SWAFLO, a method to evaluate the impact of groundwater lowering on nature in regional water management

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ABSTRACT

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This report presents a method to assess impacts of groundwater lowerings in summer or winter on nature performance. The method has been developed to enable optimization of regional water management in areas with conflicting interests of water users.
Plant species are linked to four main site factors controlled by the groundwater regime.
As a response to groundwater lowerings plant species will disappear if the site factors change to an extent that plant's ecological optimum cannot be satisfied any longer.
Impact-response relations are formulated and applied in nature areas with different sites.

Keywords: environmental dynamics, nitrogen supply, soil aeration, soil moisture supply, indication figures, rareness, nature value, minerotrophic, ombrotrophic.

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[REP/16]

CONTENTS

		Page:
1	INTRODUCTION	7
2	GROUNDWATER LOWERING AND REACTION OF PLANT SPECIES	9
2.1	Ecological background	9
2.2	Linkage of plant species and environmental factors	10
2.3	Adaptations of the WAFLO-model: SWAFLO	11
2.4	Response of plant species according to the SWAFLO-model	12
2.4.1	Environmental dynamics	12
2.4.2	Nitrogen supply	12
2.4.3	Soil aeration	13
2.4.4	Soil moisture	14
2.5	Appraisal of ecological effects	15
3	NATURE AREAS IN THE SOUTHERN PEEL AREA	19
3.1	Environmental setting	19
3.2	Minerotrophic area "De Berken"	19
3.3	Ombrotrophic areas "Deurnse/Liesselse", "Maria Peel" and "Groote Peel"	23
4	APPLICATION OF THE SWAFLO-MODEL	25
4.1	Results	25
4.2	Conclusions	25
4.3	Discussion	27
5	IMPLANTATION OF THE SWAFLO-MODEL	29
SUMMARY		31
REFERENCES		33
ANNEXES		35
I	Listing of soil types generating increased yearly mineralisation of organic matter if groundwater levels fall more than 10 cm	
II	List of species in the studied nature areas	

1 INTRODUCTION

Socio-economic development of rural areas puts an increasing pressure on the environment by interferences with the natural resources. A substantial part of impacts takes place through regional natural water systems, being a main communication channel between man-made and more natural environments.
The Southern Peel region in the southeastern part of the Netherlands is such a man-made environment where agricultural practice is the dominating activity in its economic value as well as in its impact on the natural water system. Both quantitative and qualitative aspects of the water system are of first importance for other users of the natural water resources like public water supply companies and nature conservancy.
In the Southern Peel region a study was carried out to develop a methodological approach to the analysis of regional regulation policies which enable a sustainable co-evolution of the regional socio-economic system and the natural environmental (Orlovsky and Van Walsum, 1984; Drent, 1989).
To achieve this goal a scenario generating system has been designed aimed to perform a scenario analysis by regional policy-making authorities. This scenario module is based on a system of simplified models for screening an analysis in a directive global way. The scenario module has a hierarchical structure and consists of an environmental subsystem of water quantity processes, soil nitrogen processes as well as water quality processes and a socio-economic subsystem of users of the environment. By interactions of agricultural users with the environment several distinct technologies can be discerned. Technologies have to be considered as a combination of agricultural activities involved in growing and processing of a certain crop and/or livestock. Each technology requires its own input to produce a specified output. The Regional Policy Making Authority at the upper level of the socio-economic subsystem can take decisions and impose restrictions if input of technologies are not in agreement with preferences of for instance nature conservancy. One of those inputs of technologies is water use in some subregions, possibly interfering with the groundwater regime in neighbouring nature areas. The groundwater regime on the other hand is an important key factor concerning ecological processes.
This report presents an adjusted method, originally developed by Reynen and Wiertz (1984) to assess impacts of groundwater lowerings on nature performance, which is adapted to the scenario generating module of the Southern Peel survey (Drent, 1989). The original method (the WAFLO-model) is based on the impacts of a constant drawdown of species in herbaceous vegetations of mires like rich fen, poor fen and fen meadows.
The adapted method (the SWAFLO-model) stipulates groundwater levels at the beginning of summer and winter which are optimal for nature conservation. The method evaluates the impact on

nature values of exceeding these summer and/or winter groundwater levels by any technology. Nature values are considered as indicators to measure the achievement of the preferences of the Nature Conservancy Board to nature performance.
In chapter 2 ecological background information to the used method is presented. After its introduction the adaptations of the WAFLO-model are described and the response of plant species to groundwater lowerings will be indicated. The last part of this chapter deals with the appraisal of the ecological impacts.
Chapter 3 informs about the environmental setting of three subregions of the Southern Peel having the status of nature area.
In chapter 4 the impact of groundwater lowerings is demonstrated using the three "nature" subregions as a test area. Finally the implantation of the SWAFLO-model in the scenario generating system is discussed shortly.

2 GROUNDWATER LOWERING AND REACTION OF PLANT SPECIES

2.1 Ecological background

In his classical vision on landscape Jenny (1946, 1958) related soil and vegetation to independant state factors of which topography on a regional scale can be considered as the most important (Kemmers, 1984). Differences in altitude of land surface underlie flow patterns, recharge and discharge phenomena of the regional groundwater system. Thus, a sustainable pattern of dry and wet zones in the landscape has been caused the original ecological differentiation.
During the last years ecological research stressed the importance of groundwater regimes not only on soil moisture supply but especially on the relation between both quantitative and qualitative aspects, and nitrogen and phosphorus supply to mire vegetation (Grootjans, 1980; Van Wirdum, 1981; Kemmers and Jansen, 1985a; Kemmers and Jansen, 1985b).
Soil moisture content, controlled by groundwater levels, is considered as a factor conditioning soil temperature and soil aeration. Both parameters are involved in mineralisation processes of organic matter being the main source of nutrients (N, P) of natural ecosystems. Also redox processes and hence soil acidity are controlled by groundwater levels to a great deal. The reduction-oxidation state of the soil interferes with the availability of phosphorus by dissolution of Fe(II)-P minerals. Groundwater flow through aquifers will result in an enrichment of the water by weathering processes causing a predominant presence of Ca^{2+}- and HCO_3^--ions in the groundwater. As cause of Ca^{2+}-supply from the grondwater to the root zone a high Ca^{2+}-saturation on the exchange complex has been developed in groundwater discharge areas (Kemmers and Jansen, 1985b). Even secondary calcite deposits may occur, which will result in near natural conditions of acidity. Such areas derive high proton neutralisation capacities from the regional groundwater system. Availability of phosphorus in such minerotrophic discharge areas is mainly controlled by the low solubility of Ca-P minerals. The solubility of Ca-P minerals increases when soil acidity grows. Furthermore groundwater discharge areas are favoured by a high proton neutralisation capacity and hence yield very stable habitats for plant species with regard to soil acidity and consequently to soil phosphorus availability.
Drainage of such areas even to a small extent may severely damage this delicate system of P-control by leaching Ca^{2+}-ions and pH-shift (Kemmers and Jansen, 1985b). Disturbance of this P-control system generally will increase P-levels, which is considered as the most important threatening of nature conservation in discharge areas (Van Leeuwen, 1966; Van Wirdum, 1981). Many rare and sensitive species of those stable habitats are hampered by raised P-levels and following interspecific competition.

Because there is general agreement that the supply of moisture and nutrients like N and P in wet habitats is controlled by groundwater quantity and quality parameters, four main environmental factors, related to groundwater, could be selected in order to build a simplified model to assess impact of groundwater lowering on plant performance.

- Environmental dynamics
  Although this hypothetical factor does not yet have any physical meaning it has become a central item in nature conservation related to socio-economic planning based on ecology in the Netherlands (Van der Maarel and Dauvellier, 1978). This factor is generally used to describe the extent of buffering of the plant environment to changing P-availability. As such environmental dynamics has to do with a complex interacting system of redox processes, Ca^{2+}-ion contents and soil acidity generating P-fluxes.
- Nitrogen supply
  Lowering groundwater levels in wet habitats will increase N-availability as a result of increased soil aeration and temperature. An important state variable is the total organic N-pool and biodegradability of humus related to soil type.
- Soil areation
  Next to reduction-oxidation processes soil areation is directly involved in plant performance. Plant species capable of growing in anaerobic environments by aerenchym tissue in the roots are seriously hampered by soil aeration due to groundwater lowering, as plant species adapted to aerobic environments are favoured.
- Soil moisture supply
  Levelling down the groundwater may cause shortage of water for transpiration purposes. Soil physical properties like capillary rise are important state variables depending on texture and soil type.

2.2 Linkage of plant species and environmental factors

Until now ecological knowledge is not sufficient to link response of plant species to changes of hydrological conditions in a physical way as usual in determining crop water use in agriculture (Van Wijk and Feddes, 1985).
Several researchers, however, did rank plant species along environmental gradients concerning operational factors as soil moisture and N-supply (Kruyne et al., 1967; Ellenberg, 1974; Landolt, 1977). In this way most of the plant species of Central and Western Europe were furnished by Ellenberg with figures indicating optimum plant performance related to moisture availability and nitrogen supply. He designed an ordinal scale of nine nitrogen figures, the lowermost indicating nitrogen poor, the utmost nitrogen rich conditions. Low soil moisture supply is indicated by low figures increasing up to 12 indicating immersed conditions. Plant species without preferences with

respect to water or nitrogen conditions were not provided by indication figures.
Londo (1975) made a distinction between plant species being sensitive to environmental dynamics or not. Broadly outlined species sensitive to environmental dynamics also are the rare species of the Dutch flora.

Bringing together the main environmental factors controlled by groundwater and the figures indicating optimum plant performance Reynen and Wiertz (1984) designed the WAFLO-model as an instrument to assess the impact of changed WAter conditions on FLOra.
The WAFLO-model stipulates that plant species will disappear from the vegetation if environmental conditions change as a consequence of groundwater lowerings and plant's ecological optimum cannot been satisfied any longer. The model does not provide a replacement by other species. In general, disturbance of nature will yield more common species with wide ecological amplitudes. Such species are not very valuable from the viewpoint of nature conservation. So on the basis of the ecological effects groundwater lowerings lead to less valuable circumstances.

2.3 Adaptations of the WAFLO-model: SWAFLO

The WAFLO-model was designed to assess ecological effects of groundwater lowering which are constant throughout the year. So a groundwater withdrawal is considered to result in a groundwater lowering (Δ) at the beginning of summer (Δh_s) equal to that at the beinning of winter (Δh_w). The WAFLO-model is based on a quasi-stationary model of the unsaturated zone.
In the Southern Peel survey a clear distinction has been made between groundwater levels at the beginning of summer (h_s) and at the beginning of winter (h_w). As a result of some technology (see Orlovsky and Van Walsum, 1984) different Δh_s and Δh_w values may arise. Those differences can be considerable. So the original WAFLO-model had to be adapted to this peculiarity. To achieve this goal a non-stationary model, SWATRE (Belmans et al., 1983), of the unsaturated zone was used. The SWATRE-model calculates actual transpiration from meteorological data, crop and soil properties on a daily basis. Groundwater levels can be calculated from the water balance. On the reverse the model calculates the effect of changed groundwater levels on transpiration fluxes. Compilation of SWATRE and WAFLO yields SWAFLO.
Both the SWAFLO-model and the original WAFLO-model actually consist of four submodels. Each submodel describes the response of plant species to a change of one of the four main environmental factors (section 2.1) as conditioned by groundwater lowerings both at the beginning of summer and at the beginning of winter.

2.4 Response of plant species according to the SWAFLO-model

2.4.1 Environmental dynamics

It is stipulated that plant species sensitive to environmental dynamics according to the system of Londo (1975) will disappear as soon as any lowering will occur, assuming that the groundwater level in the unperturbed situation does not exceed 80 cm below soil surface.
It is very probable that alterations of groundwater levels influence environmental dynamics not only at the beginning of summer (Gremmen et al., 1985) but also at the beginning of winter (Kemmers and Jansen, 1985a). It is assumed that no response of plant species occurs if the groundwater level at the beginning of winter in the unperturbed situation exceeds 120 cm below soil surface. Table 1 summarises plant response related to environmental dynamics.

Table 1 Impact-response relations concerning changed environmental dynamics. h_s and h_w refer to groundwater levels (cm below soil surface) at the beginning of summer and winter respectively. h_{w_0} and h_{s_0} refer to groundwater levels in the unperturbed situation.

Impact	Boundary conditions	Response
$\Delta h_s > 0$	$h_{s_0} < 80$	sensitive species
$\Delta h_w > 0$	$h_{w_0} < 120$	disappear

2.4.2 Nitrogen supply

Based on empirical knowledge The Winand Staring Centre assigned soil types generating increased mineralisation of the organic matter after lowering of shallow groundwater levels (see annex I).
It is stipulated that the assigned soils will yield a moderate increase of nitrogen supply if groundwater lowerings of more than 10 cm will occur (Gremmen et al., 1985). As a response plant species with nitrogen figures 1, 2 and 3 as well as soil moisture figures exceeding 6 will disappear. In the SWAFLO-model plant response will be applied to lowerings both of levels at the beginning of summer (h_{s_0}) and winter (h_{w_0}). Although the mineralisation process can be hampered by dry conditions during summer this effect seems not to have any significance in the wet habitats under concern, unless considerable drawdowns occur, causing soil moisture pressure heads lower than -200 cm. Although the assessment of nitrogen supply as a result of the lowering of

the groundwater level seems not to contradict general experience, more research is needed to confirm this submodel. Table 2 schedules plant response to changed nitrogen supply.

Table 2 Impact-response relations concerning changed nitrogen supply. h_s and h_w refer to groundwater levels (cm below soil surface) at the beginning of summer and winter respectively.

Impact	Boundary conditions	Response
$\Delta h_s \geqslant 10$	soil type (annex I)	species with nitrogen figures 1, 2 and 3 as well as moisture figures ⩾ 7 will disappear
$\Delta h_w \geqslant 10$	soil type pressure head soil moisture > -200 cm	species with nitrogen figures 1, 2 and 3 as well as moisture figures ⩾ 7 will disappear

2.4.3 Soil aeration

Soil aeration is considered to be of importance only at the beginning of summer (h_s). Consequently h_s will be considered as a measure of soil aeration. Gremmen (1984a) related occurrence of plant species, grouped together according to their moisture figures, to the average groundwater level in springtime. The work was based on more than 1 000 vegetation samples and on soil maps, and is considered to be representative for the Dutch flora. From this survey plant species response was deduced.
Plant species with moisture figures ⩾ 10 will disappear as soon as h_s exceeds 30 cm below soil surface. In the same way species with moisture figures ⩾ 8 and ⩾ 7 will disappear if h_s exceeds 50, 60 and 70 cm respectively. Soil aeration will not play a important role in case of groundwater levels at the beginning of summer exceeding 70 cm. It must be noted that groundwater levels related to soil aeration have to be considered as a boundary condition, irrespective the extent of Δh_s. Table 3 summarizes plant response related to soil aeration.

Table 3 Impact-response relations concerning changed soil aeration. h_s refers to the groundwater level (cm below soil surface) at the beginning of summer.

Impact	Boundary condition	Response: species with moisture figures given will disappear
Any Δh_s	$h_s > 30$	$\geqslant 10$
exceeding	$h_s > 50$	$\geqslant 9$
boundary	$h_s > 60$	$\geqslant 8$
conditions	$h_s > 70$	$\geqslant 7$

2.4.4 Soil moisture

Availability of water for transpiration is of first importance to floristic composition. Both soil moisture supply, depending on soil type, and precipitation will determine actual transpiration and consequently crop production in agriculture. Van Wirdum (1981) originally considered the relative production of an herbaceous vegetation as a measure of water stress which ought to be reflected by the spectrum of moisture figures of the vegetation under concern. Reynen and Wiertz (1984) worked out this idea and made an assessment of moisture figures in relation to the relative grass production. This assessment is based on empirical evidence (Reynen et al., 1981). Occurrence of species with equal moisture figures was related to relative grass production as could be calculated from the amount of moisture supplied by the soil and precipitation. Because the ability of soils to supply moisture is defined as the amount of water supplied by the soil during the growing season (April-October) of a 10% year of drought, precipitation data of a 10% year were used to calculate water supply. Implicitly it is supposed that the spectrum of moisture figures is not sensitive to events occurring once every ten years. Excercises, however, to calibrate moisture figures to soil moisture availability failed until now (Gremmen and ter Braak, 1984).
In the Southern Peel Survey the ratio of actual evapotranspiration over potential evapotranspiration ($E/E_p = \alpha$) as a measure of relative crop yield was used to assess plant response (table 4). Table 4 schedules plant response used in this report, related to E/E_p threshold limits. These relations do not contradict the empirical results of Gremmen (1984a).

Figure 4 Impact-response relations concerning changed soil moisture supply. h_s and h_w refer to groundwater levels at the beginning of the summer and winter repectively. α is the ratio of actual evapotranspiration over potential evapotranspiration.

Impact	Boundary conditions α	Rel. grass yield	Response: species with moisture figures given will disappear
Any Δh_s or Δh_w causing exceedence of one of the boundary conditions	< 1.0	< 99	≥ 10
	< 0.975	< 95	≥ 9
	< 0.95	< 90	≥ 8
	< 0.89	< 80	≥ 7
	< 0.83	< 70	≥ 6
	< 0.71	< 50	≥ 5
	< 0.55	< 30	≥ 4

Jansen (1983) developed a method to determine the E/E_p ratio (α) related to levels of h_s and h_w using a simulation model of the water balance of a cropped soil: SWATRE (Soil Water Actual Transpiration Extended, Belmans et al., 1983). Using precipitation data of a 10% year of drought and starting from different levels of h_s he determined at which levels of h_w a threshold limit of E/E_p was exceeded. Calculations have been made for different soil types.

It is noted explicitly that plant response is related to weather conditions with a frequency of 10%. It can be argued that not the average situation but rather more extreme weather conditions are of importance for plant response. Any structural change of h_s or h_w that will yield any critical reduction of evapotranspiration (E/E_p) during a 10% year of drought, is decisive for plant response in this submodel irrespective the climatic conditions used in the technology runs of the scenario generating module.

2.5 Appraisal of ecological effects

The WAFLO-model makes an assessment of the plant species that will disappear after groundwater lowering (Gremmen et al., 1985). This loss of species can be taken into account directly by using a relative standard of loss.

In this report a more comprehensive way of appraisal of ecological effects is chosen. Assuming that nature conservancy needs an indicator to measure the benefits of their preferences for nature, "nature value" will be used as a standard.

Although there is no general agreement on methods to appreciate ecological states, the different standards used all seem to run parallel, however. It is chosen that the vegetation derives its value from the extent of rareness of the compiling species. Rareness of species can be indicated by species frequency in a national grid system (area of grid cell is 25 km², 5 x 5 km²). Nine frequency classes are discerned in the Netherlands (Arnolds and Van der Meijden, 1975). In accordance with Reynen and Wiertz (1984) we have chosen the reciprocal of the mean value of class intervals as a measure of rareness:

$$z_i = \frac{f_9}{f_i} \qquad [1]$$

where: f_i = mean value of the class interval
f_9 = mean value of the class interval to which the most common species belong
z_i = rareness figure of species belonging to class interval

Depending on its frequency in the national grid system each species will have one of the rareness figures presented in table 5.

Table 5 Frequency classes and rareness figures of plant species based on their frequency of occurrence in a national grid system of 1 673 cells.

Frequency class	Class/intervals	Mean	Rareness figure
1	0.5 - 3.5	2	710
2	3.6 - 10.5	6	237
3	10.6 - 29.5	18	79
4	29.6 - 79.5	48	30
5	79.6 - 189.5	121	12
6	189.6 - 410.5	279	5.1
7	410 - 710.5	540	2.6
8	710 - 1210.5	927	1.5
9	1210.6 - 1673.5	1423	1

Nature values now can be calculated using:

$$V = \sum_{i=1}^{n} z_i \, \nu \, a_i \qquad [2]$$

where: V = nature value of the vegetation
z = rareness figure of species
a = multiplication factor depending on frequency of occurrence of species in a set of vegetation samples representing the vegetation type under concern
i = index counting species (i = 1, ..., n)

Groundwater lowerings will cause a loss of species and according to equation [2] will result in a decrease of nature value.
The decrease of value will be indicated by its relative standard and hence can be expressed as a percentage.

3 NATURE AREAS IN THE SOUTHERN PEEL REGION

3.1 Environmental setting

After the last glacial period, about 12 000 years ago, an important part of the Southern Peel region was covered by vaste mires being situated on the watershed region of the rivers Meuse and Aa catchments. Numerous brooklets raised from this swampy area. Nowadays only the lower courses of the brooklets are still following there original pathway to the West where they join at last the river Aa. Some of them are draining secondary catchments (Wit, 1986). Discharge of groundwater to the brook valleys may cause wet conditions along the brooklets. Consequently minerotrophic fen vegetation originally bordered the banks. Due to reclamation in the first part of the 20th century a lot of this vegetation is replaced by anthropogenic fen meadows. On a small scale relicts of those fen meadows are preserved in the nature area "De Berken", on the flanks of the brook Astensche Aa. This nature area is considered as a seperate subregion in the Southern Peel survey (no. 10 in fig. 1).
In the beginning of their development the mires on the watershed region of the two main catchments developed a minerotrophic fen character. Later on, with the thickening of the peat layers, they became ombrotrophic bog features. Being nourished by rainwater the bog became an oligotrophic and wet habitat with peat layers with thickness of more than 2 m. At the end of the last century peat digging, as fuel for heating, had been developed to a large scale activity. Afterwards the derelict land was reclaimed. Some 3 000 ha of derelict land was preserved from reclamation to agricultural area and is now protected by law and has obtained the status of nature reserve. The oligotrophic and wet circumstances have been preserved and create conditions suitable to the re-establishment of both flora and fauna elements appropriate to the bog environment. Two of those swampy nature areas are considered as separate subregions in the Southern Peel survey: Deurnse/Liesselse, Maria Peel (subregion 27) and Groote Peel (subregion 16) (see fig. 1).
Both types of nature areas, the minerotrophic fen meadows and the ombrotrophic bogs are strictly dependant on wet circumstances conditioned by high groundwater levels. So they are vulnerable to groundwater lowering in adjacent areas to which they are linked by the regional groundwater system.

3.2 Minerotrophic area "De Berken"

The nature reserve "De Berken" (no. 10 in fig. 1) is bordering the brook Astensche Aa. The ground levels of the reserve are distinctly sloping towards the brook. Hence alongside the stream higher mean groundwater levels occur than at a greater distance.

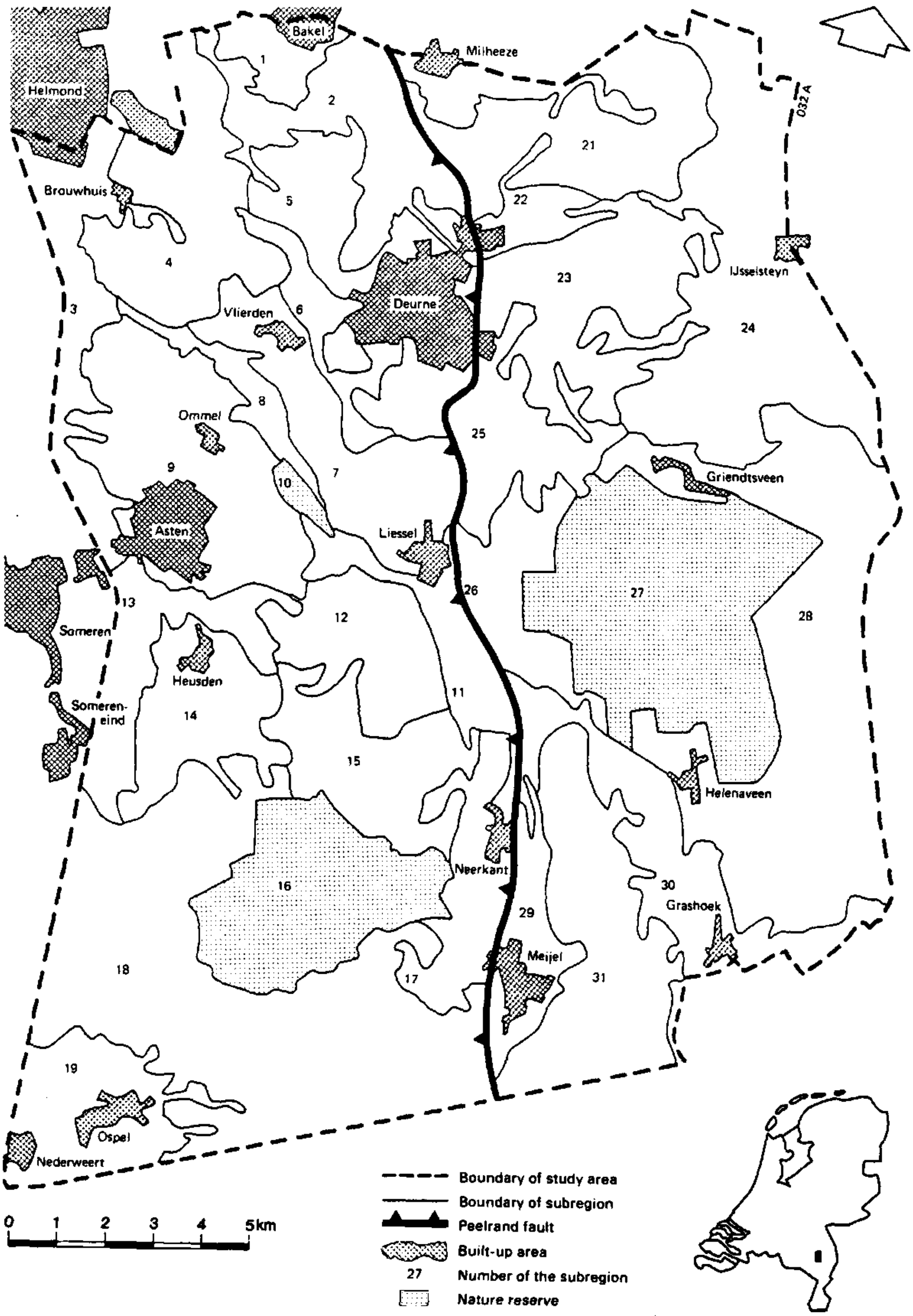

Figure 1 Subregions in the Southern Peel area based on hydrological and soil physical characteristics. Shaded subregions indicate the nature areas.

Based on these differences in altitude the reserve has been treated as two distinct parts (fig. 2). Mean levels at the beginning of summer (h_{s_0}) and winter (h_{w_0}) have been deduced from bimonthly groundwater measurements during 1982 and 1983. Both years were characterized by shortage of rain during summer. A marked surplus of rain in springtime occurred in 1983.

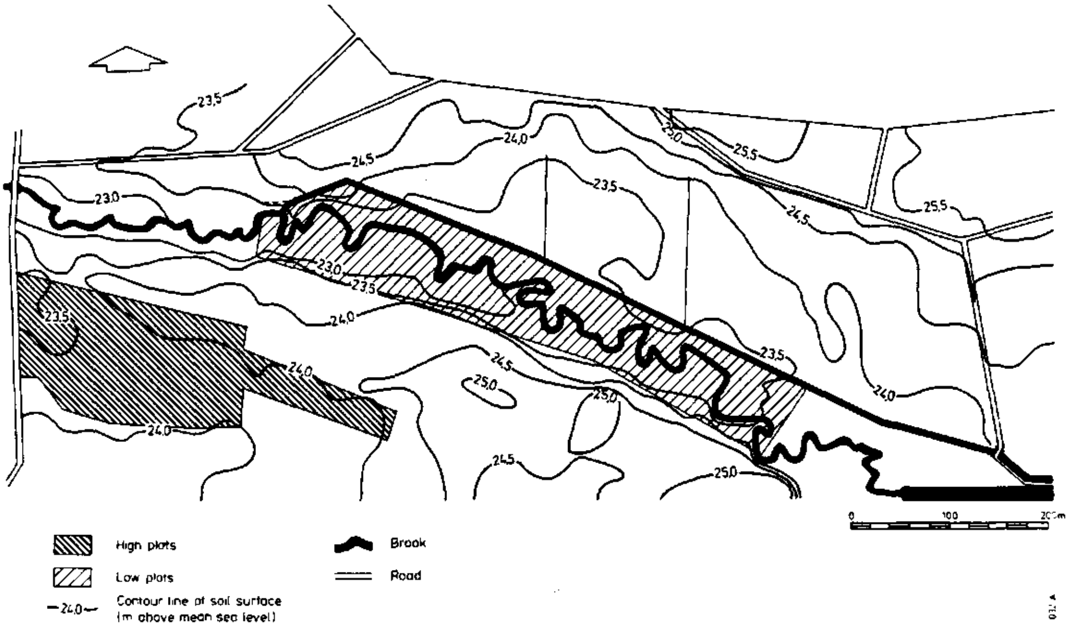

Figure 2 Detailed map of "De Berken" nature reserve. Studied plots are shaded.

Groundwater levels, shown in table 6, are considered as representative for the unperturbed situation.
Soil types are deduced from soil survey maps and can be described according to the classification system of the Winand Staring Centre as "beekeerd" soils (low plots) and "gooreerd" soils (high plots). No distinctions have been made for soil physical characteristics. Both soil types consist of fine loamy sand.

Table 6 Unperturbed groundwater levels at the beginning of summer (h_{s_0}) and winter (h_{w_0}) in "De Berken" subregion.

	Groundwater level (cm below soil surface)	
Altitude	h_{s_0}	h_{w_0}
Low plots	15.0	95.0
High plots	29.0	129.0

Soil specific threshold limits of E/E_p for the Berken subregion are related to h_s and h_w levels in fig. 3, using the method described in section 2.4.4. Fig. 3 shows different E/E_p ratios related to trajectories of groundwater level at the beginning of summer and winter.

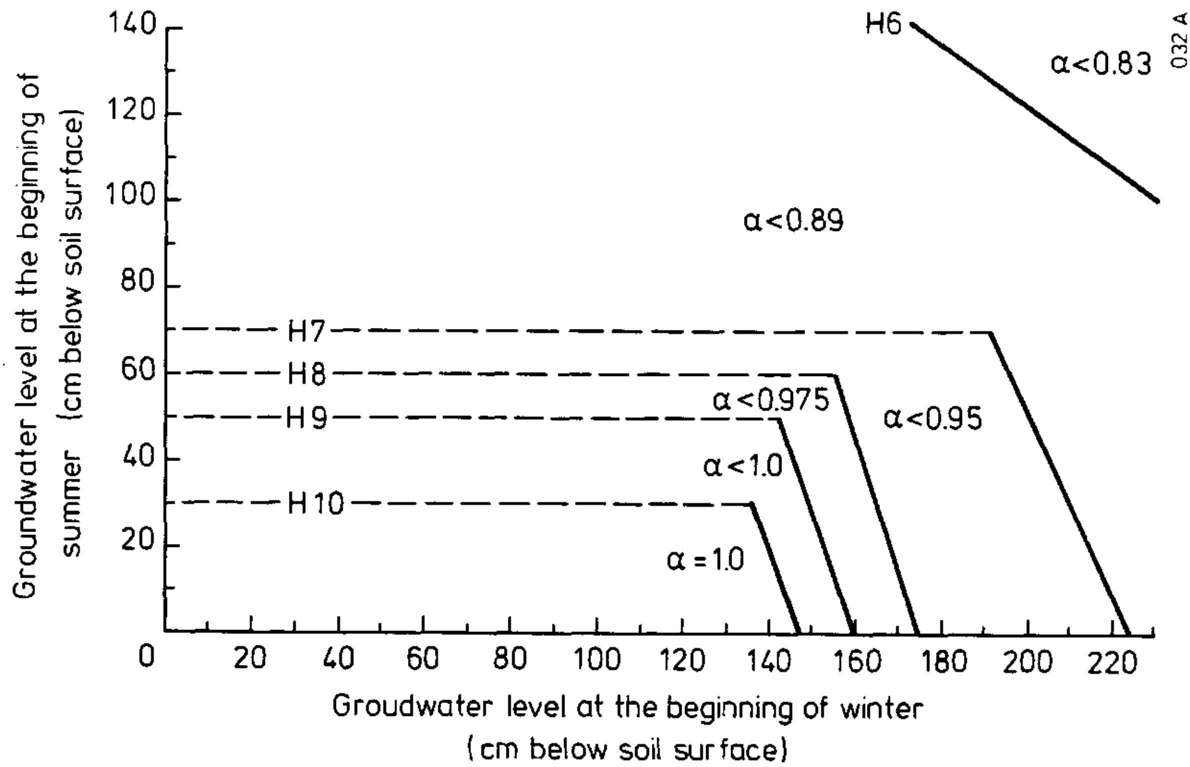

Figure 3 Ratios of α (= E/E_p) related to trajectories of groundwater levels at the beginning of summer (h_s) and winter (h_w) and plant species response concerning subregion 10 ("De Berken"). If water levels cannot longer fulfil the indicated moisture supply (α) plants with indicated moisture figures (Hn) will disappear.
Dashed lines are indicating threshold limits of groundwater levels concerning soil aeration. As a response to changing groundwater levels plant species furnished with indicated moisture figures (Hn) will disappear as soon as boundaries are exceeded.

The difference in groundwater levels is reflected by the vegetational composition of both plots. Vegetation samples collected all over the reserve (Kemmers, 1983) were subjected to the clustering technic TWINSPAN (Hill, 1979), yielding distinct local vegetation types. Two vegetation types, each covering distinct parts of the reserve were selected and considered to present the vegetational composition of the different parts. A species listing of both vegetation types is given in annex II. Figures indicating environmental conditions are included as well as frequency of occurrence of species in the set of samples constituting the vegetation type.

Both vegetation types are the starting point of the ecological impact analysis of groundwater lowering according to the SWAFLO-model.

3.3 Ombrotrophic areas; "Deurnse/Liesselse", "Maria Peel" and the "Groote Peel"

Both nature areas can be described as bog remnants. Parts of Deurnse/Liesselse, Maria Peel (subregion 27) still become prey to peat digging activities. Other parts already have been acquired by nature conservancy, where physical conditions have been made suitable to regrowth of peat. This more or less derelict subregion rather is inhomogeneous both in its groundwater characteristics and in its vegetational composition. The same situation applies to the Groote Peel (subregion 16). This subregion obtained the status of nature reserve in its entirety. Despite their obviously inhomogeneous character both subregions will be treated as a unity.
Generalizing groundwater features of those subregions can best be done using soil survey maps also indicating groundwater classes (Smidt, 1983). From these soil survey maps mean levels of h_{s_0} and h_{w_0} have been assessed (see table 7). These levels are considered representative of the unperturbed situation.

Table 7 Unperturbed groundwater levels at the beginning of summer (h_{s_0}) and winter (h_{w_0}) in the subregions 16 ("Groote Peel") and 27 ("Deurnse/Liesselse" and "Maria Peel").

	Groundwater level (cm below soil surface)	
Subregion	h_{s_0}	h_{w_0}
16	0.0	60.0
27	10.0	80.0

As can be derived from soil survey maps peat soils are dominating both subregions. Physically the soils have been divided in a peat layer (0-50 cm) and a fine sandy subsoil.
Soil specific threshold limits of E/E_p for the two subregions are related to h_s and h_w levels in fig. 4. Hence fig. 4 illustrates the sensitivity of the two peaty subregions to a change of E/E_p if groundwater lowerings occur. Plant response can directly be coupled to this change of E/E_p (see table 4).
Vegetational data are adopted from Schouwenaars (1978) describing vegetation types of the Deurnse Peel.
Combining vegetation types a new one on a higher hierarchical level could be distinguished. This vegetation type is considered to represent vegetational composition of a derelict peat land

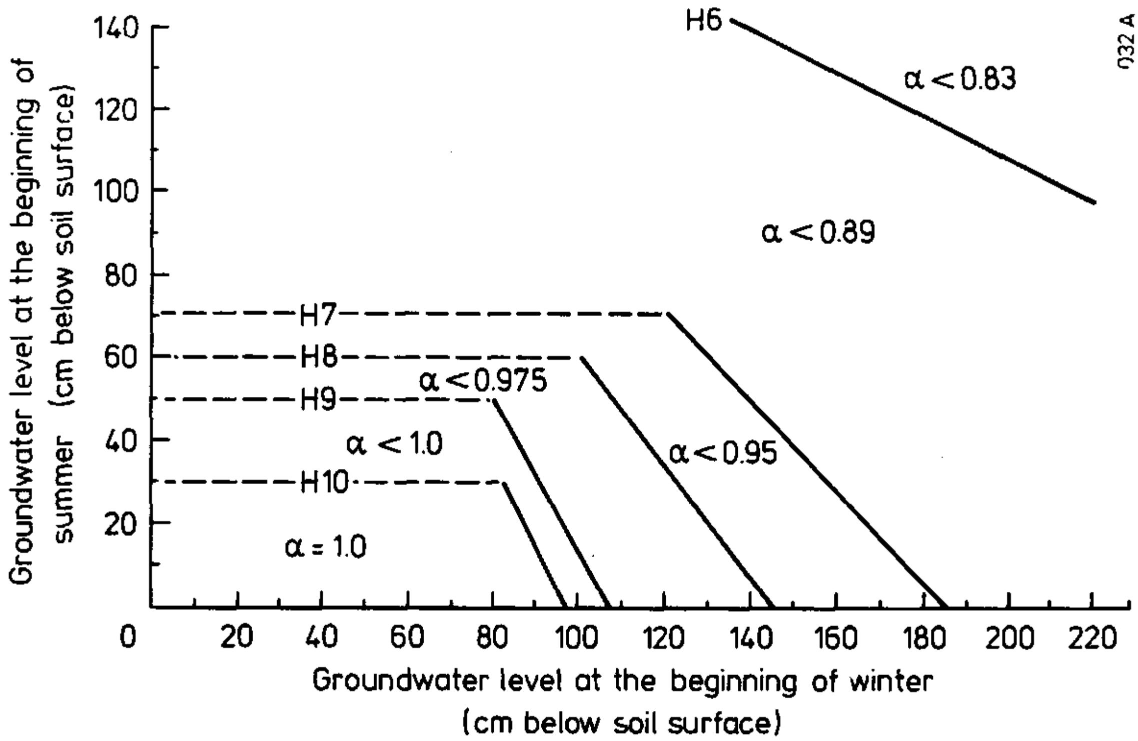

Figure 4 Ratios of E/E_p related to trajectories of groundwater levels at the beginning of summer (h_s) and winter (h_w) and plant species response concerning subregions 16 ("Groote Peel") and 27 ("Deurnse/Liesselse" and "Maria Peel"). If water levels cannot longer fulfil the indicated moisture supply (α) plants with indicated moisture figures (Hn) will disappear. Dashed lines are indicating threshold limits of groundwater levels for soil aeration. As a response, plant species furnished with indicated moisture figures (Hn) will disappear as soon as boundaries are exceeded.

with changing moisture and soil physical conditions. A listing of species, indicator figures, frequency of occurrence etc. is given in annex II. This listing is the starting point of the ecological impact analysis concerning subregion 27. No vegetational data are available from subregion 16. As the conditions of this subregion are slightly more wet than those in subregion 27 it was decided to take the vegetation types indicating only wet sites as distinguished by Schouwenaars (1978) as being representative of subregion 16. The cluster of these wet vegetation types is used as the starting point of the impact assessment of subregion 16. A listing of species of this subregion is presented in annex II.

4 APPLICATION OF THE SWAFLO-MODEL

4.1 Results

The vegetational data described in annex II and data of the unperturbed groundwater levels h_{s_0} and h_{w_0} (sections 3.2 and 3.3) are used to apply the SWAFLO-model.
The boundary conditions dealing with soil type and soil physical properties are known (3.2 and 3.3). Having formulated the response of plant species to changing environmental factors (section 2.4), the impact of imaginary groundwater lowerings can now be calculated and indicated by loss of species. As each species contributes to the value of the vegetation under concern loss of species can be expressed as relative loss of value. Figures 5 to 7 show relative loss of nature values after a change of groundwater levels at the beginning of summer (Δh_s) or winter (Δh_w).

4.2 Conclusions

"De Berken" (10)

A marked difference appears between the ecological effects of the high plots and of the low plots. The vegetation on the low plots (fig. 5a) is distinctly more sensitive to groundwater lowerings as can be derived from the relative loss of nature value. On high plots (fig. 5b) with lower levels of h_{s_0} and h_{w_0} the vegetation

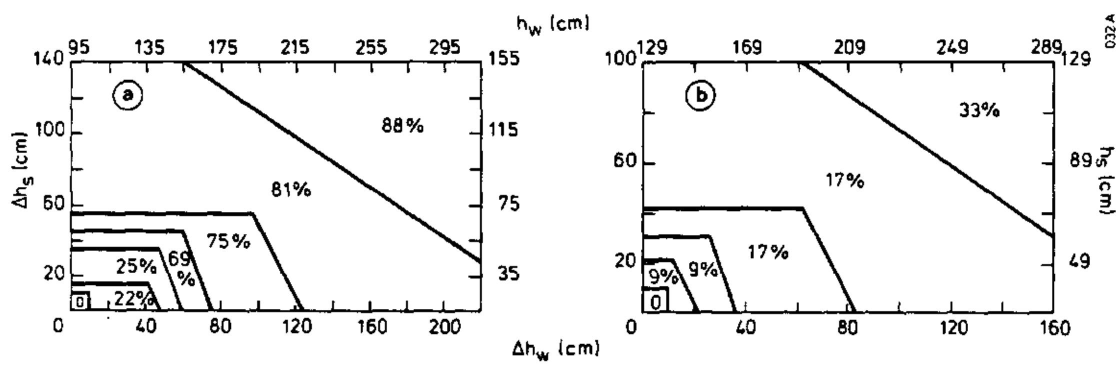

Figure 5 Relative loss of nature value in "De Berken" nature area after changed levels of groundwater at the beginning of summer (Δh_s) or winter (Δh_w). Groundwater levels (h_s, summer; h_w, winter) are indicated starting with levels in the unperturbed situation.
A. Low plots; B. High plots.

is apparently less sensitive to groundwater lowerings. Comparison of the sensitivity of both vegetation types to groundwater lowerings leads to a confirmation of the expectation: vegetation types on wet plots are more sensitive to groundwater lowering than vegetation types on dry plots.
In general it can be concluded that the two vegetation types are not sensitive to small groundwater lowerings both in spring and in summer. If Δh_s or Δh_w exceeds 10 cm species will start to disappear resulting a levelling down of nature values. It can be concluded also that the two vegetation types are more sensitive to changes of h_s than to changes of h_w.
The vegetation which is the most sensitive to groundwater lowerings has been chosen to represent the whole subregion 10.

"Groote Peel" (16)

Fig. 6 reveals that the vegetation of this subregion is very sensitive to small changes of h_{s_0} or h_{w_0}. Any change of h_{s_0} or h_{w_0} will result in a loss of vulnerable and mostly rare species contributing 30% of total nature value. Already a change of h_{s_0} or h_{w_0} of 10 cm or more has an impact on vegetation of nearly 60% loss of nature value. No marked difference in sensitivity to groundwater lowerings in spring and in summer occurs.

"Deurnse/Liesselse", "Maria Peel"

Just like in subregion 16 the vegetation is very sensitive to small changes of groundwater levels (fig. 7). The vegetation of this subregion is slightly less sensitive to groundwater lowerings which is in agreement with the slightly less wet conditions of subregion 27 compared with subregion 16.

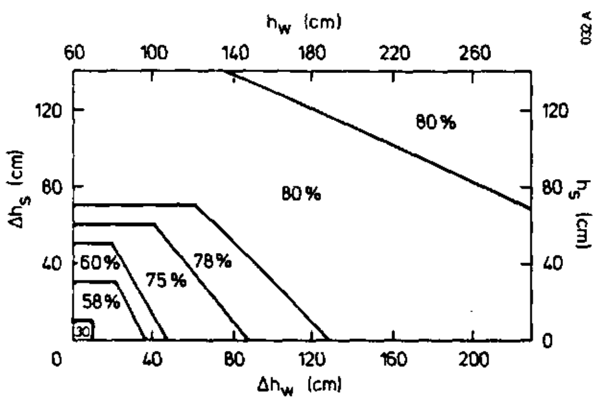

Figure 6 Relative loss of nature value in the "Groote Peel" nature area after changed levels of groundwater at the beginning of summer (Δh_s) or winter (Δh_w). Groundwater levels (h_s, summer; h_w, winter) are indicated starting with levels in the unperturbed situation.

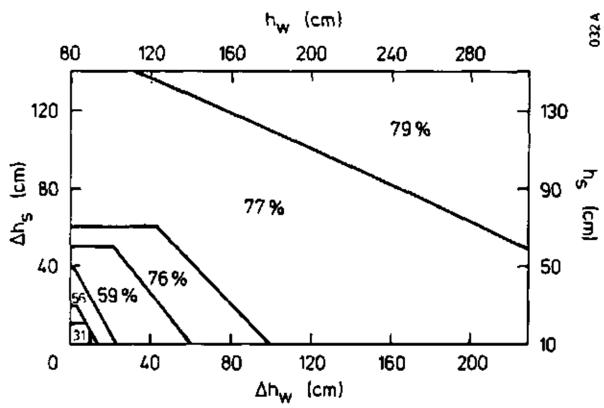

Figure 7 Relative loss of nature value in the "Deurnse/Liesselse Peel" nature area after changed levels of groundwater at the beginning of summer (Δh_s) or winter (Δh_w). Groundwater levels (h_s, summer; h_w, winter) are indicated starting with levels in the unperturbed situation.

4.3 Discussion

The SWAFLO-model presented in this paper is not physically justified. Some submodels need further improvement in a physical way. Also linkage of plant species to environmental factors and plant response related to changed conditions is not founded experimentally or in an empirical statistical way. Efforts to do so failed until now. So linkage of plants and environmental factors is based on best professional judgement of researchers with a lot of experience and empirical knowledge embodied in reports.
The SWAFLO-model seems to work adequately however. The model shows a distinct sensitivity to different levels of groundwater lowering and to different physical conditions of the soil in the unperturbed situation. The model indicates less sensitive vegetation on drier plots after groundwater lowering than on wet plots.
Another item is the verification of the model. Gremmen (1984b) tried to verificate the WAFLO-model and concluded that it was not possible to do so. The main problem is that ecological effects of groundwater lowerings are delayed by a phenomenon that can be called "memory". This delay of effects makes testing of the vegetation response to impacts only possible on the long term. Consequently the results of the SWAFLO-model cannot be interpreted in such a way that predicted ecological phenomena really can be observed after a couple of years. In fact a lot of impacts from measures other than groundwater lowering may occur

and even vegetation may be on the way to a steady state equilibrium.
The SWAFLO-model has to be used in a global and directive way just to compare several alternatives of water management!
It can be concluded that in the context of the Southern Peel survey SWAFLO is a useful module to analyse effects of water management in order to evaluate whether goals of the Regional Policy Making Authority concerning nature will be reached or not.

5 IMPLANTATION OF THE SWAFLO-MODEL

The SWAFLO-model is designed to assess ecological effects if groundwater levels exceed tolerance limits of natural vegetation as a result of any technology in neighbouring areas.
In this way an evaluation can be made of the consequence of water use of any technology in connection with the preferences of nature conservancy. The output of the scenario generating module in terms of any groundwater lowering has to be evaluated with respect to the effects for nature conservation. Nature conservancy has to decide to what extent loss of nature value is acceptable or not. If loss of nature value will not seriously damage nature performance from the viewpoint of nature conservancy the policy module (see Orlovsky and Van Walsum, 1984) can be entered in order to achieve the optimal regional socio-economic development. If loss of nature value is not acceptable a new scenario has to be generated.
The implantation of the SWAFLO-model is shortly outlined in fig. 8.

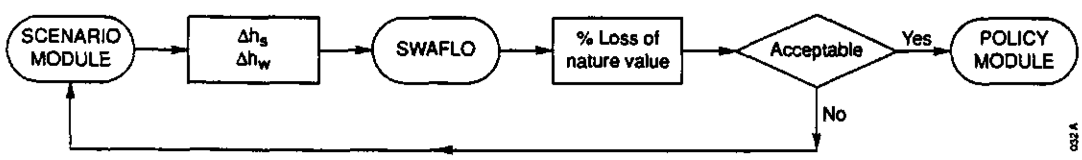

Figure 8 Implantation of the SWAFLO-model in the framework of scenario and policy modules.

SUMMARY

Regional Policy Making Authorities need methods to analyse scenarios and regulation policies of the water management which will enable a sustainable co-evolution of the regional socio-economic system and the natural environment in regions with conflicting interests of water users. This report presents the SWAFLO-model, a method to assess impacts of groundwater lowerings at the beginning of summer or winter on nature performance, indicated by nature value. The method evaluates the impact of exceeding optimal summer and winter levels on nature values of herbaceous vegetation.
Four main environmental factors, controlled by groundwater quantity and quality parameters are distinguished: environmental dynamics, nitrogen supply, soil aeration and soil moisture supply. Plant species can be ranked along these environmental factors using figures, indicating optimal plant performance, related to each of the factors. As a response to groundwater lowerings plant species will disappear from the vegetation if the environmental factors, controlled by groundwater parameters, change and plant's ecological optimum cannot be satisfied any longer. Impact-response relations are formulated.
It is assumed that the vegetation derives its nature value from the extent of rareness of the compiling species. Disappearing species will level down the nature value of the vegetation.
Three nature areas from the Southern Peel Area with distinct environmental conditions and vegetational compositions have been selected to apply the SWAFLO-model. Percentages loss of nature value after imaginary groundwater lowerings have been calculated.
The model needs further development to found changing environmental factors on physical processes in the soil water system. Despite it shows a distinct sensitivity to different levels of groundwater lowering and to different physical conditions of the soil in the unperturbed situation. The model indicates less sensitive vegetation on drier plots than on wetter plots. The SWAFLO-model can be used to evaluate the consequence of water use, as an output of a system generating scenarios of the water management, in connection with preferences of nature conservancy.

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ANNEX

Annex I Listing of soil types generating increased yearly mineralisation of organic matter if groundwater levels fall more than 10 cm. Codes in accordance with the soil classification system of the Winand Staring Centre (after Reijnen et al., 1981).

Main types	Code	Groundwater class
Peat soil	aVz	II
	Vo	I
	Vc	I
	Vz	I and II
Peaty soils	vWp	II
	zWp	II and III
	zWz	III
	zWzt	III
	vWz	II
Podzol soils	Hn21	III and V
	Hn21t	III and V
	Hn21	V
	Hn23	V
	Hn23t	III and V
Earth soils	pZg21	III
	pZg23	III
	pZg23w	III
	pZg23t	III and V
	pZn21	III and V
	pZn21t	III and V
	pZn23	III and V
	pZn23t	III and V
	pZn23	V
Clay soils	KX	II
Loam soils	PLN 5	III

Annex II List of species in the studied nature areas.

LEGEND:

Moist. = moisture figure according to Ellenberg, figures ranking from 1, indicating dry conditions to 10, indicating permanent waterlogged conditions, 0 indicates indifference

Nitr. = nitrogen figure according to Ellenberg, figures ranking from 1, indicating nitrogen poor conditions to 10 indicating nitrogen rich conditions, 0 indicates indifference

Freq. clss. = frequency class according to national grid system (see table 5)

Sens. = 1 = species sensitive to environmental dynamics
0 = species not sensitive

Occ. = occurrence of species in the set of samples constituting the vegetation type

Freq. = frequency of occurrence of species in the samples

This legend applies for the following lists of species too.

"De Berken" (high plots)

Species in nature area "De Berken" high plots	Indication figures				Field data	
	Moist.	Nitr.	Freq. clss.	Sens.	Occ.	Freq.
1 Agrostis stolonifera	6	5	9	0	2	40%
2 Alopecurus geniculatus	9	7	8	0	3	60%
3 Cerastium fontanum sep. triviale	5	5	9	0	1	20%
4 Holcus lanatus	6	4	9	0	1	20%
5 Lolium perenne	5	7	9	0	5	100%
6 Phleum pratense	5	6	8	0	3	60%
7 Plantago major ssp. major	5	6	9	0	2	40%
8 Poa annua	6	8	9	0	5	100%
9 Poa pratensis ssp. pratensis	5	6	9	0	1	20%
10 Poa trivialis	7	7	9	0	4	80%
11 Ranunculus flammula	9	2	6	0	1	20%
12 Ranunculus repens	7	0	9	0	5	100%
13 Rumex acetosa	0	5	9	0	1	20%
14 Rumex crispus	6	5	9	0	2	40%
15 Stellaria media	4	8	9	0	4	80%
16 Taraxacum sect. vulgaria	5	7	9		4	80%
17 Trifolium repens	0	7	9	0	5	100%

17 species in 5 samples, averaging 9.8 species per sample

"De Berken" (low plots)

Species in nature area "De Berken" low plots	Indication figures				Field data	
	Moist.	Nitr.	Freq. clss.	Sens.	Occ.	Freq.
1 Agrostis stolonifera	6	5	9	0	10	77%
2 Alopecurus geniculatus	9	7	8	0	11	85%
3 Anthoxanthum odoratum	0	0	9	0	2	15%
4 Bromus mollis	0	0	9	0	1	8%
5 Cardamine pratensis	9	3	9	0	10	77%
6 Carex nigra	8	2	6	0	1	8%
7 Carex ovalis	7	4	6	0	2	15%
8 Cerastium fontanium ssp. triviale	5	5	9	0	1	8%
9 Cynosurus cristatus	5	4	8	0	1	8%
10 Deschampsia cespitosa	7	3	7	0	4	31%
11 Equisetum palustre	7	3	9	0	6	46%
12 Festuca pratensis	6	6	7	0	3	23%
13 Festuca rubra ssp. rubra	0	0	9	0	4	31%
14 Galium palustre ssp. palustre	9	4	4	0	5	38%
15 Glechoma hederacea	6	7	9	0	1	8%
16 Glyceria fluitans	9	7	9	0	12	92%
17 Holcus lanatus	6	4	9	0	12	92%
18 Iris pseudacorus	10	7	7	0	1	8%
19 Juncus acutiflorus	8	3	5	0	2	15%
20 Juncus bufonius ssp. bufonius	7	0	8	0	1	8%
21 Juncus effusus	7	4	9	0	3	23%
22 Leontodon autumnalis	5	5	9	0	1	8%
23 Lolium perenne	5	7	9	0	8	62%
24 Lotus uliginosus	8	4	7	0	3	23%
25 Myosotis scorpioidis	0	0	8	0	2	15%
26 Phalaris arundinacea	8	7	8	0	1	8%
27 Plantago lanceolata	0	0	9	0	1	8%
28 Poa annua	6	8	9	0	1	8%
29 Poa pratensis ssp. pratensis	5	6	9	0	12	92%
30 Polygonum hydropiper	8	8	8	0	3	23%
31 Potentilla anserina	6	7	9	0	1	8%
32 Ranunculus acris	0	0	9	0	2	15%
33 Ranunculus flammula	9	2	6	0	2	15%
34 Ranunculus repens	7	0	9	0	12	92%
35 Rorippa amphibia	10	8	8	0	3	23%
36 Rumex acetosa	0	5	9	0	6	46%
37 Rumex crispus	6	5	9	0	4	31%
38 Stellaria alsine	8	4	6	0	1	8%
39 Stellaria graminea	4	0	8	0	1	8%
40 Stellaria media	4	8	9	0	1	8%
41 Stellaria palustris	8	2	6	0	2	15%
42 Taraxacum sect. vulgaria	5	7	9		6	46%
43 Trifolium repens	0	7	9	0	5	38%
44 Urtica dioica	6	8	9	0	1	8%
45 Veronica scutellata	9	3	5	0	1	8%

45 Species in 13 samples, averaging 13.3 species per sample

"Groote Peel"

Species in nature area "Groote Peel"	Indication figures				Field data	
	Moist.	Nitr.	Freq. clss.	Sens.	Occ.	Freq.
1 Calamagrostis canescens	9	5	6	0	3	19%
2 Calluna vulgaris	0	1	7	0	6	38%
3 Carex curta	9	2	5	0	1	6%
4 Carex rostrata	10	3	5	0	4	25%
5 Chamaenerion angustifolium	5	8	9	0	4	25%
6 Cirsium palustre	8	3	8	0	2	13%
7 Dryopteris carthusiana	0	3	7	0	4	25%
8 Eleocharis palustris ssp. palustris	10	0	6	0	1	6%
9 Erica tetralix	8	2	7	0	4	25%
10 Eriophorium angustifolium	9	2	6	1	5	31%
11 Eriophorium vaginatum	7	1	4	1	6	38%
12 Eupatorium cannabinum	7	8	8	0	1	6%
13 Festuca ovina	3	0	5	0	2	13%
14 Galium palustre ssp. palustre	9	4	4	0	1	6%
15 Holcus mollis	5	3	8	0	1	6%
16 Hydrocotyle vulgaris	9	2	8	0	1	6%
17 Juncus articulatus	8	2	8	0	1	6%
18 Juncus bulbosus ssp. bulbosus	0	0	5	0	4	25%
19 Juncus effusus	7	4	9	0	13	81%
20 Luzula campestris	4	2	8	0	1	6%
21 Lycopus europaeus	9	7	8	0	1	6%
22 Lysimachia thyrsiflora	9	3	5	0	1	6%
23 Lysimachia vulgaris	8	0	7	0	5	31%
24 Molinia caerulea	7	2	7	0	14	88%
25 Peucedanum palustre	9	4	7	0	3	19%
26 Phragmites australis	10	5	9	0	4	25%
27 Potentilla erecta	0	2	7	1	1	6%
28 Succisa pratensis	7	2	6	1	1	6%

28 species in 16 samples, averaging 5.9 species per sample

"Deurnse/Liesselse" and "Maria Peel"

Species in nature area "Deurnse/Liesselse" and "Maria Peel"	Indication figures				Field data	
	Moist.	Nitr.	Freq. clss.	Sens.	Occ.	Freq.
1 Agrostis tenuis	0	3	9	0	1	4%
2 Calamagrostis canescens	9	5	6	0	3	11%
3 Calluna vulgaris	0	1	7	0	17	61%
4 Carex curta	9	2	5	0	1	4%
5 Carex rostrata	10	3	5	0	4	14%
6 Chamaenerion angustifolium	5	8	9	0	7	25%
7 Cirsium palustre	8	3	8	0	2	7%
8 Dryopteris carthusiana	0	3	7	0	5	18%
9 Eleocharis palustris ssp. palustris	10	0	6	0	1	4%
10 Erica tetralix	8	2	7	0	8	29%
11 Eriophorum angustifolium	9	2	6	1	5	18%
12 Eriophorum vaginatum	7	1	4	1	6	21%
13 Eupatorium cannabinum	7	8	8	0	1	4%
14 Festuca ovina	3	0	5	0	3	11%
15 Festuca rubra ssp. rubra	0	0	9	0	1	4%
16 Galium palustre ssp. palustre	9	4	4	0	1	4%
17 Holcus mollis	5	3	8	0	2	7%
18 Hydrocotyle vulgaris	9	2	8	0	1	4%
19 Juncus ariculatus	8	2	8	0	1	4%
20 Juncus bulbosus ssp. bulbosus	0	0	5	0	4	14%
21 Juncus effusus	7	4	9	0	15	54%
22 Luzula campestris	4	2	8	0	3	11%
23 Lycopus europaeus	9	7	8	0	1	4%
24 Lysimachia thyrsiflora	9	3	5	0	1	4%
25 Lysimachia vulgaris	8	0	7	0	5	18%
26 Molinia caerulea	7	2	7	0	26	93%
27 Peucedanum palustre	9	4	7	0	3	11%
28 Phragmites australis	10	5	9	0	4	14%
29 Potentilla erecta	0	2	7	1	1	4%
30 Pteridium aquilinum	6	3	6	0	2	7%
31 Rumex acetosella	5	2	9	0	2	7%
32 Succisa pratensis	7	2	6	1	1	4%

32 species in 28 samples, averaging 4.9 species per sample