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Dependency of local mesotrophic fens on a regional groundwater flow system in a poldered river plain in the Netherlands

Martin J. Wassen[1], Aat Barendregt[1], Paul P. Schot[1] and Boudewijn Beltman[2]
[1] *Department of Environmental Studies, University of Utrecht, P.O. Box 80.115, NL-3508 TC Utrecht, The Netherlands;* [2] *Department of Plant Ecology, University of Utrecht, Lange Nieuwstraat 106, NL-3512 PN Utrecht, The Netherlands*

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Abstract

The effect of regional, subregional and local groundwater flow systems on mesotrophic fen ecosystems was studied in the polders of the Vecht River plain that borders the Pleistocene ice-pushed moraine of Het Gooi. Variation in the vegetation and in the habitat factors (groundwater and peat soil) of fens depends whether or not the fens are connected to the outflow of the regional groundwater system.

Changes in the regional groundwater flow system, caused by changes in the water management of the polders, are probably responsible for the deterioration of mesotrophic fens. Drastic measures will have to be taken to restore the hydrology on a regional scale if the mesotrophic fens are to be saved from extinction.

Hydrological research that integrates the results of regional and local studies is essential if the ecology of fen ecosystems is to be understood.

1. Introduction

Small fens of one to five hectares in the Central Netherlands are remnants of vast mesotrophic[1] wetlands that existed up till the beginning of this century. These ecotopes, embedded in a matrix of agricultural grassland, function as a refuge for endangered mesotraphent[2] plant species. Mesotrophic conditions are characteristic of the regional groundwater flow system in the area. There appears to be a connection between this regional system and the individual fens. This connection may well explain the mesotrophic conditions of the peat soil and the shallow groundwater in the fens. The regional groundwater flow system interacts with both subregional and local water systems. The interaction between these three hierarchical levels must be analysed to find the conditions under which the remaining mesotrophic ecosystems can survive. By obtaining an understanding of this ecological interaction humans may be able to design ways of restoring the mesotrophic wetland. This illustrates Golley's statement (1987) that a problem-solving landscape ecological approach requires consideration of the following: function of the object of interest; larger system connected to the object; components within the object which explain its behaviour, and human influence on the chorological relations within the landscape.

The Vecht River plain was famous for its rich and extended mesotrophic fen ecosystems. Of this ecological wealth, only a few remnants are left. These consist of sedge and herb species-rich vegetation with a well-developed moss layer, and contain

Correspondence to: M.J. Wassen, Department of Environmental Studies, University of Utrecht, P.O. Box 80.115, NL-3508 TC Utrecht, The Netherlands.

many endangered phanerogams and cryptogams. Outside the nature reserves, these species have almost completely disappeared. Even the reserves have lost a good deal of their characteristic species (Van den Berg and De Smidt 1985) as a result of acidification and eutrophication (Wassen *et al.* 1988, 1989a; Verhoeven *et al.* 1988). This loss of species in mesotrophic fen continues in spite of careful management: summer mowing (to prevent succession to reedland or wood), keeping water levels high (important for aquatic and marshland species) and preventing input of fertilizers from surrounding pasture land. However, two crucial ecological factors are beyond the control of the local manager: precipitation and inflow of groundwater.

Decisions that affect the quantity and quality of groundwater of systems high in the hierarchy are made by regional authorities. This means that it is important to inform these authorities that the future of rare and endangered local ecotopes is dependent on decisions relating to the management of the regional groundwater flow systems.

The mesotrophic nature of the regional groundwater flow is a result of its centuries-long journey through the nutrient-poor sandy aquifer (Wassen 1986). Since dissolution of calcite is an important geochemical process in regions with sandy aquifers (Hem 1985), the discharging regional groundwater flow is likely to be calcium-rich and mesotrophic.

The hypothesis that regional groundwater supply is the essential condition for the existence of local mesotrophic fen ecosystems has been tested in four fens in the Vecht River plain. These are situated along the gradient from the moraine to the river. Two of them contain mesotraphent communities and are therefore believed to be connected to the regional system. Of the other two fens one contains ombrophilous[3] vegetation; the other, eutraphent vegetation. This should mean that they are not connected to the regional system.

Reference areas with undisturbed conditions no longer exist in Western Europe. However, in North-east Poland in the Biebrza River valley there is still an undisturbed mesotrophic peatland of 1000 km^2. This valley is comparable with the Vecht River plain with respect to geomorphology (Zurek 1984), groundwater chemistry (Wassen *et al.* unpubl.) and vegetation composition (Palczynsky 1984). The great similarity with the Vecht River plain makes it a suitable reference area.

2. Study area

The Vechtplassen area in the central part of the Netherlands (52°07′–52°20′ N and 5°5′–5° 15′ E), is a Holocene river plain situated at the western foot of the Pleistocene ice-pushed moraine of Het Gooi (Fig. 1). The moraine is covered mainly by woodlands and partly by built-up areas and arable land. It rises to 20 m above mean sea level (a.m.s.l.) and it has groundwater levels up to 3 m a.m.s.l. The moraine consists of Pleistocene fluvial sands which form an unconfined aquifer that is 150–200 m thick. This is the main infiltration area which recharges the regional groundwater flow. At a distance of 7–10 km from the moraine runs the River Vecht.

The river plain morphology has been modified by man since the 12th century as a result of the excavation of peat for fuel. Artificial lakes formed where peat was dredged down to the Pleistocene sands. The remaining peatland was drained for agriculture. From the 19th century onwards, artificial drainage was intensified. Therefore, the plain was split up into polders of 100–1000 ha, each with its own artificially controlled surface water level. Man interfered severely with the hydrology in 1881 when a 550 ha area of Lake Loosdrecht was reclaimed and turned into the Polder Bethune (Fig. 1). This polder attracts a large quantity of groundwater as its water level is kept permanently at *c.* 4 m below sea level by pumping out water. This is the lowest level in the area. North of this polder lies the remaining 14.5 km^2 of Lake Loosdrecht.

From Polder Bethune to the foot of the Pleistocene moraine, the elevation of the polders slopes up stepwise from –3 m a.m.s.l. to +1 m a.m.s.l. The soil of the polders consists of peat on top of aeolian and fluvial sand. At a depth of 50–70 m, a sandy clay has been deposited which is semi-permeable to groundwater flow. The peat soil has a depth of 3 m close to the river and becomes shallower towards the moraine. Drainage has led to settling and mineralisation of the peat soil, which explains why the

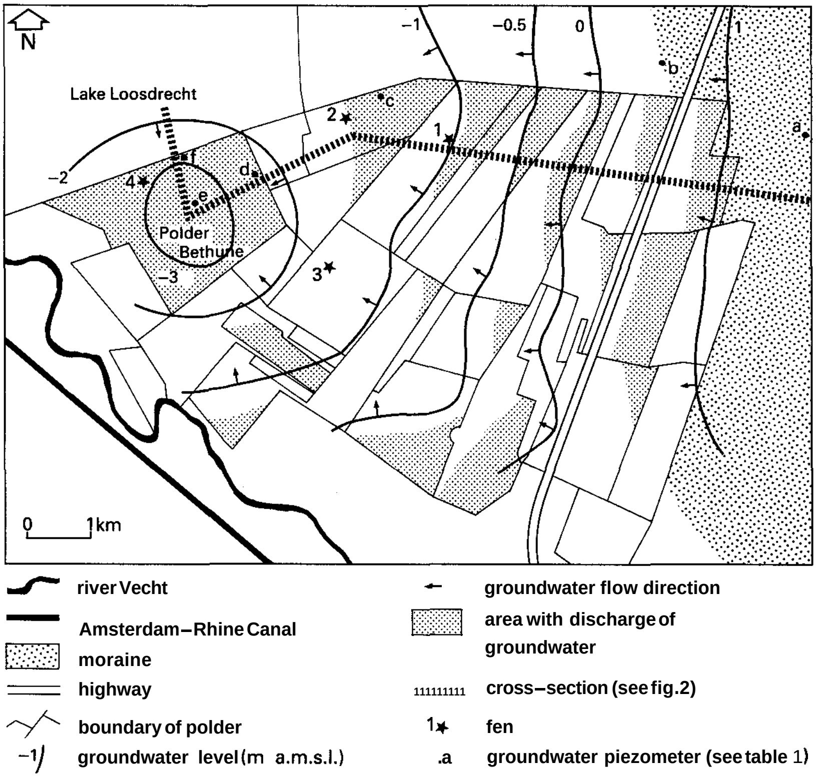


Fig. 1. **Groundwater level contour map for the Pleistocene aquifer (September, 1985) and discharge areas of groundwater.**

soil surface in the polders sank below sea level and why the part of the peatland that bordered the moraine has disappeared; now fluvial and aeolian sands crop out in the eastern polders. The polders are used mainly for dairy farming, but also contain scattered nature reserves varying in extent from **3** to **140** ha. These reserves are former turf-ponds where peat was dredged on a small scale up till the **1940s** (Van der Valk and Verhoeven **1988).** Groundwater wells up mainly into turf-ponds and especially into ditches where the semi-permeable peat and gyttja[4] layers are absent. The upward seepage of groundwater in turf-ponds decreases gradually in the time span after dredging because peat formation hampers water flow (Verhoeven ***et al.*** **1988).**

The regional groundwater flow system operates on the scale level of the total study area. The horizontal dimensions are **c. 20** km by **15** km. The flow lines of this system start in the moraine. They are several kilometers long (Schot **1989)** and are directed to the river plain.

Superimposed on this system in the studied part of the river plain are **c.** fifteen subregional groundwater flow systems. Each pair of adjacent polders can have its own system of this category. Flow lengths are shorter than two kilometres. The horizontal extension corresponds to the size of the polders: **100–1000** ha.

Numerous local groundwater flow systems are superimposed on each subregional system since each polder was split up in hundreds of pieces of land by ditches. Each piece of land can have its own local system. Flow lengths are shorter than a few hundred metres and the horizontal extension of these local systems can vary from several ha to a few m^2.

These systems are hierarchically related to each other in a nested way (Engelen and Jones **1986)** and are generated by differences in levels. These differences are either of natural or of artificial origin. The flow of the regional system is caused mainly by natural geomorphological vertical differences of **c.**

10 to 20 m. The causal factor in the subregional systems is the artificial difference in the levels of the polders. Each polder has its own fixed summer level and fixed winter level. These are kept constant for agricultural reasons. In the local systems flow is caused by differences in elevation within a piece of land or by differences in the level of a piece of land and the surrounding surface water.

This means that the two fens with mesotraphent communities are likely to receive regional groundwater. The fen with an ombrophilous community should be supplied with rainwater, the eutrophic one with surface water. Although surface water could in principle be mesotrophic, this is rarely the case in the infiltration areas within the river plain. In winter, rainwater surplus is immediately pumped out to the River Vecht to facilitate mechanical agricultural management. This increases water deficit in summer. Then, water for crop growing is supplied from the River Vecht or from the nearby Amsterdam-Rhine Canal. This water comes from the Rhine and is heavily polluted.

3. Methods

The four fens studied are located in different polders. Selection criteria for these polders were: (i) together they form a sequence from the moraine towards the river; (ii) presence of fen ecosystems. Selection criteria for fens were: (i) location in nature reserves; (ii) mown annually in July; (iii) representative vegetation structure for the polder concerned.

3.1. Regional and subregional water systems

The regional groundwater flow was simulated with the computer program FLOWNET (van Elburg *et al.* 1987), which calculates and plots flow lines for vertical inhomogeneous anisotropic sections of the subsoil. The program was applied to a cross section which extends from the moraine in the east to Polder Bethune in the west, parallel to the direction of the horizontal groundwater flow (Fig. 1). The cross section was subdivided into cells of 250 m (horizontal) and 5 m (vertical). Input consists of hydraulic head data along upper, lower, left and right boundaries and allocation of horizontal and vertical permeabilities to each cell. Hydraulic heads and surface water levels for September 1985 (average summer conditions) were used. The output is a flow pattern that includes regional and subregional groundwater flows. With this flow pattern, it is possible to localize those parts of polders that are discharge areas of regional groundwater or of subregional groundwater. The starting points of these groundwater flows can also be localized.

The groundwater composition of the regional and subregional water systems is described with data collected from groundwater piezometers with filter depths up to 90 m below surface. For all water samples, the Saturation Index for calcite was calculated after Stuyfzand (1987). With this index, water can be tested to see whether it is unsaturated and can dissolve more calcite, is supersaturated and can precipitate calcite or is at equilibrium. This appears to be a useful technique for distinguishing regional from subregional or local groundwater because regional groundwater is likely to be more saturated due to its long residence time in the sediment.

3.2. Local hydrology, habitat factors and vegetation of the fens

To determine whether groundwater in the fens originated from a regional, subregional or local water system, transects were staked out in the four fens. In each of the transects, groundwater piezometers were placed at 6 to 10 locations with filter depths of 0.5, 1.0, 1.75, 2.5 and 7 m below the surface. Hydraulic heads were measured and samples were taken from these piezometers and from the surface water 4 times in the period May 1986–November 1987 and analysed for Electro Conductivity (EC), pH, major ions and nutrients. The Saturation Index for calcite (Stuyfzand 1987) was also calculated for all these water samples. In the peat soil, the EC of the phreatic water was measured in April and November 1987 with a probe at 15 to 25 locations in each fen at depth intervals of 10 cm until sand was reached.

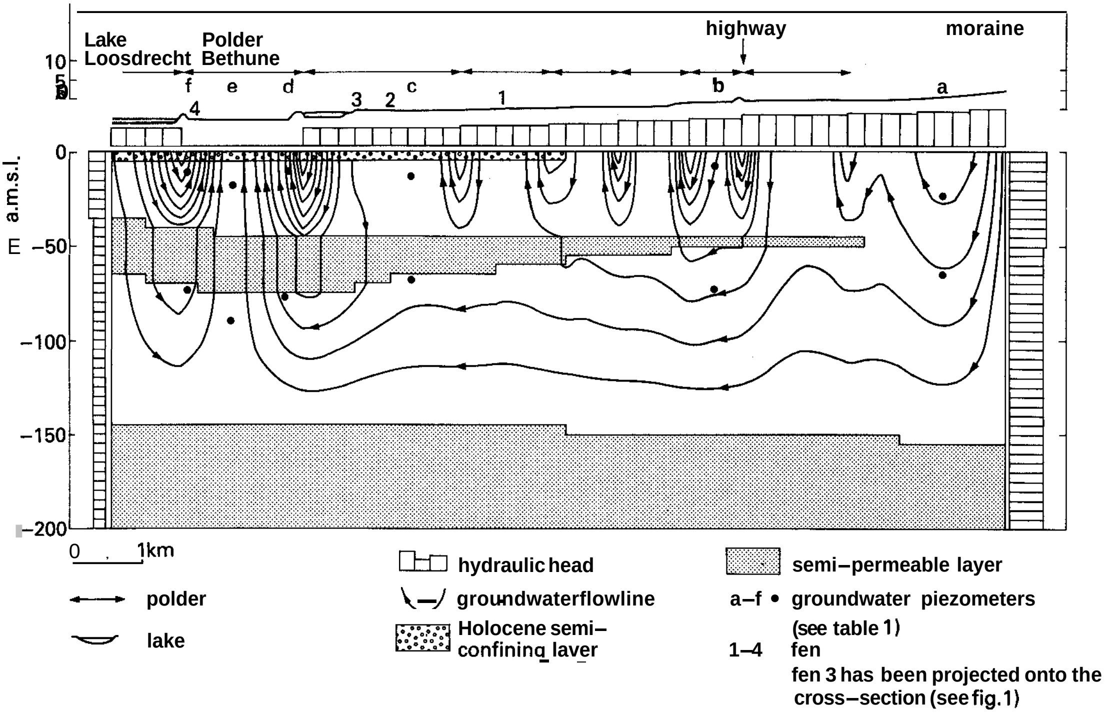


Fig. 2. Groundwater flow pattern along a vertical cross-section calculated by the program FLOWNET (September, 1985). See *Fig. 1* for location of the cross-section.

Soil texture and strata were noted when the piezometers were inserted. Peat samples were taken at the piezometer locations at a depth of 5 – 15 cm in June 1986 and analysed for bulk density, % H_2O, % organic matter, % total N (Kjehldall) and lime-potential ($pH(CaCl_2) - 1.15$). These parameters, in combination with those of the groundwater chemistry, provide useful information regarding wetness, trophic level and calcium richness of the fen ecosystem.

Species composition of the fen vegetation was recorded in June 1988 in 10 m^2 plots around the piezometer locations using a decimal scale. Biomass samples of living above-ground plant material were taken on June 21, in 4 representative 0.25 m^2 plots in each transect. In fen 4 trenches and elevations were sampled separately.

4. Results

4.1. Regional and subregional water systems

Some of the regional groundwater that is recharged on the moraine discharges in the adjacent polders, and the rest flows further westward underneath the polders and wells up in the centre of Polder Bethune (Fig. 2). Polder Bethune also collects water of local origin which infiltrates from the nearby lakes and polders. Obviously the artificially controlled surface water levels in the polders determine the vertical groundwater flow. Subregional water systems starting in a polder with a relatively high surface water level discharge in the adjacent polder with a lower surface water level.

In the fen area in between Polder Bethune in the west and the motorway in the east, groundwater of the regional water system seeps upward only in one place and only in a small quantity. Fen 1 is located in this polder (Fig. 2).

Chemical composition of the groundwater changes along the regional groundwater flow (Table 1). Recently infiltrated rainwater in or close to the moraine (sampling point a and b) does not yet contain large amounts of Ca^{2+} and HCO_3^-. On the other hand the concentration of SO_4^{2-} and NO_3^- is high at these sites, which points to pollution. Further away from the moraine, groundwater samples are rich in calcium and bicarbonate but do

Table 1. Groundwater composition (n = 1) in a sequence from the moraine towards Polder Bethune and surface water composition of the River Vecht and the Amsterdam-Rhint Canal (n = 3). Locations of piezometers are given in Fig. 1.

location	depthm a.m.s.l.	EC[1] mS/m at 25°C	pH	Ca mg/l	HCO, mg/l	Na mg/l	Cl mg/l	Mg mg/l	SO, mg/l	K mg/l	NO, mg/l	NH_4 mg/l	PO, mg/l	S.I.[2]
a	−25	27	6.1	11	10	14	21	15	57	5.0	37	.02	n.m.	−3.6
b	−20	25	6.4	20	38	17	27	1.3	23	0.9	1.9	.03	n.m.	−2.5
c	−16	37	7.5	80	245	9	14	3.2	2	0.3	0.1	.00	n.m.	−0.1
d	−18	51	7.3	81	274	25	54	9.5	4	2.5	0.1	1.2	.22	−0.3
e	−26	41	7.4	79	275	10	13	4.1	1	0.9	0.1	1.4	.07	−0.1
f	−12	54	7.3	62	223	51	91	8.6	5	3.0	0.1	3.0	.8	−0.5
a	−60	44	7.6	67	168	24	42	5.2	41	1.4	10	.08	n.m.	−0.3
b	−70	26	7.8	47	155	9	14	3.5	5	0.8	0.2	.01	n.m.	−0.1
c	−64	36	7.3	78	245	9	15	4.1	1	0.5	0.5	.60	n.m.	−0.3
d	−84	41	7.2	73	264	17	25	5.3	3	1.0	1.2	1.7	.35	−0.4
e	−89	44	7.3	86	297	9	14	5.0	2	1.0	0.1	0.7	.04	−0.2
f	−77	40	7.2	63	216	20	38	4.5	2	1.2	0.1	3.8	.29	−0.5
River Vecht		90	7.5	67	174	84	120	9.5	75	8.5	19	5.2	3.9	−0.4
A'dam Rhine		88	7.3	77	140	85	155	11	75	7.0	15	0.5	0.03[3]	−0.7

n.m. = not measured.

[1] Electro Conductivity (S = Siemens = mho)

[2] Saturation Index for calcite; − unsaturated, 0 equilibrium, + supersaturated

[3] defosforized by coagulation before suppletion to the polders.

not show calcite saturation. Subregional groundwater at the edges of Polder Bethune (sampling point d and f) is as calcium-rich as the regional groundwater that wells up in the centre (e), but in contrast to the regional groundwater it has relatively high concentrations of Na^+, Cl^-, K^+, NH_4^+ and PO_4^{3-}. This groundwater originates from surrounding lakes, which are supplied with calcium-rich but slightly brackish and eutrophic water from the River Rhine (Table 1).

Fen 1 and **2** are located in areas with relatively minor groundwater flow. The regional scale used in the groundwater flow model does not permit the groundwater flow direction at these sites to be interpreted accurately. Fen **3** is located in a subregional recharge area, and fen 4 is located in a subregional discharge area that is supplied with water coming from Lake Loosdrecht.

4.2. Species composition, productivity and habitat factors of the fens

The low productive vegetation of fen **3** has a dense moss layer consisting of ombrophilous species (Table 2). The low productive vegetation of fen 1 and 2 is characterized by mesotraphent low sedges and low herbs. Fen **4** is highly productive and has eutraphent, tall sedge vegetation that includes tall herbs. Within fen 2 and 4, the vegetation was subdivided into two types. The vegetation of transect 2B is intermediate to the vegetation of transect 2A and the vegetation of the trenches of fen **4** (A), containing low herbs as well as tall sedges. The elevated parts of fen **4 (B)** are dominated by tall grasses. Fen **3** and the elevations of fen 4 **(B)** are considerably less species-rich than the other fens. Fen 1 and **2** contain many rare and endangered mesotraphent fen species, for example, ***Carex lasiocarpa, Utricularia minor, Campylium stellatum, Ranunculus lingua.***

The peat (excluding the drained elevations of fen **4 (B)**) has a high organic matter and water content. After excavation, peat did not regrow at the elevations of fen **4** because of the low groundwater tables due to strong drainage. These elevations are also exceptional with respect to inorganic N- and P-concentrations in the fen water. These concentrations are higher probably because of the release

Table 2. Characteristic set of species, species density, biomass production and mean values of peat soil parameters (5–15 cm below surface), water levels and ionic composition of phreatic water (50 cm below surface) of the fens. Standard deviations are given between brackets.

Fen	3	1	2A	2B	4A (trenches)	4B (elevations)
Characteristic set of species[1]	*Polytrichum commune* *Sphagnum subnitens* *Sphagnum magellanicum* *Aulacomnium palustre* *Drosera rotundifolia* *Betula pubescens*	*Menyanthes trifoliata* *Carex diandra* *Pedicularis palustris* *Lychnis flos-cucculi* *Calliergon cordifolium* *Carex rostrata*	*Menyanthes trifoliata* *Carex diandra* *Pedicularis palustris* *Lychnis flos-cucculi* *Calliergon cordifolium* *Carex disticha*	*Menyanthes trifoliata* *Carex acutiformis* *Pedicularis palustris* *Lychnis flos-cucculi* *Caltha palustris*	*Dactylorhiza majalis* *Carex acutiformis* *Valeriana officinalis* *Lychnis flos-cucculi* *Caltha palustris* *Epilobium hirsutum*	*Poa trivialis* *Carex acutiformis* *Valeriana officinalis* *Festuca pratensis* *Festuca arundinacea* *Plantago lanceolata*
number of species	15 (3)	31 (3)	31 (2)	28 (11)	27 (3)	22 (7)
biomass production[2]						
phanerogams	85	120	130	250	610	490
mosses	270	65	80	70	0	0
% organic matter[3]	95 (0.7)	91 (2.6)	90 (1.5)	89 (1.4)	75 (10.4)	57 (5.7)
C/N	63 (17)	39 (7)	38 (6)	34 (4)	29 (3)	24 (0.7)
% water[4]	95 (1.9)	95 (0)	90 (0.5)	90 (1.7)	93 (4.9)	73 (4.2)
m.h.l.[5]	−4 (0.8)	4 (1.1)	7 (0.9)	7 (1.8)	7 (0.8)	−15 (5.4)
m.l.l.[5]	−11 (3.9)	−3 (0.9)	−8 (3.8)	−7 (8.0)	−1 (1.7)	−36 (2.3)
p_{lime}[6]	2.5 (0.2)	3.5 (0.4)	4.1 (0.2)	4.1 (0.2)	4.0 (0.4)	3.8 (0.0)
pH	6.1 (0.4)	6.4 (0.3)	6.9 (0.3)	6.8 (0.3)	7.3 (0.4)	6.7 (0.5)
Ca^{2+} (mg/l)	15 (5)	33 (9)	61 (21)	86 (31)	76 (14)	46 (11)
Cl^- (mg/l)	14 (3)	29 (6)	23 (5)	28 (7)	80 (11)	37 (21)
K^+ (mg/l)	.49 (.55)	.30 (.40)	1.17 (.88)	1.54 (1.67)	.79 (.97)	1.37 (1.81)
NO_3^- (mg/l)	.14 (.27)	.21 (.40)	.65 (.38)	.44 (.20)	.70 (.65)	1.60 (1.66)
NH_4^+ (mg/l)	.39 (.65)	.18 (.28)	.26 (.22)	.37 (.45)	.42 (.44)	1.65 (2.18)
PO_4^{3-} (mg/l)	.08 (.09)	.06 (.07)	.04 (.06)	.07 (.09)	.08 (.08)	.23 (.25)
S.I.[7]	−3.1 (0.7)	−2.1 (0.6)	−1.0 (0.6)	−0.9 (0.8)	−0.3 (0.6)	−1.6 (1.0)
n (relevé, soil sample)	5	10	4	4	6	4
n (water sample)	17	28	16	12	23	13

1. The characteristic set of species contains species with a presence of more than 75% in one or more fens and of less than 25% in the other fens.
2. g dry wt./m^2
3. of dry wt.
4. of fresh wt.
5. m.h.l. mean highest water level in cm above peat surface, m.l.l. mean lowest level
6. lime potential (pH_{CaCl_2}) − 1.15)
7. Saturation Index of calcite: − unsaturated, 0 equilibrium, + supersaturated

n number of observations

of nutrients by mineralisation. Furthermore, both peat and shallow groundwater of these drained sites are slightly acidified by infiltrating rainwater.

C/N ratios of the wet fens show a sequence of decreasing values from fen 3 through fen 1 and fen **2** to fen **4.** The high values in fen 3 point to oligotrophic conditions. Fen 1, **2** and **4** can be classified as mesotrophic (*cf.* Succow **1988).** Fen **4,** although still mesotrophic, is the most eutrophic of the fens studied.

Lime-potentials of the peat soil, Ca^{2+} concentrations, pH and saturation indices for the fen water show the same sequence, in that calcium-richness increases and acidity decreases from fen 3 through fen 1 to fen **2** and **4.** The trenches of fen **4** (A) have an inflow of slightly brackish water, as is shown by somewhat higher chloride concentrations. There are no large differences in the concentrations of inorganic nutrients in the groundwater of the wet fens.

It is concluded that the low productive species-rich low sedge and low herb communities of fens 1 and **2** are characterized by mesotrophic and moderately-rich to calcium-rich conditions. Abiotic conditions of the low productive moss-rich fen 3 are oligotrophic and acidic. The highly productive communities of fen **4** have calcium-rich and the most eutrophic conditions. The trenches are wet, calcium-rich and slightly brackish. The elevations are drained, which results in the release of nutrients and leaching of calcium from the peat soil.

4.3. Species composition of fen vegetation and water supply

Pearson's correlations between EC values and the concentrations of the major ions Ca^{2+}, HCO_3^-, Na^+, Cl^- and Mg^{2+} in the groundwater of the fens were all high ($r > 0.7, P < 0.0001, n = 265$), which implies that EC values can be regarded as a suitable indicator for distinguishing rainwater-like water from mineral-rich water. However, in the case of mineral-rich water, EC values are not sufficient to distinguish a Ca-HCO, water type from a Na-CI water type. Therefore Stiff-diagrams showing the concentrations of the major ions were presented for cross-sections throughout the fens.

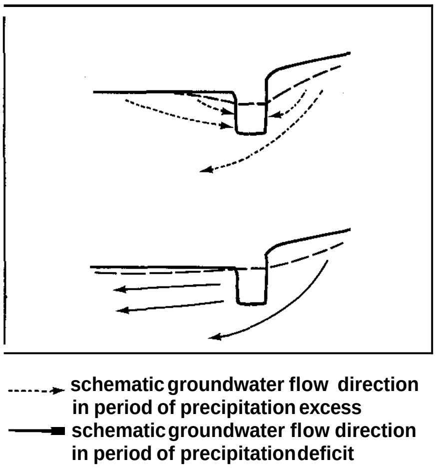


Fig. 3a. **Schematic groundwater** flow **direction in fen 1.**

4.3.1. Fen I

Hydraulic heads of groundwater and surface water show that in periods of precipitation excess the fen is drained by the ditch. In periods of precipitation deficit, the fen is supplied by surface water from the ditch. The hydraulic heads of the sandy aquifer are lower than the hydraulic heads of the phreatic groundwater of the fen most of the time, which causes a downward flow to the sandy aquifer, One concludes therefore that the fen is not fed by an upward groundwater flow from the sandy aquifer (Fig. 3a).

Water quality data show a horizontal layer of calcium-rich water in the fen, which is bordered above and below by a more mineral-poor water type (Fig. 3b). Obviously the laterally inflowing ditch water is the main water source for this fen. The groundwater composition of the sandy aquifer is very similar to that of rainwater, even to a depth of **7** m below the surface. This indicates that the sandy aquifer is recharged by infiltrating rainwater. Moreover, the surface water in the ditch is distinctly richer in Ca^{2+} and HCO_3^- than the groundwater in the aquifer. The ditch contains relatively calcium-rich water throughout the year **(57** ± **8** mg/l). It is **4** km long and is fed in the upstream part of this polder by upward seepage (Fig. 1). The calcium-richness of the ditch water and the ground-

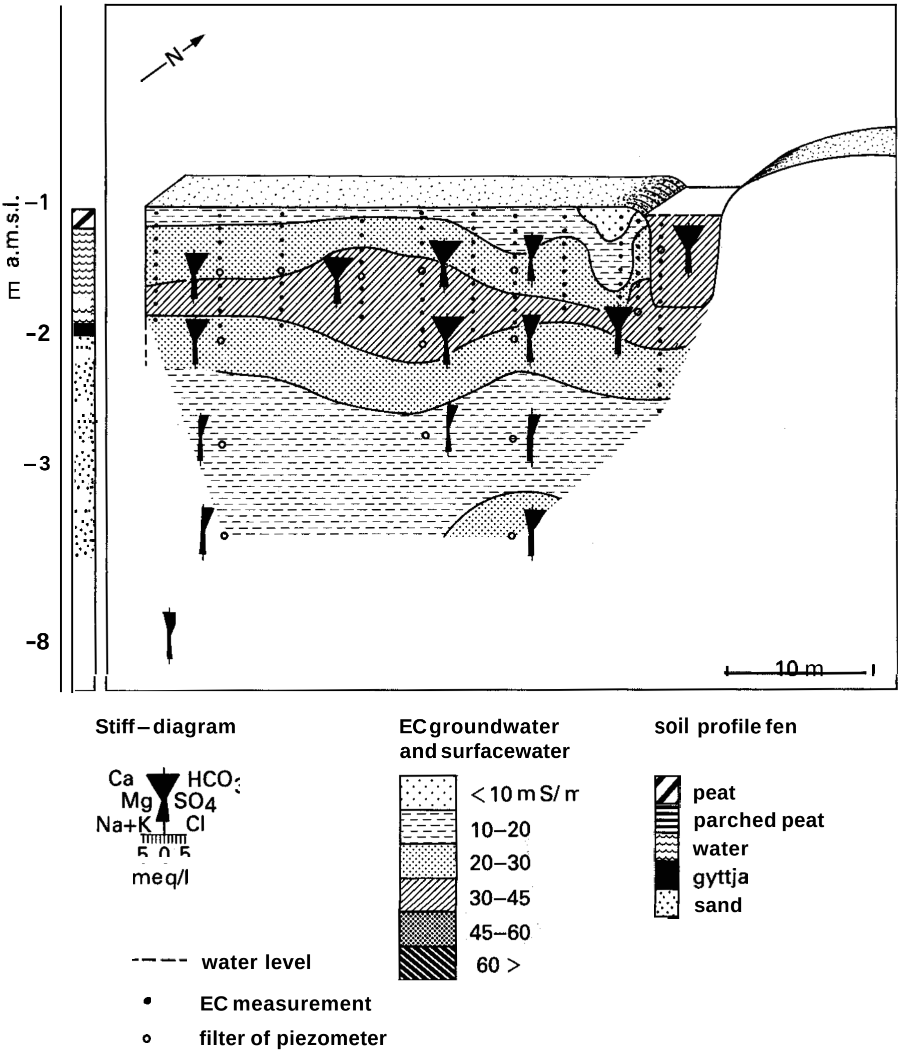


Fig. 3b. Composition of groundwater and surface water in **fen** 1 (November, **1987**).

water flow pattern (Fig. **2**) indicate that regional groundwater that infiltrated eastward of the motorway at the edge of the moraine is the water source for the ditch and thus for the fen.

It is concluded that this fen with its low productive mesotraphent vegetation is supplied predominantly by surface water, which originates from upwelling regional groundwater.

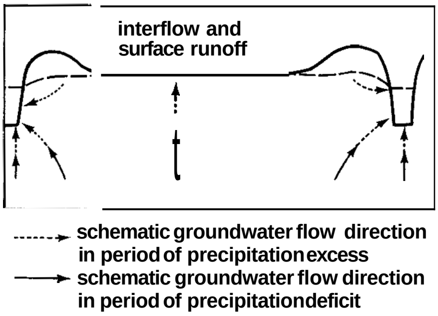


Fig. 4a. Schematic groundwater flow direction in fen **2.**

4.3.2. Fen 2

Hydraulic heads of groundwater and surface water show that the fen is supplied by upward seepage from the sandy aquifer throughout the year. Water surplus in the fen is exported by interflow and surface runoff in a direction perpendicular to the cross-section. These local data supplement the

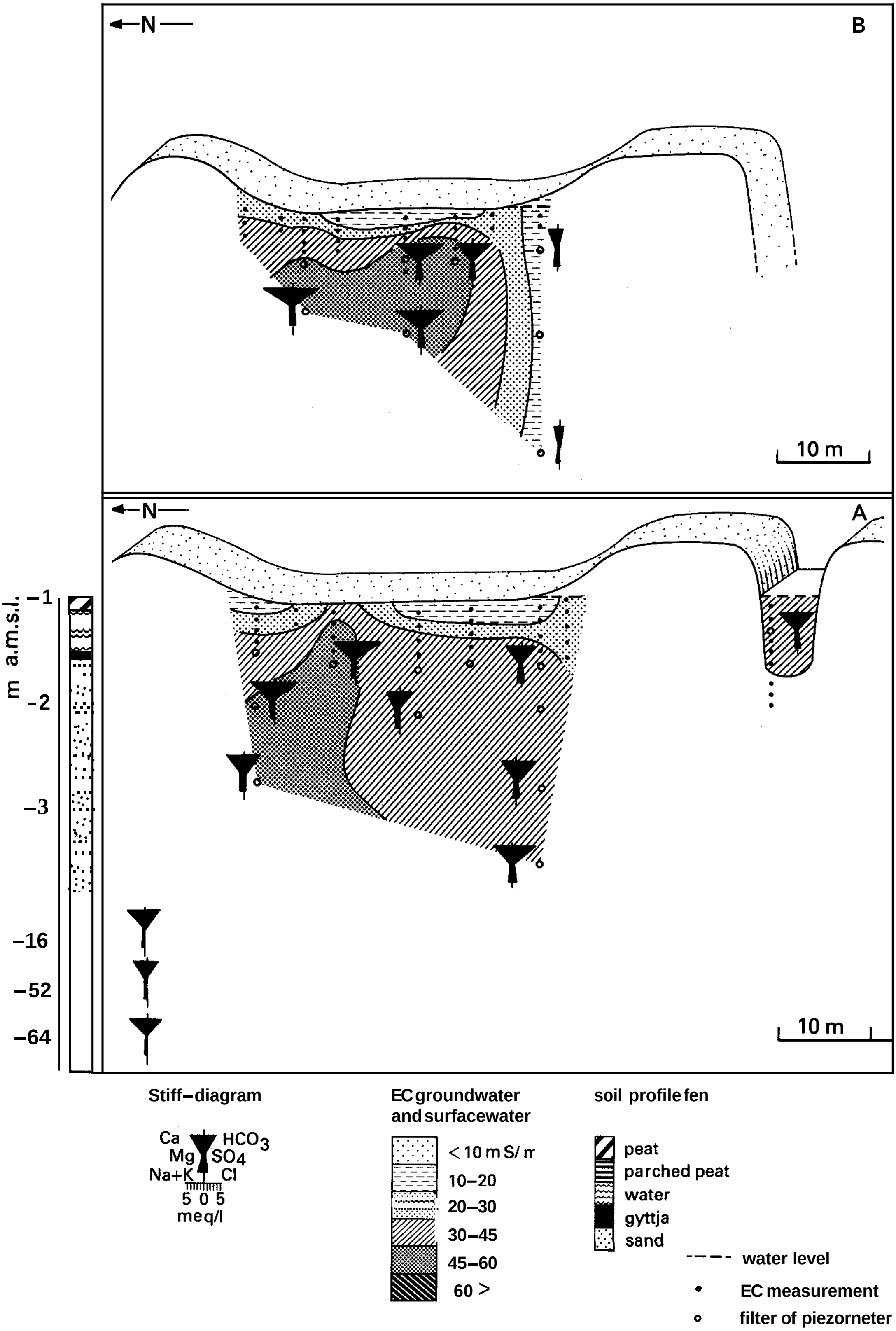


Fig. 4b. Composition of groundwater and surface water along two transects (A, B) in fen 2 (November, 1987).

results of the groundwater simulation model, which did not point to upward or downward seepage of groundwater at this location. The ditches have lower water levels than the fen throughout the year. However, they do not drain the fen (Fig. 4a) which points to a low permeability of the interjacent uncut peat ridges.

Stiff-diagrams show that the groundwater in the fen and the surface water in the ditch are rich in Ca^{2+} and HCO_3^- (Fig. 4b). Inflow to the fen of recently infiltrated rainwater from the adjacent pastures (uncut peat ridges) can be observed at only one sampling point (southern side of transect B). The shallow groundwater of the fen and the surface water show a large resemblance to the calcium-rich groundwater of the sandy aquifer at a depth of **15** to 63 m below surface. The aquifer, however, could be nourished by regional groundwater originating from the moraine or by subregional groundwater that has infiltrated into the adjacent polder (Fig. **2).** The groundwater composition below the fen resembles that of the regional groundwater in the centre of Polder Bethune. Both are calcium-rich and non-polluted (sampling point c and e, respectively; Table 1). This indicates supply of the fen by regional groundwater.

It is concluded that both the low productive mesotraphent vegetation (2A) and the somewhat more productive and more eutraphent vegetation (2B) receive predominantly regional groundwater.

4.3.3. Fen 3

This fen is recharged by rainwater in periods of precipitation excess, because the hydraulic heads in the peat are higher than those in the sandy aquifer and the level of surface water. In periods of precipitation deficit, when the water table in the centre drops, the surface water penetrates the fen from the edges. This concave water table in drought periods indicates that the lateral permeability of the fen peat is relatively low (Fig. 5a).

EC-values for the groundwater show that a shallow layer of rainwater is stored in the top-soil (Fig. 5b). EC-values increase gradually with depth, mainly because Ca^{2+} and HCO, $^-$ concentrations increase.

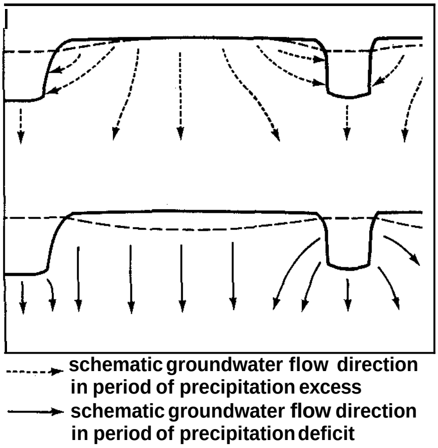


Fig. 5a. **Schematic groundwater flow direction in fen 3.**

The ditch at the southern side receives water from the River Vecht. Although this water has been diluted by rainwater from previous months it can be identified by its relatively high Na+ and Cl^- concentrations. From this ditch the river water penetrates only a dozen metres into the fen, The groundwater composition at 7 m below surface still shows the influence of infiltrated river water. The deeper groundwater of the first aquifer (43 m) and the groundwater of the second aquifer ***(66*** m) consist of a Ca-HCO, type, without influence of river water.

It is concluded that this fen with its low productive ombrophilous vegetation is nourished by a local water system consisting of rainwater.

4.3.4. Fen 4

Hydraulic heads of groundwater and surface water show that this fen receives groundwater from the sandy aquifer throughout the year. Continuous surplus of rainwater and upwelling groundwater are drained away by trenches and ditches (Fig. 6a).

Stiff-diagrams show that the fen and the ditches are fed by the adjacent lake (Fig. 6b) which is supplied in summer with water from the River Rhine. The vertical tongues of mineral-rich water seeping upwards towards the trenches shows clearly that the trenches attract lake water. In the elevated parts of this fen, infiltration of rainwater occurs; over short distance this rainwater becomes enriched by Ca^{2+} and HCO_3^-, as can be seen from the Stiff-dia-

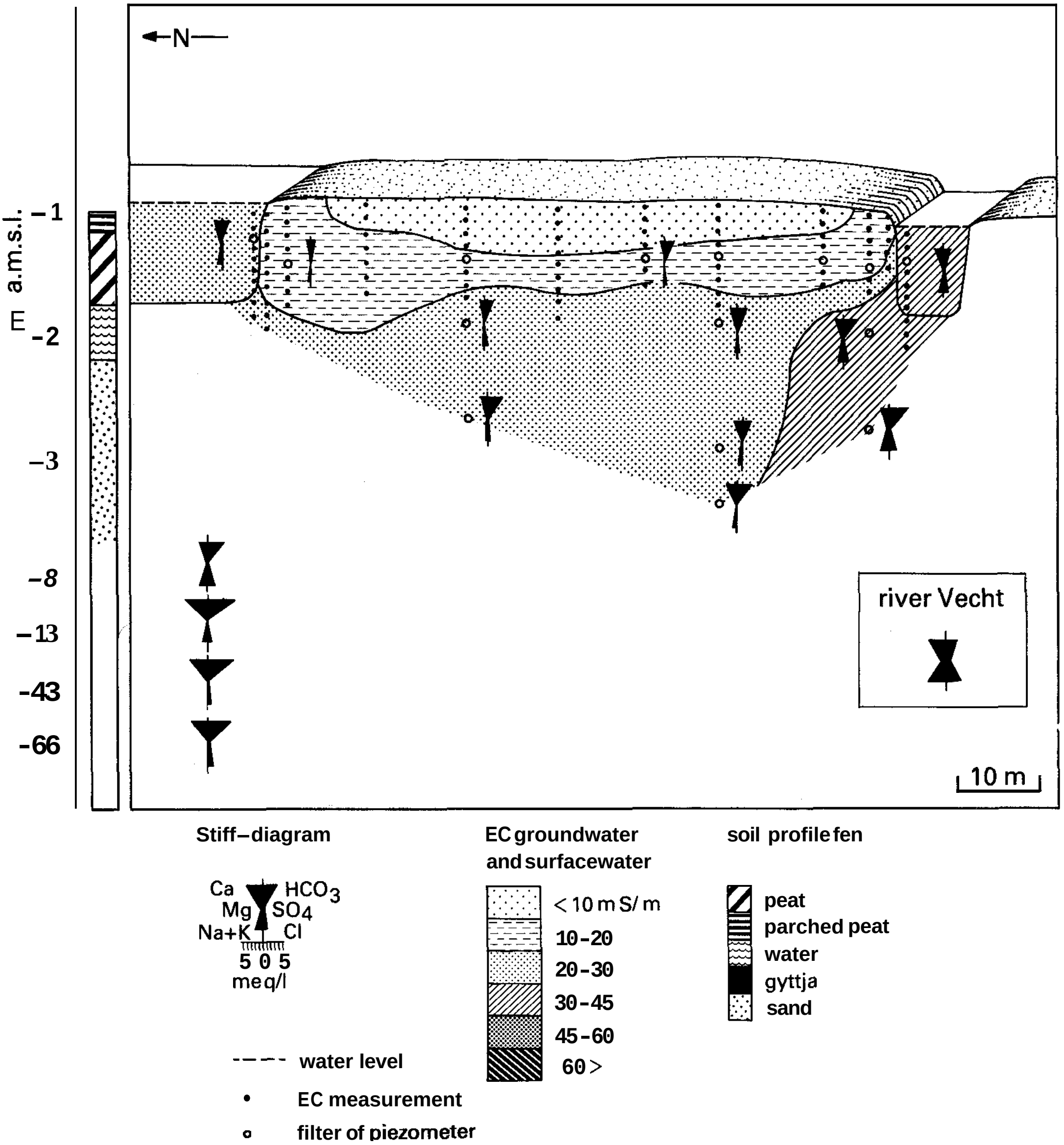


Fig. 5b. **Composition of groundwater and surface water in fen 3 (November, 1987).**

grams for the southern side of this transect. Obviously, the peat is very calcium-rich.

Chloride concentrations gradually decrease deeper into the subsoil and the chloride concentration in the fen is higher than at present in the lake. The groundwater flow model indicates infiltration of lake water to a depth of 100m below the surface. This is confirmed by isotope analyses carried out by Hettling (1985). Chloride concentration in the lake has varied largely over the last few decades (de Ruiter *et al.* 1988) because of changes in the amount of water coming from the River Rhine. This gives us an opportunity to estimate how long it has taken for the groundwater to infiltrate. The present concentration in the fen existed in the lake 10 to 15 years ago, whereas the present concentration at 77 m below surface existed in the lake more than 30 years ago.

It is concluded that the highly productive sedge vegetation of the trenches receives predominantly

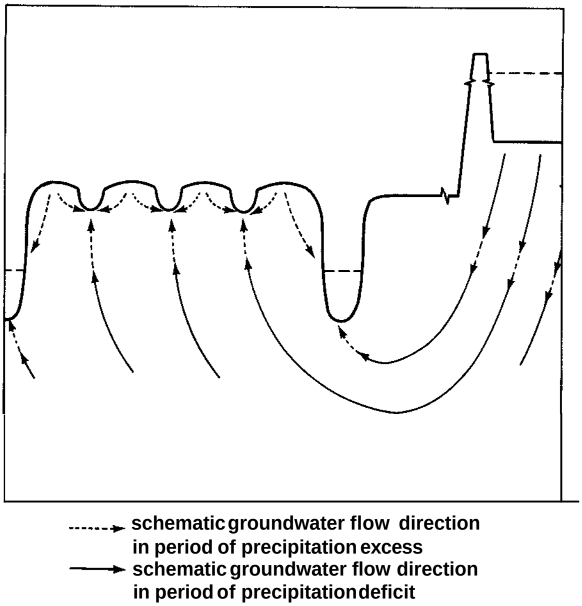


Fig. *6a*. Schematic groundwater flow direction in fen **4.**

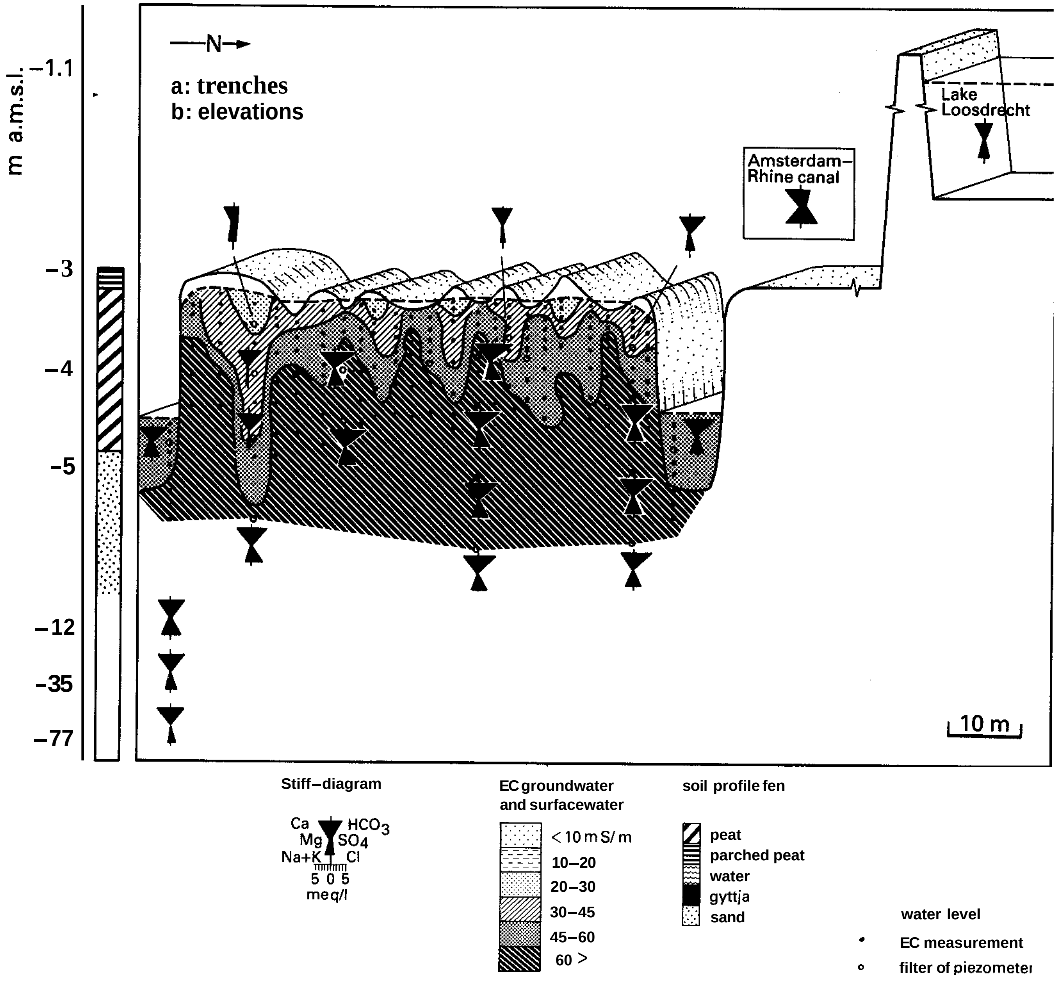
subregional groundwater which consists of lake water that has flowed a few hundred metres through the sediment. On the elevations, high productive grassland vegetation is fed predominantly by rainwater.

5. Conclusions and discussion

5.1. Regional and subregional groundwater flow systems

The simulation of the flow pattern of the regional and subregional groundwater flow systems turned out to be of great value for understanding the hierarchy and spatial distribution of groundwater flow systems on a regional scale. Subregional ground-

Fig. *6b*. Composition of groundwater and surface water in fen **4** (November, 1987). ↓



water flow systems are found spatially nested in the regional groundwater flow system, as has been demonstrated for other areas by, ***e.g.*,** Toth **(1963),** Engelen and Jones **(1986)** and Winter **(1989).**

The swift increase in Ca^{2+} and HCO, $^-$ concentrations and pH in infiltrating rainwater indicates that dissolution of calcite is an important process in the area studied. Relatively calcium-rich groundwater is already found at a depth of **60** metres under the moraine. At some distance from the moraine the subregional groundwater flow systems turned out to be just as calcium-rich as the regional groundwater flow system. This is mainly because the River Rhine supplies the subregional groundwater flow systems with calcium-rich water. The influence of the polluted Rine water is clearly expressed by the increased sodium and chloride concentrations in the subregional groundwater flow systems.

Another severe problem in recent times is eutrophication of valleys by the inflow of eutrophic regional groundwater polluted on the upland. This has been reported from many regions where the upland is densely populated or intensively used for agriculture (***e.g.*,** Madden and DeLaune **1987,** Billwitz 1988). In our case, the eutrophication comes mainly from heavily fertilized cornfields. In the future, this eutrophic groundwater will probably reach the fens and will present another threat to mesotrophic conditions.

5.2. Effect of groundwater flow systems on fen vegetation

The hydrological research on a local scale yielded information regarding the isolation of the fens or their connection with the regional and subregional groundwater flow systems. Nested groundwater flow systems were also found to exist within the fens; this demonstrates that groundwater flow systems can be distinguished from each other on a very fine scale. (Sub)regional hydrology strongly influences the local hydrology of the fens, which in turn affects the vegetation structure and species composition. Differences in the vegetation composition of the studied fens are in line with extensive mapping of fen species distribution in this part of the river plain (Beltman and Verhoeven 1988). Mesotrophic fen species are found in discharge areas of groundwater that is calcium-rich but chloride-poor. They are also found in the few recharge areas where the composition of surface water still resembles that of non-polluted calcium-rich groundwater.

Permanent recharge in combination with isolation of the surface water leads to succession in the ombrotrophic direction. C/N values for fens range from **15–30** and from **50–60** for raised bogs (Scheffer and Schachtschabel **1976).** Therefore, C/N values for fen **3** indicate a development to poor fen (‘mini-bog’): a local water system fed by rainwater and isolated from regional or subregional water systems. The present vegetation consists mainly of bryophytes, most of which are ***Sphagnum*** and ***Polytrichum*** mosses (poor fen). The peat soil at **5–15** cm below the surface, however, consists of fragments of reed and sedges (rich fen). A more recently excavated fen in the same recharge polder also shows a predominance of ***Sphagnum*** mosses. Yet, it is still floating with a high water table, although it is predominantly nourished by rainwater (Koerselman ***et al.*** in press). It was excavated approximately at the same time as fens 1 and 2, which contain ***Sphagnum*** species only sporadically. This supports the hypothesis that the successional development to poor fen is accelerated in a recharge area. A similar shift in species composition has been observed in the reedlands of the nearby Naardermeer wetland; the reason for the shift is the diminishing discharge of regional calcium-rich groundwater during the last few decades (Wassen ***et al.*** **1989a).**

The other (rich) fens still receive relatively calcium-rich groundwater or surface water. The low productive species-rich mesotraphent vegetation of fens **1** and **2** is nourished by calcium-rich regional water which is not influenced by Rhine water. The highly productive eutraphent vegetation of fen **4** is fed by a subregional water system consisting of discharging lake water, which is partly Rhine water.

The mesotraphent vegetation of fen **1** is maintained by exceptional local circumstances. From the very low ion concentrations in the sandy aquifer, it is concluded that this (almost purely) rainwater must have infiltrated very recently, probably from the adjacent pasture. This water has not infiltrated into the fen itself, because the distribution pattern of groundwater types, as was shown for November, was similar throughout the entire period of measurement. The fen is supplied with calcium-rich water by lateral inflow of surface water which is derived from a regional groundwater flow system that discharges northwards of the fen. This intruding surface water lies on top of the mineral-poor groundwater of the sandy aquifer. The regional groundwater flow is not connected directly with the fen. Relatively calcium-rich conditions are, however, maintained in the fen by the (coincidental and artificial) presence of a ditch next to the fen. This particular situation has also been observed in other fens in the Netherlands. In NW-Overijssel, low productive mesotrophic fens are found in a region where no discharge of groundwater occurs. These fens are supplied with calcium-rich surface water which is pumped out of a deep polder and which flows laterally into the fens (Van Wirdum **1982).**

Fen **2** is fed by an upward flow of regional groundwater, which discharges in the fen itself. Lateral inflow of eutrophied groundwater from the adjacent pastures is prevented to a large extent by this discharging groundwater flow. Additionally, it has become clear from the local hydrological study of this fen that the results of the regional groundwater simulation model may deviate from actual hydrological circumstances. This is probably due to the scale of the flow model and possibly to local deviations from our assumption that the cross-section of the flow model is parallel to the horizontal groundwater flow direction.

Although the productivity **and** floristic composition of the fen vegetation and C/N values of the peat soil have been proved to form a range from oligotrophic through mesotrophic to almost eutrophic conditions, inorganic nutrient concentrations of the shallow groundwater are more or less equal in the different wet fens. ***So,*** neither the eutrophying effect of the supply of river water to the eutrophic fen nor the oligotrophic conditions in the acidic fen are reflected in the inorganic nutrient concentrations of the fen water. Measurements of inorganic nutrient concentrations in the shallow groundwater apparently do not give such a clear indication of the trophic level of a mire. A probable reason is that inorganic nutrients are taken up by vegetation.

The distribution of polluted river water is best reflected by the concentration of the inert ion chloride. The still relatively low values we measured in the eutrophic fen are probably of no physiological importance for plant growth; but, in landscape ecological research of freshwater wetlands, chloride is apparently a very suitable tracer for pollution (see also Van Wirdum **1981;** Koerselman ***et al.*** in press). Nutrient concentrations are very high in river water (Table **1),** which leads to direct eutrophication of fens supplied with this water. However, the hydrochemical and microbiological processes that lead to indirect eutrophication in areas supplied by river water are not yet fully understood (Roelofs **1989).**

In the Vecht River plain, the natural hydrological zonation has been altered (Witmer **1989).** Only a small part of the regional groundwater flow at present discharges in a zone at the foot of the moraine (Schot **1989).** From a comparison of this area with the undisturbed Biebrza valley mire in Poland it can be concluded that in the past this mesotrophic zone comprised a much larger part of the river plain. Furthermore, succession to poor fen takes place only sporadically in the Biebrza valley, caused by intensified drainage of the mire by the river. The floodplain contains the most eutrophic fens (Wassen ***et al.*** unpubl.). In the Vecht plain however the groundwater surplus of the discharge belt located at the foot of the moraine is at present drained away to the river by ditches and canals. Another major part of the regional groundwater flow is directed to the deep Polder Bethune, where it wells up in the centre. A large part of this groundwater is used for drinking water supply, the rest is pumped into Lake Loosdrecht. Both discharge areas (valley margin and Polder Bethune) contain hardly any fens. ***So,*** the larger part of the regional groundwater does not supply any fen ecosystems. Nevertheless, the sequence of the fens from the moraine towards the river still reflects a natural zonation: mesotrophic fens are relatively close to the moraine and poor fen development as well as eutrophic fens are closer to the river. Even in a predominantly man-influenced landscape like the river plain studied, the vegetation of the fens is still determined for the most part by the (sub)regional hydrology.

5.3. Measures for restoring mesotrophic fen ecosystems

Changes in the regional groundwater flow system are of great impact to vegetation of fens which receive water of this system. This makes mesotrophic species-rich fens vulnerable to such changes. Conservation of such fens requires first of all conservation of the hydrological conditions. This means: no introduction of water from the polluted river, no accumulation of rainwater.

Restoration of already damaged fens is possible by restoring the mesotrophic calcium-rich regional groundwater flow towards these fens. This goal could be achieved by inundating Polder Bethune. The effect will be that the regional groundwater flow will be forced towards the surface in the polders located in between Polder Bethune and the moraine. Water losses from the recharge areas surrounding Polder Bethune will decline greatly since large parts of these areas will turn into discharge areas (Land Design Department unpubl.). For instance, the infiltration loss of *c.* 17 x 10^6 m^3/year from Lake Loosdrecht towards Polder Bethune will become almost zero (Den Hartogh 1989). The areas surrounding Polder Bethune lost their species-rich fen vegetation after they turned from discharge into recharge area. Restoration of the discharge situation will create a vital basic condition for species-rich vegetation to regenerate (see also Wassen *et al.* 1989b).

The social consequences of flooding of Polder Bethune would be: (i) development of an alternative source for the production of 25 million m^3/year drinking water; (ii) movement and resettlement of c. 25 families; (iii) destruction of means of livelihood (farms, agricultural ground); (iv) creation of an area for aquatic sports (Engelen and Kal 1985) and for the settlement of aquatic ecosystems.

Mesotrophic fen ecosystems in the more northerly part of the Vechtplassen area which suffer from eutrophication by river water supply and acidification by infiltrating rainwater (Wassen *et al.* 1988) could be saved in a similar way if the Horstermeer Polder would be changed back into Lake Horstermeer. This has been suggested as the most promising restoration option, on the basis of the results of a water quantity simulation model (Witmer 1989). No drinking water is extracted from this polder, but a complicated social factor arises since the polder harbours ca. 800 inhabitants. Therefore, local authorities oppose this water management option.

The dependency of local mesotrophic fens on the regional groundwater flow stresses the importance of management measures which go beyond the responsibility of the local manager. Since the Vecht River plain and its catchment area cover an area managed by two provinces, interprovincial decisions must be taken to keep mesotrophic fens from extinction.

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Notes

1. Oligotrophic: nutrient-poor, mesotrophic: intermediate, eutrophic: nutrient-rich.
2. Oligo-, meso-, eutraphent: organisms preferring/tolerating a certain trophic level (see note 1).

3. Ombrophilous: organism tolerating a predominantly rainwater influence.
4. Gyttja: partly organic bottom deposit in lakes and the like.

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