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RESTORING A BRINY CATCHMENT AREA

SUMMARY

The Amsterdam Water Works extracts raw water from the dunearea near the North Sea, already 130 years.

In the beginning, during 50 years, only the freatic aquifer was drained. Shortage of water made it necessary to pump water also from the deep semi-confined aquifer, where the fresh waterpocket floats on the salt water.

From 1902 until 1957 the extraction by deepwells increased from a few million m^3 per year to 21 million m^3 per year. A heavy saltwater intrusion appeared. The amount of salt water in the aquifer increased with 40%, the brackish zone enlarged with 80%.

The turning point come in 1957, when the infiltration of riverwater on the surface started. The deepwell extraction was reduced to $6 \cdot 10^6 m^3$ per year. After about 15 years it became sure that the situation of the fresh water pocket did not change. Until 1974 there was nearly no change of the depth of the boundary planes between fresh, brackish and salt water. Only the heavy upconing below the wells sagged by gravity.

During the 8 years after 1974 the deepwell extraction was lowered again, until an average of 1.75 million m^3 per year. This was possible thanks to the rather wet years, so the yield of the deepwells could be reduced without drawback for the production of drinking water.

In the mean time calculations were made for the waterbalances in the freatic and the deep aquifer. These results will be presented here. The calculations are important to predict what will happen in the near future. Because of the very slow changes of the fresh water pocket, it lasts very long

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before the progression of the process properly can be measured. To point out a policy for the next 10 to 20 years, a rough insight is wanted. This has been gained by the calculations.

Until now the measurements confirm the rough results of the calculations. Factually it became sure that the fresh water pocket below the dune-water catchment area is too small and too vulnerable for an extended extraction in the future, particularly as a result of the rather low natural recharge of the deep aquifer.

Therefore the idea of artificial recharge is developed for the deep aquifer. On this subject was reported at SWIM 1981 in Uppsala. Some more results of the study and the pilotplant will be shown here.

1. GEO–HYDROLOGICAL SITUATION

The deep aquifers are situated between 20 and 160 m below O.D. (= Mean Sea Level) and are separated from the first aquifer by a clay layer, which has an average hydraulic resistance of 12 years or 4400 days. At the depth of 160 m layers of fine sand with silt and clay layers start.

The deep aquifer itself can be divided in three important layers: two aquifers separated by a semi-pervious layer from about 60 until 90 m below O.D. This layer has a resistance varying from 500 days in the north-east to 5 days in the south of the area.

The second aquifer extends from 20 to 60 m below O.D. It consists of rather coarse sand with a total transmissivity of 10000 m^2/d. The third aquifer, from 90 until 160 m, has layer of very coarse sand. The transmissivity is about 3000 m^2/d.

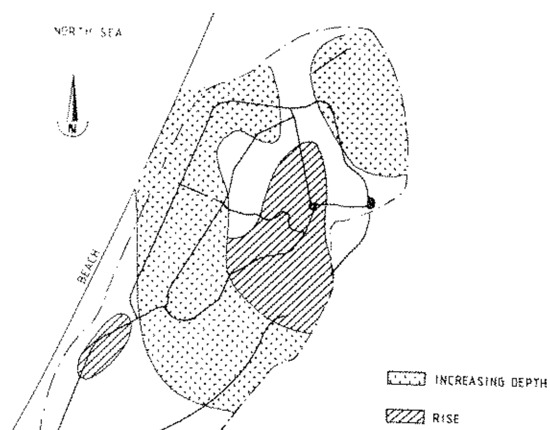

Fig. 1 – Tendency in the depth of the freshwater pocket (1982).

Nearly the total third aquifer always contained salt water, the fresh water pocket originally had a maximum depth of about 110 m at the eastside of the area.

At the westside the depth was 70 m. The thickness of the brackish zone varied from 20 m (eastside) to 10 m (westside).

The second aquifer originally was filled with fresh water. In this layer pumping by deep wells started in 1903. The pumping increased until 1957 to an amount of 21 million m^3/year. The leakage from the first aquifer is only about 7 million m^3/year. So an alarming situation arose during and after the second world war by intrusion and upconing of brackish water. This course of events was stopped by the infiltration of riverwater in 1957.

Since this year the fresh water in the second aquifer is used for quality reasons and during periods when the river-water-intake has to be stopped. It is considered as a deep safe storage. To use this storage now a number of 290 deep-wells are available with a total capacity of 3000 m^3/h. Reconstruction of the well-system is going on in order to restore the original and allowed capacity of 4000 m^3/h. This is about 40% of the wanted capacity of the catchment area.

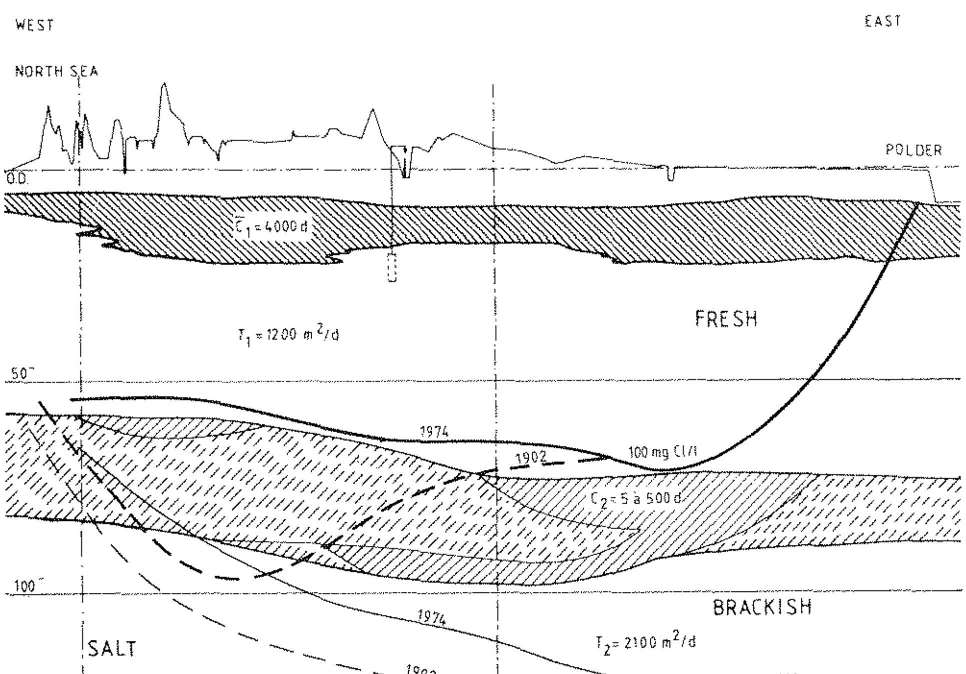

Fig. 2 – Cross-section (north).

The use of this capacity in time of disasters on the river Rhine is limited. In the first place from the point of view of the waterbalance. In about 60 days the total input per year of the second aquifer by leakage would be abstracted. Secondly there will be an immense salt water intrusion, specially by upconing from the third aquifer.

2. WATERBALANCE OF THE FREATIC AQUIFER

The two main aquifers each require a waterbalance. In the second aquifer there is fresh, brackish and salt water. Since the distribution of these three types of water is important, a separate balance for each type of water shall be wanted.

The balance of the freatic aquifer is rather simple, because the balance is made for the average catchment area and consequently there is a constant area with no horizontal flow at the boundaries.

The balance is:

$$N_n + W + O_2 = L + O + \Delta B_1 \qquad (1)$$

with:

N_n – effective rainfall

W – surface infiltration, with riverwater

O_2 – extraction from the second aquifer by deepwells

L – leakage to the second aquifer

O – extraction from the area for production

ΔB_1 – increase of the storage in the freatic aquifer.

Three factors are measured: W, O_2 and O.

The increase of storage can be calculated from the changing average value of the watertable, which is known from many piezometric tubes.

So: $$\Delta B_1 = \Delta\phi \cdot \varepsilon \cdot A \qquad (2)$$

as: $\Delta\phi$ – change of average freatic level in balance-period

ε – effective porosity as part of total volume

A – surface of balance area

The leakage to the second aquifer normally is calculated by:

$$L = \frac{\overline{\phi} - \overline{\psi}}{c} \cdot A \qquad (3)$$

where: $\bar{\phi}$ – average freatic level during balance-period
$\bar{\psi}$ – average head of fresh water in the second aquifer during balance-period
c – average resistance of semi-pervious layer.

The value for c is fixed in two ways. First there are many values for N_n known from the lysimeters, so the order of magnitude for c can be calculated from equation (1).

Secondly testcalculation for the second aquifer gave information too. Thus the value for c was fixed on 12 years (=4400 days).

It is clear that now the effective rainfall can be calculated from (1). The balance-calculations are made independent of the measured effective rainfall because of the problems with the exactitude of this observations.

3. WATERBALANCES OF THE DEEP AQUIFER

In the deep aquifer the total waterbalance can be divided in three balances for fresh, brackish and salt water. This three types of water are separated by the boundary-planes of 10 mg Cl' per liter and 10.000 mg Cl' per liter.

The balances are made for the same area as the balance of the freatic aquifer. So there is a horizontal flow at the boundaries, except for the brackish water: this one is fixed on zero because of the relatively limited thickness of the brackish zone and its low permeability. Horizontal inflow and

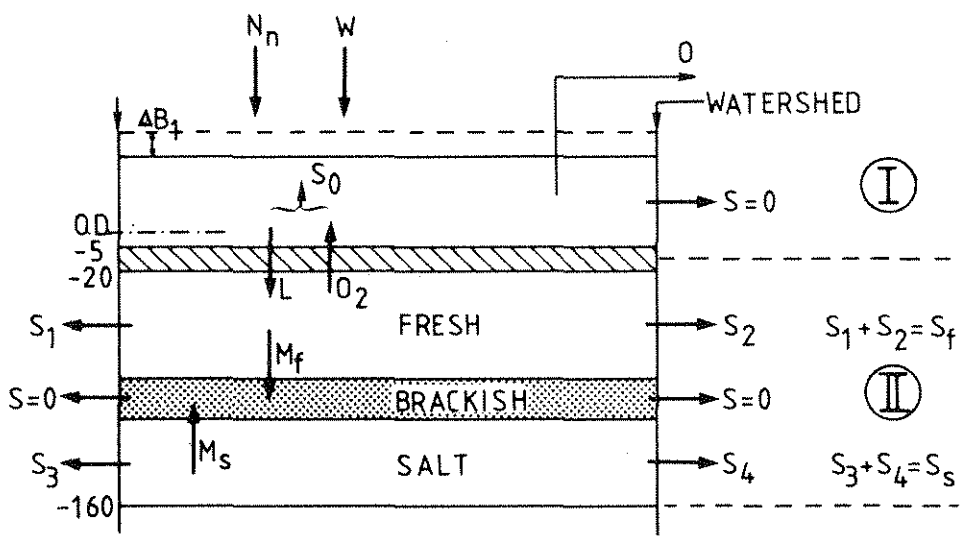

Fig. 3 – The waterbalances.

outflow are calculated at the westside and the eastside of the catchment area, not along the north and southern border because the general flow pattern is perpendicular on the coast.

The balances can be written ad follows:

fresh : $S_o + S_1 + S_2 + M_f + \Delta B_f = O$ (4)

brackish: $\Delta B_b = M_f + M_s$ (5)

salt : $S_3 + S_4 + M_s + \Delta B_s = 0$ (6)

Total : $S_o + S_1 + S_2 + S_3 + S_4 = 0$ (7)

because : $\Delta B_f + \Delta B_b + \Delta B_s = 0$ (7a)

See Figure 3 for the symbols. The factors M_f and M_s are the quantities of fresh and salt water that get lost by mixing into brackish water.

This four independent equations contain 10 factors, of which the S_o can be calculated from the waterbalance of the freatic aquifer. So another 5 equations are wanted to give a solutions for all the factors.

Testcalculations are made for the periods 1903-1956 and 1957-1974, because from the maps with the iso-lines of the depth for fresh and salt water values have been derived for the changed quantity of fresh, brackish and salt water (ΔB_f, ΔB_b and ΔB_s). For the *testcalculations* we need another 2 equations.

This 2 equations were found in the equilibrium of fresh and salt water at the west and the east boundary of the fresh water pocket (see fig. 4).

$$\psi = \frac{\rho_s \cdot \xi - (\rho_s - \rho_f) \cdot y}{\rho_f} \quad \text{(Badon Ghijben-Herzberg)} \tag{8}$$

$$\text{or: } \frac{d\psi}{dx} - \frac{d\xi}{dx} = \frac{(\rho_s - \rho_f)}{\rho_f} \cdot \frac{dy}{dx} = a \tag{8a}$$

wherein: ρ_f and ρ_s – density of fresh and salt water

ψ and ξ – head of fresh and salt water

$\frac{dy}{dx}$ – slope of the boundary plane between fresh and salt water

a – the value of *a* can be calculated from measurements

According to Darcy:

$$S_1 = -\frac{d\psi_1}{dx} \cdot T_1 \cdot b_1 \tag{9a}$$

$$S_3 = -\frac{d\xi_1}{dx} \cdot T_3 \cdot b_1 \tag{9b}$$

Here is: T_1 and T_3 transmissivity at the westside for the fresh and salt water.
b_1 = width of the westside.

The same formulas can be applied to S_2 and S_4.

So: $$\frac{S_1}{T_1 \cdot b} + \frac{-S_3}{T_4 \cdot b} = a_1 \text{ (westside)} \quad (10a)$$

and: $$\frac{S_2}{T_2 \cdot b} + \frac{-S_4}{T_4 \cdot b} = a_2 \text{ (eastside)} \quad (10b)$$

The *calculations* for the *historical data* for the years from 1854 until now, necessitate three other equations, because than the ΔB_f, ΔB_h and ΔB_s are not known. This three new ones are based on rather practical than theoretical facts.

The first idea is that in the salt water from the sea to the polder there is a constant loss of head because of the constant head in the Northsea and in the polder (ξ_1 and ξ_3):

$$\xi_1 - \xi_3 = \frac{S_4 - S_3}{T_4 + T_3} + \frac{S_4}{T_4} \cdot \frac{l}{b} \quad (11)$$

Wherein is: l – half the distance from sea to polder

b – the width of the area from north to south

T_3 and T_4 – the transmissivity of the layer with salt water at the west- and the eastside.

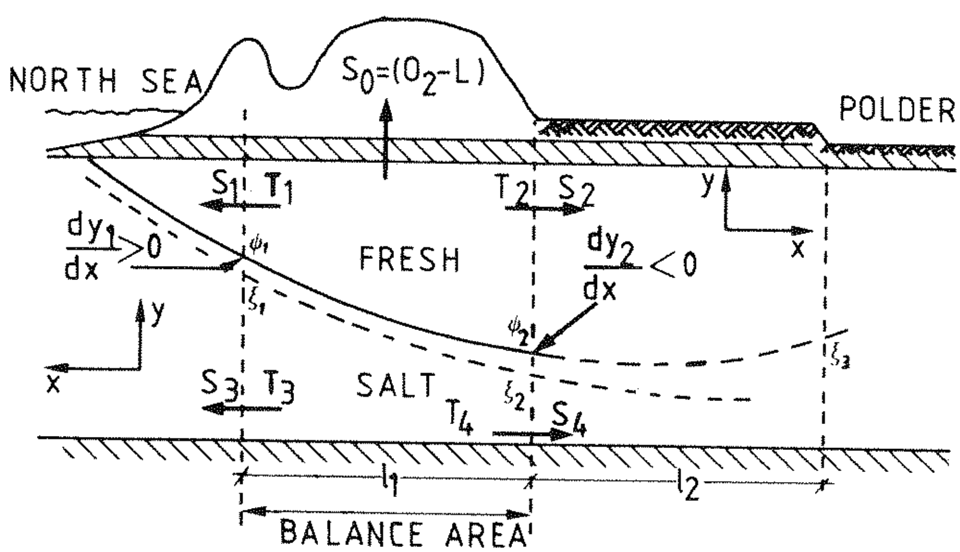

Fig. 4 – The fresh-saltwater equilibrium,

Secondly the influence of the deep extraction on the increasing thickness of the brackish zone has been used.

Factually a simple relation between the M_f and S_o and also between M_s and S_o has been fixed in such a way that the values per year together give the measured values from 1903-1974:

$$\text{if: } S_o \leq o \rightarrow M_f \text{ and } M_s = 0 \tag{12}$$

$$\text{if: } S_o > o \rightarrow M_f = 0.458\, S_o \tag{12a}$$

$$M_s = 0.056\, S_o \tag{12b}$$

This completes the set of equations for the calculations of the balances.

4. SOME RESULTS OF THE CALCULATIONS

The most important conclusions from the calculations concern the horizontal inflow of fresh water from the tongue below the sea, the outflow of fresh water to the polder and the change of the interface between fresh and brackish water.

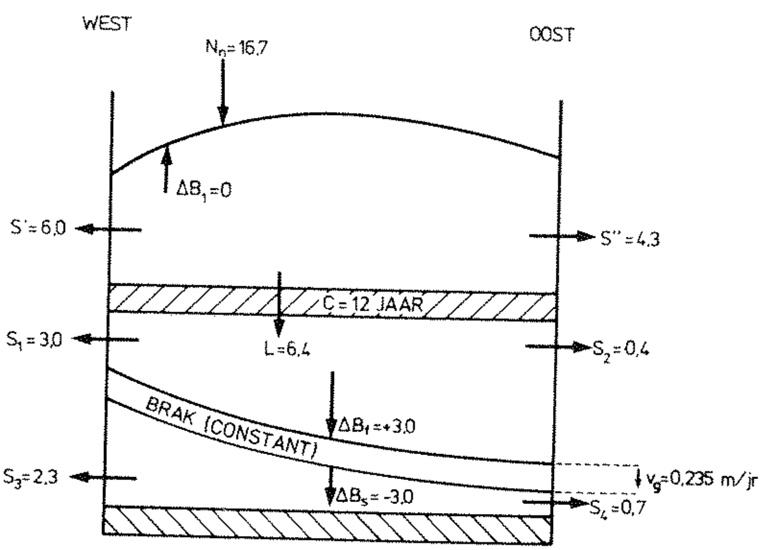

Fig. 5 - The balances in 1853.

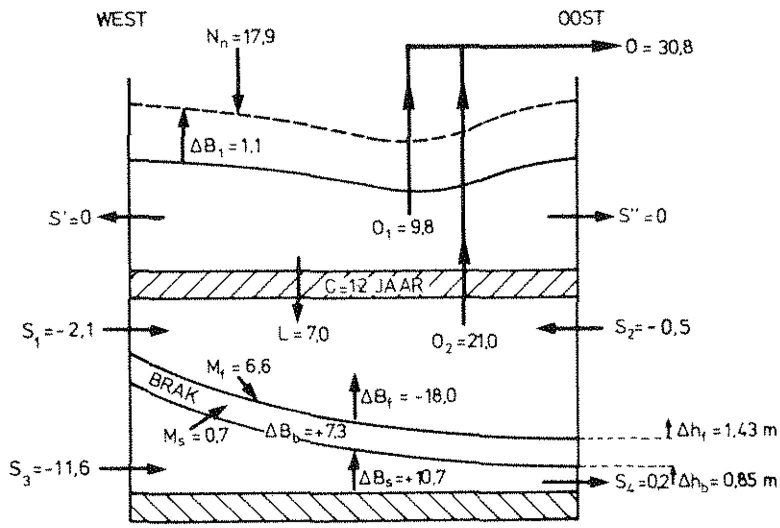

Fig. 6 - The balance in 1956.

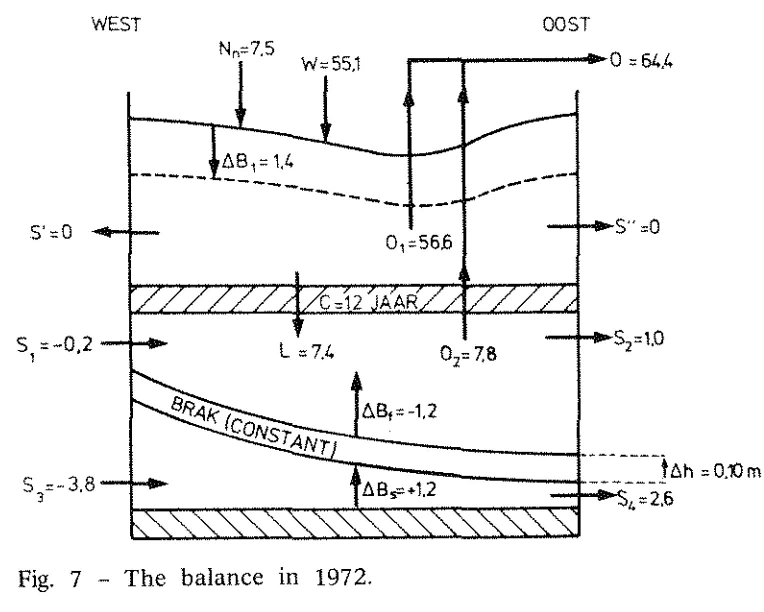

Fig. 7 - The balance in 1972.

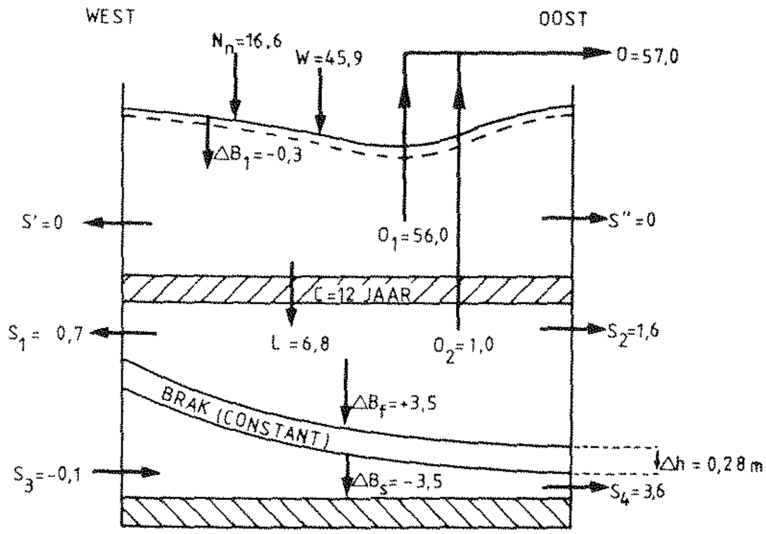

Fig. 8 – The balance in 1982.

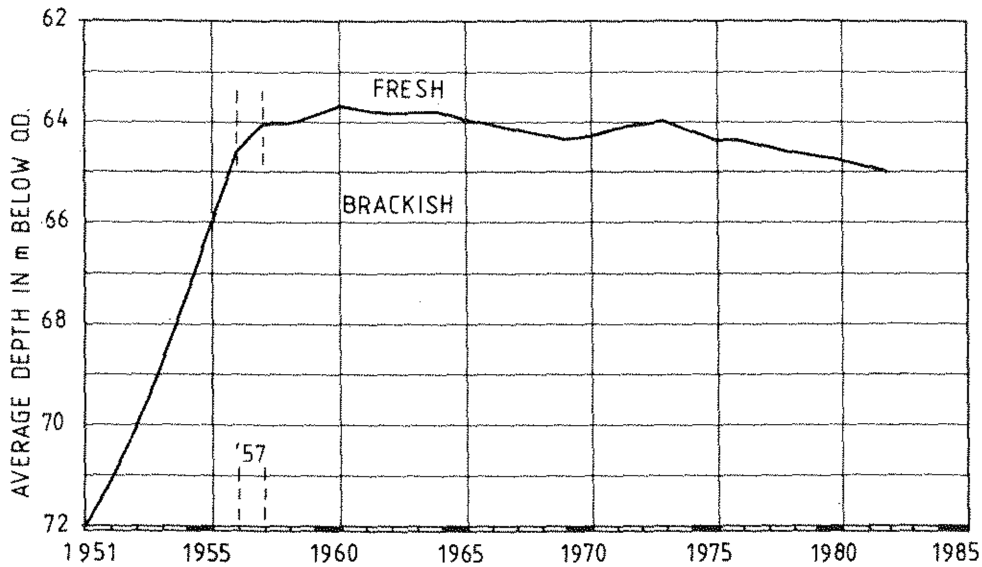

Fig. 9 – The development of the average depth of the freshwater since 1951 (calculated).

The S_1 changed from about 3 million m^3/a outflow (1853) to 2 million m^3/a inflow (1956), afterwards the outflow was about zero until 1974, since than it increased to about 0.75 million m^3/a. Thereby the inflow is stopped at the west, and a natural small outflow is restored.

The S_2, the outflow of fresh water to the east, had a rather small value (0.4 million m^3/a) until the polder was made. Than the outflow increased to 2.5 million m^3/a, but after 1902, when deep-extraction started, the outflow became negative. It now again has a positive value of about 1.6 million m^3/a. A first project now is executed to capture a part of this water with small wells.

The outflow of saltwater to the west (S_3) of about 2.3 million m^3/a changed in 1854 into an inflow of about 1 million m^3/a thanks to the new polder. Afterwards, the deepwell-extraction did increase the inflow until 12 million m^3/a (in 1956). It is now about zero, so the factual inflow of saltwater has stopped too.

The outflow of saltwater (S_4) to the east is now about 3.5 million m^3/a, therefore the saltwaterbalance is negative. Or: there must be a growing of the fresh water pocket as there is no reason for an increasing amount of brackish water.

However, it is sure that the increasing of the average depth of the fresh water pocket shall not exceed about 0.30 m per year.

The next table gives a summary of the saltwater intrusion during the period 1903-1974.

type of water	volume in million m^3			percentages		
	1903	1974	difference	1903	1974	change
fresh	949	557	− 392	54	31	− 41
brackish	173	311	+ 138	10	18	+ 80
salt	642	896	+ 254	36	51	+ 39
Total	1764	1764	0	100	100	0

As follows, the fresh water body lost 41% of its volume. The quantity of brackish water increased with 80%, the average chloride content of this zone decreased from about 3000 mg/1 to 2000 mg/1, because the difference of the volume of brackish water (138 million m^3) has been formed from 125 million m^3 of fresh water and 13 million m^3 of salt water.

If this loss of 125 million m^3 of fresh water is considered in connection of the total decrease of the fresh water (392 million m^3), it means that about 32% of the decrease got lost by mixing into brackish water and 68% has been used for the extraction.

5. FUTURE DEVELOPMENTS

Important aspects of the future situation are twofold. The capacity of the dunewaterworks is designed on 83 million m^3 per year. Only about 60 million m^3 is extracted now. Environmental interests may be reason that this capacity can not be realised with the infiltration of riverwater in the freatic aquifer. So artificial recharge of the second aquifer will be necessary to create a certain capacity for permanent extraction. This increased extraction must be designed in such a way, that no saltwater intrusion and upconing will occur.

A second problem is the size of the storage. It is considered to be small and in case of a realised capacity for the productien of drinkwater of 83 million m^3 per year, it will be too small. The reason is that the input of riverwater has to be stopped several times a year in case of accidents with poisonous matter on the river Rhine.

In dry periods, when the content of dissolved, undesirable matter is high, the input must be reduced. In this cases the deepwells shall be started to utilize the fresh water pocket as an extra storage.

At this moment the last problem is the most important one.

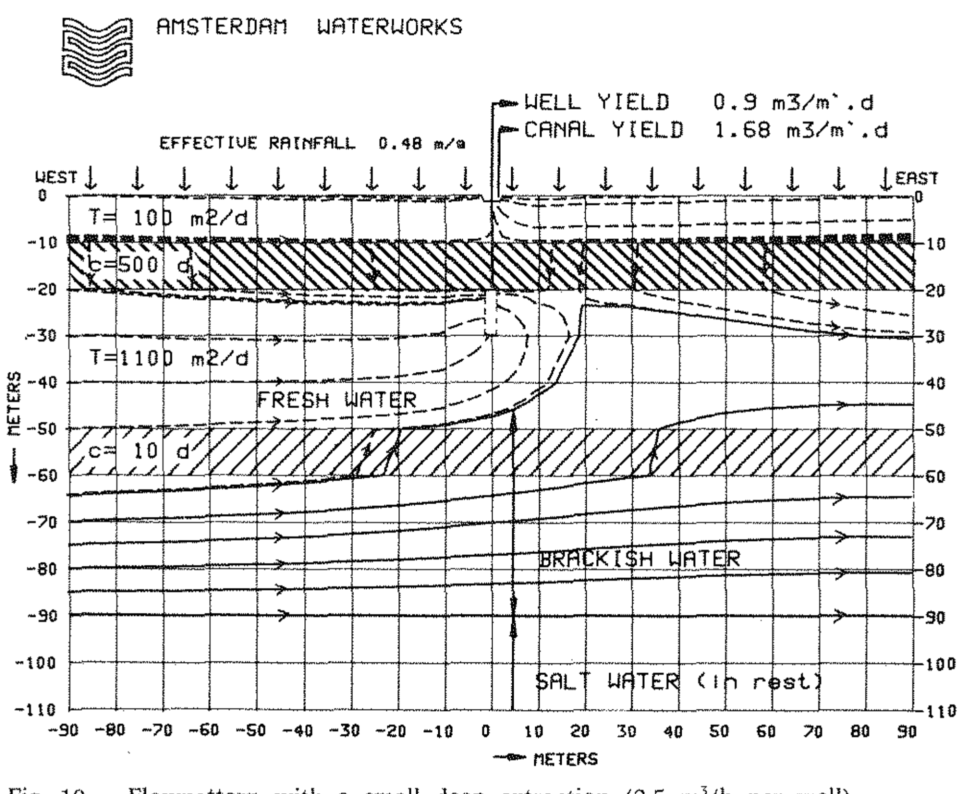

Fig. 10 – Flowpattern with a small deep extraction (2.5 m^3/h per well).

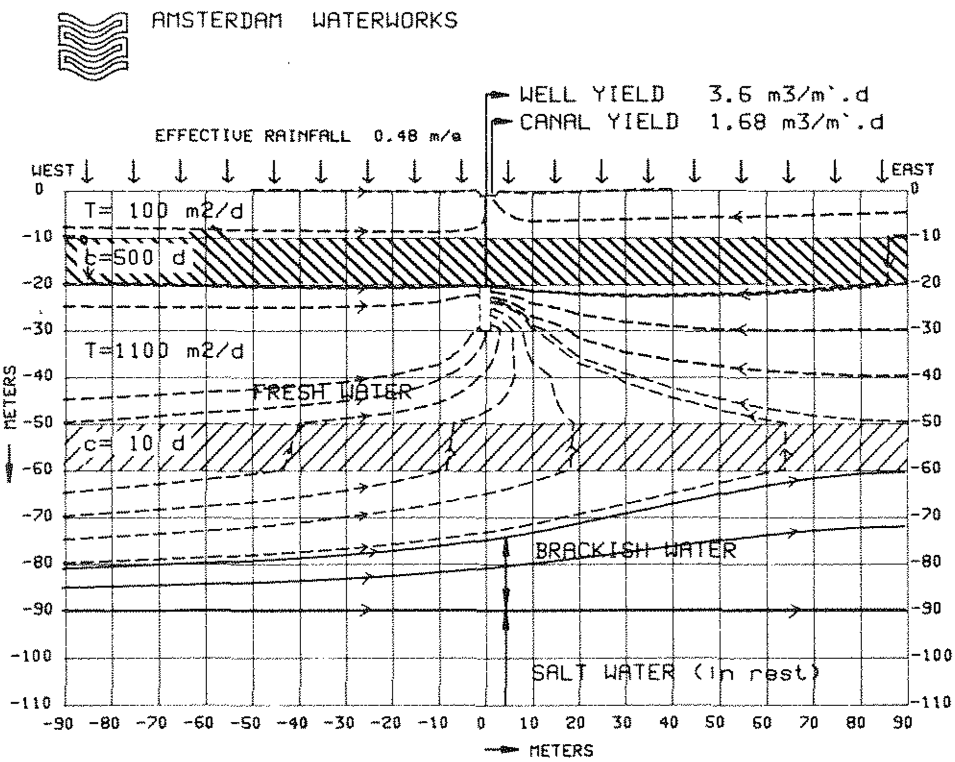

Fig. 11 – Flowpattern with an enhanced deep extraction (10 m^3/h per well).

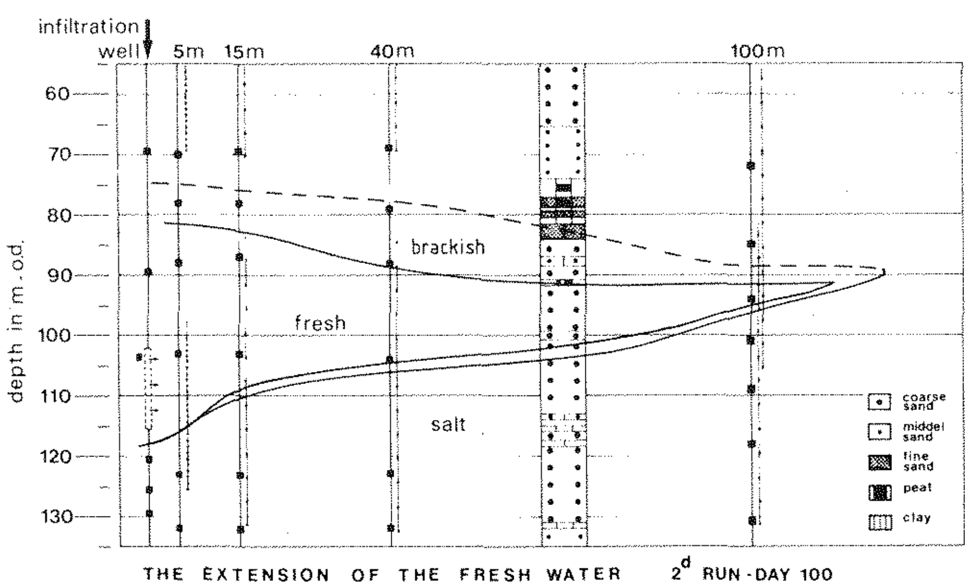

Fig. 12 – The spreading of the infiltrated fresh water. The zones of fresh, brackish and saltwater are found by geohmcabels, watersamples from filterscreens and by temperature-logging in the wells.

The solution that is studied, makes it necessary that the recharge of riverwater takes place deep below the extraction well in order to suppress the upconing of brackish and salt water. The principle is shown in the figures 9 and 10, where the flowpattern of an extraction in a natural flow is depicted with the mathematical model SLEM, designed by dr. ir. C. v.d. Akker.

The result of the calculations makes sure that the capacity of the well can be increased from 2.5 m^3/h to 10 m^3/h (3,6 m^3/m^2 d.) if the depth of the fresh water below the well can be increased with about 15m. The value of the resistance of the deep semipervious layer, in this case 10 days, is very important.

The resistance must be high enough in order that the influence of the well is spread sufficiently. But the value must be not too high, because than the infiltrated water gets lost.

In the dunewater catchment area this values in the order of magnitude of 10-50 days appear very much.

6. THE PILOTPLANT FOR DEEPWELL INFILTRATION

A testwell was installed in 1981 to check the possibility of the fresh water recharge in a salt water aquifer. In the Salt Water Intrusion Meeting 1981 at Uppsala some results have been shown. In addition new results after a longer duration are available. The maximum period of infiltration was about 500 days, when the well was stopped owing to clogging.

All the time the capacity was about 20 m^3/h, so about 250.000 m^3 was infiltrated. The brackish zone at the bottom of the lens still was very restricted, it confirms the statement that it is possible very well to create a fresh water pocket in the saltwater.

The infiltration stopped for 6 months to clean the well and to install a new pretreatmentsystem. Soon after the termination, the shape of the fresh water body had a natural state of equilibrium. From december 1982 the infiltration started again and in a short time the shape of the fresh water pocket was restored. The trials will be continued, specially in the field of pretreatment in connection with the clogging.