

OBSERVATIONS ON THE HYDROCHEMICAL GROUNDWATER SITUATION OF THE WESTERN NETHERLANDS¹

A. B. POMPER²

ABSTRACT

Pomper, A. B. 1983 Observations on the hydrochemical groundwater situation of the western Netherlands. In: J. H. J. Terwindt & H. Van Steijn (eds): Developments in physical geography – a tribute to J. I. S. Zonneveld – Geol. Mijnbouw 62: 585-592.

The western Netherlands encompasses a polder area with the land surface predominantly some tens of cm to several m below mean sea level. The history of salinization of this area has been and is governed by the geologic history, the reclamation history of the former lakes, and the hydrological groundwater situation. This has resulted in a complicated hydrochemical groundwater situation. The practical significance of studies like the one described is that processes in progress can be explained, that earlier situations can be reconstructed, and that a prediction of future situations can be made. At the start of the study only the chloride contents of the groundwater were taken into account; at a later stage other ions were included, and this gives a good conspectus of the hydrochemical groundwater situation of the area. Since in many parts of the area upward seepage occurs, the groundwater composition is of great importance for the composition of the open water.

INTRODUCTION

The groundwater situation of the western part of The Netherlands has been extensively investigated by a working party of the Institute for Land and Water Management Research (ICW). The need for these investigations originated from agricultural questions related to the contamination of the surface waters of the area by saline water. Especially horticulture, a prominent agricultural activity in the area, heavily depends on the quality of the surface waters which are used for sprinkling. An important parameter for such water use is its chloride content. Later, other water quality parameters were also investigated as parameters of the general environment. The hydrological investigations (WIT, 1974; WERKGROEP MIDDEN WEST-NEDERLAND, 1976; WERKGROEP NOORD-HOLLAND; 1982) did show that one of the most important origins of incoming water in the area is seepage from the subsurface. So at last the entire groundwater quality had to be taken into account.

This paper presents a conspectus of the results of this part of the investigations.

DESCRIPTION OF THE AREA

The investigated area consists predominantly of polders with ground levels mostly below mean sea level (NAP³). In the west the area is bordered by the North Sea (Fig. 1), in the south by branches of the River Rhine, in the northeast by Lake IJssel (a dammed former embayment of the sea), and in the southeast by the ice-pushed Utrecht Hills. Along the west coast there is a ridge of dunes.

In the polder area there are great differences in ground-level, which are due to the complicated history of reclamation. There are polders with levels between 1 m above and 2 m below NAP and polders with levels of more than 4 m below NAP (reclaimed lakes).

The surface area of the region investigated is about 3560 km². It is the most densely populated area of The Netherlands, with concentrations of larger and smaller urban units, many of which are grown together into a wide band of urban area that is surrounded and partly encircled by rural areas.

The land use of the rural areas concerns different agricultural activities: dairy farming, arable farming and horticultural activities.

¹ Manuscript submitted 1983-03-01.

² Institute for Land and Water Management Research (ICW), P.O.Box 35, 6700 AA Wageningen, The Netherlands.

³ NAP is the Ordnance Level, being in use for all level comparisons in the Dutch area.

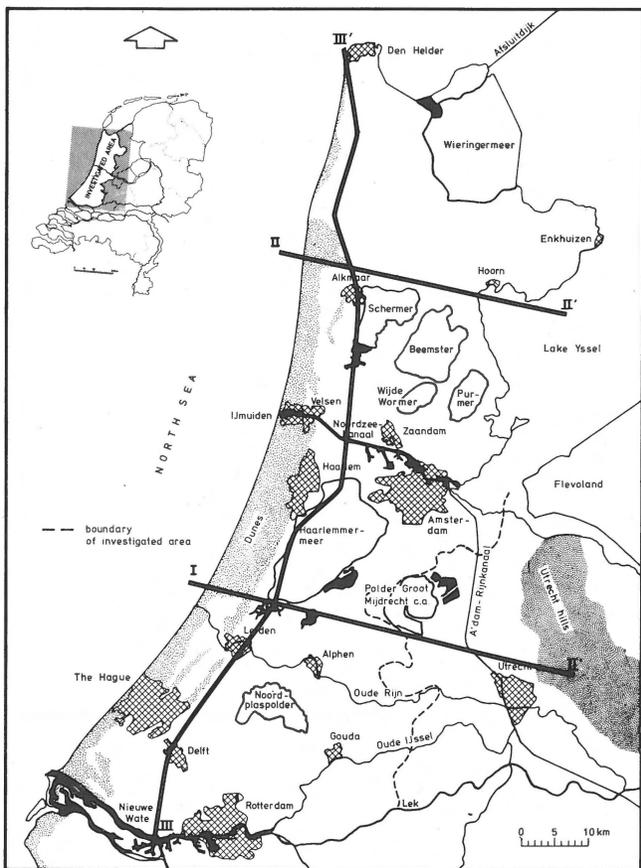


Fig. 1 General map of the investigated area.

ture. Their locations are established on geographical, pedological, hydrological, and historical grounds. Horticulture for example originated on the higher sites along the dunes and around the urban areas, arable land in the deep clayey polders, and dairy farming in the remaining often peaty areas.

The water management of the area has been in the hands of semi-private water boards since the reclamation of the area during the Middle Ages. For a more detailed description of the water management system reference is made to POMPER (in prep.).

GEOHYDROLOGICAL SITUATION

Fig. 2 gives a schematic north-south cross section of the area. The underground can generally be divided into two aquifers separated by a semi-permeable layer of different geologic origin with many interruptions. The lower aquifer is underlain by Tertiary marine clays and the upper aquifer overlain by a semi-permeable top layer. A detailed description of the situation in the underground is given in POMPER (in prep.), WERK-GROEP MIDDEN WEST-NEDERLAND (1976), WERK-GROEP NOORD-HOLLAND (1982). Here a short abstract will be given.

The hydraulic resistance of the top layer has been investigated by WIT (1974) and WIJNSMA (1979). The values of the

vertical resistances can show great variations over short ranges. The values given are averages and they mostly amount to values between 500 and 1000 days.

The transmissivity of the upper aquifer shows little differences. Over the entire area values between 500 and 1000 $m^2 \cdot day^{-1}$ are found. No reliable data are available for the vertical resistances of the underlying semi-pervious layer.

The lower aquifer can be divided in two. The lower part consists of fine grained marine, mostly loamy sands. Estimations of the hydraulic conductivities gave values between 6 and 11 $m \cdot day^{-1}$. The thickness is approximately the same (80 m) over a large part of the investigated area. Only in the most southern part of the area larger thicknesses occur. The upper part of the lower aquifer consists of coarse-grained fluvial sediments with high hydraulic conductivities. Values of more than 50 $m \cdot day^{-1}$ are predominant, whereas values of more than 100 $m \cdot day^{-1}$ also occur. The great variations in transmissivity depend, however, on the thickness of the layer. In the southern half of the area the thickness amounts to about 80 m in contrast with the northern half where values of more than 200 m occur. There is a rather narrow transition zone along a line just South of Amsterdam; south of this line the transmissivities of this layer are between 1500 and 2500 $m^2 \cdot day^{-1}$; north of the line they are more than 10000 $m^2 \cdot day^{-1}$.

Simply stated, the upper aquifer of the area shows limited variations in transmissivities and no fundamental differences in hydrological properties. In contrast, great differences in hydrological properties are found in the lower aquifer, which divides the area concerned into two parts, the northern and the southern half bordered by a narrow transition area between Amsterdam and Zandvoort.

MAP OF THE 500 ppm CHLORIDE PLANE

General

In this part of The Netherlands the chloride content of the groundwater is a good parameter for a general insight in the

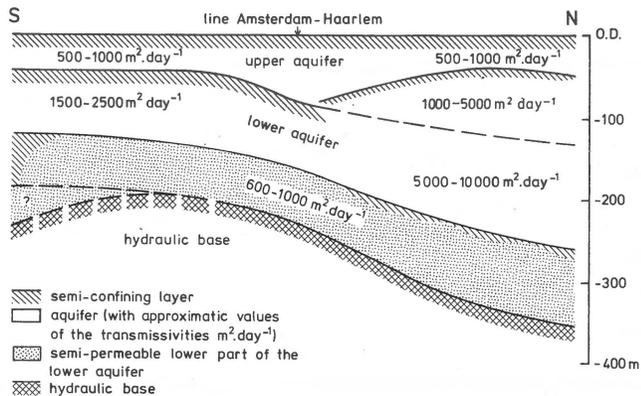


Fig. 2 Schematic north-south cross section of the area.

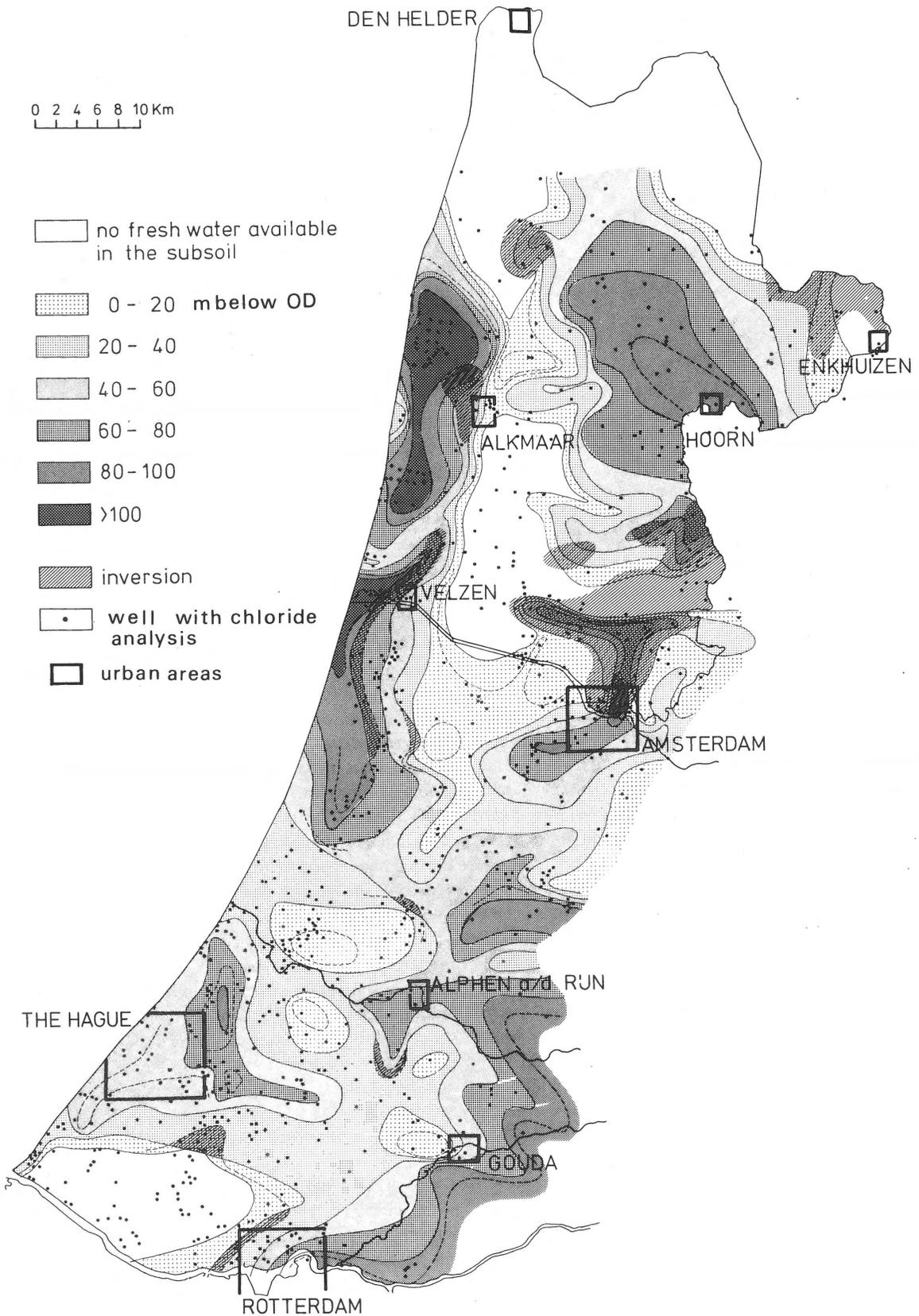


Fig. 3
The topography of the 500 ppm chloride plane of the groundwater in the investigated area.

hydrochemical situation of the area. A good starting point therefore is the description of the map of the 500 ppm chloride plane (further called 500 ppm plane).

Fig. 3 gives the map of the topography of the 500 ppm plane as published by POMPER (1981a). The choice of a value of 500 ppm chloride as parameter for the fresh – salt water interface is arbitrary. In most publications the value taken for the interface between fresh and saline water is lower, but in the area investigated large parts would be left out of the discussion because higher values do occur, just below the groundwater table.

Compiling technique

The map is a compilation of data of groundwater analyses only. The result has been compared with similar maps compiled from geophysical measurements. The situations presented in the different maps were generally in good agreement. They differed in detail, however, due partly to the limitations of the geophysical measurement techniques. GANSWIJK (pers. comm.) compiled a map of the 500 ppm plane of the southern part from his geophysical data and both maps were in good agreement. Most geophysical maps of the fresh – salt water interface, however, give the value of 150 ppm chloride and a comparison did give problems.

Data

As mentioned the map is a compilation of analyses of groundwater samples from wells. Most of the data were obtained from well archives, especially from the groundwater archive of the Netherlands Government Institute for Drinking Water Supply (RID). The available number of data has been enlarged with data from wells especially installed for the ICW investigations.

About 6500 data points were available for groundwater quality investigations, half of which gave only information on the chloride content of the samples. The distribution of the data over the area is very inhomogeneous. There are high densities of wells in urban areas and low densities in the rural areas. In the dune areas on the other hand many data were available from water catchments of the drinking water companies.

Lack of data in the northernmost part of the area prohibited the extension of the map to that part.

Discussion

The depth of the 500 ppm plane has been presented by means of contour lines. The greater the depth, the darker the shading.

It is noted that the regions with a deep 500 ppm plane are located along the fringes of the area discussed. In between, there is a 10 to 20 km wide strip with a shallow 500 ppm level.

The fresh water body along the west side of the area (deep 500 ppm levels) is due to the infiltration of precipitation water

into the dunes and it can be explained with the Ghyben-Herzberg principle. It is split into three cells: a small one in the neighbourhood of The Hague and two larger ones near Velsen and Alkmaar. They are important drinking water catchment areas. The fresh water body near The Hague extends inland and this extension correlates with a gully in the top level of the Kedichem Formation (POMPER, 1973; 1978). The two fresh water bodies in the dune area in the north of the area have their base at a deeper level than the one near The Hague. Their inland extensions are due to the existence of inversions. More attention will be given to this phenomenon further on (see next paragraph and POMPER, 1981b).

The fresh water body of the dune area is widest north of Alkmaar. This correlates with a buried deep glacial valley that extends toward Enkhuizen and which is filled with coarse-grained fluvial sands (POMPER, 1979; in prep.). This situation is similar to the one near The Hague.

The fresh water bodies at the eastern side of the area are partly different in origin from those in the dune area. In the southern half the depression of the 500 ppm level forms an extension of the fresh water body under the Utrecht Hills east of the area. It is maintained by infiltration there of precipitation water into the outcropping Pleistocene sands. There is a bulge towards Alphen aan de Rijn. It is kept in existence by infiltration from the Oude Rijn, a small Rhine branch which has a historical function in the internal water management of the surrounding area. It contains mostly fresh water and has a water level of several metres above the neighbouring polders. There is an extension of the fresh water body where the Oude Rijn crosses a gully in the top level of the Kedichem Formation, similar to the situation near The Hague. There is an inversion along its fringe.

Northeast of Alphen a/d Rijn a second bulge is found which is maintained by infiltration from an area with small lakes. In the neighbourhood of Amsterdam there is a fresh water body which for the greater part is covered by a layer of brackish water. It is possible that southwest of Amsterdam a small part of this fresh water body derives from lakes in that region, but the larger part, which has no contact with the surface, must originate from before the reclamation and the early Holocene marine inundations. The same can be said of the large fresh water body north of Hoorn. Having its base at a depth of more than 90 m in its central part, it has had no recent supply and must originate at least from the last time that fresh surface water was present. This is in agreement with conclusions from the hydrochemical studies of WITT (1980) and WITT ET AL. (1981).

This fresh water body has a western extension toward a postglacial buried valley. There it connects with the fresh water body in the dunes near Alkmaar. Along the fringe of this fresh water body many inversions are found which create such complicated situations that they cannot be shown in a simple map such as the one presented. (A detailed presentation is given in POMPER, 1981a).

The central strip with shallow 500 ppm levels coincides with the deep polder area. It is noteworthy that this salt water area

is split into cells in the southern part of the area. In the north the salt water cells occupy larger areas. In the southwestern part of this strip, south of The Hague, there is a large area where the groundwater has chloride contents higher than 500 ppm. This area has been flooded by the sea during a long time in the early Middle Ages and it has only been reclaimed since the 11th century (VAN STAALDUINEN, 1979). Along the fringes of this salt water area inversions are found.

There is a small salt water cell west of Gouda. It is located near the place where the Hollandse IJssel cuts into the coarse grained Pleistocene sandy sediments next to the deep Alexander Polder (6 m below NAP). To the north, two other salt water cells also coincide with deep polders.

North of the Oude Rijn, there is another salt water cell. On its southern side it is bordered by the Oude Rijn fresh water infiltration body, at its northern side by the inland extension of the fresh dune water body near Velsen.

Between Velsen and Alkmaar in the west and Amsterdam and Hoorn in the east, there is one large salt water area. Although the landscape shows large differences in elevation, as does the southern half of the area, the salt water body cannot be divided into separate cells. Over a large area groundwater near the surface has a chloride content higher than 500 ppm. This salt water area is bordered in the north by a small depression in the 500 ppm level near Alkmaar. Among other things this depression is due to the presence, up to several years ago, of a polder with high groundwater levels and a large area with lakes and ditches. In the meantime the farm water management of the area has been improved by a lowering of the groundwater level and by other land consolidating works which will result in a rise of the 500 ppm level.

Farther north scarce data indicate that groundwater is brackish up to ground level. It concerns an area that has been reclaimed rather recently (the Wieringermeerpolder was finished in 1932). Before reclamation the several polders were regularly flooded by the sea. In some polders it is not yet possible to get reliable information on the chloride content of the top layers, because these polders are still being flushed to wash out sea salts.

Inversions

In this paper several times the phenomenon of inversions of the 500 ppm plane has been mentioned. Inversions mostly indicate a hydrological system which has not yet reached a steady state. Due to the hydrogeological situation a steady state situation is not to be expected within a reasonably short period and for the time being it can be regarded to be stable. POMPER (1981b) calculated that stability depends on two parameters, the difference in density ($\rho_{\text{salt water}} - \rho_{\text{fresh water}}$) and the value of the transmissivity of the aquifer concerned. When there is a sharp interface between fresh and saline water, the borderline between unstable and imaginary stable situations is expressed by: $(\rho_s - \rho_f)/T = 3.4$, where ρ_s is the density of saline water, ρ_f the density of fresh water ($= 1$) and T the

transmissivity. When fresh water gradually grades into salt water a complicated situation occurs, which cannot easily be expressed mathematically. At this moment there is therefore no unique expression that describes the natural situation. VAN DER MOLEN (pers. comm.) states that an inversion can only be maintained for a longer period at a certain location if it is protected at the top by a clay layer, or at least by a layer with a very low hydraulic conductivity.

As mentioned inversions have been observed in many places. They can occur as a result of either one of two processes, both of which are observed in the area:

- an area with fresh groundwater is flooded by saline water which infiltrates into the top layers;
- fresh water from fresh water bodies intrudes coarse grained layers in neighbouring saline areas, whereas covering finer grained layers still contain salt water.

Between Rotterdam and south of The Hague several inversions are observed. They are due to sedimentation of marine fine clays during the early Middle Ages. Washing out of the saline formation water did not occur because of the extremely low hydraulic conductivities of the layers. South of Alphen an inversion occurs as a result of intrusion of fresh water into the coarse grained upper aquifer from the fresh water body under the Oude Rijn, whereas the covering layers remain saline. A similar explanation can be given for the inversions in the neighbourhood of Velsen and Alkmaar. They have been caused by subsurface inflow of fresh water from the dune water bodies into the neighbouring saline deep polders.

The situations along the fringes of the fresh water body north of Hoorn are very complicated. Explanations can only be given after more detailed investigations.

NORTH-SOUTH CROSS SECTION THROUGH THE SALINE AREA

To gain more information on the hydrochemical groundwater situation in the central saline strip, a cross section through this area has been compiled (Fig. 4). Apart from a simple indication of the geohydrological situation, the hydrochemical groundwater situation is given in contour lines of the chloride content, and the composition of the main ions in the groundwater in Stiff diagrams at the locations of the observation filters.

The observation of POMPER (in prep.) that a partition of the area occurs along an east-west line just south of Amsterdam, also can be identified in the chloride concentrations of the groundwater in the area. South of that line, values of 10000 ppm are not exceeded, whereas north of it at a greater depth values of somewhat more than 15000 ppm chloride occur. (In the southern half of the area one boring was available with a chloride value of more than 20000 ppm, which cannot be explained with the available theories but which may be due to an analytical error).

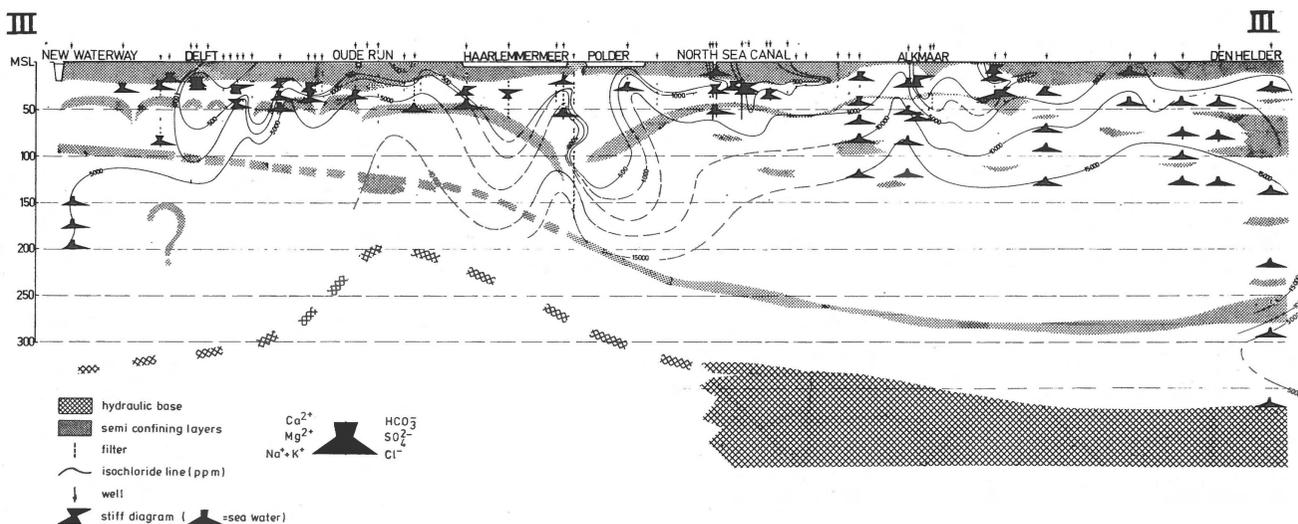


Fig. 4
Hydrochemical north-south cross section through the area. For the location see Fig. 1.

The fact that in the entire area, chloride values were never observed equal to that of seawater (19500 ppm chloride) shows that the observed samples always are mixtures of fresh and salt water. A similar observation can be made for the chloride content of the lower fine grained part of the lower aquifer. It appeared that the chloride values never exceed 8000 ppm in the area investigated.

The general conclusion must be that there is an unfinished salinization process in the subsoil. In the following paragraphs this will be discussed in more detail.

THE SALT BALANCE OF GROUNDWATER IN THE SUBSOIL

In Fig. 4 the ion balance of groundwater samples is given, beside that of seawater. The Stiff diagrams (STIFF, 1951) give the ion percentages of the total amount of the most common cations and anions respectively. For the absolute values the absolute value of at least one ion must be given. So the chloride concentrations mentioned (preceding section) give a view on the total ion concentrations. The form of the diagram, however, already gives an insight in the *relative* water composition.

It can be observed that in the lower aquifer in the northern half of the area the relative water composition equals that of seawater. In the upper aquifer over the entire area and in the lower aquifer in the southern part remarkable differences show between the composition of seawater and groundwater. The main differences concern the contents of sulphate and bicarbonate. There is also often a relative decrease in the sodium and potassium contents and an increase of calcium. In the upper aquifer of the northernmost part of the area there is only a decrease in the sulphate content.

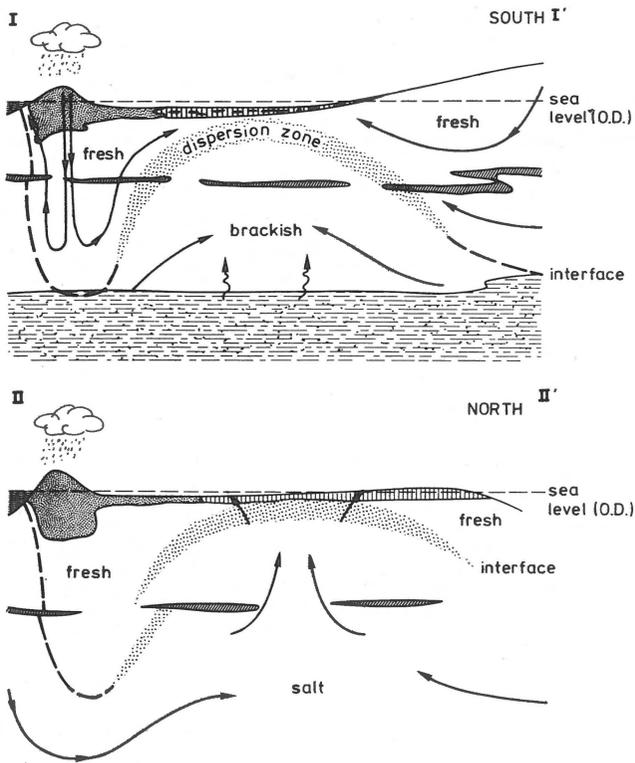
DISCUSSION

The hydrochemical groundwater situations in both parts of the area shall be explained separately. The reason for this is that in the southern part of the area the fresh water body beneath the dunes has its base down to the base of the hydrological system, at least in the fine grained lower part of the lower aquifer (Fig. 5). Because of the great thickness of the lower aquifer in the northern half of the area there is a great gap between the base of the fresh water bodies under the dunes (at some 100 m below NAP) and the top of the fine grained layers at the lower part of the lower aquifer (at some 240 m below NAP) as well as the hydrological base (at some 320 m below NAP).

These differences in hydrological situation concur with the chloride balance of the area as presented in Table I, mainly compiled from data from WIT (1974; pers. comm.).

From Table I can be read that in the area south of the North Sea Canal the in- and outflow of chloride are more or less in balance. VAN DAM (1974) even predicts from theoretical calculations that the established gradual flushing out of salts will proceed until the steady state situation has been reached, on condition that no changes, natural or man-made, will be induced.

Since there is an underground barrier against inflow of salt water from the sea consisting of fresh water bodies beneath the dunes, the origin of the salts observed cannot be inflow from the presently neighbouring North Sea. MEINARDI (1974, 1975) explains the existence of saline water in the subsoil by dispersion, and bases this on VERRUIJT's mathematical treatment of steady state dispersion across an interface (VERRUIJT, 1971). With VERRUIJT's method the depth of the fresh - salt water interface can be calculated from the ratio between the densities of both waters (c/c_0), the distance from the water



location see fig. 1

- aeolian and marine sands in the coastal dune area
- Holocene toplayers
- dispersion zone
- coarse grained fluviatile sediments
- clay layers
- Tertiary

Fig. 5
Schematic e-w cross sections through the northern (bottom) and the southern (top) part of the area, indicating the differences between the processes of salinization in the area. For the location see Fig. 1.

divide, and the size and shape of inhomogeneities in the sediments concerned. Comparison of the calculated interface depth by MEINARDI (1974) is in good agreement with the observations. In that case the origin of the salts observed is not the North Sea, but the deeper fine grained lower Pleistocene and Tertiary sediments.

Thus the water in the subsoil of the southern part of the area can be regarded as a mixture by dispersion of recently infiltrated precipitation water in the dune area and the Utrecht Hills (ice-pushed coarse grained Pleistocene sediments) and salt formation water from the deeper layers of early Pleistocene and Tertiary origin.

The explanation for the origin of the existing situation also explains the difference in composition between seawater and groundwater in the southern area. Although the observed salts originally were sea salts, their residence time is that long that even slow processes can have changed their composition, as for example in the case of sulphates. It is well-known that

Table I

Water balance of the aquifers in the western Netherlands (tons chloride per year)

South of the North Sea Canal:	
Subsurface inflow:	
from the west side (seaside)	465.0
from the east side (landside)	16.5
across the North Sea Canal	7.5
total	489.0
Outflow by seepage to the land surface	
total	495.0
difference	- 6.0
North of the North Sea Canal:	
Subsurface inflow:	
from the west side (seaside) excl.	
Velsen industrial area	1300.0
Velsen industrial area	725.0
from the north side	44.0
from the east side	1700.0
total	3769.0
Outflow:	
by seepage to the land surface	2280.0
subsurface outflow across the North Sea Canal	7.5
total	2287.5
difference	+ 1481.5

sulphate is reduced by the activity of sulphate-reducing microbes under anaerobic circumstances. If much organic matter is available in the subsoil the process may be fast, but in the given situation it was a very slow process and the difference with seawater may even be a rough parameter for the time that the original salts have been present in the subsoil.

The groundwater flow system in the northern half of the area is fundamentally different from that in the southern half. Because of the high transmissivity of the lower aquifer in this subarea, there is a strong inflow of water both from the east and the west. From Table I can be seen that the subsurface inflow of chloride and the outflow in the northern half are not in balance: the area shows that salinization is still increasing. Since in that area there is a gap between the base of the dune area fresh water body and the base of the hydrological system, there is a basic difference with the southern half in the origin of salts in the groundwater. In the northern half salts and groundwater in the deeper layers have the same origin.

From the hydrochemical groundwater situation in the northern part of the area its hydrological history can be read:

- At the beginning of the present era a flooded peat area with a tidal drainage system existed. Through tidal gullies seawater infiltrated and thus salt water penetrated the originally fresh water containing subsoil.
- During the Middle Ages this tidal system gradually closed and the existing situation was conserved for a few centuries.
- Since the seventeenth century the existing lakes were reclaimed. The differences introduced in hydraulic head

between phreatic and deep groundwater set up an intense inland directed groundwater flow. This first flushed out the fresh water present in the deep layers in an upward direction, thus making the upper layers less saline.

- Improvements of the water management (most in the northern half of the area) gave a new impuls to the salinization

All stages of this process can be found in the hydrochemical groundwater situation:

- fresh water in the surroundings of Hoorn as a relict of early Holocene or upper Pleistocene origin;
- fresh and saline water in the upper aquifer of early Medieval origin, the composition of salts in the saline water showing large differences with that of seawater;
- salt water in the lower aquifer, having recently infiltrated from the North Sea, thus with a salt composition equal to that of seawater.

REFERENCES

- Meinardi, C. R. 1974 The origin of brackish groundwater in the lower part of the Netherlands - Trans. 4th Salt Water Intrusion Mtg, Int. Hydrol. Decade (Ghent, Belgium): 85-106.
- 1975 Brackish Groundwater Bodies as a result of Geological History and Hydrological Conditions - RID-mededelingen 75-1: 22 pp.
- Pomper, A. B. 1973 Evidence of the influence of man on the natural processes related with salinization of groundwater in the western part of the West Netherlands - Trans. 3rd Salt Water Intrusion Mtg, Int. Hydrol. Decade, (Copenhagen, Denmark): 40-46.
- 1978 An estimation of chloride intrusion in the Midwest Netherlands during the Pleistocene Epoch - Proc. 5th Salt Water Intrusion Mtg, Int. Hydrol. Decade (Medmenham, Great Britain): 114-125.
- 1979 Werkgroep Noord-Holland VIII. De geologische en geohydrologische opbouw van Noord-Holland benoorden het Noordzeekanaal - Nota ICW 1135: 74 pp.
- 1981a Hydrochemical observations in the subsoil of the western part of the Netherlands. In: Intruded and relict groundwater of marine origin - Int. Hydrol. Progr. 7th Salt Water Intrusion Mtg, (Uppsala, Sweden), Report ICW 2: 101-111.
- 1981b A possible explanation of the occurrence of inversions in the chloride content of groundwater in the western Netherlands - Geol. Jahrb. C29; Techn. Bull. (nw ser.) ICW 8: 205-215.
- Stiff, J. R. H. A. 1951 The interpretation of chemical water analyses by means of patterns - J. Petr. Techn., Techn. Note 84.
- Van Dam, J. C. 1974 Depletion of saline groundwater by seepage - Trans. 4th Salt Water Intrusion Mtg, Int. Hydrol. Decade (Ghent, Belgium).
- Van Staaldunin, C. J. 1979 Geological map of the Netherlands, sheet Rotterdam-West (37W) - Rijks Geologische Dienst (Haarlem).
- Verruijt, A. 1971 Steady dispersion across an interface in a porous medium - J. Hydrol. 14: 337-347.
- Werkgroep Midden West-Nederland 1976 Hydrologie en waterkwaliteit van Midden West-Nederland - Regionale Studies ICW 9: 101 pp.
- Werkgroep Noord-Holland 1982 Kwaliteit en kwantiteit van grond- en oppervlaktewater in Noord-Holland benoorden het IJ - Regionale Studies ICW 16: 186 pp.
- Wit, K. E. 1974 Hydrologisch onderzoek Midden West-Nederland - Nota ICW 792: 116 pp.
- Witt, H. 1980 Werkgroep Noord-Holland X. Het chloridegehalte van het grondwater in Noord-Holland benoorden het IJ en het Noordzeekanaal - Nota ICW 1173: 12 pp.
- Witt, H., E. Van Rees Vellinga & K. E. Wit 1981 Werkgroep Noord-Holland XXV. Toename en afname door grondwaterstroming van chloride, stikstof en fosfaat in de ondergrond van Hollands Noorderkwartier - Nota ICW 1285: 14 pp.
- Wijnsma, M. 1979 Werkgroep Noord-Holland VII. Vertikale weerstand van het afdekkend pakket in Noord-Holland - Nota ICW 1162: 9 pp.