BRACKISH-SALINE WATER MOVEMENT IN THE SOUTHERN PART OF THE AMSTERDAM DUNE WATER AREA, 1925-2025

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The movement of the brackish-saline water in a cross-section below the southern Amsterdam Dune Area along the North Sea Coast was simulated over 1925-2025, using actual development and taken measures until 1999 and possible future measures afterwards. The model itself was verified for a well researched 1981 cross-section and carried out using finite differences for the freshwater heads and stream function simultaneously.

Introduction

The famous sandy flower bulb fields bordering the southern part of the Amsterdam Dune Water Area need groundwater levels at about 60 cm below ground surface, within a couple of cm accuracy. Recent changes in the hydrologic systems of the dunes and a winter season with much damage to the bulbs raised concern about the groundwater levels and their potential changes.

Gradually rising groundwater levels, due to changes of the fresh-salt water interface, after earlier reduction of extraction, was put forward as a potential cause. To investigate this claim, the movement of the fresh/salt water interface and its impact on the phreatic groundwater table were simulated for the period 1925 to 2025, taking into account former and future measures in the hydrologic system of the dune area.

The 3600 ha large, so-named Amsterdam Dune Area along the North Sea coast has been used for water extraction since 1853. Many changes have occurred since then, like digging of canals in the phreatic aquifer, drilling of wells in the second aquifer since 1902 and the introduction of artificial groundwater recharge in 1957. Today, 70 million m^3 of drinking water is supplied from the area, of which about 60 stem from artificially infiltrated river water. During the entire period the hydrologic system changed and likely will change further in the near future, reducing the net extraction, to preserve wet nature values.

The simulation was carried out in a 130 m deep cross-section from 5 km in the North Sea to 15 km landinward. The cross-section was chosen because: 1) It iseasier to manage the density flow and interface movement, while the groundwater flow being perpendicular to the coast; 2) It provides a better insight into the flow system, because both the heads and the stream function may be used; 3) The necessary geologic, hydrologic and density data for this cross-section had been collected before by Stuyfzand (1988); 4) The cross-section cuts all areas and extractions that are of interest.

Important features are the three aquifers, the bottom of the system at 130 m depth and the chloride interfaces. Further, the dunes as a natural recharge area. The flat bulb fields adjacent to the dunes and the low-lying Haarlemmermeer polder, a former lake, which was put dry in 1852. Its current surface water level is 6 m below mean sea level, causing a base flow from the North Sea and an inland movement of the salt water wedge at a speed of about 2000 m/century. The dunes discharges towards the North Sea in the west and the adjacent flower bulp area in the east, where the dense surface water system maintains the groundwater table at about 0.6 m below mean sea level. In the eastern part of this area, surface water infiltrates and flows eastward to discharge to the surface system in the west part of the low Haarlemmermeer polder. The fresh water forms a large, lens-shaped body, passed underneath by salt water from the North Sea. Further, this part of the dunes contains a western and an eastern extraction canal parallel to the North Sea. Below the east canal, a line of extraction wells tap the second aquifer between 30 and 40 m depth. Further east an old groundwater pumping station called Hillegom, abandoned in 1982, extracted from the same aquifer.

The models for the head (Phi) and stream (Psi) function

The groundwater flow is simulated as sequential steady states at one-year intervals. The effect of changing extractions is taken into account immediately, after which a gradual change of the density field takes place, which in turn alters the flow field.
Both the head and the stream function are calculated. These fields constitute each other's mirror; their combination provides much more insight than each one on its own.
Where the density is equal to the chosen reference value, head- and streamlines are perpendicular. (To see this, equal *y*- and *x*-scales must be used. This is virtually the case in Fig. 3, which is a detail of Fig. 1, showing the extraction by the wells of P.S. Hillegom). More importantly, between each pair of streamlines the flow of water is the same. We can thus immediately read from the picture the amount of water flowing everywhere in the model. The head and stream function increments are given in the title of the simulation figures.

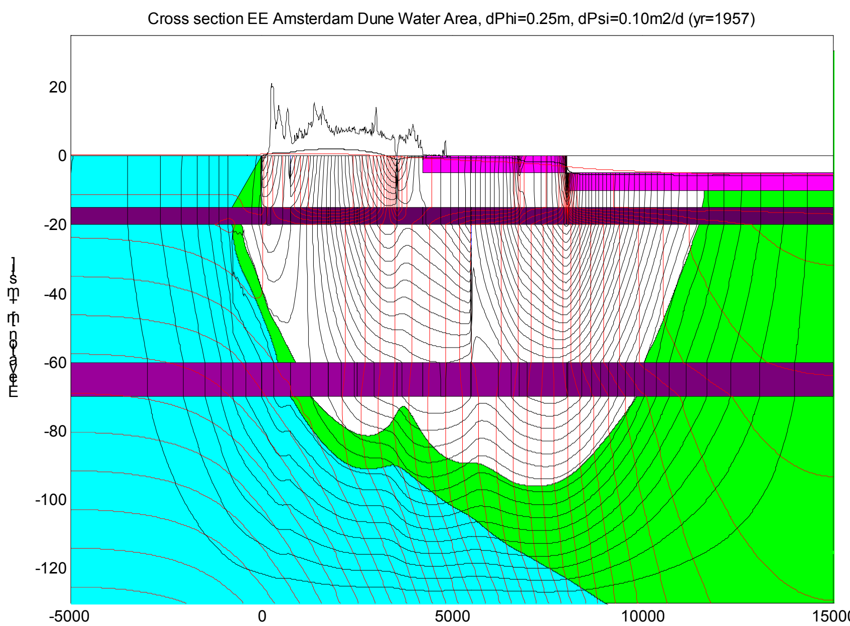

Fig. 1: Cross-section showing the dunes and the low-lying polder at *x*>8000 m, three aquifers and two aquitards, the fresh, brackish (5000 mg Cl⁻/l) and salt water (16000 mg Cl⁻/l) bodies, the iso-stream and iso-freshwater head lines, the head at –5 m and the extractions in the top aquifer in the west and east of the dunes and in the second aquifer, at *x*=5500 m.

Displacement of the density field is based on the stream function. Internal sources such as wells lead to multi-valuedness. They are explicitly dealt with by means of so-called branch-cuts (Van den Akker, 1982).
Fundamentally, Darcy's law is expressed using fluid pressure p [F/L^2] and intrinsic conductivity κ [L^2]. It is more convenient, however, to use a head ϕ [L] and hydraulic conductivity k [L/T]. This is done by defining a head ϕ [L] as:

$$\phi = \frac{p}{\rho_0 g} - y$$

with y [L] the upward coordinate, g [F/M] the gravity constant and ρ_0 a fixed, but arbitrary reference density.

Though the choice of ρ_0 is arbitrary, we mostly set ρ_0 equal to that of fresh water, in which case head and stream lines will be perpendicular in the fresh water part of the system. Sometimes we use the salt water density instead, to focus on the heads in the saline part of the aquifer (Compare Figs 5 and 6).

Choosing the main directions of the conductivity tensor parallel to the *x*- and *y*-axis, Darcy's law becomes:

$$q_x = -k_x \frac{\partial \phi}{\partial x} = -\frac{\partial \psi}{\partial y} \; ; \qquad q_y = -k_y \left(\frac{\partial \phi}{\partial y} + \delta \right) = +\frac{\partial \psi}{\partial x} \tag{2}$$

Where the hydraulic conductivity equals $k = \frac{\rho_0 g \kappa}{\mu}$ [L/T], $\delta = \frac{\rho - \rho_0}{\rho_0}$ [-] and Ψ [L^2/T] is the defined stream function and μ [FT/L^2] the fluid viscosity.

Volumetric fluid continuity demands:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = q \tag{3}$$

Which gives us the differential equation to be solved:

$$\frac{\partial \left(k_x \frac{\partial \phi}{\partial x} \right)}{\partial x} + \frac{\partial \left(k_y \frac{\partial \phi}{\partial y} \right)}{\partial y} = -q - \frac{\partial (k_y \delta)}{\partial y} \tag{4}$$

showing that we can compute the head in any density driven system, by adding the density terms to the source terms of the model. Clearly, the boundary conditions have to be adapted as well.

Continuity of head, around an arbitrary path in the flow system, yields:

$$\oint_S \phi \, ds = 0 \;\rightarrow\; \frac{\partial^2 \phi}{\partial x \partial y} - \frac{\partial^2 \phi}{\partial y \partial x} = 0 \tag{5}$$

Inserting Darcy's law and the definition of the stream function ψ, we obtain the differential equation to be solved by the psimodel:

$$\frac{\partial}{\partial x}\left(\frac{1}{k_y} \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial y}\left(\frac{1}{k_x} \frac{\partial \psi}{\partial y} \right) = -\frac{\partial \delta}{\partial x} \tag{6}$$

These two differential equations are similar and can be solved by the same standard model code. To compute Ψ instead of ϕ we replace k_x by $1/k_y$ and k_y by $1/k_x$ and to use the density term $\partial \delta / \partial x$ as the source term in the model input. As can be seen from the two differential equations, the stream function cannot deal with internal sources. Internal sources and sinks in the stream function are dealt with by so-called branch cuts running from them to an edge of the model.

These two equations can be solved by a general, simple, two-dimensional mesh-centred finite difference model. The only difficulty seems to be the implementation of the density term.

Discretising the differential equation is done by integrating it over the volume that is represented by each model node. For the density term this becomes:

$$\int_{X_1}^{X_2} \int_{Y_1}^{Y_2} \frac{\partial (k_y \delta)}{\partial y} dy dx = \int_{X_1}^{X_2} \left[k_y \delta \right]_{Y_1}^{Y_2} dx \tag{7}$$

For the stream function model we have to evaluate

$$\int_{Y_1}^{Y_2} \int_{X_1}^{X_2} \frac{\partial \delta}{\partial x} dx dy = \int_{Y_1}^{Y_2} \left[\delta \right]_{X_1}^{X_2} dy \tag{8}$$

This implies that $k_y\delta$ needs to be integrated along the top and bottom of each "node-volume" only. This can be done exactly, if a convenient spatial distribution of the density field is used. Possibilities are to use a single density in each cell, or to apply sharp interfaces or a density field defined by a series if iso-density lines, or any integratable function.

Eq. 8 shows that we have to integrate the dimensionless density δ along the vertical sides of each nodal volume of the psimodel. This can also be done exactly with a conveniently chosen spatial density distribution.

The multi-valued stream function around internal sources and sinks can be dealt with by means branchcuts, i.e. lines at which the stream function value jumps (Van den Akker, 1982). By choosing the branch cuts vertically from the top of the model, they will show up as vertical screens discharging to the top of the model (Fig. 2, Fig 3).

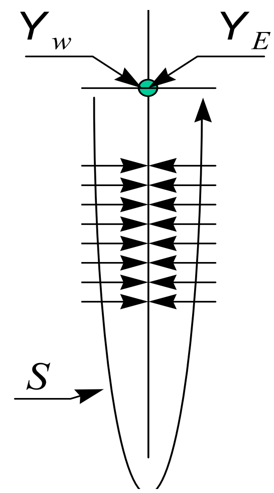

Figure 2: branch cut with flow to extraction screen

The stream function ψ_E in Fig. 2 follows from ψ_W :

$$\psi_E = \psi_W + \int_S \vec{q} \cdot \vec{n} \, dS \qquad (9)$$

With q [L/T] the specific discharge along the branch cut and n the direction vector perpendicular to it. We add the jump to the model by adding the integral to the node equations to the right of a branchcut. Because this integral can be computed in advance, it enters the model as a source or sink. Because the stream function at branch cuts now has two values, contouring has to be done in parts and the results put together in a single figure. The detailed result is shown (Fig. 3).

The flux perpendicular to a density interface can directly be computed from the stream function:

$$v_n = \frac{\partial \psi}{\partial s} \qquad (10)$$

where ds is taken along an interface (or an iso-density contour). The sign of this flux corresponds to the definition of the stream function. In our model iso-density contours are given explicitly as lines separating water bodies with different densities. Numerical dispersion does not occur with this method, though high-frequency instabilities may occur at interfaces, due to lack of smoothness of $\partial\psi/\partial s$ at cell boundaries. These can be avoided with a smoothing filter having a working length of several times the cell length. (In this case, where we used cell lengths of 25 m, the filter length is of the order of one hundred m, which is considered acceptable).

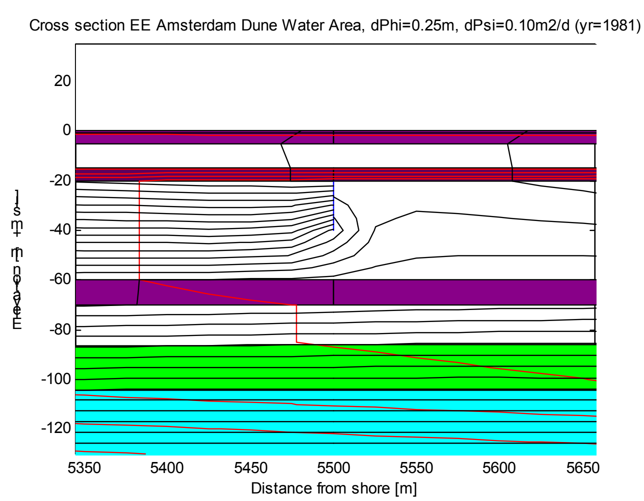

Fig. 3: Detail of Fig. 1, showing the stream function with internal source (vertical branch cut)

The finite difference model is implemented as a function, taking as arguments the cell node coordinates, a matrix of horizontal and vertical conductivities, a matrix defining given heads and one with given injections (extractions are

negative injections). The results are the nodal matrices of the heads and flows. These "flows" now include the density contribution:
[Phi,Q]=**flatmod**(x,y,kx,ky,FPhi,FQ).
After subtracting the density distribution the stream function is computed using the obtained flows Q and used as an input of the psimodel, together with the density contribution (see (8)). The result is the stream function at all nodes. The only difference between both models for the head and the stream function is the necessary processing of branch cuts in the latter. The model was used with cells 25 m wide and 5 m high, that is, a total of 800x26 cells or 801x27 nodes.

The modelled cross-section

Cross-section EE' as researched by Stuyfzand (1988) is relevant for this study (Fig. 4). It runs perpendicular to the coast in the west through the dunes, the flower bulb area (De Zilk), pumping station Hillegom, ending at the deep Haarlemmermeer polder. Almost all necessary information is given for the 1981 situation. When testing the model results for this section (Figs 5 and 6), only minor adaptations had to be made to it. The salt water heads below the dunes proved to be most sensible to the extend of the fresh water wedge, which in turn depends on the resistance of the first aquitard. This was used to calibrate the aquitard resistance below the North Sea. The heavy salt water above the fresh water below the North Sea is unstable and so the exact situation is uncertain. Fresh water was assumed in the aquitard above the fresh wedge and the shape of the brackish water zone was taken as shown (Fig. 1). Stuyfzand's (1988) chloride contours were minimally adapted to the different densities used here, based on the underlying chloride data. The brackish water interface below pumping station Hillegom was adapted to the streamlines of the model to make it compatible with the cross-sectional approach taken here. It is tempting to compare the field data with the model results. To simplify this, Fig. 5 shows the fresh water heads and Fig. 6 the salt water heads, Stuyfzand's Fig. 4 has both.
The sections clearly show the salt water wedge heading landinward towards the Haarlemmermeer in the east. The amount can be read by counting streamlines times 0.1 m^2/d. The heads can be found be counting head lines times 0.25 m, starting with 0 at the North Sea at *z=0*.

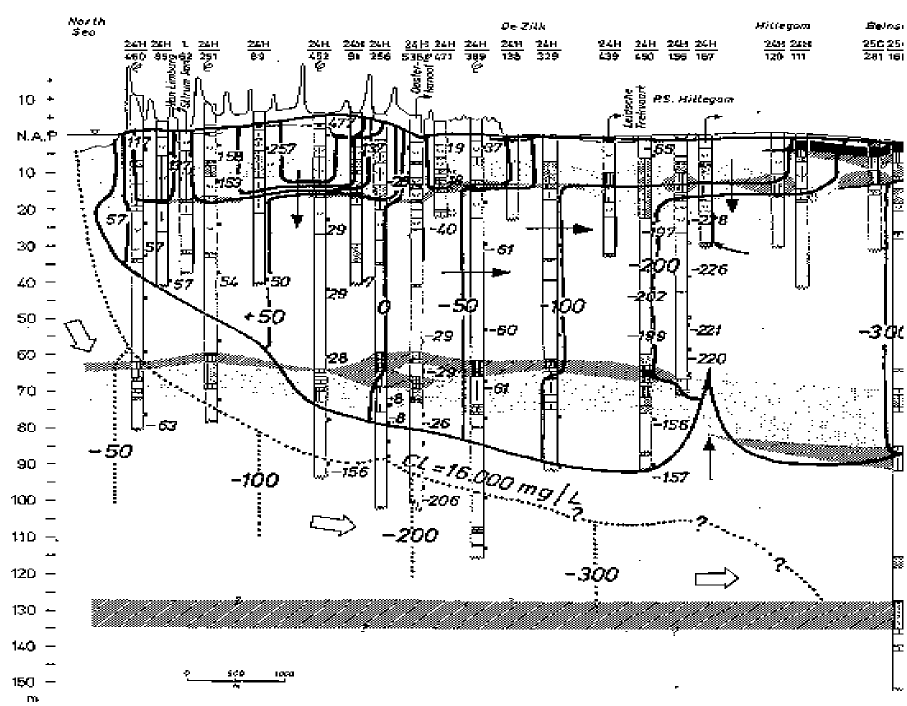

Fig. 4: Cross-section EE' according to Stuyfzand (1988)

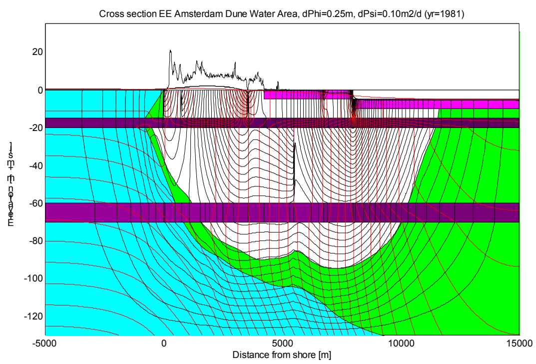

Fig. 5: Situation 1981, fresh water heads

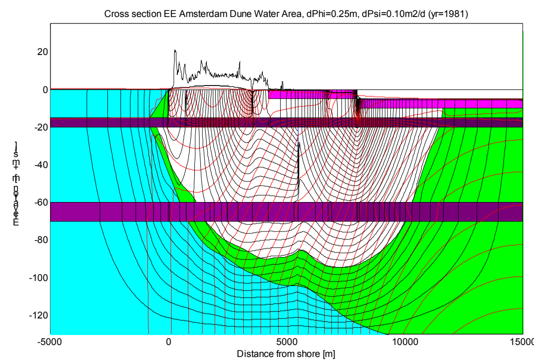

Fig. 6: Situation 1981, salt water heads

Changes over time (1925-2025)

The simulation is done for the period 1925-2025, which is divided into subperiods with constant extractions and canal levels. Natural recharge (1 mm/d), sea and polder head conditions are unchanged over the entire simulation time span.

Starting situation, 1925

Fig. 7 shows the starting situation in 1925, the year that the east canal was taken into use, together with its line of extraction wells. Pumping station Hillegom had been extracting since 1876. The 1925 situation resembles that of 1981, more so because from 1957 to 1981 no deep well extraction along the east canal took place. From this, the "1925 situation" was assembled by using the brackish water interface of 1981, and shifting salt water interface backward in time over 50 years (=1000 m). This procedure is considered reasonable as errors will partly disappear in the 1925-1957 simulation period.
Fig. 8 gives the computed displacement of the interfaces over 1925-1956. Fig. 1 gives the 1957 result showing its substantial brackish water upconing below the east canal, which complies with the salination of these wells during the 1950's (Betuw, W. van, 1999).
During the 1957-1981 period the wells along the east canal were off, with the extraction by P.S. Hillegom increasing from 1 to 1.7 Mm^3/a. Fig. 10 shows the eastward movement of the cone of brackish water and the salt wedge, again in 5-year steps. Fig. 9 provides the 1981 situation
The cone of brackish water has moved eastward after stopping the east canal extraction wells in 1957. This corresponds with the stream lines. Disappearance of a cone of brackish water is an extremely slow, centuries taking process, contrary to upconing.
P.S. Hillegom was abandoned in 1982, while during 1984-1994 extraction by the east canal wells resumed, but at a four times lower rate.
In February 1995 the west canal was shut down and refilled with sand. This resulted in increased westward flow. In 1996 the water level in the east canal was raised by 50 cm. In 1998 the extraction of the wells along the east canal was stopped once more. Fig. 12 provides the interface displacements during the period 1980-2000 and Fig. 11 the simulated situation for 1999, corresponding to the measures that have actually been taken.
To provide a picture for the impact of a measure that might be taken in the near future, the last remaining extraction, that of the phreatic east canal itself, was switched off in 2000 (in the model only). The displacements of the interfaces is given in Fig. 14 and the end situation for 2025 in Fig. 13.

Even by then the brackish water cone will not have disappeared completely. The discharge from the dune area has now largely increased both towards the sea in the west and the land in the east. The brackish water wedge has thinned. The streamlines show that the fresh water lens below the dunes now moves downward and extends to the east. The flow of saline water to the Haarlemmermeer polder continues at its own pace. The saline water toe even starts bending upward to finally, after hundreds to thousands of years salinise the Haarlemmermeer polder (Oude Essink, 1996).

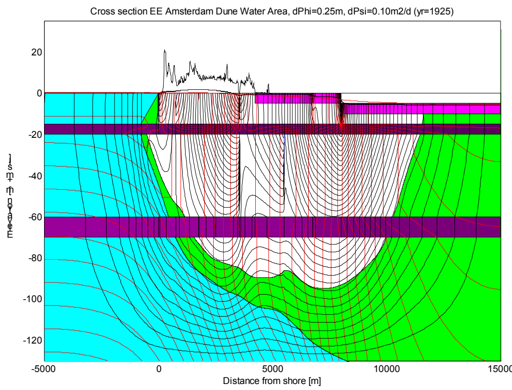

Fig. 7: Start situation, 1925

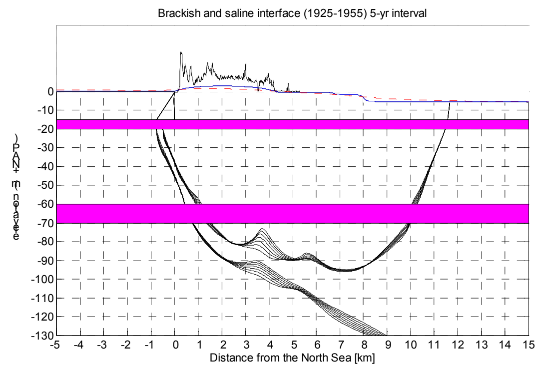

Fig. 8: Interface displacements 1925-1955

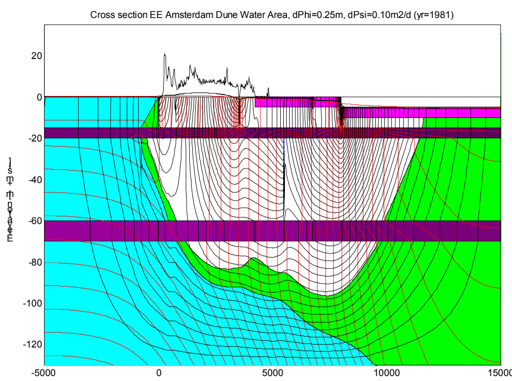

Fig. 9: Simulated situation for 1981

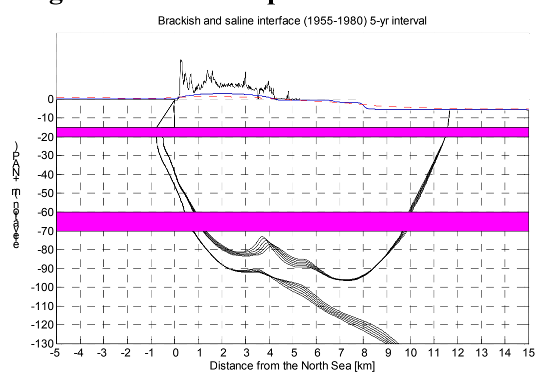

Fig. 10: Interface displacements 1955-1980

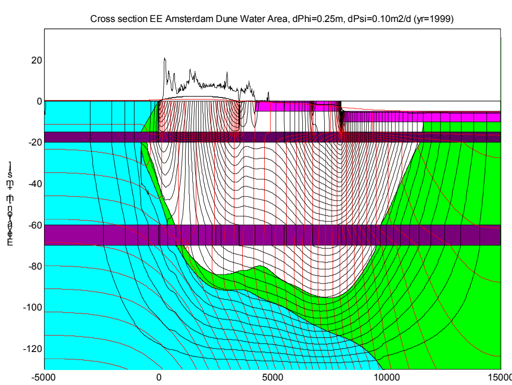

Fig. 11: Situation 1999

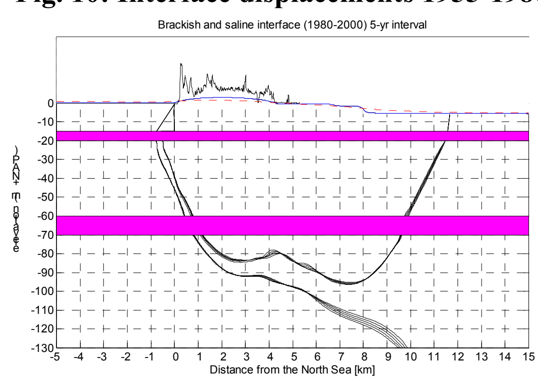

Fig. 12: Interface displacement 1980-2000

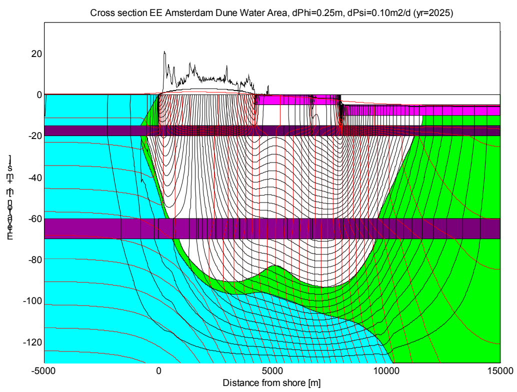

Fig. 13: Situation 2025

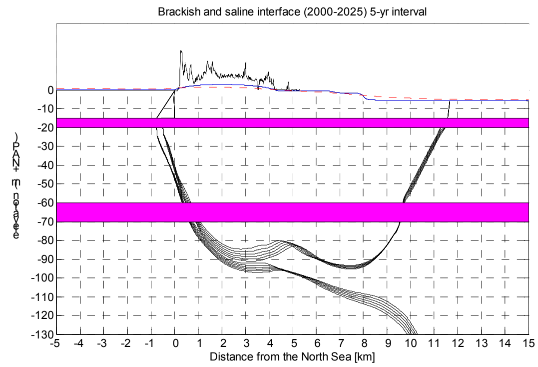

Fig. 14: Interface displacement 2000-2025

Conclusions

Stuyfzand's (1988) cross-section proved directly applicable for modelling. The use of fresh and salt water heads simplified the verification of the model. The stream function completed the flow picture, allowing visual quantification of the local discharge. Much insight was gained from the development and speed of displacement of the interface over time. The original question about the effect of the gradual displacement on the phreatic groundwater tables could be answered as well. This effect proved negligible, even in the second aquifer, i.e. at most 5 cm below the dunes, zero below the bulb fields and less than 2 cm elsewhere. The model also showed the position of the brackish water interface to be practically stagnant below the Haarlemmermeer polder, implying that little change in seepage to be expected for the next century or so.

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