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FRESH WATER WINNING AND SALT WATER ENCROACHMENT IN THE AMSTERDAM DUNE WATER CATCHMENT AREA

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ABSTRACT

In the Amsterdam dune-water catchment area, a fresh-water lens of some 40 to 90 m thickness is resting on salt water in the lower aquifer, located at a depth of 20 m to 160 m – O.D. Waterextraction from the lower aquifer has disturbed the fresh-water/salt-water interface, extending it into a zone of dispersed, brackish water. For many years, the extraction area has been overdrawn. This article will discuss salinity conditions in the Amsterdam catchment area, and draw up a comparison between its current stock of fresh water and the original volume present before the start of waterwinning in the area.

With the introduction, in 1957, of artificial recharge through infiltration of Rhine-water into the upper aquifer above 15 m – O.D., water extraction from the lower aquifer, which had been hampered by increasing salt-water contamination of the wells owing to the upconing of brackish water, was virtually stopped.

The lower aquifer, however, still holds a vast stock of fresh water, which, if developed by a system of intermittent extraction, could substantially contribute to the water supply of the greater Amsterdam area.

1. INTRODUCTION

The dune-water catchment area of the Amsterdam Water Supply Board is situated along the Dutch North Sea coast, south of the city of Haarlem. Waterwithdrawal in this area – some 36 sq. km – started as early as 1853, by the simple method of draining a system of open canals, dug for the purpose (fig. 1).

By this type of development, water was extracted from the upper phreatic aquifer, and it was not until many years later that the presence of a vast stock of semi-confined water of excellent quality was discovered deeper down in the subsurface.

In the catchment area, the subsurface at greater

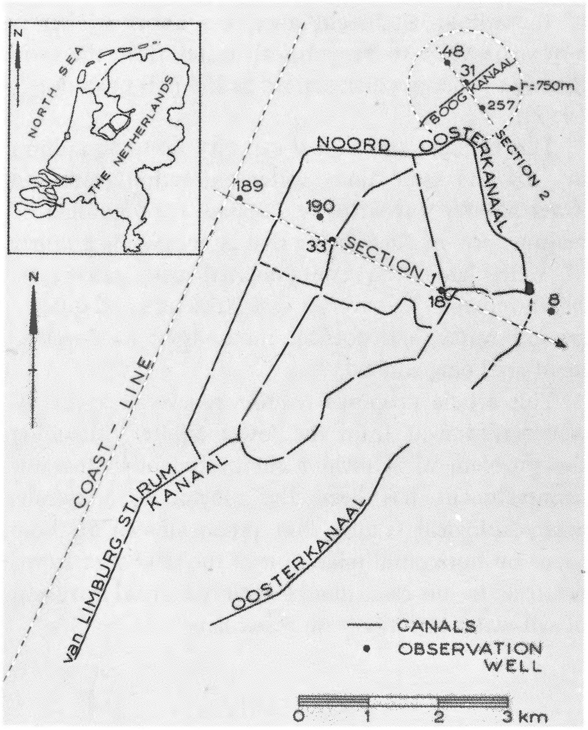

Fig. 1
Situationmap of the catchment area.

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depth is saturated with salt water. The fresh water is limited to a fresh-water pocket, or lens, under the dunes. Since 1903, water has been extracted from the lower subsurface by a system of wells.

The volume of waterwithdrawal in the Amsterdam catchment area has been gradually stepped up (table 1).

TABLE 1. Volumes of waterwithdrawal

Water extracted (x 1 million m^3)

	Upper aquifer	Lower aquifer	Total
1900	9	–	9
1925	14	6	20
1956	10	21	31
1970	57^x	7	64

x Including 52 million m^3 artificial river-water recharge

The only natural source of replenishment for the whole system is effective precipitation, which, for the entire catchment area, is no more than 13 million m^3 annually. Consequently, the system has been overdrawn for more than 25 years.

In order to achieve a more intensive exploitation of the whole catchment area, the upper aquifer is now artificially recharged with water from the river Rhine, a process which started in 1957 (Biemond, 1957).

This brought the annual capacity up to 83 million m^3. At the same time, water extraction from the lower aquifer was virtually stopped, for a number of reasons, one of them being that an increasing number of wells had been contaminated with salt-water. There remains, however, a vast stock of good-quality ground water, and possible methods of its development are being studied.

This article proposes to discuss several aspects of waterwithdrawal from the lower aquifer, including the problem of salt-water encroachment. Salt-water encroachment has been the subject of numerous geohydrological studies, but practically all of these focus on horizontal migration of the salt-water front, whereas, in our case, there is mainly vertical intrusion of salt-water into the fresh-water lens.

2. GEOLOGY

The conditions for fresh-water development in the Amsterdam catchment area are largely determined by its geological situation. The geological build-up of the area can be derived from a large number of scattered boreholes, 35 of which go down to depths of over 80 m – O.D. Many of them have been turned into observation wells for level and quality checks of the ground water. For the deeper boreholes, annual water analyses are being made and a number of recent bores have permanent electrode systems for ground-water salinity inspection (Walter, 1967).

Fig. 2 shows the stratigraphic and hydrological sequence of the subsurface. Most important, from a geohydrological point of view, is the *clay-layer* located at a depth of 18 m – O.D., from now on referred to as *clay-layer*. Quite often, this clay-layer fails to show up in geological logs, but its presence is indicated by a general resistance to vertical waterflow at this level throughout the area. Several bores show loam or clay-layers at various depths between 60 m and 90 m – O.D. Especially in the northern part of the catchment area, these layers divide the lower aquifer into two sub-aquifers. In the following paragraphs, it will be shown that these layers, from now on referred to as *loam-layer*, are of major importance, locally, to the rate of salt-water contamination in the extraction wells.

3. HYDROLOGICAL SITUATION

The *clay-layer* divides the subsurface into an upper and a lower aquifer. The lower aquifer's semi-pervious base is located at 160 m – O.D. (fig. 2). Due to their effective separation, both aquifers have their own flow regimen. In some places, the difference in head is several meters, with a current average, for the whole area, of 2.25 m. In 1957, the year which ended a long period of intensive extraction from the lower aquifer, the elevation head in the lower aquifer had dropped as low as 1 m – O.D. Today, the head has recovered to a level of 0.5 m + O.D. or more. In the lower aquifer, the watershed is fairly close to the sea coast, so that relatively little fresh water is lost to the seaside. Most of the water infiltrating through the clay-layer flows to the landside. Part of it is directly recovered in wells and another portion adds to the stock of water in the fresh-water lens.

In salt-water, conditions are different. The boundary conditions for the salt-water flow below the fresh-water lens are, to the west of the catchment

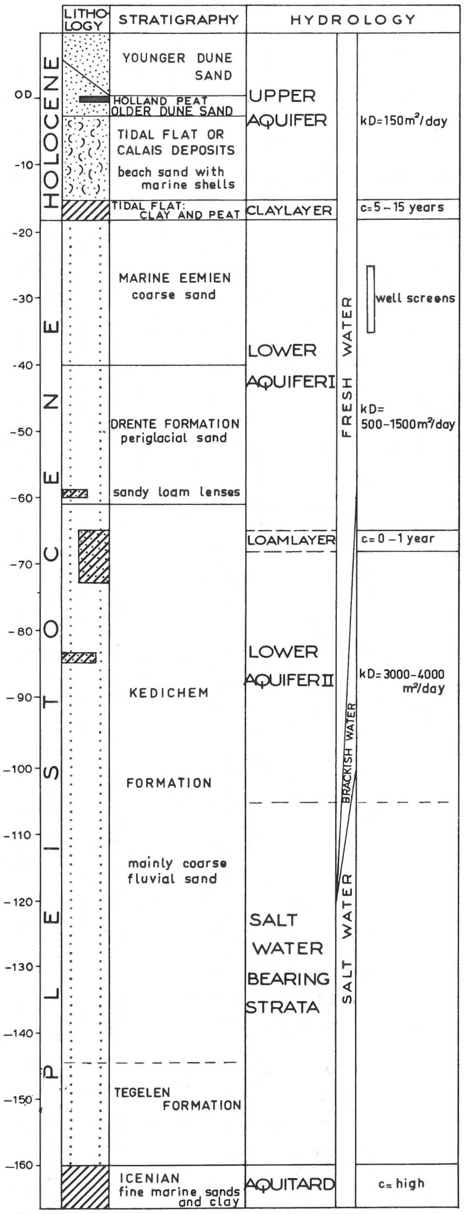

Fig. 2
Stratigraphy and hydrology of the subsurface.

area, mean sea level of 0.15 m – O.D. and, to the east, the Haarlemmermeer-polder level of 5.75 m – O.D. The seepage flow, caused by the low level of the Haarlemmermeer-polder – a reclaimed tract – is creating a serious salt-water intrusion problem in the polder's many ditches.

The hydrological constants of the catchment area have been established through water-balances and numerous pumping tests (Huisman, 1958). Fig. 2 shows the average rates of transmissivity (kD) of the aquifers and resistance (c) of the semipervious layers. These constants appear to differ widely throughout the area.

The recharge of the lower aquifer from the upper aquifer varies with the difference in head on either side of the *clay-layer*. The current recharge volume is about 10 million m^3 annually, and annual extraction from the lower aquifer averages some 4 million m^3. Frequent readings show that, after decades of overdraft, the stock of water in the fresh-water lens has been on the increase since 1957.

In the southern region of the extraction area, the fresh-water lens under the dunes is strictly separated from the underlying salt-water by an interface of no more than 5 m thickness. This sharp interface is "washed clean" by fresh-water flowing along it, the effect of which outstrips that of interfacial diffusion. In areas where the *loam-layer* is well-developed, the original stock of salt-water is hardly, if at all, displaced by fresh-water. In fig. 3, this stock is indicated as "residual brackish water". Fig. 3 is based on hundreds of ground-water analyses, carried out since 1903. It shows the area in cross-section, perpendicular to the coastline. This section is marked "section 1" in fig. 1. In the western part of this cross-section, it will be seen that, owing to groundwater extraction between 25 m and 35 m – O.D., the original sharp fresh-water/salt-water interface has extended into a transition zone of some 50 m thickness. An example of this phenomenon will be discussed in detail in paragraph 7.

4. FORMATION OF THE FRESH-WATER LENS

The formation of the Older Dunes (fig. 2) started about 4000 years ago, when a coastal strip, covering the site of the present catchment area and the dunes east of it, began to build up gradually to a level above its surroundings. The formation proceeded in several stages and resulted in a series of barriers running parallel to the coast. The oldest barriers are those lying furthest inland. (Jelgersma and Van Regteren Altena, 1969). In their final stage, the Older Dunes covered a strip at least 8 km wide. It is generally assumed that the Older Dunes were rather

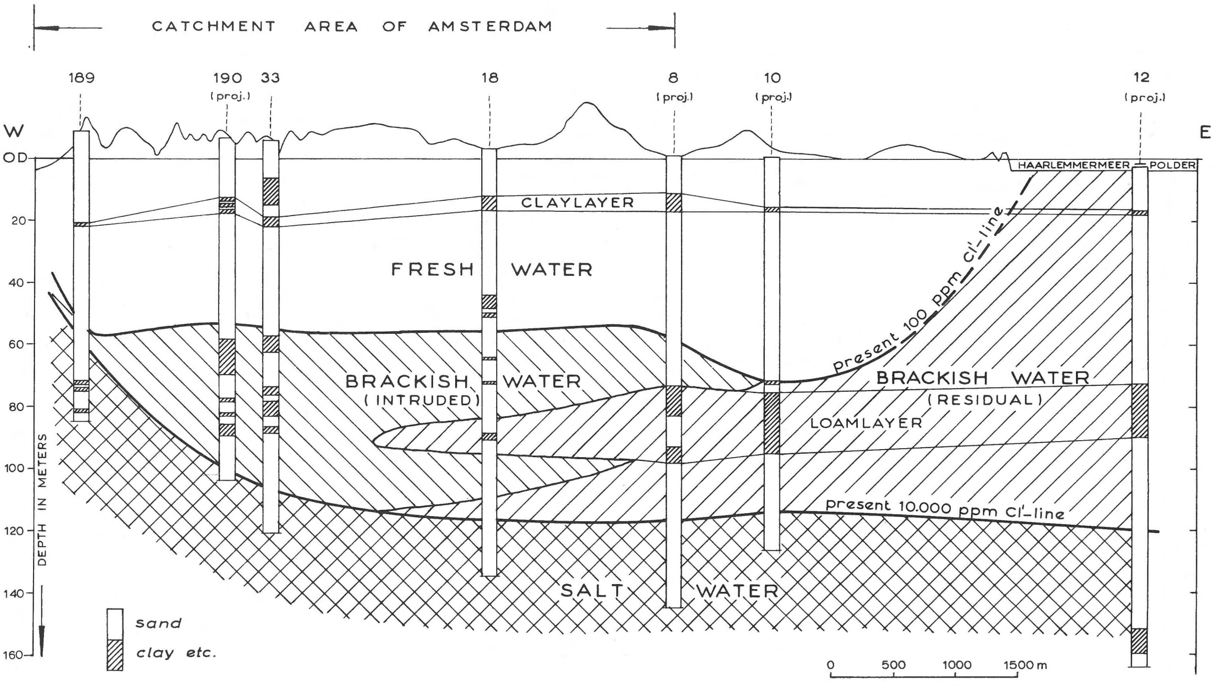

Fig. 3
Hydrological cross-section (= section 1 in fig. 1).

low, much lower, at any rate, than the Younger Dunes, some of which are as high as 40 m + O.D.

Prior to the formation of the Older Dunes, the landscape was flat, proof of which can be found in the marine tidal flat and beach deposits. The entire subsoil was saturated with salt-water. Precipitation could effect no more than superficial desalinization, because the higher density (ρ) of the sub-surface water prevented fresh-water from penetrating deeply into the subsoil. Salt-water (ρ_s= 1,020 kg/m^3) can only be displaced by fresh-water (ρ_f = 1,000 kg/m^3) it sufficient fresh-water has accumulated to provide a certain overpressure. Accordingly, it was only after the first of the Older Dunes had formed, some 4000 years ago, that precipitation began to build up a body of fresh-water. The original, elementary equation for the depth of the fresh-water lens was given by Bhadon Ghyben and Herzberg.

The formula is:

$$H = \frac{\rho_f}{\rho_s - \rho_f}$$

According to this theory, the depth of the fresh-water lens (H) resting on the salt-water is about 50 m for every meter of fresh water (h) above mean sea level. The equation is only valid if the salt and the fresh-water are in a state of "dynamic equilibrium", with flow-directions largely tending to the horizontal. In practice, the maximum recorded depth of the interface between the fresh-water and the underlying salt-water is between 120 m and 130 m – O.D. The interface's lowest point is located halfway under the Older Dunes. The Younger Dunes, formed after A.D. 1200, are much higher. They constitute a strip no more than 4 km wide, covering the western part of the Older Dunes complex. Consequently, the eastern boundary of the Younger Dunes overlies the deepest part of the fresh-water lens. The formation of the Younger Dunes no doubt had some additional effect on the shape of the fresh-water lens. At any rate, new boundary conditions were introduced with the reclamation of the Haarlemmermeer-polder, in 1850. As a result of this intervention in natural conditions and of waterwinning from the lower aquifer, which started in 1903, the fresh-water/salt-water interface is no longer stationary. Since 1903, a major change has also begun in the thickness of the interface. This process will be discussed in more detail in the following paragraphs.

The actual shape of the fresh-water lens has been the subject of detailed studies, including a series of tests, conducted on a Hele-Shaw model by the Government Institute of Drinking Water Supply in the Netherlands, (Santing, 1955) and a number of calculations on the shape of the fresh-water lens, performed by the Amsterdam Mathematical Centre (Venhuizen, 1968).

Recent studies have made it quite clear that the *loam-layer* creates conditions that are of vital importance to the development and subsequent changes of the dispersion zone. One of the questions still waiting for a satisfactory solution concerns the amount of time required for the formation of such a fresh-water pocket, or, in other words, the time it takes for the lens to reach a static condition. It is commonly assumed that, under the conditions now prevailing in the dune catchment area, the build-up of a fresh-water lens would take some 1000 years, which indicates that, prior to human interference, which started some hundred years ago, the fresh-water lens must have been in a state of equilibrium for a considerable time.

5. DEEP-WATER WINNING

Since 1903, water has been extracted from the lower aquifer by a system of wells, screened at depths between 25 m and 35 m – O.D. Owing to the limited suction lift of the vacuum pumps, the wells had to be drilled at the lowest possible spots. In practice, this means that all of the 502 wells are located along the canals, marked on the separate map which will be discussed later in this article. The wells located along the Westerkanaal and the Van Limburg Stirumkanaal have been used for water-extraction until 1955, when they were abandoned on account of increasing salt-water contamination.

This use of small-capacity wells, scattered over a wide area, delays the movement of significant quantities of brackish water. Those wells that are located over well-developed sections of the *loam-layer* may operate at higher capacities. Well-capacities are varying between 5 and 15 m^3/h. The distance between the wells is 25, 50 or 100 m. Between 1910 and 1971, a total of 600 million m^3 has been extracted from the lower aquifer. In the next paragraph, it will be explained what this means in terms of the total available stock.

6. FRESH-WATER STOCKS

Any computation of ground-water stocks in water-bearing strata is essentially deceptive. The very work "stock" seems to imply the possibility of consumption, because stocks are usually open to some kind of use. The vast reserves of groundwater found to be present by such computations foster the belief that there is no need to worry about future supplies.

For the Amsterdam catchment area, however, this kind of computation is quite relevant and, for several reasons, even interesting. Firstly, because the area is a hydrological unit, and, secondly, because the available data make it possible to calculate the stocks available at two different points in time, separated by a period of no less than 60 years. The volume of

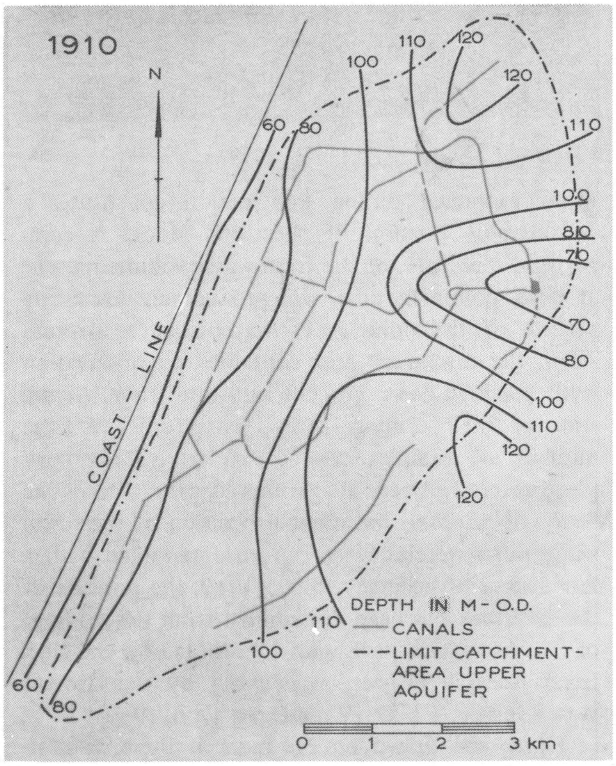

Fig. 4
Contour map of the 100 p.p.m. isochlor in 1910 and 1970. The dotted line also marks that portion of the lower aquifer, referred to in the tentative fresh-water balance at the end of paragraph 6.

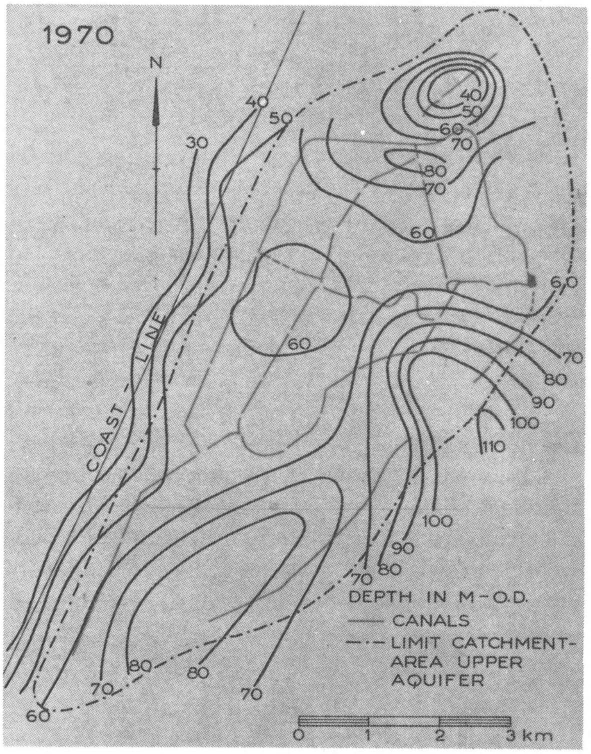

Fig. 4

water extracted during that period constitutes a considerable portion of the total stock. A comparison, therefore, of the fresh-water volume present at both points in time, will produce an interesting picture of the dune area's water-balance. Around 1910, the catchment area contained 23 observation wells reaching down into the salt-water zone. At the time of their drilling, a few years earlier, a large number of samples was drawn from temporary piezometers, placed at various depths. From the analyzed samples, the original position of the fresh-water/salt-water interface can be determined with a fair degree of accuracy. Since 1910, the position of the interface has been determined from the readings of 35 observation wells and the results of a geo-electrical research project, carried out by the Ground Water Survey, T.N.O. (Van Dongen, 1969).

Fig. 4 was drawn on the basis of these data, to show the position of the 100 p.p.m. isochlor, as it was in 1910 and 1970.

Meanwhile, it should be noted that the 100 p.p.m. isochlor distinction has no special meaning in a physical sense, that is, in terms of groundwater flow. The distinction is made, because water with a Cl′-ion content only slightly exceeding 100 p.p.m. is of no direct importance for domestic or industrial use.

The volume of fresh-water between the two 100 p.p.m. isochlors and the clay-layer at 18 m – O.D. has been established by planimetry. Assuming a porosity of 0.4 (table 2).

TABLE 1. Volumes of fresh water

Year	fresh-water between *clay-layer* and 100 p.p.m. isochlor
1910	1450 million m^3
1970	850 million m^3

The above quantities only pertain to that portion of the lower aquifer underlying the catchment area of the upper aquifer (fig. 4). For this portion of the lower aquifer, a tentavive fresh-water balance (< 100 p.p.m. Cl') is given at the end of this paragraph. In paragraph 5 it was said that a total of 600 million m^3 had been extracted from the lower aquifer. It would, however, be wrong to conclude that the decrease in stock exactly matches the extracted quantity. For one thing, the lower aquifer is recharged through the overlying *clay-layer* and, apart from this, deep water has been attracted from outside the balance area during the period of intensive exploitation. Consequently, the total volume of fresh-water has been much greater than 1450 million m^3. Part of this volume was lost by underground flow, another part has been extracted for supply, and still another significant portion has mixed with salt-water to form the present brackish zone. Part of this water has, of course, also moved away. A detailed survey of the waterbalance of the 60-year interval might be interesting, but would be somewhat beyond the scope of this article.

For our present purpose we have made a water balance, roughly indicating the quantities involved.

7. SALINITY SURVEY OF THE BOOGKANAAL-AREA

The Boogkanaal constitutes the northernmost part of the catchment area (fig. 1). Owing to its relatively low waterlevel of 1.75 m – O.D., the canal attracts

TABLE 3
Tentative balance of fresh-water (< 100 p.p.m. Cl') in the lower aquifer between 1910-1970 (million m³). The area in question is marked in fig. 4.

+		–	
Stock of fresh-water 1910	1450	Stock of fresh-water 1970	850
recharge through *clay-layer*	500	deep-water winning	600
underground inflow – underground outflow (approx.)	200	mixed with salt-ground-water approx.	700
approx.	2150	approx.	2150

water from the upper aquifer. Next to the waterline, 20 wells have been drilled at distances of 50 m, with screens in the lower aquifer. Due to the canal's particular low level, the wells are of the artesian type, each supplying some 10 m^3/h. The Boogkanaal deep-water winning system has been in operation since the start of waterwithdrawal from the lower aquifer, in 1903. Between 1903 and 1970, a total of over 131 million m^3 has been extracted here, in a fairly continuous process. In the Boogkanaal area, the *loam-layer* is almost entirely absent. The 100 p.p.m. isochlor, originally found at 120 m – O.D., has gradually risen to 35 m – O.D. in the centre of the row of wells, at the site of observation well 31 (fig. 5). The fact that the elevation is not due to a local upconing of brackish water is proved by analyses of water from boreholes 48 and 257, where a similar rise of the 100 p.p.m. isochlor has been found. The rise observed at 257 was stronger than at 48, which is explained by several factors. One of them is the water extraction from the lower aquifer along the Noordoosterkanaal at a distance of 500 m from the Boogkanaal, which was started in 1948. Another factor is the water extraction, in the same area, by the Water Supply Board of the nearby village of Zandvoort. The original direction of ground-water flow is also playing a part.

Fig. 6 shows the situation in 1970. Figs. 5 and 6 indicate that, near bore 31 the 100 p.p.m. isochlor has moved upward some 95 m, and that the 10,000 p.p.m. isochlor has risen about 40 m. Both figs. are based on the assumption that the transition zone was originally a sharp interface. The elevation velocity of the 100 p.p.m. isochlor is quite constant. At the Boogkanaal, it is 1.4m/year, and at 500 m distance it averages 1 m/year.

On the basis of this information, we can work out a schematic waterbalance for an area with a radius of 750 m around the centre of the Boogkanaal (fig. 1).

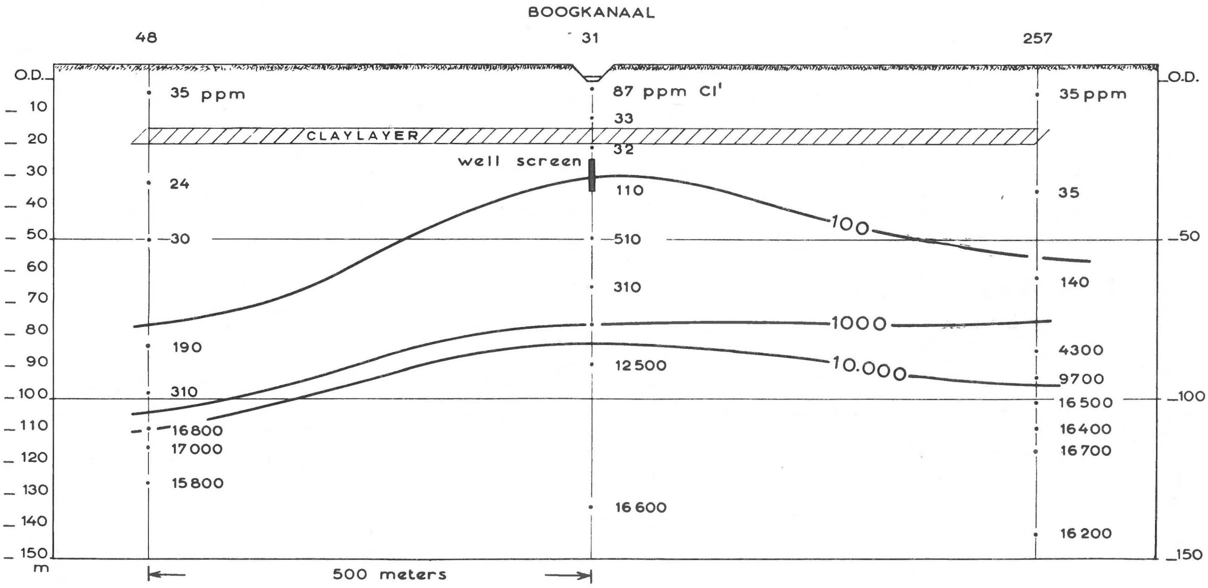

Fig. 5
The hydrological situation in 1970. Cross-section perpendicular to the Boogkanaal, showing the 100, 1000 and 10,000 p.p.m. isochlors. (= section 2 in fig. 1).

For this area, the waterbalance of the lower aquifer, to the extent that it is saturated with water containing up to 100 p.p.m. Cl', is:

$$Q = D - Dm + R + Fi - Fo$$

in which

Q = the volume of extracted ground water;
D = Depletion of fresh ground water stock (< 100 p.p.m. Cl');
Dm = that portion of D mixing with salt-water, thus enlarging the brackish dispersion zone;
R = recharge of the lower aquifer through the *clay-layer;*
Fi = horizontal inflow;
Fo = horizontal outflow.

Extraction (Q) = 2 million m^3/year. Depletion (D) is computed as follows: Elevation velocity of the 100 p.p.m. isochlor is put at 1 m/year. For a porosity of 0.4, D equals 700,000 m^3/year. Recharge (R) is computed from the difference in head on either side the *clay-layer* and the resistance of the *clay-layer* (4000 etm), and is found to be 200,000 m^3/year. Fi = 2 million m^3/year, Fo = 400,000 m^3/year. The value thus found for Dm is 500,000 m^3/year. From this schematic waterbalance it is evident that there is little direct recharge into the lower aquifer, due to high resistance of the *clay-layer* in and around the Boogkanaal area.

This favours the rise of salt and brackish water. Owing to the low rate of recharge, deep-water extraction along the Boogkanaal tends to deplete the available stock. Water extracted from the lower aquifer in the Boogkanaal wells now has an average Cl'-concentration of 95 p.p.m.

Fig. 5 shows that, within a few years, deep-water extraction from the Boogkanaal will have to be stopped on account of the increased Cl'-concentration. From the waterbalance it is also clear that depletion of the fresh-water stock entails a perhaps even greater loss of fresh-water through mixing with salt-water. But this particular point still calls for more detailed research.

8. SALT-WATER CONTAMINATION OF THE WELLS

From figs. 3 and 4 it is clear that practically throughout the catchment area fresh-water is found to a depth of at least 60 m – O.D. As the wells are screened between 25 m and 35 m – O.D., there are at least 25 meters of fresh-water between the screens and the underlying salt-water zone. There is, however, a vertical waterflow which accounts for most of the salt-water intrusion in the wells. Due to the sharp

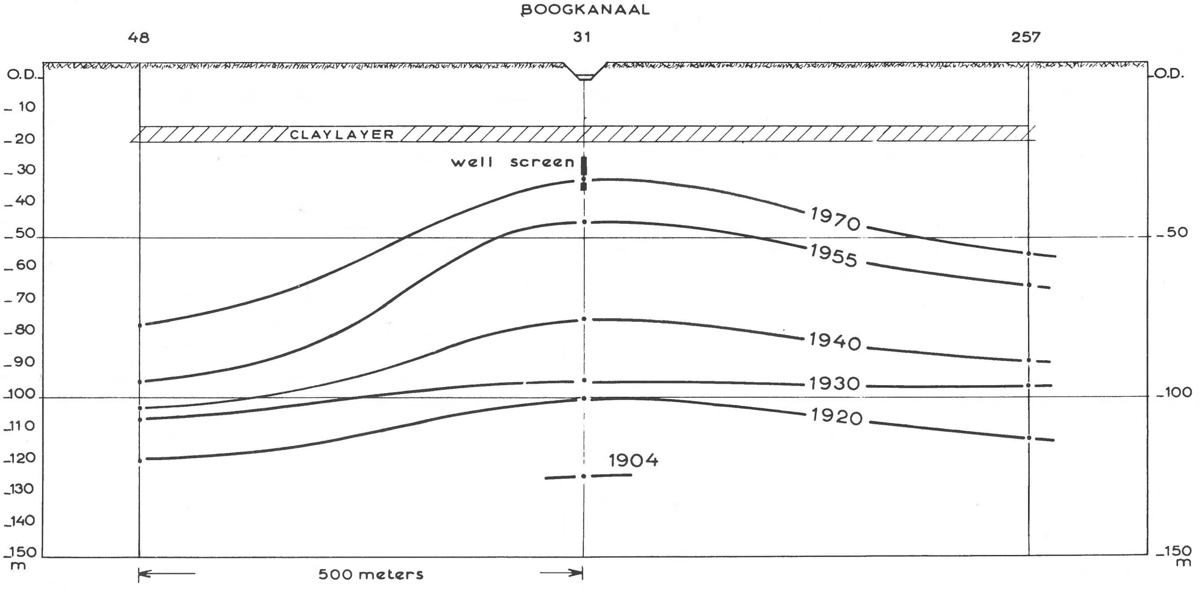

Fig. 6
Rise of the 100 p.p.m. isochlor. Cross-section perpendicular to the Boogkanaal. (= section 2 in fig. 1).

drop in head in the wells, narrow cones of brackish water are drawn up to the well-screens from the underlying dispersion zone. In some cases, the cones rise from brackish zones situated as much as 50 m below the screens. In case of upconing, the Cl′-ion concentration in the bottom section of the wellscreen is always higher than that in the top section. The process of upconing is discussed in an interesting article by Huisman (1954). As in 1954, a good mathematical explanation for this phenomenon has not yet been found.

Pennink (1914) was the first to draw attention to salt-water contamination of the extraction wells in the Amsterdam catchment area. The process took on more serious proportions in the forties and fifties, when waterwinning from the lower aquifer was greatly intensified. The table below (table 4) shows the increasing Cl′-ion concentration in the wells over the last few years of extraction, and also the situation that arose after deep-water extraction had been largely discontinued. Original dune water has a Cl′-ion-concentration of some 30 p.p.m. For a better understanding of the table, it should be noted that a well that has been contaminated with salt-water during a period of intensive extraction, will again produce original dune-water after some time of rest. The table clearly shows the desalinization of a number of wells since 1956/57. If extraction is resumed, the wells will be re-contaminated after some time, but experience in this field is only fragmentary. In one particular case, however, (the Barnaart-Schusterkanaal) it was found that the wells, after a ten-year rest, still showed no trace of contamination six months after extraction had been resumed. As indicated in the table, not all of the 502 wells were sampled in the years listed, nor were the samples always drawn from the same wells, so that the figures can only serve as a rough estimation.

TABLE 4
Cl′-ion concentration in a number of wells.

	<40 p.p.m.	40-100 p.p.m.	⩾100 p.p.m.	
Year	number of wells			wells total
1950	228 (64%)	105 (30%)	21 (6%)	354 (100%)
1956/57	217 (56%)	134 (34%)	40 (10%)	391 (100%)
1959	201 (72%)	62 (22%)	16 (6%)	279 (100%)

Salt-water encroachment in 1956/57, the year which ended a long period of intensive extraction from the lower aquifer, is marked on the separate color map. The map clearly shows the importance of the *loam-layer* for the rate of salt-water contamination of the wells. As mentioned before, this layer is most effective in the north-eastern part of the catchment area, and it appears from the map that in this very region no salt-water contamination of the wells has been found, despite intensive exploitation. This applies especially to the wells along the Sprenkelkanaal, the Oude Beek and the Van der Vlietkanaal, and also to parts of the Noordoosterkanaal, the Verlengde Oosterkanaal and the Nieuwkanaal. There is a possibility that a *loam-layer* has also prevented salt-water encroachment in the northern part of the Van Limburg Stirumkanaal. In most other places, wells appeared to be contaminated, even if the 100 p.p.m. isochlor hardly ever reached as high as the bottom of the well screens. Contamination in these places, notable along the Oosterkanaal and the southern section of the Nieuwkanaal, is caused by upconing of brakcish water.

9. CONCLUSION

In this article we have discussed several instances of the distribution of fresh, salt and brackish water in the Amsterdam dune water catchment area. We have also discussed the change in this distribution since the start of waterwinning in the area. Most of the instances described apply to the north of the catchment area, where changes have been most drastic. In the less intensively developed southern part of the extraction area however, the fresh-water/salt-water interface has also risen, as shown in fig. 4. Waterwinning in the south was concentrated along the Oosterkanaal and the Van Limburg Stirumkanaal. In the area between the two canals, the 100 p.p.m. isochlor has risen 30 m. In this extensive section, as in others, the elevation of the fresh-water/salt-water interface is due to a drop in head in the lower aquifer. In the south of the catchment area, however, where the clay-layer is least resistant, there is relatively intensive recharge from the upper aquifer. Due to this, the fresh-water/salt-water interface has not been drawn out significantly.

The clay-layer is of key importance, because it separates the upper aquifer from the lower aquifer. Owing to this effective separation, the lower aquifer is barely affected by the artificial infiltration of Rhine-water into the upper aquifer. However in the lower aquifer salt-water encroachment may increase because of the high resistance of the *clay-layer* Salt-water encroachment in the lower aquifer springs from two different sources:

1. The rise of the fresh-water/salt-water interface, and its extension into a dispersion zone.
2. The local upconing of brackish water under individual wells.

All available data from the lower aquifer indicate that, apart from some recharge through the *clay-layer.* withdrawal from this level would mean depletion of the aquifer. It will be impossible to develop all of the 850 million m^3 of fresh ground-water still present in the lower aquifer of the extraction site.

One of the additional problems created by the elevation of the salt-water level is its activation of salt-groundwater seepage flow from the sea to the Haarlemmermeer-polder. During extraction periods, when the head under the dune catchment area is low, seepage flow to the polder is limited, but after winning is discontinued, the seepage flow continues under the catchment area towards the polder.

However, the present rate of salt-water encroachment does not imply, that deep-water winning should be stopped altogether. The Amsterdam Water Supply Board is now using the lower aquifer as a reserve stock for periods when the quality of Rhine-water for artificial recharge is particularly poor. During such periods, good quality drinking water may be obtained by a process of mixing infiltrated river water with water from the lower aquifer. In general, deep-water winning will continue to serve as a source of water-supply in emergency-situations.

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