SOLUTE TRANSPORT BY GROUNDWATER FLOW TO WETLAND ECOSYSTEMS

Paul Schot

C. H. van der Weyden

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Met dank voor de geboden hulp!

Paul

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SOLUTE TRANSPORT BY GROUNDWATER FLOW TO WETLAND ECOSYSTEMS

The environmental impact of human activities

TRANSPORT VAN STOFFEN DOOR GRONDWATERSTROMING
NAAR MOERASECOSYSTEMEN
De milieu effecten van menselijke activiteiten

(met een samenvatting in het Nederlands)

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Voor mijn ouders en schoonouders

In gedachten aan Jan van der Wal

CONTENTS

1. GENERAL INTRODUCTION 9

2. HYDROLOGY OF THE NAARDERMEER; INFLUENCE OF THE SURROUNDING AREA AND IMPACT ON VEGETATION 17
P.P. Schot, A. Barendregt and M.J. Wassen
(Agricultural Water Management, 14 (1988), pp.459-470)

3. GROUNDWATER SYSTEMS ANALYSIS OF THE NAARDERMEER WETLAND, THE NETHERLANDS 33
P.P. Schot
(In: Simpson, E.S. & J.M. Sharp, eds. (1990), Selected papers from the 28th International Geological Congress, Washington, 1989. Hannover: IAH Selected Papers on Hydrogeology, Volume 1, pp.257-269)

4. REGIONAL CHANGES IN GROUNDWATER FLOW PATTERNS AND EFFECTS ON GROUNDWATER COMPOSITION 47
P.P. Schot and A. Molenaar
(Journal of Hydrology, submitted)

5. HUMAN IMPACT ON REGIONAL GROUNDWATER COMPOSITION THROUGH INTERVENTION IN NATURAL FLOW PATTERNS AND CHANGES IN LANDUSE 67
P.P. Schot and J. van der Wal
(Journal of Hydrology, submitted)

6. CALCIUM CONCENTRATIONS IN WETLAND GROUNDWATER IN RELATION TO WATER SOURCES AND SOIL CONDITIONS IN THE RECHARGE AREA 85
P.P. Schot and M.J. Wassen
(Journal of Hydrology, submitted)

7. DISCUSSION AND CONCLUSIONS 101

REFERENCES	111
SUMMARY	119
SAMENVATTING (Dutch)	123
DANKWOORD	129
CURRICULUM VITAE	131
LIST OF PUBLICATIONS	133

CHAPTER 1

GENERAL INTRODUCTION

1. DETERIORATION OF WETLAND VEGETATION ON THE VECHT RIVER PLAIN

The Vecht river plain in the Central Netherlands consists largely of freshwater wetland. Wetlands east of the river are historically renown for their great variety of aquatic- and fen vegetation (Meyer & de Wit, 1955; Van Zinderen Bakker, 1942). This variety is related to the natural gradient in water composition which is characterised as rather nutrient-poor (mesotrophic) at the eastern edge of the river plain and nutrient-rich (eutrophic) near the river. In the Netherlands a comparable vegetation gradient exists to some extent only in the northwest part of the province of Overijssel (Provinciaal Bestuur van Noord-Holland, 1986). The ecological value of the eastern Vechtstreek has been recognised in several national, regional and local policy plans.

From comparisons of vegetation surveys from the eastern part of the Vecht river plain over the period 1935-1984 it appeared that a marked deterioration of wetland vegetation has occurred (Van de Berg & de Smidt, 1985; Provinciaal Bestuur van Noord Holland, 1986). Shortly after World War II a decline in the variety of wetland vegetation started, which strongly increased from the second part of the 1950s and still continues. A severe reduction occurred in the abundance of low-productive fens. In particular species disappeared of the Class *Parvocaricetea*[1], especially of its species-rich alliance *Caricion davallianae* (Wassen, 1990). These are replaced by species of highly-productive wetlands of eutrophic environment.

It is generally believed that the *Caricion davallianae* fens are dependent on fresh, rather nutrient-poor groundwater rich in iron and especially calcium (Van Wirdum, 1986; Grootjans, 1985; Wassen et al., 1989). Calcium and iron are believed to exert a limiting effect on nutrient availability to plants through precipitation or complexation as calcium- and iron phosphates (Patrick, 1974; Kemmers, 1986; Wassen, 1990).
In the Vecht river plain this type of water naturally originates from the adjacent ice-pushed ridge 'Het Gooi', which consists mainly of nutrient-poor sands and gravels. The ridge has elevations up to 30 m above the plain and is a regional recharge area which supplies the river plain through

[1]nomenclature according to Westhoff & den Held, 1979.

groundwater flow and subsequent upward seepage.

Based on the foregoing, the deterioration of wetland vegetation in the Vecht river plain has been attributed to past groundwater management (Provinciaal Bestuur van Noord-Holland, 1986). Over the past century, especially since the second World War, groundwater extraction on the ridge strongly increased. As a consequence the flow of rather nutrient-poor groundwater towards the river plain diminished. Decreased upward seepage resulted in a decrease in mesotrophic plant environments and water shortages in summer. Water shortages on the river plain are met by import of external polluted surface water, which led to eutrophication. Barendregt et al. (1986) showed that this eutrophic suppletion water has a strongly negative effect on the mesotrophic aquatic- and fen vegetation.

Management aiming at the conservation and restoration of aquatic- and fen vegetation on the Vecht river plain is therefore directed towards regeneration of upward seepage of groundwater deriving from the ridge. For example, in the Provincial Groundwater Management Plan a 50% reduction of groundwater extraction on the ridge has been proposed (Provinciaal Bestuur van Noord-Holland, 1986).
At the same time groundwater pollution on the ridge has increased. The naturally nutrient-poor sands on the ridge have become richer in nutrients and other elements as an effect of strong increase in urban settlement, industry, traffic and of agricultural intensification (Janssen & Verkroost, 1989). In time this will affect the vegetation in the river plain through solute transport by groundwater flow. Increased upward seepage from the ridge as a restoration measure may then eventually have adverse effects, thus necessitating alternative water management options.
Such considerations are the subject of this thesis.

2. THIS THESIS

The general aims of this thesis are to:
1. Identify and describe the processes of solute transport by groundwater flow to wetlands in the eastern Vecht river plain.
2. Determine the extent to which this transport of solutes is influenced by human activities.

Within this general framework, specific research questions related to wetland vegetation on the Vecht river plain are:
- what is the present composition of groundwater underlying the ridge

and the Vecht river plain; to what extent is the groundwater polluted by human activities?
- what is the present groundwater flow pattern; are pollutants transported towards the river plain?
- which hydrochemical processes are ecologically important; are pollutants retarded or chemically altered during flow?
- is regeneration of upward seepage from the ridge a good restoration option; are there alternatives?

The thesis is confined to solute transport in the saturated zone. Dispersive and diffusive transport as well as transport by density flow are not considered. The solutes studied comprise those which are generally analysed for groundwater samples, i.e. major ions (Cl, Na, Ca, HCO_3, Mg, SO_4), nutrients (NO_3, NH_4, PO_4, K), Fe, Mn, SiO_2 and the parameters pH and EC. Short-term (seasonal and annual) fluctuations in groundwater flow are not specifically considered.

The scale of study is mainly regional. Data on geology, groundwater hydraulic heads and groundwater composition have been compiled for four topographic map sheets (25H, 26C, 31F, 32A, scale 1:25000) with a total area of 500 km². The Naardermeer wetland comprising 7 km² has been studied in more detail.

The research has been conducted in a multi-disciplinary setting at the Department of Environmental Studies of the University of Utrecht. Within this Department a group of biologists/ecologists, physical geographers/(geo)hydrologists, public administrators and environmental planners work on the joint research theme 'Social and Ecological Aspects of Water Management'. The region of 'Het Gooi' and the eastern Vecht river plain in the Central Netherlands is one of the study areas.

3. THEORETICAL ASPECTS OF SOLUTE TRANSPORT BY GROUNDWATER FLOW

Groundwater composition at a certain location is determined by:
- the composition of the primary water source (precipitation or surface water)
- the natural or human-induced increase in solute concentrations during infiltration as an effect of landuse (concentration by evaporation, pollution)
- soil conditions (moisture condition, lithology) and the chemical

processes in the soil zone related to these conditions
- the groundwater flow pattern, which determines the path through sediments in the subsoil
- the aquifer characteristics c.q. lithology of the sediments passed
- the hydrochemical processes during flow through the saturated zone; these processes are determined by the composition of inflowing groundwater and the lithology of aquifer sediments.

From the above it follows that two main components need to be considered in the analysis of solute transport by groundwater flow, i.e. convective groundwater flow and factors influencing solute concentrations. These components may show steady state or dynamic characteristics.

3.1. Uniform groundwater composition along a flow line

Groundwater composition along a flow line is uniform when the initial water composition in the recharge area is constant in time, the convective groundwater flow pattern is in a steady state and groundwater composition is not affected by hydrochemical processes in the aquifer. Solutes in the recharge groundwater are transported conservatively by convective flow to the locations where groundwater performs certain functions, e.g. upward seepage areas in wetlands or wells for public drinking water supply.
The initial groundwater composition can be determined from analyses of groundwater samples from the recharge area or estimated from knowledge on the composition of the primary water source, landuse and soil conditions in the recharge area.
Convective flow of groundwater can be described from the basis of hydraulic heads using Darcy's law. It may also be deduced from tracers. A tracer is a groundwater parameter which behaves in a conservative way, i.e. it is influenced solely by convective transport and not by hydrochemical processes. The application of tracers to determine convective flow is based on the principle that a certain type of recharge area is characterized by specific concentrations of a tracer. Examples of environmental tracers are the chloride ion and the oxygen-18 isotope. The distribution pattern of such tracers provides an indication of the groundwater flow pattern.
Likewise, radioactive tracers are used (e.g. tritium, carbon-14) which are not representative for an area of recharge but for the time of recharge. The spatial distribution of radioactive tracers provides information on recharge- and discharge areas and on flow velocities.

3.2. Changes in convective groundwater flow; type-1 fronts

Temporal changes in groundwater flow patterns may connect groundwater discharge areas to new recharge areas with a different initial groundwater composition. This will produce a front in groundwater composition along the new flow lines, denoted as a type-1 front in this thesis.
Type-1 fronts may be detected by comparison of the present groundwater flow pattern deduced from hydraulic heads with the distribution of environmental tracers in the subsoil. When the tracer values on the downstream side of the front differ from that expected on the basis of present flow patterns (using hydraulic heads), then changes in flow patterns are deemed to have occurred.
Type-1 fronts may also be determined from a comparison of computer simulations of the contemporary flow pattern with past groundwater flow patterns.

3.3. Changes in initial groundwater composition; type-2 fronts

Temporal changes in initial groundwater composition may result from changes in the composition of the primary water source, changes in landuse (e.g. pollution) or changes in soil conditions (e.g. moisture condition, leaching). These changes result in type-2 fronts which may be detected as follows:

- *Through tracers*: In a number of cases changes in initial groundwater composition are accompanied by changes in the concentration of certain tracers. Since tracers are not subject to hydrochemical processes, all tracer fronts not caused by changes in flow patterns indicate a change in initial groundwater composition. An example is the chloride ion which is present in many pollution types and of which increasing concentrations may indicate a type-2 front. However, changes in initial groundwater composition are not always accompanied by a change in tracer concentration.
- *Through mass balance calculations*: Type-2 fronts lead to different masses on both sides of the front. Mass balance calculation may thus reveal a type-2 front. Unfortunately, some of the data necessary for mass balance calculations may be lacking; e.g. data on gasses such as CH_4 during methanogenesis or N_2 during denitrification.

3.4. Hydrochemical processes; type-3 fronts

Hydrochemical processes lead to retardation or conversion of solutes. These

result in a water quality transition zone or 'front' in the direction of flow, denoted in this thesis as a type-3 front.
The occurrence of hydrochemical processes can be detected by using a mass balance. Total mass remains constant across a type-3 front, in contrast to type-2 fronts. Tracer concentrations also remain constant.

When a change in convective groundwater flow or in initial groundwater composition is not characterized by a change in tracer concentration and when a mass balance calculation is not possible due to a lack of data, these type-1 or type-2 fronts cannot be distinguished unambiguously from a type-3 front.
In that case model simulations of the contemporary and past flow patterns may provide information on type-1 fronts. Type-2 fronts may be distinguished from type-3 fronts on the basis of specific information from the study area on land use changes in the recharge areas and general knowledge and experience with respect to groundwater hydrochemical processes. This is in fact speculation about what is the most likely situation.

4. RESEARCH METHODOLOGY AND THESIS STRUCTURE

The deteriorating aquatic- and fen vegetation of the eastern Vecht river plain is assumed to be dependent on upward seepage of groundwater deriving from the ridge. The deterioration is ascribed to hydrological changes outside the wetland areas themselves. Chapter 2 studies the relation between seepage from the ridge and the distribution of plant species in the Naardermeer wetland. Secondly, the influence of the surrounding area on hydrological attributes in the wetland is analysed.

A description of solute transport must be based primarily on knowledge on the groundwater flow pattern. In chapter 3 the contemporary steady state convective groundwater flow pattern is simulated with the groundwater model FLOWNET along a cross-section over the Naardermeer wetland. Verification of the simulated flow pattern based on hydraulic heads is provided by the distribution of the environmental tracers chloride, oxygen-18 and tritium. Groundwater chloride and nitrate concentrations are used to ascertain whether polluted groundwater is transported towards the wetland.

The long-term dynamic character of groundwater flow is studied in chapter 4. FLOWNET is used to simulate steady state groundwater flow patterns along a cross-section from the ridge to the Vecht river for four points in time; viz., the 14th century, 1885, 1941 and 1985. These simulations represent the most important human-induced hydrological changes in the study area over the past 600 years. The regional changes in groundwater flow patterns over this period are deduced from the differences observed between the results of steady state simulations for each point in time. The environmental tracers chloride and oxygen-18 are used to evaluate the effect of these changes on groundwater composition (type-1 fronts).

Chapter 5 provides an overview of regional groundwater composition in the study area. Multivariate statistical analyses are applied to deduce the factors controlling groundwater composition and the main resulting water types. The results are used to determine the existence of type-2 and type-3 fronts and the human impact on regional groundwater composition.

For the restoration of wetland vegetation on the Vecht river plain, regeneration of upward seepage from the ridge has been proposed in order to provide groundwater which is relatively rich in calcium and iron and poor in nutrients. Chapter 6 tests whether groundwater from the ridge is the only source for this type of water or whether other sources are available in the study area.

Chapter 7 discusses the results of separate chapters in the context of the general aims of the thesis; the identification of solute transport processes and the environmental impact of human activities on wetlands through influence on solute transport. Finally, the implications for the restoration of wetland plant communities on the Vecht river plain are discussed.

CHAPTER 2

HYDROLOGY OF THE WETLAND NAARDERMEER; INFLUENCE OF THE SURROUNDING AREA AND IMPACT ON VEGETATION

P.P. Schot, A. Barendregt and M.J. Wassen

(Agricultural Water Management, 14 (1988), pp. 459-470)

ABSTRACT

The Naardermeer is a polder located in the central Netherlands at the foot of a sandy ice-pushed ridge. It has been put on the list of internationally important wetlands (Ramsar Convention). Groundwater flow is directed from the ice-pushed ridge in the east towards the river plain in the west. Seepage from the ice-pushed ridge occurs in the eastern part of the Naardermeer while in the western part infiltration occurs as a result of low water levels in the adjacent polders. During the past decades the water levels in the Naardermeer have become steadily lower due to increasing groundwater extractions in the hill ridge and lowering of the water levels in the adjacent polders. External surface water is suppleted to compensate water deficits in summer. These changes form a possible threat to the preservation of the botanical significance of the Naardermeer.

In 1985 a survey was started to establish the relation between hydrology and the occurrence of plant species in the Naardermeer. The hydrological data shows that water quantity and quality in the Naardermeer are strongly influenced by the surrounding area. As concerns quantity, the water input by seepage is inadequate to compensate for water loss through infiltration. This results in a mean net infiltration of 0.4 mm/day. The influence of the surrounding area also emerges from the quality of the groundwater. In the seepage area groundwater is generally of the calcium-bicarbonate type. In the most eastern part of the seepage area groundwater occurs with high nutrient load originating from polluted surface water just outside the Naardermeer. Infiltration recorded from piezometric data was confirmed by the presence of water with rain water attributes in the upper groundwater layers.

In the area a clear relationship exists between the pattern of hydrological attributes and the vegetation pattern in reed marshes. Vegetations related to the quality of rain water occur in a random pattern in the Naardermeer. Vegetations related to water rich in calcium and bicarbonate occur in the seepage area where they are supplied directly by groundwater of the calcium-bicarbonate type. Furthermore, they occur in the infiltration area

where they are supplied by surface water. The surface water originates from groundwater in the seepage area which flows into the infiltration area. This seepage driven flow will prevent the suppletion water from spreading all over the Naardermeer. This is important as most of the species present respond negatively to the quality of the suppletion water.
This study illustrates the importance of hydrological information for the conservation of nature in wetlands. The impact of both internal and external (upstream and even downstream) processes has to be considered.

INTRODUCTION

The Naardermeer is a natural lake located in the central Netherlands. Attempts to reclaim the lake for agricultural purposes in the 17th and 19th century failed mainly due to economic reasons. When the city of Amsterdam planned to use the lake as a wastedump it was bought by nature conservationists in 1906. Thus the Naardermeer, a polder formed by surface water and adjacent marshes, became the first nature reserve in the Netherlands. The Naardermeer is famous as a bird sanctuary but it is also of botanical importance and it has been put on the list of internationally important wetlands (Ramsar Convention).
Being a wetland, nature conservation and management in the Naardermeer are mainly related to hydrological factors. Major problems are the reduced supply of groundwater due to withdrawal in the recharge area Het Gooi for drinking-water and also the subsurface loss of water to adjacent polders with lower surface water levels. These problems resulted in steadily lower water levels in the Naardermeer during the past decades. Initially surface water from outside the polder Naardermeer was supplied during summer periods to prevent parching and mineralisation. Although this was a good quantitative hydrological solution, the eutrophic suppletion water was considered to be of inappropriate quality. Therefore, suppletion was stopped from 1959 until 1985, when it became possible to supply IJmeer water. This water is subjected to dephosphorisation before entering the Naardermeer. It has relatively high chloride, sodium and sulfate contents but is relatively low in nutrient load.
The influence of the present hydrological conditions on the wetland vegetations in the Naardermeer is uncertain. Therefore, a study was made of the influence of the surrounding area on hydrological attributes and the impact of these attributes on the distribution of plant species in the Naardermeer. Insight in these relations will form the basis for hydrological management inside and outside the polder.

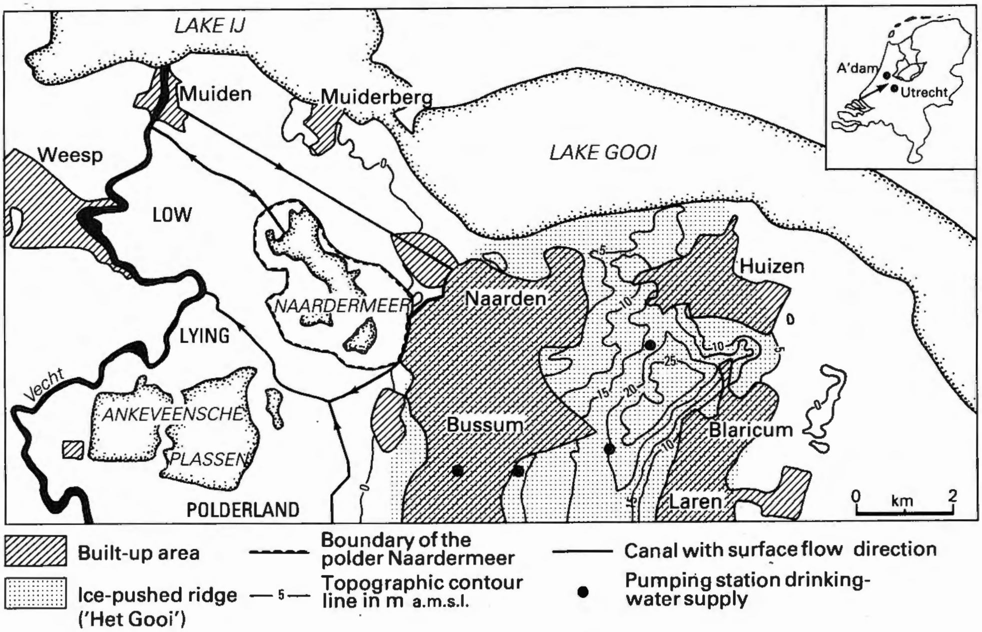


Fig. 1. *Location of the polder Naardermeer.*

CHARACTERISTICS OF THE AREA UNDER INVESTIGATION

The Naardermeer is located 15 km southeast of the city of Amsterdam (Fig. 1). The 7 km^2 area is topographically flat with elevation ranging from M.S.L. - 0.3 m in the east to about M.S.L. -0.8 m in the central and western part. It consists mainly of lakes, ditches and marshes fringed by woodland. The most eastern part is used as pasture.

To the east the Naardermeer is bordered by the region of Het Gooi. This ice-pushed ridge ranges in elevation form 0 to 30 m above M.S.L. and land use is mainly composed of built-up areas, heath and forests. To the north, south and west the Naardermeer is bordered by agricultural polderland ranging in elevation from about - 0.7 m in the east to - 1.4 m in the west near the river Vecht.

The region Het Gooi consists mainly of unconsolidated Pleistocene fluvial sands and gravel which form an unconfined aquifer of 150-200 m thickness. To the west of Het Gooi this aquifer is covered by relatively thin Pleistocene and Holocene deposits. Geological information regarding the Naardermeer

was obtained during the drilling for the groundwater observation network. A semi-confining layer of clay and peat deposits is found increasing in thickness from 0.5 m in the east at the edge of the pastureland to about 2 - 3 m in the western part. In the east fine eolian sands lie at the surface. This layer of about 4 m thickness lies on top of coarse fluvioglacial sands which are known to be less than 15 m thick. Both Pleistocene layers dip to the west and are found below the Holocene clay and peat deposits in the rest of the Naardermeer.
Because of its high elevation, Het Gooi is a regional infiltration area with relatively high groundwater levels up to 2 m above M.S.L. This results in a continuous flow of groundwater from the infiltration area to the low-lying polderland in the west. Part of this groundwater replenishes the Naardermeer through seepage.

METHODS

Data on the hydrogeological conditions in the Naardermeer were obtained by establishing a network of 35 groundwater observation points inside and partly upstream of the Naardermeer. At each point a cluster of three or four PVC-pipes was placed with filters at dephts between 0.5 and 8 m below the surface. Filter depths depend on water depth and maximum depth reached with the applied hand-held suction drill. Filter lengths range from 0.1 to 0.5 m. From October 1985 until November 1986 each month water levels were recorded and water was sampled in each of the groundwater pipes. In addition surface water samples were taken at a number of places. From the water sampled 27 parameters were determined, including temperature, electro-conductivity (EC), pH, major ions, nutrients and several trace elements. The interpretations in this paper also take into account surface water levels in and groundwater levels around the Naardermeer as recorded by others.
Insight in solute transport was obtained by comparing flow pattern with water quality. The vertical groundwater flow pattern has been simulated using a stationary two-dimensional finite difference groundwater model which calculates and plots equipotential and flow lines in a vertical inhomogeneous anisotrophic section.
To establish the relation between abiotic environmental factors and the occurrence of plant species, a total of 44 groundwater pipes with filters at 0.5 m below the surface were added to the groundwater observation network. The groundwater pipes were placed in a random pattern in the Naardermeer. Water levels were recorded and water samples were taken from these pipes in March, July and October 1986. The water samples were

analysed for the parameters mentioned above. Data on plant species were recorded according to Tansley (1926) within a two meter radius around all 0.5 m pipes. Additional information on the distribution of plant species was obtained by a survey on acre-scale by the authors, supplemented by data from Provinciale Waterstaat Noord-Holland (1985).
The presence of plant species was plotted on maps to study their spatial distribution. The observations of plant species around the groundwaterpipes were clustered using an average linkage cluster analysis. For each cluster, average values were calculated of water quality parameters and water level below the surface. Differences in these abiotic parameters between clusters were evaluated using Student's t-test ($p < 0.05$).

RESULTS

Influence of the surrounding area on hydrology

Quantity

Fig. 2 shows a groundwater level contour map. This map is based on monthly groundwater levels in the Pleistocene sand aquifer averaged over the one-year period October 1985 - October 1986. Groundwater levels in the Naardermeer range from M.S.L. - 0.65 m in the east to - 1.40 m in the west. Groundwater flow is directed roughly from east to west.
In the east groundwater is phreatic and the water level contours follow the topographic contour of Het Gooi. In the southern part of the Naardermeer the flow lines change direction from west to southwest. North of the railway there is a groundwater divide in the Grote Meer directed southeast-northwest. Flow lines are directed away from the divide to the southwest, west, north and even northeast.
In Fig. 3b the vertical groundwater flow pattern along section P-P' (Fig. 2) is given. The vertical flow pattern is based on computer simulations using the finite difference groundwater model FLOWNET (Van Elburg et al., 1986). To include groundwater quality only the uppermost 10 meters of the aquifer are shown. Due to the vertical exaggeration (about 30*) in Fig. 3b the flow lines are directed almost completely vertical. However, to get a more suggestive illustration the flow directions have been drawn somewhat schematically.
The vertical components of groundwater flow in the Naardermeer are determined by differences in groundwater and surface water levels. This is illustrated schematically in Fig. 3a. In Het Gooi infiltration takes place. Between Het Gooi and the Naardermeer there is a canal called Karnemelksloot. Its relatively high water level of M.S.L. - 0.3 m results in infiltration to the underlying groundwater. The groundwater level in the

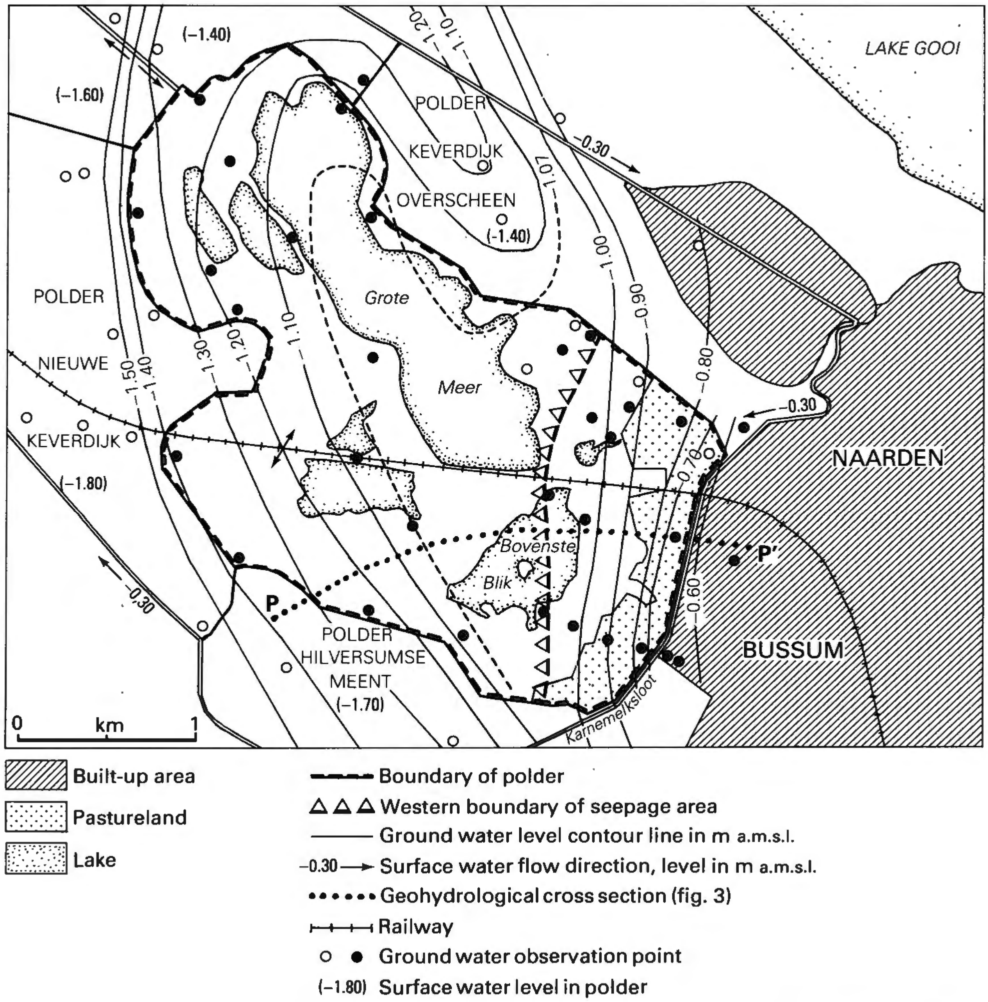


Fig. 2. ***Groundwater level contour map of the Pleistocene sand aquifer. Levels are averaged over the one-year period Oct. '85 - Oct. '86.***

eastern part of the Naardermeer is determined by the phreatic level in Het Gooi. The positive difference between groundwater level and the surface water level of the Naardermeer results in upward seepage in this part of the Naardermeer. During the period October 1985 - October 1986 the average surface water level was M.S.L. - 1.04 m. Consequently the average

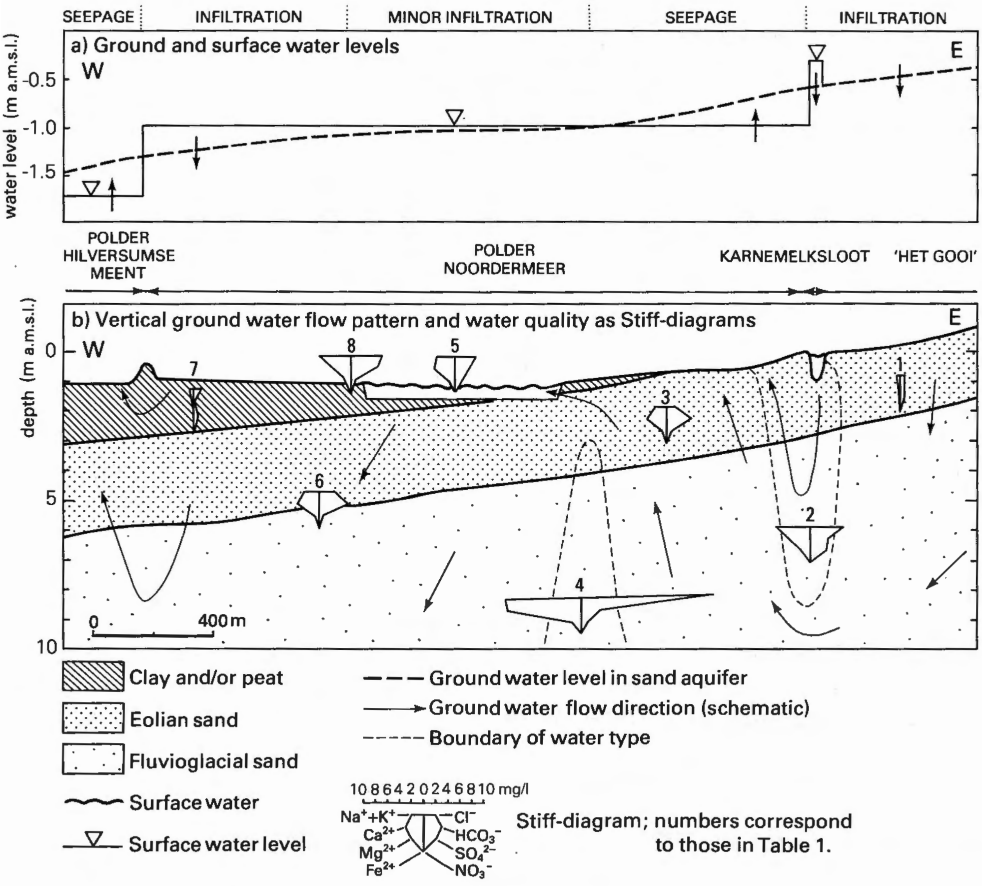


Fig. 3. *Geohydrological cross section P-P'.*

boundary of the seepage area is given by the groundwater level contour of -1.04 m. The location of this contour roughly coincides with the eastern edge of the area with surface water (Fig. 2). This indicates that groundwater levels at the western side of the seepage area are to a large extent controlled by surface water levels. This is also apparent from Figs. 2 and 3a where in the area with lakes the levels of groundwater and surface water are equal. As a consequence small changes in either groundwater level (upward) or surface water level (downward) in this area can easily result in a change in the direction of the vertical flow component. For that reason in some months the boundary of the seepage area is found considerably more

to the west, especially in the Grote Meer. In general, with a relatively constant surface water level and groundwater levels in winter higher than in summer, the seepage area can be expected to enlarge in winter and contract in summer. In practice, however, deviations from this general rule are found. In the western part of the Naardermeer the piezometric levels are lowered due to the relatively low surface water levels in the adjacent polders (up to 0.8 m lower in the Polder Nieuwe Keverdijk). In this area infiltration of surface water and precipitation excess will take place. Infiltration is also clear from the difference in phreatic and piezometric water level (up to 0.37 m) measured at the western groundwater observation points. These water level differences result from the vertical flow resistance of the Holocene clay and peat deposits in this area. In the sandy seepage area vertical flow resistances are so low that water level differences are too small for accurate measurement.
The net results of seepage and infiltration can be evaluated using a water balance:

$$P + Su + Se = E + D + I + \delta St$$

where:
- P = precipitation
- Su = suppletion of external surface water
- Se = seepage
- E = evapotranspiration
- D = discharge of surface water
- I = infiltration
- δSt = change in storage

For the period October 1985 - October 1986 the following values (in mm/year) were calculated:

$$751 + 251 + Se = 608 + 212 + I + 43$$

The net result of seepage and infiltration over the Naardermeer polder (Se - I) amounts to -139 mm/year or -0.4 mm/day. Accordingly, yearly infiltration in the western part exceeds seepage in the east. Values for net input calculated by Witteveen and Bos (1981) for the period 1969 - 1979 range from 0 to -0.25 mm/day. The larger input deficit resulting from our calculation is problably due to suppletion of surface water in the summer of 1986 leading to increased infiltration and decreased seepage. This effect was intensified by the dry summer of 1986 resulting in relatively low groundwater levels.

Quality

Groundwater quality is also influenced by the surrounding area. Groundwater quality in the seepage area is related to land use in the recharge area lying east of the Naardermeer. Infiltration induced by low water levels in the surrounding polders, results in groundwater quality resembling that of surface water or precipitation. This is illustrated in Fig. 3b in which water quality is visualised as Stiffdiagrams (Stiff, 1951) and related to the groundwater and surface water flow pattern in the Naardermeer. In Table 1 some characteristic water quality parameters of these watertypes are listed. The numbers between brackets in the text below correspond to those of the watertypes in Fig. 3b and Table 1.
Infiltration of precipitation in Het Gooi results in a relatively low dissolved solids content of groundwater (1). As most of the recharge takes place in the urban areas of Bussum and Naarden (Fig. 1), the infiltration water can be polluted locally. The Karnemelksloot contains water from lake IJmeer in

Table 1. Characteristics of groundwater and surface water quality in the Naardermeer.

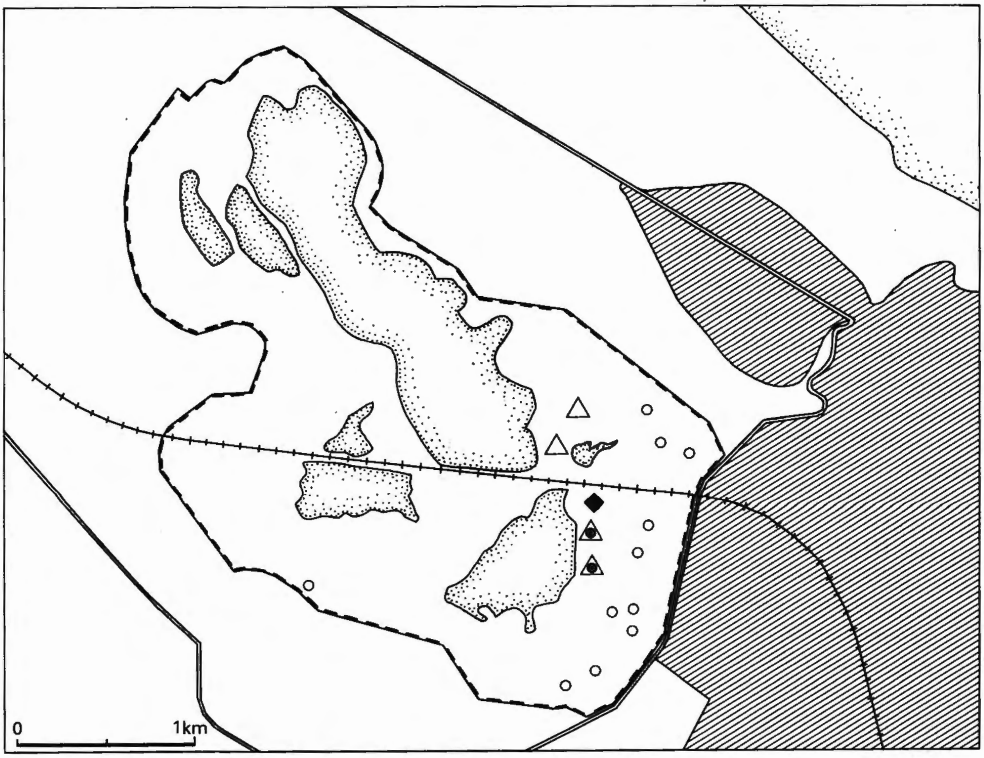
	1	2	3	4	5	6	7	8
EC	300	1000	500	2000	625	660	170	820
pH	<5.5	7.0	7.0	7.5	8.2	7.0	4.1	5.9
Cl	20	190	55	750	120	95	30	180
SO_4	20	120	35	50	50	15	35	30
HCO_3	30	175	260	190	150	310	0	250
Ca	15	70	65	240	65	80	7	55
NO_3	2	6	1	<1	<1	1	<1	<1
NH_4	<1	8	1	<1	<1	4	4	<1
PO_4	0.1	4.7	0.2	0.1	<0.1	0.4	0.7	0.1

Column numbers correspond to those in Fig. 3b. Concentrations in mg/l, EC in µS/cm.
1= infiltration of precipitation in Het Gooi
2= infiltration of surface water in the Karnemelksloot
3= seepage of fresh groundwater in the Naardermeer
4= seepage of brackish groundwater in the Naardermeeer
5= surface water from lake Bovenste Blik in the Naardermeer
6= infiltration of surface water from lake Bovenste Blik
7= infiltration of precipitation in the Naardermeer
8= infiltration of suppletion water from lake IJmeer

which up to September 1985 sewage effluent of Bussum and Naarden was discharged. Water high in salts and especially nutrients (2) infiltrates and is transported to the Naardermeer, where it seeps up in the most eastern part of the pastureland. The largest part of the seepage water, however, is of the calcium-bicarbonate type. It evolved from type (1) which has dissolved $CaCO_3$ on its way through the aquifer. The chloride, sulfate and nutrient contents are somewhat higher than those resulting from natural processes only, indicating the influence of human polution. Close to the western border of the seepage area brackish water (4) is found. In this area the deepest flow lines reach the surface bringing up the brackish water that underlies the whole Naardermeer, generally at a depth of some tens of meters. This seepage water is high in chloride and calcium and relatively low in sodium resulting from cation-exchange accompanying salt water intrusion.
As a result of seepage in the eastern part of the Naardermeer the total groundwater discharge to the west decreases. This leads to a strongly reduced groundwater slope under the lakes (Fig. 3a). Most water in this area will therefore be transported as surface water which has a much lower resistance to flow. Surface water (5) shows a chloride content of 120 mg/l which is the result of mixing of the different types of seepage water and precipitation. It is characterized by a high pH accompanied by a relatively low bicarbonate content. This is caused by CO_2 loss from the surface water, either to the atmosphere or through biological activity or caused by both. Precipitation of $CaCO_3$ appears to be unimportant as calcium content hardly diminishes.
In the western part of the Naardermeer infiltration takes place. During infiltration of surface water CO_2 and ammonium dissolve in water due to breakdown of organic material in the Holocene clay and peat layer (6). The uptake of CO_2 leads to lower pH and increased bi-carbonate content. The chloride content in (6) is somewhat lower than in (5). This is either caused by a relatively high chloride content in (5) due to the location of the sampling point near areas of brackish seepage or by a relatively low content in (6) due to mixing with precipitation. On the land areas infiltration of precipitation will result in low dissolved solids content and pH (low pH also due to organic acids) and relatively high ammonium and phosphate contents (7). During the summer of 1986 this type of water was in some places replaced by suppletion water from lake IJmeer (8) percolating from the surface water into land areas.

Impact of hydrology on vegetation

The occurence of seepage and infiltration in the Naardermeer (Fig. 2) was compared with the spatial distribution of plant species.
Most species occur over the whole of the Naardermeer area. Examples of



● Carex diandra, Epipactis palustris, Valeriana dioica
◆ Carex lasiocarpa
○ Equisetum fluviatile
△ Salix repens

Fig. 4a. ***Distribution of a number of plant species which are restricted to the seepage area of the Naardermeer.***

these species are *Caltha palustris, Carex curta, Carex paniculata, Carex pseudocyperus, Dactylorhiza majalis, Juncus subnodulosus* and *Potamogeton lucens.*
The following plant species are restricted to the seepage area; *Carex diandra, Carex lasiocarpa, Epipactis palustris, Equisetum fluviatile, Potamogeton acutifolis, Potamogeton trichoides, Salix repens, Valeriana dioica* and *Veronica beccabunga*. In Fig. 4a a number of these species are shown.
Another group is restricted to the infiltration area: *Carex rostrata,*

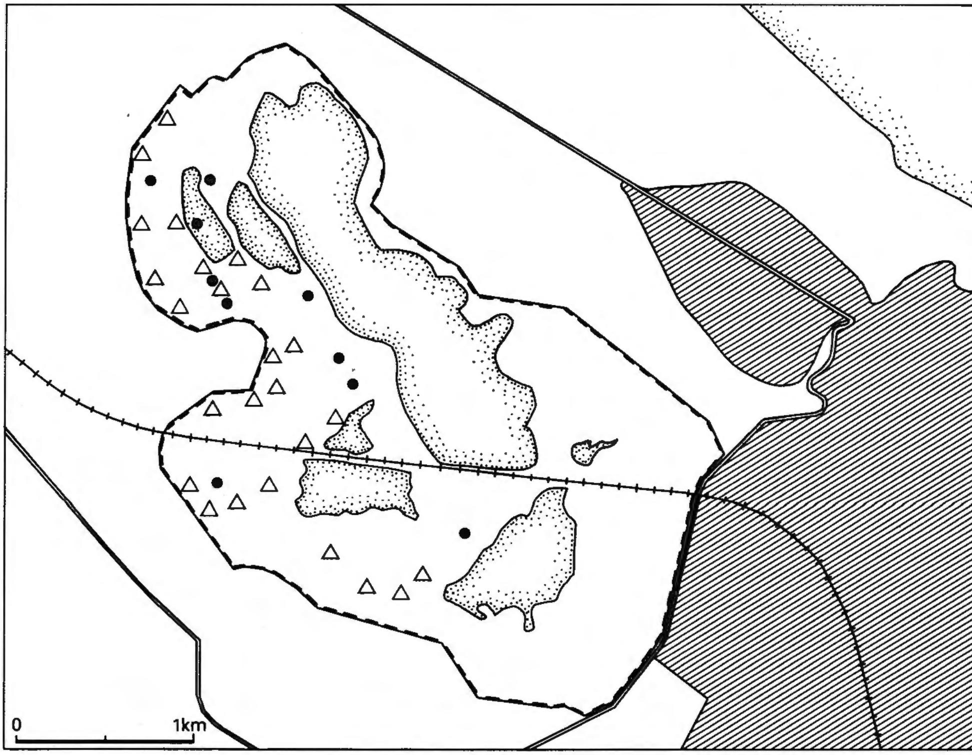


Fig. 4b. Distribution of a number of plant species which are restricted to the infiltration area of the Naardermeer.

Myriophyllum verticillatum, *Stratiotes aloides* and *Utricularia vulgaris*. The latter two species (Fig. 4b) are often found in areas with a sapropelium layer. Sapropelium in the Naardermeer was found to be restricted almost completely to the infiltration area, where accumulation of sapropelium on the bottom of lakes and ditches is favoured by the downward transport of water and by ciculation currents induced by the prevailing westerly winds.
To study the abiotic factors controlling the spatial distribution of plant species, a cluster analysis of the vegetation data was used. The analysis yielded three groups of species combinations: reedlands with e.g. *Thelypteris palustris* (A), reedlands with e.g. *Sphagnum flexuosum* (B) and woodland (C). The *Thelypteris* reedlands can be divided into two subgroups:

one with (A1) and one without (A2) species of *Calthion palustris* and *Cicuto-Caricetum pseudocyperi* (Westhoff & den Held, 1969). The first (A1) is a species-rich vegetation type. The reedlands with *Sphagnum flexuosum* (B) contain very few species. Frequent species in this type of reedland are *Carex curta*, *Drosera rotundifolia*, *Eriophorum augustifolium* and *Polytrichum commune (Caricion curto-nigrae)*. The woodlands (C) belong to *Alnion glutinosae*.
For each cluster the mean values of abiotic parameters were calculated. The waterlevels in the reedlands (A and B) do not differ and are constantly higher than those in the woodlands. Water quality in the *Thelypteris*-reedlands differs from that in the *Sphagnum*-reedlands and woodlands. Calcium and bicarbonate content, pH, EC and Ionic Ratio (Van Wirdum, 1980) are higher and potasssium content is significantly lower in the *Thelypteris*-reedlands (A). The differences between the *Sphagnum*-reedlands and the woodlands are small; only chloride and ammonium content are significantly higher in the woodlands. The subgroups A1 and A2 of the *Thelypteris*-reedlands show no differences in water level or water quality.
The results show a clear relationship between hydrological factors and the occurrence of plant species in the Naardermeer. The woodlands are relatively dry and found in a zone which surrounds the lakes and reedlands. The *Sphagnum*-reedlands (B) are mainly supplied by rain water. They are distributed in a random pattern over the Naardermeer as they are not dependent on groundwater or surface water. The *Thelypteris*-reedlands (A) are related to calcium and bicarbonate rich water. The occurrence of subgroup A1 is restricted to the seepage area. In this area the species of A1 are supplied by groundwater of the calcium-bicarbonate type (Fig. 3b, Table 1). Subgroup A2 occurs in the seepage area and on places in the infiltration area, where surface water can reach the plant-species. Groundwater from the seepage area flows to the infiltration area as surface water (Fig. 3b). In this way species of subgroup A2 can also be fed by (surface) water rich in calcium and bicarbonate.

DISCUSSION

The great number of species of mesotrophic and eutrophic wetlands present in the Naardermeer shows the ecological value of the Naardermeer. Vegetation types A1 and A2 occur in places with water rich in calcium and bicarbonate. This type of water is supplied by seepage of groundwater, either directly in the eastern part of the Naardermeer or indirectly by flow of surface water from the seepage area into the infiltration area. Moreover, seepage of groundwater is important to prevent the spread of suppletion

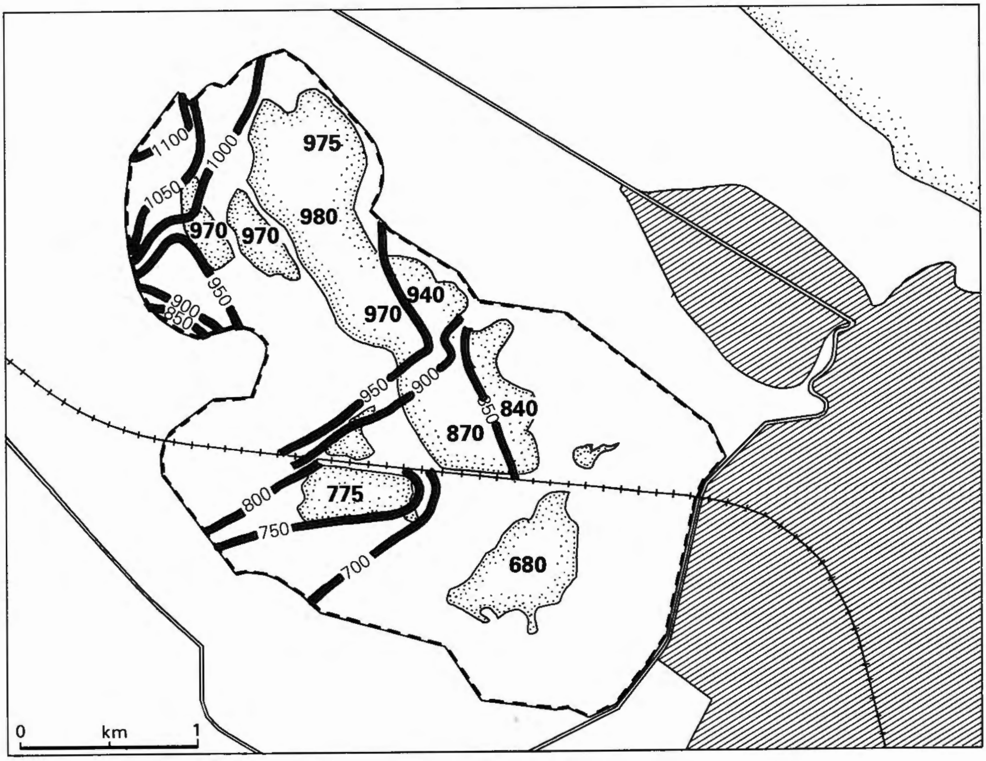


Fig. 5. Electrical Conductivity of surface water in the Naardermeer after a summer with suppletion (Sept. 1986). EC in μS/cm (25°C).

water over the whole of the Naardermeer as most of the species present respond negatively to IJmeer water (Wassen, et al., 1986). At present the spread of the suppletion water is mainly restricted to the northwestern part of the Naardermeer, even after the dry summer of 1986 (Fig. 5). The most southern influence is found near the passage of surface water underneath the railway (arrows in Fig. 5).

Preservation or improvement of the botanic values of the wetland Naardermeer is strongly related to hydrological factors. Especially seepage of groundwater is found to be important. Measures to increase seepage may comprise lowering of the surface water level in the Naardermeer. However, this would lead to adverse effects as the reedlands depend on high water levels. Moreover, mineralisation of organic material would lead to increased

availability of nutrients which is considered undesirable.
As hydrology in the Naardermeer is influenced by the surrounding area, management of the nature reserve must not be restricted to the polder itself. Measures outside the polder must be directed towards increased groundwater levels around the Naardermeer. In the provincial groundwater managementplan (Provinciaal Bestuur Noord-Holland, 1986) measures have already been formulated to increase the flow of groundwater from Het Gooi. Amongst others, these measures comprise the closing down of pumping station Bussum (about 4 km southwest of the Naardermeer) before 1990 and a reduction of total groundwater extraction from Het Gooi by 50%.

CHAPTER 3

GROUNDWATER SYSTEMS ANALYSIS OF THE NAARDERMEER WETLAND, THE NETHERLANDS

P.P. Schot

(In: Simpson, E.S. & J.M. Sharp, eds. (1990), Selected papers from the 28th International Geological Congress, Washington, 1989. Hannover: IAH Selected papers on Hydrology, Volume 1, pp. 257-269).

ABSTRACT

A large number of wetland nature reserves are present on the Vecht river plain in the Central Netherlands. Mesotrophic plant communities in these wetlands are threatened due to a.o. groundwater extraction in the adjacent recharge area and drainage in the river plain.
A groundwater systems analysis was carried out in order to formulate measures towards conservation and restoration of the wetland ecosystems. Use was made of:

1. *a computer model to calculate groundwater flow lines*
2. *data on groundwater composition to determine groundwater origin and the spatial distribution of solutes*
3. *environmental isotopes to determine groundwater origin and groundwater age*

This paper presents a case-study of the Naardermeer wetland. Five groundwater systems are distinguished which make clear the relation between quantity and quality of groundwater. Moreover, they enable evaluation of the effects of hydrological changes on the wetland and provide a basis for impact assesment of groundwater pollution.

INTRODUCTION

The Vecht river plain is located in the Central Netherlands between Amsterdam and Utrecht. It contains a large number of wetlands of which several have been designated as nature reserves (Fig. 1). An essential part of the flow of water and solutes in the wetlands occurs through inflow and outflow of groundwater. Most groundwater is recharged in the sandy ridge east of the river plain.
Over the last few decades the supply of groundwater has decreased as a

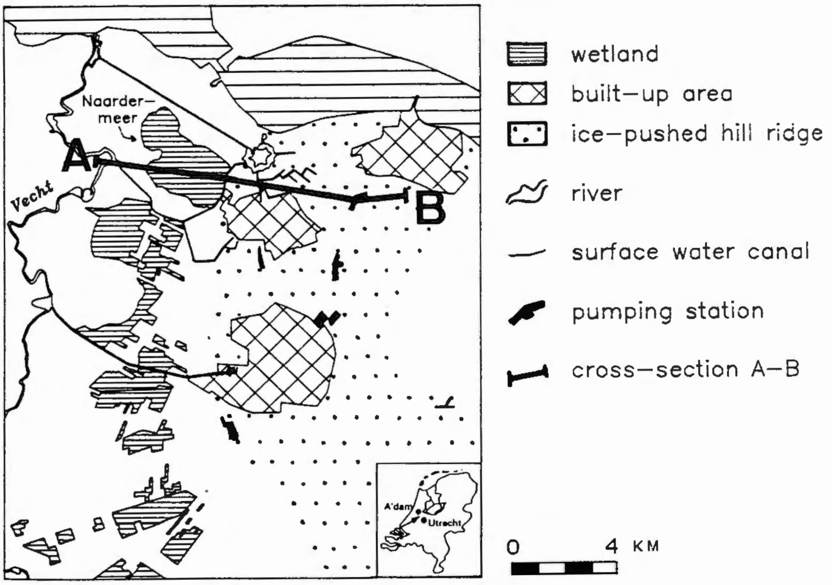


Fig. 1. Location of wetlands on the Vecht river plain.

result of groundwater extraction from the ridge for industrial and drinking water supply (Witmer, 1986). Besides, human activities in urban areas on the ridge pose a threat to groundwater quality (Janssen & Verkroost, 1989). Artificial drainage of the river plain for agricultural purposes constitutes an additional problem.

Decreased seepage along with drainage in the river plain result in water deficits in the wetlands during dry summer periods. These deficits are compensated by suppletion of surface water from the Vecht river. This polluted, eutrophic water has negative effects on the occurence of mesotrophic plant species in the wetlands (Barendregt et al., 1985). Mesotrophic water is provided primarily by seepage flow of groundwater (Provinciaal Bestuur van Noord-Holland, 1986; De Smidt et al., 1986). Management directed towards preservation and restoration of mesotrophic wetland ecosystems must therefore take into account the role of groundwater. A hydrological framework is needed to formulate adequate measures. For this purpose a regional groundwater systems analysis was carried out (Schot, 1989). It describes the flow of groundwater and solutes to and from the mesotrophic wetland ecosystems in the river plain. In this paper a case-study of the Naardermeer wetland is presented.

METHODS

The following methods were employed in the regional groundwater systems analysis to describe the transport of groundwater and solutes:

1) Two-dimensional computer simulation of groundwater flow lines.
   The groundwater model FLOWNET was used to calculate and plot flow lines for a vertical inhomogeneous anisotropic section of the subsoil. The vertical groundwater flow pattern is of particular importance as it shows the connection between recharge areas and discharge areas. Input consists of hydraulic head data along upper, lower, left and right boundaries and allocation of horizontal and vertical permeabilities to each cell. Details of FLOWNET are given by Van Elburg & Engelen (1986).
2) Chemical analysis of groundwater and surface water.
   Chemical analysis of groundwater is necessary to determine the spatial distribution of solutes in groundwater. Changes in solute concentrations in the direction of flow may reflect hydrochemical processes. In addition, the chemical composition of groundwater was used as a tracer of recharge areas.
3) Isotope analysis of groundwater and surface water.
   Oxygen-18 and deuterium were used to trace infiltration of surface water and mixing of waters of different origin. Tritium and carbon-14 were used to determine groundwater age. Finally, carbon-13 provided information concerning hydrochemical processes.

Each method has its own specific use in the determination of solute transport by groundwater flow. However, each in itself does not contribute the comprehensive information necessary to fully describe this complex process. The best results are obtained from an integrated approach (e.g. Hendry et al., 1983) in which the results of the separate methods are combined into an integral understanding of the problem. During recent years this integrated approach has been given a theoretical and systematic basis in the concept of groundwater systems analysis (Engelen and Jones, 1986). A groundwater system may be defined as a coherent unit of groundwater and earth materials in space and time, natural or influenced by man. Groundwater systems connect recharge areas with discharge areas.
The specific use of each of the methods in the analysis of flow systems is illustrated through cross-sections of the wetland Naardermeer which show a number of the variables mentioned above. The results are integrated to delineate groundwater systems which are used to evaluate the effects of hydrological changes and groundwater pollution.

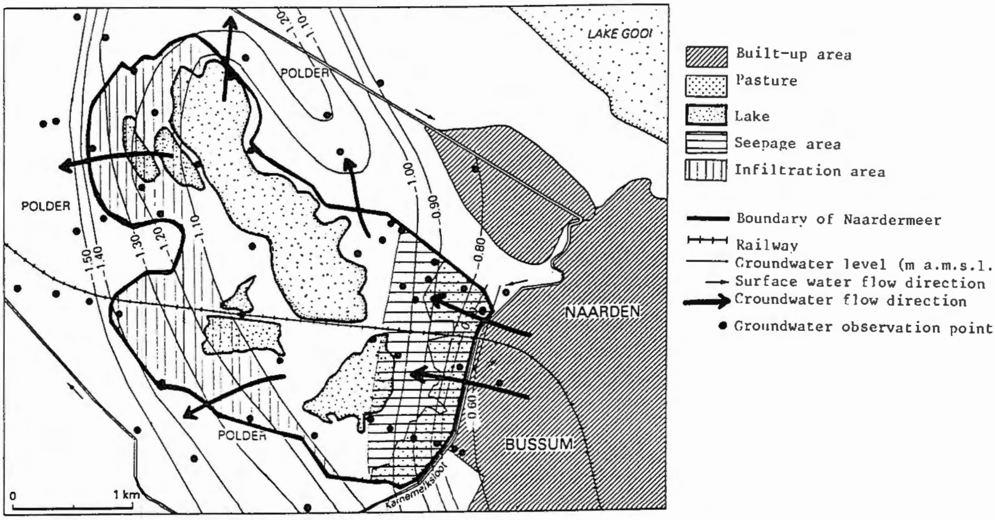


Fig. 2. Groundwater level contour map for the Pleistocene aquifer (average levels Oct.'85-Oct.'86).

DESCRIPTION OF THE NAARDERMEER AREA

The Naardermeer is located 15 km southeast of the city of Amsterdam (Fig.1). It consists mainly of lakes, ditches and marshes fringed by woodland. In 1906 the Naardermeer became the first nature reserve in the Netherlands. It is famous as a bird sanctuary but it is also of botanical importance and has been put on the list of international important wetlands (Ramsar Convention).

The 7 km² wetland is topographically flat with an elevation of about -0.8 m above mean sea level (a.m.s.l.). To the east the Naardermeer is bordered by the region of Het Gooi ranging in elevation from 0 to 30 m a.m.s.l. This ice-pushed ridge consists mainly of unconsolidated Pleistocene fluvial sands and gravel which form an unconfined aquifer of 150-200 m thickness. In the Naardermeer area west of the ridge this aquifer is covered by Pleistocene coarse fluvioglacial sands with a maximum thickness of 15 m and fine eolian sands of about 4 m. On top, a semi-confining layer of Holocene peat and clay deposits is found, increasing in thickness from 0 m in the east to about 2-3 m in the west of the Naardermeer.

The Naardermeer and surrounding agricultural areas are polders with artificially controlled surface water levels.

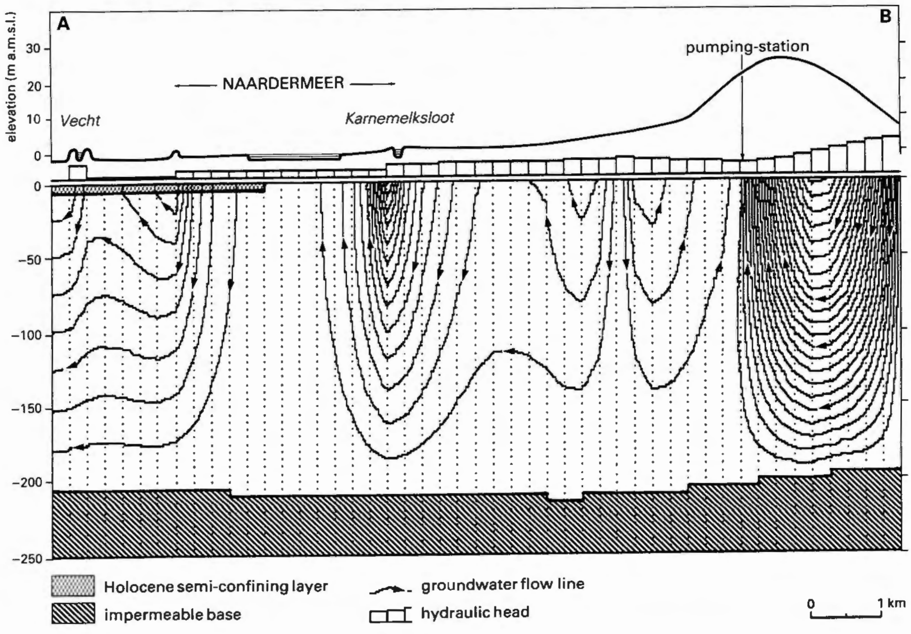


Fig. 3. Vertical groundwater flow pattern along cross-section A-B calculated by the program FLOWNET (average summer conditions).

RESULTS

Groundwater flow

Fig. 2 shows a groundwater level contour map for the Pleistocene sand aquifer. Groundwater flow is from the topographic high recharge area Het Gooi in the east to the Vecht river in the west. Seepage and infiltration areas can be derived from differences between phreatic (or surface) water level and piezometric groundwater level. In the Naardermeer seepage occurs in the eastern part, infiltration in the western part. In the central lakes-area surface water and piezometric water levels are more or less equal (Schot et al., 1988).

Fig. 3 shows preliminary results of the groundwater model along cross section A-B for September 1985 (average summer conditions). In the eastern part of the ridge infiltration water is transported towards the wells of the Huizen groundwater extraction. Somewhat to the west a low topographic elevation causes upward groundwater flow under the town of Naarden. Vertical groundwater flow in the river plain is clearly determined by the artificially controlled surface water levels in the polders. Groundwater from the ridge flows upward in the eastern part of the Naardermeer. In the western part of the wetland infiltration occurs as a result of the lower surface water level downstream. This is also reflected in fig. 2 by horizontal groundwater flow directions within the Naardermeer towards the adjacent polders. The high surface water level of the Vecht river also results in infiltration.

The overall pattern of seepage and infiltration at the surface as calculated by the groundwater model compares well to that on existing maps which were compiled from differences in piezometric groundwater level and surface water level.

Groundwater quality

Chloride is considered nonreactive in most hydrogeological environments and may therefore be used as a tracer for various groundwater sources. Fig. 4 shows chloride concentrations along cross-section A-B. Note that depth in fig. 4 is only 70 m contrary to 250 m in fig. 3.

The ridge contains fresh groundwater which is discharged into the eastern part of the Naardermeer. The deep groundwater in the northern Vecht river plain is brackish as a result of Holocene marine transgressions with intrusions of salt water from the surface into the underlying fresh groundwater through density flow (Engelen, 1981). In the Naardermeer brackish water is found at the western edge of the seepage area where deep flow lines reach the surface. Chloride concentrations under the Karnemelksloot canal, under the lakes and ditches in the western Naardermeer and under the Vecht river reflect infiltration of surface water.
The observed trend in chloride concentrations can be used as a check on the vertical groundwater flow pattern in Fig. 3. The occurrence of low chloride concentrations in the eastern part of the Naardermeer is in agreement with the flow lines in the model, which indicate precipitation on the ridge as source of this groundwater. Chloride concentrations and flow lines also show corresponding infiltration depth of surface water from the Vecht which is in the order of 50-60 m. However, the flow lines in the western part of the Naardermeer show infiltration to depths of over 150 m, while chloride concentrations indicate infiltration depth at present is in the order of 20 m. This indicates that the boundary between the Naardermeer infiltration water

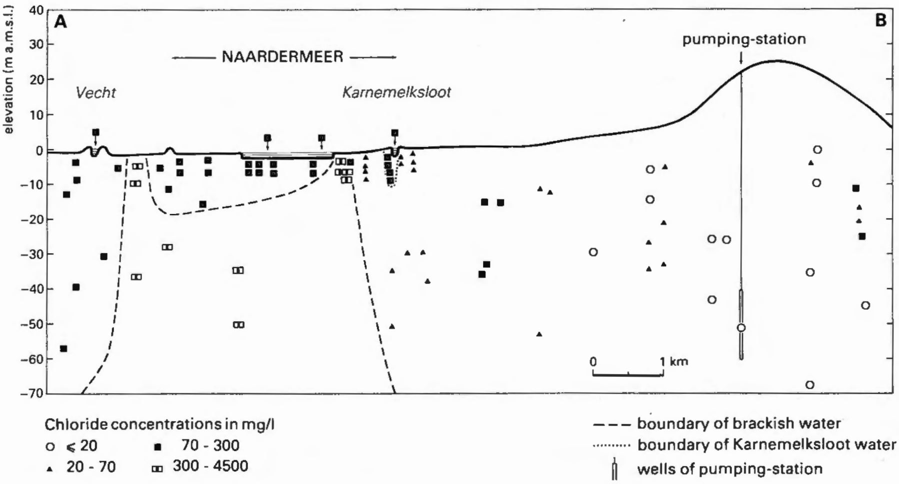


Fig. 4. Chloride concentrations along cross-section A-B.

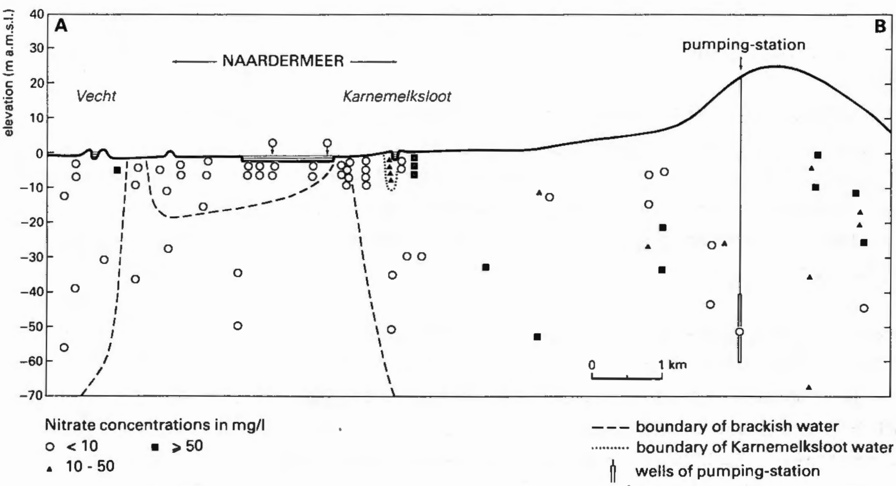


Fig. 5. Nitrate concentrations along cross-section A-B.

and the brackish groundwater is still moving downward and a stationary situation has not yet been reached.

Apart from the use as a tracer of groundwater flow, chloride may also indicate groundwater pollution. Concentrations in groundwater recharge by precipitation are below 20 mg/l (Leeflang, 1938; KNMI/RIVM, 1987; Schot,

1989).
Higher concentrations in groundwater in the ridge (Fig. 4) indicate pollution by human activities, mainly in urban areas (through cesspools, leaky sewerage, etc.). Pollution is also reflected by nitrate concentrations (Fig. 5). Groundwater from the ridge shows concentrations clearly in excess of natural values which are below 10 mg/l (Schot, 1989). A considerable amount of samples show concentrations which even exceed drinking water standards (50 mg/l NO_3-).

Groundwater isotopes

In geohydrology stable isotopes, especially oxygen-18, are used to study problems related to the origin of waters. In general oxygen-18 values of groundwater reflect those of precipitation in the recharge area. Deviating values may originate from mixing with water of different isotopic composition or from evaporation. Evaporation tends to concentrate the heavier water molecules, containing oxygen-18, in the remaining water. Evaporation occurs mainly from surface water present in lakes, pools and ditches in the river plain.

Radioactive isotopes like tritium are used to study groundwater age. Tritium concentrations of groundwater decrease in time due to radioactive decay. This makes it possible to use tritium for (relative) age determination. Generally a distinction is possible between relatively old groundwater and groundwater which has a component of precipitation which infiltrated during the last 30 years.

In fig.6 oxygen-18 concentrations along cross-section A-B are shown. In the ridge $\delta^{18}O$ values vary from -7.7 to -7.2 ‰, which correspond to average values in precipitation in the study area (Mook, 1984). These values are also found in the area with seepage of fresh groundwater in the eastern part of the Naardermeer. Under the Karnemelksloot canal and in the central and western part of the Naardermeer $\delta^{18}O$ values reflect infiltration of surface water which has been subject to evaporation ($\delta^{18}O$ > -5.5 ‰). Upward seepage of Naardermeer infiltration water in the adjacent polder is reflected by the $\delta^{18}O$ value in the shallow well directly west of the Naardermeer. Groundwater under the Vecht river shows values comparable to those in the ridge and in precipitation. However, the groundwater model and the chloride concentrations indicate infiltration of surface water from the Vecht river. The major source of Vecht water is the Rhine river with a $\delta^{18}O$ value of -9.0 ‰ (Mook, 1984). The oxygen-18 concentrations under the Vecht river must therefore be interpreted as Rhine water enriched by evaporation.

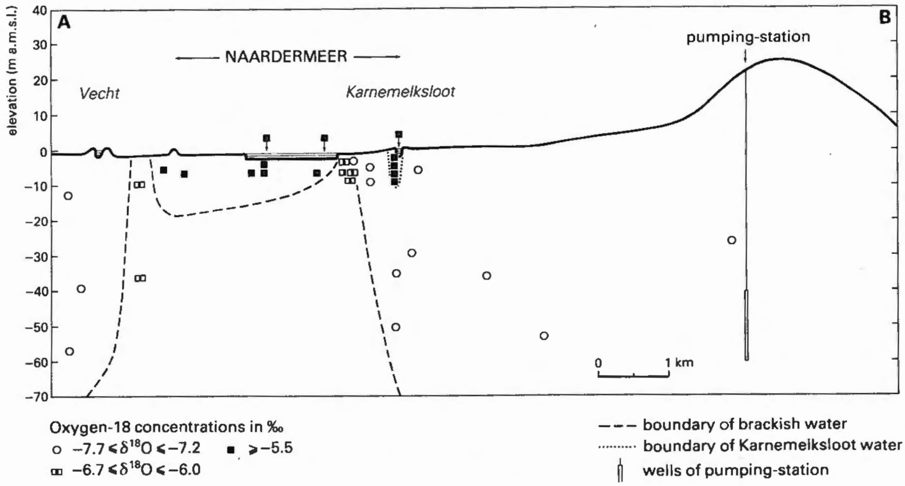


Fig. 6. Oxygen-18 concentrations along cross-section A-B. Concentrations are expressed as the deviation (δ) in parts per thousand from Standard Mean Ocean Water.

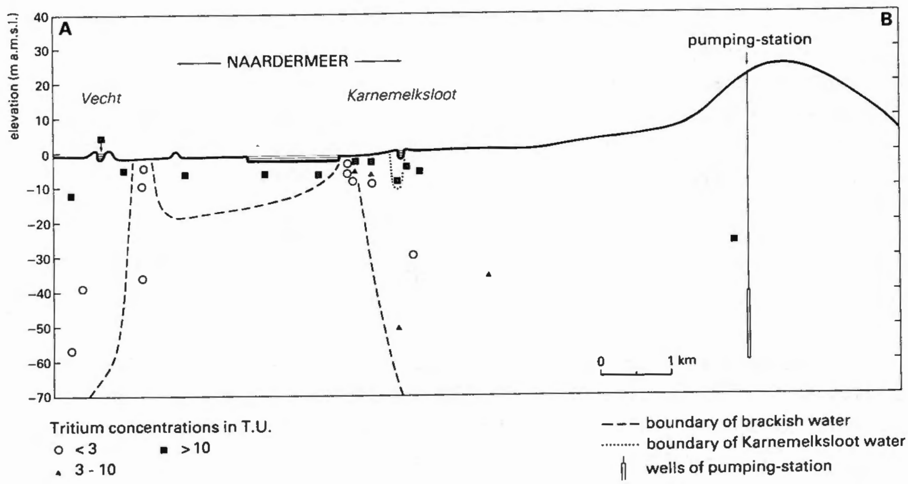


Fig. 7. Tritium concentrations along cross-section A-B. One Tritium Unit equals one tritium atom in 10^{18} atoms.

The corrected values range from -6.7 to -6.1 °/₀₀ indicating that the fresh groundwater component at the time had been subject to evaporation before infiltration.

The tritium concentrations of groundwater along cross-section A-B (Fig. 7) are subdivided in three groups:

- tritium values below 3 T.U. indicate relatively old groundwater which infiltrated at least 30 years ago (1 Tritium Unit equals 1 tritium atom in 10^{18} atoms),
- tritium values between 3 and 10 T.U. indicate mixing of old and young groundwater or groundwater of approximately 30 years,
- tritium values above 10 T.U. indicate relatively young groundwater recharged during the last 30 years.

Brackish groundwater shows the lowest tritium values in accordance with its middle Holocene origin. Water from the ridge shows increasing age on its way to the seepage area of the Naardermeer. Values in the shallow filters in the seepage area indicate mixing with recent, locally infiltrated precipitation. Tritium values under the Karnemelksloot canal, the central and western Naardermeer and Vecht river confirm recent infiltration of surface water.

Groundwater systems

Combination of the information from the foregoing sections makes it possible to delineate groundwater systems in the Naardermeer area (Fig. 8). The main groundwater systems and their characteristics are as follows.

1. ***The groundwater extraction system.*** Extraction from the ridge for drinking water supply is the driving force of this completely man-made system. In the east the system is bordered by the main regional groundwater divide, in the west it has created its own artificial groundwater divide.
2. ***The ridge system.*** This natural groundwater system originated from the topographic difference between the ridge and the low lying polderland. Infiltration water from the ridge is transported to the eastern part of the Naardermeer. The seepage water is of the calcium-bicarbonate type due to calcite dissolution in the groundwater on its way from the ridge to the wetland. On several places in the ridge the groundwater shows moderate to strong pollution. In the most western part of the seepage area in the Naardermeer the flow lines from the ridge system force old brackish groundwater to the surface.
3. ***The Karnemelksloot canal system.*** This small local groundwater system is induced by the hydraulic head difference between the surface water of the Karnemelksloot canal and the underlying groundwater of system 2. Water from the canal infiltrates and seeps up in the most eastern part of the Naardermeer. As the canal is partly supplied by effluent from a sewage purification plant, the groundwater from this system pollutes the wetland.

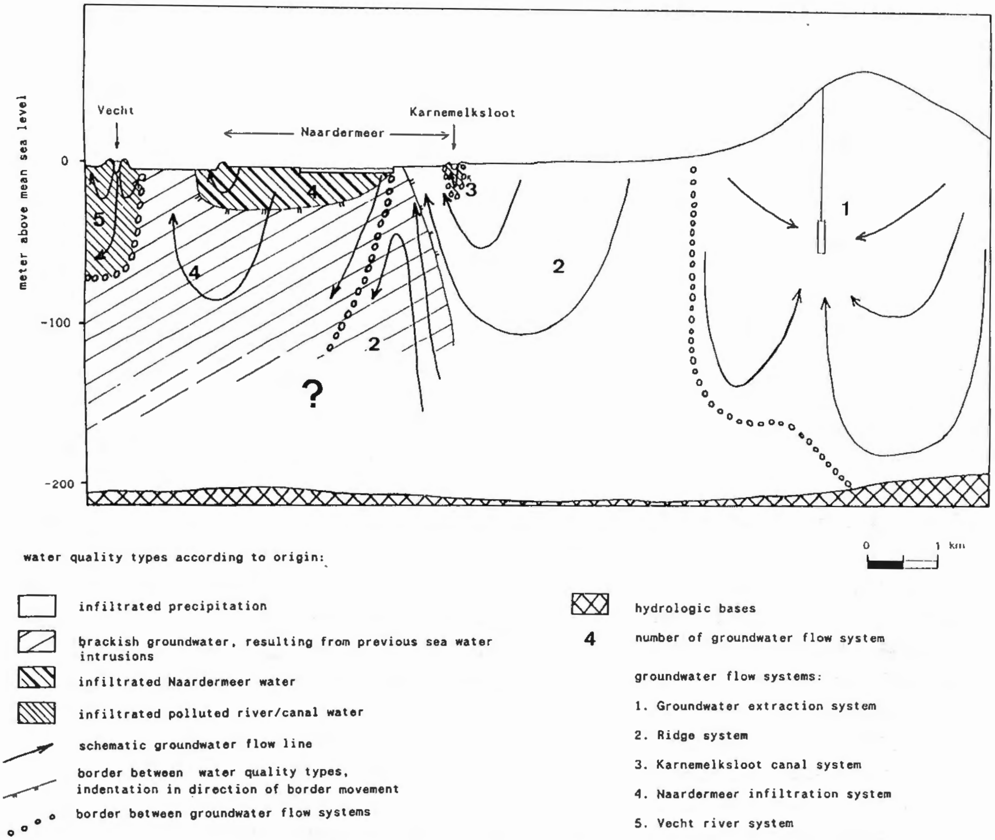


Fig. 8. Groundwater flow systems and water quality types along cross-section A-B.

4. ***The Naardermeer infiltration system.*** Seepage water from the east of the Naardermeer is transported further into the wetland by way of ditches. The difference in surface water level between the Naardermeer and the surrounding polders created a system of infiltration in the west of the Naardermeer wetland with subsequent seepage in the adjacent polders. Groundwater quality in this system is a mixture of local precipitation with seepage water from systems 2 and 3. The infiltration water from the Naardermeer replaces old brackish groundwater under the river plain. Part of this brackish groundwater is discharged in the polder west of the Naardermeer.

5. ***The Vecht river system.*** Water from the Vecht river infiltrates to a depth of about 60 m. This is the result of a large hydraulic head difference (about 1.5 m) between the river and the adjacent polder areas. Although chloride content of the Vecht river is about 200 mg/l, it is relatively low compared to chloride concentrations in the brackish groundwater system from which it is therefore easily distinguished.

DISCUSSION

The applied methods partly confirm each other by showing the same trends and partly they are supplemental. The numerical model provides information on groundwater flow systems in the Naardermeer area. The simulation results make clear the connection between recharge areas and discharge areas of groundwater. Contents of chloride, oxygen-18 and tritium in groundwater can be used as a rough check on the simulated groundwater flow patterns, but also provide additional information. Chloride concentrations confirm infiltration on the ridge and subsequent seepage of water from the ridge in the eastern part of the Naardermeer. Furthermore, the front between fresh and brackish groundwater in the Naardermeer infiltration system indicates that this system is relatively young, as fresh water has not yet fully replaced the old brackish groundwater. Oxygen-18 values confirm infiltration of surface water from the Karnemelksloot, the Naardermeer and the Vecht river. Trends in tritium values agree with those displayed by the other methods. Moreover, they give an impression of groundwater age and indirectly of system scale. The groundwater flow systems and water quality types in fig. 8 present an overall view on the available information.

The groundwater systems analysis enables evaluation of the effects of hydrological changes. The original volume of the ridge system has decreased by the size of the groundwater extraction system. The effect of extraction is a reduced discharge of the ridge system into the Naardermeer. This effect is intensified by a decreased input to the ridge system through increased construction of sewerage in the urban areas upstream of the wetland (Janssen & Verkroost, 1989). As a result of decreased discharge the western boundary of the ridge system shifted eastward. This was compensated by the flow of brackish water up to ground surface at the western edge of the seepage area in the Naardermeer. Thus the groundwater systems enable an explanation of the seepage of brackish groundwater in the eastern part of the wetland. Chemical analyses of the brackish seepage water in the eastern part of the wetland confirm the foregoing hypothesis. High calcium and relatively low sodium contents point

to cation-exchange reactions, where sodium from the brackish groundwater replaced calcium from the adsorption complex of the soil (Schot et al., 1988). This indicates salination of a former fresh water aquifer (Geirnaert, 1973). Moreover, analyses of lake water near the seepage area show an increase in chloride content over the past decades (ZAG, 1986). This may be accounted for by the recent discharge of brackish groundwater in the eastern part of the Naardermeer.
The effect of the low surface water levels in the polders adjacent to the Naardermeer is reflected in the development of the Naardermeer infiltration system.

The groundwater systems provide a tool for impact assesment of groundwater pollution in the ridge. Groundwater pollution is evident from chloride and nitrate concentrations (Fig. 4 and 5) and from other parameters (Provinciale Waterstaat van Noord-Holland, 1985). Depending on their position in the hierarchy of flow systems, the pollutants will either discharge through the wells of the drinking water supply (system 1) or in the wetland (system 2). To determine the eventual concentrations in the discharge area of a groundwater system, the physical and chemical processes along the flow path need to be considered. Changes in solute concentrations especially are to be expected in organic layers, e.g. during seepage through organic debris on the bottom of lakes and ditches. Determination of hydrochemical processes which affect water quality in the wetlands on the river plain, is still in progress.

The hydrological changes discussed above affect the ecosystems of the Naardermeer. Changes in vegetation composition during the past hundred years were studied by Barendregt et al. (in prep.). Forty years ago plant species characteristic for mesotrophic wetland ecosystems were abundantly present in the seepage area of the Naardermeer (Meyer and de Wit, 1945). Recent vegetation relevees in the seepage area show that at present most of these species are absent in places with brackish groundwater and occur exclusively in areas with seepage of calcium bicarbonate groundwater (Wassen et al., 1989). It appears that the shift in groundwater systems is followed by changes in vegetations in the wetland Naardermeer.

Management which aims at the conservation and development of mesotrophic wetland ecosystems must focus primarily on the ridge groundwater system. In this respect the Groundwater Management Plan of the Province of Noord-Holland (Provinciaal Bestuur van Noord-Holland, 1986) provides a step in the right direction. It comprises a reduction of the extraction of groundwater from the ridge by 50%. This will restore the flow of groundwater from the ridge system which is favourable to the species of mesotrophic wetland ecosystems. Furthermore the boundary of the ridge system in the Naardermeer will move to the west forcing the brackish groundwater system downward, out of reach of the plant roots.

In addition measures may be recommended towards decreasing the volume of water lost through the Naardermeer infiltration system. The owner of the Naardermeer nature reserve has purchased land in the adjacent polders which opens possibilities to increase surface water levels surrounding the Naardermeer. Groundwater model calculations show that a reduction of water loss of 18 % in summer is possible with the proposed increases in polder water levels (Timmermans, 1988).

Both increase in seepage water and decrease of infiltration from the Naardermeer will reduce the need for supply of external polluted surface water during dry summer periods.

CHAPTER 4

REGIONAL CHANGES IN GROUNDWATER FLOW PATTERNS AND EFFECTS ON GROUNDWATER COMPOSITION

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ABSTRACT

Wetlands on the Vecht river plain in The Netherlands are threatened by pollution of groundwater on the adjacent ridge 'Het Gooi'. To asses the impact of this pollution, information is needed on the present groundwater flow pattern and hydrochemical processes occurring during flow. In the determination of hydrochemical processes past changes in flow patterns must be taken into consideration.

Over the past 600 years impoldering and groundwater extraction have induced important hydrological changes in the study area. Exercises with a two dimensional finite difference groundwater model were used to study the effects on regional groundwater flow patterns. Steady state simulations along a vertical section were carried out for four different points in time, viz. the 14th century, 1885, 1941 and 1985. Changes in flow patterns are inferred from a comparison of the steady state simulations. The results indicate that groundwater flow changed from a simple pattern under natural conditions to a complex flow pattern dominated by artificially man-controlled hydraulic heads at present.

The computer simulations are used to estimate the effect of changes in flow patterns on regional groundwater composition. Data on the distribution of chloride and oxygen-18 in groundwater provide a verification of the estimated effects and information on the present position of the fresh-brackish groundwater interface in the study area. Isochrones calculated by the model are used to estimate the position of this front where data on water composition are absent. The future displacement of the fresh-brackish groundwater front is inferred from the position of successive isochrones, assuming that the present flow pattern will remain in steady state.

The computer simulations provide a general framework for the determination of hydrochemical processes in future studies addressing the impact of groundwater pollution on wetlands in the river plain.

INTRODUCTION

Groundwater composition attracts increasing attention over the past several decades. This is caused primarily by the emergence of a large number of groundwater pollution problems which exist virtually all over the world. Predictions of the extent of groundwater pollution need to consider the present flow pattern and hydrochemical processes. Groundwater flow largely controls the transport of polluted water in the subsurface over time.
The flow pattern can be deduced from hydraulic head data, e.g. through the use of a numerical groundwater flow model. Hydrochemical processes which occur naturally in a region are generally deduced from the changes observed between the initial (unpolluted) groundwater composition in the recharge area and groundwater composition at various points along the present flow line.
Changes in flow patterns may connect discharge areas to new recharge areas that are characterized by groundwater with a different composition. Because groundwater flow is relatively slow, it may take considerable time before water from the new recharge area reaches the discharge area. Somewhere along the flow lines a front will exist marking groundwater originating from the old recharge area and groundwater originating from the new recharge area. Differences in groundwater composition along a flow line on both sides of such a front result from differences in infiltration water quality in the old and new recharge areas. These must not be misinterpreted as being due to hydrochemical processes in the aquifer. Fronts in water composition due to changes in flow patterns may be denoted as type-1 fronts, in order to distinguish them from type-2 fronts due to changes in recharge water composition in time in a particular recharge area and type-3 fronts due to hydrochemical processes (Schot, 1991).

Wetlands located on the Vecht river plain in The Netherlands are threatened by pollution of groundwater on the adjacent ridge 'Het Gooi'. To asses the impact of this pollution on the wetland ecosystems, information is needed on the present groundwater flow pattern and hydrochemical processes occurring during flow. It has been shown that groundwater flow patterns in the area have changed as an effect of human intervention, i.e. impoldering on the river plain and groundwater extraction on the ridge (Schot, 1990). Effects of changes in flow patterns on groundwater composition are expected when a change in recharge area has occured from the ridge to the river plain or vice versa.
The purpose of this paper is to obtain insight into the main changes in groundwater flow patterns which occurred in the Gooi and Vecht area over the past 600 years. The effects of these changes on groundwater

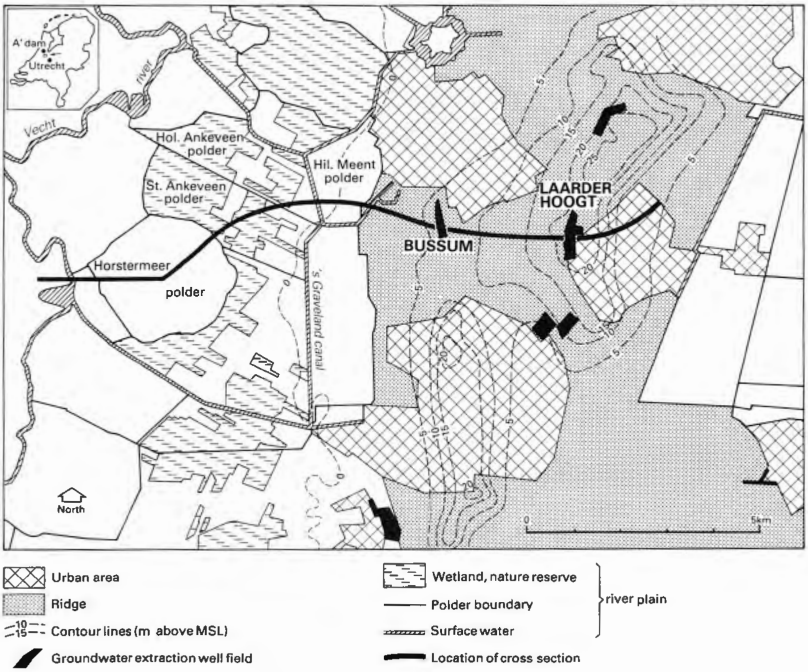

Fig. 1. Location of the study area

composition are evaluated in order to establish type-1 fronts. Knowledge on these fronts are of importance for the correct determination of hydrochemical processes in future studies addressing the impact of groundwater pollution on wetland ecosystems in the area.

DESCRIPTION OF THE STUDY AREA

The study area is located in the Central Netherlands (Fig.1). Its main topographic features are the sandy ice-thrusted hill ridge 'Het Gooi' and the adjacent plain of the Vecht river. Elevation ranges between 0 and +30 m NAP for the ridge and between 0 and -3 m NAP for the Vecht river plain (NAP: Dutch ordnance level as related to mean sealevel). Present landuse on the ridge consists of urban areas surrounded by woodland and heath. The river plain is mainly used for dairy farming. Besides, a large number of wetland nature reserves are present (Fig. 1).

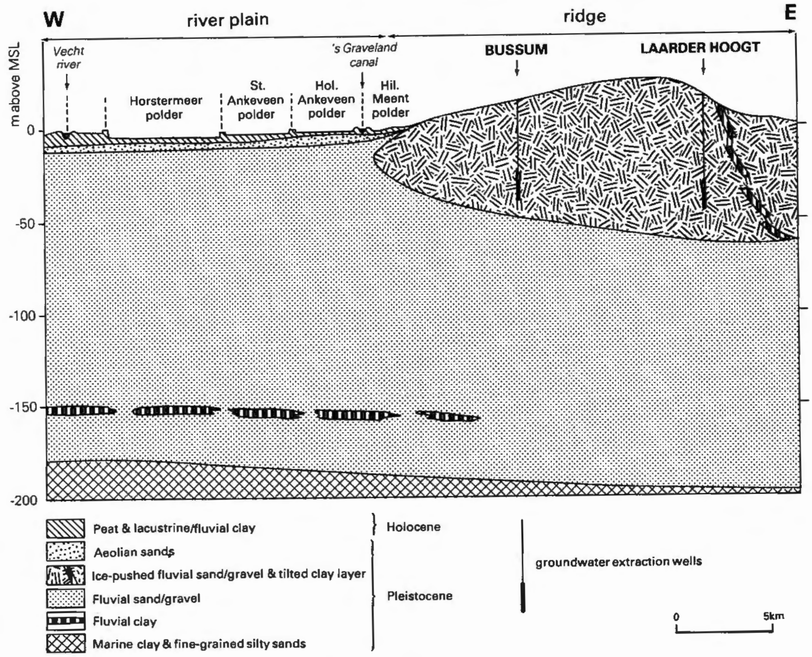

Fig. 2. Geological cross section of the study area (for location see Fig. 1)

Groundwater flows in sediments of Quarternary age. At a depth of -150 to -200 m NAP, early Pleistocene (Pretiglian) marine clays and fine-grained silty sands are found. These are generally considered as a no-flow boundary for groundwater in the study area (Witmer, 1989). Some 150 to 200 m fluvial sands and gravels were deposited on top of these marine sediments (Fig.2). At a depth of 150-160 m a discontinuous layer of clay is present which interfingers laterally with sand.
Ice contact formed a ridge in the upper part of the Pleistocene sands and gravels. Fluvioglacial and aeolian sands with thickness increasing from only 1-2 m at the flanks of the ridge to 15 m in the direction of the Vecht river were deposited on top of the preglacial fluvial sands and gravels in the river plain.
The Holocene sea level rise and the subsequent rise in groundwater levels led to peat growth in the Vecht river plain. These peat deposits are locally intercalated with fluvial or marine clays and form a semi-confining layer on top of the Pleistocene aquifer.

Natural groundwater flow is directed from the ridge towards the Vecht river

plain. From the twelfth century onward, the marshy river plain has increasingly been drained for agricultural purposes (Van Raam, 1979). Systems of connected ditches were dug to create polders in which the surface water level is artificially controlled by windmills, steam- or diesel engines or electrical pumps to discharge excess water. As a result of oxidation and mineralisation of the top peat layer, the ground surface continually subsided. To keep the polders drained, surface water levels also had to be lowered. The average reduction in polder water levels in the Vecht river plain from 1900 until the present has been 40 cm (Witmer, 1989).
A deep polder was created by reclamation of the natural lake Horstermeer in 1882. In this polder the water level is maintained at about -3.5 m NAP, which is about 1.5-2 m lower than in the surrounding polders. This low water level exerts a dominant effect on groundwater flow directions (Fig. 3c) and necessitates the discharge of about 30 * 10^6 m^3/year of water from the Horstermeer polder.
Groundwater extraction from the ridge for public drinking water supply started in 1888. Following the increase in population, groundwater extraction has steadily increased to a total of 15.6 * 10^6 m^3/year in 1988. In parts of the ridge groundwater levels have been lowered by more than 1 m over the past century (Fig. 3a-c).

Three main groundwater types are distinguished in the study area: groundwater recharged on the ridge, groundwater recharged on the river plain and brackish groundwater. Following Holocene marine transgressions seawater invaded the surface of the study area, mainly in the northwest. Through density flow from the surface the seawater entered the aquifer where it mixed with fresh groundwater (Engelen, 1981). As a result, part of the groundwater in the river plain is brackish.

GENERAL METHODOLOGY

Changes in regional groundwater flow patterns in the study area were deduced from exercises with the computercode FLOWNET (Van Elburg & Engelen, 1986). This two dimensional steady state groundwater model uses a finite difference appoach to calculate the potential function and stream function for a vertical, inhomogeneous, anisotropic section of the subsoil. The resulting coefficients matrices for both functions are solved using the Incomplete Choleski Conjugate Gradients (ICCG(0)) iterative method (Meijerink and Van der Vorst, 1977). Model input consists of effective porosity and horizontal and vertical permeability for each cell. Along the upper, lower, left and right boundaries of the model section, either constant

head or no-flow conditions need to be specified. The model does not simulate dispersion and diffusion.
Steady state computer simulations of groundwater flow were carried out for four different times, representing the most important hydrological changes over the past 600 years, i.e. impoldering and groundwater extraction:

- *14^{th} century; the natural groundwater flow pattern.*
  The Vecht river is without dikes, the Horstermeer is still a lake, there are no polders and there is no groundwater extraction from the ridge.
- *1885.*
  The Vecht river has been diked, the Horstermeer has been reclaimed and several other, less deep, polders have been created. Groundwater extraction on the ridge has not yet started.
- *1941.*
  Polder levels have been lowered by 10 to 45 cm since 1885 (Fig. 4). Groundwater extraction on the ridge is about 7 * 10^6 m^3/year, which is ca. 50 % of that in 1985.
- *1985; the present groundwater flow pattern.*
  Polder levels have been lowered by another 10 to 45 cm. Groundwater extraction on the ridge has increased to ca. 14 * 10^6 m^3/year.

The main changes in regional groundwater flow patterns over the past 600 years were evaluated by comparing the results of the simulations.

Initial calibration was carried out by permeability adjustments in the 14^{th} century simulation. Next, the 1985 flow pattern was simulated starting with the permeabilities from the 14^{th} century, which where then further calibrated. Known recharge and discharge patterns at the surface and groundwater discharge fluxes at the Laarderhoogt and Bussum extraction locations and in the Horstermeer polder were used as calibration criteria.
Verification was carried out with the 1941 hydraulic head distribution and the adjusted permeabilities from the 1985 simulation as input. The calculated discharges at the groundwater extraction locations and in the Horstermeer polder were compared to the actual discharges.
The sensitivity of the simulated flow patterns was analysed using realistic variations in model parameters as input.

The effect of changes in flow patterns on regional groundwater composition is estimated from the computer simulations. The changes in groundwater composition inferred from the computer simulations are compared to the distribution of chloride and oxygen-18 concentrations in groundwater along the modelled cross-section. These tracers provide a rough verification of the simulated flow patterns.
In addition, chloride and oxygen-18 concentrations have been used to give an indication of the present position of the fresh-brackish groundwater front

in the study area. To estimate the position of this type-1 front where data on water composition are absent, time steps were incorporated in the model and isochrones were calculated. Isochrones reflect the position of type-1 fronts in time when dispersion, diffusion and hydrochemical processes are left out of consideration. The future displacement of the fresh-brackish groundwater front is inferred from the position of successive isochrones, assuming that the present flow pattern will remain in steady state.

THE USE OF TRACERS FOR VERIFICATION OF FLOW PATTERNS

Different types of recharge areas in the study area are characterised by specific concentrations of chloride and oxygen-18. Because these parameters are not affected by hydrochemical processes in the aquifer they indicate the origin of the groundwater. Chloride and oxygen-18 can thus be used as a rough verification of groundwater flow patterns.
The ridge is recharged by precipitation mainly during winter months. Chloride contents in the precipitation excess are below 20 mg/l. Ridge groundwater shows mean $\delta^{18}O$ values of -7.5 °/₀₀ with maximum values below -7.2 °/₀₀ (Hettling, 1985; Schot, 1989).
In the river plain higher $\delta^{18}O$ values are observed in recharge water due to evaporation. This occurs mainly from surface water present in lakes, pools and canals and also to a lesser degree in peat and clay layers, where infiltration of precipitation is hampered by low permeability. Chloride content of surface water in the vicinity of the model section generally ranges between 60 and 110 mg/l (ZAG, 1986). These chloride concentrations are affected by suppletion of Vecht river water. The main source of Vecht water is the Rhine river which showed increasing chloride concentrations over the past century from about 30 mg/l to maximum values at present of about 300 mg/l. A $\delta^{18}O$ value of -8.7 °/₀₀ has been measured for the Vecht river (Hettling, 1985) which is comparable to that of the Rhine river (-9.0 °/₀₀; Mook, 1984).
The brackish groundwater shows chloride contents well over 300 mg/l, generally between 3000 and 4500 mg/l. All $\delta^{18}O$ values have been corrected for mixing with seawater ($\delta^{18}O \approx 0$ °/₀₀) using chloride content to determine the percentage of seawater present in the groundwater sample.
Information on the chloride content of groundwater in the study area was obtained from several sources, while $\delta^{18}O$ values were obtained from samples taken by the first author and from Van der Linden and Appelo (1988).

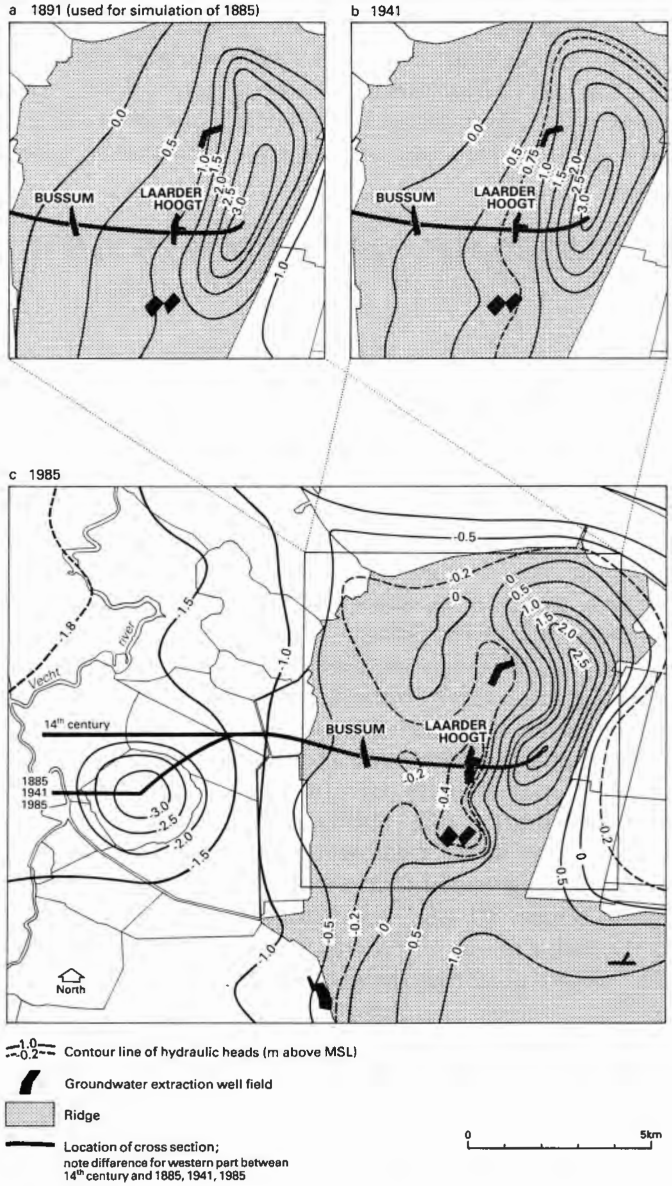

Fig. 3. Groundwater hydraulic heads in the Pleistocene aquifer for 1891, 1941 and 1985 (for sources: see text).

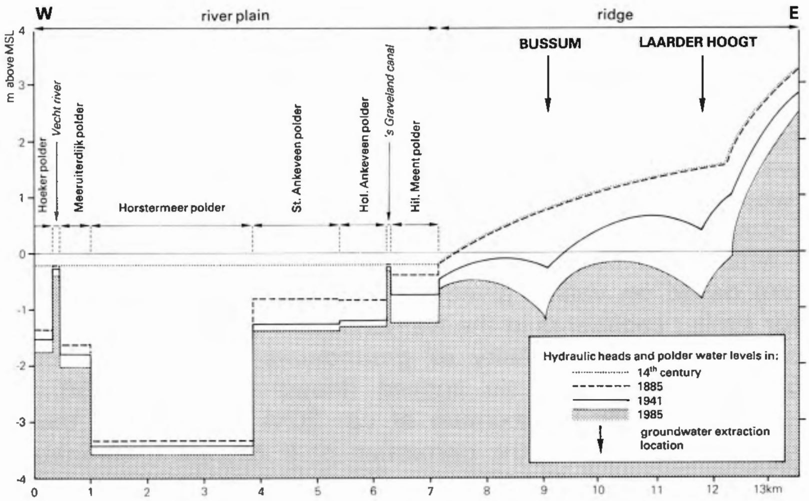

Fig. 4. Hydraulic heads and polder water levels along the model section for four points in time (for sources: see text).

MODEL CONSTRUCTION

Simulations were carried out for a section running from the ridge in the east towards the Vecht river in the west (Fig. 3). Its location was chosen in order to show the effects of the two major human interventions to natural groundwater flow patterns; viz. draining of the river plain, especially reclamation of the former lake Horstermeer, and the increasing extraction of groundwater from the ridge for public water supply during the past century. The section was taken parallel to the horizontal groundwater flow direction in 1985 in order to prevent difficulties arising from flow perpendicular to the section. This condition is approximately satisfied for all the simulated points in time, except for the most western part of the section in the 14th century as the Horstermeer was not yet reclaimed at that time. The western part of the section was therefore adapted for the 14th century simulation, assuming overall groundwater flow at the time was in an east-west direction (Fig. 3c). This has no effect on the comparison of groundwater flow patterns for the different points in time, because all waterlevels in the Vecht river plain in the 14th century were set at the same level.

Total section length is 13,500 m and total depth is 200 m. The groundwater model is comprised of 4320 cells divided into 270 columns of 50 m and 16

rows of 12.5 m. The number of columns and rows was chosen in such a way that the horizontal and vertical dimensions of the cells are approximately of the same order.
Horizontal permeabilities were obtained from a previous groundwater modelling study by Witmer (1989). To account for anisotropy a factor 10 (K_h/K_v) was taken for clays and peat. A factor 5 was taken for the fluvial sands, which are fairly homogeneous exept for some intercalated thin bedded discontinuous clayey facies. In the ridge these sands are tilted through which the anisotropy factor was reduced to 2. The anisotropy factors are based on values given by De Vries (1980) and Engelen et al. (1988) for similar sediments in the Netherlands.
To account for variable density of groundwater under the river plain, a permeability correction can be applied (Maas & Emke, 1989). Chloride concentrations indicate a maximum of ca. 20% seawater in the brackish groundwater, which makes the correction of K negligible compared to the intrinsic uncertainty in K due to extrapolation of permeability measurements at a limited number of points.
Data on effective porosities are absent and therefore arbitrary values of 0.35 for sand and gravel and 0.1 for clay were assigned (Bear, 1979).

Two zero flow boundaries are present. The right boundary is taken as the regional groundwater divide on the ridge. The position of this divide is approximately the same for all time periods considered. The lower boundary is taken at the hydrological base which consists of impermeabele clays and fine-grained silty sands (Witmer, 1989).
Constant heads were specified along the left and upper boundaries of the vertical section. Hydraulic heads at the left boundary were determined from measurements in nearby shallow observation wells, while the vertical hydraulic head gradient was inferred from Witmer (1989). For the upper boundary phreatic water levels are specified. The polders in the Vecht river plain contain a substantial area of surface water present as lakes, pools and ditches. The phreatic water levels of the land area are closely related to these surface water levels. For the river plain the artificially controlled surface water levels are therefore taken to represent the phreatic water levels. Close to the polder boundaries the sharp drop in polder levels has been somewhat smoothed by input of intermediate hydraulic heads. This is in agreement with field measurements.

Historic data on hydraulic heads and polder water levels for the time periods before 1985 were obtained from Dopheide & Pouteray (1982) who made an inventory of literature and archives pertaining to polder levels and hydraulic heads in the study area. They present data on groundwater levels in the ridge starting from 1891 (Fig. 3a, b) and on polder levels from 1880 (Fig.

4).
Data on natural groundwater levels (14^{th} century) are not available. Because groundwater extraction in 1891 was minimal, it was assumed that the natural phreatic water level in the ridge was approximately the same as that in 1891 (Fig. 3a). The phreatic water level in the Vecht river plain was set to mean sea level which was about -0.2 m NAP in the 14^{th} century (Louwe Kooymans, 1974).
For 1885 the phreatic water level in the ridge was also taken to be the same as that in 1891, assuming that the effect of the first polders in the river plain on water levels in the ridge was negligible.
Groundwater levels in the ridge for the 1941 simulation are given in Fig. 3b. For 1985, data on hydraulic heads were obtained from TNO-DGV Institute of Applied Geoscience and polder water levels from the Provincial Public Works Department of North-Holland (Fig.3c).
Hydraulic heads in brackish water were corrected to equivalent fresh water heads. All hydraulic heads and polder water levels used as input for the model simulations for the four different points in time can be obtained from Fig. 4.

CALIBRATION, VERIFICATION AND SENSITIVITY ANALYSIS

The initial simulation of the natural groundwater flow pattern (14^{th} century) showed upward groundwater flow at the sharp decrease in the hydraulic head slope present in the eastern part of the ridge (Fig. 4). Under natural conditions groundwater flow in the ridge must be directed downward. This could only be achieved by introducing a tilted clay layer in the eastern part of the ridge (Fig. 2). There is physical evidence from boreholes (Offerein, 1983) and from a pumping test (Hey, 1976) that a semi-permeable layer is indeed present in places in the northeastern part of the ridge. Moreover, groundwater modelling by Witmer (1989) showed that the steep hydraulic head slope in the ridge could only be simulated when transmissivities in an east-west direction were taken smaller than in a north-south direction. Tilted clay layers are a phenomenon frequently reported in ice-pushed sediments.
The adjusted permeability distribution from the 14^{th} century simulation was used for the 1985 simulation. It appeared that the calculated infiltration and seepage pattern at the upper boundary closely matched that on infiltration-seepage maps from regional groundwater studies (Provinciale Waterstaat van Noord-Holland, 1986; Witmer, 1989; Schot, 1989). Calibration of discharges at the extraction locations and in the Horstermeer polder was, however, necessary by adjustment of permeabilities of the Holocene top layer in the river plain and of the ice-thrusted sands in the ridge.

Verification with the 1941 simulation showed that the actual and calculated groundwater discharges at the Bussum and Laarderhoogt groundwater extractions and in the Horstermeerpolder are of the same order (Table 1). Additional verification on the basis of the tracers chloride and oxygen-18 is discussed in the section on the effects of changes in flow patterns on groundwater composition.

Table 1. Calculated and actual discharges (m^3/yr) for 1941 at the Bussum and Laarderhoogt groundwater extraction locations and in the Horstermeer polder (sources: Dopheide & Pouteray, 1982; Hooghoudt, 1945)

1941	Bussum	Laarderhoogt	Horstermeer
calculated discharge	$1.2 * 10^6$	$0.9 * 10^6$	$32 * 10^6$
actual discharge	$1.4 * 10^6$	$0.8 * 10^6$	$29 * 10^6$

Sensitivity analyses showed that the simulated flow patterns are relatively insensitive to changes in horizontal permeability values. Anisotropy on the other hand strongly influences the flow patterns; low anisotropy factors tend to make flow systems deeper and horizontally more restricted.
Near the groundwater extractions and in the Horstermeer polder convergence of flow lines occurs. The effect of convergence has been corrected by lowering permeability values in the direction of flow proportional to the decrease in distance between two converging flow lines (pers. comm. FLOWNET-authors Hemker and Van Elburg). It was found that this had virtually no effect on the spatial distribution of flow systems.
The simulated flow patterns were found to be most sensitive to the shape of the hydraulic head distribution at the upper model boundary. A convex head distribution results in downward flow, a concave head distribution in upward flow. The position of inflection points therefore is critical to where flow lines change direction from downward to upward flow.
The number of colums and rows determine the degree to which the true hydraulic head distribution may be approximated. Therefore the effect of increasing numbers of rows and columns on the simulated flow patterns was tested. As differences in hydraulic head occur mainly along the upper boundary, the model results appeared especially sensitive to the number of columns. After testing different combinations of rows and columns a configuration of 270 columns and 16 rows was considered optimal, given the maximum number of cells of FLOWNET (ca. 4800).

RESULTS OF THE GROUNDWATER FLOW SIMULATIONS

The natural groundwater flow pattern (14^{th} century)
Natural groundwater flow shows a simple pattern (Fig. 5a). Recharge occurred on the ridge and water flowed towards the river plain where it discharged in a zone at the foot of the ridge. The difference in elevation between the ridge and the river plain was the main driving force for groundwater flow. Seepage at the foot of the ridge was transported as surface water in a westerly direction towards the Vecht river. Surface water flow in the peatmarshes occurred in a number of small brooks, which have been identified on soil maps. The, partly brackish, groundwater in the river plain was largely stagnant as significant differences in hydraulic head were absent.

The groundwater flow pattern in 1885
Drainage of the river plain had started through the creation of a number of polders including reclamation of lake Horstermeer in 1882. This had a large effect on the groundwater flow pattern (Fig. 5b). As a result of differences in polder levels groundwater flow was created from polders with a relatively high level to those polders with a relatively low level. The low polder level of the reclaimed Horstermeer (-3,3 m NAP) had a particularly dominating effect on groundwater flow. Water is attracted not only from the surrounding polders but also from the ridge, the Vecht river and the polder west of the Vecht river. Since part of the groundwater from the ridge flows towards the Horstermeer polder, the amount of discharge as well as the area with groundwater seepage at the foot of the ridge decreased. This is consistent with modelling results by Witmer (1989).

The groundwater flow pattern in 1941
Groundwater extraction on the ridge started in 1888 and had increased to about 2.2 * 10^6 m^3/year by 1941 at the Bussum and Laarderhoogt extraction locations. Groundwater flow at these locations is directed upward, representing discharge through the pumping wells (Fig. 5c). As a result of extraction, groundwater flow was reversed in parts of the ridge and new groundwater divides were created. This greatly reduced the flow of groundwater towards the river plain. Because the difference in polder level between the Horstermeer and the other polders in the river plain also decreased, the pattern of groundwater flow in the river plain has remained essentially the same since 1885. The 's-Graveland canal has become somewhat more elevated relatively to the adjacent polders resulting in increased infiltration of surface water from the canal.

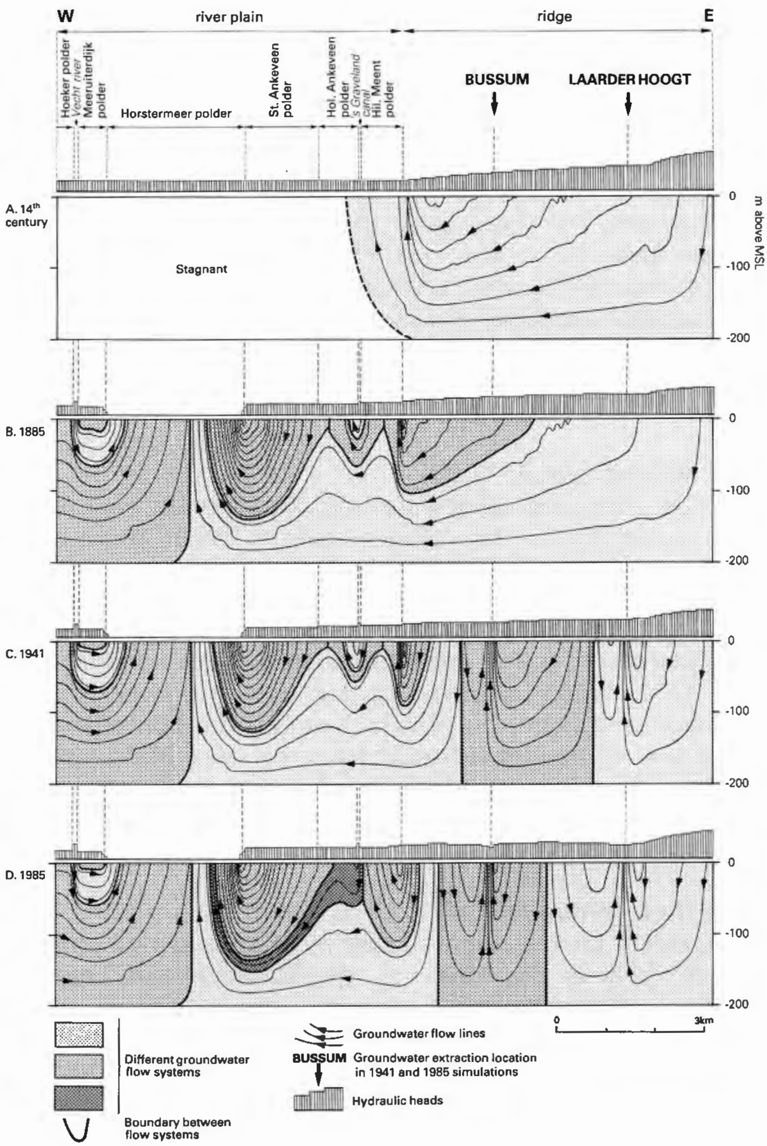

Fig. 5. Results of the groundwater flow simulations
a) 14th century
b) 1885
c) 1941
d) 1985

The present groundwater flow pattern (1985)
By 1985 total groundwater extraction at Bussum and Laarderhoogt had increased to about 5.8 * 10^6 m^3/year. As a result the divide between groundwater flowing towards the Bussum location and towards the river plain shifted somewhat to the west. In contrast to 1941 the discharge at the Laarderhoogt location had exceeded that of the Bussum location in 1985. This led to a westerly shift of the groundwater divide between the two extraction locations. The level of the Hilversumse Meent polder was lowered by 45 cm since 1941. A considerable increase in depth of the groundwater flow lines towards this polder occurred as a result of a larger difference in hydraulic head between this polder and the adjacent ridge. The increased groundwater extraction from the ridge and the increased discharge of groundwater in the Hilversumse Meent polder have decreased groundwater flow from the ridge towards the river plain even further. This resulted in a considerable increase in both the amount and depth of infiltration of surface water from the 's-Graveland canal. The water level of the canal has remained almost constant since 1941 and is about 1 m higher than that in the adjacent polders in 1985.

EFFECT OF CHANGES IN FLOW PATTERNS ON GROUNDWATER COMPOSITION

Extraction of groundwater changed and in some parts even reversed flow directions in the ridge. However, as infiltration of precipitation remained the main source for recharge, the changes in flow direction did not alter the overall groundwater composition in the ridge.
Groundwater in the central and western part of the river plain was largely stagnant under natural conditions. As a result of impoldering new flow systems began to develop. Fresh water originating from lakes, pools and ditches and from local precipitation on the river plain began to replace the stagnant brackish groundwater body. Deep regional flow of fresh groundwater from the ridge towards the Horstermeer polder also started to replace part of the brackish groundwater.

Chloride and oxygen-18 concentrations in wells along the western part of the cross-section are shown in relation to the simulated 1985 flow pattern in Fig. 6. The 1985 simulation may be considered roughly representative for groundwater flow in the river plain over the past century, taking into account that no drastic changes in flow patterns between 1885, 1941 and 1985 are visible in Fig. 5.
Groundwater in the ridge shows $\delta^{18}O$ values between -7.8 and -7.4 ‰

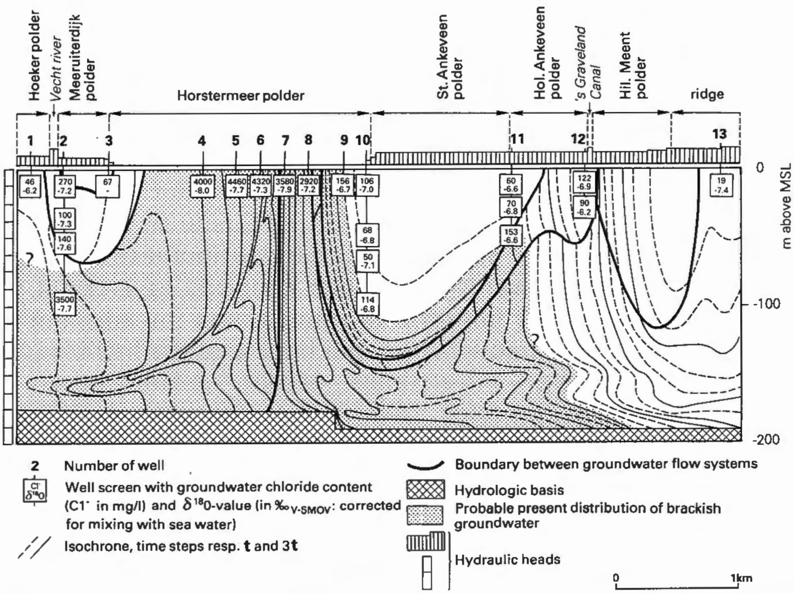

Fig. 6. Relation between groundwater flow patterns and groundwater composition for the western part of the cross section

with chloride contents generally below 20 mg/l (well 13 and other wells not shown here). This indicates precipitation as the main source of recharge. Chloride and $\delta^{18}O$ values of well 12 are higher than those observed in ridge groundwater indicating infiltration of surface water from the 's-Graveland canal which at present has reached a depth of at least 26 m. The relatively high chloride contents and $\delta^{18}O$ values of wells 10 and 11 reflect infiltration of surface water from the river plain affected by suppletion of Vecht river water and evaporation.

The deepest screens of wells 10 and 11 show increased chloride contents compared to the more shallow screens. As chloride contents of surface water in the river plain were lower in the past than at present, high chloride contents at these screens must result from mixing with brackish groundwater as a result of dispersion. This mixed water is also found in well 9 marking the transition in the Horstermeer polder from already fresh groundwater near the edges to still brackish groundwater in the centre. In the mixed water the corrected $\delta^{18}O$ values are higher than those observed on the ridge. The fresh water component in the mixed water thus originates from the river plain.

In the Horstermeer seepage of old, formerly stagnant, brackish groundwater

occurs, with chloride concentrations generally increasing towards the centre. Well 8 shows tracer values which are possibly already slightly affected by mixing with fresh groundwater. The corrected $\delta^{18}O$ values in brackish groundwater (wells 4-8) range from -7.2 to -8.0 ‰ which corresponds to those in ridge groundwater. During the initial forming of the brackish groundwater by density flow of seawater from the surface, the fresh water present in the aquifer at the time therefore probably originated from the ridge. This is consistent with the simulation of the natural groundwater flow pattern.
The fresh groundwater in the western part of the Horstermeer polder is derived from the Vecht river and adjacent polders. Infiltration of Vecht river water has at present reached a depth of between 60 and 100 m according to chloride contents.

The tracer data provide a rough indication of the present position of the fresh-brackish groundwater interface (Fig. 6). Between wells 8 and 11 the position of the interface has been inferred on the basis of the form of the calculated isochrones for the 1985 simulation, assuming these are roughly representative for the development of the flow systems under the Vecht river plain over the past century. The outflow of brackish groundwater to the west of well 4 has been inferred from chloride concentrations of ditch water in the Horstermeer (Van der Linden & Appelo, 1988). The boundary of brackish water observed in ditches compares well to the the boundary of the Vecht groundwater system as simulated by the model. This implies that the fresh-brackish groundwater interface of the flow system recharged to the west of the river has not yet reached the surface. The displacement of fresh water infiltrated in the polder west of the Vecht river can not be deduced from the calculated isochrones in this system, because for the initial time step the model assumes that water starts flowing on the left boundary instead of at the surface. Due to a lack of data on groundwater composition the position of the interface in this system, as well as in groundwater flowing from the ridge towards the Horstermeer had to be estimated.
It may be anticipated that in the future all outflow of brackish groundwater in the Horstermeer polder eventually will cease. This can be deduced from the isochrones pattern which indicates that the fresh groundwater front will gradually move towards the centre and towards the surface of the Horstermeer. Outflow of brackish water may stop at different points in time for different parts of the Horstermeer. This is due to differences between the flow systems with respect to flow velocities and in distance from the present fresh-brackish interface to the centre of the Horstermeer. Van der Linden and Appelo (1988) found that the front between fresh and brackish groundwater in the southern part of the Horstermeer polder has moved considerably towards the centre since 1942, while in the northern part the

position of the front remained approximately the same. Freshening of the aquifer near the Horstermeer by water from the surrounding polders occurs relatively fast as a result of the steep slope in hydraulic heads near the border of the Horstermeer. The short distance between isochrones in deep groundwater under the river plain indicates that replacement by fresh groundwater from the ridge is much slower.
The future termination of outflow of brackish groundwater in the Horstermeer has been postulated earlier by Van Dam (1987). The computer simulations in this paper provide a somewhat quantitative foundation of this proposition.

DISCUSSION

The results of the numerical groundwater modelling exercises should be interpreted in view of the approach used and the uncertainties inherent to groundwater modelling.
The hydraulic heads for the natural situation are not known. In the ridge natural hydraulic heads were assumed equal to those observed in 1891. This seems plausible as groundwater extractions were minimal at the time. In the river plain topographic elevation differences are virtually absent. Peat development occurred under the influence of rising groundwater levels in pace with the Holocene sea level rise. Natural phreatic levels were therefore assumed to approximate sea level.
Hydraulic heads at the upper boundary for the ridge in 1885 (1891) and 1941 were derived from maps compiled by Dopheide and Pouteray (1982). Although these maps are based on actual well data collected by the water supply companies, the number of data locations is not specified and therefore the accuracy of the hydraulic head distribution is uncertain. For the left boundary the hydraulic heads for 1885 and 1941 are not known. They were calculated from the known phreatic (polder) levels for 1885 and 1941 at the left boundary assuming a vertical hydraulic head gradient equal to that in 1985.
Calibration of the model is difficult due to a lack of hydraulic head data in deep groundwater. Differences in hydraulic heads between shallow and deep groundwater can be expected especially in the ridge due to the presence of (tilted) clay layers.

In spite of these uncertainties, the results of the groundwater modelling exercises can be considered indicative of the changes in groundwater flow patterns in the study area over the past century. This can be concluded from the following facts.

The infiltration-seepage pattern at the upper boundary calculated for the 1985 simulation closely matched that on maps from several regional groundwater studies. Verification with the 1941 simulation showed that the calculated discharges compare well with those actual measured at the groundwater extraction locations and in the Horstermeerpolder.
Chloride and $\delta^{18}O$ values confirm that precipitation is the dominant source of recharge on the ridge and that chloride-enriched and slightly evaporated water infiltrates in the river plain. The distribution of these tracers is therefore consistent with the simulations for 1885, 1941 and 1985, which is an indication that these simulations may be considered representative of the real flow patterns.
The 14th century simulation is consistent with peat soil data and old vegetation maps from the river plain which point to vegetation types depending on fresh, relatively nutrient-poor groundwater in a zone at the foot of the ridge. This water naturally originated from the ridge. The presence of a number of small brooks identified on soil maps starting at the foot of the ridge and running towards the Vecht river are evidence of a large outflow of ridge groundwater under natural conditions.

The simulations indicate that important changes in groundwater flow patterns have occurred in the study area over the past century as a result of large scale impoldering and groundwater extraction. Groundwater flow changed from a simple pattern dominated by the topographic elevation difference between the ridge and the river plain to a complex flow pattern dominated by artificially man-controlled hydraulic heads.
As a result of impoldering a number of infiltration-discharge flow systems have developed in the river plain between polders with relatively high surface water levels to those with relatively low levels. The low polder level of the reclaimed lake Horstermeer has a particular large impact on flow patterns; water is attracted not only from the surrounding areas but also from the ridge.
Groundwater extraction for public water supply changed flow directions over large areas on the ridge. Moreover, it greatly reduced the flow of groundwater towards the river plain. Nowadays only water recharged in the most western part of the ridge reaches the river plain.
Although clearly transient flow conditions were studied with a steady state groundwater flow model, the overall regional changes in flow patterns emerge unmistakable from the comparison of simulations for different points in time.

The effects of changes in flow patterns on groundwater composition were most profound in the river plain. Hydraulic head differences created by impoldering, especially of the Horstermeer polder, created new flow

systems. The stagnant groundwater body under the river plain was activated and brackish groundwater started to be replaced by fresh water recharged in the river plain or in the ridge. The surface water levels of the Vecht river and the 's-Graveland canal have remained relatively constant compared to the adjacent polders. This resulted in infiltration of surface water from the river and the canal. Since these surface waters are polluted by a.o. sewage effluent, this has an adverse effect on groundwater quality.
It is important to notice that the fresh-brackish groundwater interface is caused by changes in groundwater flow patterns (type-1 front) and not by hydrochemical processes. In this particular case this is quite obvious, because of the clear chemical contrast between fresh and brackish groundwater. In other cases, however, this may be less clear, for example at locations where natural groundwater composition under the river plain is not brackish but consists of fresh groundwater recharged on the ridge. Due to a change in flow pattern this water may be replaced by precipitation recharged through peat on the river plain. Differences in solute concentrations over the resulting fresh-fresh groundwater interface may erroneously be interpreted as being due to hydrochemical processes.
The computer simulations in this paper provide a general framework as to where one may expect type-1 fronts in the study area. This enables a better interpretation of groundwater samples in terms of hydrochemical processes occurring in the aquifer, which is of importance for future studies addressing the impact of groundwater pollution on wetlands in the river plain.

Aknowledgements

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CHAPTER 5

HUMAN IMPACT ON REGIONAL GROUNDWATER COMPOSITION THROUGH INTERVENTION IN NATURAL FLOW PATTERNS AND CHANGES IN LANDUSE

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ABSTRACT

The relations between groundwater composition, landuse, soil conditions and flow patterns on a regional scale are studied for the Gooi and Vechtstreek area in the Netherlands. The densely populated area consists of an ice-pushed ridge with dry sandy soils bordered by the Vecht and Eem river plains with wet peat and clay soils.
R-mode factor analysis and Q-mode cluster analysis were applied to a set of 1349 groundwater analyses to determine the factors controlling groundwater composition and the main resulting water types.
The results indicate that groundwater composition in the study area is affected on a regional scale by human activities through changes in landuse and intervention in natural flow patterns.
On the ridge groundwater is recharged by precipitation which dissolves carbonates from the matrix of the sandy aquifer. Increased solute concentrations in shallow groundwater, especially of nitrate, sulfate and potassium, indicate increased pollution resulting from urbanization and agricultural intensivation over the past decades.
In the Vecht river plain infiltration occurs as a result of drainage of polders and groundwater extraction on the ridge. Recharge occurs by precipitation and polluted surface water to which ammonium, organic complexes and carbonic acid are added through decomposition of organic matter in the peat and clay soils. The carbonic acid results in enhanced dissolution of carbonates present in the soil and underlying sandy aquifer. Oxygen depletion and subsequent low redox potentials result in denitrification, dissolution of manganese and iron oxides and sulfate reduction. The flow of groundwater from high-level to low-level polders causes displacement of a former stagnant brackish groundwater body under the Vecht river plain accompanied by increased mixing of fresh and brackish groundwater.

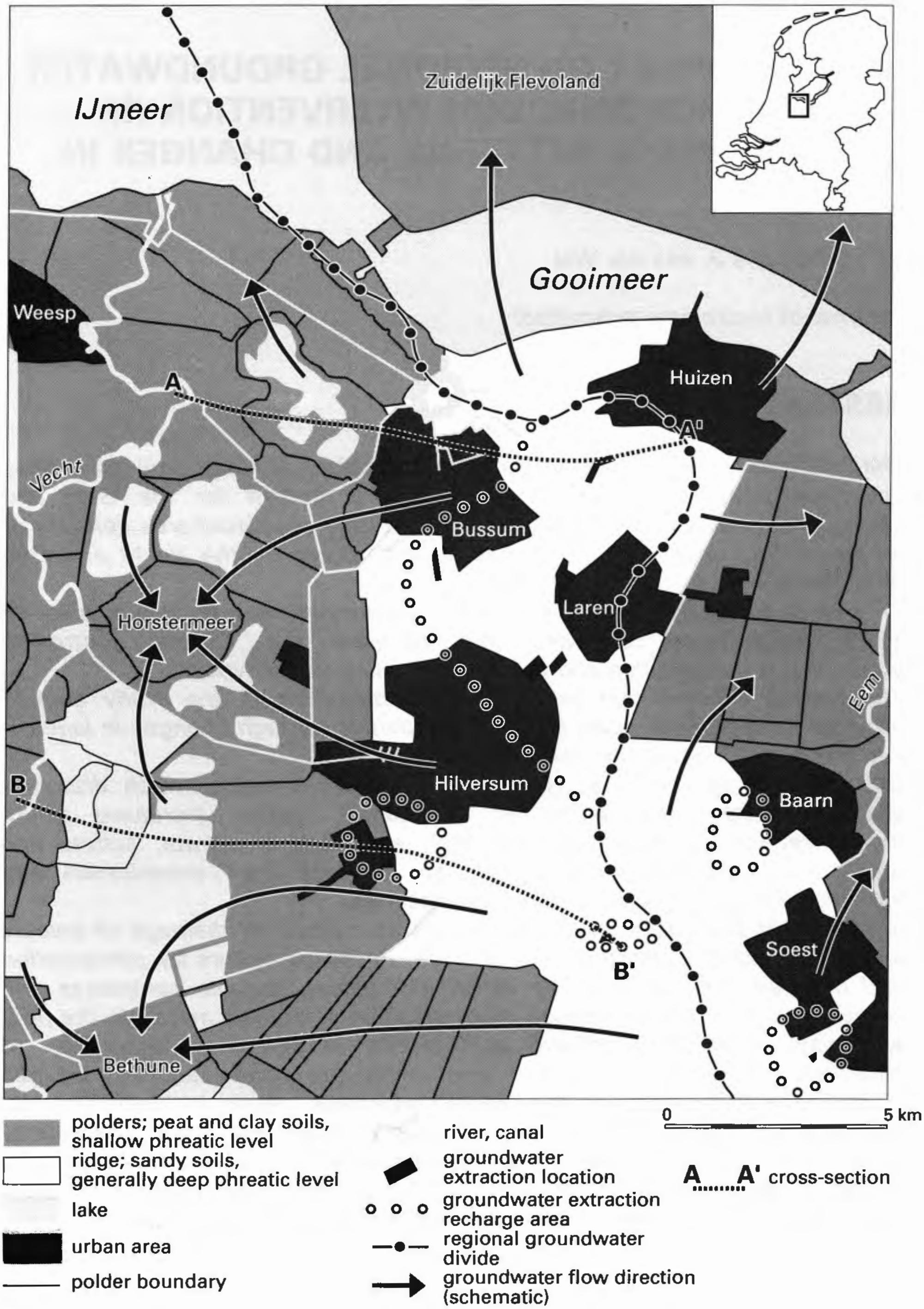

Fig. 1. Location and topography of the study area.

INTRODUCTION

Groundwater serves a number of important functions for mankind and in nature. These functions are often related to groundwater composition, which is increasingly influenced by human activities. To assess whether groundwater will maintain its present function in future, it is necessary to obtain insight into the factors determining groundwater composition.
Groundwater composition at a certain location is determined by initial water composition during infiltration, by groundwater flow patterns and by characteristics of the aquifer.
The initial water composition is primarily related to the origin of the recharge water, e.g. precipitation or surface water. During infiltration changes in water composition may occur through natural processes or through human activities dependent on soil conditions and landuse (e.g. evaporation, dissolution of fertilizers).
Flow patterns determine the spatial displacement of groundwater and solutes through the subsurface. Groundwater flow depends on natural factors (elevation differences, lithology) and on human interventions (groundwater extraction, drainage).
The evolution of groundwater composition along the flow path is determined by physical, chemical and biological processes. The occurrence of these processes depends on the initial water composition together with the conditions in the aquifer part which the water passes.

Groundwater provides an important source for drinking water supply, agriculture and wetland ecosystems in the Gooi and Vechtstreek area in the Central Netherlands (Witmer, 1986; Schot et al., 1988). This paper aims at determining the main groundwater types in this region and the factors which control their composition. Groundwater composition is considered in relation to landuse, soil conditions and groundwater flow patterns on a regional scale.

DESCRIPTION OF THE AREA

The study area comprises an area of 500 km^2 (Fig. 1). Its main topographic feature is a sandy ridge with elevation ranging from 0 to 30 m above mean sea level. The ridge was created by glaciers during the Saale ice-age through pushing of existing fluvial sediments. To the east and west the ridge is bordered by the broad and flat-lying Eem and Vecht river plains.
Landuse on the ridge changed considerably over the past century (Harten,

1976). Heath and extensively used arable lands were increasingly replaced by human settlements. Agricultural landuse was intensified through application of manure and fertilizers. Nowadays landuse on the ridge consists of urban areas surrounded by woodland, heath and agricultural areas.
The naturally marshy river plains have increasingly been drained for agricultural purposes. Systems of connected ditches were dug to create polders in which surface water levels and hence phreatic levels are artificially controlled. Lakes present on the Vecht river plain resulted from natural causes and from peat excavation which started in the sixteenth century and ended around 1920 (Van Raam, 1979). Nowadays the river plains are mainly used for dairy farming. The Vecht plain also contains a number of wetland nature reserves.

The main aquifer consists of thick layers of Pleistocene fluvial sands and gravels on top of semi-permeable marine clays and silty sands at 150 to 200 m below sea level. In the river plains the aquifer is in places divided into two or three subaquifers by horizontal fluvial or marine clay layers. During the Holocene a semi-confining layer was formed in the river plains on top of the Pleistocene aquifer, consisting of peat deposits locally intercalated with fluvial or marine clays (Witmer, 1989). Soils in the river plains are generally wet and rich in organic matter or clay, as opposed to dry and sandy soils on the ridge.
Natural groundwater flow is directed from the ridge towards the surrounding areas. Extraction of groundwater for public drinking water supply created a number of artificial groundwater flow systems in the ridge (Fig. 1). In the river plains the creation of polders resulted in the development of numerous infiltration-discharge systems with groundwater flow from high-level to low-level polders. Especially the deep polders Bethune, Horstermeer and Zuidelijk Flevoland have a large effect on groundwater flow patterns (Fig. 1). On the ridge recharge occurs predominantly through precipitation, while in the river plains recharge may consist of either precipitation or surface water (Schot, 1989; Schot and Molenaar, 1990).

Groundwater extraction from the ridge and drainage of polders resulted in water deficits in the Vecht plain in summer periods (Witmer, 1986). To maintain high water levels for agriculture the polders are supplied by Vecht river water, containing high concentrations of sodium, chloride, calcium, magnesium and nutrients.
In the northern part of the study area a former arm of the North Sea has been dammed and changed into fresh water lakes (IJmeer, Gooimeer). Part of the groundwater in the northwestern part of the study area is brackish as a result of mixing of fresh groundwater with sea water. The sea water

entered the fresh water aquifer from the surface through density flow following Holocene marine transgressions (Engelen, 1981; Van der Linden and Appelo, 1988).

DATA SET AND METHODS OF DATA ANALYSIS

Data on groundwater composition are available from routine analyses by drinking water supply companies and from various geohydrological studies. Over 6000 analyses covering a time period of one century (1889-1988) have been accumulated for the purpose of this study.
Multivariate statistical techniques can be used to reduce the number of variables or cases into a smaller number which in principle contain the same information as the original data. Factor analysis and cluster analysis are among the most widely used multivariate statistical techniques in hydrology (Seyhan et al., 1985). Factor analysis is usually applied in R-mode to find relations between variables. Its main objective is to rearrange the variables into a minimum number of independent factors or components that retain as much of the information stored in the original variables as possible (SAS, 1985). Cluster analysis is basically a classification technique commonly used in Q-mode to group cases (Seyhan and Keet, 1981).
In geohydrology, factor analysis proved successful in providing information on hydrochemical processes, while cluster analysis has been applied for the purpose of grouping groundwater samples according to their overall chemical composition (Dawdy and Feth, 1967; Ashley and Lloyd, 1978; Hoogendoorn, 1983; Steinhorst and Williams, 1985; Seyhan et al., 1985; Dekkers et al., 1986 & 1989; Usunoff and Guzman, 1989; Varsanyi, 1989).
In this paper R-mode factor analysis and Q-mode cluster analysis are applied to determine the factors controlling regional groundwater composition in the study area and the main groundwater types resulting from these factors.

To obtain a suitable set of hydrochemical data for multivariate analysis the raw database was preprocessed (see section 4). For the resulting dataset an univariate statistical overview is presented and concentrations in groundwater are compared to those in the mean precipitation excess.
A simplified Pearson correlation coefficients matrix is presented to indicate the bivariate relations between hydrochemical parameters which form the basis for the multivariate analysis results.
Factor extraction was carried out by principal components analysis. Three components were retained with eigenvalues greater than one (Kaiser, 1960). Varimax rotation was applied to obtain uncorrelated components (SAS, 1985).

Clusters were calculated by means of Ward's minimum variance method which tends to join clusters with a small number of observations (SAS, 1985). Insight is thus obtained into water types which are significant on a regional scale. A similarity level was chosen so as to obtain a comprehensible number of six clusters representative of the main regional groundwater types.

PREPROCESSING OF HYDROCHEMICAL DATA

The primary database contains practically all analyses of groundwater samples taken in the study area over the past century. In total 6087 analyses and 18 hydrochemical parameters were input along with data on sampling location and altitude, type of well, screen depth and length and origin of the analysis.
Analyses of brackish groundwater ($Cl^- > 300$ mg/l) were discarded as this type of water is of no practical use. The large concentrations in these analyses would completely dominate the multivariate statistical analyses, thus masking the more important hydrochemical processes in fresh groundwater.
For a number of wells time series of groundwater analyses are available, especially for the wells of the public drinking water supply. To avoid spatial bias in the statistical analyses a large number of analyses at these locations have been discarded, while care was taken for the remaining analyses to be representative of the original time series.
Many groundwater analyses contain missing values for one or several hydrochemical parameters. Missing values influence the results of the correlation- and factor analyses as coefficients across the correlation matrix are calculated from different numbers of variable pairs. Furthermore, cluster analysis cannot handle missing values. To obtain as large a set as possible of complete groundwater analyses, less important and little analysed variables were discarded (Kjeldahl-N, NO_2^-, EC and COD). PO_4^{3-} and SiO_2 were also left out of consideration as a preliminary principal components analysis showed these variables to be independent components not correlated with other hydrochemical variables.

The remaining set of 1349 complete groundwater analyses with 12 hydrochemical parameters was used for multivariate statistical analyses. Normality of hydrochemical parameters was tested by inspection of histograms and calculation of skewness factors. Common logarithmic transformation to obtain normality was necessary for all parameters except calcium, bicarbonate and pH. Standardisation was applied to get parameter

*Table 1. Univariate overview of the 1349*12 dataset used for statistical analyses. Concentrations in mg/l, sampling depth in m below surface. Concentrations in mean precipitation excess according to Schot (1989).*

	Minimum	25%	Median	75%	Maximum	Skewness coeff.	Mean in precipitation excess
pH	3.7	6.6	7.3	7.8	8.7	-1.2	4.0
Cl	6	15	30	59	290	2.2	15
HCO_3	0	55	115	206	669	1.0	-
SO_4	0	6	18	37	349	3.1	18
Na	3	10	16	35	193	2.1	9
Ca	1	28	45	66	198	0.9	2
Mg	0	2	4	6	66	4.3	1
K	0.2	0.9	1.5	3	290	18.9	0.6
NO_3	0	0.1	0.4	3.3	250	4.2	9
NH_4	0	0.0	0.2	1.3	74	6.9	5
Fe-total	0	0.1	1	5	90	4.3	0.4
Mn-total	0	0.05	0.21	0.52	10	4.9	0.0
Sampling year	1967	1980	1983	1986	1988	-2.7	-
Sampling depth	0.4	4	31	62	277	1.7	-

Table 2. Simplified Pearson correlation matrix ($r \geq |0.3|$). Strong correlations ($r \geq |0.7|$) underlined, moderately strong correlations $r \geq |0.5\text{-}0.7|$) dashed underlined.

	pH	Cl	HCO_3	SO_4	Na	Ca	Mg	K	NO_3	NH_4	Fe	Mn
pH	.											
Cl		.										
HCO_3	0.31	0.38	.									
SO_4			0.31	.								
Na		$\underline{0.94}$	0.43		.							
Ca		0.50	0.83		0.49	.						
Mg		0.56	0.54		0.56	0.58	.					
K	-0.34	0.42		0.35	0.43		0.49	.				
NO_3			-0.36	0.41					.			
NH_4	-0.38	0.37	0.35		0.37		0.35	0.40		.		
Fe	-0.33		0.35	-0.34					-0.46	0.60	.	
Mn	-0.37						0.30		-0.30	0.48	0.53	.

Table 3. Results of the Principal Components Factor Analysis with Varimax rotation. Only component loadings ≥ |0.5| included.

	F1	F2	F3
pH		-0.76	
Cl	0.78		
HCO_3	0.80		
SO_4			0.78
Na	0.78		
Ca	0.87		
Mg	0.76		
K			0.59
NO_3			0.71
NH_4		0.77	
Fe-total		0.75	
Mn-total		0.69	
expl. var.	3.58	2.63	2.36
cum. var. (%)	29.9	51.8	71.5

Table 4. Median values for clusters, arranged according to principal components model. Concentrations in mg/l, EC in µS/cm, depth in m below surface. Highest concentration per variable underlined.

		clus1	clus2	clus3	clus4	clus5	clus6
	Ca	34	39	43	17	66	<u>97</u>
	HCO_3	79	29	130	19	194	<u>346</u>
F1	Na	11	19	10	16	<u>55</u>	32
	Cl	18	35	15	28	<u>80</u>	58
	Mg	2	7	3	3	6	<u>8</u>
	NH_4	.0	.1	.3	1.8	.8	<u>3.3</u>
F2	Fe-total	.0	.2	3.5	2.6	1.3	<u>12</u>
	Mn-total	.03	.13	.28	.37	.41	<u>.50</u>
	pH	7.9	6.2	7.3	<u>5.7</u>	7.1	7.2
	SO_4	21	<u>51</u>	6	16	34	3
F3	NO_3	3.1	<u>50.7</u>	.2	.4	.3	.1
	K	.9	<u>6.4</u>	1.0	2.0	2.4	2.1
	EC	220	403	277	232	590	674
	Observations	297	130	351	128	356	87
	Mean depth	46	15	76	2.5	39	33

values at the same order of magnitude.
Reliability of the data was tested by charge balance calculations using all available parameter values. Deviations from electro-neutrality are within 5% deviation for 80% of the samples and within 10% deviation for 93% of the samples. This indicates that the reliability of the data is sufficient to study the main regional hydrochemical processes and water types.

RESULTS OF THE STATISTICAL ANALYSIS

Table 1 presents an univariate statistical overview of the 1349 * 12 dataset. Complete analyses are present from 1967 onward but most analyses (84%) date from the last ten years (1978-1988). Concentrations of hydrochemical parameters in groundwater are generally higher than mean concentrations in the precipitation excess (see Table 1). For sulfate, nitrate and ammonium, however, more than half the analyses show concentrations in groundwater below those in the precipitation excess. Apparently these parameters in groundwater are predominantly affected by removal mechanisms (e.g. reduction, adsorption).

Strongest correlations are observed between sodium and chloride and between calcium and bicarbonate (> 0.70; Table 2). Moderately strong correlations (0.5-0.7) are observed for magnesium with all four foregoing parameters and between calcium and chloride. Iron correlates moderately strongly with ammonium and manganese. A relatively large number (36%) of correlation coefficients are moderately weak (0.3-0.5), which may indicate that most parameters are influenced by more than one hydrochemical process.

Table 3 presents the principal components analysis results. The three components obtained account for some 71% of the observed variance. Differences in explained variance between components are relatively small.
The results of the cluster analysis are shown in the form of a dendrogram in which Stiff diagrams (Stiff, 1951) aid interpretation in terms of groundwater types (Fig. 2). The 3-dimensional form of the dendrogram allows for reproduction of similarities between clusters on different branches. Table 4 presents median parameter values per cluster. The main division between clusters is brought about by differences in TDS reflected in the EC. Further subdivisions result from differences in redox potential (pe), acidity (pH) and presence of pollutants (NO_3^-, SO_4^{2-}, K^+).

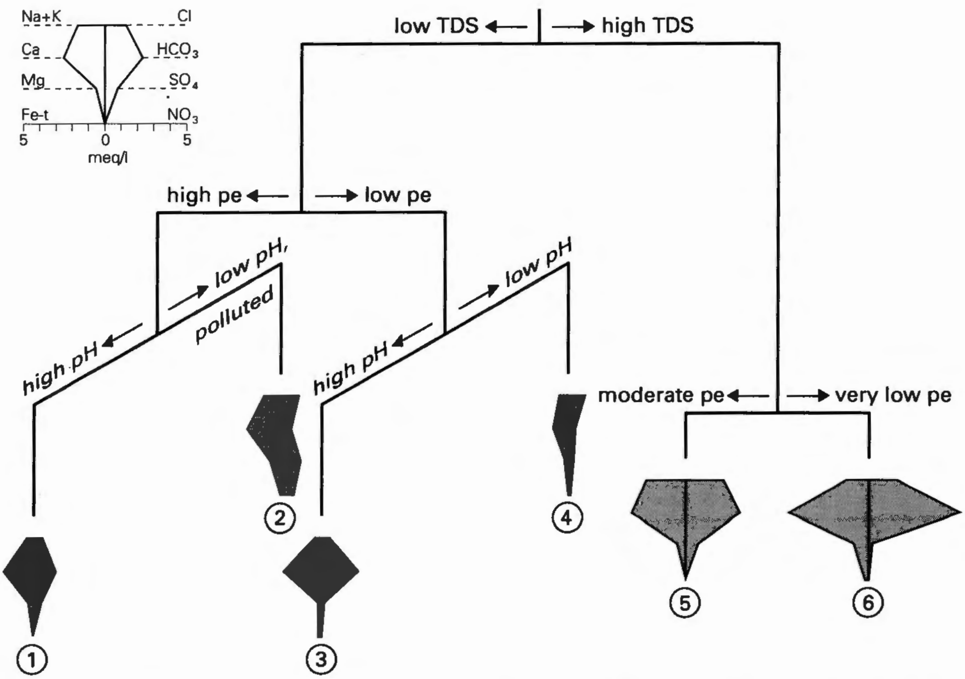

Fig. 2. Three-dimensional dendrogram of Ward's method cluster analysis. Cluster numbers encircled. The Stiff diagrams and texts indicate the main divisions between clusters and are based on median concentrations per cluster (see Table 4).

INTERPRETATION OF PRINCIPAL COMPONENTS AND CLUSTERS

Principal components

Principal components are interpreted in terms of factors determining groundwater composition by considering variables with a component loading outside the range -0.5 to 0.5 (Table 3).

The combination of calcium, bicarbonate and magnesium in component 1 points to dissolution of carbonates, while sodium, chloride and magnesium suggest mixing with seawater or infiltration of surface water influenced by suppletion of Vecht river water. Increased calcium, magnesium, sodium and chloride concentrations may also indicate recharge by polluted water from agricultural lands or from urban areas.

Component 2 represents presence of organic matter. Mineralisation results in production of ammonium and carbonic acid and consequently high loadings for ammonium and pH (negative). Dissolved organic complexes form an important source for iron and manganese. Additionally, iron and manganese oxides may be used as oxidants of organic matter and dissolve in this process. In the river plains organic matter is abundantly present in the Holocene peat and clay soils and also to a lesser degree in the fluvial and marine clay layers dividing the main aquifer into subaquifers. In the ridge organic matter is present in organic pollution from leaking sewage, cesspools and manure.

Sulfate, nitrate and potassium characterize component 3 and point to pollution from various sources, such as manure, fertilizer and sewage water. In a number of cases component 3 indicates infiltration of polluted surface water or influence of brackish water (high sulfate and potassium, low nitrate).

Clusters

The regional distribution of groundwater types is shown through maps for each cluster. The mutual relation between different clusters is displayed along two cross-sections from the ridge to the Vecht river parallel to the groundwater flow direction (Fig. 1). Maps and cross-sections are used to determine the relation of groundwater composition to landuse, soil conditions and groundwater flow patterns. Groundwater flow patterns along the cross-sections are based on Schot (1990) for section A-A′ and on Hettling (1985) and Schot (1989 and unpublished isotope data) for section B-B′.

Clusters 1 and 2 are almost exclusively found on or close to the ridge in accordance with their oxidized character (Figs. 3 and 4). Cluster 1 contains analyses of relatively unpolluted, calcium bicarbonate water generally found under heath. Cluster 2 represent typical polluted calcium sulfate water types with high sulfate, nitrate, potassium and magnesium concentrations, located in or near urban areas on the ridge and in agricultural areas in the transition zone to the Vecht plain. The average depth of cluster 2 samples is low compared to that of cluster 1 samples, resp. 15 and 46 m below ground surface, which is also clear from the cross-sections. This indicates increased groundwater pollution during recent years. A general evolution of cluster 2 into cluster 1 water types by hydrochemical processes is ruled out by the different chloride concentrations, reflecting natural values for cluster 1 and pollution for cluster 2.

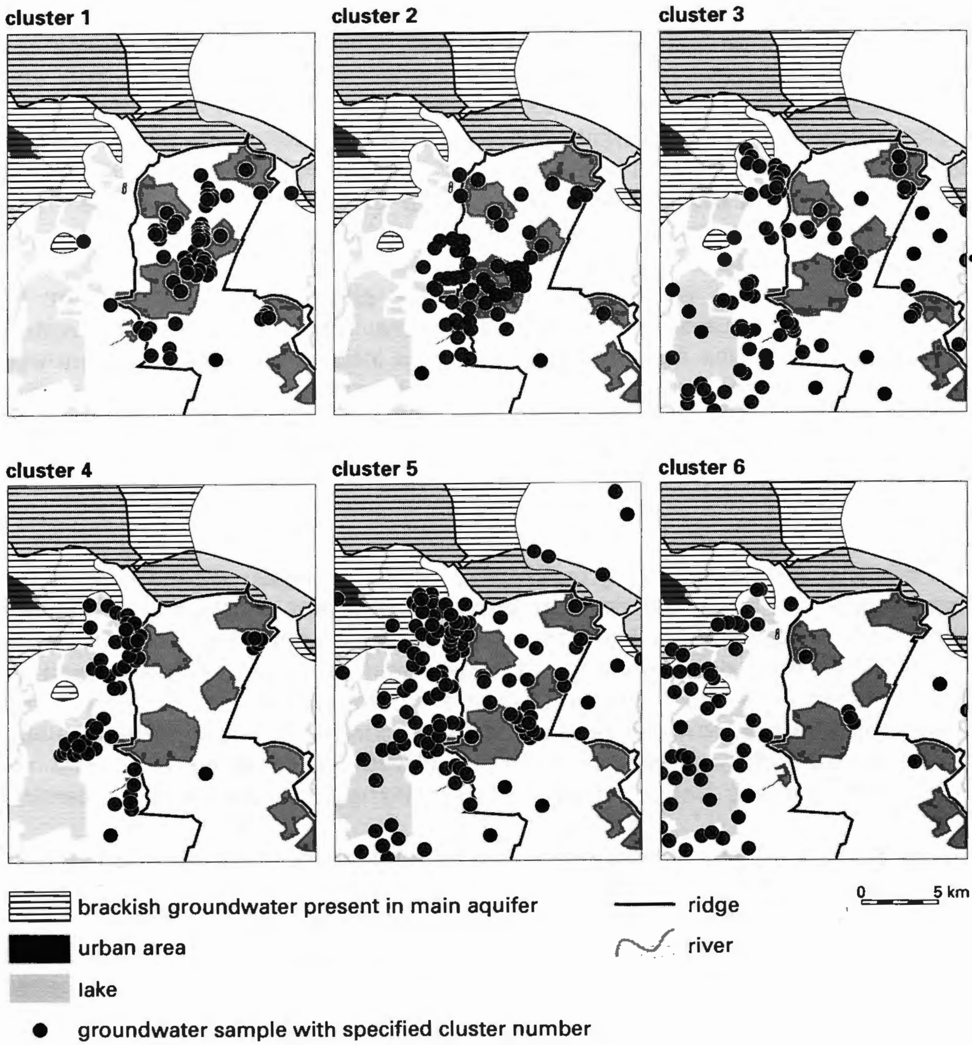

Fig. 3. Spatial distribution of clusters.

On the ridge cluster 3 reflects rather deep, unpolluted groundwater which may have evolved out of cluster 1 water types during prolonged flow. Increased manganese and iron contents and low nitrate and sulfate contents point to a lowered redox potential brought about by oxidation of dissolved organic matter. This is consistent with small but significant increases in ammonium and in calcium, bicarbonate and magnesium following CO_2 production. In the river plains cluster 3 water types reflect old groundwater originating from the ridge or shallow samples taken in reedlands (Fig. 4). These reedland samples consist of local precipitation neutralised by solution of calcium carbonate present in the soil.
Cluster 4 represents acid (median pH is 5.7), moderately reduced analyses mostly from the Vecht river plain (Fig. 3). Average sample depth is 2.5 m with a narrow range indicating water from peat layers. Mineralisation results in production of CO_2, H^+, ammonium and organic complexes and possibly manganese and iron dissolution under relatively low pe conditions. Median chloride contents equal that in precipitation with open water evaporation (concentration of 6.1; Schot, 1989), implying an average crop factor for the wetland vegetation of close to 1.0.

Clusters 5 and 6 display high TDS contents, especially of chloride, sodium, calcium and bicarbonate. Differences in redox potential result in higher iron, calcium and bicarbonate and lower sulfate contents in cluster 6 compared to cluster 5. Chloride concentrations point to recharge by sources other than precipitation.
Cluster 5 water types may originate from pollution on the ridge or in the transition zone to the Vecht plain, from infiltration of surface water in the Vecht plain and from mixing with brackish water (Figs. 3 and 4). Cluster 6 samples are primarily found in the western part of the Vecht plain following recharge of surface water through peat layers. Mineralisation produces organic complexes, ammonium and CO_2 followed by enhanced dissolution of carbonates. Low pe conditions result in sulfate reduction and in dissolution of iron and manganese oxides.

DISCUSSION

The results of the applied multivariate statistical techniques provide insight into the factors controlling regional groundwater composition in the Gooi and Vechtstreek area and an overview of the main resulting groundwater types. Groundwater composition is primarily determined by the following factors.
1) Dissolution of carbonates. This hydrochemical process predominantly

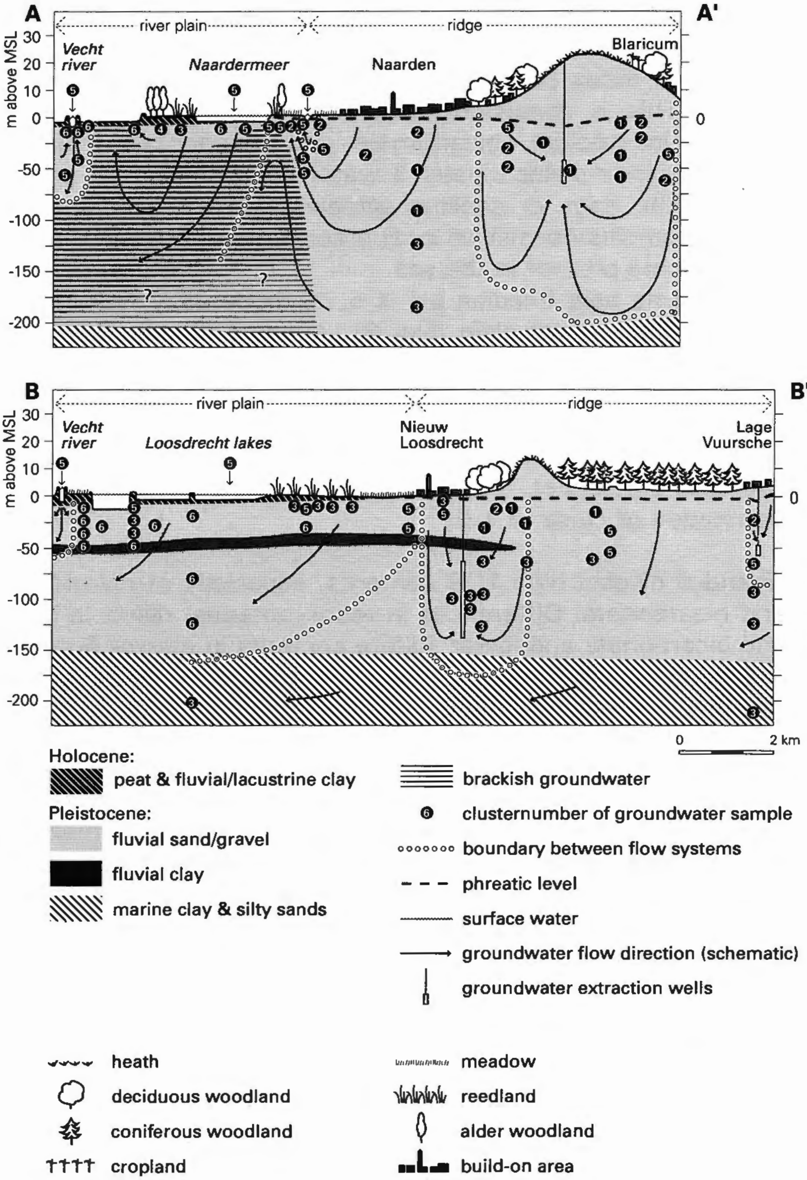

Fig. 4. Distribution of clusters along cross-sections A-A′ and B-B′ in relation to landuse and groundwater flow patterns (for location see Fig. 1).

controls calcium and bicarbonate concentrations and to a lesser degree magnesium concentrations. The six clusters all have calcium as the major cation while bicarbonate is the major anion for four clusters.

2) Decomposition of organic matter. Mineralisation produces ammonium, carbonic acid and organic complexes. Oxygen depletion may result in denitrification, dissolution of manganese and iron oxides and finally sulfate reduction.
3) Pollution. Application of manure and fertilizers, leaking sewage and cesspools are the main sources for high nitrate, sulfate and potassium concentrations.
4) Recharge of surface water affected by Vecht river water. This is the main source for high sodium and chloride concentrations in fresh groundwater of the western part of the study area.
5) Mixing of fresh and brackish groundwater.

Plotting the spatial distribution of clusters enables consideration of groundwater composition in relation to landuse, soil conditions and flow patterns. The cluster maps not always seem to be straightforward and are only roughly consistent with what could be expected on basis of regional soil conditions and groundwater flow patterns (Fig. 1). This is primarily caused by spatial differences in landuse, which cannot be displayed in the necessary detail with the map scale used. On the other hand, genetically different groundwater types may be grouped in the same cluster. Cluster 5, for example, contains samples of rather dilute groundwater recharged on the ridge, of groundwater affected by infiltration of surface water in the Vecht plain and of mixed fresh-brackish groundwater. The cross-sections allow for a more detailed comparison of groundwater composition, landuse and groundwater flow patterns. Moreover, they provide insight into the evolution of groundwater composition with depth.

Human activities considerably affect groundwater composition in the study area, directly through different forms of landuse and indirectly through intervention in natural groundwater flow patterns.
Pollution from a number of different sources is an obvious example of a direct influence, noticeable especially on the ridge where population density is high. Polluted water types are generally found in relatively shallow groundwater indicating increased pollution resulting from changes in landuse (urbanization, agricultural intensivation) over the past decades.
Indirect effects are noticeable mainly in the Vecht river plain. Groundwater extraction resulted in a decreased supply of groundwater from the ridge, while differences in polder water levels created groundwater flow from high-level to low-level polders. These factors resulted in seepage areas changing into infiltration areas starting mineralisation of peat layers and associated

secondary hydrochemical processes like denitrification, dissolution of manganese and iron and sulfate reduction. Groundwater extraction and drainage necessitated suppletion of polders and natural wetlands with polluted Vecht water. Subsequent infiltration of suppletion water resulted in groundwater with a Vecht water-like composition. Finally, the flow of groundwater from high-level to low-level polders caused displacement of the former stagnant brackish groundwater body under the Vecht river plain (Schot and Molenaar, 1990) resulting in increased mixing of fresh and brackish groundwater.
Taking an overall view it must be concluded that human activities affect groundwater composition in the study area on a regional scale.

High calcium and bicarbonate concentrations deserve special attention. Dissolution of carbonates is a naturally occurring process as is evidenced by unpolluted water types in the ridge (clusters 1 and 3). Calcium and bicarbonate concentrations generally increase slightly with depth as a result of addition of carbonic acid from mineralisation of organic matter present in small clay lenses in the sandy aquifer (cluster 3). Groundwater from the ridge flows towards the adjacent low-lying areas. High calcium and bicarbonate concentrations in Dutch river plains are therefore often interpreted as indicators for seepage of groundwater recharged in elevated sandy areas.
Hoogendoorn (1983) suggested that high calcium and bicarbonate concentrations in areas with shallow water tables may not be caused by seepage of old, 'mature' groundwater but rather by local recharge through a biologically active soil. The high soil CO_2-pressure caused by mineralisation of organic matter then constitutes the driving force for strong dissolution of calcium bicarbonate.
In the study area cluster 6 shows highest calcium and bicarbonate concentrations. The low pe conditions and high ammonium concentration point to mineralisation processes. Thus for the study area highest calcium and bicarbonate concentrations are indeed associated with local recharge through peat layers as suggested by Hoogendoorn. On the other hand, chloride concentrations in cluster 6 indicate recharge by surface water affected by added Vecht river water which displays high calcium and bicarbonate contents even before infiltration.
Definite conclusions about the interpretation of calcium and bicarbonate concentrations, and likewise of other chemical parameters, must be based on a more detailed, quantitative study in which the vertical distribution of water types is related to lithology, past and current groundwater flow patterns and changes in infiltration water quality over time. Such a study with respect to hydrochemical processes in wetlands of the Vecht river plain is currently in progress.

Acknowledgements
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CHAPTER 6

CALCIUM CONCENTRATIONS IN WETLAND GROUNDWATER IN RELATION TO WATER SOURCES AND SOIL CONDITIONS IN THE RECHARGE AREA

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ABSTRACT

Over the past decades species-rich low-productive rich fen vegetation in Western European lowland wetlands show a decline and are replaced by highly-productive rich fen on one hand and poor fen and bog on the other hand. High groundwater calcium concentrations are generally believed to constitute an important conditioning factor for the vegetation of rich fens. Management for the protection of low-productive rich fens therefore generally aims at conservation of calcareous groundwater conditions in the root zone of lowland wetlands. In this paper the occurence of calcium-rich groundwater in lowland wetlands is related to water sources and soil conditions in the recharge area for an area in the Central Netherlands. The chemical composition of the following genetic groundwater types is compared: groundwater recharged at a sandy ridge adjacent to the wetland area (ridge water), groundwater recharged by precipitation within the wetland (peat water) and groundwater recharged by infiltrating surface water in the wetland. Objective hydrological criteria are used to classify groundwater analyses according to recharge area.

All genetic groundwater types contain calcium. In contrast to what is generally assumed, lowest concentrations are observed in ridge water. Higher calcium concentrations are attained in groundwater recharged in wetlands, especially in infiltrated surface water. Nutrient concentrations in infiltrated surface water are, however, significantly higher than those in ridge water and peat water. The main conclusion for nature conservation strategies is that calcium-rich, mesotrophic conditions in the root zone of lowland wetlands can be brought about not only by seepage of ridge water, but also by seepage of peat water.

It is recommended to make oxygen-18 analysis standard procedure in geohydrological wetland research, as it proved an essential criterion for the distinction between genetic groundwater types. Calcium concentrations are generally not suitable as tracers of different types of recharge areas.

INTRODUCTION

The species composition of freshwater wetland vegetation of Western European lowlands has changed considerably over the past decades (De Molenaar, 1980; Van de Berg & De Smidt, 1985). Low-productive rich fen vegetation shows a decline and is replaced by highly-productive rich fen on one hand and poor fen and even bog on the other hand (Succow, 1988; Giller & Wheeler, 1988; Verhoeven et al., 1988; Wassen et al., 1990).
Low-productive rich fen has a characteristic species-rich vegetation of low sedges, herbs and brown mosses. During development to a highly-productive rich fen a shift to a species-poor vegetation of tall sedges, grasses and herbs occurs. Poor fens have a low productivity but compared to low-productive rich fens they are less species-rich and *Sphagnum* species are present in the moss layer. Bogs are very species-poor and have a moss layer dominated by *Sphagnum* and *Polytrichum* (Westhoff & Den Held, 1969; Wheeler, 1980a, b, c).

The development of low-productive rich fen to highly-productive rich fen is caused by drainage and subsequent mineralisation of the peat (Succow, 1988) or by eutrophication resulting from the inflow of polluted groundwater or surface water (Verhoeven et al., 1988; Roelofs, 1989).
The development of low-productive rich fen to poor fen and bog is partly a natural process (autogenic succession) but in many cases this succession is accelerated by human interferences (allogenic succession; e.g. Succow, 1988; Wassen et al., 1989). Groundwater in rich fens shows significant higher calcium and bicarbonate concentrations and a higher pH than poor fens and bogs which led to the conclusion that these abiotic parameters constitute an important conditioning factor for the vegetation of rich fens (Waughman, 1980; Kemmers, 1986).
Calcareous conditions in the root zone in lowland wetlands in the Netherlands are generally attributed to upward seepage of groundwater from adjacent elevated sandy recharge areas, where infiltrating precipitation dissolves calcite from the sediment matrix during flow towards the low-lying river valleys (Van Wirdum, 1980; Beltman, 1984; Grootjans et al., 1985; Kemmers, 1986; Wassen et al., 1989). Over the past decades this type of groundwater seepage has decreased as a result of an increased extraction of groundwater from the elevated recharge areas for public and industrial water supply.
The decline of low-productive rich fens in lowland wetlands in the Netherlands has therefore been linked to the decreased seepage of calcium-rich groundwater (e.g. Grootjans et al., 1988; Beltman & Grootjans, 1986; Wassen et al. 1990).

It is, however, not clear if calcareous conditions in groundwater in lowland freshwater wetlands originate only from groundwater seepage from elevated recharge areas. Hoogendoorn (1983) noticed that shallow groundwater in elevated sandy recharge areas in the Eastern Netherlands is aggressive and undersaturated with respect to calcite and therefore concluded that calcite has been leached from the upper part of the aquifer. He calculated the maximum possible calcium concentration if this aggressive, unsaturated groundwater would dissolve calcite until saturation in the deeper, unleached part of the aquifer. The calcium concentrations observed in shallow groundwater of the adjacent lowland were, however, significantly higher than those calculated. Hoogendoorn therefore suggested a local origin for this groundwater in contrast to seepage from the elevated recharge areas. The higher calcium concentrations are supposed to be derived from dissolution of calcite which is present in a biologically active, hydromorphic soil zone.
Hydrochemical calculations based on open and closed system theory of calcite dissolution, show that the highest Ca concentrations are indeed to be expected in water which has infiltrated locally through a calcite containing soil (e.g. Appelo, 1988).

Management for the protection of rich fens generally aims at conservation of calcareous groundwater conditions in the root zone. Knowledge on how such conditions come about is therefore of direct importance.
In this paper the hypothesis of Hoogendoorn is tested, which assumes a local recharge source for fresh groundwater with a high calcium concentration in Dutch lowland wetlands. For this purpose the chemical composition of groundwater recharged locally in the wetlands is compared with that of groundwater from an elevated sandy recharge area for an area in the Central Netherlands.

THEORETICAL CONSIDERATION OF CALCITE DISSOLUTION

Dissolution of calcite is controlled mainly by CO_2 concentration in water which provides the acid necessary for dissolution (Stumm & Morgan, 1970; Bolt & Bruggenwert, 1976). CO_2-pressure in precipitation is in the order of $10^{-3.5}$. Soil air pCO_2 can be considerably higher (10^{-2} to $10^{-1.5}$) due to CO_2 production through root respiration and bacterial decomposition of organic matter. Two extreme situations may be distinguished with calcite dissolution (Garrels & Christ, 1965):

1. Open system dissolution under constant CO_2-pressure. This is the case for a calcite containing soil in which calcite dissolves until saturation at

the fixed CO_2-pressure. CO_2 which is used during calcite dissolution is immediately replenished as a result of the constant soil CO_2-pressure.

2. Closed system dissolution in which calcite is absent in the soil zone. Recharge water loaded with CO_2 from the soil zone is transported downward where it may encounter calcite in deeper layers. In this case dissolved CO_2 concentration is lowered during calcite dissolution in the absence of a CO_2-production source.

Open system dissolution of calcite leads to higher Ca and HCO_3 concentrations in groundwater compared to closed system dissolution (Table 1). Open system dissolution is characterized by a near-neutral pH and a high CO_2-pressure matching that of soil air. High pH and low pCO_2, down to less than atmosperic CO_2-pressure, point to closed system dissolution.

Table 1. Summary of possible concentrations in water in which calcite dissolves until saturation at around 25°C (from Appelo, 1988).

Presence of calcite		absent		absent in soil zone, present in deeper layers		present in soil zone	
Type of dissolution system		open		closed		open	
soil air:							
pCO_2	(atm)	$10^{-2.0}$	$10^{-1.5}$	$10^{-2.0}$	$10^{-1.5}$	$10^{-2.0}$	$10^{-1.5}$
water:							
pCO_2	(atm)	$10^{-2.0}$	$10^{-1.5}$	$10^{-4.1}$	$10^{-2.6}$	$10^{-2.0}$	$10^{-1.5}$
Ca	(mg/l)	-	-	12	40	64	100
Alkalinity	(mg/l HCO_3)	0.6	1.2	37	122	183	305
pH		4.9	4.6	8.7	7.7	7.3	7.0
EC	(mS/m)	0.1	0.2	6.5	20	32	50

DESCRIPTION OF THE STUDY AREA

The study area is located in the Central Netherlands (Fig.1). Its main topographic feature is a sandy ridge ranging in elevation from 0 to 30 m above mean sea level. To the east and west the ridge is bordered by the flat-lying Eem and Vecht river plains.

At a depth of 150-200 m below mean sea level a sequence of Early Pleistocene marine clays and silty sands is present which is generally considered as the basis for groundwater flow (Witmer, 1989). The main aquifer was formed during the Middle Pleistocene as fluvial sands and gravels were

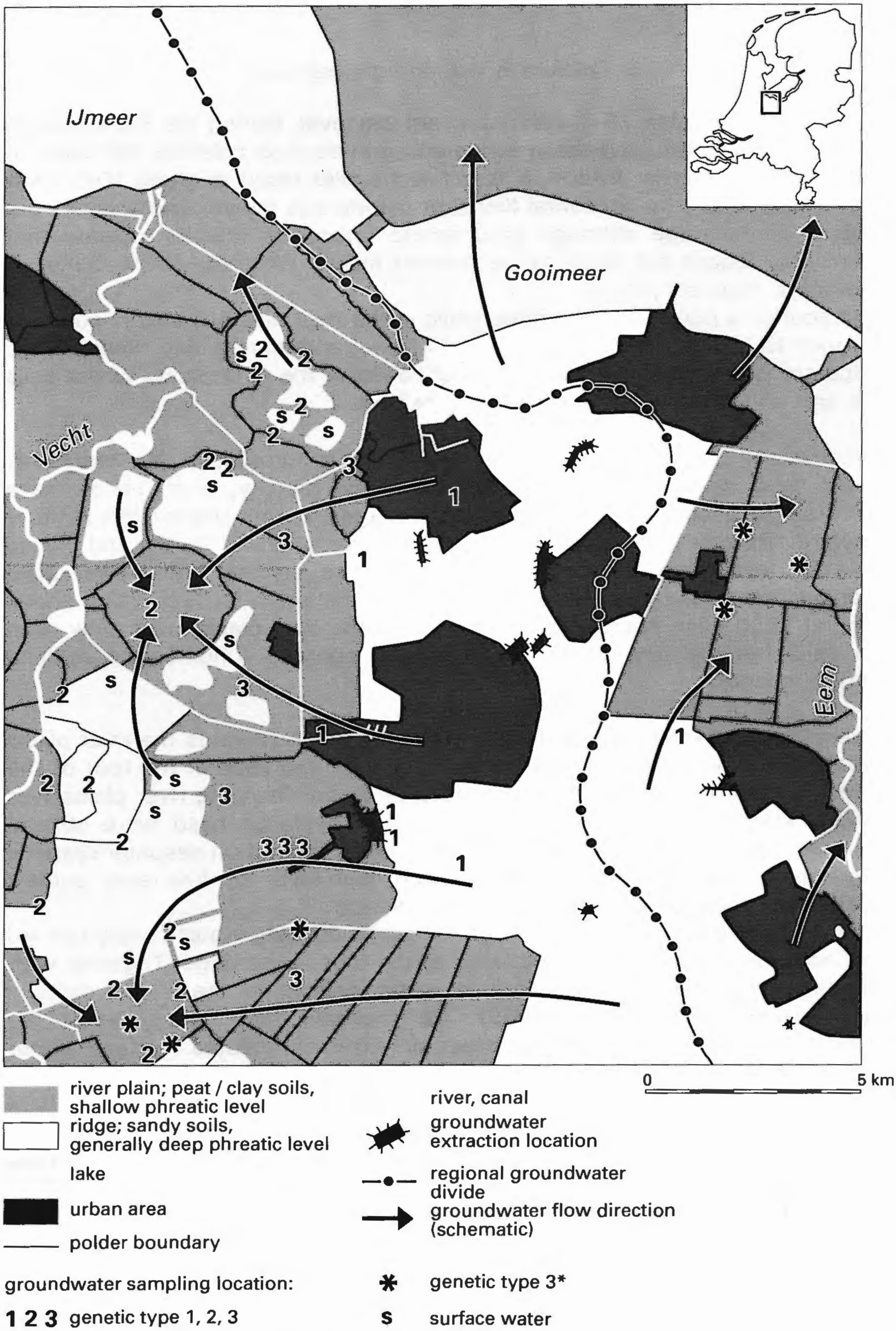

Fig. 1. Location and topography of the study area.

deposited upto some 20 m below present sea level. During the Saale ice-age moving glaciers thrusted these sands and gravels thus creating the ridge. In places the aquifer is divided in two (Vecht river plain) or three (Eem river plain) subaquifers by horizontal fluvial or marine clay layers. These layers are absent in the ridge although groundwater modelling studies indicate that tilted clay lenses are likely to be present locally (Witmer, 1989; Schot & Molenaar, manuscript).
The aquifer is phreatic in the ridge while in the river plains it is semi-confined through Holocene layers of peat and of fluvial and marine clay. Soils on the ridge are generally dry and sandy as opposed to the river plains where soils are wet and rich in organic matter and/or clay.

Landuse on the ridge consists of urban areas surrounded by woodland, heath and agricultural areas. The naturally marshy river plains have increasingly been drained for agricultural purposes from the twelfth century onward. Polders were created in which surface water levels and hence phreatic levels are artificially controlled. Lakes on the Vecht river plain resulted from natural causes and from peat excavation for fuel which ended around 1920 (Van Raam, 1979). Nowadays the river plains are mainly used for dairy farming. The Vecht river plain also contains a number of wetland nature reserves.

Overall groundwater flow is directed from the ridge towards the river plains where groundwater discharges through seepage in a zone at the foot of the ridge. Under natural conditions groundwater in the flat-lying river plains was largely stagnant as significant differences in hydraulic head were absent. Following drainage of the river plains numerous infiltration-seepage systems developed with groundwater flow from high-level to low-level polders (Schot, in press; Schot & Molenaar, manuscript).
Groundwater extraction on the ridge for public drinking-water supply has led to decreased seepage in the wetlands at the foot of the ridge. Together with drainage of polders this resulted in water deficits in the Vecht plain in summer periods (Witmer, 1989). To maintain high water levels for agriculture the polders are supplied by external polluted surface water derived from the Rhine river.

Regional groundwater composition in the study area is primarily determined by dissolution of carbonates, mineralisation of organic matter (mainly on the river plains), urban and agricultural pollution, infiltration of polluted surface water (mainly on the Vecht river plain) and mixing of fresh groundwater with brackish groundwater (Schot & Van der Wal, manuscript). Brackish groundwater is defined as $300 < Cl < 10000$ mg/l (Stuyfzand, 1986) and is present in the main aquifer in the northwestern part of the study area.

The wetland nature reserves on the Vecht river plain are of international importance because of their well developed succession series. Over the last decades, however, especially low-productive rich fens are deteriorating. Management of regional authorities focuses on protection of these low-productive rich fens by conservation of calcareous conditions in the root zone. For this purpose water management aims at restoration of the flow of calcareous groundwater towards the river plain by decreasing the amount of groundwater extracted for public and industrial water supply on the ridge (Provinciaal Bestuur van Noord-Holland, 1986).
Allowing for local differences in the geohydrological situation, the study area may be considered to be roughly representative for other lowland areas in the Netherlands where low-productive rich fens are found.

METHOD

Initial groundwater composition is determined by recharge water composition. The main source for groundwater recharge is precipitation while in the wetlands on the Vecht river plain surface water constitutes an additional recharge source. During infiltration changes in recharge water composition may occur through physical, biological and chemical processes depending on soil conditions. A further evolution of water composition may occur during groundwater flow depending on the geochemical conditions in the aquifer which consists mainly of unconsolidated quartz sands and gravels. It is assumed no significant CO_2 production occurs in the aquifer beneath the soil zone.
With respect to groundwater composition in freshwater wetlands on the Vecht river plain three main genetic types may be distinguished; ridge water, infiltrated surface water and peat water. The distinction is based on the principal differences present in the study area with respect to recharge sources (precipitation versus surface water) and soil conditions (dry sandy soils versus wet peat soils). Fig. 2 shows the genetic groundwater composition types in relation to a conceptual representation of the principal groundwater flow systems in the study area.

For each genetic type average groundwater composition is calculated on the basis of analyses of groundwater samples from the study area.
A Student's t-test (SAS, 1985) is used to asses whether the true means of chemical or isotope parameters of two different genetic groundwater types are equal or unequal, i.e. whether significant differences in groundwater composition are present between the genetic types. First, a F'(folded) statistic (Steel & Torrie, 1980) is computed to test for equality of the two

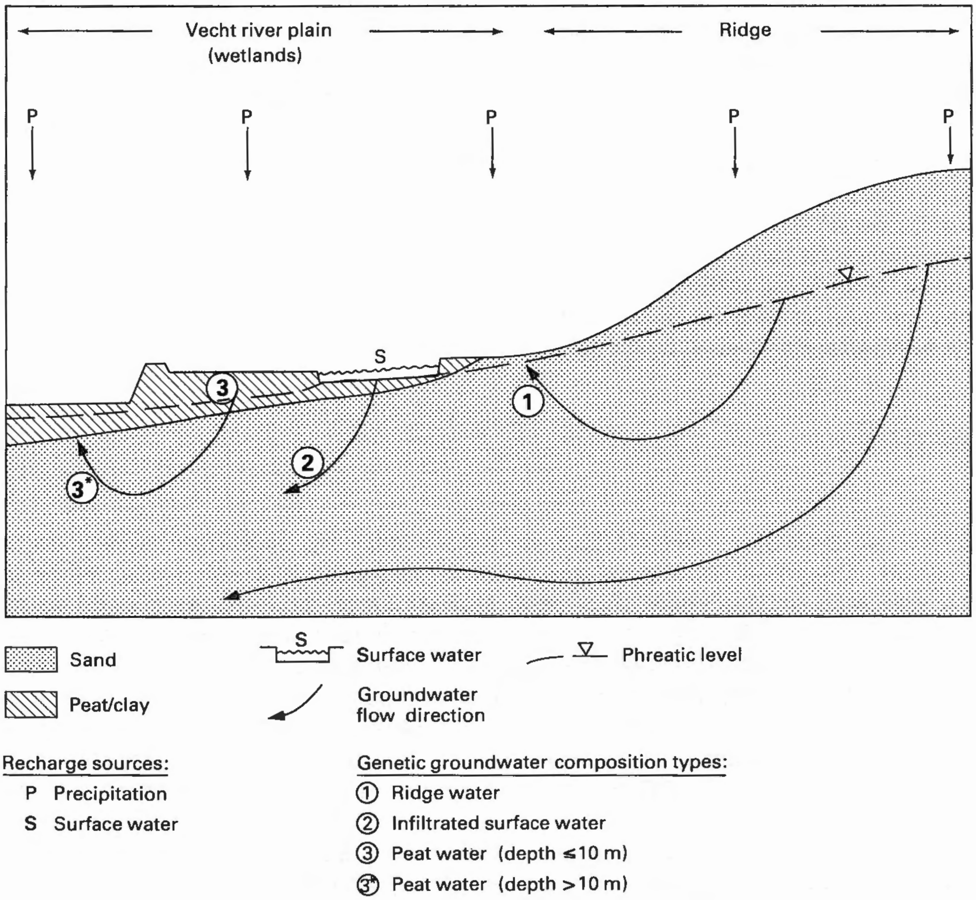

Fig. 2. Schematic cross-section of the study area showing genetic groundwater composition types in relation to a conceptual representation of the principal groundwater flow systems (based on Schot, 1989; 1990).

variances. The t-test then calculates a t statistic for equal variances and an approximate t for unequal variances.
The results of the t-test with respect to Ca and HCO_3 concentrations enable a conclusion on the validity of the hypothesis of Hoogendoorn. Significant differences between other chemical parameters are related to the observed differences in Ca and HCO_3 concentrations.

The chemical composition of the genetic groundwater types, and also that of surface water in the wetlands for reference, is calculated from a database containing 228 groundwater and 21 surface water analyses from the study area. Each analysis includes 15 chemical parameters, an oxygen-18 analysis and sometimes one or more other isotope parameters.

Reliability of the data was tested by charge balance calculations. For the 68 analyses used in the calculations, 96 % are within 5% deviation from electro-neutrality. Only three analyses show a deviation between 5 and 10%.

For each analysis the following parameters have been calculated: CO_2-pressure (pCO_2), calcite saturation index (SI_c), HCO_3, TIC and CO_3. The calculation method described by Stuyfzand (1989) has been used which is relatively simple in as far as input parameters are restricted to temperature, pH, electrical conductivity, alkalinity and the concentrations of calcium and sulfate. Alkalinity is assumed equal to the sum of HCO_3 and CO_3 concentrations. Calcium concentrations are corrected for complexation as $CaSO_4{}^{o}$. The method is applicable for temperatures 0-90°C, pH 4.35-9.5 and ionic strenght 0-700 mmol/l or electrical conductivity 0-5200mS/m (20°C) and produces results for TIC and calcite saturation with an accuracy comparable to those of speciation models like WATEQF (Plummer et al., 1976).

CLASSIFICATION OF GROUNDWATER ANALYSES

Essential in the approach is that for each groundwater sample an objective assesment is possible of the genetic type it represents. For that purpose use is made of the following criteria:

Location. Taking the general groundwater flow pattern in the study area into consideration, the sampling location provides a first indication of the general soil conditions in the recharge area of the groundwater sampled. Samples from the ridge have infiltrated on the ridge. Samples from the river plains may originate either from the ridge or from the river plain (Fig. 2).

Oxygen-18 concentration. Average δ18O values of groundwater reflect those in precipitation times a concentration factor due to evaporation. Groundwater δ18O values in Pleistocene sandy infiltration areas in the Eastern Netherlands amount to -7.5 ± 0.5 ‰ (Mook, 1984). All δ18O values have been corrected on basis of Cl content for possible mixing with brackish water. When corrected δ18O values are higher than those in groundwater from the elevated infiltration areas (> -7.0 ‰) they have been subjected to increased evaporation compared to those on the ridge. Increased evaporation occurs mainly from surface water and to a lesser degree from the peat and clay layers in the wetlands as infiltration is

Table 2. *Criteria for the classification of groundwater samples as genetic groundwater composition types.*
Brackish groundwater (300 < Cl⁻ < 10000 mg/l) is left out of consideration.

Genetic type	Location	Oxygen-18 (°/₀₀ V-SMOW)	Cl^- (mg/l)	NO_3^- (mg/l)
1 = ridge water	ridge	$\delta^{18}O < -7.0$	< 20	< 1
2 = infiltrated surface water	Vecht river plain	$\delta^{18}O > -4.7$		
3 = peat water (depth ≤ 10 m)	river plain	$-7.0 < \delta^{18}O < -6.0$	< 31	< 1
3*= peat water (depth > 10 m)	river plain	$-7.0 < \delta^{18}O < -6.0$	< 31	< 1

hampered by low hydraulic conductivity.
Chloride concentration. The conservative chloride ion can be used as a tracer of various groundwater sources. Groundwater recharged by precipitation will reflect chloride concentration in precipitation times a concentration factor due to evaporation. External surface water shows relatively high chloride contents (ca. 100-300 mg/l). Groundwater pollution is generally reflected by increased chloride contents which enables the use of chloride to exclude polluted samples. Polluted groundwater may lead to misinterpretation of natural groundwater composition, e.g. through increased Ca concentrations from fertilizer application.
Nitrate concentration. Nitrate concentrations in natural groundwater are generally below 1 mg/l (Meinardi, 1976; Appelo et al., 1982; STOM, 1983). Higher concentrations may therefore point to pollution. Since pollution is not reflected by increased chloride concentrations for all cases, nitrate is used as an extra tracer to exclude samples affected by pollution.

Groundwater samples can be classified according to genetic type on the basis of specific combinations of the above criteria (Table 2).
Type 1 samples originate from wells on the ridge (Fig. 1). Their δ18O value is < -7.0 °/₀₀, which is approximately the average upper boundary observed in recent precipitation. This requirement excludes a number of samples from the ridge with relatively high δ18O values. These samples represent old groundwater from a period when oxygen-18 concentration, and possibly also chemical composition, of precipitation differed from that in recent precipitation. The chloride and nitrate criteria exclude samples of polluted groundwater. The Cl concentration of 20 mg/l equals the average chloride

content of precipitation (5 mg/l; KNMI/RIVM, 1985) times a maximum concentration factor for the ridge of 3.8 (Appelo et al., 1982).
Type 2 samples originate from the Vecht river plain. To certify that the groundwater sample reflects infiltrated surface water, δ18O must be larger than the smallest δ18O value observed in surface water samples from wetland lakes on the Vecht river plain, i.e. -4.7 °/₀₀.
Type 3 samples originate from wetlands on the Vecht river plain and were taken in or directly below peat layers. As a result of a larger concentration factor in peat layers higher δ18O values may be expected for type 3 samples compared to those of type 1. To exclude possible influences of infiltrated surface water δ18O must be significant lower than that of type 2 samples. Thus a safe requirement has been formulated for type 3 samples; $-7.0 < \delta 18O < -6.0$. Pollution by agricultural activities is excluded through the chloride and nitrate requirements. The chloride concentration of 31 mg/l has been calculated on the basis of the average concentration in precipitation times a concentration factor of 6.1 (open water evaporation).
For the interpretation of Ca and HCO_3 concentrations of type 3 samples it appeared necessary to consider deep samples, not taken in or directly below the peat layer, separately. Deep type 3 samples (> 10 m below ground surface) are hereafter denoted as type 3*.

RESULTS

Fig. 3 shows the relation between calcium concentration, pCO_2 and calcite saturation for each genetic groundwater type. The diagram facilitates interpretation of calcium concentrations in terms of open and closed system dissolution of calcite. For clarity, the following discussion is based on average parameter values for each genetic groundwater type (Table 3).

Groundwater of type 1 (ridge water) is close to saturation and shows characteristics of closed system calcite dissolution. Calcium and bicarbonate concentrations, pCO_2 and pH resemble those in Table 1 for soil air pCO_2 of $10^{-1.5}$. Apparently calcite has been leached from the upper part of the aquifer on the ridge and is present only in deeper parts of the aquifer where it dissolves under closed conditions. Dissolved CO_2 is used up during calcite dissolution and the final calcium concentration is consequently relatively low.

The calcium concentration of type 3 groundwater (shallow peat water) resembles that of type 1. CO_2-pressure is, however, significantly higher in type 3 indicating open system dissolution of calcite. The strong

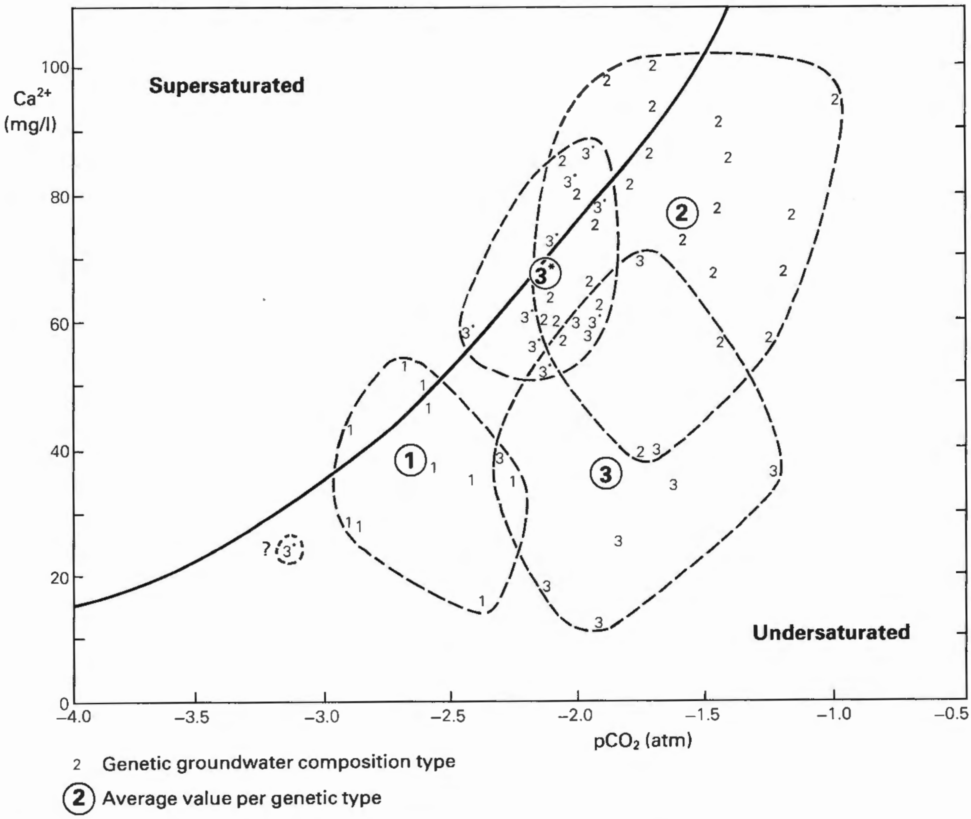

Fig. 3. The relation between CO_2-pressure (pCO_2), calcium concentration and calcite saturation (diagram from Holland et al., 1964).

undersaturation of type 3 groundwater indicates insufficient calcite is present in the wetland peat layers. As the water remains agressive (high pCO_2, TIC > HCO_3, low pH) it has the potential to dissolve additional calcite.

This is indeed observed during the evolution of type 3 groundwater into type 3*. The calcium concentration is significantly increased as shallow groundwater from peat layers flows through the Pleistocene sand aquifer underlying the wetlands. Calcite is dissolved almost until saturation in type 3* groundwater indicating calcite is sufficiently present in the sand aquifer. The decreased CO_2-pressure indicates that dissolution conditions change from open in the peat layers to closed in the sand aquifer as water comes out of reach of CO_2 sources.

Table 3. Average composition of genetic groundwater types. Surface water (S) is included for reference. Concentrations of HCO_3, pCO_2, SI_c, and CO_3 are calculated. SI_c is calcite saturation index ($SI_c = 0$ for saturated water). Concentrations in mg/l, pCO_2 in atm., TIC in mg/l HCO_3, EC in mS/m, ^3H in Tritium Units, $\delta^{18}O$ in ‰$_{V\text{-}SMOW}$, depth in meter. Significant differences between parameter values of genetic types, 3 and 3 are indicated by letters (t-test, $p < 0.01$). Values followed by different letters are statistically unequal; values without a letter are statistically equal. Values between brackets indicate that the number of samples is less than that indicated by N.*

Genetic type	1 ridge water	S surface water	2 infiltr. surface water	3 peat water (shallow)	3* peat water (deep)
Ca	37[a]	53	75	34[a]	63[b]
HCO_3	122[a]	127	268	123[a]	229[b]
TIC	129[a]	140	327	170	249[b]
pCO_2	-2.6[a]	-2.6	-1.7	-1.8[b]	-2.1[b]
SI_c	-0.3[a]	-0.1	-0.5	-1.4[b]	0.0[a]
pH	7.7[a]	7.7	7.1	6.8[b]	7.5[a]
CO_3	0.3[a]	0.9	0.4	0.1[b]	0.5
Na	9	58	33	9	9
Mg	2.5	7.6	8.4	5.5	4.2
SO_4	11	45	7	15	1
Fe	3.8	0.2	9.6	7.3	5.8
Mn	0.13	0.05	0.50	0.32	0.15
NH_4	0.2	0.3	5.5	1.0	0.9
PO_4	0.07	0.03	0.38	0.34	0.19
K	1.0	5.3	2.6	2.0	1.5
SiO_2	10.4[a]	2.2	15.7	12.8	19.8[b]
EC	24[a]	59	57	25	35[b]
^3H	2	34	23	(29)	1
$\delta^{18}O$	-7.5[a]	-3.5	-3.9	-6.7[b]	-6.3[c]
Cl	14	96	67	16	12
NO_3	0.16	0.16	0.15	0.26	0.20
Depth	72	0	26	3.6	68
Watertype	$CaHCO_3$	CaCl	CaHCO3	$CaHCO_3$	$CaHCO_3$
N	10	13	25	8	12

The highest calcium concentration is found for type 2 groundwater (infiltrated surface water). Together with the high pCO_2 this points to open system dissolution. The observed calcium and bicarbonate concentrations and pH correspond well to those in Table 1 for open system dissolution with calcite present in the soil zone.
Calcite saturation increases from highly undersaturated for type 3 to almost saturated for type 3*. This indicates that, in wetland infiltration areas, calcite is more readily available in sediment on the bottom of lakes and ditches than in peat layers. This may originate from calcite precipitation in surface water following volatilisation of dissolved CO_2 as a result of differences in CO_2-pressure in surface water and in the atmosphere. CO_2 uptake by biological activity may be another cause of calcite precipitation in surface water.

The calcium concentrations of genetic groundwater types 1 and 3 are relatively low and statistically indifferent. Type 3 groundwater, however, is highly undersaturated with respect to calcite. A comparison of final calcium concentrations between genetic types should therefore be based on types 1 and 3*. These types are statistically indifferent with respect to calcite saturation (slightly undersaturated) and show comparable groundwater age ('old'; low tritium (^3H) in Table 3) and sampling depth.
The calcium concentration in type 3* groundwater is found to be significantly higher than in type 1 groundwater. Therefore, it may be concluded that the hypothesis of Hoogendoorn is correct, i.e. in the wetlands of the study area higher final calcium concentrations are attained in groundwater recharged by local precipitation than in seepage of groundwater from the adjacent ridge.

DISCUSSION

In the foregoing the calcium concentrations have been compared of different genetic groundwater types in freshwater wetlands on the Vecht river plain. The validity of the conclusions depend on the applied method and its assumptions and uncertainties.
It has been attempted to prevent faulty classification of groundwater analyses by defining narrow criteria for the distinction between genetic groundwater types. Moreover, analyses need to meet not only one but all of a combination of criteria, which makes erroneous classification unlikely.
For the comparison of genetic types average groundwater composition is used. Due to the narrow criteria the final number of analyses per genetic type is relatively small. Moreover, parameter values within genetic types

show variation. Therefore, a t-test was performed with a low probability level ($p < 0.01$) to assure that the differences observed are significant and may safely be assumed to represent real differences.

The most critical parameter in the calculation of calcite saturation and CO_2-pressure is pH. During sampling of groundwater through air lift or vacuum pumping volatilisation of dissolved CO_2 may occur followed by an increase in pH. In the groundwater sample pCO_2 becomes too low and calcite saturation becomes too high compared to the actual groundwater. This implies that the actual groundwater has an extra potential to dissolve calcite which would consequently lead to higher calcite and bicarbonate concentrations. Volatilisation is probably highest in groundwater with a high pCO_2 while in open systems more additional calcite can be dissolved. Calcium concentrations would thus increase most in genetic types 2 and 3 which would confirm the main conclusions.

It has been concluded that groundwater recharged locally within a wetland can attain comparable or higher calcium concentrations than groundwater recharged on the ridge. Calcareous groundwater conditions in the root zone of rich fens can therefore be brought about not only by upward seepage of ridge water but also by seepage of groundwater recharged in adjacent wetlands.
This is of direct importance for nature conservation strategies.
When it is assumed that calcium-rich groundwater s.s. is important for low-productive rich fens then water management should focus on seepage of groundwater in general, no matter what the origin of the groundwater.
However, calcareous conditions as such may not have a direct effect on plant growth. In low-productive rich fens the availability of especially phosporus appears to be low (Waughman 1980, Wassen et al., in press). Patrick (1974) and Kemmers (1986) ascribe an important role to the Ca^{2+}-ion for phosphate availability to plants through precipitation of Ca-P minerals. Wilson and Fitter (1984) suggested that micro-organisms decrease phosphate availability through conversion of inorganic-P to organic forms under calcium-rich conditions. It remains unclear, however, whether phosporus is the limiting factor in low-productive rich fens, since many contradicting results have been published upon the relation between phosporus and also nitrogen and potassium contents in groundwater and soil and species composition along the rich fen - poor fen - bog gradient (e.g. Waughman, 1980; Wilson & Fitter, 1984; Verhoeven et al., 1988a; Verhoeven & Arts, 1987; Succow, 1988; Koerselman et al., in press).
Upward seepage of ridge water and of peat water show nutrient concentrations which are statistically equal at a $p < 0.01$ level. Only at a $p < 0.05$ level a higher ammonium concentration is observed in seepage of

peat water. In contrast, however, calcium concentration is significantly higher in upward seepage of peat water ($p < 0.01$), which may exert a limiting effect on phosphorus availability to plants. Infiltrated surface water shows even higher calcium concentrations, but the concentrations of all nutrients are also significantly higher than those in ridge water and peat water.
The main conclusion for nature conservation is therefore that calcium-rich mesotrophic conditions in the root zone can be realised not only by seepage of groundwater from elevated sandy recharge areas, but also by seepage of peat water.

Comparison of groundwater composition between genetic types was possible only through the use of objective criteria.
It must be stressed that the calcium concentration in a groundwater sample generally does not provide a suitable tracer of the origin of the groundwater. Fig. 3 indicates that an overlap in calcium concentrations exists between the various genetic groundwater types. Therefore calcium concentrations alone should not be used as indicator of the recharge area of the sampled groundwater.
In contrast, the oxygen-18 isotope provided essential information for the distinction of genetic groundwater types. Oxygen-18 analysis should therefore become standard procedure in geohydrological wetland research.

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CHAPTER 7

DISCUSSION AND CONCLUSIONS

1. SOLUTE TRANSPORT BY GROUNDWATER FLOW

Solute transport by groundwater flow in the Gooi and Vecht area is characterised by steady state and dynamic elements of convective groundwater flow and of solute concentrations in the direction of flow.

1.1. Steady state convective groundwater flow

The present (1985) convective groundwater flow patterns have been deduced from hydraulic heads and from environmental tracers.

The steady state numerical groundwater model FLOWNET has been used to simulate the present-day groundwater flow patterns along cross-sections from the ridge towards the Vecht river (chapters 2, 3 and 4). The cross-sections were taken in the direction of lateral flow as deduced from groundwater contour maps.
Groundwater flow patterns are controlled by natural topographic elevation differences between the ridge and the river plain, by groundwater extractions on the ridge and by polder- and surface water levels in the Vechtstreek. Groundwater from the ridge is transported towards the adjacent polders where it is discharged by upward seepage and towards the Horstermeer polder. In the Vecht river plain numerous infiltration-discharge groundwater flow systems connect polders with relatively high surface water levels to polders with relatively low levels. Such flow systems also connect the canals and the Vecht river to the adjacent polders. In some places water recharged on the river plain infiltrates to depths of 150 m in the 200 m deep aquifer system.

Environmental tracers have been used to verify the groundwater flow patterns simulated by the groundwater model (chapters 3 and 4).
Groundwater chloride and oxygen-18 concentrations confirm precipitation as the main source of recharge on the ridge and seepage of ridge water in the eastern part of the Naardermeer wetland. Moreover, they confirm infiltration of surface water from canals, wetland lakes and the Vecht. Groundwater tritium values along the Naardermeer cross-section indicate recent groundwater recharge by precipitation on the ridge and on the river plain from the Karnemelksloot canal, the Naardermeer lakes and the Vecht.

Increasing age is shown in groundwater from the ridge on its way to the upward seepage area of the Naardermeer and in downward flowinginfiltrated Vecht river water. Brackish groundwater shows the lowest tritium values in accordance with its middle Holocene origin.

The tracer values thus confirm that the principal features of the contemporary groundwater flow patterns are correctly calculated by the groundwater model.

1.2. Changes in convective groundwater flow; type-1 fronts

Changes in tracer values in the direction of the present groundwater flow indicate the existence of fronts in groundwater composition.
In the Naardermeer fronts have been found between fresh and brackish groundwater which have been interpreted as the effect of antropogenous changes in groundwater flow patterns. This implies that the long-term dynamics of groundwater flow are important in the study area.

The long-term dynamic character of groundwater flow has been further studied by comparing simulations of the steady state groundwater flow pattern for four points in time which represent the most important hydrological changes over the past 600 years (chapter 4).
The simulations indicate that groundwater flow patterns changed considerably in the Gooi and Vecht area. The natural simple flow pattern dominated by the topographic height difference between the ridge and the Vecht river plain changed to a distorted, complex flow pattern dominated by artificially man-controlled hydraulic heads, especially during the past century.
The results confirm the interpretation in chapter 3 of the fronts in the Naardermeer wetland as being the effect of antropogenic changes in groundwater flow patterns.

Changes in flow patterns have also affected groundwater composition; e.g. the replacement of brackish groundwater under the river plain by fresh water derived from precipitation and surface water.
It is important to notice that these fronts are indeed caused by changes in flow patterns and not by chemical processes. Because of the clear contrast between fresh and brackish groundwater types the fronts described in chapters 3 and 4 are quite obvious due to changes in flow patterns. In other cases, however, this is less clear. For example, when groundwater recharge changes from precipitation on the ridge to precipitation through peat on the river plain, this is reflected only by oxygen-18 concentration rather than by

groundwater flow patterns might have gone unnoticed, leading to an erroneous interpretation of groundwater composition and hydrochemical processes.

The combined use of a numerical groundwater flow model and environmental tracers has been essential in discriminating changes in groundwater composition as a result of past changes in groundwater flow patterns. The use of environmental tracers, especially oxygen-18, is therefore strongly recommended in wetland related research.

1.3. Changes in initial groundwater composition; type-2 fronts

Increased pollution of groundwater is observed on the ridge (chapter 5). In contrast to deeper groundwater, shallow groundwater on the ridge shows clear characteristics of pollution through high nitrate, sulfate and potassium concentrations and an above-natural concentration of the tracer chloride. Therefore changes in initial groundwater composition (increasing pollution) occurred on the ridge during recent decades.

On the Vecht river plain several wells located in recharge areas reflect increased pollution of surface water from the Vecht river, the canals and wetland lakes. Shallow filters show increased chloride concentrations compared to deeper filters. Wells with more than one sample per filter show increased chloride concentrations in time.

1.4. Hydrochemical processes; type-3 fronts

A number of type-3 fronts due to hydrochemical processes have been identified (chapters 5 and 6). These processes appear from changes in groundwater composition in the direction of flow which are not caused by type-1 or type-2 fronts. Changes may be deduced from differences in concentrations either between the precipitation excess and groundwater or between shallow groundwater and deeper groundwater in recharge areas.

Shallow groundwater on the ridge shows increased calcium, bicarbonate and magnesium concentrations and pH and decreased ammonium and nitrate concentrations compared to the precipitation excess. This indicates dissolution of calcium- and magnesium carbonates and uptake of nutrients by vegetation in the root zone.
The evolution of ridge groundwater during prolonged flow can be deduced from a comparison of shallow groundwater with deeper groundwater, both

unpolluted. Increased manganese and iron contents and decreased nitrate and sulfate contents point to a lowered redox potential. Reduction is brought about by oxidation of organic matter, either dissolved or present in small clay lenses in the aquifer, as evidenced by increases in ammonium and in calcium, bicarbonate and magnesium following CO_2 production.

On the river plain the precipitation excess may be compared with shallow peat groundwater. Peat water shows increased manganese, iron, calcium, bicarbonate and magnesium concentrations and pH and decreased concentrations of ammonium, nitrate and also sulfate compared to the precipitation excess. This indicates processes such as dissolution of carbonates, mineralisation of peat, reduction of nitrate and sulfate and dissolution of organic complexes containing iron and manganese or oxidation of manganese- and iron oxides.
The evolution of shallow peat water during prolonged groundwater flow is reflected in significant increases in calcium and bicarbonate concentrations as well as in pH and calcite saturation. This indicates further calcite dissolution until saturation in the Pleistocene sand aquifer underlying the surficial peat layers on the Vecht river plain.

2. IMPACT OF HUMAN ACTIVITIES ON SOLUTE TRANSPORT TO WETLANDS

The impacts of human activities on wetlands in the Vecht river plain are numerous and varied.

2.1. Impact on groundwater flow

The groundwater model simulations in chapter 4 indicate that groundwater flow patterns in the study area were changed on a regional scale by human intervention.
On the Vecht river plain drainage induced numerous infiltration-discharge groundwater flow systems from polders with relatively high surface water levels to those with relatively low levels.
Groundwater extraction for public water supply changed and in places reversed flow directions in the ridge. Moreover, it greatly reduced the flow of groundwater towards the river plain. This is consistent with the modelling results of Witmer (1989).
Although not considered in detail in this thesis, groundwater flow patterns

were also affected by changes in landuse. Vegetation changes, such as artificial replacement of deciduous woodland by coniferous forests, and urbanisation decreased the quantity of groundwater recharged on the ridge through increased interception and discharge of precipitation by sewerage.

2.2. Impact on groundwater composition

Human activities also affected groundwater composition on a regional scale. Causes are the modification of natural groundwater flow patterns and changes in landuse.

The effects of changes in flow patterns on groundwater composition are most evident on the Vecht river plain. Groundwater extraction caused a decrease of groundwater supply from the ridge, while differences in polder water levels created groundwater flow from high-level to low-level polders. These factors resulted in seepage areas changing into infiltration areas. Groundwater composition changed as seepage water from the ridge was replaced by surface water from lakes and by local precipitation. This was accompanied by mineralisation of peat and associated secondary hydrochemical processes like denitrification, dissolution of manganese and iron and sulfate reduction.
Water deficits on the river plain in summer have necessitated the supply of external surface water. This supply has a negative environmental effect as the surface water is severely polluted. The subsequent infiltration of this supplementary water from wetland lakes gave the groundwater a Vecht water- or IJmeer water-like composition. Direct infiltration from the Vecht river and the canals (e.g. 's-Graveland canal, Karnemelksloot) led to pollution in adjacent polder areas through subsequent seepage.
Fresh water from the Vecht river plain and from the ridge started to replace the formerly stagnant brackish groundwater body underlying the Vecht river plain. Moreover, this resulted in increased mixing of fresh and brackish groundwater.

Landuse has changed considerably over the past century as a result of an increase in population density, especially on the ridge. Heathland and extensively used arable lands were increasingly replaced by the expanding towns. Agricultural landuse was intensified through application of organic and artificial fertilizers and pesticides. These factors have led to increasing pollution of groundwater on the ridge, caused mainly by cess-pools, leaking sewerage lines, manure and fertilizers.
Pollution on the ridge becomes apparent from chloride and nitrate concentrations along the cross-sections over the Naardermeer. The

Pollution on the ridge becomes apparent from chloride and nitrate concentrations along the cross-sections over the Naardermeer. The multivariate analysis of groundwater composition indicate above-natural solute concentrations in ridge groundwater on a regional scale for a.o. sulfate, potassium, magnesium and sodium. Furthermore, in several places contaminants like tri- and perchloroethene, heavy metals and bromacil have been found in ridge groundwater (e.g. Provinciale Waterstaat van Noord-Holland, 1985; 1986). Although the regional distribution of these contaminants has not been established they indicate the severe pollution of ridge groundwater with numerous compounds.
The ridge consists mainly of sands and gravels and contains only minor amounts of organic matter and clay. Therefore, conversion and retardation are not expected to have a large effect on contaminant concentrations during transport of groundwater through the aquifer. This is supported by the fact that in several places high concentrations of nitrate and sulfate are already common to a depth of 60 m and in some places are observed even to 90 m. Potassium and especially phosphate show retardation, although in several places clearly above-natural concentrations have been observed to depths of 60 m for potassium and 20 m for phosphate.

On the river plain the surface water of the Vecht river and the canals became increasingly more polluted. Suppletion of this polluted water to polders led to a general deterioration of surface water composition in most of the lakes and ditches on the Vecht river plain. Through infiltration of surface water, and subsequent seepage to adjacent polders, the groundwater and wetland nature reserves were also affected. Direct pollution of groundwater on the river plain by agricultural activities occurs especially in the transition zone near the ridge.

3. CONSERVATION AND RESTORATION OF WETLAND VEGETATION

3.1. Impact of groundwater composition on vegetation

A clear relationship has been found between hydrological attributes and the vegetation pattern in the Naardermeer wetland. The cluster analysis in chapter 2 indicates that the *Caricion davallianae* fen vegetation (type A1) is related to mesotrophic groundwater rich in calcium and bicarbonate. Moreover, it appears that the changes in fen vegetation in the eastern part of the Naardermeer over the past decades can be directly attributed to a man-induced shift in groundwater flow (chapter 3). Seepage of fresh species characteristic for fresh, relatively nutrient-poor wetland ecosystems were abundantly present in the seepage area of the Naardermeer (Meyer & de Wit, 1945). Recent surveys show that most of these species are now absent at locations with upward seepage of brackish groundwaters and occur exclusively in areas with calcium bicarbonate water (Wassen et al., 1989).

The relation between fresh, mesotrophic, calcium-rich groundwater and the presence of *Caricion davallianea* vegetation is generally observed in wetlands across the Vecht river plain (Beltman & Verhoeven, 1988; Wassen et al., 1990) and in freshwater wetlands elsewhere in The Netherlands, Germany, the United Kingdom and Poland (Van Diggelen et al., in press; Succow, 1988; Boyer & Wheeler, 1989; Wassen et al., in press).

3.2. Sources of mesotrophic calcium-rich groundwater

Two sources of mesotrophic calcium-rich groundwater are present in the study area, i.e. ridge groundwater and peat groundwater (chapter 6). Upward seepage of ridge water and of peat water show nutrient concentrations which are statistically equal at a $p < 0.01$ level (t-test). At a $p < 0.05$ level seepage of peat water shows a higher ammonium concentration. In contrast, however, calcium concentration is significantly higher in upward seepage of peat water which may exert a limiting effect on phospohorus availability to plants in the root zone. Although calcium concentrations are even higher in infiltrated surface water, the concentrations of all nutrients are also significantly higher than those in ridge water and peat water. Iron concentrations are statistically equal for all groundwater types.

It is important to notice the similarity between ridge water and peat water. Both are calcium-bicarbonate water types with a low chloride concentration and a high Ionic Ratio (Ca/(Ca+Cl) in meq/l; Van Wirdum, 1980). Analyses of groundwater samples from wetland areas in the Netherlands showing such characteristics are generally interpreted as ridge water. Without oxygen-18 data and a proper analysis of (local) groundwater flow patterns peat water is easily confused with ridge water.

3.3. Conservation and restoration strategies for wetland vegetation

Natural, unpolluted, ridge water provides a suitable source for the conservation and restoration of mesotrophic aquatic- and fen vegetations on the Vecht river plain. However, in the coming decades a severe deterioration

in the quality of upwardly seeping ridge water may be anticipated. Groundwater on the ridge has become increasingly polluted over the past decades. As dissolved pollutants are transported by groundwater flow they form a threat to the wetland ecosystems on the Vecht river plain.
The suitability of different water types for wetland vegetations can be evaluated with the hydro-ecological model ICHORS (Barendregt et al., 1985). The model calculates the probability to encounter any of some 200 wetland plant species given a certain water composition. Polluted groundwater from the ridge appeared to have strongly negative effects on the wetland vegetations of the Vecht river plain (Wassen et al., 1986).
A sustainable improvement of groundwater quality on the ridge can only be achieved by halting the infiltration of pollutants from urban areas, agriculture, industry, traffic, etc. This will be a difficult and slow process. Moreover, even if a total pollution stop is achieved, the effects of past pollution will continue for decades or even centuries.

Wetland management must therefore also consider water sources other than ridge groundwater as alternatives for the suppletion of wetlands with external polluted surface water. Based on chemical water composition it appears that peat water offers the best alternative water source for unpolluted ridge groundwater.
The suitability of upward seepage of peat water may be indicated by the fact that *Caricion davallianae* fens are still present in a considerable number of places in the Noorderpark, located in the southernmost part of the Vecht river plain in the study area. The Noorderpark contains extensive peat areas and a large number of infiltration-discharge flow systems from polder to polder (Schot, 1989). Recharge by precipitation can thus develop peat water which subsequently seeps upward in adjacent polders. It is therefore very likely that the rather extensive presence of mesotrophic fens in the Noorderpark is related to the upward seepage of peat water.
The suitability of peat water may also be deduced from calculations with the ICHORS-model. Wassen et al. (1986) used groundwater from the Kortenhoef polder as input water composition. This groundwater consists of peat water, although it was erroneously interpreted as ridge water by Wassen et al. Peat water appeared to offer high probabilities for mesotrophic wetland vegetations.

Up to now wetland management is directed towards regeneration of upward seepage of ridge groundwater. This has been based on the assumption that mesotrophic plant communities are dependent on calcium-rich mesotrophic ridge water. However, calcium-rich mesotrophic groundwater may also be derived from local precipitation through peat layers on the river plain. Moreover, seepage of unpolluted ridge water is assumed. The future deterioration of ridge groundwater composition has not been accounted for. This has the following implications for wetland management:

- Pollution in the peat recharge areas must be avoided in order to keep peat water clean. This is of importance for the conservation, or potential development, of mesotrophic fen vegetation on locations with upward seepage of peat water. Preventing new pollution in these recharge areas is far more easy than sanitation of existing polluted ridge water.
- Peat water can be used as alternative source for external polluted surface water to compensate water deficits in wetlands in summer.

The spatial distribution of different genetic groundwater types in the study area can be roughly deduced from general flow patterns, which indicate whether groundwater was recharged on the ridge or on the Vecht river plain (e.g. chapter 4; Schot, 1989).
Water infiltrated on the river plain may consist of either peat water or infiltrated surface water. A definite distinction between these water types can be made on the basis of existing or newly collected groundwater samples, using the criteria in chapter 6. Chloride and nitrate concentrations are generally available for existing samples. However, information on oxygen-18 content will usually necessitate additional field sampling. It is therefore recommended that in future oxygen-18 analysis will become standard procedure in wetland related research.

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SUMMARY

This thesis deals with solute transport by groundwater flow and the way in which solute transport is affected by human activities. This in relation to wetland ecosystems.

Wetlands in the eastern part of the Vecht river plain in The Netherlands are historically renown for their great variety of aquatic and fen vegetation. Over the past decades a marked deterioration of wetland vegetation has been observed. In particular species of the alliance *Caricion davalianae* disappeared. It is generally believed that the *Caricion davalianae* are dependent on rather nutrient-poor (mesotrophic) calcium-rich groundwater. In the Vecht river plain this type of water naturally originates from the adjacent sandy ice-pushed ridge 'Het Gooi'. Upward seepage of ridge water in the river plain has decreased over the past decades as an effect of increasing groundwater extraction for public water supply on the ridge. The resulting water shortages on the Vecht river plain in summer are met by import of external polluted surface water. This eutrophic water has negative effects on the mesotrophic aquatic and fen vegetation. Provincial groundwater management is therefore directed towards regeneration of upward seepage of groundwater from the ridge.

At the same time groundwater pollution on the ridge has increased. In time this may affect the vegetation on the river plain through solute transport by groundwater flow. Increased upward seepage from the ridge may thus have adverse effects. Specific research questions related to the vegetation on the river plain are:

- to what extent is the groundwater under the ridge polluted?
- are pollutants transported towards the river plain?
- are pollutants retarded or chemically altered during flow?
- is regeneration of upward seepage a good restoration measure; are there alternatives?

Chapter 1 describes a theoretical background. The main components in the analysis of solute transport by groundwater flow are convective groundwater flow and factors influencing solute concentrations. Convective groundwater flow can be described from the basis of hydraulic heads and tracers. Hydrochemical processes are inferred from differences in solute concentrations observed in the direction of flow. Differences in groundwater composition along a flow line may also result from changes in flow patterns and changes in recharge water composition. Such transitions in water composition are reffered to in this thesis as type-1 and type-2 fronts. Hydrochemical processes lead to type-3 fronts.

A step by step approach is presented for the analysis of solute transport by groundwater flow. First the present steady state groundwater flow pattern is determined. This flow pattern is verified with tracers by which transitions

in groundwater composition due to changes in flow patterns may be deduced. The development of these type-1 fronts is further studied by comparison of the present flow pattern with flow patterns on different times in the past. Next it is determined whether type-2 fronts are present. Finally, the remaining differences in groundwater composition in the direction of flow, which do not represent type-1 or type-2 fronts, are interpreted in terms of hydrochemical processes.

Chapter 2 describes the relation between hydrology and the occurence of plant species for the Naardermeer wetland. Quantity and quality of water in the Naardermeer are strongly influenced by the surrounding area. Especially important are upward seepage of calciumbicarbonate groundwater from the ridge and seepage of polluted water from an adjacent canal as well as infiltration of surface water and precipitation within the Naardermeer induced by low surface water levels in adjacent agricultural areas.
In the Naardermeer a clear relationship exists between hydrological attributes and the vegetation pattern in reed marshes. *Thelypteris palustris* reedlands are related to calciumbicarbonate water. This type of water is supplied directly by groundwater in the seepage area. It is transported further to the infiltration area by surface water. Species of *Calthion palustris* and *Cicuto-Caricetum pseudocyperi* are restricted to the seepage area. Reedlands with *Sphagnum flexuosum* are distributed in a random pattern over the Naardermeer.
The study illustrates the importance of hydrological information for the conservation of nature in wetlands. The impact of both internal and external (upstream and even downstream) processes has to be considered.

Chapter 3 decribes a groundwater systems analysis of the Naardermeer. The present groundwater flow pattern along a vertical section is simulated with the 2-dimensional, finite difference model FLOWNET. The simulated flow pattern is verified with the tracers chloride, oxygen-18 and tritium. The chloride and oxygen-18 concentrations indicate that changes in groundwater flow patterns have occurred in the Naardermeer. These changes have induced differences in water composition in the present flow direction (type-1 fronts).
The delineation of groundwater systems enables evaluation of the effects of groundwater extraction and groundwater pollution on the ridge. The reduced discharge of groundwater from the ridge resulted in a shift in groundwater systems. As an effect upward seepage of brackish groundwater in the Naardermeer was induced. This led to changes in the wetland vegetation. Moreover, it appears that the vegetation in the Naardermeer is threatened by polluted groundwater from the ridge.

The effects of changes in flow patterns on groundwater composition are considered in more detail in chapter 4. FLOWNET is used to simulate steady

state groundwater flow patterns along a cross-section from the ridge to the Vecht river for four points in time; viz., the 14th century, 1885, 1941 and 1985. These simulations represent the most important human-induced hydrological changes in the study area over the past 600 years.
The simulations indicate that groundwater flow changed from a simple pattern under natural conditions to a complex flow pattern dominated by artificially man-controlled hydraulic heads at present. On the ridge flow directions changed over large areas through groundwater extraction for public water supply. As precipitation remained the main source of recharge this had no effect on overall groundwater composition in the ridge. On the river plain impoldering induced infiltration-discharge flow systems between polders with relatively high surface water levels to those with relatively low levels. Type-1 fronts in groundwater composition were created as the naturally stagnant groundwater under the river plain was replaced by precipitation recharged through peat and by surface water from lakes, canals and the Vecht river. Since the surface waters are often polluted by a.o. sewage effluent this has an adverse effect on groundwater quality.

Chapter 5 provides an overview of regional groundwater composition in the study area in relation to changes in recharge water composition in time and hydrochemical processes. Multivariate statistical analyses are applied to determine the factors controlling groundwater composition and the main resulting water types. Increased solute concentrations in shallow groundwater on the ridge, especially of nitrate, sulfate and potassium, indicate increased pollution over the past decades as a result of urbanization and agricultural intensivation (type-2 front). The main hydrochemical process on the ridge is dissolution of carbonates from the matrix of the sandy aquifer. On the Vecht river plain decomposition of organic matter in the peat and clay soils adds ammonium, organic complexes and carbonic acid to infiltrating precipitation and (polluted) surface water. Production of carbonic acid results in enhanced dissolution of carbonates present in the soil and underlying sandy aquifer. Oxygen depletion and subsequent low redox potentials result in denitrification, dissolution of manganese and iron oxides and sulfate reduction. The displacement of brackish groundwater under the Vecht river plain by fresh recharge water is accompanied by mixing of fresh and brackish ground-water by dispersion.

In chapter 6 the calcium concentration in wetland groundwater is considered in view of the formulation of restoration measures for mesotrophic vegetation on the Vecht river plain. Calcium concentrations are related to differences in water sources (precipitation versus surface water) and soil conditions (dry sandy soils versus wet peat soils) in the recharge area. Three main genetic groundwater types are distinguished: groundwater recharged at the ridge (ridge water), groundwater recharged by precipitation within the wetland (peat water) and groundwater recharged by infiltrating surface water.

Groundwater samples are classified according to genetic type on the basis of objective hydrological criteria, i.e. sampling location and concentrations of oxygen-18, chloride and nitrate.
In contrast to what is generally assumed, lowest calcium concentrations are observed in ridge water. Higher calcium concentrations are attained in groundwater recharged in wetlands, i.e. in peat water and especially in infiltrated surface water. However, nutrient concentrations in infiltrated surface water are significantly higher than those in unpolluted ridge water and in peat water. Nutrient concentrations in unpolluted ridge water and peat water are statistically equal. This is of direct importance for nature conservation strategies. Calcium-rich, mesotrophic conditions in the root zone can be realised not only by seepage of groundwater from elevated sandy recharge areas, but also by seepage of peat water.
It is further recommended to make oxygen-18 analysis standard procedure in geohydrological wetland research, as it proved an essential parameter for the distinction between genetic groundwater types. Calcium concentrations are generally not suitable as tracers of different types of recharge areas.

Chapter 7 discusses the results of separate chapters in the context of the general aims of the thesis, i.e. the identification of solute transport and the way in which solute transport is influenced by human activities. Groundwater composition in the study area appeared to be affected not solely by hydrochemical processes but also by changes in flow patterns and changes in recharge water composition, both as an effect of human activities. The identification of these type-1 and type-2 fronts is necessary in areas with a strong human influence in order to prevent misinterpretation of hydrochemical processes.
Finally, conservation and restoration strategies for wetland plant communities on the Vecht river plain are discussed. In the near future a severe deterioration in the quality of ridge water seeping upward on the river plain may be anticipated, which will continue for decades or even centuries. This forms a threat to the mesotrophic wetland ecosystems. Peat water appears to offer the best alternative water source for unpolluted ridge groundwater as it is mesotrophic and calcium-rich. Peat water can be used as alternative source for external polluted surface water to compensate water deficits in wetlands in summers. To keep peat water clean, wetland management must prevent pollution in peat recharge areas. This is of importance for the conservation and potential development of mesotrophic fen vegetation on locations with upward seepage of peat water.

SAMENVATTING

Dit proefschrift behandeld het transport van stoffen door grondwaterstroming en de wijze waarop menselijke activiteiten dit transport beïnvloeden, een en ander in relatie tot moerasecosystemen in de Vechtstreek.
De oostelijke Vechtstreek is van oudsher bekend vanwege de grote verscheidenheid in water- en moerasvegetaties. Gedurende de afgelopen decennia is in deze verscheidenheid een duidelijke achteruitgang waargenomen. Met name de soortenrijke verlandingsvegetaties van het Knopbies-verbond (*Caricion davallianae*) zijn sterk achteruitgegaan. Algemeen wordt aangenomen dat deze vegetaties afhankelijk zijn van matig voedselarm (mesotroof) calciumrijk water. Dit water kwelt in de Vechtstreek op aan de rand van de stuwwal van Het Gooi. De kwel is in de loop van deze eeuw sterk afgenomen door toenemende onttrekking van grondwater in Het Gooi voor de drinkwatervoorziening. De mede hierdoor in de zomer optredende watertekorten in de polders van de Vechtstreek worden aangevuld door de inlaat van vervuild, eutroof boezemwater uit de Vecht, het Amsterdam-Rijn kanaal en het IJmeer. Dit water heeft een negatief effect op de mesotrafente moerasvegetaties in de Vechtstreek. Het provinciaal grondwaterbeleid is daarom gericht op het herstellen van de kwelstroom uit Het Gooi.
Tegelijkertijd is de grondwater vervuiling op de stuwwal toegenomen. Het transport van verontreinigingen door grondwater kan na verloop van tijd de vegetatie van de Vechtstreek beïnvloeden. Een toename van de kwel uit de stuwwal kan aldus negatieve effecten hebben. Voor de vegetaties in de Vechtstreek zijn o.a. de volgende vragen van belang:
- in hoeverre is het grondwater onder de stuwwal vervuild?
- worden vervuilende stoffen verplaatst naar de Vechtstreek?
- worden vervuilende stoffen tijdens de stroming vertraagd of omgezet?
- is regeneratie van kwel uit de stuwwal een goede restauratie maatregel voor mesotrafente vegetaties; zijn er alternatieven?

Hoofdstuk 1 geeft een theoretische achtergrond. De belangrijkste componenten bij de analyse van het transport van stoffen door grondwater zijn de convectieve grondwaterstroming en factoren die de concentratie van stoffen in het grondwater beïnvloeden. Convectieve grondwaterstroming kan worden afgeleid uit stijghoogten en met tracers. Hydrochemische processen in het grondwater worden afgeleid uit verschillen in watersamenstelling waargenomen in de richting van de stroming. Waterkwaliteitsverschillen langs een stroomlijn kunnen echter ook ontstaan ten gevolge van veranderingen in het stromingspatroon en veranderingen in de samenstelling van het infiltratiewater. Dergelijke overgangen in grondwatersamenstelling worden hier respectievelijk aangeduid als type-1 en type-2 fronten. Hydrochemische processen leiden tot type-3 fronten.
In dit proefschrift wordt een gefaseerde analyse gepresenteerd van het

transport van stoffen door grondwaterstroming. Eerst wordt het huidige stationaire stromingspatroon afgeleid op basis van stijghoogten. Daarna vindt verificatie plaats met tracers, waarbij kan worden vastgesteld of zich overgangen in watersamenstelling in de stroomrichting voordoen die het gevolg zijn van veranderingen in stromingspatronen. Het ontstaan van deze type-1 fronten wordt nader onderzocht door vergelijking van het huidige stromingspatroon met stromingspatronen op verschillende tijdstippen in het verleden. Vervolgens wordt nagegaan of zich type-2 fronten voordoen. De overige waterkwaliteitsverschillen in de stroomrichting, welke geen type-1 of type-2 fronten weerspiegelen, worden tenslotte verklaard uit het optreden van hydrochemische processen.

In hoofdstuk 2 wordt voor het Naardermeer de relatie onderzocht tussen de hydrologie en het voorkomen van plantesoorten. De kwantiteit en de kwaliteit van water in het Naardermeer worden sterk beïnvloed door het omliggende gebied. Van belang zijn met name kwel van calciumbicarbonaat water uit Het Gooi, kwel van vervuild water uit de aangrenzende boezem en infiltratie van plassenwater en neerslag binnen het Naardermeer onder invloed van lage polderpeilen in aangrenzende landbouwgebieden.
Binnen het Naardermeer bestaat een duidelijke relatie tussen de hydrologie en de verspreiding van plantesoorten. Het voorkomen van moerasvarenrietlanden (*Thelypterido-Phragmitetum*) is gecorreleerd met de aanwezigheid van calciumbicarbonaat water. Directe aanvoer van dit type water vindt plaats door kwel uit Het Gooi. Indirecte aanvoer treedt op door de stroming van kwelwater via het oppervlaktewaterstelsel naar het infiltratiegebied van het Naardermeer. Soorten van het Dotterverbond en van de Waterscheerling-Cyperzegge associatie (*Calthion palustris* en *Cicuto-Caricetum pseudocyperi*) komen alleen voor in het kwelgebied. Rietlanden met Slank veenmos (*Sphagnum flexuosum*) komen verspreid voor. De studie illustreert het belang van hydrologische informatie voor het natuurbehoud in laagveengebieden. Er dient rekening te worden gehouden met interne processen maar vooral ook met externe processen, die zowel bovenstrooms als benedenstrooms kunnen optreden.

Hoofdstuk 3 beschrijft een analyse van grondwatersystemen in het Naardermeer. De huidige grondwaterstroming in het verticale vlak is gesimuleerd met het 2-dimensionale eindige differentie model FLOWNET. Het gesimuleerde stromingspatroon is geverifieerd met behulp van de tracers chloride, zuurstof-18 en tritium. De chloride en zuurstof-18 concentraties geven aan dat veranderingen in stromingspatronen zijn opgetreden in het Naardermeer. Deze veranderingen hebben geleid tot verschillen in watersamenstelling in de richting van de huidige stroomlijnen (type-1 fronten).
De indeling in grondwatersystemen geeft inzicht in de effecten van drinkwateronttrekking en grondwatervervuiling in Het Gooi. Afname van de kwel uit Het Gooi heeft een verschuiving in grondwatersystemen tot gevolg gehad.

Dit heeft geleid tot verzilting van het grondwater in het kwelgebied van het Naardermeer. Hierdoor is een verandering opgetreden in de daar aanwezige vegetatie. Tevens blijkt dat de vegetatie in het Naardermeer wordt bedreigd door verontreinigd grondwater.

Veranderingen in stromingspatronen en de effecten op de grondwatersamenstelling worden nader onderzocht in hoofdstuk 4. Met FLOWNET worden stromingspatronen gesimuleerd langs een verticale doorsnede van de stuwwal naar de Vecht voor vier verschillende tijdstippen; de 14^e eeuw, 1885, 1941 en 1985. Deze simulaties weerspiegelen de belangrijkste hydrologische veranderingen als gevolg van menselijke ingrepen in Gooi en Vechtstreek gedurende de afgelopen 600 jaar. Uit de simulaties blijkt dat het van nature eenvoudige stromingspatroon in de loop der tijd is veranderd in een complex patroon dat wordt gedomineerd door kunstmatig gehandhaafde stijghoogten.
De grondwaterstroming in de stuwwal is over grote gebieden veranderd onder invloed van de drinkwateronttrekkingen. Dit heeft echter geen effect gehad op de grondwatersamenstelling omdat de neerslag de voornaamste bron van grondwateraanvulling is gebleven. Inpoldering in de Vechtstreek heeft geleid tot infiltratie-kwel stroming van polders met een relatief hoog peil naar polders met een relatief laag peil, waardoor type-1 fronten zijn ontstaan. Het van nature stagnante brakke of zoete grondwater onder de Vechtstreek wordt hierbij vervangen door lokale neerslag die infiltreert door veenlagen of door oppervlaktewater uit plassen, sloten en boezemwateren. Oppervlaktewater is vaak verontreinigd waardoor infiltratie een negatief effect kan hebben op de grondwaterkwaliteit.

Hoofdstuk 5 geeft een overzicht van de regionale grondwatersamenstelling in Gooi en Vechtstreek. Dit heeft tot doel veranderingen in de samenstelling van infiltratiewater vast te stellen en hydrochemische processen af te leiden. Multivariate statistische technieken worden toegepast om vast te stellen welke factoren de grondwater samenstelling beïnvloeden en wat de belangrijkste watertypen zijn.
In ondiep grondwater op de stuwwal worden verhoogde concentraties waargenomen van met name nitraat, sulfaat en kalium. Deze wijzen op een toegenomen vervuiling over de afgelopen decennia als gevolg van de bevolkingsgroei en landbouw intensivering in Het Gooi (type-2 front). Het voornammste hydrochemische proces in de stuwwal is oplossing van kalk. In de Vechtstreek leidt afbraak van organisch materiaal uit veen- en kleilagen tot verhoogde gehalten aan ammonium, organische complexen en koolzuur in neerslag en oppervlaktewater dat infiltreert. De productie van koolzuur leidt tot versterkte oplossing van kalk uit de bodem en het onderliggende zandige watervoerende pakket. Zuurstofverbruik en afname van de redoxpotentiaal leiden tot denitrificatie, oplossing van mangaan- en ijzeroxiden en sulfaatreductie. De verplaatsing van brak grondwater onder de Vechtstreek door

infiltratie van neerslag en oppervlaktewater gaat gepaard met menging van brak en zoet grondwater door dispersie.

In hoofdstuk 6 wordt het calciumgehalte van grondwater in de Vechtstreek onderzocht in verband met restauratiemaatregelen voor mesotrafente vegetaties. De calcium concentraties worden gerelateerd aan verschillen in type infiltratiewater (neerslag versus oppervlaktewater) en bodemomstandigheden (droge zandige bodems versus natte veenbodems) in het herkomstgebied van het grondwater. Drie grondwatertypen worden onderscheiden naar genese: neerslag geïnfiltreerd op de stuwwal, neerslag geïnfiltreerd in veengebieden in de Vechtstreek en geïnfiltreerd oppervlaktewater. Grondwater analyses worden geclassificeerd naar genetisch type op basis van objectieve hydrologische criteria, te weten de monsterlocatie en de concentraties van chloride, zuurstof-18 en nitraat.
In tegenstelling tot wat algemeen wordt aangenomen vertoont grondwater afkomstig van de stuwwal de laagste calcium concentraties. Hogere calcium concentraties worden aangetroffen in grondwater geïnfiltreerd in de Vechtstreek, dat wil zeggen in veenwater en vooral in geïnfiltreerd oppervlaktewater. De nutriëntenconcentraties in geïnfiltreerd oppervlaktewater zijn echter significant hoger dan die in onvervuild stuwwalwater en in veenwater. De nutriëntenconcentraties in onvervuild stuwwalwater en veenwater zijn statistisch gelijk. Dit is van direct belang voor het natuurbeheer in laagveenmoerassen. Kalkrijke, mesotrofe condities in de standplaats kunnen niet alleen gerealiseerd worden door kwel van water uit relatief hoge zandige infiltratiegebieden, maar ook door kwel van veenwater dat is ontstaan uit neerslag geïnfiltreerd in (nabijgelegen) veengebieden.
Zuurstof-18 bleek een essentiële parameter voor het onderscheiden van verschillende genetische grondwatertypen. Aanbevolen wordt om zuurstof-18 standaard te analyseren in watermonsters genomen ten behoeve van ecohydrologisch onderzoek. Calciumconcentraties zijn in het algemeen niet geschikt als gidsstof voor het herkomstgebied van het grondwater.

In Hoofdstuk 7 worden de resultaten van de afzonderlijke hoofdstukken bediscussieerd in de context van de doelstellingen van het proefschrift; beschrijving van het transport van stoffen door grondwaterstroming en de wijze waarop menselijke activiteiten dit transport beïnvloeden. De grondwatersamenstelling in Gooi en Vechtstreek blijkt niet alleen te worden beïnvloed door hydrochemische processen, maar ook door veranderingen in grondwaterstromingspatronen en veranderingen in infiltratiewatersamenstelling, beide als gevolg van menselijke activiteiten. Het identificeren van deze type-1 en type-2 fronten is noodzakelijk in gebieden met een sterke menselijke beinvloeding om onjuiste interpretatie van hydrochemische processen te voorkomen.
Tenslotte worden strategiën besproken voor het behoud en de restauratie van laagveenvegetaties in de Vechtstreek. In de nabije toekomst kan een

sterke verslechtering worden verwacht van de kwaliteit van kwelwater uit Het Gooi die tientallen jaren of zelfs eeuwen kan voortduren. Dit vormt een bedreiging voor de mesotrafente moerasecosystemen. Het beste alternatief voor schoon stuwwalwater is veenwater. Dit water is calciumrijk en relatief voedselarm. Veenwater kan worden aangewend als alternatief voor de suppletie van natuurgebieden in zomerperioden met vervuild boezemwater. Teneinde veenwater schoon te houden dient vervuiling in veen-infiltratiegebieden te worden voorkomen. Dit is van belang voor het behoud en de potentiële ontwikkelling van mesotrafente vegetaties in gebieden met kwel van veenwater.

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CURRICULUM VITAE

Paul Schot werd geboren op 29 maart 1958 te Balikpapan, Indonesië. Hij woonde 2 jaar in Indonesië en 8 jaar in Nigeria en verhuisde daarna naar Nederland. Van 1970 tot 1976 werd de Atheneum-B opleiding doorlopen op de Dalton-scholengemeenschap te Voorburg. Na de propaedeuse Civiele Techniek aan de Technische Hogeschool Delft volgde in 1977 een overstap naar de studie Fysische Geografie aan de Vrije Universiteit te Amsterdam. Het doctoraal examen werd afgelegd in 1984 in de richting Hydrogeologie en Geografische Hydrologie met als bijvak Isotopenhydrologie. Tijdens de doctoraal fase werd in totaal 8 maanden besteed aan diverse student-assistentschappen, o.a. ten behoeve van het Waterkwaliteits Onderzoek Loosdrechtse Plassen (WOL). Vanaf 1984 werkt hij bij de Interfacultaire Vakgroep Milieukunde aan de Rijksuniversiteit te Utrecht. Daar werd binnen het multi-disciplinaire onderzoeksprogramma 'Maatschappelijke en Ecologische Gevolgen van de Waterhuishouding' onderzoek uitgevoerd naar grondwaterstroming en grondwaterkwaliteit in Gooi en Vechtstreek dat wordt beschreven in dit proefschrift.

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- STELLINGEN -

1. Publikaties waarin conclusies over de herkomst van grondwater uitsluitend zijn gebaseerd op calciumconcentraties in grondwater, moeten met argwaan worden gelezen.
   (dit proefschrift)

2. De grondwatersamenstelling weerspiegeld vaak vroegere hydrologische omstandigheden. Bij de interpretatie van grondwater analysen wordt met dit historische karakter te weinig rekening gehouden.
   (dit proefschrift)

3. Computersimulaties van grondwaterstroomlijnen dienen geverifieerd te worden met in het grondwater aanwezige tracers.
   (dit proefschrift)

4. Het woord *kwel* is aan een herdefinitie toe; was het vroeger een aanduiding voor een last of kwelling, in recente hydro-ecologische literatuur lijkt het eerder een synoniem voor zegening.

5. Ecologen dienen termen als *oligotroof*, *mesotroof* en *eutroof*, alsook *rijk* en *arm*, te definieren middels concentratiegrenzen voor (verschillende verbindingen van) elementen als N, P, K, Ca, e.d.

6. Voor de oplossing van de meeste milieuproblemen ontbreekt het meer aan kennis over de beïnvloeding van het menselijk gedrag dan aan kennis over natuurwetenschappelijke processes.

7. Er wordt veel tijd en geld verspild aan het verzamelen van nieuwe wetenschappelijke gegevens, voordat bestaande gegevens voldoende zijn geïnterpreteerd of geherinterpreteerd op basis van nieuwe inzichten.

8. Er dient een einde te komen aan de groei van het aantal publikaties voordat wetenschappers alleen nog tijd hebben om hun eigen artikelen te lezen.

9. De vele wetenschappers en ambtenaren, tot ministers aan toe, die zich de laatste jaren met mest bezighouden, zijn niet noodzakelijkerwijs blijven steken in de Freudiaanse anale fase.

10. It's better to burn out, than to fade away.
    (Neil Young, 1978)

Proefschrift Paul Schot
Solute transport by groundwater flow to wetland ecosystems
Utrecht, 7 februari 1991.