sown, more than 50% probability of a relative yield that exceeds 50% of potential yield.
M, maize, S, Sorghum. If sown, more than 50% probability of a relative yield that exceeds 75% of potential yield.

most vulnerable to diseases (see Nunes et al., 1986). Vulnerability of maize to some pests is also higher after October. Some pests are favoured when, in a limited area, maize crops are grown the whole year round, thus always providing host plants. This is a negative consequence of a sowing strategy that might be correct from an agro-hydrological viewpoint.

Neither has consideration been given to the obvious fact that potential yields vary with monthly incoming net radiation and temperature. Potential yields are higher during the warm period (October–March) and lower during the colder period (April–September).

Tables 10 and 11 suggest that there are many years in which better yields are obtained by sowing either sooner or later than the 'most favourable periods' as indicated in Table 12. Moreover, in some years the consequence of delaying sowing for the favourable periods is catastrophic because rainfall in that period remains too low. Therefore, when stock-building capacity for food is negligible (as for most small family-holdings) the common practice in Southern Mozambique is to sow whenever enough rain has fallen. From a risk-spreading point of view this might be logical; on the other hand, a consequence is that seeds are often completely lost. This strategy requires disposability of seeds.

Although there are many shortcomings in the method presented above, and in the assumptions made in the model SWETAM, this study results in a better understanding of the phenomena of rainfall irregularity in Southern Mozambique and its consequences for cereal crops in rainfed agriculture. Furthermore, the study clarifies the importance of several characteristics of both crop (root penetration, canopy development, plant density) and soil (texture, organic matter content) for the efficiency of water use.

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REFERENCES

Belmans, C., Wesseling, J.G. and Feddes, R.A., 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrol., 63: 271–286.

Doorenbos, J. and Kassam, A.H., 1979. Yield response to water. Irrig. Drain. Pap. 33, Food and Agricultural Organization, Rome, 193 pp.

Doorenbos, J. and Pruitt, W.O., 1977. Crop water requirements. Irrig. Drain. Pap. 24, Food and Agricultural Organization, Rome, 144 pp.

Feddes, R.A., Kowalik, P.J. and Zaradny, H., 1978. Simulation of field water use and crop yield. Simulation Monographs, Pudoc, Wageningen, 189 pp.

Nunes, E., Sousa, D. and Sataric, I., 1986. Research on the constraints to maize production in Mozambique. In: Proc. 1st Eastern, Central and Southern Africa Regional Maize Workshop, 10–17 March 1985, Lusaka, Zambia. CIMMYT, Mexico, pp. 67–79.

Schouwenaars, J.M., 1986. An agro-hydrological study on sowing-strategies for rainfed-production in Southern Mozambique. UEM/LUW/PSW-Project Research Report, 1. Meded. Vakgroep Cultuurtech. 91, Agricultural University, Wageningen, 63 pp.

Thornthwaite, C.W. and Mather, J.R., 1954. The computation of soil moisture. In: Estimating soil tractionability from climatic data. New Jersey, Publications in Climatology, 7. Centerton, NJ, pp. 397–402.

Van Keulen, H., 1975. Simulation of water use and herbatic growth in arid regions. Simulation Monograph, Pudoc, Wageningen, 176 pp.

Research on Plant-Soil-Water Relations and its Role in Understanding Sowing Strategies

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Abstract. Rainfed agriculture in southern Mozambique is very risky. In this study, different simulation models are used to analyse sowing strategies for maize. Water balance and crop growth are described by using both simple and more detailed approaches. Differences in results are discussed. Besides water-yield relations, many other aspects are important for understanding sowing strategies. In this study, attention is given to the problems related to the impact of pests and diseases, the quality of storage facilities and the availability of alternative food crops. It is concluded that for the analysis of sowing strategies, detailed descriptions of the plant-soil-water relations are only useful when other production aspects are well understood in quantitative terms. Otherwise, preference should be given to simple water-balance and crop-growth models.

Key words. Water balance models, crop yield models, sowing strategies, Mozambique.

1. Introduction

Rainfed crop production in the sandy coastal zone of southern Mozambique is mainly practised by small family farming units. Cropping centers on the (marginal) production of foodcrops like cassava (*Manihot sp.*)), maize (*Zea mais*)), groundnut (*Arachis hypogea*), sweet potato (*Ipomea batatus*), cowpea (*Vigna sp.*), pigeonpea (*Cajanus cajan*) and vegetable crops like squashes, pumpkins (both *Cucurbita sp.*)) and okra (*Hibiscus esculentus*).

Commonly mixed cropping is practised with low plant densities for maize. Average production is very low (for cereals, less than 1000 kg ha^{-1}) and yields vary considerably. In the sandy soils, capacity for water retention is very low.

Available water for crops depends on the amount and distribution of rainfall, water retention characteristics of the soil, and on crop characteristics such as rooting depth and plant-density. Water demand by the crops depends on climatic conditions and crop characteristics such as the length of the growing period, leaf-area, etc.

Yields vary considerably with the amount and distribution of rainfall during the growing period. For cereals, critical periods for water deficit are the stages of flowering and tasseling. As a consequence, yields have a stochastic nature that is strongly determined by rainfall characteristics. Under these conditions, farmers in many regions have developed strategies of minimizing risks rather than of maximizing production. To understand these strategies, quantitative information on the probability distribution of yields over a long period should be available. Often, yield data are scarce and then deterministic models must be applied to simulate yields over a long period. For the development of adequate simulation models for crop growth, detailed knowledge of both biological (e.g. pests, diseases) and environmental processes (e.g. climate, soil) is required. Many processes can only be described globally. Due to the absence of site-specific information, many of the parameters and variables in the models must be estimated. Different approaches can be followed, varying from simple to very detailed ones.

If we want to apply these models to evaluate sowing strategies in a semi-arid region, the question arises over which models should be used. The applicability of a certain model depends on the availability and accuracy of the required input data. The necessity for using accurate knowledge and detailed models depends on the objectives of the study.

When models, like a water-balance or crop-yield model, are instruments to study only some aspects of a complex problem, an additional criterion for their selection should be used. When only little knowledge and/or information is available about other production aspects or when these aspects play a dominant role over those described by the models, it is questionable whether detailed models should be used. Detailed water balance models are available and it is possible to determine yield reduction as a consequence of water deficit by combining these models with a crop-growth model. However, production levels under optimal water supply depend on the impact of pests, diseases, and soil fertility.

Yield reduction by water deficit has to be superposed upon other biological, environmental, managerial, and socio-economic factors (see Figure 1).

The considerations mentioned above have led to this study in which a comparison between simple and detailed models for water use and crop growth has been made.

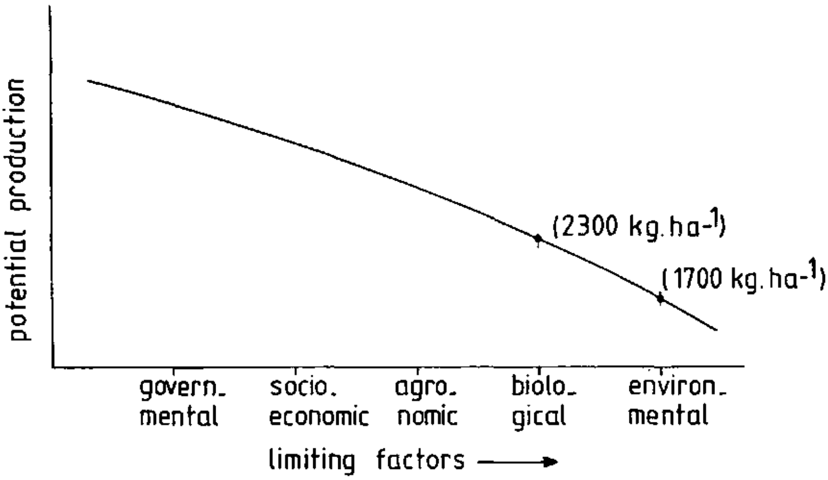

Fig. 1. Limiting factors for potential production.

Due to the absence of accurate field observations, calibration of the models with yield data was not possible. The models have been applied to evaluate sowing strategies for maize in the sandy coastal zone of southern Mozambique.

2. A Comparison of Water Balance Models

2.1. A SIMPLE APPROACH: THE SWETAM MODEL

The model SWETAM simulates variations in soil-water content within the root zone based upon simple concepts of water losses by evaporation from bare soil and through crop canopy (Schouwenaars, 1986, 1988). Water uptake from the soil is determined according to the approach of Thornthwaite and Mather (1954) who suggested that plant-water use decreases linearly from the upper to the lower limits of available soil water. Water flow within the soil profile is disregarded and a uniform soil-water distribution within the root zone is assumed.

Its application requires that the soil profile in the root zone is rather uniform and capillary fluxes from the groundwater are negligible. In the SWETAM model, run-off and the interception of precipitation by the crop are neglected. Water-balance terms are calculated for 5 day periods (pentads). For a given pentad, the amount of available water in the root zone depends on rooting depth, soil-water retention characteristics, and the prevailing meteorological conditions in the preceding pentads.

2.2. A DETAILED APPROACH: THE SWATRE MODEL

In the model SWATRE, the soil profile is divided into layers with different hydraulic conductivity and water-retention characteristics. Water uptake by roots is considered to be a function of the pressure head. At the end of each time step, soil-water distribution within the profile is determined, using numerical solutions for the non-steady equations of water flow. A description of the model is given by Belmans *et al.* (1983) and Feddes *et al.* (1978). Run-off is determined as a function of precipitation and soil permeability. Interception is determined as a function of precipitation. A distinction is made between soil-evaporation and transpiration using information about the development of the leaf-area index. Capillary fluxes from the soil layers below the root zone are calculated. The model SWATRE requires daily input data.

In contrast to the SWETAM model, the application of the SWATRE model requires information about hydraulic conductivity for a wide range of soil-water conditions and the relation between pressure head and water uptake by roots must be known.

2.3. RESULTS AND CONCLUSIONS

Using daily meteorological data of the agro-meteorological station in Maputo ($25^0 53^1$ S, $32^0 36^1$ E), four periods were selected to analyse the water-budget terms of

Table I. Selected periods to analyse the water balance for a maize crop in Maputo with the models SWETAM and SWATRE

Period	Precipitation (mm)	Rainfall characteristics
1. Dec. 77–Apr. 78	584	high, in peaks
2. Feb. 78–May 78	321	irregular, high at the beginning, very low at the end
3. Oct. 83–Jan. 84	377	high during period of flowering and tasseling
4. Sep. 84–Dec. 84	158	very low

a maize crop (*Zea mays*) with two different plant densities. One with a maximum soil-cover fraction of 1.0 and another with a maximum of 0.5. The main criterion for the selection of these periods was a large difference in precipitation. (Table I).

Then both SWETAM and SWATRE were applied for the same set of data of precipitation, potential evapotranspiration, rooting depth, and soil characteristics. Schouwenaars (1986) presented results for the cumulative values of the water-balance terms (precipitation, interception, soil evaporation, transpiration, and percolation) at the end of the growing period. Run off can be neglected on these sandy soils. It was concluded that for periods with high rainfall, the neglection of interception in the SWETAM model leads to an overestimation of available soil water and transpiration for a crop with high plant density. For low plant densities, as is common in southern Mozambique, differences caused by interception were very small. When compared to the SWATRE model, soil-evaporation in the SWETAM model was estimated to be too high for dry conditions and too low for high rainfall. The differences between the results of both models, which were caused by interception and soil evaporation, vary with plant density. Mostly, they lead to an overestimation of transpiration in the SWETAM model, except in the case of extreme low rainfall when transpiration was underestimated as a consequence of neglecting capillary rise.

Swennenhuis (1987) presented results of the comparison for high plant densities, using cumulative values for the water balance terms in the subsequent phases of crop-growth. These results are presented in Table III. It was concluded that differences in the estimation of transpiration between both models strongly depend on the prevailing rainfall characteristics. In periods of average rainfall, no systematic differences between the results could be found.

Under extreme wet and dry conditions, differences can be significant, as a consequence of the factors discussed above. When this occurs in periods during which the crop is vulnerable for drought (e.g. flowering stage), this may lead to serious errors in the estimation of relative yields, as well be discussed in the next section.

3. A Comparison of Crop-Growth Models

3.1. A SIMPLE APPROACH: THE DOORENBOS FORMULA

Research on yield reduction by water deficit mostly concentrates on the effect of water stress under sub-optimal conditions and mainly focuses on the benefits of supplemental irrigation. Much of this work is summarized by Doorenbos and Kassam (1979). They proposed the following relation for various crops

$$(1 - Y_{act}/Y_{pot}) = f \cdot (1 - ET_{act}/ET_{pot}) \quad (1)$$

in which Y = yield (kg/ha) and ET = evapotranspiration (mm). The ratio Y_{act}/Y_{pot} is known as relative yield and the ratio ET_{act}/ET_{pot} as relative evapotranspiration.

Within each growth stage, the sensitivity for water deficit is expressed by the yield reduction factor f. For the respective growth stages of maize (vegetative, flowering, seed formation and ripening) Doorenbos and Kassam give f-values of 0.4, 1.5, 0.5 and 0.2.

Final relative yield can be calculated by introducing the relative yield of a certain growth stage as the potential yield for the following stage.

3.2. A COMPLEX APPROACH: THE WOFOST-MODEL

The crop-growth model WOFOST (World Food Simulation) was developed at the Centre for World Food Studies in Wageningen. This model simulates both potential and water-limited production using the following approach (see Van Keulen and Wolf, 1986): Part of the gross assimilation of a crop is needed for respiration, the remaining energy is used for dry-matter production (net assimilation). During plant development, the distribution of produced matter over the different parts of the plant changes. During the vegetative phase, it is distributed over the roots, leaves, and stem. After flowering, all dry-matter increase benefits the storage organs. The model WOFOST calculates daily dry-matter production as the difference between gross assimilation and respiration. Its distribution over the different plant organs is determined by using crop-specific partitioning factors which vary during the growing period. Yield consists of the economically useful plant parts (for maize: storage organs). Dry matter production under water stress is determined by multiplying gross assimilation by relative transpiration.

The WOFOST model needs daily input data of actual and potential transpiration. When both the water-limited and potential yield have been calculated, the relative yield can be determined.

3.3. RESULTS AND CONCLUSIONS

For the four periods presented in Table I, Swennenhuis combined the results of the water-balance models SWETAM and SWATRE with both the WOFOST model and the Doorenbos formula. For the SWATRE model, which may be regarded as the

Table II. Relative yields of maize in Maputo for four periods as determined with the SWATRE model in combination with the crop-growth model WOFOST and the Doorenbos formula

	Period 1[a]	Period 2	Period 3	Period 4
WOFOST	0.36	0.08	0.28	0.08
DOORENBOS	0.34	0.05	0.25	0.06

[a]For explanation of periods, see Table I.

most accurate water-balance model, results are presented in Table II. It can be concluded that for the selected periods, relative yields for maize calculated with the SWATRE–Doorenbos combination are very similar to those obtained with the SWATRE–WOFOST combination. Swennenhuis concluded that the Doorenbos approach is sufficiently accurate for the analysis of sowing strategies.

Using the Doorenbos formula, an additional analysis was made of the impact of differences between (evapo-)transpiration obtained with the SWETAM and SWATRE models on relative yields. Results are presented in Table III. As mentioned before, when dry periods coincide with drought-sensitive growth stages, these differences may lead to substantial errors in yield estimation. This means that, under these conditions, emphasis should be laid on the improvement of the water balance.

4. A Simple Method to Analyse Sowing Strategies

4.1. A MODEL TO SIMULATE YIELDS UNDER ALTERNATIVE SOWING STRATEGIES

The model SWETAM was applied to simulate yields of maize for five stations over a period of *ca.* 30 years (Schouwenaars, 1986, 1988). Field observations indicated that crops are sown when total precipitation within a 5 day period exceeds 20 mm. Each month in the subsequent years was analysed to find whether conditions were suitable for sowing and, if so, the water-balance terms during the growing period were determined. This is only done once a month. In reality, there might be more periods within this month with favourable conditions for sowing.

Values for the reduction factor f in Equation (1) are given by Doorenbos and Kassam (1979). It is questionable whether these values may be used for the varieties of maize grown in southern Mozambique and for low plant densities. In this study, the periods of different growth stages are fixed. In reality, crop-response to ambiental factors is probably more flexible. Because of the low plant densities in this study, it was decided to use relative transpiration instead of relative evapotranspiration as used in Equation (1).

A second approach consists of relating yield reduction directly to relative transpiration. This means that the reduction factor f is assumed to be 1. In this study, relative yield was determined by using different combinations of the two approaches, as will be discussed later.

For low plant densities, relative yields were calculated using the results of the SWETAM model. Maximum available soil water is taken at 5% and rooting depth

Table III. Evapotranspiration as determined with SWETAM and SWATRE and relative yields obtained with the Doorenbos formula for four periods and different growth stages of a maize crop in Maputo

	Potential evapotranspiration (mm)		Actual evapotranspiration (mm)		Relative yield	
	SWETAM	SWATRE	SWETAM	SWATRE	SWETAM	SWATRE
Period 1:[a]						
Vegetative	185.8	185.7	97.4	82.8	0.81	0.78
Flowering	80.6	81.9	58.2	59.6	0.47	0.46
Seed formation	174.1	172.9	131.0	105.3	0.41	0.37
Ripening	27.0	27.0	9.8	15.2	0.36	0.34
Total	467.5	476.5	296.3	262.9	0.36	0.34
Period 2:						
Vegetative	165.6	165.6	88.0	82.9	0.81	0.80
Flowering	68.6	69.7	20.1	28.5	0.00	0.09
Seed formation	121.4	119.9	33.2	32.4	0.00	0.06
Ripening	16.8	13.8	5.6	3.4	0.00	0.05
Total	327.4	369.0	146.9	147.2	0.00	0.05
Period 3:						
Vegetative	152.2	152.7	88.7	90.7	0.83	0.84
Flowering	84.5	82.0	74.7	52.4	0.69	0.39
Seed formation	214.9	217.8	110.0	98.8	0.52	0.28
Ripening	36.9	36.6	13.7	16.7	0.46	0.25
Total	488.7	489.1	287.2	258.7	0.46	0.25
Period 4:						
Vegetative	145.6	145.6	67.8	54.9	0.79	0.75
Flowering	81.5	78.8	46.8	34.7	0.28	0.12
Seed formation	204.9	208.6	58.0	50.6	0.18	0.07
Ripening	43.8	43.2	4.5	5.3	0.15	0.06
Total	475.8	476.2	177.0	145.5	0.15	0.06

[a]For explanation of periods, see Table I.

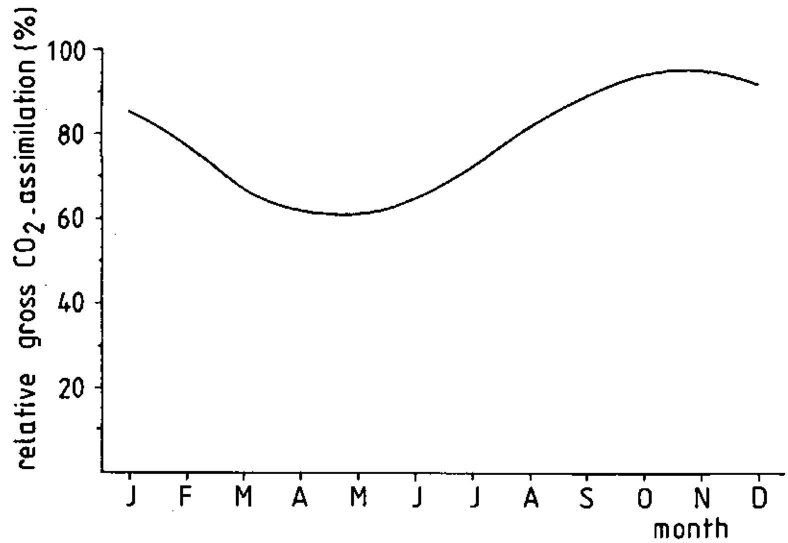

Fig. 2. Gross CO_2 assimilation in southern Mozambique during the growing period, expressed as percentage of (maximum) assimilation in December. The indicated month is the first month of the growing period of 115 days. Latitude 26°S.

at the end of the growing period is 1.0 m. From an analysis of relative yields obtained with the SWETAM model and actual production rates of *ca.* 1000 kg ha^{-1}, potential production under conditions of maximal CO^2 assimilation was assumed at 1700 kg ha^{-1}. Here, potential production is defined as yield without limitation by water deficit, but under the prevailing conditions of low fertility and occurring pests and diseases (Figure 1).

Daily gross CO^2 assimilation varies during the year with a maximum in December. Relative CO^2 assimilation is determined for each month within a growing period, i.e. CO^2 assimilation as a percentage of that in December. From these monthly values, an average value over the growing period is derived (Figure 2). Potential production in a given growing period is determined by multiplying the relative CO^2 assimilation by the maximum value of 1700 kg ha^{-1}. Data of gross CO^2 assimilation are given by Goudriaan (1982).

Actual production for an average family unit is calculated assuming that the area used for maize is 1.2 ha per year. For an average family, consumption required for calories and proteins is assumed at 130 kg month^{-1}. To satisfy protein needs at least 100 kg month^{-1} should be consumed.

Actual consumption of maize per family depends on storage and perspectives of the standing crops. Furthermore, a very important factor is the availability of alternative food.

The latter is not taken into account in this study and attention is only given to maize production and consumption. It is supposed that 25 kg per ha is used for sowing. With these assumptions, it is possible to determine actual consumption per month over a period of *ca.* 30 years and to evaluate different sowing strategies (Pelgrum, 1987).

4.2. ALTERNATIVE SOWING STRATEGIES

In this study, results are presented of an analysis of different strategies for the station Manhica (20°24' S, 32°48' E).:

- strategy 1: 1.2 ha is sown in December,
- strategy 2: 0.4 ha is sown in September, December and March, respectively,
- strategy 3: 0.1 ha is sown every month.

When in a given month rainfall is insufficient, the area that should be sown in that month (according to the strategy) will be sown as soon as rainfall permits, eventually in addition to other areas planned for sowing.

The impact of different assumptions about yield reduction and storage losses on preferences for sowing is analysed for strategies 1, 2 and 3. Relative yields were calculated with the f-values given by Doorenbos (option (a)) and with values for f equal to 1 (option (c)). In option (b), the mean values of these two approaches were used. Options (a), (b) and (c) can be regarded as representing a maize crop with low, medium, and high resistance for drought, respectively. Monthly storage losses were estimated at 0, 5, and 10%, respectively, representing good, medium, and bad storage facilities.

In southern Mozambique, the best months for growing maize from an agro-hydrological viewpoint (i.e. with lowest risks for water deficit) unfortunately coincide with the warmest period (December, January) in which pests and diseases cause severe yield reduction (see Nunes *et al.*, 1986). As a consequence, most people concentrate sowing at the beginning and end of the warm period (i.e. October and April). To analyse this strategy, potential production rate has to be adapted to these relatively better growing conditions. No quantitative information about the impact of pests and diseases in the different periods is available. From an analysis of relative yields obtained with the SWETAM model and of actual yields of *ca.* 1000 kg ha^{-1}, it was assumed that, in the growing periods starting in October and April, potential production can be taken at 2300 kg ha^{-1}. This leads to

- strategy 4: 0.6 ha is sown in October and April, respectively.

4.3. RESULTS AND CONCLUSIONS

When selecting a preferable strategy, the problem arises that the criteria to decide upon are not well understood and vary. For instance, when alternative food is available throughout the year, preference is given to the maximization of production. However, when critical periods occur without alternative food supply, then preference is given to the minimization of the length of these critical periods. An attempt has been

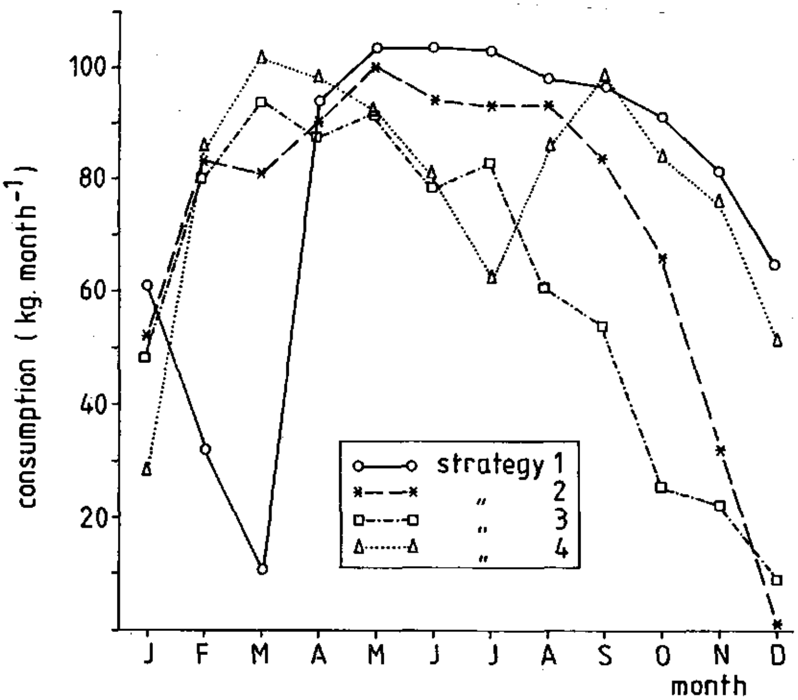

Fig. 3. Mean monthly consumption of maize for Manhica during the period 1957–85 for four sowing strategies. For explanation of sowing strategies, see text.

made to describe the latter option by defining a month as critical when consumption is less than 50% of the minimal required maize food. An analysis has been made for critical periods of 3 months and for periods of more than 3 months. The four strategies were analysed for yield-reduction option (b) and for 5% storage losses. Mean monthly consumption is given in Figure 3. Mean annual consumption and the number of critical periods are given in Table IVA. For the first three strategies, results for varying storage losses are presented in Table IVB and results for varying yield-reduction options are presented in Table IVC. The results clearly demonstrate the precarious food situation in southern Mozambique. All strategies lead to a very low food supply.

In Table V, the preferences are summarized for sowing under different conditions and for different criteria. It can be concluded that decisions on sowing are influenced by many factors. Water availability plays a very important role but can only be evaluated in combination with many other aspects.

5. Conclusions and Discussion

The results of the study presented above demonstrate that conclusions about preferences for a certain sowing strategy should be based upon quantitative information about various aspects. Besides rainfall distribution and soil and crop characteristics,

Table IV. Mean annual consumption of maize and occurrence of critical periods in Manhica during the period 1957–1985

IVA: for 5% storage losses and yield reduction option (b)[a]

Strategy	Mean annual consumption (kg)	Critical periods[a] (months)	
		3	>3
1	942	4[b]	8
2	866	5	4
3	735	8	8
4	943	5	3

IVB: for 0% and 10% storage losses and yield reduction option (b)

	Storage losses 0%			Storage losses 10%		
Strategy	Mean annual consumption (kg)	Critical periods (months)		Mean annual consumption (kg)	Critical periods (months)	
		3	>3		3	>3
1	1185	0	1	789	10	14
2	958	2	4	804	7	7
3	761	8	7	713	6	10

IVC: for 5% storage losses and yield reduction options (a) and (c)

	Yield reduction option (a)			Yield reduction option (c)		
Strategy	Mean annual consumption (kg)	Critical periods (months)		Mean annual consumption (kg)	Critical periods (months)	
		3	>3		3	>3
1	804	5	11	1081	1	3
2	734	10	11	1029	2	0
3	566	6	15	915	6	3

[a]For explanation, see text.
[b]Number of years of occurrence.

information about the impact of pests and diseases, storage losses, and the availability of alternative food and manpower, also has to be considered.

It can be concluded that production rates under optimal water supply for the region-specific conditions have to be known. A good approximation of yield reduction by pests and diseases and by extreme low-soil fertility is essential for the evaluation of sowing strategies.

When this information is only partially available, it seems reasonable to assume that simple water-yield models can be used. Hence, then a more detailed description

Table V. Summary of preferences for the strategies 1, 2 and 3 for different conditions and criteria

	Alternative food available; criterion: maximizing annual consumption			No alternative food available; criterion: minimizing critical periods		
	Storage losses			Storage losses		
Drought resistance	0%	5%	10%	0%	5%	10%
low (option a)[a]	1	1	2	1	1	3
medium (option b)	1	1	2	1	2	2
high (option c)	1	1	n.e.[b]	n.e.	2	n.e.

[a]for yield reduction options, see text.
[b]not examined.

of the water balance and corresponding yields do not substantially improve the analysis of sowing strategies, since other important information is missing. The study presented here gives some indications about the relative importance of the different factors affecting yields and sowing strategies.

A further validation of the water balance and crop growth models will be carried out at the Faculty of Agronomy in Maputo. Further research has to be done on quantative methods which allow a better analysis of the data obtained by using different approaches and models.

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References

Belmans, C., Wesseling, J. G., and Feddes, R. A., 1983, Simulation model of the water balance of a cropped soil: SWATRE, *J. Hydrol.* **63**, 271–286.

Doorenbos, J. and Kassam, A. H., 1979, Yield response to water, Irrig. and Drainage Paper 33, Food and Agricultural Organization, Rome.

Feddes, R. A., Kowalik, P. J., and Zaradny, H., 1978, *Simulation of Field Water Use and Crop Yield*, Pudoc, Wageningen.

Goudriaan, J., 1982, Potential production processes, in Penning de Vries F. W. T. and H. H. van Laar (eds) *Simulation of Plant Growth and Crop Production*, Pudoc, Wageningen, pp. 98–113.

Keulen, H. van and Wolf, J., 1986, *Modelling of Agricultural Production: Weather, Soils and Crops*, Pudoc, Wageningen.

Nunes, E., Sousa, D., and Sataric, I., 1986, Research on the constraints to maize production in Mozambique, in *Proc. 1st Eastern, Central and Southern Africa Regional Maize Workshop, 10–17 March 1985, Lusaka, Zambia*, CIMMYT, Mexico. pp. 67–79.

Pelgrum, R., 1987, A study on sowing strategies for maize and sorghum; a simulation for analyzing risks of rainfed production in southern Mozambique, Scriptie Dept. of Land and Water Use, Agric. University Wageningen.

Schouwenaars, J. M. 1986, An agrohydrological study on sowing strategies for rainfed production in southern Mozambique. UEM/LUW/PSW-project research report n.1. Mededeling n.91, Dept. of Land and Water Use, Agric. University Wageningen.

Schouwenaars, J. M., 1988, Rainfall-irregularity and sowing strategies in southern Mozambique, *Agric. Water Management*, **13**, 49–64.

Swennenhuis, J., 1987, An analysis of different approaches to the simulation of water balances and crop production; a case study for southern Mozambique, Scriptie Dept. of Land and Water Use, Agric. University, Wageningen.

Thornthwaite, C. W. and Mather, J. R., 1954, The computation of soil moisture, in Estimating soil tractionability from climatic data, *Publ. in Climatol.* 7, Centerton, New Jersey 397–402.

A model approach to analyse sowing strategies for maize in southern Mozambique

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Abstract

In southern Mozambique, rainfall is concentrated in the rainy period between October and April. Year by year fluctuations of rainfall are extremely wide and rainfall is very erratic. In the sandy soils of the coastal zone, capacity for water retention is very low. Production and consumption of maize is also affected by losses caused by pests and diseases and post-harvest losses. A simple water balance and crop growth model was applied to simulate production of maize for different sowing strategies. Available maize for consumption per month for an average family farming unit was determined for the period 1957-1985. Model parameters which describe soil water availability were varied to study their impact upon sowing strategies. Also values for potential production were varied. For maximizing yearly consumption the preferred strategy almost fully depended on losses by pests and diseases and post-harvest losses. However, regarding the decision criterion of minimizing the periods with food shortage the preferred sowing strategy greatly depended on water-availability and potential production levels.

Keywords: sowing strategies, simulation model, optimization, Mozambique

Introduction

In southern Mozambique, mean annual rainfall decreases from 800-1000 mm near the coast to 550 mm in the interior (50-75 km from the coast). Rainfall is concentrated in the rainy period between October and April. Year by year fluctuations of rainfall are extremely wide and rainfall is very erratic. Maize is the most important cereal crop. Its average production is very low (less than 1000 kg ha^{-1}) and yields vary considerably with the amount and distribution of rainfall during the growing period. In the sandy soils, capacity for water retention is very low (5-10 %). It seems common practice to sow maize in small quantities throughout the whole year, whenever rainfall is sufficient. However, the most important period for sowing is September-October. This is not the most favourable period from an agrohydrological viewpoint. Risks for water deficiency are lower when sowing in the period December-January. Probably, earlier sowing can be explained by the almost perma-

Table 1. Monthly precipitation (mm) and evaporation data (mm) for Manhica (period 1957-1985).

Month	Precipitation[1]			Penman evaporation[2]
	L	M	H	
Sep	9	24	45	119
Oct	38	59	73	150
Nov	48	65	101	158
Dec	57	78	150	170
Jan	73	116	217	167
Feb	47	132	234	138
Mar	57	100	132	127
Apr	41	58	111	100
May	15	31	87	76
Jun	10	19	39	59
Jul	0	14	34	64
Aug	3	16	33	86
Year	726	932	1183	1414

Data from Mozambican Meteorological Service

[1] L in 25 %; M in 50 %; H in 75 % of the years, precipitation is lower; i.e.: for L 75%, for M 50% and for H 25% probability of exceeding the indicated value.

[2] For net short-wave radiation the following equation was used: $R_n = 0.75\ R_{sa}\ (0.29 + 0.42\ n/N)$ where R_{sa} is short-wave radiation at top of atmosphere and n/N is sunshine (fraction).

nent food shortage, inducing people to sow as early as possible, and by the higher risks for damage caused by pests and diseases in later periods.

Model approach was used to understand better the logic of certain sowing strategies. Therefore a selection was made of some environmental factors which were expected to play a role in preferences for sowing strategies. Emphasis was laid on water availability, depending on rainfall, soil properties and plant density. The impact of losses caused by pests and diseases and by inadequate storage facilities was analysed in quantitative terms. The effect of different potential production levels under the poor soil fertility conditions was studied. The objective of this study was to analyse the relative importance of the selected factors to improve our understanding of a part of the complex problems related to decisions on sowing strategies. Therefore, a sensitivity analysis was made. The period 1957-1985 was examined. In the study area was Manhica, situated at about 20 km from the coast (25°24'S, 32°48'E). Monthly precipitation and evaporation data are listed in Table 1.

Simulation of sowing strategies

Rainfed crop production in the sandy coastal zone of southern Mozambique is practised mainly by small-family farming units. Each family cultivates different fields (machambas) with a total area of 1-2 ha. Most important food crops are cassava (*Manihot* sp.), maize (*Zea mays*), groundnut (*Arachis hypogaea*), sweet potato (*Ipomoea batatas*), cowpea (*Vigna* sp.) and pigeonpea (*Cajanus cajan*). Commonly mixed cropping is practised with low plant densities for maize.

Actual production of maize for an average family unit was calculated, assuming that the area used for maize was 1.2 ha year^{-1}. For an average family, required consumption for calories and proteins was set at 130 kg per month. To satisfy protein needs, a minimum of 100 kg per month should be consumed. Actual consumption of maize in a certain month was determined taking into account the stored quantities and the perspectives of the standing crops. In reality the availability of alternative food is very important, but in this study attention was only given to maize production and maize consumption. The sowing rate was set at 25 kg ha^{-1}. With these assumptions it was possible to determine actual available maize for consumption per month over a longer period and to evaluate different sowing strategies. The following strategies were examined:

— Strategy 1: 0.1 ha was sown every month.
— Strategy 2: 0.4 ha was sown in September, December and March, respectively.
— Strategy 3: 1.2 ha was sown in December.

When in a given month rainfall was insufficient, the area that should be sown in that month (according to the strategy) was sown as soon as rainfall permitted, in addition to other areas planned for sowing.

Weight losses of 20-50 % are very common when food is stored for one year (Hall, 1970). To study the impact of these losses the monthly reduction of stored quantities was set at 0, 5 and 10 %, respectively.

When selecting a preferable strategy the problem arises that the criteria to decide upon are not well understood and vary. For instance, when alternative food is available throughout the whole year, then for maize preference might be given to the maximization of production. However, when this is not available, preference might be given to the minimization of the length of the periods with shortage of maize ('critical periods'). A critical period was defined as a period in which consumption was less than 50 % of the minimal required maize food. An analysis was made for critical periods of 3 months and for periods of more than 3 months.

Modelling yields for maize

A simple approach: the SWETAM model

In the water balance model SWETAM, variations in soil water content within the rootzone were simulated using simple concepts of water losses by evaporation from bare soil and through crop canopy. Details of this model were described by Schouwenaars (1988). The ratio between actual and potential transpiration was described as a function of the volumetric water content of the soil. In the sandy soils of the coastal zone the low water holding capacity creates deep redistribution of infiltrated water. For these soils a uniform soil water distribution within the rootzone was assumed and water flow within the soil profile was disregarded.

These assumptions required that the soil profile in the rootzone was rather uniform and capillary fluxes from the groundwater were negligible. In the SWETAM model, run off and the interception of precipitation by the crop was neglected.

Water balance terms were calculated for 5-day periods (pentads). For a given pentad the amount of available water in the rootzone depended on rooting depth, soil water retention characteristics and the prevailing meteorological conditions (precipitation) in the preceding pentads. Field observations indicated that crops were sown when total precipitation within a 5-day period exceeded 20 mm. Sowing conditions were analysed for each month in the subsequent years. If in a certain month conditions were suitable for sowing the water balance terms during the growing period were determined. This is only done once a month. In reality there might be more periods within a month with favourable conditions for sowing.

Initial soil water storage was determined using precipitation data over the 30 days preceding the sowing date and taking into account the losses by evaporation during this period.

In southern Mozambique in many fields sweet potato and groundnut are grown in between the maize plants. Normally these intercropped plants only cover a small fraction of the soil (<25 %) and their growing periods do not correspond to those of maize. For the analysis of the water balance they were neglected. In this study, maize with a maximum soil cover of 50 % (low plant density) and of 100 % (high plant density) were considered. Rooting depth was determined as a linear function of the square root of time.

Crop coefficients for maize as given by Doorenbos & Pruitt (1977) were used to determine potential evapotranspiration (ET_{pot}) from Penman-evaporation data. The ratio between potential transpiration (T_{pot}) and ET_{pot} was taken as a linear function of the soil cover. The latter was simply described as a function of time (assuming an S-shaped growing curve). Maximum soil cover was variable.

Yield reduction by water deficit

Little research has been performed on the impact of water deficit on yields of the local varieties of maize in southern Mozambique. Doorenbos & Kassam (1979) proposed the following simple relation:

$$1 - Y_{actual}/Y_{potential} = f \quad (1 - T_{actual}/T_{potential})$$

in which Y is yield (kg ha^{-1}) and T transpiration (mm). The ratio Y_{act}/Y_{pot} is known as relative yield. The ratio T_{act}/T_{pot} is known as relative transpiration. The reduction factor f was set at 0.4 for the vegetative period (0-50 days), 1.5 for the flowering period (51-65 days), 0.5 for the seed formation period (66-105 days) and 0.2 for the ripening period (106-115 days) (Doorenbos & Kassam, 1979). For Manhica, relative yields were calculated (Table 2).

Schouwenaars et al. (1988) evaluated both simple and detailed water balance models (SWETAM versus SWATRE[1]) and crop growth models (Doorenbos-approach versus WOFOST[2]). They selected periods with big differences in distri-

[1] For a description of SWATRE see Belmans et al., 1983.
[2] Developed at the Centre of World Food Studies, Wageningen; see van Keulen & Wolf, 1986.

Table 2. Simulated relative yields[1] for maize at Manhica.

Year[2]	Month of sowing											
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
56-57	–	–	–	–	–	–	–	–	5	4	3	1
57-58		4		6	5	5	4	3				
58-59	6	6	6	4	4	5	5		4		3	
59-60	4	3	4	5	5	4	6	3	3			
60-61	5		4	3	2	3	2			5	3	3
61-62		4	5	3	1		1					
62-63		5	4	4	4	4	6	4	5	2	1	
63-64			6	5	5	3	3	3				
64-65		5	3	3	5	5	4		2		3	5
65-66	5	3	4	6	6	5	5		4	2		
66-67	3	1	4		6	6	4	4			1	
67-68		1	4		5	5		4				
68-69	4		2		6	6	5	3	2			
69-70		4	2	1					4	1		
70-71	4	4	4	6	5	5	3	3	3			
71-72		3		6	5	5	6	4	3			
72-73		4	3	3	5	6	4	3	3		2	
73-74	4	4	4	6	6	6	5	3	1			
74-75		5	5	6	6	4	4		4	1		
75-76		2	3	3	2	6	5	5	4	1		
76-77			4	6	6	3	3	1				
77-78			5	6	6	4	2	3			2	
78-79	4		2	1	4	4	4	–	–	–	–	
79-80	4	3	5	6	5	4	1	2	–	–	–	–
80-81	–	–	5	4	2	5	5	2	2			
81-82	2	5	5	5	2	5	3	3				
82-83	1	1			2		3		4			3
83-84		5	3	5	4	5	2	5			3	
84-85	3	1	3	6	6	6	5					

[1] Defined as the ratio between actual production (with limited water use) and potential production. Classification: blank: no sowing, –: no data, 1: 0.00-0.25, 2: 0.25-0.37, 3: 0.38-0.50, 4: 0.50-0.62, 5: 0.63-0.75, 6: 0.75-1.00 of potential production.

[2] 29 years analysed, period 1957-1985.

bution and total amount of rainfall. Then both water balance models were applied for the same set of data for precipitation, potential evapotranspiration, rooting depth, soil cover and soil characteristics. Differences in the estimation of actual transpiration between both water balance models appeared to depend on the prevailing rainfall characteristics. Only for extremely dry or wet periods systematic differences between the results could be found. When dry periods coincided with drought-sensitive growth stages with the SWETAM model considerable errors in the estimation of relative yields could be made. For all selected periods the relative yields obtained with the SWATRE-Doorenbos combination were very similar to those obtained with the SWATRE-WOFOST model. For the objectives of this study the simple approach of Doorenbos & Kassam gave satisfactory results.

Potential yields

Actual production levels mostly vary between 500 and 1000 kg ha $^{-1}$. Little information is available about the potential production levels. Relative yield (kg ha^{-1}) was calculated by multiplying the ratio $Y_{actual}/Y_{potential}$ by potential production. Potential production was defined as the yield under optimal water supply and (low) natural fertility, without reduction caused by pests and disease. When fertility is the main limiting factor it is questionable whether differences in CO_2-assimilation within a year, lead to differences in potential production levels as defined above. It was decided to use potential production levels which varied as a result of reduced CO_2-assimilation in colder periods, following the method described by Goudriaan (1982). Maximum potential production levels (i.c. under maximum CO_2-assimilation) of 1700 kg ha^{-1} and 2300 kg ha^{-1} were used as input in the SWETAM model.

Yield reduction by pests and diseases

The best months for growing maize from an agrohydrological viewpoint (i.c. with lowest risks for water deficit) unfortunately coincide with the warmest period (December and January, see Table 1). In this period, pests and diseases cause severe yield reduction (Nunes et al., 1986). To assess the negative impact of pests and diseases, potential production levels were reduced, only for growing periods starting in the period September-February. The value for this reduction factor was uncertain, so different values were used to study its effect on sowing strategies. For growing periods starting in the period October-January, values of 0, 25 and 50 % were used. The period of gradual increase and decrease of occurrence of pests and diseases was taken into account by taking only half of these values for growing periods starting in September and February.

A sensitivity analysis

Water availability

For modelling water use by a crop it has to be known which part of the total available soil water is easily available. The transpiration rate (i.e. the ratio T_{act}/T_{pot}) is found to be relatively unaffected by the soil water content over a considerable range, and only when the water content falls below a given value, the transpiration rate starts to decrease (Gardner, 1983). In the SWETAM model both the total available water and the fraction which is easily available could be varied. After depletion of the easily available water, the water uptake (i.e. transpiration rate) was supposed to decrease linearly with the water content. Using these concepts in the SWETAM model, 3 different options (A, B and C) were used (Fig. 1a). With Option A, plants are more vulnerable for short dry periods than with Option C, where during the first period of drought plants still are able to extract enough water from the soil to satisfy their needs. For the sensitivity analysis the differences between the above-mentioned

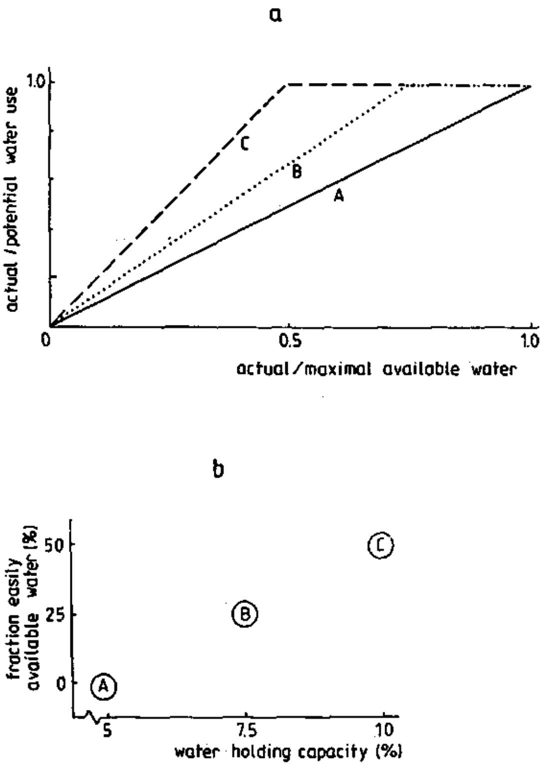

Fig. 1a. The ratio between actual and potential water use (relative water use) as a linear function of the ratio between actual and maximal available water for 3 options (A, B and C).

Fig. 1b. The selected combinations of water holding capacity and fraction easily available water (the latter refers to the traject in Fig. 1a where relative water use equals 1). The relative water availability is low for Option A, medium for B and high for C.

Options A, B and C were enlarged by varying the maximum water holding capacity (set at 5 %, 7.5 % and 10 % for Options A, B and C, respectively). The final combinations are presented in Figure 1b.

In combination with the different values describing the impact of pests and diseases and storage losses, simulations were carried out. Figure 2a and Figure 3a present results for the criterion of maximizing average yearly consumption. Figure 2b and 3b present results for the criterion of minimizing the number of critical periods. For every combination of losses 3 values are presented, the best of which is indicated. The upper value is for Strategy 1, the medium one is for Strategy 2 and the lower one is for Strategy 3.

It is possible to analyse alterations in preferences caused by changed values for losses. In the figures lines are distinguished indicating for which values at both axes (losses) there are changes in the optimum strategy.

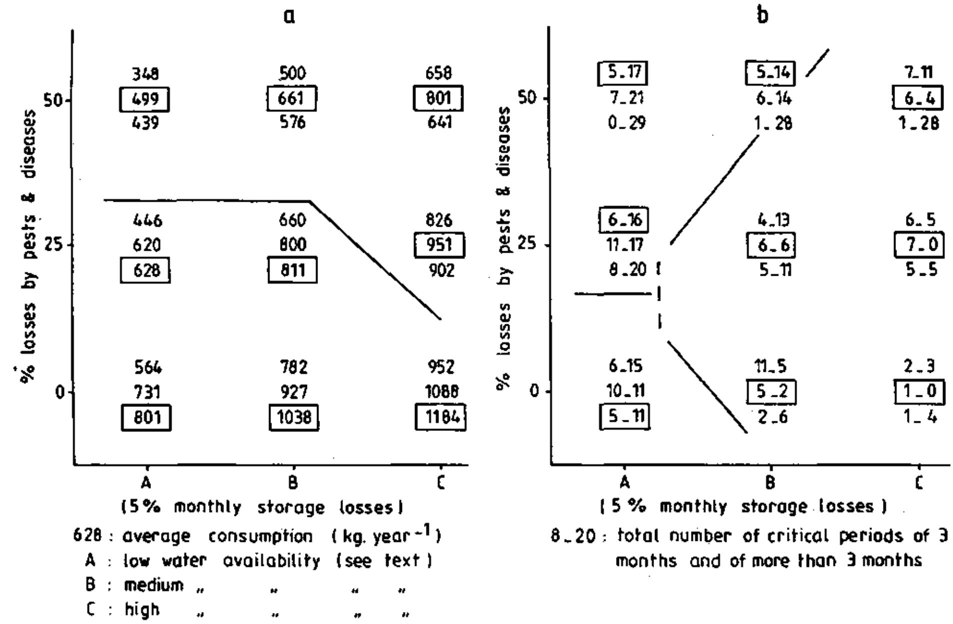

Fig. 2. Optimum strategies for maize as influenced by water availability (A, B and C) and for different losses by pests and diseases. a: for maximizing average yearly consumption; b: for minimizing critical periods.

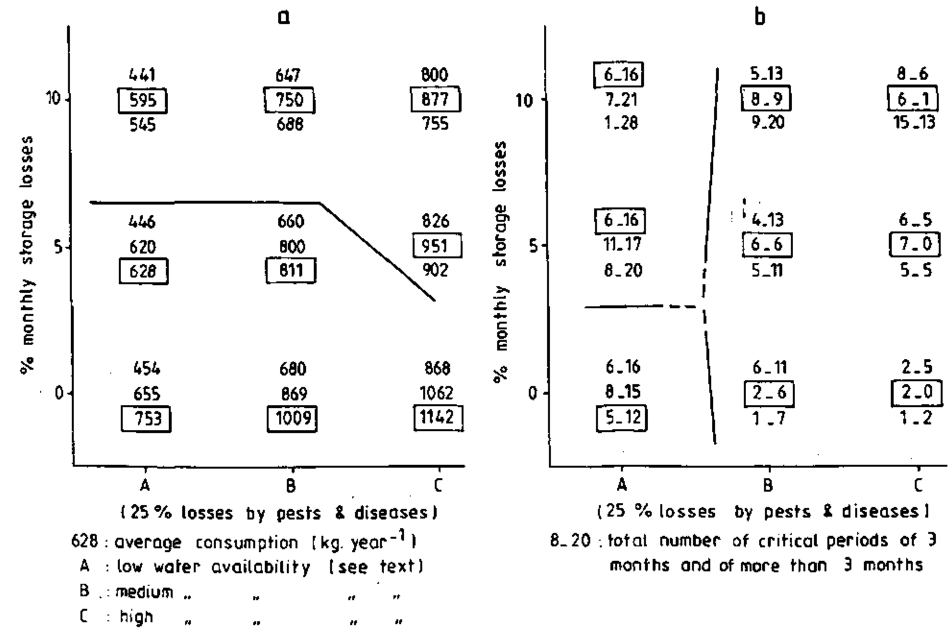

Fig. 3. Optimum strategies for maize as influenced by water availability (A, B and C) and for different storage losses. a: for maximizing average yearly consumption; b: for minimizing critical periods.

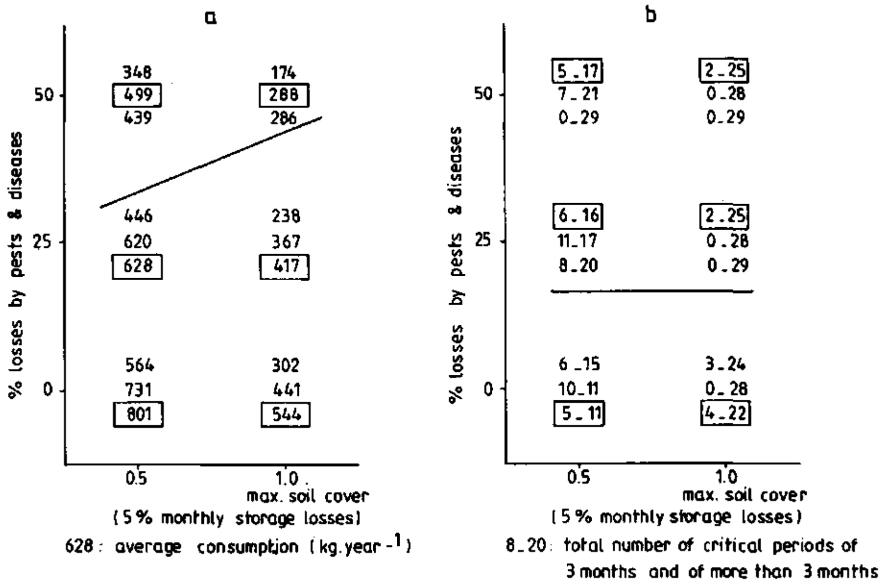

Fig. 4. Optimum strategies for maize as influenced by plant density. a: for maximizing average yearly consumption; b: for minimizing critical periods.

Plant density

The ratio between potential transpiration and potential soil evaporation is a function of the soil cover development. In dry periods, actual soil evaporation decreases rapidly when the top layer dries out. Hence, with low plant densities more water per unit area is available for transpiration than with high plant densities. Under low densities, a plant which expands its roots horizontally can profit from this extra water. It is not well known under which plant densities there is an optimum use of the available soil water. This also holds for the optimum use of available nutrients. First results of field trials in Maputo indicated that the optimum plant density was different for fertilized and non-fertilized plots.

The impact of plant densities upon actual transpiration was examined with some simplifications. Maximum soil cover at the end of the growing period was set at 50 % and 100 %. It was assumed that in the first case the roots of a single maize plant occupy a soil volume twice as large as in the latter case. Another simplification was made by assuming that potential production per ha was equal for the two plant densities. Such a simplification was questionable because it can be argued that, for a certain soil fertility, there is an optimum plant density for which the crop maximally exploits the available nutrients.

The impact of plant density upon preferences in sowing strategies was analysed for a soil with a marginal water availability (A, Fig. 1). Monthly storage losses were set at 5 %. Results are presented in Figure 4.

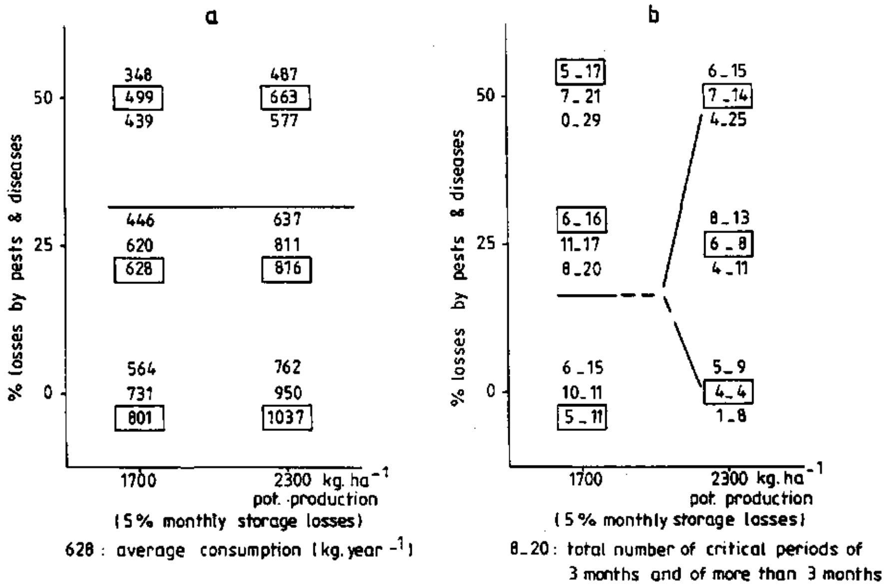

Fig. 5. Optimum strategies for maize as influenced by potential production. a: for maximizing average yearly consumption; b: for minimizing critical periods.

Potential production

The impact of potential production levels upon preferences for sowing strategies was examined by taking two different values for maximal potential production: 1700 and 2300 kg ha^{-1} for a soil with marginal water availability (A, Fig. 1) and for monthly storage losses of 5 %. Results are presented in Figure 5.

Conclusions and discussion

Water availability

For all simulations (A, B and C; Fig. 1), when maximizing the average yearly consumption, Strategy 3 (sowing once a year in December) is preferred when yield reductions by pests and diseases and storage losses are small. Of course for simulation C total yearly consumption will be higher as for simulation A, where water availability is marginal. When losses increase, Strategy 2 (sowing in September, December and March) becomes preferable. It is clearly shown that for maximizing yearly consumption the impact of losses upon preferences is by far dominant over water-availability. However, regarding the decision criterion of minimizing critical periods the preferred sowing strategy does greatly depend on water-availability. When the latter is marginal (A) only for low losses Strategy 3 is prefered and then an increase of losses leads to a preference for Strategy 1 (a scattered strategy, sowing each month). If water-availability increases (B and C) this scattered strategy becomes less attractive and also Strategy 3 will become less attractive for the farmer, even for low losses. Under a relatively high availability of soil water (C) for all combinations of losses Strategy 2 is preferable. Hence, when minimizing risks for food shortages (besides maize no alternative food available), water availability plays a dominant role in sowing strategies. When the water availability improves, soon Strategy 2 becomes preferable, independent of rates of losses.

Plant density

Given the questionable assumptions used in the simulation for different plant densities, results must be regarded with caution. For all strategies, production and consumption levels for high density were much lower than for low density (Fig. 5a). More research is needed to analyse the impact of plant density upon production. However, it can be concluded that the preference for a certain sowing strategy is dominated by losses by pests and diseases. Here again a concentrated strategy is preferred when these losses are low, whereas a scattered strategy gives the best results when these losses are high. When plant densities are further lowered, resulting in a higher production, it may be expected that Strategy 2 will become attractive. Obviously, for lower plant densities the errors made by the used model simplifications will increase.

Potential production

A somewhat higher potential production level roughly gives the same alterations in preferences than a better soil water availability, which were discussed earlier. For the analysed conditions of low soil water availability the results for a potential production level of 2300 kg ha^{-1} (Fig. 5) approximate the results obtained with a level of 1700 kg ha^{-1} with a somewhat better soil water availability (Fig. 2). Strategy 2 may become attractive when growing conditions are improved and when it is tried to minimize the risks for shortages. For maximizing average consumption, a higher potential production has no effect on the preferred sowing strategy.

Decision criteria

Of course, under all farming conditions attempts are needed to reduce losses and to improve water availability and soil fertility (i.c. potential production). If this is successful, production and consumption levels will increase. However, when we focus on optimal sowing strategies it can be concluded that in regions with little access to (markets for) alternative food, an improvement of water availability and soil fertility will result in other sowing strategies. This does not hold for regions where alternative food is available. Under these conditions, sowing strategies will alter only when losses by pests and diseases and/or storage are reduced.

One of the main problems in analysing sowing strategies is of an agro-economic nature. In this study this is made clear by presenting 2 criteria to decide upon for optimization, i.e. maximizing average yearly maize consumption and minimizing occurrence of periods with shortages. However, many other criteria can be used (a.o. Schweigman, 1985) and whether these correspond with the ones used by farmers in Mozambique will depend on environmental factors (region, soils) and socio-economic factors (market, labour availability, alternative income, etc.).

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References

Belmans, C., J. G. Wesseling & R. A. Feddes, 1983. Simulation model of the water balance of a cropped soil: SWATRE. *Journal of Hydrology* 63: 271-286.

Doorenbos, J. & A. H. Kassam, 1979. Yield response to water. Irrigation and Drainage Paper 33. Food and Agricultural Organization, Rome, 193 pp.

Doorenbos, J. & W. O. Pruitt, 1977. Crop water requirements. Irrigation and Drainage Paper 24. Food and Agricultural Organization, Rome, 144 pp.

Gardner, W. R., 1983. Soil properties and efficient water use: an overview. In H. M. Taylor, W. R. Jordan & T. R. Sinclair (Eds), Limitations to efficient water use in crop production, pp. 45-64. American Society of Agronomy.

Goudriaan, J., 1982. Potential production processes. In: F. W. T. Penning de Vries & H. H. van Laar (Eds), Simulation of plant growth and crop production, pp. 98-113. Pudoc, Wageningen.

Hall, D. W., 1970. Handling of storage of food grains in tropical and sub-tropical countries. Food and Agricultural Organization, Rome, 350 pp.

Keulen, H. van & J. Wolf, 1986. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen, 479 pp.

Nunes, E., D. Sousa & I. Sataric, 1986. Research on the constraints to maize production in Mozambique. In: Proceedings of the First Eastern, Central and Southern Africa Regional Maize Workshop, Lusaka (Zambia), pp. 67-79. CIMMYT, Mexico.

Schouwenaars, J. M., 1988. Rainfall-irregularity and sowing strategies in southern Mozambique. *Agricultural Water Management* 13: 49-64.

Schouwenaars, J. M., G. H. Pelgum & J. Swennenhuis, 1989. Research on plant-soil-water relations and its role in understanding sowing strategies. *Water Resources Management* 2: 255-267.

Schweigman, C., 1985. Operations research problems in agriculture in developing countries. University Press, Khartoum/Tanzania Publishing House, Dar es Salaam/University Press, Groningen, 361 pp.

PART III

MODEL STUDIES ON WATER MANAGEMENT IN BOG RELICTS

3.1 The impact of water management upon groundwater fluctuations in a disturbed bog relict

published in:
Agricultural Water Management 14 (1988) 439-449

3.2 Hydrological research in disturbed bogs and its role in decisions on water management in the Netherlands

published in:
Proceedings of the Symposium on the hydrology of wetlands in temperate and cold regions. Joensuu, 6-8 june 1988. Publications of the Academy of Finland 4 (1988) 170-177

3.3 Calibration of the model SWAMP

THE IMPACT OF WATER MANAGEMENT UPON GROUNDWATER FLUCTUATIONS IN A DISTURBED BOG RELICT

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ABSTRACT

In many disturbed bog relicts in northwestern Europe, attempts have been made to restore the hydrological conditions required for the reestablishment of ombrotrophic plant communities. Water management measures were taken to reduce water losses and to raise (ground)water levels in the bog relicts. Experiences show that after having taken these measures, on many sites groundwater levels remain low at the end of the summer. Suitable conditions for the regeneration of a Spagnum vegetation mostly are restricted to permanently inundated sites.

The study presented here aims to clarify the importance of different hydrological characteristics such as hydro-physical properties of the peat layers, transpiration, downward water losses, etc. for the water fluctuations in bog relicts. A groundwater simulation model for peaty soils was developed (SWAMP, Soil Water Modelling in Peat), which makes it possible to evaluate alternative water management measures. In this study the model was used for a location in the Deurnese Peel area in the Netherlands.

The results of this study demonstrate the importance of the hydro-physical characteristics of the peat layers for the pattern of groundwater fluctuations. More than any other hydrological variable it seems to be the pore size distribution within the upper peat layers that determines groundwater fluctuations. Probably in most disturbed bog relicts, the hydro-physical properties of the upper layers are not suited for the establishment of a Spagnum vegetation directly on the substrate. Only on permanently inundated sites floating mats of Spagnum peat can develop. On these sites gradually the required hydro-physical conditions within the young upper peat layers are created.

INTRODUCTION

In many disturbed bog relicts in northwestern Europe attempts have been made to restore the hydrological conditions required for the reestablishment of ombrotrophic plant communities. A review of these water management measures for the Netherlands is given by Schouwenaars (1982). Eggelsmann (1982) and Kuntze and Eggelsmann (1982) summarize experiences and perspectives for northwestern Germany.

In some Dutch bog relicts the first hydrological measures were taken already before 1980. In particular during the last decade, in many relicts dams were constructed to minimise water losses and to raise the water level. It is generally accepted that for a successful regeneration of Sphagnum peat growth, groundwater depth during the vegetation period should not fall lower than ca. 40 cm below surface. Experiences in the Netherlands show that, even with complete saturation of the peat layers at the beginning of the vegetation period, on most locations groundwater depth at the end of a normal summer is lower than 50 cm below surface. Often these low groundwater levels are explained by referring to the disturbing drainage activities which were carried out during the period of peat excavation. These activities resulted in deep open drains often reaching into the sandy formation beneath the peat. Another explanation is that drainage activities in neighbouring areas have decreased water pressure in the sand layers, resulting in increased downward water losses from the peat. As a consequence water management measures mostly focus on:

- increasing the resistance of the peat sand boundary layers by refilling deep ditches, using strongly humified peat with a very low permeability,
- increasing the groundwater level in adjacent areas to increase water pressure in the underlying sand layers.

Hydrological research in undisturbed bog reserves tends towards the conclusion that for the prevailing climatological conditions in the Netherlands and northwestern Germany yearly downward water fluxes should not exceed 50 mm (Eggelsmann, 1969; Ter Hoeve, 1965).

Differences between the present groundwater fluctuations and those known from undisturbed bogs partly result from changed hydro-physical properties of the upper peat layers. Schouwenaars (1982) in this respect refers to changes in pore size distribution in the peat layers resulting from:

- temporary or permanent drainage or
- removal of the upper slightly humified peat layers.

As a consequence strongly humified peat can be found at the surface in most places.

The study presented here aims to clarify the importance of different hydrological characteristics such as hydro-physical peat properties, transpiration, downward water losses etc. for the water fluctuations in a bog relict in the Deurnese Peel area.

THE MODEL SWAMP

To evaluate the possibilities to restore the required hydrological conditions at a given location, it is useful to develop a simulation model for groundwater fluctuations. In this model site specific information, especially about hydro-physical properties of the peat layers and downward water losses has to be incorporated. Given the common scarcity of reliable field data the model should be based upon a simple calculation procedure, but guarantee a good approximation of the different terms of the water balance. Therefore the model SWAMP (Soil WAter Modelling in Peat) was developed. In this model the different terms of the water balance are determined by using meteorological data (precipitation, evaporation), characteristics of the vegetation (potential transpiration, depth of rootzone) and hydrological characteristics of the peat layers, peat sand boundary layer and underlying sandy formations.

The model SWAMP simulates the water balance of the unsaturated zone, using simplified approaches for the determination of downward and upward fluxes and water uptake by roots. In the study presented here water balance terms are totalized for 10-days periods.

Near-equilibrium conditions

In most disturbed bog relicts groundwater level fluctuates between 0 and 1 meter below surface. Hydro-physical properties of the peat layers guarantee a high water content (above 50%), even within the upper layers. In general, under the prevailing conditions with high groundwater levels, suction forces in the upper layers remain small. Caris (1987) has found maximum values of ca. 20 kPa during a dry summer period. Under these conditions capillary flux is sufficient to minimise water deficit for the vegetation. The near-equilibrium conditions allow the development of a simplified model for the water balance of the unsaturated zone.

Evapotranspiration

For a given vegetation potential evapotranspiration E_{pot} over a 10-days period is determined by multiplying Penman evaporation E_o by a vegetation factor k_c : $E_{pot} = k_c E_o$

Actual evapotranspiration is determined in the following way. Precipitation results in infiltration into the rootzone and water content increases. When at the beginning of the 10-day's period the phreatic level and the total water content are known, it can be determined whether infiltration results in a soil water content that exceeds field capacity. If so, percolation through the unsaturated zone is assumed to be slow and part of the surplus water to be available for evapotranspiration. If the potential evapotranspiration is not satisfied by the surplus water in the rootzone, capillary fluxes occur. When phreatic level is low, capillary fluxes might be insufficient to complete transpiration demand. Then it is supposed that the water content in the rootzone will reach values that are lower than under equilibrium conditions. This is a result of water extraction from the rootzone, which is determined according to the method given by Thornthwaite and Mather (1954).

Percolation to the saturated zone leads to an increasing water level, but only occurs when after infiltration the water content in the unsaturated zone exceeds field capacity. If not, the amount of infiltrated water results is a somewhat higher water content. Then again capillary fluxes and, eventually, extra water extraction from the rootzone determine the amount of water available for transpiration.

When the water level is above surface, actual evapotranspiration is taken equal to Penman evaporation.

Capillary fluxes

For some locations in the Groote Peel area Stokkermans and Wösten (1986) have determined capillary fluxes for different suction forces in

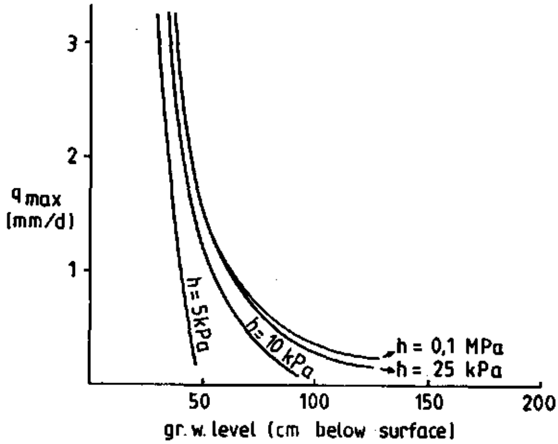

Fig. 1 Maximum capillary flux in relation to groundwater level for strongly humified peat; h is suction force in top layer (after Stokkermans and Wösten, 1986).

the upper layer. In Fig. 1 the results for strongly humified peat are given. In accordance with the assumptions of near-equilibrium conditions, in this study it is supposed that in the upper peat layer suction values remain relatively small.

To obtain an unique relationship between groundwater level and maximum capillary rise, one curve must be derived from the various curves in Fig. 1. This curve can be described by the general form:

$$q_{max} = ((w_m - w) / a)^b . c \qquad \text{(Eq. 1)}$$

where q_{max}: maximum capillary flux (mm/d)

w_m : groundwater level below which $q_{max} \approx 0$ (cm)

w : groundwater level (cm)

a,b,c: soil specific parameters

Downward water losses

Downward fluxes result from the difference between water pressure in the upper peat layers and the water pressure in the underlying aquifer. Resistance of peat formations for vertical water flow can be extremely high. The peat sand boundary is characterised by a very low permeability. Various authors found values less than 2. 10^{-4} m/day (Ter Hoeve, 1965; Schouwenaars, 1978; Blankenburg, 1986). For strongly humified peat with a thickness varying from 0.4 to 3 m vertical resistance ranges from 2000 to 10.000 days (Haarman, 1986). In the model SWAMP values for the water pressure in the aquifer and vertical resistance are needed as input. Horizontal water flow is neglected.

Groundwater fluctuations

A simple method was developed to estimate specific equilibrium soil water content in a uniform soil (Schouwenaars, 1987). When the soil profile above the minimum groundwater level can be regarded as uniform and near-equilibrium conditions prevail, it is possible to describe total water content in the peat layers as a function of groundwater depth. Hysteresis is neglected because suction forces remain very low, even during a dry period. This enables the determination of groundwater fluctuations as a result of downward water losses, capillary fluxes or percolation. The general form of the relation between groundwater depth (w) and total volumetric water content (v) under near-equilibrium conditions is given by:

$$v = v_{max} - a.W^{b} \qquad \text{(Eq. 2)}$$

where v_{max}: total volumetric water content of the peat layers when the entire profile is saturated (mm)
a,b : soil specific parameters, derived from the water retention characteristics (different from a,b in eq. 1)
W : groundwater depth (mm)

runoff

It is supposed that runoff occurs when groundwater level is above a certain minimum. Runoff characteristics depend on the water level and site specific conditions.

CALIBRATION OF THE MODEL

For the calibration of the model it is preferable to have measured values for as many variables as possible. In this study calibration only was possible with a minimum set of data. A location in the northern part of the Deurnese Peel area was choosen (5°53'E, 51°26'N), for which the following data were available for the period 1981-1984:

- groundwater level (measured with 15-days intervals)
- water pressure in underlying sandy aquifer (idem)
- precipitation per decade for Deurne (5°48'E, 51°28'N)

Average values (over 30 years) for Penman evaporation per decade were available for Gemert (5°41'E, 51°33'N).

The selected site in the northern part of the Deurnese Peel is a location where after peat excavation a relict with a thickness of ca. 3 meter was left behind. Beneath the peat layers there is a 'gyttja' layer with a thickness of 0.5 m. The latter is formed by both organic and mineral sediments. The relict is superficially drained (small ditches with the bottom at 0,3 m below surface) and consists of strongly humified peat. Water retention characteristics of the different soil layers were analysed and were found to be very similar to those for strongly hunified peat as given by Stokkermans and Wösten (1986).

Values for a and b in Eq. 2 are 2 . 10^{-3} and 1.6 respectively. For maximum capillary fluxes Eq. 1 was used. From Fig. 1 it was derived that for strongly humified peat values for w_m, a, b and c are 100, 25, 3 and 0.2 respectively.

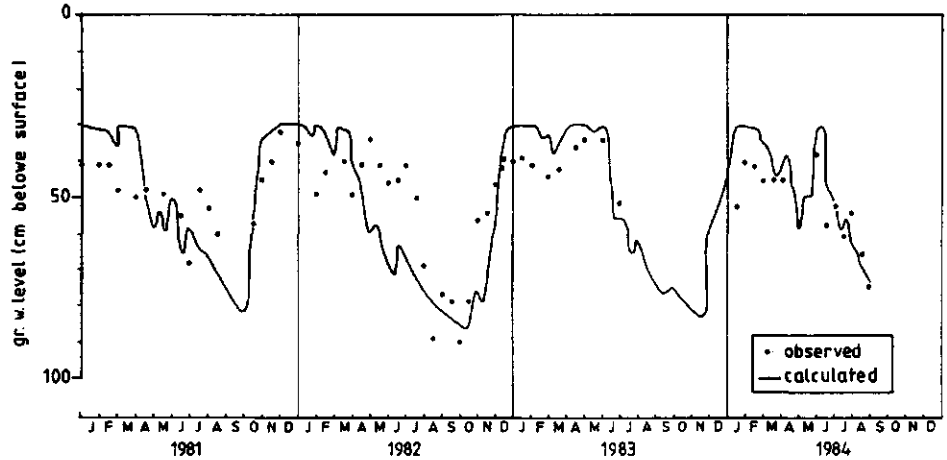

Fig. 2 Measured and calculated values for groundwater fluctuation for the selected location in the Deurnese Peel area.

Table 1. Water balance terms in mm over the period 1981-1984 for the selected location in the Deurnese Peel area.

year	1981	1982	1983	1984
precipitation	863	638	735	859
evapotranspiration	459	442	466	470
downward water losses	101	96	99	103
runoff	303	100	188	268
storage	0	0	-18	+18

Vegetation is dominated by Molinia caerula, with a coverage of 80%, whereas Calluna vulgaris and Erica tetralix cover ca. 20%.

To determine water uptake by roots according to Thornwaite and Mather the thickness of the rootzone was estimated at ca. 0.3 m.

The model SWAMP was used to simulate groundwater fluctuations for the period 1981-1984. Tentative values for vertical resistance (C) of peat and gyttja layers were varied from 1000 to 10.000 days, and values for the vegetation factor (k_c) ranged from 0.6 to 0.8. This factor was taken constant during the vegetation period. It was concluded that for this location, C should be taken equal to 7000 days and k_c should be taken 0.7.The results of the simulation are presented in Fig. 2. For the various years water balance terms as calculated with the SWAMP model are given in Table 1.

The calibration was hampered by the following restrictions:
- the large distance between the selected location and the station with precipitation records (station Deurne at 7 km);
- the absence of information about runoff characteristics.

Taking into consideration these difficulties and the simplifications of the SWAMP model, it may be concluded that the measured and calculated values for the groundwater table over the period 1981-1984 show reasonable agreement.

In spring and early summer of 1982 groundwater levels are somewhat higher than calculated. Partly this might be explained by an incorrect estimation of the site specific parameters that describe runoff at this location. The bottom of the ditches is taken at 0.3 m below surface, but it varies considerably. Also frost might delay runoff.

THE EVALUATION OF ALTERNATIVE WATER MANAGEMENT MEASURES

For the restoration of wet conditions in disturbed bog relicts, one or more of the following measures can be taken:
- the construction of dams (i.e. reduction of runoff);
- the refilling of ditches which reach into the underlying sandy layers. For this purpose peat with a very low permeability has to be used (i.e. reduction of downward water losses);
- the cutting of bushes and trees (i.e. reduction of interception and evapotranspiration);
- the creation of a hydrological bufferzone in adjacent areas where the groundwater level is raised. This results in an increase of water pressure in the aquifer beneath the peat (i.e. reduction of downward water losses).

To evaluate the impact of alternative water management measures for the selected location in the Deurnese Peel, the model SWAMP was applied. For the period 1955-1984 precipitation data per decade were available for the station Deurne. Penman evaporation per decade was estimated using the 30-years average values per decade given for the station Gemert.

As mentioned in the introduction, in present-day bog relicts the upper peat layers may differ strongly from those in undisturbed bogs. For strongly humified peat, soil-physical characteristics (e.g. pore size distribution) are different from those as known for slightly humified peat. The impact of different hydro-physical properties of the upper peat layers was examined. Therefore groundwater fluctuations were simulated for the hypothetic situation that the upper layer consists of young Sphagnum peat. For the latter hydro-physical properties are described by Romanov (1968). From the data given by this author values for parameters a and b in Eq. 2 can be derived. They were estimated at 0.125 and 1.2 respectively. The alternative measures and conditions for which the simulation was made, are the following:
- 1, none;
- 2, dams with maximum water level at the surface;
- 3, as 2, but with water pressure in the sand increased by 1 m;
- 4, dams with maximum water level at 0.15 m above the surface;
- 5, as 2, but with hydro-physical conditions as known for undisturbed young Sphagnum peat

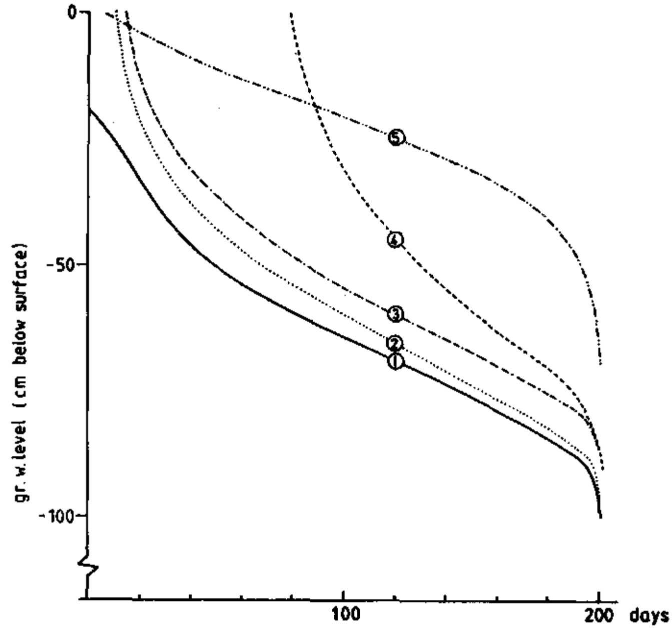

Fig. 3. Frequency distribution for groundwater depth during the period from 1 April to 10 October (200 days) under 5 alternative water management measures and conditions.

Table 2. Water balance terms in mm under 5 alternative water management measures and conditions (precipitation 742 mm = 100%)

No	potential evapotranspiration	actual evapotranspiration	downward water losses	runoff
1	480	455 (61.3%)	99 (13.3%)	188 (25.3%)
2	497	476 (64.2%)	105 (14.1%)	161 (21.7%)
3	494	480 (64.7%)	60 (8.0%)	203 (27.3%)
4	556	516 (69.5%)	101 (13.6%)	125 (16.9%)
5	491	490 (66.2%)	116 (15.6%)	134 (18.1%)

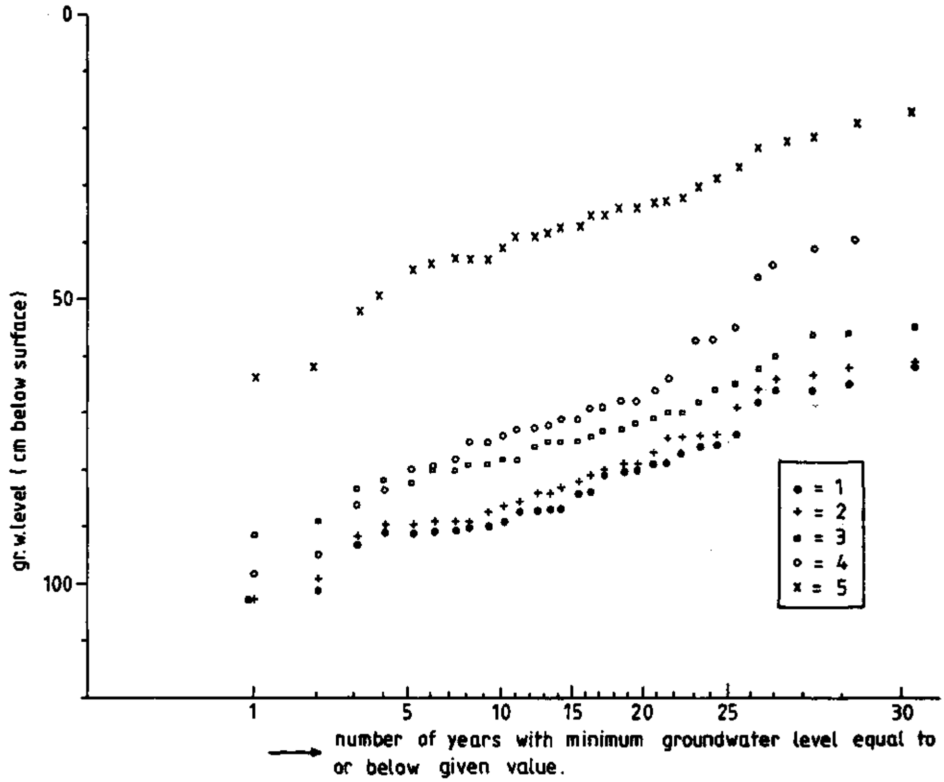

Fig. 4. Frequency distribution of extreme low groundwater levels for 5 alternatives.

Simulated groundwater fluctuations for the period 1955-1984 were analysed. For the vegetation period, which was taken from 1 April to 10 October (200 days), frequency distributions are presented in Fig. 3. The curves in Fig. 3 indicate the number of days in which groundwater levels are higher than a given value. Various authors (Niemann, 1973; Jansen and Kemmers, 1979) have found that these site specific frequency distributions are an important characteristic to explain vegetation response to hydrological conditions.

Minimum values of groundwater depth for each year were analysed. In Fig. 4 the frequency distributions of extreme low groundwater levels are presented for the 5 alternatives. In Table 2 average values of the yearly water balance terms for the 5 alternatives are given.

DISCUSSION AND CONCLUSIONS

From Fig. 2 and Fig. 3 it can be concluded that some water management measures have a very limited impact on the frequency distribution for groundwater depth in the vegetation period.

The construction of dams and inundation (alt. 2,4) do have an important impact on water depth in spring but these measures do not prevent that groundwater levels reach low values at the end of the summer.

For this location in the Deurnese Peel the impact of a bufferzone around the peat relict by which water pressure in the sand is increased with 1 meter, also is very limited (alt. 3).

It can be concluded that groundwater fluctuations, as known for undisturbed highmoor peat, are realized under the conditions of alternative 5 only. The main difference with the other alternatives is that in this case the upper 40 cm of the peat layers was supposed to be a young Sphagnum peat layer with the hydro-physical properties as known from an undisturbed 'living' bog.

From the results of the simulation it can be concluded that if the simplifications of the model SWAMP are valid, for the regeneration of highmoor-bog vegetation the hydro-physical characteristics of the upper layer are of utmost importance. Once a young Sphagnum-peat layer with a sufficient thickness has been established, the conditions are fulfilled to guarantee a suitable groundwater fluctuation pattern over a longer period. The question that remains is, how to create suitable growing conditions for the Sphagnum species, so that an active layer is formed with the desired hydro-physical characteristics. The results of the model SWAMP indicate that the reestablishment of a Sphagnum vegetation directly on a peat layer with the characteristics of the selected site in the Deurnese Peel is very unlikely. Hydro-physical conditions of these layers are not suited and the frequency of groundwater-levels deeper than 40 cm, is too high. In these areas the only practicable solution seems to be the creation of permanent inundated sites, where floating mats of Sphagnum species are able to fluctuate with the water level and permanent water logging of the Sphagnum layers is guaranteed.

After a floating Sphagnum vegetation has established, gradually a thicker layer of young Sphagnum peat will be formed and open water will be colonised. Permanently inundated sites gradually will be changed with temporarly inundated ones and on the long term a raised bog can develop. In such a case hydro-physical conditions are created by the vegetation and its dead organic matter, and the desired hydro-physical conditions for bog regeneration will become permanent, even without permanent inundation. This process is illustrative for an important phenomenon in the succession of vegetation. Species can gradually create the conditions that limit competition with other species and from which their successors (in this case other, more demanding Sphagnum species) can benefit.

The conclusions mentioned above are based upon a simplified simulation of the groundwater level fluctuation. In this study qualitative hydrological aspects were neglected. However, in some regions, present-day nitrogen content in precipitation may well exceed the critical values for some of the more demanding Sphagnum species. Moreover the model SWAMP needs to be tested in more detail for other locations.

REFERENCES

Blankenburg, J., 1986. Moorkundlich-hydrologische Voraussetzung der Wiedervernassung von Hochmooren. Telma, 15 (in prep.)

Caris, J., 1987. Onderzoek naar de mogelijkheden voor toepassing van het waterbalansmodel Swatren voor een hoogveenrestant. MSc-thesis, Dept. of Land and Water Use, Agric. Univ. Wageningen.

Eggelsmann, R., 1969. Uber den unterirdischen Abfluss aus Mooren. Die Wasserwirtschaft, 50: 149-154, Stuttgart.

Eggelsmann, R., 1982. Möglichkeiten und Zielzetzungen für eine Regeneration von Hochmooren -hydrologisch betrachtet. Inf. Natursch. Landschaftspfl. 3: 167-117, Wardenburg.

Haarman, F.G. 1986. Geohydrologisch onderzoek in de Deurnese en Liesselse Peel. MSc-thesis, Dept. of Land and Water Use, Agric.Univ. Wageningen.

Hoeve, J. ter, 1965. Over de waterhuishouding van een hoogveenreservaat in de Engbertsdijksvenen., Cultuurtechn.Tijdschrift. (5), 4: 169-179, Utrecht.

Jansen, P.C. and Kemmers, R.H. 1979. Onderzoek naar de relatie vegetatie-waterhuishouding in het komgrondenreservaat Tielerwaard-West, deelrapport 2: berekening van enkele hydrologische grootheden., I.C.W. nota 1143, Wageningen.

Kuntze, H. and Eggelsmann, R. 1982. Zur Schutzfähigkeit nordwest-deutscher Moore. Telma, 11: 197-212, Hannover.

Niemann, E., 1973. Grundwasser und Vegetationsgefüge. Nova Acta Leopoldina suppl. nr. 6, band 38. Barth, Leipzig.

Romanov, V.V., 1968. Hydrophysics of bogs. Ed. Monson Bindery Ltd., Jerusalem.

Schouwenaars, J.M., 1978 De Deurnese en Liesselse Peel; verslag van een onderzoek naar vegetatie en waterhuishouding. MSc-thesis, Dept. of Land and Water Use, Agric. Univ. Wageningen.

Schouwenaars, J.M., 1982. Massnahmen im Wasserhaushalt der niederländischen Hochmoorreste - Zur Kenntnis der Anforderungen für ~~eine~~ Hochmoorregeneration. Telma, 12: 219-234.

Schouwenaars, J.M. 1987. A simple method to estimate specific equilibrium soil water content in a uniform soil. Journ. of Hydrology (95): 13-17.

Stokkermans, J.S.C. and Wosten, J.H.M., 1986. Bodemfysische karakteristieken van 7 veenhorizonten uit de Groote Peel. Stiboka, report nr. 1907, Wageningen.

Thornthwaite, C.W. and Mather, J.R., 1954. The computation of soil moisture in: Estimating soil tractionability from climatic data Publ. in Climatology vol. 7 (3): 397-402, Centerton, New Yersey.

HYDROLOGICAL RESEARCH IN DISTURBED BOGS AND ITS ROLE IN DECISIONS ON WATER MANAGEMENT IN THE NETHERLANDS

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ABSTRACT

In disturbed bogs attempts are made to restore the hydrological conditions required for the reestablishment of bog vegetation.
A simulation model for groundwater fluctuations is used to evaluate different water management options. Fluctuations are strongly influenced by the hydro-physical properties of the peat relicts. The impact of internal- and external water management measures depend on hydrological conditions, such as the fraction of the area covered with water, its spatial distribution and seepage to the underlying aquifer.
It is concluded that hydrological research primarily should focus on the selection of the most suitable sites for restoration.
In areas where seepage exceeds 150 $mm.year^{-1}$, bufferzones might be recommended. Detailed models of plant-soil-water relations are only useful when site-specific hydrological characteristics are known. If not, simple models are preferred. Further research on hydrological constraints for bog regeneration is needed to develop criteria for decisions on water management. Some results of field research in the Engbertsdijksvenen area are presented.

KEYWORDS

Hydrology of disturbed bogs; Restoration; Water management; Simulation models

INTRODUCTION

In The Netherlands bog relicts cover ca. 9000 ha, which is only 5% of the area covered by bogs in the 17th century. In disturbed bogs hydrological conditions are different from those in undisturbed bogs. Vegetation indicates relatively dryer conditions with species as *Molinea caerulea*, *Calluna vulgaris* and *Betula pubescens*. In many areas relicts of the original bog-forming vegetation can be found such as *Sphagnum* species (e.g. *S.cuspisatum*, *S.papillosum*, *S.magellanicum*, *S.rubellum*), *Andromeda polifolia*, *Oxycoccus palustris* and *Narthecium ossifragum*. In some areas regrowth of *Sphagnum* can be observed, mostly in and around permanent inundated sites, where floating mats with ombrotrophic vegetation have developed (Schouwenaars,1982).

In The Netherlands and north-western Germany most of the bog relicts are managed as nature reserves or will be managed as such when peat mining activities have ended. Because of the scarcity of oligotrophic wetlands in this part of north western Europe, the main objective for management in disturbed bogs is the restoration of suitable conditions for the reestablishment of bog vegetation. The problems related to the hydrology of these areas are discussed by Blankenburg and Kuntze (1987). Eggelsmann (1987) describes experiences in northwestern Germany and presents guidelines for rewetting and restoration.

Activities of the peat mining companies have resulted in many open drains, often reaching into the underlying sandy aquifer. Alternative methods of peat excavation have resulted in differences in topography and relief. In The Netherlands the upper slightly humified (Sphagnum-)peat layers mostly were removed and most disturbed bogs consist of relicts of strongly humified peat.

In many areas it is possible to create inundation after refilling deep open drains and the construction of dams. However, even after full saturation in the winter period, frequently groundwater depth in summer is more than 50 cm below surface. Hydro-physical properties of the peat layers, which are completely different from those in undisturbed bogs, are of great importance to understand this phenomenon. In humified peat, water storage capacity and ability to shrink and swell are lower than in young Sphagnum peat.

In The Netherlands both internal- and external water management measures are taken to restore the required hydrological conditions. Internal water management focusses on the increase of storage capacity by creating open water within the area. External management focusses on the reduction of downward water losses by creating hydrological bufferzones around the area (v.d.Molen,1981).

A simulation model for groundwater fluctuations was developed to evaluate the impact of these water management measures under different conditions (Schouwenaars, 1988). In this study different water management options are compared and the importance of research on site specific hydrological characteristics is discussed.

MODELLING THE WATER BALANCE OF DISTURBED BOGS

Introduction

In peatlands spatial variability of hydro-physical soil properties is very high. These properties influence hydrological conditions and plant growth. Nutrient status of the soil, grazing, frequency of fires and vegetation management are closely related to vegetation development. Composition and structure of the vegetation in and above the soil are important for its water use. Due to lack of exact knowledge of both plant- and site specific characteristics, modelling of these plant-soil-water relations is only possible when many assumptions are made.

A detailed model: SWATRE

Detailed one- and two-dimensional models are available to describe water movement in a soil. Calibration and validation of these models is mostly done for agricultural crops. An example is the SWATRE model in which the soil profile is divided into layers with different hydraulic conductivity and water retention characteristics. At the end of each time step soil water distribution within the profile is determined, using numerical solutions for the non-steady equations of water flow. A distinction is made between soil evaporation and transpiration using information about the development of the leaf-area index. The model SWATRE requires daily input data. A description of the model is given by Belmans et al.(1983). Caris (1987) applied this model to simulate groundwater fluctuations in a disturbed bog covered with *Molinea caerulea*. For a site with strongly humified peat, water retention characteristics and unsaturated hydraulic conductivity under different pressure heads were determined. For the calculation of horizontal and vertical water losses permeability and thickness of the peat layers were determined. Water pressure in the underlying sandy aquifer was measured. Daily precipitation- and (Penman-)evaporation data were used.
In the SWATRE model a description of the water uptake function of the plant is needed, i.c. parameters have to be given which describe to what extent water use is limited under different pressure heads in the rootzone. Results of the SWATRE model strongly depend on these parameters. For most (semi-)natural vegetation no reliable information about the water uptake function is available. The SWATRE model is also very sensitive for values of unsaturated hydraulic conductivity. These considerations lead to the conclusion that for its application in disturbed bogs very detailed field research is required. Given the spatial diversity in disturbed bogs it is questionable whether detailed models, like the SWATRE model, should be used to evaluate water management options.

A simple model: SWAMP

The model SWAMP (Soil WAter Modelling in Peat) is a water balance model based upon simple concepts of soil water distribution in the unsaturated zone and water uptake by plants. It is supposed that in the peat layers near-equilibrium conditions prevail. For these conditions a unique relation between water storage in the soil and groundwater level can be derived (Schouwenaars,1987). Under dry conditions water storage may be less than for equilibrium conditions and then soil water content and water uptake by roots is determined according to the method described by Thornthwaite and Mather(1954). Water balance terms are calculated for 10-days periods.

Water retention characteristics, depth of rootzone, resistance to downward water flow and water pressure in the underlying aquifer must be known. Capillary rise has to be described as a function of groundwater depth. A brief description of the SWAMP model and its application is given by Schouwenaars(1988).

A comparison of detailed and simple models

For a location in the Deurnese Peel area in The Netherlands both the SWATRE- and SWAMP model were used. The same input data were used and differences in results are caused by differences in concepts used to describe water flow. Results of both models are very similar. Calculated groundwater fluctuations correspond with measurements. However, calibration of the models is only possible with reliable data for evapotranspiration and seepage. Different sets of values for these two variables result in the same pattern of groundwater fluctuations. When e.g. evapotranspiration is estimated too low, a good aproximation of measured groundwater levels can be reached by an overestimation of seepage. This is a generally known problem in modelling which only can be reduced if values for model variables are exactly known. In the case studied above, these data were not available.

Research for model development

In the Engbertsdijksvenen area, situated in the eastern part of the Netherlands, lysimeter experiments have started to study potential and actual evapotranspiration of *Molinea caerulea*, *Calluna vulgaris* and *S.papillosum*. The lysimeters are weighted at intervals, varying from 3 to 9 days. From these observations a relation between a calculated reference evapotranspiration (e.g. Penman) and actual evapotranspiration for different soils and groundwater levels can be derived. This research has to be carried out during some years with both wet and dry summer periods. For the interpretation of its results development of leaf-area during the vegetation period must be described in detail, because spatial variability of vegetation and soil cover in disturbed bogs is high. In different parts of the Engbertsdijksvenen runoff is measured. Downward water losses are determined by analysing the water balance in the winter period when evapotranspiration is negligible.

For the application of water balance models capillary fluxes must be described. For the peat layers used in the lysimeters water retention curves and unsaturated hydraulic conductivity were determined. Capillary fluxes under different pressure heads in the rootzone were calculated. When it is assumed that for a given groundwater depth pressure head in the rootzone is constant, it is possible to derive a unique relation between maximum capillary flux and groundwater level. This method is applied in the SWAMP model.
For humified peat (H 6-7) results are presented in Fig.1.

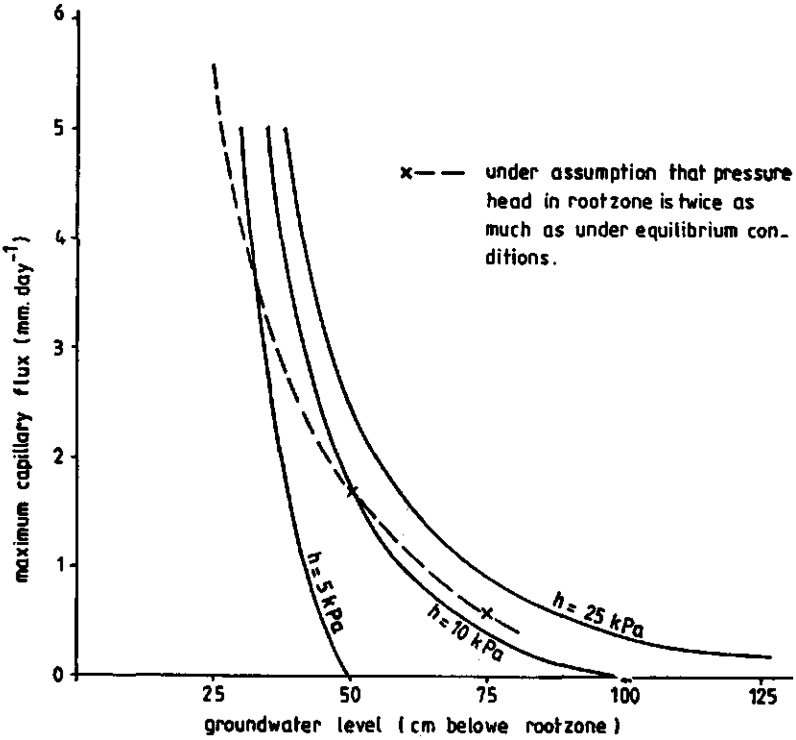

Fig.1 Maximum capillary fluxes in strongly humified peat (H6-7) under different pressure heads in the rootzone (h)

Changes in water volume (Δ V, $cm^3.cm^{-2}$) were determined in relation to changes in groundwater level (Δ W, cm) and storage coefficients (Δ V / Δ W, -) were calculated. For illustration, some results are presented in Fig.2. During the period of measurement changes in surface level did not occur.

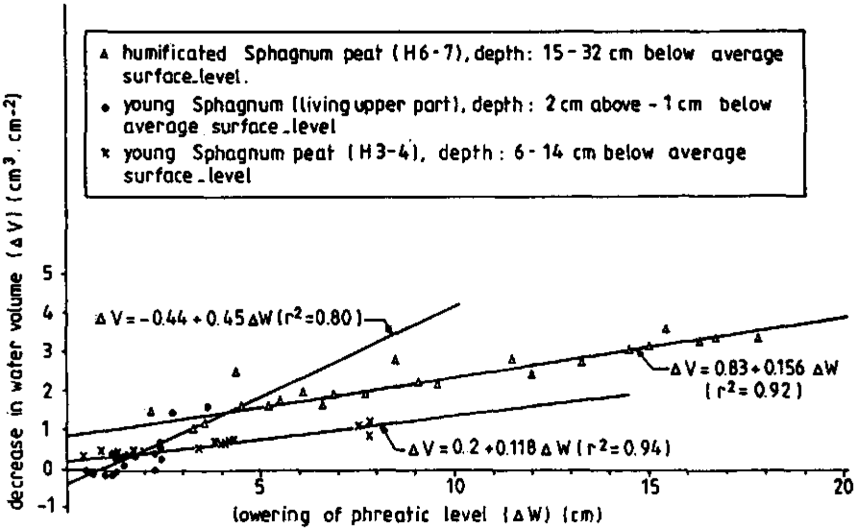

Fig.2 Relation between changes in water volume and changes in groundwater level for different peat layers

In bogs storage capacity is influenced by shrinkage and swell of the upper peat layers. To illustrate its impact on storage capacity an example from the Engbertsdijksvenen area is discussed. In a peat relict (thickness ca.4m.) with an upper layer of sligh-tly humified peat (H 4-5) average surface level fluctuation is 5 cm.year^{-1}. Phreatic level fluctuates from 55 to 5 cm below a reference level. At maximum shrinkage dry bulk density is taken at 0.10 gr.cm^{-3}. If shrinkage and swell is restricted to the upper meter, average bulk density at maximum swelling is 0.095 gr.cm^{-3}. When water content in the upper 5 cm is taken at 50% then ca. 3 cm.^{3}cm^{-2} is needed to realize this swelling with a constant phreatic level. The latter raises 50 cm. and with a storage coefficient of 0.12 (as calculated for moderately humified Sphagnum peat in Fig.2) this corresponds with an increase in water storage of 6 cm^{3}.cm^{-2}. So, total increase in water storage is 9 cm^{3}.cm^{-2}, while phreatic level changes from 55 to 10 cm below surface. This means that the ratio between change in water storage (cm^{3}.cm^{-2}) and change in phreatic level (cm below surface!) is 0.20 which is almost twice as much as estimated from Fig.2. Research as discussed above is essential for the further development of adequate water balance models for disturbed bogs.

SIMULATION OF GROUNDWATER FLUCTUATIONS IN THE ENGBERTDIJKSVENEN

UNDER DIFFERENT WATER MANAGEMENT OPTIONS

Area and spatial distribution of open water

In open water, level fluctuations are limited when compared with those of the phreatic level in a soil. In disturbed bogs inundated sites can be created and when lateral water exchange occurs between these sites and neighbouring peat ridges, groundwater fluctuations in the latter will be reduced. Infiltration rates depend on permeability of the peat layers. The amount of infiltrated water reaching a given site furthermore depends on its distance from open water. In disturbed bogs, as a consequence of peat mining activities, a great variability exists in both area and spatial distribution of open water. By water management measures these characteristics can be manipulated to limit groundwater fluctuations.

Three different water management options

In the Engbertsdijksvenen area the hydro-physical properties of different peat layers were examined. For an analysis of their impact upon groundwater fluctuations in this study the following two hypothetical soil types were selected (Table 1):

TABLE 1

Summary of hydro-physical properties in 2 hypothetical soil types

	soil A	soil B
maximum water content (%)	80	90
dry bulk density ($gr.cm^{-3}$)	0.20	0.10
storage coefficient ($cm^3.cm^{-2}$)	0.15	0.30

In this study the impact of different water management options is examined for a hypothetical area with a fraction open water of 0.10. The model SWAMP is applied for the two different soil types (Table 1).

A simple approach is followed in which infiltration rates at a given site depend on soil type (permeability) and spatial distribution of open water. When there is a difference between phreatic level and open water level, the water volume ($cm^3.cm^{-2}$) which has to be drained or infiltrated to equal both levels can be determined. When the spatial distribution of open water is limited (concentration of open water at certain sites), it is assumed that actually 25% of this volume is drained or infiltrated. When the open water is equally distributed within the area, this value is taken at 50%. This implies that in soil

B with a storage capacity of 30%, (Table 1) in both cases the volume of infiltrated water is twice as much as in soil A.

It was found that in the Engbertsdijksvenen area large differences in seepage exist between the different parts of the area. In this study two hypothetical cases are distinguished with downward water losses of 100 $mm.year^{-1}$ and 200 $mm.year^{-1}$, respectively.

Under the measured differences between phreatic level and water pressure in the underlying aquifer these values correspond with a vertical resistance in the peat layers of 4000 and 2000 days.
For the Engbertsdijksvenen Ganzevles and Janmaat (1987) examined horizontal water flow in the underlying aquifer. They concluded that the creation of a bufferzone around the area will raise water pressure in the aquifer only locally and with a maximum of 0.5 m. In this study the impact of an increase in water pressure is examined in option 1, where downward seepage is reduced by 50% (external water management measure). Internal measures are examined in options 2 and 3 where an increase of the permanently inundated area is simulated. In option 2 the percentage of open water is increased from 10% to 25%. In option 3 it is increased from 10% to 50%.

The model SWAMP is applied to simulate groundwater fluctuations in the Engbertsdijksvenen over a 30-years period (1957-1986). Daily precipitation data were available. For open water evaporation (30-years) average values per decade are used, calculated with the Penman-formula. For areas covered with vegetation potential evapotranspiration was estimated at 80% of open water evaporation.

Results and conclusions
In the period 1957-1984 mean annual precipitation was 754 mm. Mean annual evapotranspiration of areas with vegetation was ca. 480 mm and evaporation in open water was ca. 600 $mm.year^{-1}$.
The frequency distribution of the groundwater level for the actual situation and for the 3 options is analysed. Groundwater levels with a probability of exceedance of 80% during the summer-period (1 April-15 October) are presented in Table 2 and 3. The 80%-probability level is arbitrarily choosen and serves as a criterion for decisions when groundwater levels should be as high as possible.
The required ecological conditions for the reestablishment of bog vegetation are not fully understood. To guarantee a minimum removal of nutrients in the vegetation period, the frequency of superficial runoff in the summer period might be of importance. In Table 2 and 3 also the probability of exceedance of a groundwater level of 10 cm below surface is presented, which is arbitrarily choosen as a criterion for decisions when frequency of superficial flow should be increased.

TABLE 2

Characteristics of groundwater fluctuations in soil A for different water management options (period 1957-1986)

seepage	100mm.year^{-1}				200mm.year^{-1}			
infiltration	25%		50%		25%		50%	
	gwl[1]	fr[2]	gwl	fr	gwl	fr	gwl	fr
-ACTUAL SITUATION (fraction water: 0.10)	68	14%	65	15%	81	10%	78	10%
-OPTION 1 (ca. 50% reduction in seepage)	58	19%	57	20%	66	15%	63	15%
-OPTION 2 (fraction water: 0.25)	58	15%	51	17%	75	9%	69	10%
-OPTION 3 (fraction water: 0.50)	54	16%	44	19%	75	9%	66	10%

[1] groundwater level below surface, which is exceeded during 80% of the vegetation period (1 April-15 October)

[2] frequency of exceedance of a groundwaterlevel of 10 cm below surface during the vegetation period

TABLE 3

Characteristics of Groundwater fluctuations in Soil B for Different Water Management Options (period 1957-1986)

seepage	100mm.year^{-1}				200mm.year^{-1}			
infiltration	25%		50%		25%		50%	
	gwl[1]	fr[2]	gwl	fr	gwl	fr	gwl	fr
-ACTUAL SITUATION (fraction water: 0.10)	45	22%	44	24%	59	12%	58	12%
-OPTION 1 (ca. 50% reduction in seepage)	39	28%	38	30%	45	22%	44	23%
-OPTION 2 (fraction water: 0.25)	39	23%	38	26%	58	12%	56	12%
-OPTION 3 (fraction water: 0.50)	39	22%	35	25%	63	8%	62	8%

[1], [2] see Table 2

Differences in hydro-physical properties of the 2 soil types cause great differences in results. It can be concluded that once when *Sphagnum* regrowth occurs, storage capacity in the upper layer will increase and gradually the required hydro-physical properties will be restored. Probably perspectives for this development are best in floating mats at permanently inundated sites.

For a given soil type results of the different options greatly depend on downward water losses.
The average yearly seepage cannot exceed the average precipitation surplus of the region. In the Engbertsdijksvenen a yearly seepage of about 200 $mm.year^{-1}$ in combination with a high storage capacity in the area (soil B), leads to frequent winter periods without superficial discharge. Here, in these years water levels in the following summer are relatively low. Under these conditions an increase of inundated sites does not have a desirable impact. When more than ca. 50% of the area consists of open water even a negative impact is observed (Table 3).
When seepage is more than ca. 150 $mm.year^{-1}$, it should be examined if it can be reduced to ca. 100 $mm.year^{-1}$. If not, perspectives for the improvement of hydrological conditions are poor.

In the Engbertsdijksvenen, water management in peat relicts with a low storage capacity (stor.coeff.in soil < 0.25) and with downward seepage less than ca. 150 $mm.year^{-1}$, should focus on an increase of storage capacity by the creation of inundated sites. In soils with low permeability its positive impact will be greatly improved when these inundated sites are equally distributed over the area in small units.
When water management focusses on an increase of superficial runoff during the vegetation period, then also in relicts with relatively low downward losses, attempts to reduce these losses should be recommended.

DISCUSSION AND CONCLUSIONS

The study presented above clearly demonstrates that perspectives for the restoration of the required hydrological conditions depend on site-specific hydrological conditions. Given the spatial diversity of these characteristics, field survey should focus on the selection of the most suitable sites. In many bog relicts areas can be found where only internal water management measures should be considered. As mentioned before regrowth of Sphagnum will improve the hydrophysical conditions in the upper peat layers. This implies that external water management measures only have a temporary function (some decennia). Detailed knowledge of the plant-soil-water relations is only useful when combined with detailed information about hydrological characteristics of a given site. If these are only partially known, simple models of the plant-soil-water system should be used.

Decisions on water management must be based on well established criteria derived from environmental constraints for bog regeneration. More research on the hydrological aspects is required.

References

Blankenburg, J. and Kuntze, H., 1987. Moorkundlich-hydrologische Voraussetzungen der Wiedervernassung von Hochmooren. Telma 17, 51-58.

Caris, J., 1987. Onderzoek naar de mogelijkheden voor toepassing van het waterbalansmodel Swatre voor een hoogveenrestant. Dept. of Land and Water Use, Agricultural University Wageningen.

Eggelsmann, R., 1987. Okotechnische Aspekte der Hochmoor-Regeneration. Telma 17, 59-94.

Ganzevles, P. and Janmaat, R., 1987. Een hydrologisch modelonderzoek naar de waterhuishouding van het natuurreservaat De Engbertsdijks-venen en zijn omgeving. Dept. of Land and Water Use, Agricultural University, Wageningen.

Molen, W.H.van der, 1981. Uber die Breite hydrologischer Schutzzonen um Naturschutzgebiete in Mooren. Telma 11, 213-220.

Schouwenaars, J.M., 1982. Massnahmen im Wasserhaushalt der nieder-landischen Hochmoorreste - Zur Kenntnis der Anforderungen fur eine Hochmoorregeneration. Telma 12, 219-234.

Schouwenaars, J.M., 1987. A simple method to estimate specific equilibrium soil water content in a uniform soil. J. of Hydrology 95, 13-17.

Schouwenaars, J.M., 1988. The impact of water management upon ground-water fluctuations in a disturbed bog. Agric.Water Manag. 14, 439-449

Thornthwaite, C.W. and Mather, J.R., 1954. The computation of soil moisture. In: Estimating soil tractionability from climatic data. Pbl. in Climatology 7, 397-402. Centerton, New Yersey.

CALIBRATION OF THE MODEL SWAMP

1. Description of the SWAMP model

The model SWAMP (Soil Water Modelling in Peat) was developed as a tool for the evaluation of different water management options in bog relicts. It is a quasi-two dimensional model, which determines the water balance terms at a given site, the depth of the phreatic level and the water content in the unsaturated zone. To find analytical solutions for the physically based flow equations, a number of simplifying assumptions were used. The most important are:

- the different soil layers are homogeneous
- in each time step (decades; 10 or 11 days) water flow in the soil is stationary
- in the unsaturated zone near-equilibrium conditions prevail
- maximum capillary flux is a function of the groundwater depth
- water extraction from the rootzone is a linear function of the soil water content

A short description of the model was given in chapter 3.1. For the simulations presented in chapter 3.2, some of the original model concepts were modified. Here, the most important modifications are treated without going into details.

i. For near-equilibrium conditions in the unsaturated peat layers, it is possible to derive a unique relation between the total volumetric water content in the entire soil profile and the depth of the phreatic level (Schouwenaars,1987). Field studies in the Engbertsdijksvenen have shown that for peat soils the water retention properties, as obtained from 100 cc undisturbed soil samples often yield too low values for the water storage coefficients. In a study of Eggink (1988) the water storage coefficients, thus obtained, appeared to be the major source of error when applying the SWATRE model. Better estimates on the relation between groundwater depth and water storage were obtained from the lysimeter experiments treated in chapter 4.2.
In these experiments also the potential evapotranspiration of a *Molinia* vegetation was accurately determined. These lysimeter values were finally used in the models to be verified.

ii. At certain sites horizontal water flow may occur between peat ridges and neighbouring inundated sites or waterholding trenches. During dry and warm periods a diurnal pattern can be observed, because during the day soil water is extracted by evapotranspiration, followed by (partial) refilling at night (Fig.1). In the SWAMP model, such horizontal water flow

($mm.day^{-1}$; infiltration or drainage) is determined as a function of the difference between phreatic level and open water level (m) and the drainage resistance of the system (days). This method is to be preferred over the tentative method used in the sensitivity analysis (chapter 3.2). The drainage resistance can be determined from measurements on horizontal permeability and width of the peat ridges.

iii. In the SWAMP model the procedure for the determination of runoff has been changed after the analysis of discharge measurements in small catchments in both the Engbertsdijksvenen (Sterk, 1990) and Lichtenmoor in the Federal republic of Germany (Schouten, 1988). Runoff can be determined in two ways, depending on the conditions at the simulated site:

- as a function of the open water level in an important drain, situated near the site selected for groundwater simulation.
- as a function of the groundwater level at the site, when such drain is absent.

This function is simply described with one or two parameters, obtained from field measurements on the relation between the discharge, measured at the outflow point of the catchment and the water level (open water or groundwater) at the observation site.

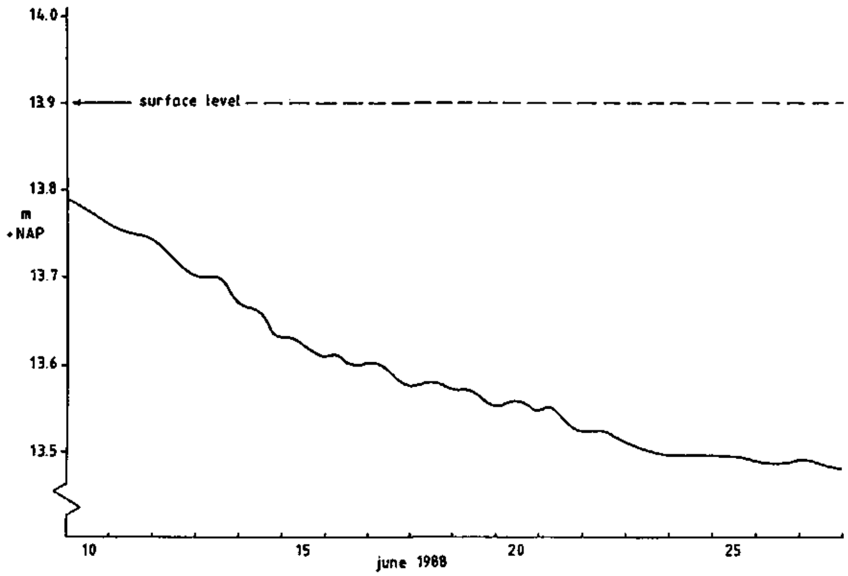

Fig.1 Daily groundwaterlevel fluctuations in a peat ridge between two waterholding drains (distance:4 m) in a rainless period in june 1988 (Engbertsdijksvenen)
-at the end of the period the water level reaches the bottom of the drain and horizontal water flow becomes negligible

iv. In the model the basic time step is 10 days. For discharges from open water courses, however, this time step is too long and time steps of one day or smaller are required. For the calculation of the water balance terms the decades were divided in daily periods. To keep the model as simply as possible, the daily values for precipitation and evapotranspiration were inserted as averages over the decade. For every decade the daily water balance terms are totalized and the (ground)water level at the end of the decade is determined. It will be shown that this results in somewhat different values for runoff as calculated with real daily values for precipitation and evapotranspiration, whereas calculated groundwater levels are similar.

2. The collection of data in the Engbertsdijksvenen

In chapters 4.1, 4.2 and 4.3 the results of hydrological research in the Engbertsdijksvenen over the period 1987-1989 are presented. In this chapter information obtained from these field studies will be used for a calibration of the SWAMP model.

meteorological data
Rainfall was recorded at different sites within the study area. Meteorological equipment has been installed to determine reference evapotranspiration with the method presented by Makkink (1957). Values for open water evaporation were derived from these Makkink values, using the correction factors presented by De Bruin (1987).

lysimeter studies on evapotranspiration
Lysimeter experiments were carried out to study potential evapotranspiration of *Molinia caerulea* and *Sphagnum papillosum* in relation to the above mentioned reference evapotranspiration. Different treatments were applied to study the actual evapotranspiration at different depths of the water table. Undisturbed soil columns with vegetation were taken with a sampling device, having a diameter of 40 cm and a length of 50 cm. These columns were inserted in a lysimeter of the same size, closed at the bottom. 4 columns were covered with *Molinia caerulea* and 8 with *Sph. papillosum*. The selected sites represent the most important differences in peat properties within the study area.

soil physical properties
The lysimeter experiments provide accurate field data on water storage coefficients in the different peat layers. This coefficient (-) is defined as the ratio between the change in water volume ($cm^3.cm^{-2}$) and the change in water table depth (cm). Total weight of the lysimeters and water table depth are measured simultaneously and this enables an analysis of the water storage coefficient. For the peat layers used in the lysimeters, undisturbed samples of 100 cc were taken and water retention curves and unsaturated

hydraulic conductivity were determined. The observed water storage coefficients indicate that the fraction available soil water in these soils is higher than determined from the water retention curves. The differences probably can be explained by biological activity in the 25-35 cm deep rootzone (e.g. root channels and cracks, which were excluded in the 100 cc samples). Based upon k-h-θ relations obtained for the 100 cc samples capillary fluxes were determined for different suction heads in the rootzone.

superficial runoff from small catchments

In the study area 3 catchments were selected (Engbertsdijk-Oost (EO): 25 ha, Nieuwe Leidijk (NL): 23 ha, Oude Leidijk (OL): 15 ha). Discharge measurements started in 1987. In EO 30-40% of the area is covered by former drains, permanently waterholding and densely distributed within the area at distances from 3-5 meter. Thickness of the peat relicts varies from 2.5 - 3.5 meter. The highest parts are covered with less humified peat. Runoff reacts promptly on rainfall (after 1-2 days) but remains rather low (in the winter 1988-1989 maximum run-off was 3 $mm.day^{-1}$) and shows less fluctuations than for the other catchments.

In NL open water covers 10-15%. At the bottom of an inundated site of 2 ha, the peat layer is 0.5 to 1.0 m thick. In the other parts thickness of the peat relicts varies from 1.5 - 2.5 m., with some less humified peat at the highest parts. In the measurement period the maximum discharge was 7 $mm.day^{-1}$ and peak discharge occurred 2 days after heavy rainfall.

In OL open water area is 80% with only 20-30 cm peat at the bottom. Here maximum observed discharge was 3 $mm.day^{-1}$. After heavy rainfall peak discharges occured after 5 days. This illustrates the high storage capacity in areas with many inundated sites.

vertical and lateral subsurface water losses

With weekly observations on both phreatic and open water levels, combined with some groundwater level recorders it was possible to select periods of some weeks during which total water storage within the catchments did not change. For these periods, precipitation, evapotranspiration (very low in winter) and runoff were determined. The unknown term of the water balance, i.c. total vertical and lateral subsurface water loss, was calculated. In wet periods with a high water level these losses were highest and then lateral flow in the upper soil layers may be significant. From the water balance studies it appeared that the vertical hydraulic resistance of the deeper strongly humified peat layers is about 3500-4000 $days.m^{-1}$. In the Engbertsdijksvenen yearly downward seepage varies from 80 $mm.yr^{-1}$ to the average precipitation surplus in the region, which is about 200 $mm.yr^{-1}$. At sites which receive surplus water from adjacent areas, total yearly seepage can still be larger.

3. Calibration

3.1 method

In this chapter the results of the model calibration for three sites are presented. In the calibration procedure, values for the different parameters used in the SWAMP model were determined with the results of the field research, described above. After a few trial runs only a few parameters which were difficult to assess correctly, like those describing capillary flow, needed to be determined by inverse parametrization. The calculated groundwaterlevel at the end of a decade (cm below surface) and total runoff per decade (mm) are compared to the observed values.

3.2 the Engbertsdijk-Oost catchment

This catchment is rather homogeneous. As a result of the peat cutting method practised here, peat ridges of 3 to 6 m in width lie in between water holding trenches (1 to 3 m in width). At location B156, situated in the centre of the catchment, the groundwaterlevel in the middle of the ridge was observed weekly. The site is covered with *Molinia* and potential evapotranspiration was derived from the reference evapotranspiration (Makkink) using the correction factors presented in chapter 4.3. The fraction open water at this site is set at 30%. The open water level almost equals the phreatic level in the centre of the ridge and the drainage resistance can be taken very low (50 days). At this site the thickness of the peat layers is 3.5 m. The upper 0.5 m consists of moderately humified peat. Based upon the results of the study on vertical hydraulic resistance (chapter 4.1) this resistance is set at 13000 days for the ridge and at 11250 days for the peat layer under the bottom of the trenches. The piezometric head in the sand was derived from weekly measurements at three nearby locations. The water storage coefficient of the peat was set at 20%, in accordance with the values measured in the lysimeter experiments presented in chapter 4.2. Capillary water supply is supposed to equal evapotranspiration demand. A linear relation was found between superficial discharge (i.c. runoff) from the catchment and the groundwaterlevel at B156. The latter is almost equal to the open water level. The water balance is simulated for the period from 1 October 1988 to 30 september 1989. Precipitation and Makkink-reference evapotranspiration per decade are presented in Table 1.
The calculated and observed values for the phreatic level are presented in Fig.2 and for runoff in Fig.4.

TABLE 1

Precipitation (P) and Makkink-reference evapotranspiration (E_r) (mm) per decade in the period 1 October 1988 - 30 September 1989

	Oct			Nov			Dec			Jan			Feb			March		
dec	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
P	44	10	2	6	33	15	37	48	8	12	9	3	7	42	13	31	23	26
E_r	10	6	7	5	3	2	2	1	2	2	2	4	5	5	5	8	8	17

	April			May			June			July			Aug			Sep		
dec	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
P	21	20	17	0	10	0	28	0	30	38	0	35	17	6	43	7	31	17
Er	12	13	16	32	32	46	23	48	33	32	27	33	27	31	21	19	18	12

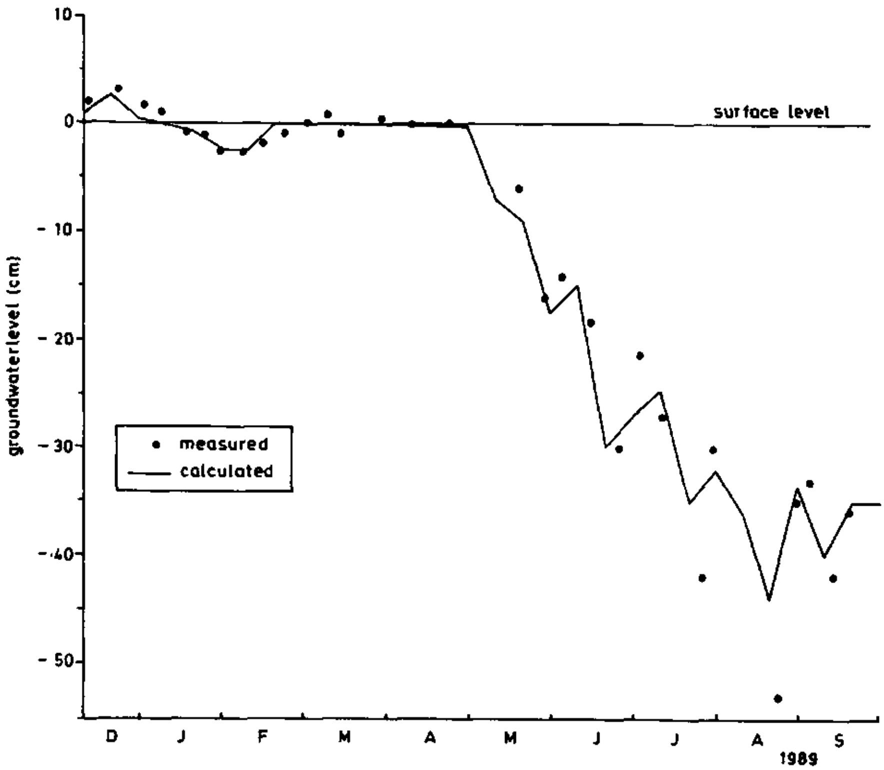

Fig.2 Calculated and measured groundwaterlevel at location B156

At location B313 a water level recorder was installed. Here, the fraction open water is 40%. It is a wet site with a rather open vegetation composed by *Molinia caerulea*, *Eriopherum vaginatum* and *Erica tetralix*. As an adjustable parameter two values for potential evapotranspiration were taken: 90% and 100% of those of a dense *Molinia* vegetation. The soil water storage coefficient is set at 30% and capillary supply is assumed to satisfy evapotranspiration demand. The thickness of the peat layer is the same as for location B156 and the same values for vertical hydraulic resistance are used. Also here, the drainage resistance is taken very low (50 days). Again, a linear relation between water level and runoff could be derived. Results are presented in Fig.3. It seems that 90%-potential evapotranspiration gives the best results, in accordance with the rather open character of the vegetation.

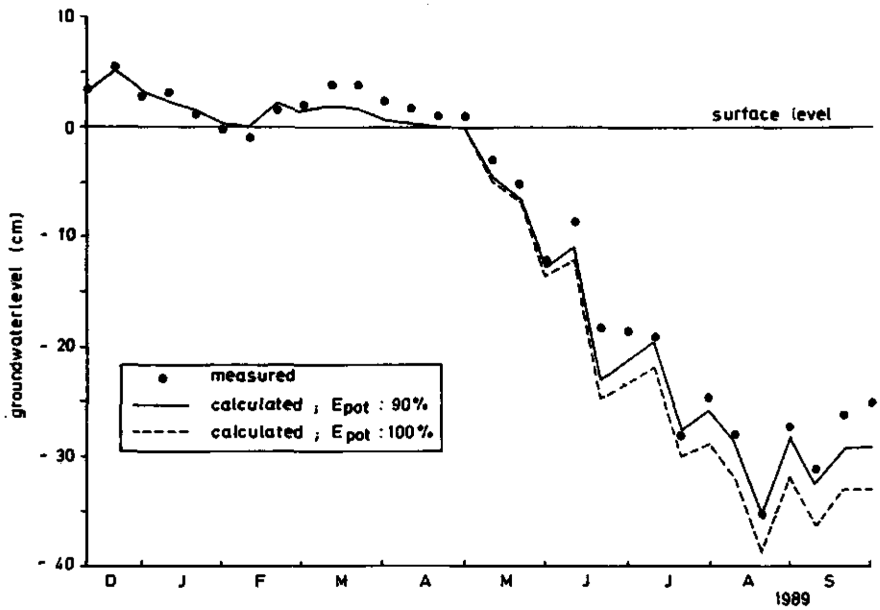

Fig.3 Calculated and measured groundwaterlevel at location B313

Calculated runoff in the simulations for site B156 and B313 (with 90%-potential evapotranspiration) is compared with the observed values for the entire EO-catchment (Fig.4). For site B313 an extra run with the SWAMP model was made with real daily values for precipitation and potential evapotranspiration, instead of the average daily values per decade. The results are presented in Fig.4.

The difference between calculated values for runoff (X_c) and measured values (X_m) can be expressed as:

$$F = \sum_{i=1}^{n} (X_{ci} - X_{mi})^2$$

This F-value is determined for the two runs for site B313 (F_{313} and F_{313D}, the latter with real daily input) and for the run for site B156 (F_{156}). The model results for runoff of both sites (B313 and B156) were averaged and these average values were compared with the measured ones ($F_{313/156}$).
The 'relative efficiency' (RE) is used as an indicator for the goodness of fit for these different runs (McCuen and Snyder, 1986).
For its calculation a reference run has to be selected.

$$RE = 1 - F_{run\,x} / F_{reference}$$

Here, the run for site B313 with the average daily input is choosen.
For B156, RE = -0.21; for B313 with real daily input, RE = -0.26; for B156/B313 combined, RE = 0.16.

It can be concluded that errors in the calculation of runoff are mainly due to errors in parameter estimation for runoff. The differences between the sites within one catchment (B156 versus B313) are greater than the differences between measured and calculated values. The impact of using average instead of real daily meteorological data is of less importance. For all simulations the total runoff is in good agreement with the measured discharge (Fig.4). The totals for the different simulations are similar because in the SWAMP model, under the given weather conditions, the total amount of runoff depends on the vertical hydraulic resistance of the peat layers (downward losses).

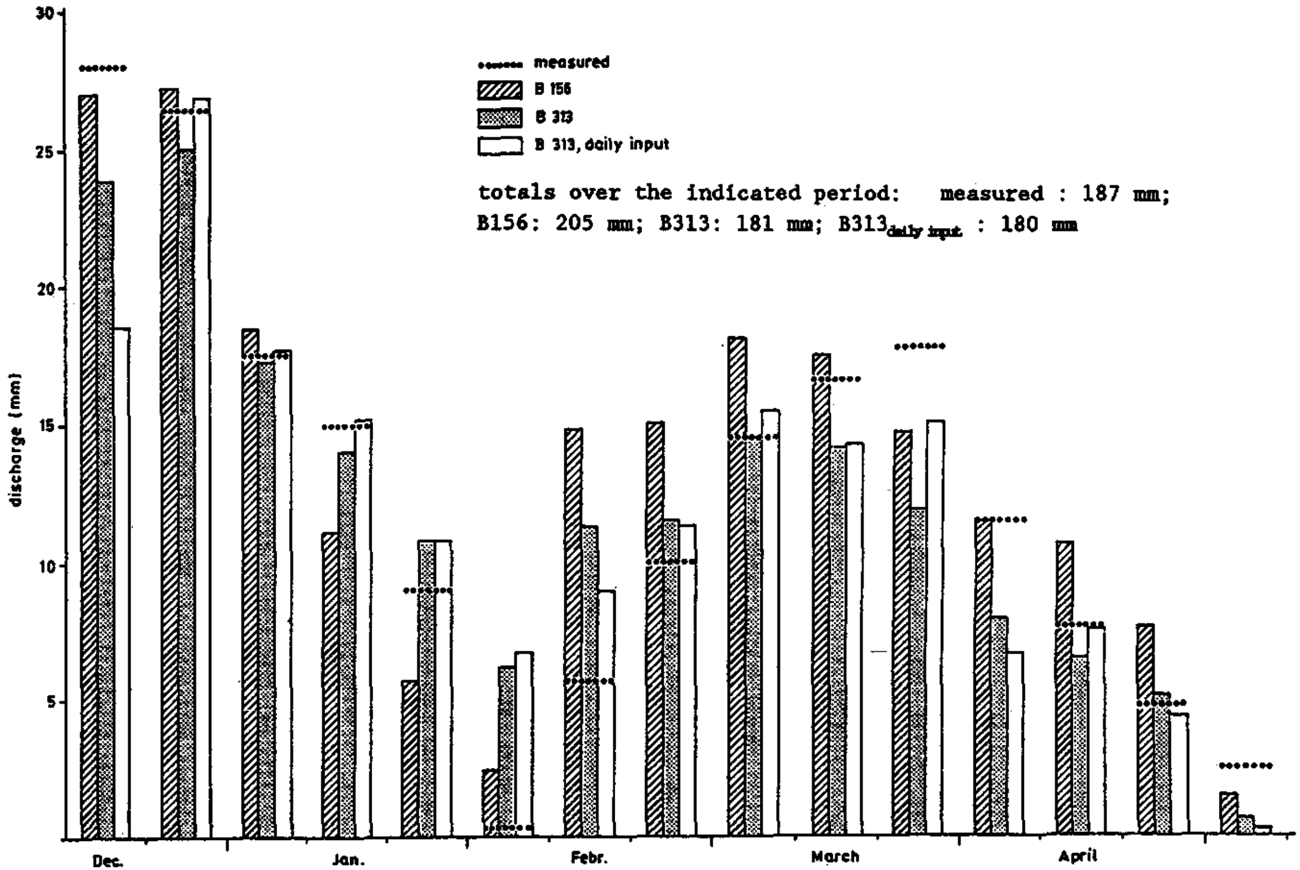

Fig.4 Calculated runoff for different simulations and measured runoff in the catchment Engbertsdijk-Oost

3.3 the Nieuwe Leidijk catchment

Most of this catchment consists of drier parts with only a few small water holding trenches. Location B308 was selected for the calibration. It is situated in the centre of an area, fully covered with a dense *Molinia* vegetation. The groundwaterlevel was observed weekly. The small trenches (0.3 m in width, 0.3 m in depth, distance 20 m.) are completely dry during the summer period. Their distance is 20 m. The permeability of the strongly humified peat layer is very low and infiltration and drainage by these trenches can be neglected.
At this site the thickness of the peat layers is 2 m and the vertical hydraulic resistance is set at 7500 days. The piezometric head in the sand was derived from weekly measurements at two nearby locations. The water storage coefficient of the peat was set at 22%, in accordance with the measured values presented in chapter 4.2. In the model SWAMP capillary water supply is described as a function of the phreatic level. In the first instance a relation was derived from the data about capillary rise as given in chapter 4.2. When the relatively dry area, described above, becomes inundated runoff occurs and the water flows through depressions to a permanently inundated site. The latter covers about 10% of the catchment and the average thickness of the peat layer at its bottom is 0.7 m. Here, vertical resistance is set at 2500 days.
In the model the fraction open water is set at 10% and horizontal water flow (infiltration and drainage) between this inundated site and the location B308 is negligible. Therefore, drainage resistance is taken very high (10.000 days). The discharge from the catchment is directly related to the open water level, using the discharge equation of the weir. From tests it was concluded that with these measurements the discharge might have been systematically underestimated by 15%.
The calculated and observed values for the groundwaterlevel are presented in Fig.5 and for the open water level in Fig.6. The comparison of the model results with the measured discharge is hampered by the fact that during a wet period with a high groundwater level some superficial runoff occured at the northwestern edge of the catchment. This quantity is not measured and the observed values in Fig.7 indicate too low values for this period (december 1988).

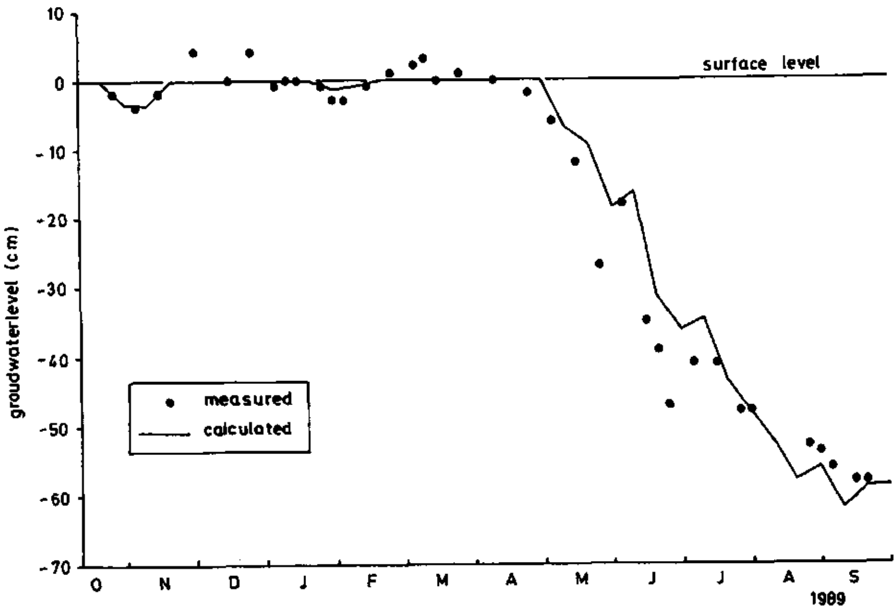

Fig.5 Calculated and measured groundwaterlevel at location B308

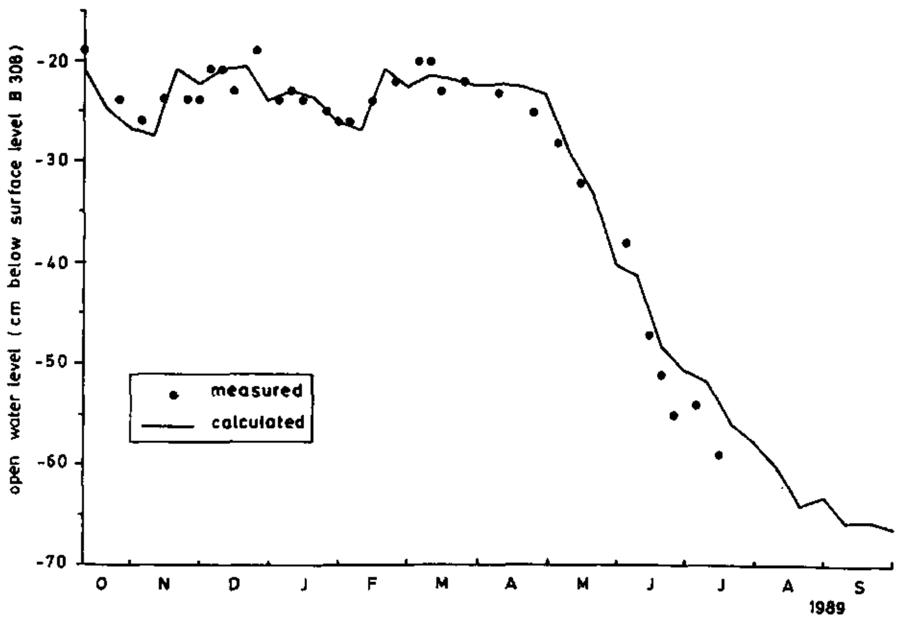

Fig.6 Calculated and measured open water level at location B308

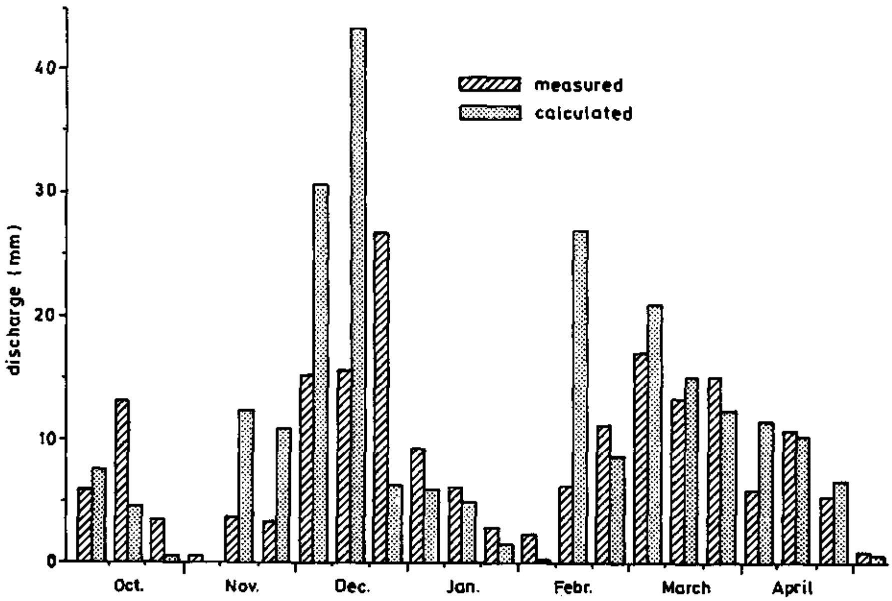

Fig.7 Calculated runoff at location B308 and measured runoff in the catchment Nieuwe Leidijk

totals over the indicated period: measured: 195 mm;
when systematically underestimated with 15%, measured: 230 mm;
B 308: 245 mm

4. Conclusions and Discussion

Bog relicts are characterized by a very high spatial variability in hydrological properties. In the calibration procedure presented here, the different parameter values of the SWAMP model were determined by field research. Inverse parametrization was only applied for some parameters, which were difficult to assess directly from field observations. For location B313 in the EO-catchment this concerns the parameter for potential evapotranspiration. For location B308 in the NL-catchment the parameters describing maximum capillary flux as a function of the groundwater depth were adjusted. It can be concluded that when applying the SWAMP model, or any other model, to simulate groundwaterfluctuations at a given site, site-specific information is needed and some calibration will be required. This means that the model can only be validated, when applying it for the same location for another period. In this study this was not possible. It can be concluded that if the most relevant model parameters are known, the SWAMP model accurately simulates the different water balance terms and the corresponding water level fluctuations. However, in many studies the parameter values will have to be estimated roughly because exact field data are missing.

Water management measures in bog relicts are meant to change the hydrological conditions. For instance, the construction of dams and compartments will change the characteristics of superficial runoff. When at inundated sites floating mats of *Sphagnum* spp. develop, evapotranspiration will change. Some of these changes can be estimated rather accurately and the corresponding parameter values in the SWAMP model can be adapted. However, the gradually changing hydrological conditions at the surface and the resulting shift in vegetation requires a model concept where the respective parameter values also are gradually changed. More research on the hydrology of both undisturbed and regenerating bogs is required to develop such 'ecologically based' simulation models.

5. References

Bruin, H.A.R. de, 1987. From Penman to Makkink. In: Hooghart,J.C. (Ed.) Evaporation and weather. TNO/CHO Proceedings and Information 39: 5-31

Eggink, H., 1988. The application of the model SWATRE in a study on evapotranspiration in a bog relict. Scriptie Dept. of Land and Water Use, Wageningen Agricultural University, 23 pp. (in Dutch)

Makkink, G.F., 1957. Testing the penman formula by means of lysimeters. J. of the Institution of Water Engineers 11: 277-288

McCuen, R.H. and Snyder,W.M., 1986. Hydrologic modeling - statistical methods and applications. Prentice-Hall, Englewoods Cliff, New Jersey

Schouten, L.S.M., 1988. A study on the applicability of the model SWAMP to simulate the water balance of the Lichtenmoor area (F.R.G.) for the period 1983-1986. Scriptie Dept. of Land and Water Use, Wageningen Agricultural University, 46 pp.

Schouwenaars, J.M., 1987. A simple method to determine specific equilibrium soil water content in a uniform soil. J. of Hydrology 95: 13-17

Sterk, G., 1990. Calibration of the model SWAMP and its application for the evaluation of water management measures in the Engbertsdijksvenen. Scriptie Dept. of Hydrology, Soil Physics and Hydraulics, Wageningen Agricultural University, (in prep.)

PART IV

FIELD STUDIES ON THE HYDROLOGY OF A BOG RELICT IN THE NETHERLANDS

4.1 Hydraulic resistance of peat layers and downward seepage in bog relicts

accepted for publication in:
International Peat Journal (1990)

4.2 Hydrophysical properties of peat relicts in a former bog and perspectives for Sphagnum regrowth

accepted for publication in:
International Peat Journal (1990)

4.3 A study on the evapotranspiration of *Molinia caerulea* and *Sphagnum papillosum*, using small weighable lysimeters

submitted for publication in:
Journal of Hydrology

HYDRAULIC RESISTANCE OF PEAT LAYERS AND DOWNWARD SEEPAGE IN BOG RELICTS

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ABSTRACT

In many bog-relicts in north-western Europe it is tried to restore the former bog vegetation. To create suitable ecological and hydrological conditions for this ombrotrophic vegetation it is tried to reduce the water losses. To evaluate the impact of different water management measures it is important to quantify downward seepage from the bog relicts towards the underlying aquifer.
In the Engbertsdijksvenen (Netherlands) the water balances of three small catchments (15-25 ha) were studied. In the winterperiod downward seepage varies from ca. 0.2 $mm.day^{-1}$ (in more than 2.5 m thick strongly humified peat relicts) to ca. 1.4 $mm.day^{-1}$ (from pools with on average only a 20 cm thick peat layer at the bottom). It is found that the vertical hydraulic resistance of the lower strongly humified Sphagnum peat layers is an almost linear function of their total thickness. Values are in the range of 3500 - 4000 $days.m^{-1}$, which corresponds to an average saturated hydraulic conductivity of ca. 0.25 - 0.30 $mm.day^{-1}$.

1. INTRODUCTION

In the Netherlands bog relicts cover about 9000 ha, which is only 5% of the area occupied by bogs in the 17th century. In most of these relicts the upper peat layers have been cut away and the thickness of the remaining peat layers varies considerably. In the Netherlands as well as in Lower Saxony (Federal Republic of Germany) most of these areas are managed as nature reserves or will be managed as such after the peat mining activities have ended. Because of the scarcity of oligotrophic wetlands in this part of northwestern Europe, the main objective for their management is the restoration of the original bog vegetation. Eggelsmann (1988) describes experiences in Germany and presents hydrolo-

gical guidelines for rewetting and restoration. Joosten (1989) discusses several options for the regeneration of bogs.
In many relicts it can be observed that in summer the groundwaterlevel drops below 40 cm depth, which is commonly accepted as the critical level for the growth of bog plant communities (Verry, 1988).
In recent studies (Schouwenaars (1988a,b) and Schouwenaars and Vink (1990)) it is shown that the hydro-physical properties of the upper peat layers play a dominant role in the groundwater fluctuation-pattern. During peat mining the bogs were drained and in many bog relicts deep open drains cut into the underlying sandy aquifer. As a consequence, downward seepage from these areas has increased when compared to undisturbed bogs. From the water balance of a relatively undisturbed bog in Königsmoor (F.R.G.), Eggelsmann (1960) found a downward seepage of 35-40 $mm.year^{-1}$. Blankenburg and Kuntze (1987) argue that the thickness of the remaining peat layers, originally the lowest, oldest and most compacted ones with a very low permeability, should be at least 0.5 m to guarantee that downward water losses remain less than 60 $mm.year^{-1}$.
In many bog relicts it is tried to reduce downward seepage by refilling the open drains reaching into the underlying aquifer and by diverting agricultural drainage channels that cross the areas.
For several bog relicts one argues that only the creation of hydrological bufferzones would reduce the losses to an acceptable level. One of the problems in the design of such zones is that the vertical permeability of the peat relicts varies considerably. As a consequence the hydraulic resistance of the peat layers can only be estimated roughly. The experiences mentioned above have led to this study in which the water balances of three small catchments in a bog relict are analysed and downward seepage is determined . This enables the study of seepage in relation to the thickness of the peat layers and the piezometric heads in the aquifer beneath the peat. It is tried to draw some general conclusions about the relation between the thickness of peat remnants and seepage from bog relicts.

2.DESCRIPTION OF THE STUDY AREA

The study area of 850 ha (Fig.1) is situated in the eastern part of the Netherlands near the border with the F.R.G. ($52^{0}28^{1}$N, $6^{0}40^{1}$E).
In the Weichsel glacial, near the end of the Pleistocene era, eolian sands were deposited. In the Holocene, peat growth started on these sands, becoming general during the Atlanticum (8000 - 5000 B.P.). In this period, several meters of oligotrophic *Sphagnum* peat were formed, which are now strongly humified ('black' peat, Schwarztorf).
In the sub-Atlanticum (from ca. 3000 B.P.) 'young' *Sphagnum* moss peat was formed under relatively cold and wet conditions. In some parts of the study area these layers, which are slightly to moderately humified are still present ('white' peat, Weisstorf). Their thickness varies from 0.5 to 1.5 meter. In most parts of the area they were completely removed

by the peat mining industry. As a consequence, the older strongly humified peat lies at the surface. The different peat mining concessions in the Engbertsdijksvenen expired between 1953 and 1983 and thereafter the State Forestry Service began to manage these areas with the aim to re-establish the original ombrotrophic bog vegetation.

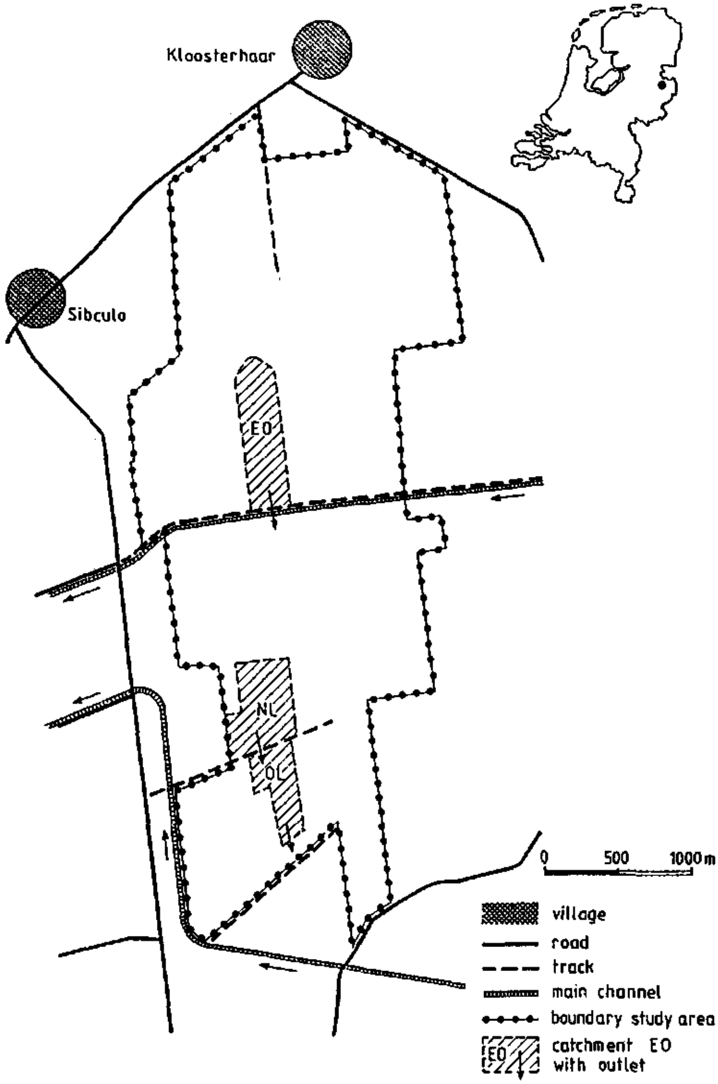

Fig.1 The Engbertsdijksvenen area and the location of the catchments.

After excavation, vegetation development on the remaining bare peat soils has lead to a dense cover of *Molinia caerulea*, often with *Betula pubescens*. In most parts of the study area, water levels were raised by the construction of small dams in former drains. Under these wet conditions birches have less chances and heather species like *Calluna vulgaris* and *Erica tetralix* may become dominant. The peat mining activities resulted in large spatial differences in topography and consequently in different properties of the upper peat layers. Some species, like *Andromeda polifolia* and many *Sphagnum* species seem to grow exclusively on sites where the less humified peat layers are still present.
The mean annual precipitation in the area is 754 mm. Mean annual evaporation from open water is about 600 mm and evapotranspiration from vegetated sites is estimated at about 480 mm.

3.WATER BALANCE STUDIES

3.1 water balance terms

Bogs and bog relicts are ombrogeneous, which means that they are only fed by precipitation. They are situated on relatively high parts of the landscape. Therefore their waterbalance is simple:

$$P = E + R + L + S + \Delta B$$

where P is precipitation, E is evapotranspiration, R is superficial runoff, L is lateral water loss through the peat relicts, S is downward seepage and Δ B is the change in water storage within the catchment. All terms can be expressed in mm per period.

3.2 catchments

Three catchments were selected for measurements. They show differences in topography, fraction of open water and thickness of the peat layers (Fig.1).
The Engbertsdijk-Oost (EO) catchment is 25.5 ha and shows a very regular pattern of peat ridges (width:3 to 5 m) alternating with parallel water holding gullies (width: 1 to 5 m). About 30% of the area consists of open water. In the northern part the total thickness of the peat layers is 4 m, the upper meter being only slightly humified. In the southern part this upper layer has been removed and here the moderately to strongly humified peat relict is about 2.5 m thick. Because the gullies are about 0.5 m deep the minimum thickness of the peat layers within the catchment is 2 m. Superficial runoff occurs in the winter period and this water flows southwards, perpendicular to the orientation of the ridges and gullies, overflowing the former at low places. Two larger

drains have the same north-south orientation but in recent years they were blocked to rewet the area. Vegetation is dominated by *Molinia caerulea*. Locally the heather species *Erica tetralix* is abundant.

The Nieuwe Leidijk (NL) catchment is 22.7 ha and has only 10% permanently open water. The greater part consists of a 2 m thick strongly humified peat relict. At intervals of 15 to 20 m there are small water-holding blocked drains. In a smaller part a 0.5 m thick slightly humified peat layer still remains on top of the former 2 m thick layer. Excess water flows to a long-shaped shallow pool with an outlet to the south. The thickness of the peat layer below its bottom varies from 0.4 to 1 m. Most of the area is fully covered with a dense *Molinia* vegetation.

The Oude Leidijk (OL) catchment is 15.0 ha and 70% of its area is covered with open water. These large pools were created when after peat cutting the lowest parts were inundated. At the bottom of these pools the thickness of the peat relicts varies from 0.2 to 0.8 m and some former drains reach into the underlying sand. In the eastern part the peat relicts are 1.5 to 2 m. Outside the pools vegetation is dominated by *Molinia* and *Betula pubescens*. The OL catchment receives the discharge from the NL catchment.

3.3 rainfall

Rainfall was recorded at two sites. One recorder with permanent registration was installed near Kloosterhaar in the northern part of the study area. In the NL catchment a raingauge was installed where weekly totals were recorded. The measurement error is estimated at 2%.

3.4 evapotranspiration

Potential evapotranspiration was calculated by multiplying the reference values of Makkink (Feddes, 1987), obtained from a nearby meteorological station, by a correction factor.
De Bruin (1987) and Feddes (1987) shows that in summer the factor to be used for the calculation of open water evaporation varies from 1.30 in April to 1.17 in September. In the winterperiod many sites in the study area are inundated and almost no green plants are present. However, the dead leaves of *Molinia* cause an important evaporation of intercepted water. Therefore in this study the correction factor for winter periods is taken at 1.1. The error is estimated at 5%.
For summer periods the factor has been determined from lysimeter experiments (Schouwenaars, 1990).

3.5 discharge measurements

In the EO-catchment weekly cumulative values of the discharge were measured with a watermeter installed in a tube with a diameter of 10 cm. Its accuracy is very high and measurement errors are estimated at 5%. In the other catchmets a V-shaped long crested weir was installed and water levels were permanently recorded. With a discharge lower than ca. 5 liters.sec^{-1}, as often occurred in the winterperiod 1988-89, its accuracy is low. From tests in these periods it was concluded that discharge might have been systematically underestimated by 15%.

3.6 water storage

At different sites open water and groundwater levels were permanently recorded. In addition, weekly observed piezometers were used. The average density is 1 observation per 3 ha. For the peat soils in question the water storage coefficient is taken at 25% (Schouwenaars and Vink, 1990). For each catchment the different sites are supposed to be representative for a given part of the catchment. Hence, the changes in total water storage can be derived from the observed water level fluctuations. Because of the great spatial diversity of both the pattern of peat relicts and their hydrophysical properties the errors in the determination of stored water quantities are significant and taken at 30%. To reduce the impact of these uncertainties the periods for which water balances are determined are selected in such a way that on both the first and the last day of the balance period the observed water levels are almost equal.

3.7 lateral and downward seepage

These terms are determined from the water balance equations, using the measured values of the terms discussed above.

4. THE RELATION BETWEEN HYDRAULIC RESISTANCE AND THICKNESS OF THE PEAT LAYERS

In the case of downward seepage Darcy's equation for the relation between flux density q (m.day^{-1}), the difference in hyuraulic head between two points Δ H (m) and the hydraulic resistance c (days) is:

$$q = \Delta H / c \qquad (1)$$

The hydraulic resistance can also be described as :

$$c = d_1/k_1 + d_2/k_2 + \ldots. + d_n/k_n$$

where d is thickness (m) and k the hydraulic permeability ($m.day^{-1}$) of the respective layers (i=1,n) between the two points.
Measurements of the phreatic levels in the peat and the piezometric heads in the underlying sand layer, combined with measured downward fluxes allow the determination of the total hydraulic resistance of the peat layers.

Many authors have shown that the hydraulic permeability of peat layers decreases with increasing decomposition rate of the peat (e.g. Baden and Eggelsmann(1963), Boelter(1969)). Hence, in a bog profile hydraulic resistance is concentrated in the lowest strongly humified peat layers. We can describe the vertical hydraulic resistance c as a function of total thickness of the peat layers D as follows:

$$c = a \cdot D^b \; (a > 0 \;, \; b > 0) \qquad (2)$$

For a peat profile with slightly humified peat on top of strongly humified peat one may expect the value for parameter b to be less than 1. Eq.1 and 2 give:

$$q = \Delta H / a \cdot D^b \qquad (3)$$

Every catchment was divided into sub-areas (i=1,n). For every sub-area i, with a given average thickness of the peat D_i, Eq.3 was applied, using data of both phreatic tubes and deep piezometers.
With an area A_i of the sub-area i, the total seepage Q_c ($m^3.day^{-1}$) of the catchment is:

$$Q_c = \sum_{i=1,n} q_i \cdot A_i$$

combined with Eq.3:

$$Q_c = \sum_{i=1,n} H_i \cdot A_i / a \cdot D_i^{\,b} \qquad (4)$$

For every catchment the difference between the measured seepage Q_m (from the water balance) and the calculated Q_c can be determined.
A sensitivity analysis was made for different sets of values for a and b in Eq.4.

5. RESULTS

The waterbalance terms for different periods in the winter 1988-1989 are presented in Table 1. Totals for downward and lateral seepage are given as the calculated average over the balance period and expressed in $mm.day^{-1}$.

TABLE 1
Water balance terms ($mm.day^{-1}$) for 3 catchments in the Engbertsdijksvenen in the winterperiod 1988-1989

	precipitation	evapotranspiration	storage loss	discharge [2]	downward +lateral seepage	estimated error[1]
ENGB.DIJK-OOST						
8 dec- 9 jan	2.17	0.17	0.58	2.38	0.20	+/- 0.21
14 dec- 3 march	1.85	0.40	0.16	1.44	0.17	+/- 0.10
8 dec-14 march	1.89	0.37	0.06	1.35	0.23	+/- 0.08
NIEUWE LEIDIJK						
16 nov- 3 jan	2.48	0.21	0.01	1.36	0.92	+0.05/-0.25
16 nov-18 jan	2.22	0.21	-0.05	1.05	0.91	+0.05/-0.21
16 nov-24 jan	2.05	0.21	0.02	1.15	0.71	+0.04/-0.21
16 nov-16 febr	1.83	0.29	-0.08	0.94	0.52	+0.05/-0.19
23 dec-24 febr	1.26	0.36	0.08	0.82	0.16	+0.04/-0.16
3 jan-16 febr	1.07	0.38	-0.18	0.44	0.07	+0.06/-0.12
OUDE LEIDIJK						
25 oct-30 nov	1.47	0.45	0.71	-0.12	1.85	+0.24/-0.20
16 nov- 9 febr	1.76	0.16	0.05	0.67	0.98	-0.06/-0.14
14 dec-24 febr	1.75	0.34	0.12	0.36	1.17	-0.03/-0.13
14 dec-14 march	1.89	0.41	-0.05	0.08	1.45	+0.03/-0.05
25 oct-14 march	1.89	0.40	-0.29	0.13	1.06	+0.07/-0.13

[1] based upon the following errors for the different terms: precipitation: 2%, evapotranspiration: 5%, storage loss: 30% discharge for watermeter (EO): 5%. For the weirs in NL and OL discharge might be systematically underestimated by 15%.

[2] For the OL-catchment the difference between its discharge and the recharge from the NL-catchment.

TABLE 2

Calculated downward seepage in the 3 catchments using a unique relation between thickness of the peat layers and hydraulic resistance and its comparison with the seepage determined from the water balance studies.

catch-ment	sub-area	area	head loss [1]	thickness peat layers	hydraulic resistance	downward seepage	total downward loss
		A (ha)	H (m)	D (m)	$c=3500.D^{1.0}$ (days)	q_c ($mm.day^{-1}$)	Q_c ($m^3.day^{-1}$)
EO	1	2.5	3.0	4.0	14000	0.21	5.36
	2	8.5	2.5	3.5	12250	0.20	17.35
	3	3.0	2.5	3.0	10500	0.24	7.14
	4	8.0	2.5	2.5	8750	0.29	22.86
	5	3.5	2.0	2.0	7000	0.29	10.00

							62.71
NL	1	2.7	2.5	2.5	8750	0.29	7.71
	2	14.1	2.0	2.0	7000	0.29	40.29
	3	3.8	1.5	1.5	5250	0.29	10.86
	4	2.1	1.8	0.5	1750	1.03	21.60

							80.46
OL	1	3.8	1.0	0.2	700	1.43	54.29
	2	7.2	1.2	0.3	1050	1.14	82.29
	3	4.0	1.5	1.5	5250	0.29	11.43

							148.01

[1] When the piezometric head in the sand is below the peat basis only the head loss over the peat layers is regarded

From Table 1 it can be concluded that downward and lateral losses are highest in periods with high rainfall. In these periods with high water levels some unmeasured superficial runoff (leakage) may occur and lateral flow through the upper slightly humified peat layers (if present) may be substantial. In the northern part of the EO-catchment some lateral seepage may occur in the 0.5 - 1.0 m thick less humified upper peat layer (slightly humified with relatively high horizontal permeability). For this catchment the average downward seepage is estimated at 0.15 - 0.20 $mm.day^{-1}$. In the northwestern part of the NL-catchment some lateral outflow was observed through the 0.5 m thick upper peat layer. Given these observations average downward seepage in the NL catchment is estimated at 0.25 - 0.50 $mm.day^{-1}$.
For the OL catchment average downward seepage is estimated at 1.0 - 1.4 $mm.day^{-1}$.

An example of the calculations based upon Eq.4 is presented in Table 2 ($c = 3500\ D^{1.0}$).

A further examination of the hydraulic resistance was made by varying the values for the parameters a and b in Eq.4.
In Table 3 both the measured and the calculated downward seepage are presented for the most relevant values of a ($3500 < a < 4500$) and b ($0.7 < b < 1.0$).

TABLE 3
Measured downward seepage from the 3 catchments and calculated values using different parameter sets for the relation between thickness of the peat and its hydraulic resistance

catch-ment	measured average seepage ($mm.day^{-1}$)	measured total seepage ($m^3.day^{-1}$)	calculated seepage with $c = a \cdot D^b$ (days) ($m^3.day^{-1}$): a=3500 b=0.7	a=3500 b=0.8	a=3500 b=0.9	a=3500 b=1.0	a=3000 b=1.0	a=4000 b=1.0
EO	0.15-0.20	38- 51	86	77	70	63	73	55
NL	0.25-0.50	57-114	90	86	83	80	94	70
OL	1.00-1.40	150-210	104	116	131	148	173	130

6. CONCLUSIONS AND DISCUSSION

From Table 3 it is concluded that the hydraulic resistance c of the peat layers in the study area can be described as a function of their total thickness D by using Eq.2, where:

$$3500 < a < 4000 \quad \text{and} \quad b \sim 1.0$$

In Table 3 it shown that with these c-values the downward seepage in the OL-catchment is somewhat underestimated. Some former drains reaching into the sand probably cause the measured seepage to be higher than the calculated values.
For D > 1 m a lower b-value (e.g. 0.7) would result in a reduced resistance and higher losses. For D < 1 m results will be opposite (Table 3: EO- and OL-catchment, respectively).
For the moderately to strongly humified peat layers in the study area there is no indication that values for b should be taken less than 1.0.

In most part of the study area the piezometric head in the sand is below the base of the peat. For the calculation of downward fluxes through the peat layers as a function of their total hydraulic resistance only the head loss over the peat layers is of importance. During the winter period the phreatic water level mostly equals surface level. In that case, which does not hold for pools (e.g. OL-catchment), downward seepage is independent on the thickness of the peat layers and always yields about 0.25 - 0.30 $mm.day^{-1}$. This value corresponds well with the average vertical saturated hydraulic conductivity of the strongly humified peat layers in the study area, for which Schouwenaars and Vink (1990) found values from 0.1 to 0.6 $mm.day^{-1}$. This implies that yearly downward seepage amounts to 80-100 mm. Before peatland exploitation piezometric heads in the underlying sand were higher and downward seepage from the undisturbed bog in the study area probably has been 60-80 $mm.year^{-1}$, which is about twice as much as found for Königsmoor (Eggelsmann, 1960).
When water conservation measures lead to the creation of permanent pools the seepage at these sites will depend on the ratio between waterdepth and thickness of the peat layers at the bottom. With a waterdepth of 1 m above a peat layer of 2 m, seepage will be about 0.40 $mm.day^{-1}$ (1.5 times 0.27 $mm.day^{-1}$). In the pools of the OL-catchment with a waterdepth of 0.8 m above a peat layer with an average thickness of 0.2 m, seepage is about 1.4 $mm.day^{-1}$. This is only possible during the winter period when runoff from neighbouring areas flows into the OL-catchment. During spring this inflow will end and from then onwards the lowering of the water levels in the pools will reduce seepage.

The conclusions mentioned above may be valid for bogs and bog-relicts in general. However, it is evident that caution is required because accurate estimations of seepage as a closing term of the water balance are hardly possible. Given the high spatial variability in thickness of the peat relicts within the catchments, estimates on area and thickness of the peat for sub-areas can only be approximate. As a consequence a detailed analysis of the hydraulic resistance is difficult. Nevertheless this study shows that by studying different catchments having significant differences in hydrological properties satisfactory results can be obtained, because reasonable agreement exists between water balance measurements and calculations based on the hydrophysical properties of the peat layers.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Baden, W. and Eggelsmann, R., 1963. Zur durchlässigkeit der Moorböden. Zeitschrift für Kulturtechniek und Flurbereinigung 4, 226-254.

Blankenburg, J. and Kuntze, H., 1987. Moorkundlich - hydrologische Voraussetzungen der Wiedervernässung von Hochmooren. Telma 17:51-58

Boelter, D.H., 1969. Physical properties of peat as related to degree of decomposition. Soil Science Society of America Proceedings 83, 606-609

Bruin, H.A.R. de, 1987. From Penman to Makkink. In: Hooghart, J.C. (Ed.) Evaporation and weather. Proc. and Inform./TNO Comm. Hydr. Res., The Hague, 39: 3-31

Eggelsmann, R., 1960. Über den unterirdischen Abfluss aus Mooren. Wasserwirtschaft 50: 149-154

Eggelsmann, R., 1988. Wiedervernässung von Hochmooren. Die Geowissenschaften 11: 317-322

Feddes, R.A., 1987. Crop factors in relation to Makkink reference crop evapotranspiration. In: Hooghart, J.C. (Ed.) Evaporation and weather. Proc. and Inform./TNO Comm. Hydr. Res., The Hague, 39: 33-45

Joosten, H.J.H., 1989. Bog regeneration in the Netherlands; a review Proceedings Symposium on Peatland Ecosystems and Man - an Impact Assesment. Dundee, Scotland (in prep)

Molen, W.H. van der, 1981. Über die Breite hydrologischer Schutzzonen um Naturschutzgebiete in Mooren. Telma 11, 213-220.

Schouwenaars, J.M., 1988a. The impact of water management upon groundwater fluctuations in a disturbed bog relict. Agricultural Water Management 14, 439-449

Schouwenaars, J.M., 1988b. Hydrological research in disturbed bogs and its role in decisions on water management in the Netherlands. Proc.

Symposium on the Hydrology of Wetlands in temperate and cold regions, Joensuu. Publ. Academy of Finland 4/1988, 170-177
Schouwenaars, J.M., 1990. A study on the evapotranspiration of*Molinia caerulea* and *Sphagnum papillosum*, using small weighable lysimeters. Journal of Hydrology, (in prep)
Schouwenaars, J.M. and Vink, J.P.M., 1990. Hydrophysical properties of peat relicts in a former bog and perspectives for Sphagnum regrowth International Peat Journal, 4 (in prep.)
Verry, E.S., 1988. The hydrology of wetlands and man's influence on it. Proceedings Symposium on the hydrology of wetlands in temperate and cold regions, Joensuu. Publ.Academy of Finland 5/1988, 41-61

HYDROPHYSICAL PROPERTIES OF PEAT RELICTS IN A FORMER BOG AND PERSPECTIVES FOR SPHAGNUM REGROWTH

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ABSTRACT

In this study the hydrophysical characteristics of peat layers in a partly cut-away peatland nature reserve are presented. The main objective is to discuss these properties in relation to growing conditions for *Sphagnum* moss species. Information about evapotranspiration and water storage coefficients is provided by lysimeter experiments. Water retention characteristics, hydraulic conductivity and capillarity are analysed.

In living bogs water level fluctuations are very limited (less than 30-40 cm). In partly mined bogs the mostly elder, more humified upper peat layers differ strongly from those in undisturbed bogs. When after rewetting of partly cut-away bogs (regeneration, rehabilitation) *Sphagnum* regrowth occurs, during some decades the young *Sphagnum* layer will be less than 30 cm. During this first phase of regeneration the young *Sphagnum* plants are vulnerable to drought because their thickness is still too limited to establish sufficient 'self-regulating buffer' mechanisms to prevent a further lowering of the water table.

These mechanisms are closely related to hydrophysical properties of the upper peat layers.

1. INTRODUCTION

In the Netherlands water management measures are taken to promote the regrowth of *Sphagnum* species in many of the remaining partly cut-away peatlands. (Schouwenaars,1988). For a better understanding of the hydrology of these peatlands a field survey was carried out in the Engbertsdijksvenen. The study area is situated in the eastern part of the Netherlands, near the border with the Federal Republic of Germany ($52^{0}28^{1}$N, $6^{0}40^{1}$E).

This study deals with the hydrophysical characteristics of the upper peat layers. Romanov (1968) and Ivanov (1981) have described their importance for the hydrology of undisturbed bogs. Also Ingram and Bragg

(1984) argue that the hydrophysical properties of the upper living layer of *Sphagnum* mosses ('acrotelm'; Ingram and Bragg,1984) are responsible for a high water storage capacity and a high rate of horizontal water flow in this layer.
In this way the upper layer plays an essential role in the regulation of water losses and water level fluctuations. In living bogs water level fluctuations are very limited (less than 30-40 cm). The deeper, more humified (i.e. decomposed) peat layers ('catotelm') differ strongly from the upper layer.
Previous studies have shown extremely large differences in structure, bulk density and porosity between peat types. The high spatial variability (both horizontal and vertical) of peat properties in bog areas makes a correct assessment of representative values for properties like conductivity and bulk density extremely difficult. Boelter (1965,1969) presented values for hydraulic conductivity and water storage characteristics of undecomposed *Sphagnum* moss peat which clearly demonstrate the rapid change of these values over the upper 45 cm of a living bog. Values for the more decomposed deeper peat layers are much lower than for undecomposed peat and likewise show great variability. Baden and Eggelsmann (1963) in an extensive overview with numerous data, clearly illustrate the problems related to measurement methods. They show that in peaty soils the subfossil plant remains determine hydraulic conductivity, which decreases with increasing degree of humification (i.e. decomposition). Saturated hydraulic conductivity of different types of peat is shown to be dependent on bulk density. Renger et al. (1976) found that also unsaturated hydraulic conductivity and capillary fluxes decrease with increasing bulk density. A very important and complicating factor in areas which have been drained is that degree and duration of this drainage influence the subsidence and soil consolidation and result in different bulk densities for the same type of peat.
Kuntze (1966) shows that capillary rise in *Sphagnum* moss peat soils is related to their degree of humification. However, for both younger (H < 5 : von Post scale) and older (H > 5) peat indicator values for capillarity are widely spread and often within the same range of magnitude. For the older peat capillary rise on average seems somewhat higher.
The publications mentioned above, which are only a fraction of the studies on the hydrophysics of peat soils, illustrate that simplified approaches in the determination of hydrophysical characteristics in peat soils are hardly possible. The method presented by Bloemen (1983) underestimates the complexity of these soils. For model applications in a given peatland, field research is needed to obtain reliable parameter estimations.

In the Engbertsdijksvenen area hardly any information on hydrophysical properties was available. During the last decades peat mining activities resulted in large differences in properties of the upper peat layers.

In the Weichsel glacial, near the end of the Pleistocene era, eolian sands were deposited. In the Holocene, peat growth started on these sands, becoming general during the Atlanticum (8000-5000 B.P.). In this period, several meters of oligotrophic peat were formed, which are now strongly humified ('black' peat, Schwarztorf). In the sub-Atlanticum (from ca. 3000 B.P.) 'young' *Sphagnum* moss peat was formed under relatively cold and wet conditions. In some parts of the study area these layers, which are slightly to moderately humified (H3-4) are still present ('white' peat, Weisstorf). Their thickness varies from 0.5 to 1.5 meter. In most parts of the area however, they were completely removed by the peat mining industry. As a consequence, strongly humified peat lies at the surface.

The different peat mining concessions in the Engbertsdijksvenen expired between 1953 and 1983 and thereafter the State Forestry Service began to manage these areas with the aim to reestablish the original ombrotrophic bog vegetation.

After excavation, vegetation development on the remaining bare peat soils has lead to a dense cover of *Molinea caerulea.* Under dry conditions *Betula pubescens* (birch) invaded these sites. In most parts of the study area, water levels were raised by water management measures (i.c. construction of small dams in former drains). Here birches have less chances and heather species like *Calluna vulgaris* and *Erica tetralix* are present. Some species, like *Andromeda polifolia* and many *Sphagnum* species seem to grow exclusively on the less humified peat layers. This is also observed in many other areas. (Podschlod, 1988).

In this study the hydrophysical differences between representative peat layers are presented. The main objective is to discuss these properties and relate them to growing conditions for different plant species. Attention will be given to perspectives for *Sphagnum* regrowth.

METHODS

2.1 lysimeters

Undisturbed soil columns were taken with a sampling device, having a diameter of 40 cm and a length of 50 cm. (Fig.1) These columns were inserted in a lysimeter of the same size, closed at the bottom. Fig.2 schematically illustrates at which sites the different samples were taken.

Four columns were covered with *Molinea caerulea* (M1-4), four with *Calluna vulgaris* (C1-4) and eight with *Sphagnum papillosum* (S1-8). The selected sites represent the most important differences in peat properties within the study area. The lysimeters were installed in a 50 cm deep hole with a diameter of ca. 50 cm, to enable weighing. The space between the lysimeter and the wall of the hole was covered with litter to prevent evaporation.

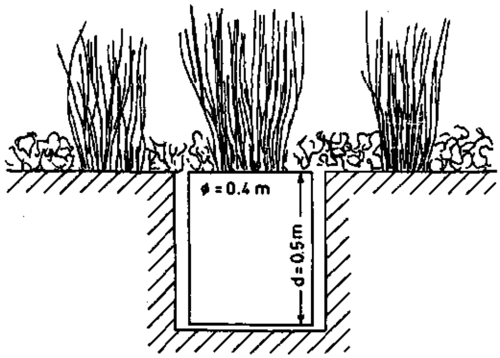

Fig.1 Dimensions of the lysimeters

The lysimeters were taken out using a tripod and replaced after measurement. A spring loaded scale was used for weighing. Its accuracy is about 0.05 kg which corresponds to a water layer of 0.4 mm depth. In the period 11 May - 26 September 1988 the lysimeters were weighed in intervals, varying from 3 to 9 days, depending on the weather conditions. In the period 5 May - 29 September 1989 this was repeated and lysimeters S5-S8 were added. These lysimeters were taken at a superficially drained site where in the past no peat has been cut away. In addition a soil column of 80 cm length and with a diameter of 24 cm was taken from a soil layer of 40 - 120 cm below surface (Fig.2).
Schouwenaars (1990) reports on the evapotranspiration studies carried out with these weighable lysimeters.

2.2 water storage coefficients

Besides information about evapotranspiration, the lysimeter experiments provide accurate field data on water storage coefficients in the different layers. Total weight of the lysimeters and water table depth are measured simultaneously and this enables an analysis of the relation between total soil water storage (both in the saturated and unsaturated zone) and water table depth.
Differences in weight result from changes in total water storage (ΔV). The latter can be expressed in mm water layer, taking into account the surface area of the lysimeter (0.125 m^2). In this study the ratio between ΔV and the corresponding change in water table depth (ΔW) was examined. This ratio is defined as water storage coefficient.

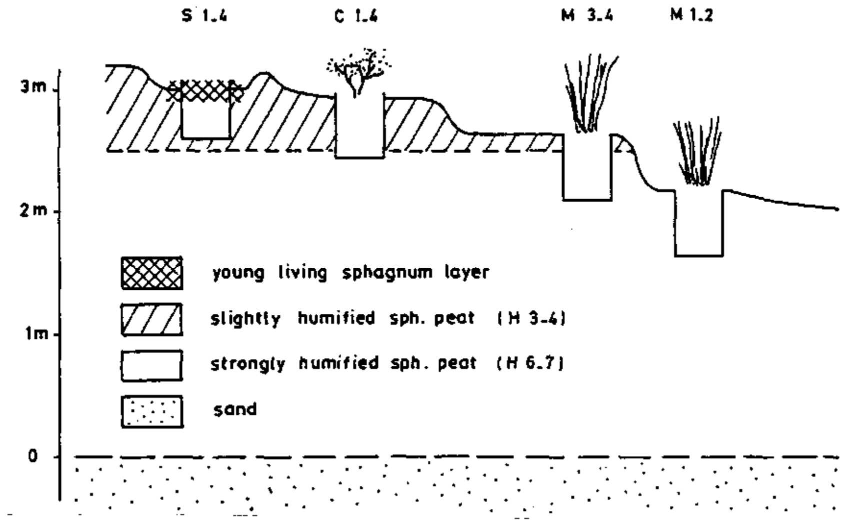

Fig. 2 Schematic overview of sample locations in the study area

2.3 saturated vertical hydraulic conductivity

From the same sites as selected for the lysimeters, 100 cc undisturbed samples were taken vertically at depths of 15 and 35 cm. They were used for the determination of the saturated hydraulic conductivity.

2.4 water retention curves

The same samples were used to determine soil water content as a function of pressure head. After complete saturation water outflow through ceramic plates was measured under increasing air pressure at the top of the samples. This was done for pressures of 1, 3, 6.1, 10, 30 and 100 kPa. Then the samples were dried at 105 °C during 48 hours.

2.5 capillary fluxes and water suction

To study capillary fluxes under dry conditions two lysimeters (M4 with *Molinea* vegetation and S4 covered with *Sphagnum papillosum*) and the soil column were installed in a glasshouse. In the lysimeters two tensiometer cups were inserted, at 15 and 35 cm respectively. In the soil column tensiometers were inserted at 20, 35 and 50 cm depth. In the soil column the water table was maintained at a constant level of 70 cm below the bare surface. Lysimeter S4 was initially completely filled with water and during the following measurement period no water was added. When lysimeter M4 was taken out of the field it was comple-

tely unsaturated and in the glasshouse no water was added. Water losses from the lysimeters and the soil column were determined by weighing. For S4 this was done with intervals of 2 days during the first month and during the second and third month in intervals of 5 - 10 days. The measurement interval for the soil column experiment, which lasted about 2 months, also varied from 5 - 10 days. At the same time water levels were determined and water suctions in the different layers were measured using a tensiometer with an electronic pressure transducer.
With the information obtained from the water retention curves it was possible to determine changes in soil water content of the unsaturated zone. In combination with total water losses and changes in phreatic level an analysis of capillary fluxes was made. In this way unsaturated hydraulic conductivity at different water suction values could be determined and k-h-θ relations could be deduced. Based on a pseudo-stationary approach presented by de Laat (1980) for two representative soil types (slightly humified H3-peat (lysimeter S4) and strongly humified H6-peat (soil column)) an analysis was made of capillary rise as a function of groundwater level and suction head at the bottom of a rootzone.

3. RESULTS

3.1 water retention curves

Under field conditions in these peat soils the most relevant range of water suction values is from 0 to 100 kPa (pF=0 to pF=3.0). Results for strongly humified Sphagnum peat (H6), representing lysimeters M1-4, are shown in Fig.3A and for slightly humified Sphagnum peat (H3) in Fig.3B. These samples represent lysimeters C1-4. In lysimeters S1-4 the upper 5 cm is formed by a green living *Sphagnum*-layer followed by a ca. 10 cm thick layer of dead *Sphagnum* parts (H1-2). The samples taken at 15 cm depth represent the transient zone between this upper 'acrotelm' and the underlying slightly humified Sphagnum peat layers (H3), which were at the surface before *Sphagnum* regrowth occurred (ca. 10-15 years ago). The samples taken at 35 cm depth represent Sphagnum peat layers with humification degree 3. Results for the S1-4 lysimeters are presented in Fig.3C.
Fig. 3A,3B and 3C show remarkable differences in available soil water in the range from 0 to 100 kPa. Storage coefficients are highest in living *Sphagnum* layers and decrease with increasing degree of humification.

3.2 storage coefficients

The storage coefficients were determined by relating the decrease in water storage in the lysimeters with the lowering of the water table. This was done by linear regression, for which good correlations were obtained. In Fig.4 results for lysimeter S2 are presented and in Fig.5 for lysimeter S4 under field conditions. For the glasshouse experiment with S4 the results are presented in Fig.6.
Results for all lysimeters are listed in Table 1.

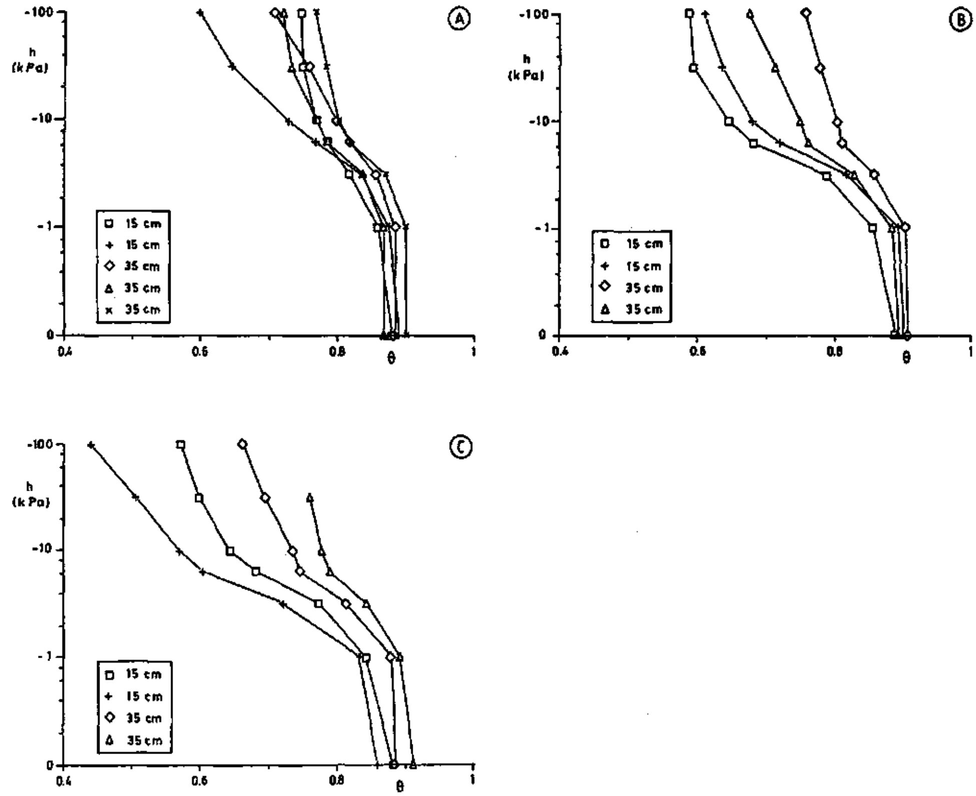

Fig. 3 Water retention curves
(A: lysimeters M1-4; B: lysimeters C1-4;
C: lysimeters S1-4)

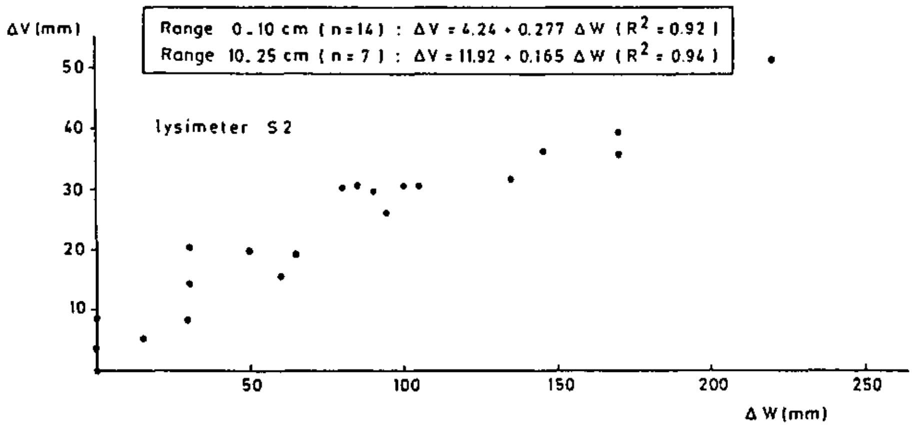

Fig.4 Relation between decrease in water storage (ΔV) in relation to the lowering of the water table (ΔW) for lysimeter S2 (the highest observed value for water storage is taken as reference (ΔV and ΔW equal zero) and the other observations are related to it)

For lysimeters S1-4 and C1-4 results show good agreement with the water retention characteristics, in contrast to M1-4. The causes of this difference will be discussed later on.

3.3 saturated hydraulic conductivity

The values for the vertical saturated hydraulic conductivity are presented in Table 2. High values are found for the *Sphagnum* lysimeters (S1-5), even at 35 cm depth. In the other columns, values are generally lower. due to more compact structure or higher degree of humification. The large contrast between topsoil (15 cm) and subsoil (35 cm), however cannot be fully explained by these factors, as will be discussed later on.

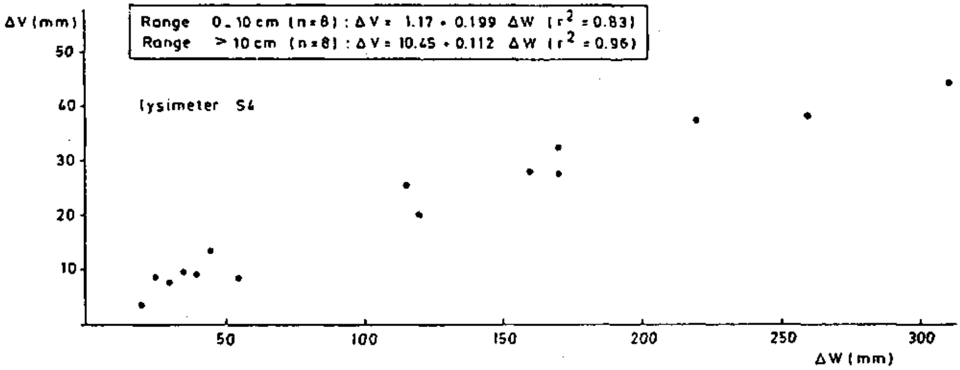

Fig.5 Relation between decrease in water storage (ΔV) in relation to the lowering of the water table (ΔW) for lysimeter S4 under field conditions (the highest observed value for water storage is taken as reference (ΔV and ΔW equal zero) and the other observations are related to it)

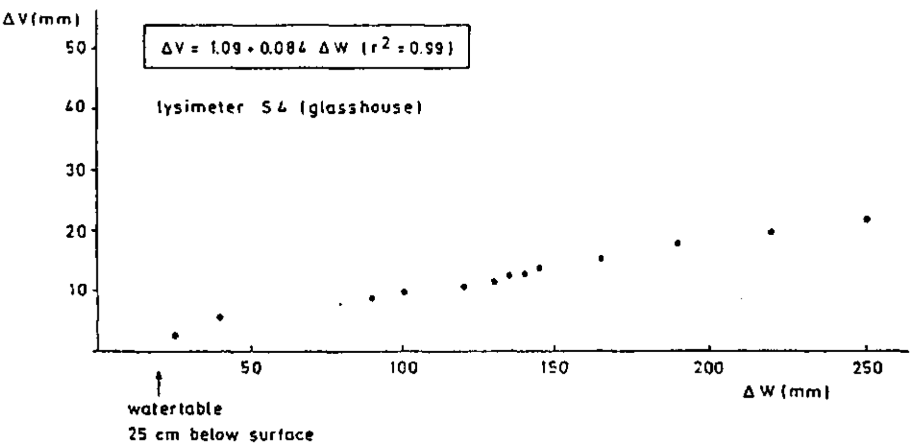

Fig.6 Relation between decrease in water storage (ΔV) in relation to the lowering of the water table (ΔW) for lysimeter S4 under glasshouse conditions (the highest observed value for water storage is taken as reference (ΔV and ΔW equal zero) and the other observations are related to it)

TABLE 1

Water storage coefficients as determined from the lysimeter experiments

lysimeter	depth (cm below surface)	storage coefficient [1]	$n^{2)}$	correlation coefficient (r^2)
M1	10-35	0.27	19	0.93
M2	0-30	0.18	16	0.96
M3	0-10	0.33	7	0.98
M4	5-13	0.14	6	0.92
C1	4-32	0.12	18	0.96
C2	0-35	0.11	19	0.96
C3	20-38	0.12	12	0.86
C4	0-23	0.13	10	0.95
S1	0-10	0.29	14	0.89
	10-25	0.17	5	0.99
S2	0-10	0.28	14	0.92
	10-25	0.17	7	0.94
S3	0-10	0.28	11	0.74
	10-30	0.17	11	0.96
S4	0-10	0.20	8	0.83
	10-30	0.11	8	0.96
S5	0-15	0.27	10	0.91
S6	5-20	0.23	8	0.92
S7	5-15	0.23	11	0.80
S8	0-15	0.34	12	0.94

[1] regression coefficient obtained from linear regression between change in water storage (ΔV ($cm^3.cm^{-2}$)) and change in water depth (ΔW (cm)) (for illustration see also Fig.4)

[2] number of observations

TABLE 2

Saturated hydraulic conductivity
(Col-samples represent soil column: M-samples represent lysimeters M1-4; C-samples represent lysimeters C1-4; S-samples represent lysimeters S1-4)

sample	depth (cm)	k ($cm.day^{-1}$)	sample	depth (cm)	k ($cm.day^{-1}$)
Col 1	15	1.15	M 1	15	3.70
Col 2	15	0.44	M 2	15	0.75
Col 3	35	0.04	M 3	35	0.37
Col 4	35	0.01	M 4	35	9.34
Col 5	35	0.06	M 5	35	0.01
C 1	15	5.69	S 1	15	2.59
C 2	15	3.26	S 2	15	7.19
C 3	35	0.29	S 3	35	11.52
C 4	35	0.68	S 4	35	6.71
			S 5	35	2.14

3.4 unsaturated hydraulic conductivity and capillary fluxes

During glasshouse experiments, capillary rise was determined and suction heads at different depths were measured. In Fig.7 k-h-θ relations are presented. The k-h relation obtained from lysimeter S4 is assumed to be representative for H3-peat and the one for the soil column is representative for H6-peat. For the latter the values for k are somewhat higher. After combination of these k-h relations with the water retention characteristics, Table 3 was derived. For different flux densities of the capillary rise the relation between height above the water table and suction head has been calculated. Results are presented in Fig.8.

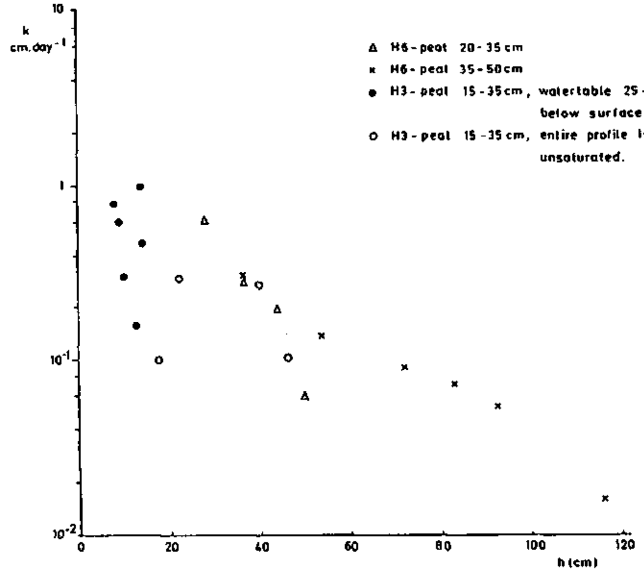

Fig.7 Unsaturated hydraulic conductivity (k) for different suction heads (h) as determined with the lysimeter experiments in the glasshouse
(H6-peat: measured in the soil column ; H3-peat: measured in lysimeter S4)

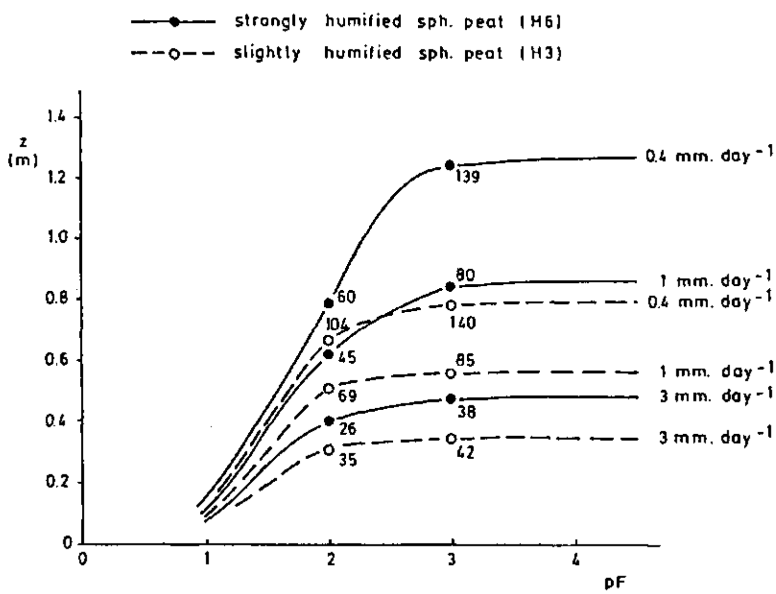

Fig.8 The relation between suction head (pF (=log h)) at the bottom of the rootzone and the depth of the water table below the rootzone (z in m.) for different capillary fluxes (mm.day^{-1})

TABLE 3
Unsaturated hydraulic conductivity (k) for different suction heads (h) and corresponding soil water content (θ) as estimated representative for H6-peat (obtained from the soil column experiments) and for H3-peat (obtained from the experiments with lysimeter S4)

H6 - peat			H3 - peat		
h (cm)	k ($cm.day^{-1}$)	θ ($cm^3.cm^{-3}$)	h (cm)	k ($cm.day^{-1}$)	θ $(cm^3.cm^{-3})^{-1}$
0	1.00	0.88	0	7.00	0.87
10	0.70	0.86	10	1.00	0.84
20	0.50	0.84	20	0.30	0.78
31	0.40	0.83	31	0.20	0.74
50	0.20	0.78	50	0.10	0.64
100	0.04	0.74	100	0.02	0.60
250	0.003	0.70	250	0.0005	0.57
500	0.0008	0.68	500	0.00005	0.53
1000	0.00016	0.66	1000	0.000003	0.50

4. DISCUSSION AND CONCLUSIONS

Results from this study enable a comparison of hydrophysical properties of some representative peat layers in the study area. In partly mined bogs the mostly older and more humified upper peat layers differ strongly from those in undisturbed bogs.

For lysimeters S1-4 and C1-4 values for the storage coefficient, obtained from the lysimeter experiments show good agreement with the water retention characteristics. This does not hold for the lysimeters M1-4, with a *Molinea* vegetation, characterized by an intense rootzone in the upper 30 cm. and some cracks in the upper layers. The storage coefficients obtained from the lysimeter experiments are more reliable than those derived from the water retention measurements in 100 cc samples. Here, during sampling it was tried to exclude the cracks and bigger roots, because they would influence (i.c. hamper) the determination of water retention and hydraulic conductivity.

It is shown that for the sites M,C and Col, saturated hydraulic conductivity of the samples taken at 15 cm depth is 10 to 100 times higher than of those taken at 35 cm depth. These differences cannot fully be explained by differeces in peat type or humification degree but probably are caused by biological activity in the upper part of the soil. Saturated hydraulic conductivity is highest for less to slightly humified peat (lysimeters S1-4 and C1-4). For C1-4 at 35 cm depth it has to be noted that here the peat layer is characterized by a very pronounced horizontal layered structure. In fact, layers from 35 cm depth in lysimeters S1-4 are formed in the same period of *Sphagnum* bog growth as those at a depth of 15 cm in lysimeters C1-4 (see also Fig.2).

From the glasshouse experiment with lysimeter S4 it is concluded that under dry conditions with relatively low water levels (25 - 45 cm below surface), capillary rise in these layers is sufficient to satisfy a low evaporative demand of the top layer. During the period of measurement in the glasshouse (more than 30 days with an average evapotranspiration of 0.8 $mm.day^{-1}$) water was delivered from the saturated zone.

In the dry summer of 1989 water levels in the lysimeters S5-8 (young *Sphagnum* -peat, Fig.2) dropped to about 35 cm depth. With the watertable in the range from 10 to 35 cm, evapotranspiration rates of 2 $mm.day^{-1}$ were observed. The gradual and constant lowering of the water table indicates that much of this water was delivered from the saturated zone.

Capillary rise is different in a H6-peat soil than in a H3-peat soil. In H3-peat soils a higher water storage capacity and a resulting better water availability, makes that for equal water extraction rates (by evapotranspiration) the resulting lowering of the water table and increase in suction head in the upper layer is much less than in H6-peat. When from a H6-peat soil 60 mm water is extracted the water level will fall to ca. 70 cm and capillary fluxes will not exceed 1 $mm.day^{-1}$. After 60 mm extraction from a H3-peat soil (with a *Sphagnum* cover without rootzone) water level will be at ca. 40 cm below surface and capillary fluxes of ca. 2 $mm.day^{-1}$ are still possible. This example shows that in these peat soils capillary water supply and water availability should be clearly distinguished.

In living bogs, hydrophysical properties of the 'acrotelm' play an essential role in maintaining a high water level with very limited fluctuations. Schouwenaars (1990) shows that besides a high water storage coefficient in a living *Sphagnum* layer, also reduction of evapotranspiration contributes to a only limited lowering of the water table during a dry period. Evapotranspiration is reduced when the water table drops below 10-15 cm depth. Then, the upper living *Sphagnum* plants dry out and become yellowish.
This phenomenon is in good agreement with results presented by Verry (1988).

When after rewetting of partly cut-away bogs (regeneration, rehabilitation) *Sphagnum* regrowth occurs, during some decades the young *Sphagnum* layer will be less than 30 cm and then in dryer periods the water table may drop below 30-40 cm below surface. This is caused by the limited water storage coefficient of the underlying older and more humified Sphagnum peat layers. The resulting increased microbiological activity may hamper the development of the ombrotrophic *Sphagnum* plant communities. So, during the first phase of regeneration young *Sphagnum* plants are vulnerable to drought because their thickness is still too limited to establish sufficient 'self-regulating buffer' mechanisms to prevent a further lowering of the water table.

When after peat excavation a strongly humified peat soil (e.g.H6-peat) is covered with *Molinea* it will be almost impossible to establish a *Sphagnum* vegetation. This is largely supported by field observations (e.g. Podschlod, 1988). Not only will hydrophysical properties of these peat soils result in lower water tables, but also evapotranspiration rates of a *Molinea* vegetation remain high even in dry periods (Schouwenaars, 1990). This implies that when after such a period excess of rainfall occurs it will take a longer period before high water levels are restored. As a consequence, these sites are characterized by high water level fluctuations, which favour plant species like *Molinea*. Here the only possibility for *Sphagnum* regrowth is in floating mats after permanent inundation of the area (e.g. Joosten (1989) and Schouwenaars (1988)).

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Baden, W. and Eggelsmann, R., 1963. Zur durchlässigkeit der Moorboden. Zeitschrift für Kulturtechniek und Flurbereinigung 4, 226-254.

Bloemen, G.W., 1983. Calculation of hydraulic conductivities and steady state capillary rise in peat soils from bulk density and solid matter volume. Zeitschrift für Pflanzenernaehrung und Bodenkunde 146, 460-473

Boelter, D.H., 1965. Hydraulic conductivity of peats. Soil Science 100, 227-231

Boelter, D.H., 1969. Physical properties of peat as related to degree of decomposition. Soil Science Society of America Proceedings 83, 606-609

Ingram, H.A.P. and Bragg, O.M., 1984. The diplotelmic mire: some hydrological consequences reviewed. Proceedings 7th International Peat Congress. Dublin, vol.I, 220-234

Ivanov, K.E., 1981. Water movement in mirelands. Academic Press, London

Joosten, J.H.J., 1989. Bog regeneration in the Netherlands. Proceedings Symposium Peatland Ecosystems and Man - an impact assessment. Dundee (in prep)

Kuntze, H., 1966. Die messung des geschlossenen und offenen Kapillarsaumes in natürlich gelagerten Böden. Zeitschrift für Pflanzenernahrung, Düngung und Bodenkunde, Band 113, Heft 2, 97-106

Laat, P.J.M. de, 1980. Model for unsaturated flow above a shallow water table. Agric. Research Reports 895, Pudoc, Wageningen, 126 p.

Podschlod, P., 1988. Vegetationsentwicklung ehemaliger Torfabbaugebiete in Hochmooren des bayerischen Alpenvorlandes. Tuexenia 8: 31-53

Renger, M., Bartels, R., Strebel, O. and Giesel, W., 1976. Kapillarer Aufstieg aus dem Grundwasser und Infiltration bei Moorböden. Geolisches Jahrbuch, F3, 9-51

Romanov, V.V., 1968. Hydrophysics of bogs. Ed. Monson Bindery Ltd., Jerusalem

Schouwenaars, J.M., 1988. The impact of water management upon groundwater fluctuations in a disturbed bog relict. Agricultural Water Management, 14, 439-449

Schouwenaars, J.M., 1990. A study on the evapotranspiration of *Molinea caerulea* and *Sphagnum papillosum*, using small weighable lysimeters. Journal of Hydrology, (in prep)

Verry, E.S., 1988. The hydrology of wetlands and man's influence on it. Proceedings Symposium on the hydrology of wetlands in temperate and cold region, Joensuu. Publications Academy of Finland 5/1988, 41-61

A STUDY ON THE EVAPOTRANSPIRATION OF *MOLINIA CAERULEA* AND *SPHAGNUM PAPILLOSUM* , USING SMALL WEIGHABLE LYSIMETERS

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ABSTRACT

For a better understanding of the hydrology of bogs and bog-relicts experimental research on the evapotranspiration of *Molinia caerulea* and *Sphagnum papillosum* was carried out in the Engbertsdijksvenen (Netherlands). Small weighable lysimeters were used to study the relation between evapotranspiration and water table depth.
It was found that the potential evapotranspiration of a *Molinia* vegetation is closely related to its Leaf Area Index. In peatlands, the actual evapotranspiration from a site covered with *Molinia* will equal potential values when dry periods do not exceed one month. If longer , leaf development is affected by water stress.
The potential evapotranspiration of a *Sphagnum papillosum* vegetation is higher than for *Molinia*. However, actual evapotranspiration by *Sphagnum* shows a sharp decrease when the water level drops below 15 cm depth. Consequences for the perspectives of *Sphagnum* regrowth are discussed.

evapotranspiration, lysimeters, natural vegetation, bogs

INTRODUCTION

Water management in and around nature reserves is often hampered by insufficient knowledge of their water balance. The latter is often influenced by human activities. The water balance of bogs is changed when they are drained and cut over (Baden and Eggelsmann,1964).
In the 11-th century about 7% of the area of The Netherlands was covered by bogs. Virtually all of these areas were cut over (a.o. for fuel). Only in a few bogs this process has not been completed and at present attempts are made to restore these drained and partly cut-over remnants, ultimately aiming at the regeneration of bog growth. For this purpose, the existing drains are provided with dams in order to restore the hydrological conditions required for the regrowth of *Sphagnum* species

(Schouwenaars,1988). For a better understanding of the hydrology of bog relicts experimental research on evapotranspiration was carried out in the Engbertsdijksvenen (Netherlands).

Ingram (1983) in an extensive overview concludes that evapotranspiration from wetlands depends on their vegetation and that for treeless bogs it is about equal to open water evaporation, as calculated with Penman's equation (Penman, 1948). Eggelsmann (1964) summarizes results of experimental research in different European bogs and estimates their yearly evapotranspiration at 500 - 530 $mm.year^{-1}$.
For *Sphagnum* spp. Nichols and Brown (1980) found maximal evapotranspiration rates with a water table at about 5 cm below surface, becoming considerably lower when a depth of more than 15 cm was reached. Verry (1988), quoting different authors, reports such a critical depth to occur at about 30 cm below surface, whereas Virta (1966) observed a remarkable decrease in evapotranspiration when water levels are lower than ca. 10 cm below surface. Of course, the hydrophysical properties of the peat layers play a dominant role in the availability of water for the plants. In a compact moss layer with a high density of stems (e.g. *Sphagnum imbricatum*) capillary rise is higher than in a moss layer with a less compact structure. For different *Sphagnum* spp., Ivanov (1981) presents data about the height of the moss surface above the mean level of the water table. These values vary from 0-1 cm for *S. cuspidatum* to 25-35 cm for *S. fuscum* .

In this study the impact of a lowering water table on the evapotranspiration is investigated. Small weighable lysimeters are used. Other lysimeter studies on (semi-)natural vegetation in wetlands are mostly restricted to evapotranspiration with a constant high water level (e.g. Koerselman and Beltman, 1988)

DESCRIPTION OF THE STUDY AREA

The study area is situated in the eastern part of the Netherlands, near the border with the Federal Republic of Germany (52°28'N, 6°40'E). Mean annual precipitation is 765 mm and mean annual open water evaporation according to Penman's equation is about 620 mm. Mean temperature is 8.8°C. In the vegetation period (15 April - 15 Oct.) mean daily temperature varies from about 10°C to 16.5°C.

The Engbertsdijksvenen originally were part of a vast area covered by bogs. Since the Middle Ages the peripheral parts have been brought under exploitation, whereas the central part of the bog was drained and partly cut over in the 19-th and early 20-th century. The different peat mining concessions in the Engbertsdijksvenen expired between 1953 and 1983 and thereafter the National Forestry Service began to manage these areas with the aim to reestablish the original vegetation.

The dominant species in the study area is *Molinia caerulea*. Heather species like *Erica tetralix* and *Calluna vulgaris* may dominate locally. *Sphagnum* spp., especially the pioneer *S.cuspidatum*, frequently grow at permanently inundated sites, e.g. in the former drains. In such places floating mats of *Sphagnum* vegetation may develop and after some time other species colonize these mats. In the Engbertsdijksvenen *S.papillosum* is a frequently observed species along the banks of former ditches at sites with limited water fluctuations.

METHODS

lysimeters

Lysimeter observations were carried out with the species *Molinia caerulea* and *Sphagnum papillosum*. Undisturbed soil columns covered with these plant species were taken to a depth of 50 cm with a sampling device, having a diameter of 40 cm. (Fig.1). These columns were inserted in a lysimeter of equal size, closed at the bottom. Fig.2 schematically illustrates at which sites the different samples were taken. The selected sites represent the most important differences in peat properties within the area (see Table 1).

Four *Molinia* lysimeters were used (M1-M4). They were installed in a 50 cm deep hole with a diameter of approximately 50 cm to enable weighing. The space between the lysimeter and the wall of the hole was covered with litter to prevent evaporation.

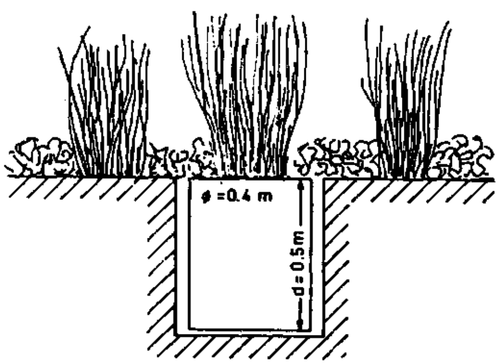

Fig.1 Dimensions of the lysimeters

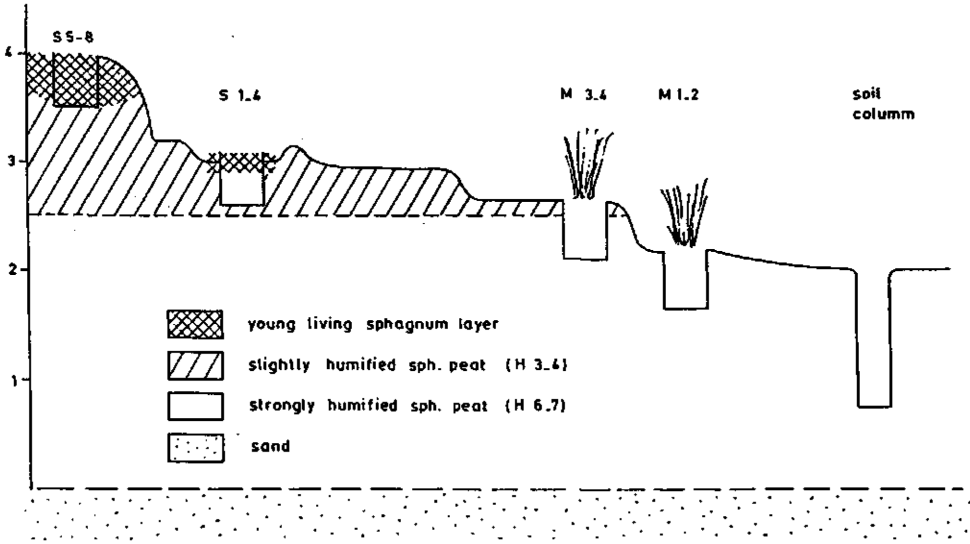

Fig.2 Schematic overview of sample locations in the study area

TABLE 1

Hydrophysical properties of the peat layers in the lysimeters determined with samples taken at the same sites

lysimeter	depth (cm)	volumetric water content (%) [1] at pF0	pF2	pF3	saturated hydraulic conductivity (cm.day^{-1}) [2]	humification degree (von Post) scale
M1-M4	15	88	74	66	0.8 - 3.7	H5-6
	35	88	78	72	0.01 - 0.37	H6-7
S1-S4	15	87	60	50	2.6 - 8.1	H2-3
	35	90	74	70	2.2 -11.5	H3
S5-S8	25	85	65	54		H2-3

[1]average value

[2]lowest and highest value

In 1988 four *Sphagnum* lysimeters were used (S1-S4). In 1989 four more were added (S5-S8). They were situated in a waterholding blocked drain. During the measurement period their position was regularly adjusted to maintain the top of the lysimeters about 10 cm above the water level in the drain.
The lysimeters were taken out with a tripod and replaced after measurement. A spring loaded scale was used for weighing. Its accuracy is about 0.05 kg, which corresponds to a water layer of 0.4 mm depth.

In the periods 11 May - 26 September 1988 the lysimeters M1-M4 and S1-S4 were weighted at intervals, varying from 3 to 9 days, depending on the weather conditions. In the period 5 May - 19 September 1989 this was repeated and lysimeters S5-S8 were addded.
In 1988 for each vegetation type two lysimeters were regularly filled to maintain a relatively high water table (M1-M2 and S1-S2). The water table in M3-M4 and S3-S4 was allowed to drop, although in the *Sphagnum* lysimeters minimum levels were maintained at about 30 cm.
In 1989 the treatments were adjusted. During the first phase of the measurement period the lysimeters M1-M2 were kept at a relatively high water level. In August their waterlevels were allowed to drop gradually and in September they had become entirely unsaturated.

From May to mid- August 1989 for the *Sphagnum* lysimeters the same treatment as in 1988 was repeated. The lysimeters S1-S2 and S5-S6 were kept wet, whereas the lysimeters S3-S4 and S7-S8 had lower levels. From mid-August onwards, however, the water levels in the lysimeters S1-S2 and S5-S6 were kept low, whereas those of S3-S4 and S7-S8 were regularly filled to maintain a high water level.
The different treatments are summarized in Table 2.

In 1988, during dry periods (e.g. May,June) S3 and S4 were filled regularly to avoid dying of the upper parts of the *Sphagnum* plants. If necessary, water was added to keep the water table around 30 cm depth. In 1989 a further lowering was accepted.

After heavy rainfall it was sometimes necessary to drain the lysimeters in order to maintain acceptable differences in water levels between the two groups (e.g. M1-M2 versus M3-M4). This was also necessary to prevent superficial runoff from the lysimeters.

TABLE 2

The different experimental treatments in the lysimeters

		Molinia				*Sphagnum*							
period	lys.	1	2	3	4	1	2	3	4	5	6	7	8
may-sept 88		h	h	l	l	h	h	l	l				
may-july 89		h	h	l	l	h	h	l	l	h	h	l	l
aug-sept 89		l	l	l	l	l	l	h	h	l	l	h	h

explanation; h: maintained at relatively high water level
l: relatively low water levels, depending on weather conditions

Additional experiments were done with the lysimeters M4 and S4. In September 1988 they were placed inside the laboratory and tensiometers were installed, two at a depth of 15 cm and two at 35 Evapotranspiration and suction heads were measured and capillary fluxes were analysed. Schouwenaars and Vink (1990) will report on these hydrophysical aspects of the lysimeter experiments.

At the start of the field experiments of 1989 the lysimeters M4 and S4 had become unsaturated over the entire depth and very dry. The upper (brown) layer of *Sphagnum* in S4 seemed to have died completely.

rainfall
Rainfall was measured with a tipping bucket raingauge at 0.9 m. height (average maximum height of surrounding *Molinia* tussocks). Totals for 30 minutes-intervals were recorded. Also a non-recording raingauge was installed at 0.4 m height to determine cumulative precipitation during every measurement-interval.

reference evapotranspiration
Meteorological equipment was installed to measure a.o. global short wave radiation at 2 m height ($W.m^{-2}$) and air temperature at 1.3 m height (°C). Both data were recorded in 30-minutes intervals. Reference evapotranspiration (Er) was determined using the equation given by Makkink (1957):

$$\lambda \cdot Er = 0.65 \frac{s}{s + \gamma} K^{\downarrow} \qquad (W.m^{-2}) \qquad (1)$$

where : λ = latent heat of vaporization of water ($J.kg^{-1}$)
E_r = reference evapotranspiration (Makkink) ($kg.m^{-2}.s^{-1}$)
s = slope of the saturation water vapour pressure temperature curve at air temperature ($kPa.K^{-1}$)
γ = psychrometer constant ($kPa.K^{-1}$)
$K^{\downarrow}$ = global radiation ($W.m^{-2}$)

Eq.1 has the advantage that only easily measurable quantities like global radiation and air temperature are needed. For The Netherlands the method gives a fair estimate of the reference evapotranspiration (maximum for short grass, Feddes (1987)).

vegetation cover and leaf area index

The *Sphagnum* lysimeters S1-S4 contained a 35-40 cm thick undisturbed slightly humified peat layer (humification degree 3 on the Von Post scale) with on top a 10-15 cm thick young *Sphagnum papillosum* layer. The *Sphagnum* layer had formed during the past 10-20 years as a result of rewetting of the sampling site. Lysimeters S5-S8 contained undisturbed profiles taken from a site covered with *S.papillosum.* They consist of the deeper situated dead moss parts with on top living *Sphagnum* in vertically oriented stems with green tops of about 3-5 cm length. These stems grow in a dense mat with some very small shrubs of *Erica tetralix*. The latter were frequently cut away but some regrowth occurred and its average coverage is about 10%. During dry periods the *Sphagnum* tops in the lysimeters with low water levels dry out and become yellowish-white. After a rainy period new shoots are formed at about 3-5 cm below the top of the stem and gradually (in 1-2 weeks) the upper layer turns green again. Part of the stems died during inundation periods. These features illustrate the high vulnerability of *Sphagnum papillosum* for fluctuations in water levels.
The development of the assimilating (green) fraction of the *Sphagnum* lysimeters is presented in Table 3.

TABLE 3

Development of the fraction covered with green living stems in the *Sphagnum* lysimeters

lysimeter	S1	S2	S3	S4	S5	S6	S7	S8
1988								
21 june	95	85	35	50	-	-	-	-
4 july	95	90	35	50	-	-	-	-
18 july[1)]	95	85	50	40	-	-	-	-
1989								
6 june	40	70	80	10	-	-	-	-
20 june	30	50	10	0	10	5	5	30
11 july	60	80	10	5	15	20	5	30
23 aug	60	70	60	25	40	20	30	30
5 sept	60	70	60	25	40	20	30	40

[1)]constant during the rest of the vegetation period

In the *Molinia* lysimeters differences in above ground shoot biomass probably result in different potential evapotranspiration rates. In between the newly grown leaves, litter of preceding years is accumulated and will probably act as a mulch layer, severely limiting soil evaporation. To study the relation between leaf area and (evapo-)transpiration the leaf area index (LAI, total area of green leaves per unit surface area ($cm^2.cm^{-2}$)) was determined at regular intervals. In 1988 and 1989 this was done for the lysimeters and in 1988 also for a random sample of 5 *Molinia* plants outside. From the latter an average value for the LAI under field conditions was determined. When for the lysimeters a relation can be found between potential evapotranspiration and their leaf area, the average 'field'-value for the LAI enables the determination of potential evapotranspiration for a site covered with *Molinia*.
Once in every month for each plant (lysimeters and in 1988 also for 5 random samples outside) the green shoots were counted and divided into different length-classes (10 cm intervals). For the random samples the average area (cm^2) for each length-class was determined, by measuring average width and average green length. At the end of the season (September, October) the leaves die off starting from the leaf tip.
It has to be noted that the leaf area determined according to the method described above may differ from the values obtained using other methods (e.g. weighing of green leaves). In this study the objective is to establish a quantitative relation amongst the different lysimeter-plants and to relate them to average field conditions. Therefore, the equations found in this study are only valid for LAI-values, obtained by the method described above.

RESULTS

Weather conditions

For every measurement interval cumulative values for precipitation and reference evapotranspiration are presented in Table 4. The summer of 1988 was rainy, whereas 1989 was drier, although a few heavy showers occurred.

TABLE 4

Precipitation and evapotranspiration data for the measurement intervals of the lysimeter experiments in the Engbertsdijksvenen

year 1988			1989		
date	precipitation (mm)	Makkink evapotranspiration (mm)	date	precipitation (mm)	Makkink evapotranspiration (mm)
			8 may[1)]	-	-
18 may	-	-	19 may	10.1	35.3
24 may	6.9	13.2	25 may	0.0	28.5
27 may	0.1	9.1			
1 jun	22.7	9.9			
6 jun	20.3	12.2	5 jun	18.1	33.5
14 jun	11.4	16.9	15 jun	9.0	32.5
17 jun	0.0	10.0	21 jun	1.0	7.7
20 jun	0.0	24.3			
27 jun	0.0	12.2	26 jun	6.5	20.4
4 jul	42.7	18.7	3 jul	42.5	20.2
9 jul	21.5	11.6	11 jul	17.0	29.0
13 jul	5.4	11.8	18 jul	59.0	6.1
25 jul	22.1	11.0	25 jul	3.0	43.8
1 aug	23.8	17.2	31 jul	26.5	14.1
8 aug	0.7	19.9	15 aug	10.0	18.6
22 aug	25.8	19.3	23 aug[2)]	5.5	65.0
29 aug	35.8	11.8	30 aug	37.5	13.3
5 sep	3.6	13.5	5 sep	10.5	8.9
9 sep	3.8	10.1	12 sep	1.5	4.2
13 sep	0.6	17.5			
19 sep	27.1	19.3	19 sep	29.1	10.2
26 sep	21.3	6.8			
18 may-26 sep:	366.5	291.1	19 may-27 sep:	239.5	372.8
daily average:	2.78	2.21		1.81	2.82

[1)] start of first period with lysimeter experiments

[2)] start of second '' ''

Molinia

At the end of the measurement period the height of the plants (i.c. stalks) varied from 40 to 90 cm. In the direct surroundings of the lysimeters frequent trampling had resulted in a dwarfed vegetation. During thunderstorms, when heavy rainfall was combined with strong winds, the high, relatively isolated lysimeter plants intercepted more water than the raingauges. Therefore, in the elaboration phase it was decided to exclude observation intervals during which recorded precipitation exceeded 25 mm.

Another error in the determination of actual evapotranspiration results from differences in time at which the different lysimeters were weighed (some hours). In this study only water balance terms were analysed for periods longer than 5 days, combining cumulative values of the shorter measurement intervals.

Differences in plant biomass and green leaf area between the lysimeters will affect potential transpiration of the individual plants. It may be expected that in the beginning of the growing season their impact is more pronounced than at the end. Above a certain leaf area value, further plant development hardly influences potential transpiration, because of increasing shading of the lower leaves. When leaf area values (LA) during the measurement period of 1988 are related to the evapotranspiration ratio (E_m/E_r) it is found that for the range studied ($LA < 12.10^3\ cm^3$), the following relation gives the best statistical approximation:

$$E_m \,/\, E_r = 0.202 \,.\, LA^{\,0.242} \qquad (r=0.83) \qquad (2)$$

where E_m = measured evapotranspiration (mm)
E_r = reference evapotranspiration (mm) (Eq.1)

However, the relation described in Eq.2 is physically impossible, because with an increasing Leaf Area, the E_m/E_r-values should reach a limit. Another relation is given by Eq.3:

$$E_m \,/\, E_r = 2.1 \,.\, (\, 1 - e^{\,0.35\,(LA/1250)}\,) \qquad (r=0.69) \qquad (3)$$

Both relations are indicated in Fig.3. In this study preference is given to Eq.2 because it results in a higher correlation (statistically). For lysimeters M1-M4 the E_m/E_r-ratio determined for 1989 is presented in Fig.4. Its relation with the Leaf Area as described by Eq.2 (derived for the conditions of 1988) is also indicated and this equation appears to give a good approximation for the lower LA values at the beginning of the growing period. For low LA values Eq.3 would result in too low values for the E_m/E_r ratio.

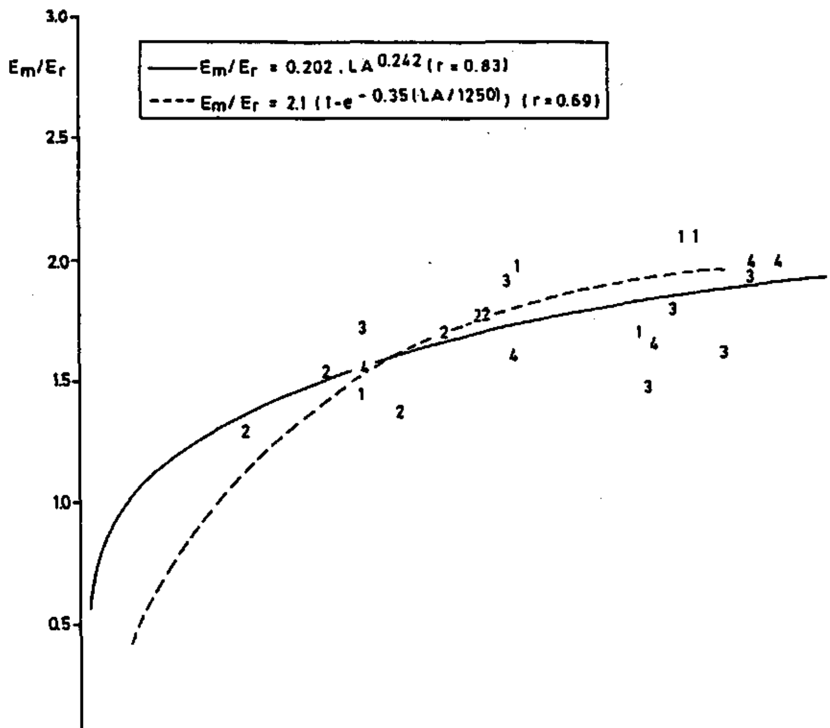

Fig.3 Relation between evapotranspiration ratio (E_m/E_r) and leaf area (LA) for the *Molinea* lysimeters for the wet summer in 1988

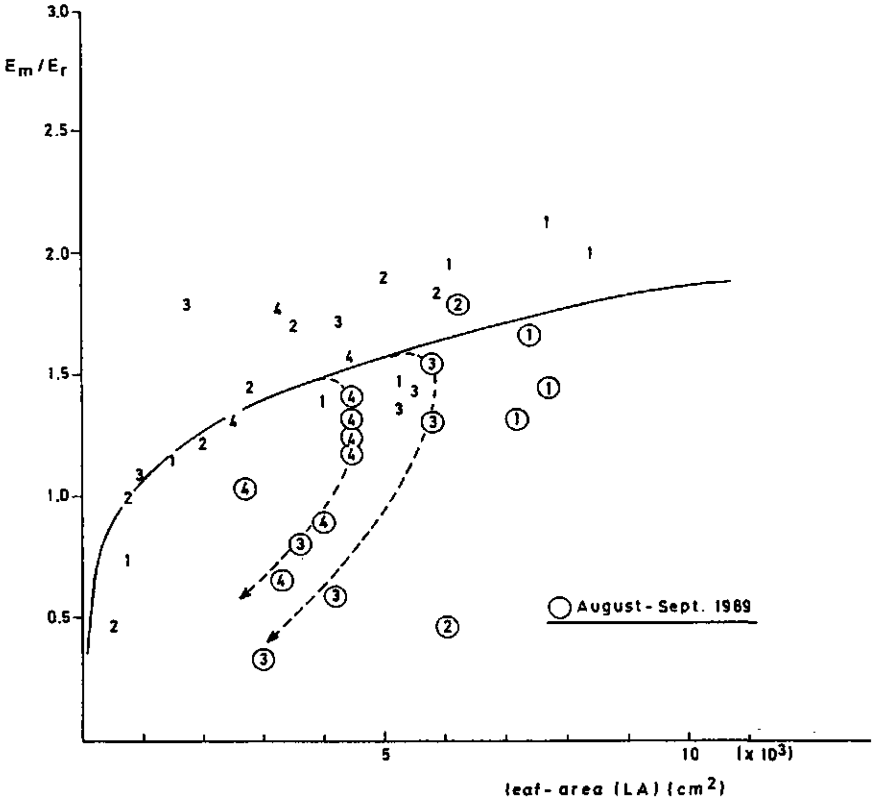

Fig.4 Relation between evapotranspiration ratio (E_m/E_r) and leaf area (LA) for the *Molinea* lysimeters for the dry summer in 1989

For a correct interpretation of potential evapotranspiration of a site covered with *Molinia* , the leaf area values of the random field samples of 1988 were used. In 10 *Molinia* plots of 25 m^2 the number of *Molinia* tussocks were counted. Values vary from 108 to 138 plants with an average of 125. So, average plant density is 5 plants.m^{-2}. The leaf area values of the samples are used to determine the LAI- development over the growing season (Fig.5). The superficial area of the lysimeters is 0.125 m^2, so here density is 8 plants.m^2. Now, Eq.2 can be converted to relate the potential evapotranspiration of *Molinia* with the LAI for field conditions:

$$E / E_r = 0.794 \cdot LAI^{0.24} \qquad (4)$$

The development of the E / E_r ratio, obtained by using Eq.4, is indicated in Fig.5.

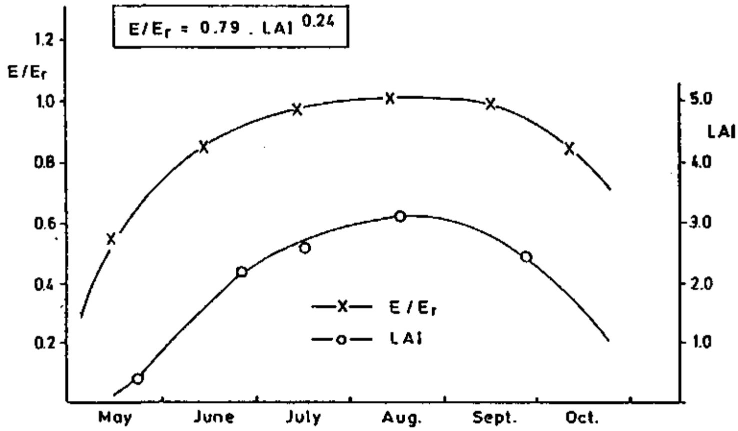

Fig.5 Development of Leaf Area Index (LAI) and evapotranspiration ratio (E/E_r) for a *Molinea* vegetation during the growing season.

Sphagnum papillosum

Sphagnum plants have no roots and hence their water supply greatly depends on capillary rise. With the exclusion of periods in which total rainfall exceeded 25 mm, most of the remaining rainy periods were characterized by frequent small showers. It may be expected that during such rainy periods evapotranspiration is less depending on capillary rise. As a consequence only on days when Makkink reference evapotranspiration (E_r) exceeds precipitation (R) a more pronounced dependency on capillary fluxes may be expected. This has lead to an analysis in which only the actual (E_m-R) and the potential soil water supply (E_r-R) are regarded. Their values were obtained from a daily analysis of precipitation data. The ratio between (E_m- R) and (E_r- R) is analysed in relation to water table depth. Results for the lysimeters S1-S2 and S5-S6 (same treatments, Table 1) are presented in Fig.6 and for S3-S4 and S7-S8 in Fig.7.

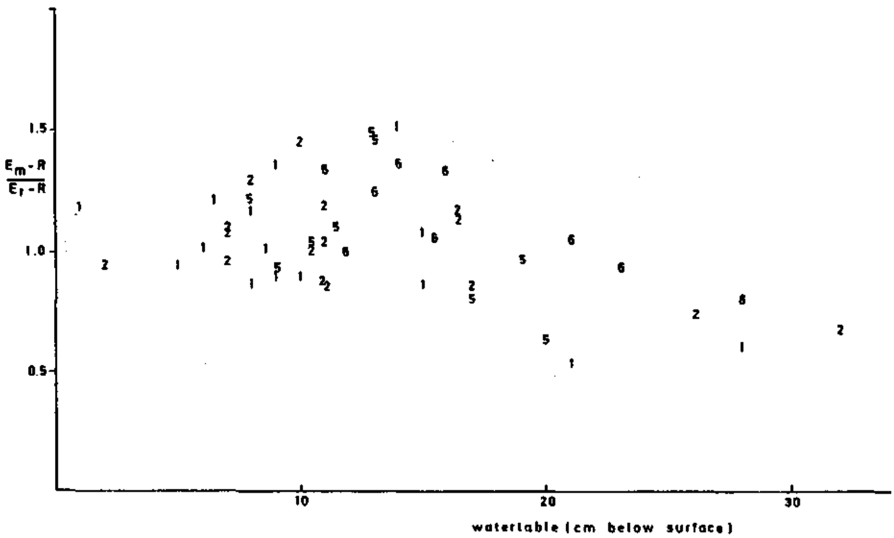

Fig.6 Relative water supply ($(E_m\text{-}R)/(E_r\text{-}R)$) in relation to water table depth in the *Sphagnum* lysimeters S1-S2 and S5-S6

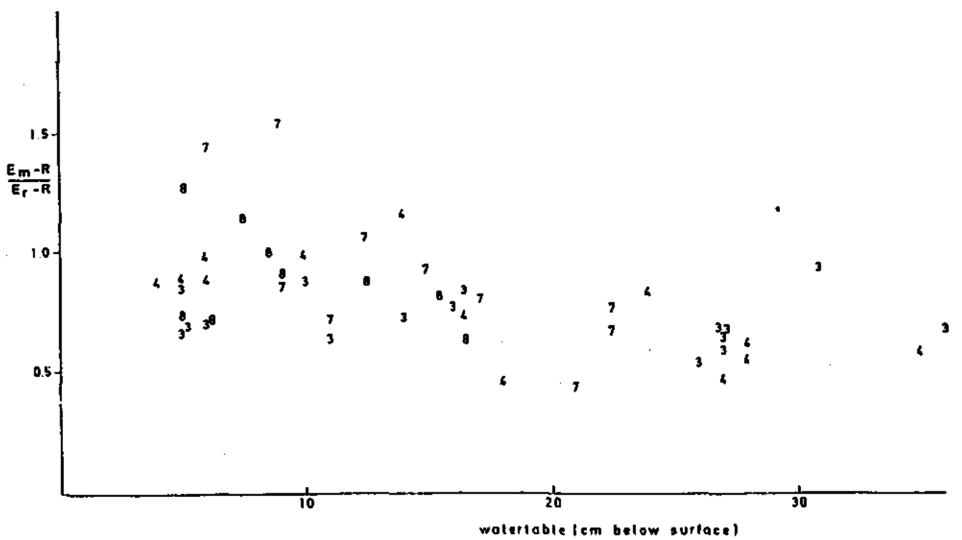

Fig.7 Relative water supply ($(E_m\text{-}R)/(E_r\text{-}R)$) in relation to water table depth in the *Sphagnum* lysimeters S3-S4 and S7-S8

CONCLUSIONS

From Fig.3 it can be concluded that under the (relatively rainy) weather conditions of 1988 no reductions due to water stress occurred in the *Molinia* lysimeters. For lysimeter M4 this was even noticed under extreme dry glasshouse conditions where after 30 days with an average evapotranspiration of 2.4 $mm.day^{-1}$ the water suction at 15 cm depth still did not exceed 20 KPa (pF 2.3). It seems that plants with a deep root system in these peat soils (solid matter content < 15%) are sufficiently supplied with soil water during dry periods not exceeding one month.
After a separate analysis of lysimeters M1-M2 and lysimeters M3-M4 respectively, it was concluded that in 1988 no significant differences could be found between these two groups. Therefore in Fig.3 they are grouped together. The latter conclusion also resulted from an analysis of the relation between actual (i.c. measured) evapotranspiration and groundwater depth. Although in 1988 water levels in M3-M4 were kept lower than those in M1-M2, no relation could be found between water levels and actual evapotranspiration.

In the period May-July 1989 the watertables in lysimeters M1-M2 were maintained at a high level (Table 1) and for this period results show good agreement with those of 1988. From August onwards they were no longer supplied with water and during one month (September) they were fully unsaturated. In that period in the lysimeters the average volumetric soil water content (derived from total weight) was 70 - 75%, which corresponds to suction heads between 10 and 100 kPa (pF 2 -pF 3, Table 2) . When initially the entire profile would have been saturated, at that time the amount of water extracted by the plants would have been about 50 mm. Under these conditions no significant reduction in evapotranspiration could be observed (Fig.4).
At the start of the measurements in 1989 the lysimeters M3 and M4 were dry (i.c. unsaturated over the entire profile). In Fig.4 it is shown that the leaf development was seriously hampered by water shortage. The maximum LA was 5800 cm^2 for M3 (July 10th) and 4500 cm^2 for M4 (rather constant from June 6th to the end of August). In that period the average volumetric water content in the lysimeters was about 50%, which corresponds to a suction head between 100 and 1600 kPa (pF 3 - pF 4.2, Table 2). When initially the entire profile would have been saturated at that time the amount of water extracted by the plants would have been 120 mm. This indicates that in dry periods the *Molinia* vegetation in the first instance reduces its leaf development and that during a considerable time (May-July) the E_m/E_r-ratio still can be described as a function of this (reduced) Leaf Area (Eq.2). However, a sharp decline in the E_m/E_r-ratio was observed in August and September 1989 (Fig.4, lysimeters M3 and M4).
In the field there were hardly any indications of water shortage for the *Molinia* plants, although in some tufts leaves started to dry out at their top in September, when the water table was at about 80 cm below

surface. In the field the roots of a single *Molinia* plant occupy a soil volume which is 1.6 times larger than for a lysimeter plant. Furthermore, in the lysimeters capillary fluxes from the saturated zone stops as soon as the phreatic level reaches the bottom of the lysimeter.

It is concluded that the peat soils of the study area are able to provide enough water to the plants to satisfy their potential evapotranspiration demand, also during dry periods not exceeding one month.

In Fig.5 it is shown that the potential E/E_r-ratio is approximately 1.0 in July. In May and June the *Molinia* plants show a delay in growth as compared to other short grass vegetation types. After July the vegetation shows evapotranspiration rates equal to the Makkink reference values. In the period September-October a rapid decline occurs due to the dying of the leaves.

In Fig.6 it is shown that for a *Sphagnum papillosum* vegetation the water supply is optimal when the water level is at 10-15 cm below surface. For the lysimeters S3-S4 and S7-S8, which were exposed to dry conditions at the start of the measurements in 1989 (Table 1) water supply is best at a water depth of about 10 cm.(Fig.7). For all *Sphagnum* lysimeters it is shown that when the water table drops below 15 cm depth, the ratio E_m-R/E_r-R is reduced to about 0.6-0.8 and remains fairly constant with a further lowering of the water table. As it might be expected that the results will depend on the total evaporative demand, the measurement periods were divided into groups with different values for the Makkink reference evaporation. However, no relation could be found between the E_m-R/E_r-R ratio and total evaporative demand. Because plant growth is related to the E_m/E_r-ratio rather than to the ratio E_m-R/E_r-R, it should be remarked that the former will be somewhat lower than the latter when $E_m > E_r$. The opposite will be true when $E_m < E_r$.

The glasshouse experiment with lysimeter S4 in 1988 showed that under dry conditions with relatively low water levels (25-35 cm below surface), water supply is sufficient to satisfy a low evaporative demand of the top layer. In the 30-days period that a phreatic level could be observed , average evapotranspiration was 0.8 $mm.day^{-1}$. The gradual and constant lowering of the water table indicates that much of this water was delivered by capillary rise from the saturated zone. The maximum suction head at 15 cm depth was 3 kPa (pF 1.5). In the dry summer of 1989 water levels in the lysimeters S5-S8 dropped to about 35 cm depth. With the water table in the range from 10 to 35 cm, evapotranspiration rates of 2 $mm.day^{-1}$ were observed. Also in this dry summer the constant lowering of the water table indicates that much of the evaporated water continued to be delivered from the saturated zone.

DISCUSSION

Some of the results presented in this study can only be fully understood from the hydrophysical properties of these peat soils. Schouwenaars and Vink (1990) will report on these aspects. Different methods exist to calculate potential evapotranspiration. Also different methods can be used to describe leaf area development. When the values for the E_m/E_r-ratio obtained in this study are used to determine potential evapotranspiration from reference evapotranspiration, the Makkink formula (Eq.1) has to be used. If another method is used, then its relation to Makkink values has to be known. Reference values obtained with Penman's equation for open water evaporation are 17-30% higher in summer than those of Makkink (Feddes,1987). As the main objective of this study was to analyse differences between different types of vegetation under different water level conditions, these methodological problems are not very important for the conclusions of this study.

For a *Molinia* vegetation evapotranspiration in May is low and about 50% of open water evaporation. In the period July-September it will be about 80% of the open water evaporation. The presence of this vegetation on strongly humified peat soils with a limited water storage coefficient will result in low water levels during most summers (more than 60 cm depth) (Schouwenaars and Vink, 1990). This severely limits the possibility for the regrowth of *Sphagnum* species.

During the first phase after rewetting when young *Sphagnum* layers gradually develop on top of an older peat layer, the system is vulnerable for dry periods. Ability to shrink with a lowering water table, as known for undisturbed bogs, is still limited. As shown in this study evapotranspiration is reduced in dry periods. The *Sphagna* may stop growing and become yellowish-white, but regrowth is possible afterwards. This means that in regions with frequent dry summer periods, the growth of *Sphagnum* spp. is hampered and total actual evapotranspiration of a *Sphagnum* vegetation will be less than in more humid regions. In the latter evapotranspiration from bogs will almost equal open water evaporation based upon Penman's equation. Only in dry periods exceeding 2 weeks actual evapotranspiration will be less.

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REFERENCES

Baden,W. and Eggelsmann,R., 1964. Der Wasserkreislauf eines nordwestdeutschen Hochmoores. Schriftenr. Kurat. Kult., Hamburg, 12, 1-156

Eggelsmann,R., 1964. Die Verdunstung von Hochmoore und deren hydrologischen Einfluss. Dt. Gewasserkundl. Mitt. 8, 138-147

Feddes,R.A., 1987. Crop factors in relation to Makkink reference crop-evapotranspiration. In: Hooghart,J.C.(Ed.) Evaporation and weather. TNO/Cie. Hydr. Research, The Hague, Proc. and Inform. 39, 33-45

Ingram,H.A.P., 1983. Hydrology. In: Gore,A.J.P. (Ed.), Mires: Swamp, Bog, Fen and Moor. Ecosystems of the World, vol.4A. Els.Sci.Publ., Amsterdam, 67-158

Ivanov,K.E., 1981. Water movement in mirelands. Academic Press, London, 276 pp.

Koerselman,W. and Beltman,B., 1988. Evapotranspiration from fens in relation to Penman's potential free water evaporation (E_0) and pan evaporation. Aquatic Botany 31, 307-320

Makkink,G.F., 1957. Testing the Penman formula by means of lysimeters. J. of the Institution of Water Engineers 11: 277-288

Nichols,D.S. and Brown,I.M., 1980. Evapotranspiration from a *Sphagnum* moss surface. J. of Hydrology 48, 289-302

Penman,H.L., 1948. Natural evapotranspiration from open water, bare soil and grass. Proc.Roy.Soc.Acad., 193, 120-145

Schouwenaars,J.M., 1988. The impact of water management upon groundwater fluctuations in a disturbed bog relict. Agric. Water Management, 14, 439-449

Schouwenaars,J.M. and Vink,J.P.M., 1990. Hydrophysical properties of peat relicts in a former bog and perspectives for *Sphagnum* regrowth. International Peat Journal, 5 (in prep.)

Verry,E.S., 1988. The hydrology of wetlands and man's influence on it. Proc. Symp. on Hydrol. of Wetlands in temperate and cold regions, Joensuu. Publ. Acad. of Finland 5/1988, 41-61

Virta,J. 1966. Measurement of evapotranspiration and computation of water budget in treeless peatlands in the natural state. Comment. Phys.-Math.Soc.Sc.fenn., 32 (11), 1-70

SUMMARY

SOWING STRATEGIES FOR MAIZE IN RAINFED AGRICULTURE IN SOUTHERN MOZAMBIQUE

Rainfed crop production in the coastal zone of southern Mozambique is mainly practised by small family farming units. Each family cultivates different fields (machambas) with a total area of 1 - 2 ha. On the sandy soils the most important cereal crop is maize (*Zea mays*). Other important foodcrops are cassave (*Manihot sp.*), groundnut (*Arachis hypogea*), sweet potato (*Ipomoea batatas*), cowpea (*Vigna sp.*) and pigeonpea (*Cajanus cajan*). Mixed cropping with low plant densities for maize is most common in this area.
Mean annual precipitation decreases from 800-1000 mm near the coast to 550 mm in the interior (50-75 km from the coast). Rainfall is concentrated in the rainy period between October and April. It is highly irregular and its yearly fluctuations are extremely high.
In the sandy soils capacity for water retention is very low (5-10% of its volumetric content). Here, the average production of maize is very low (less than 1000 $kg.ha^{-1}$) and yields vary with the amount and distribution of rainfall during the growing period. Although a concentration period can be distinguished, it seems common practice to sow maize in small quantities throughout the whole year whenever rainfall is sufficient. The most important time for sowing, however, is September-October. From an agrohydrological point of view this is not the most favourable period . Risks for water deficiency are lower when sowing would start in the period December-January. Probably the earlier sowing can be explained by the almost permanent food shortage, inducing people to start as early as possible , and by the higher risks for damage caused by pests and diseases in later periods. In this study it is tried to understand the logic of certain sowing strategies with the use of a model approach. Therefore a selection has been made of some environmental factors which are expected to play a role in preferences for sowing strategies. Emphasis is laid on water availability, depending on rainfall, soil properties and plant density. The impact of losses caused by pests and diseases and by inadequate storage facilities and the impact of different potential production levels is analysed in quantitative terms.

For the simulation of maize yields the simple water balance and crop growth model SWETAM was developed. Actual production of maize for an average family unit is calculated with assumptions about cultivated area, potential production, yield reduction by water deficit and by pests and diseases. Required consumption levels were determined based upon calorie- and protein needs. Actual consumption of maize in a certain month is determined taking into account the stored quantities and the perspectives of the standing crops.

In reality, it is very important whether alternative food is available. In this study this is not taken into account and attention is only given to maize production and consumption. With these assumptions it is possible to determine the actual amount of maize available for consumption per month over a longer period and to evaluate different sowing strategies. For the period 1957-1985 the conditions in Manhica were examined, situated at about 20 km from the coast (25°24'S, 32°48'E). The following strategies were analysed:

- strategy 1 : 0.1 ha is sown every month
- strategy 2 : 0.4 ha is sown in September, December and March, respectively
- strategy 3 : 1.2 ha is sown in December

When selecting a preferable strategy the problem arises that the criteria to decide upon are not well understood and do vary. For instance, when alternative food is available throughout the whole year then for maize preference might be given to the maximization of production. However, when this is not available, then preference might be given to the minimization of the length of the periods with shortage of maize ('critical periods'). In this study a critical period is defined as a period in which consumption is less than 50% of the minimal required maize food. An analysis has been made of critical periods with a length of 3 months and of more than 3 months.

For all simulations, when maximizing the average yearly consumption, strategy 3 (sowing once a year in December) is to be preferred when yield reductions by pests and diseases and storage losses are small. When losses increase, strategy 2 (sowing in September, December and March) becomes preferable. It is clearly shown that for maximizing yearly consumption the impact of losses upon preferences is by far dominant over water-availability. However, regarding the decision criterion of minimizing critical periods the preferred sowing strategy does greatly depend on water-availability. When water supply is marginal and losses are low, strategy 3 is preferred. An increase of losses then leads to a preference for strategy 1 (sowing in every month). With an inrease of water-availability this scattered strategy becomes less attractive and also strategy 3 will become less attractive for the farmer, even for low losses. Under a relatively high availability of soil water for all combinations of losses strategy 2 is preferable. Hence, when minimizing risks for food-shortages (besides maize no alternative food available), water-availability plays a dominant role in sowing strategies. When it improves strategy 2 soon becomes preferable, independent of the rate of losses. The impact of plant densities upon sowing strategies is negligible when compared to the dominant role of yield reduction by pests and diseases. Here again a concentrated strategy is preferred when this reduction is low, whereas a scattered

strategy gives the best results when it is high. A somewhat higher potential production level roughly gives the same alterations in preferences than a better soil water-availability, discussed earlier.
Of course, under all farming conditions attempts are needed to control pest and diseases, to reduce storage losses and to improve water availability and soil fertility (i.c. potential production).
If this is succesful, production and consumption levels will increase. However, when we focus on optimal sowing strategies it can be concluded that in regions with little access to (markets for) alternative food, an improvement of water availability and soil fertility will result in other sowing strategies. This does not hold for regions where alternative food is available. Under these conditions sowing strategies will alter only when losses by pests and diseases and/or storage are reduced.

One of the main problems in analysing sowing strategies is of an agro-economic nature. In this study this is made clear by presenting 2 criteria to decide upon for optimization, i.e. maximizing average yearly maize consumption and minimizing occurrence of periods with shortages. However, many other criteria can be used. Whether these correspond with the ones used by farmers in Mozambique, will depend on environmental factors (region, soils) and socio-economic factors (market, labour-availability, alternative income, etc.).

SUMMARY

**WATER MANAGEMENT IN BOG RELICTS
IN THE NETHERLANDS**

In the Netherlands virtually all bogs have disappeared as a result of peat cutting and cultivation. At present the total area of bog relicts is about 9000 ha. They are severely disturbed by drainage, peat cutting and fire. Only locally, some very small remnants of the original bog vegetation, dominated by *Sphagnum* spp., have survived. Nowadays, the dominating species are *Molinia caerulea*, *Betula pubescens*, *Calluna vulgaris* and *Erica tetralix*. Since about 1970 in several bog relicts attempts have been made to restore environmental conditions suitable for the reestablishment of the original bog vegetation. The most important activity is rewetting. This can be done by both internal and external water management measures. Internal options focus on the prevention of outflow through ditches to restore a high water teable and an increase in water storage capacity near the surface to limit the water level fluctuations. External management options (e.g. hydrological buffer-zones) focus on the reduction of downward water losses to maintain a high water level.

Ecological constraints for bog regeneration are not fully known. Many of the management practices are based upon the current knowledge about required groundwater fluctuations. It is commonly accepted that in summer the water table depth should not be lower than about 30-40 cm.
After the drainage of bogs the hydrophysical properties of the upper layers are, partly irreversibly, changed. When the *Sphagnum* mosses die off, heather and grass species invade the site and these rooting plants are able to extract the water from deeper layers. The moss layer with its high water storage capacity, is replaced by a more compacted slightly to moderately decomposed peat layer with a lower storage capacity. Both factors lead to a further lowering of the water table in summer. Aeration will result in higher decomposition rates by (micro-)biological activity. These processes reduce the possibilities for the reestablishment of the former *Sphagnum* vegetation and it is questionable whether these changes can be reversed. Another problem is whether the changed input rates of nutrients from the atmosphere (e.g. nitrogen deposition) will affect the reestablishment and development of the ombrotrophic bog vegetation in rewetted areas.

In this study some aspects of the hydrology of bog relicts, relevant to the problem of regeneration, are presented. To study some of these aspects an extensive field research has been carried out in the Engbertsdijksvenen (Netherlands; 52°28'N, 6°40'E) in the period 1987-1989. Main attention is given to the quantitative hydrological aspects.

Their consequences for water management measures focussing on bog regeneration will be discussed. Small weighable lysimeters were used to study the evapotranspiration of *Sphagnum papillosum* and *Molinia caerulea*. Contrary to plants with a root-system, *Sphagnum* mosses depend on capillary water supply to satisfy transpiration demand. The latter is highest in summer and then dry periods of more than one week may already result in a reduced evapotranspiration. When water supply is not limited, evapotranspiration from a *Sphagnum* vegetation is somewhat higher than for open water. This can be observed at water levels of about 5-10 cm below the tops of the *Sphagnum* stems.
Also the actual and potential evapotranspiration of *Molinia cearulea*, the dominating plant species in the Dutch bog-relicts, was examined. It was concluded that this species is able to extract sufficient water from a peat soil to guarantee evapotranspiration at potential values, even after a dry period of one month with the groundwater at 70-80 cm depth. It was found that potential evapotranspiration of *Molinia* is closely related to its LAI-index.
In most of the Engbertsdijksvenen area the upper peat layers have been completely removed and the deeper more humified peat lies at the surface. From the lysimeter experiments, values for the water storage coefficient in peat layers with different degree of humification were obtained. In moderately to slightly humified peat at 15 to 35 cm depth, water storage is much lower than in the upper 10 cm of living *Sphagnum* moss. In strongly humified peat its value is also lower. In these soils it was observed that the presence of root channels and small cracks may locally lead to a higher water storage in the rootzone than would follow from the determination of water retention characteristics in soil samples.
Peat mining has resulted in a great variety in thickness of the peat relicts in the study area. The hydraulic resistance of strongly humified peat was determined at 3500-4000 days.m^{-1} and yearly downward seepage towards the underlying sandy aquifer varies from 80 - 200 mm.yr^{-1}. The latter value equals the average precipitation surplus in the region, and thus represents the maximum value if no water from outside enters.
Limited water level fluctuations can be observed at sites with a high fraction of open water, evenly distributed over the area. This guarantees the infiltration of water into the peat remnants between the inundated sites. In strongly humified peat, infiltration is already severely limited at distances of more than 5 meter from an open water site.

To analyse the importance of different hydrological properties of a given site, the water balance model SWAMP was developed.
The most important factors are: water storage in the peat layers, (horizontal) infiltration from waterholding trenches or from inundated sites and downward seepage. Different water management measures were evaluated after the simulation of their impact upon groundwater fluctuations over a 30-year period.

The results of these model studies demonstrate the importance of the water storage characteristics near the surface. Measures to increase the storage capacity near the surface may be essential. When e.g. the fraction open water within the area is enlarged and when this water is evenly distributed over the area with small peat ridges in between, considerable stabilization of groundwaterlevels can be achieved. In the Engbertsdijksvenen this internal water conservation option appaers to be crucial when downward seepage is less than 100-150 $mm.yr^{-1}$. When downward losses are higher, external measures to reduce these losses have to be considered. The average yearly precipitation surplus of the region determines the 'critical' amount of seepage, above which reductions in seepage may become essential.

In both the field and model studies it is demonstrated that perspectives for bog regeneration depend on site-specific hydrological conditions. In general, in studies on water management, attention should be given to both the internal and external options.

Further research is needed on the ecological and hydrological constraints for bog regeneration.
It has to be realized that, when succesful, a re-developing bog system will gradually regain the intrinsic regulation mechanisms. For example, when after 50-100 years a young living *Sphagnum* moss layer has developed on top of more humified peat layers, its water storage properties and its evapotranspiration characteristics will result in reduced water level fluctuations. When its thickness is more than 30-40 cm the unsuitable hydrophysical properties of the underlying humified peat will no longer influence these fluctuations. Hence, artificial management measures to guarantee limited fluctuations should only have a temporary function. Ultimately, a self-regulating system, less depending on human interference should develop. The knowledge about bog-systems indicates that they are robust enough to withstand climatic fluctuations like a succession of dry years and that they possess good perspectives for further peat growth.

SAMENVATTING

PROBLEEMGERICHT ONDERZOEK NAAR PLANT-BODEM-WATER RELATIES

Plant-water-bodem relaties spelen een belangrijke rol in veel landbouwkundig en ecologisch onderzoek.
De water- en nutrientenopname door een gewas of een natuurlijke vegetatie is afhankelijk van bodemeigenschappen zoals textuur, porositeit, organisch stofgehalte, doorlatendheid, kationenuitwisselingscapaciteit, enz. Voor het beschrijven van deze bodemeigenschappen zijn verschillende parameters ontwikkeld. Zo worden de bodemvochtcondities in de onverzadigde zone beschreven met behulp van het vochtgehalte, de bijbehorende zuigspanning en de doorlatendheid. Deze bodemfysische eigenschappen zijn afhankelijk van textuur en organisch stofgehalte. De wortelontwikkeling is ondermeer afhankelijk van mechanische (indringingsweerstand) en hydrologische bodemeigenschappen (vochtgehalte). De mate waarin water en nutrienten door de plant worden opgenomen bepaald de groei en daarmee de struktuur van het plantendek.

Voor de beschrijving van de relaties in een plant-bodem-water systeem zijn vele modellen ontwikkeld. In deze studie wordt allereerst ingegaan op enkele algemene problemen verbonden aan het gebruik van deze modellen in plan- of beleidsvoorbereidend onderzoek (probleemgerichte studies). Dit wordt onderscheiden van het meer fundamentele onderzoek naar de fysische en ecologische processen in het plant-bodem-water systeem (procesgerichte studies). Bij probleemgerichte studies is een belangrijke vraag in hoeverre meer kennis op onderdelen van het systeem zal bijdragen tot een beter inzicht t.b.v. beslissingen.
Het is dus de vraag welke de gewenste inbreng is van de agro-hydroloog die de plant-bodem-water relaties bestudeerd, in het bijzonder in verhouding tot de inbreng van andere disciplines die andere onderdelen van het probleem bestuderen en beschrijven.

Er wordt een methode besproken om al in een vroeg stadium van het onderzoek d.m.v. een gevoeligheidsanalyse te verkennen welke mate van nauwkeurigheid gewenst is bij de studie naar de plant-bodem-water relaties als onderdeel van een (gebruikelijk) veelomvattend probleem.
Ter illustratie wordt gebruik gemaakt van een tweetal voorbeeldstudies. Deze worden hieronder kort samengevat.

ZAAISTRATEGIEËN VOOR MAIS IN DE REGENAFHANKELIJKE LANDBOUW IN HET ZUIDEN VAN MOZAMBIQUE

In de kuststreek in het zuiden van Mozambique wordt de landbouw bedreven op kleine percelen (machamba's) met een totale omvang van 1 à 2 ha per produktie-eenheid (i.c. familie). Meestal wordt er een gemengde teelt toegepast waarin mais als voedselgewas een belangrijke rol speelt.
De meeste neerslag valt in de regenperiode vanaf oktober tot april. De regenval is zeer onregelmatig en de jaarlijkse verschillen zijn groot. Het watervasthoudend vermogen van de hier voorkomende zandgronden is gering. De gemiddelde opbrengst van niet geirrigeerde mais op deze arme gronden is erg laag (minder dan 1000 kg.jaar^{-1}). Behalve van de bodemvruchtbaarheid hangt de opbrenst sterk af van de hoeveelheid neerslag en de verdeling daarvan over de groeiperiode.
Weliswaar is er sprake van een periode waarin mais bij voorkeur gezaaid wordt, maar het is een vrijwel algemeen gebruik om gedurende het gehele jaar kleine hoeveelheden te zaaien, zodra het daarvoor genoeg geregend heeft.
De belangrijkste zaaiperiode is september-oktober. Deze periode is vanuit een oogpunt van waterbeschikbaarheid niet de meest geschikte. Om de risico's voor droogte te verminderen zou beter in december-januari gezaaid kunnen worden. Belangrijke redenen om vroeger te zaaien zijn de verminderde kansen op ziekten en plagen en het vrijwel konstante voedseltekort, hetgeen de mensen aanzet tot het zo vroeg mogelijk zaaien als enigzins mogelijk is.
In deze studie zijn modelsimulaties uitgevoerd om inzicht te krijgen in de achtergronden van bepaalde zaaistrategieën. Enkele milieufaktoren zijn geselecteerd en hun invloed op de voorkeur voor bepaalde zaaistrategieën is onderzocht. Dit is op kwantitatieve wijze gedaan met behulp van een eenvoudig waterbalans- en gewasgroeimodel.

Het beschikbare water voor het maisgewas is afhankelijk van de hoeveelheid en de verdeling van de neerslag, van het watervasthoudend vermogen van de bodem en van gewaseigenschappen zoals worteldiepte, wateropname en plantdichtheid. De waterbehoefte hangt af van het klimaat en gewaseigenschappen zoals de lengte van de groeiperiode, de gewashoogte en de bladoppervlakte. Belangrijke factoren voor de gewasopbrengst zijn verder de (lage) bodemvruchtbaarheid en de invloed van ziekten en plagen. De maisconsumptie wordt verder beinvloed door het voorraadbeheer na de oogst.

Met behulp van het simulatiemodel werd voor een gemiddelde familie-eenheid de maisconsumptie per maand bepaald over een totale periode van 28 jaar. Dit gebeurde voor drie verschillende zaaistrategieën, variërend van een totale spreiding over het jaar tot slechts eenmaal per jaar zaaien.

Voor inzicht in zaaistrategieën is het vereist te weten op grond van welke criteria de beslissingen genomen worden. Wanneer er bijvoorbeeld in het gehele jaar ander voedsel dan mais beschikbaar is, kan er voorkeur gegeven worden aan het maximaliseren van de maisproduktie. Wanneer er echter geen alternatief voedsel is, zou de voorkeur gegeven kunnen worden aan het minimaliseren van de perioden met maistekorten.
In deze studie wordt geconcludeerd dat in regio's waar geen toegang is tot een voedselmarkt, de verbetering van bodemvruchtbaarheid en waterleverend vermogen van de bodem kan leiden tot een verandering in zaaistrategie (gericht op risicominimalisatie). Echter, in een regio waar alternatief voedsel verkrijgbaar is, zal opbrengstmaximalisatie worden nagestreefd. Dan zullen alleen een vermindering van opbrengstreducties t.g.v. ziekten en plagen en een vermindering van voorraadverliezen effect hebben op de strategie-voorkeur.

Wanneer niet duidelijk is welke (sociaal-economische) criteria voor de bevolking relevant zijn en een groot aantal produktiefactoren (bodemvruchtbaarheid, ziekten en plagen) niet goed gekwantificeerd kunnen worden, is de bijdrage van de agrohydroloog beperkt. Er kan in een dergelijke situatie volstaan worden met eenvoudige plant-bodem-water modellen, omdat verdere detaillering op onderdelen van de plant-bodem-water relaties niet bijdraagt aan een beter inzicht in het bestudeerde probleem.

WATERBEHEER IN HOOGVEENGEBIEDEN IN NEDERLAND

In Nederland zijn alle hoogveengebieden verstoord door ontwatering en vervening. Deze z.g. 'hoogveenrestanten' beslaan gezamenlijk een oppervlakte van 9000 ha, hetgeen ongeveer 5% bedraagt van de oppervlakte hoogveen in de 17° eeuw. In Nederland worden deze gebieden momenteel als natuurgebied beheerd. In Nedersaksen (B.R.D.) is de totale oppervlakte aan hoogveenrestanten veel groter. Hier zal in de toekomst, na het afronden van de vervening die momenteel plaatsvindt, zo'n 60.000 ha als natuurgebied beheerd gaan worden.
In deze gebieden geldt als belangrijkste beheersdoelstelling het waar mogelijk herstellen van de oorspronkelijke hoogveenvegetaties. In de hoogveenrestanten wijken de hydrologische condities sterk af van die in ongestoord hoogveen. De drogere omstandigheden hebben geleid tot een andere vegetatie.
In vrijwel alle terreingedeelten zakken de waterstanden in het veen in de zomer regelmatig dieper dan 40 cm -m.v., welk nivo algemeen beschouwd wordt als de kritieke grens voor de groei van hoogveenvegetaties.

De bodemfysische eigenschappen van de bovenste veenlaag spelen een belangrijke rol bij de waterstandsfluctuatie. In een 'levend' hoogveen is de waterbergingscapaciteit in de bovenste bodemlaag zeer groot. Deze laag wordt gevormd door *Sphagna* (veenmossen). Hier zijn tussen de al dan niet vergane plantenresten zoveel grotere porien aanwezig, dat de capillaire wateraanvoer beperkt is en de verdamping bij dalende waterstanden snel afneemt. Door beide oorzaken (grote berging, verdampingsreductie) blijven de waterstandsfluctuaties in hoogvenen beperkt.
In de hoogveenrestanten ligt t.g.v. de vervening matig tot sterk gehumificeerd veen aan de oppervlakte. De bergingscoefficient van de aanwezige toplagen is dan ook veel geringer dan in 'levend' hoogveen. De begroeiing bestaat in veel terreingedeelten overwegend uit *Molinia caerulea* (pijpestrootje). Deze grassoort blijft in deze veenbodems ook in drogere perioden nog lang maximaal verdampen.

Tijdens de vervening werden de hoogvenen ontwaterd en in veel gebieden werden diepe waterlopen tot in het onderliggende zand gegraven. Als gevolg hiervan is de wegzijging van water naar de ondergrond toegenomen. In veel hoogveenrestanten wordt geprobeerd om door het weer afdichten van deze diepe waterlopen (met 'zwartveen') de neerwaartse waterverliezen te beperken. Soms wordt voor belangrijke waterlopen een alternatief tracé om het gebied heen gekozen. In een aantal gevallen kan de wegzijging alleen worden beperkt d.m.v. hydrologische bufferzone's rond het hoogveengebied. Met deze 'externe' waterbeheersingsmaatregel wordt dan geprobeerd de waterstandsdalingen in het gebied tijdens de zomer te beperken. Of dit een juiste optie is hangt af van de hydrologische omstandigheden in het gebied.

Een andere (of aanvullende) maatregel is het vergroten van de waterberging in het gebied, d.m.v. waterconserveringsmaatregelen (intern beheer). De waterbergingscoëfficient van open water is 1.0 en terreingedeelten met veel geinundeerde plekken worden dan ook gekenmerkt door veel geringere waterstandschommelingen. Dit geldt m.n. wanneer de onderlinge afstand tussen deze plassen gering is en aldus een goede uitwisseling van water met de tussenliggende veenpakketten gegarandeerd is. Dit kan ook het geval zijn bij greppels en door vervening ontstane laagten die na afdamming weer water bevatten.
De hydrologische processen die leiden tot een hoge waterbergingscapaciteit en kleine waterstandsfluctuaties zijn zowel afhankeljk van tereinkenmerken (de fractie open water en haar ruimtelijke verdeling) alsook van eigenschappen van het plant-bodem-water systeem (poriëngrootteverdeling, verdamping).

Ook in de studie naar het waterbeheer van hoogveenrestanten wordt geconcludeerd dat de beslissingscriteria niet altijd duidelijk zijn. Er is meer ecologisch onderzoek vereist om de randvoorwaarden voor hoogveengroei te formuleren. Wanneer het voor de nutriëntenhuishouding vereist is dat er een bepaalde hoeveelheid water oppervlakkig wordt afgevoerd, zal de beperking van de wegzijging een belangrijk middel zijn (extern beheer). Wanneer vooral beperkte waterstandsfluctuaties nagestreefd dienen te worden kan veelal worden volstaan met waterconserveringsmaatregelen (intern beheer).

Voor het inzicht in het hydrologisch functioneren van hoogvenen en hoogveenrestanten is gedetailleerde kennis over de plant-bodem-water relaties onmisbaar. Bij het modelleren hiervan in een bestaande terreinsituatie zullen de ruimtelijke heterogeniteit en het gebrek aan parameterwaarden toch veelal leiden tot een voorkeur voor eenvoudige modellen.

CURRICULUM VITAE

Josephus Maria Schouwenaars werd geboren in Boxtel op 11 september 1954. Na de lagere school doorliep hij van 1966-1970 de MULO-B en van 1970-1972 de HBS-B, beiden in Boxtel. In 1972 begon hij aan zijn studie aan de Landbouwhogeschool in Wageningen, waar hij in 1978 het ingenieursdiploma behaalde in de studierichting Cultuurtechniek-B.

Na zijn studie werkte hij in de periode 1978-1982 als wetenschappelijk medewerker bij de vakgroep Cultuurtechniek van de Landbouwhogeschool. Daar verzorgde hij onderwijs in de natuurbouw en in studentenonderzoek wat door hem begeleid werd lag de nadruk op de waterhuishouding van natuurgebieden.
In de periode 1983-1985 werkte hij voor DGIS in de funktie van docent agrohydrologie aan de Landbouwfaculteit van de Eduardo Mondlane Universiteit in Mozambique. Met deze Universiteit heeft de Landbouwuniversiteit Wageningen een samenwerkingsverband. Hij heeft zich in Maputo in het onderzoek gericht op het verband tussen zaaistrategieën en regenval. De daarbij ontwikkelde modellen vormden de basis voor een vervolgstudie waaraan hij in Wageningen verder gewerkt heeft.
Vanaf 1986 is hij weer als universitair docent verbonden aan de Landbouwuniversiteit in Wageningen. Bij de vakgroep Cultuurtechniek werd het werk aan de waterhuishouding van natuurgebieden weer opgepakt en heeft hij onderzoek verricht naar de hydrologie van hoogveengebieden.
Sinds de vorming van de vakgroep Hydrologie, Bodemnatuurkunde en Hydraulica in 1989, werkt hij bij deze vakgroep.