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SALINIZATION OF A WELL FIELD CAUSED BY A SHORT-CIRCUIT BETWEEN TWO AQUIFERS

SUMMARY

The water quality of a well field in the northern part of the Netherlands, with an annual production of 11.5 million m³, is seriously affected by salinization. Chloride concentration has increased from 40 mg/1, considered normal in this area, to more than 200 mg/l in some of the production wells. This is caused by a short-circuit through a clay layer between the producing aquifer and an underlying aquifer which contains brackish water.

Investigations leading to this conclusion consisted of a geo-electrical and a geohydrological survey, including the analysis of hydrochemical data, and of temperature measurements in observation and production wells. Temperature measurements in the observation wells proved to be particularly essential for understanding of the salinization mechanism. The original temperature field has also been reconstructed by model calculations which take into account lateral lithological variations in the subsoil. Comparison of this field with the actual temperature field gave good indications of the upward movement of brackish water and of the short circuit location. This short-circuit originates in a Pleistocene glacial gully, within which clay layers between the two aquifers have been removed.

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1. INTRODUCTION

In Noordbergum, in the northern part of the Netherlands, two well fields of the N.V. Waterleiding Friesland (Waterworks of Friesland) are located at a mutual distance of 1.5 km (Figure 1).

Since 1956, when the second field (Ritskebosch) was brought into service, the annual production of each well field has grown to 11.5 million m^3. In 1977 a large increase in chloride concentration was observed in production wells at both fields. This concentration had risen from about 40 mg/l, considered as normal in this area, to more than 200 mg/l in some of the wells.

In order to make predictions for the future, the mechanism of this serious salt water intrusion had to be studied and the waterworks contracted the International Water Supply Consultants IWACO B.V. to carry out hydrogeological investigations [2, 3].

At the beginning of this study the origin of the brackish groundwater was unknown and a programme was started to obtain more basic data by the following investigations:

1) geo-electrical survey (soundings and profiling);
2) geological investigations;
3) hydrochemical studies;
4) temperature/depth measurements in observation wells and temperature measurements of water in the production wells;
5) hydrogelogical investigations including pumping tests and water balance studies.

In this paper special emphasis is placed on results of geothermal investigations from the youngest well field « Ritskebosch ». In brief, it was found that at this site salt water intrusion into the producing aquifer takes place through a short circuit with the underlying aquifer which contains brackish water.

In the northen (oldest) well field salinization is found to originate by another mechanism, viz. a « normal » lateral attraction of brackish water from the North Sea lying to the north-west.

Having established the salinization mechanisms of the two well fields, a second phase of investigation has involved the calculation of travel times for fresh and brackish water present in the aquifers. From these, prognoses have been derived of the chloride concentrations for several future production strategies.

1.1. Hydrogeological schematization

Subsoil at the well field location can be schematized by three main units (Figures 2 and 7).

1. – The hydrogeological base at a depth of –240 m NAP (Dutch datum level), located at the transition from clayey to more sandy deposits of marine Pleistocene origin. Below this base the deposits contain fossil salt water.

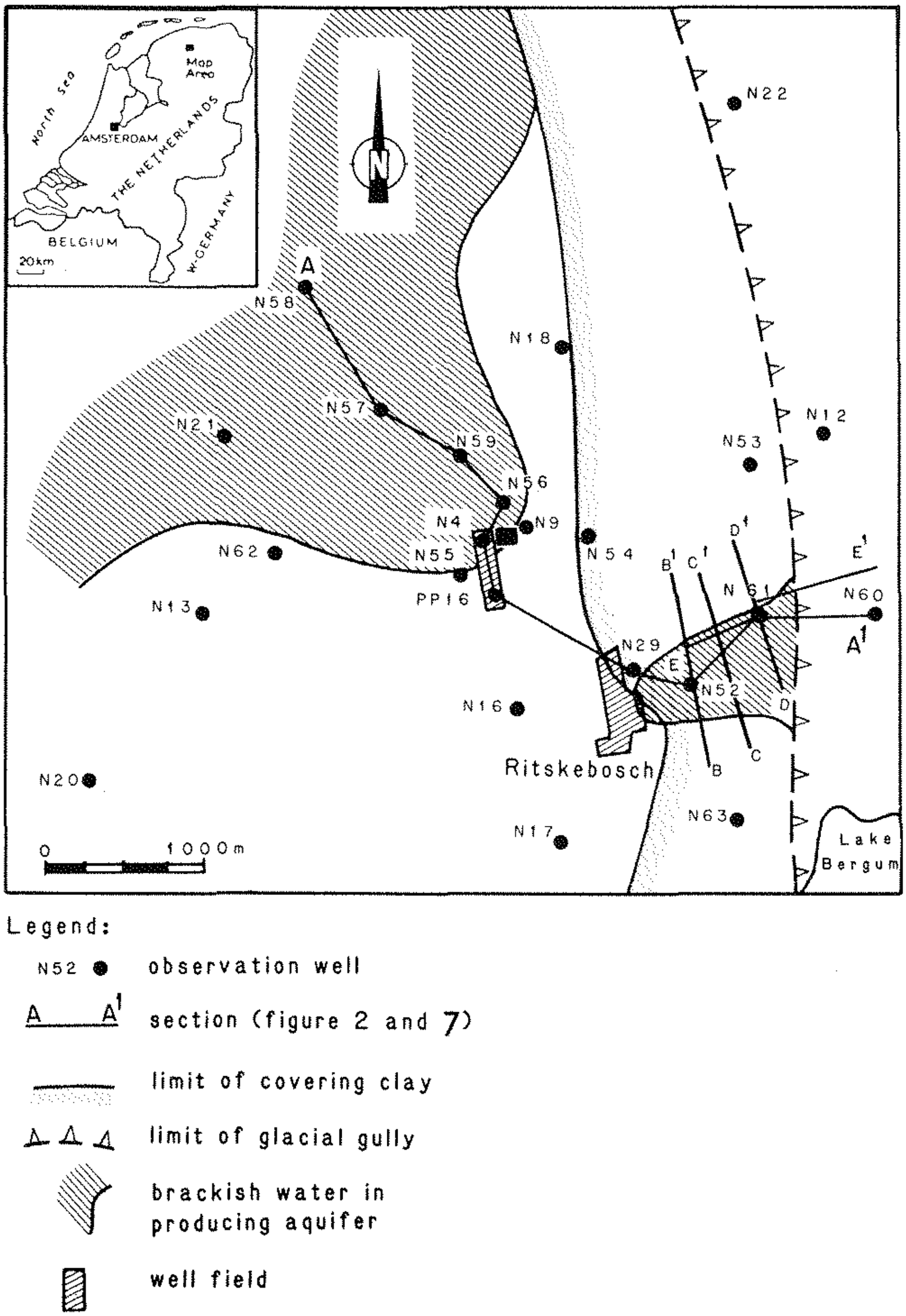

Fig. 1 - Location map and brackish water occurrence in the upper (producing) aquifer; this paper deals with the well field Ritskebosch.

2. - Two aquifers; the upper at a depth from 60 to 150 m and the lower from 160 to 240 m. Both aquifers consist of coarse fluviatile Pleistocene sands and contain semi-confined water. Permeability of the upper aquifer is 6×10^{-2} m^2/s (5000 m^2/d) and of the lower aquifer 4×10^{-2} m^2/s (3500 m^2/d). The aquifers are divided by a clay layer (« Clay of Tegelen ») at a depth of 150 to 160 m. This clay, with a high resistance to vertical groundwater flow, has been found in all boreholes, except those drilled in the Pleistocene erosion gully east of the well fields. However, from a geological point of view, there were previous doubts about the continuity of this layer outside the gully.

3. - The covering layers, consisting mainly of Pleistocene glacial deposits. East of the well field these form deposits which alternate with thick clay layers, located in a deep erosion gully.

Over this gully a heavy clay of very low permeability is found which to the west changes into fine loamy sand with clay layers. All these deposits are covered by very fine sands (5 to 10 m thick) and a thin layer of loamy clay.

2. THE RESISTIVITY SURVEY

The purpose of geo-electrical sounding and resistivity profiling was to attempt the delineation of the brackish groundwater and to select optimum lo-

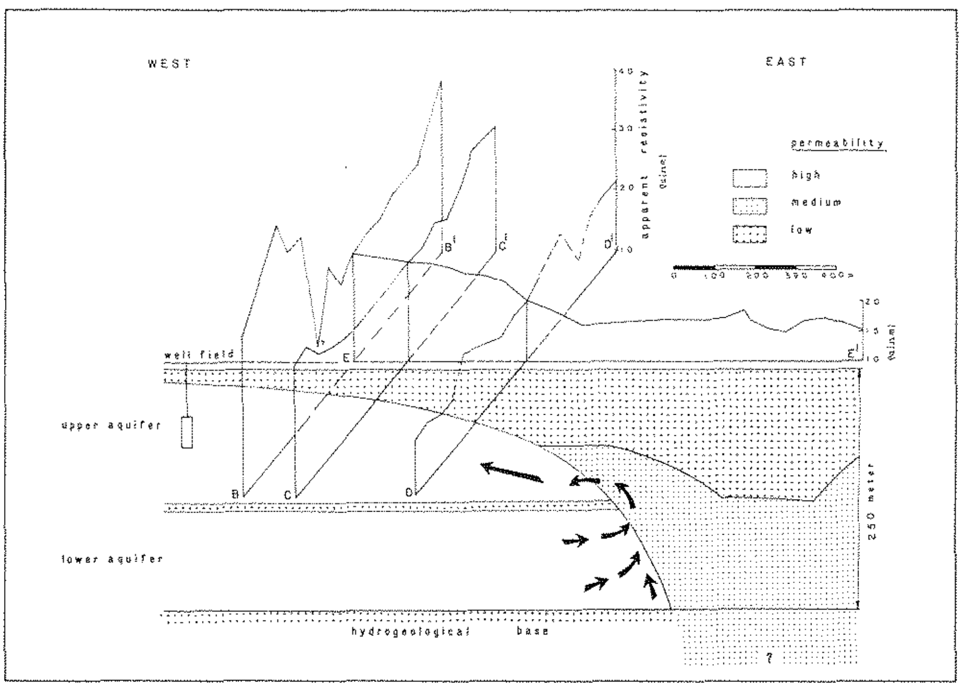

Fig. 2 - Diagram of apparent resistivities (a/2 = 50 m, L/2 = 300 m) and hydrogeological schematization; for location of sections see figure 1.

cations for a test drilling programme. To supplement older resistivity data, 12 new vertical electrical soundings, 3 north-south resistivity profiles and one east-west profile were carried out (Figures 1 and 2). The section closest to the well field (B-B') clearly shows a resistivity low opposite the well field. However, sections C-C' and D-D' do not show such a clear anomaly. Resistivities decrease to the east and reflect an increase in thickness of the covering clay layers. The E-W profile shows a knickpoint which marks the western border of the gully.

Three test wells reaching the hydrological base were drilled on the basis of this resistivity survey.

3. HYDROCHEMICAL AND GEOTHERMAL INVESTIGATIONS

The purpose of hydrochemical and geothermal studies was to gain a better insight into the following problems:

a) the origin and flow path of brackish groundwater pumped at Riskebosch;

b) to furnish clear proof of groundwater flow from the lower into the upper aquifer via sandy deposits of the glacial gully;

c) the evidence of clay layer continuity between the two aquifers; gaps in this layer could be of great importance for groundwater flow.

3.1. Hydrochemistry

In the area studied five water types can be distinguished based on differences in the proportional distribution of principal anions and cations.

1) Sodium chloride ($NaCl$) type water in the northwestern part of the area. This water was intruded into the aquifer during holocene marine transgressions and is also found beneath the hydrogeological base.

2) Calcium bicarbonate ($CaHCO_3$) type water; the normal product of infiltrated rain water.

3) Calcium chloride ($CaCl_2$) type water; the result of brackish or salt $NaCl$-water infiltration into an aquifer which originally contained fresh $CaHCO_3$ type water.

4) Calcium-sodium bicarbonate ($Ca/Na\ HCO_3$) type water; this is fresh water with a small enrichment of Na and is found in the upper aquifer between the infiltration area ($CaHCO_3$ water) and the area with $CaCl_2$-water.

5) Mixed water; originated from mixing of $CaHCO_3$ and $NaCl$ type waters without distinct cation exchange.

$CaCl_2$ type and $NaHCO_3$ type waters are the result of cation exchange processes [1]. $CaCl_2$ type water shows the effect of sea water entering a fresh water aquifer; in this process Na ions from the sea water are exchanged for Ca ions adsorbed onto clay particles and organic material. $NaHCO_3$ type water originates by the reverse process in which $CaHCO_3$ type water replaces salt water in an aquifer.

Results of the hydrochemical study are presented in figures 7 and are based mainly on analyses of samples from the new test wells.

3.2. Geothermy

Temperature-depth curves have been recorded for this study in most of the observation wells and pumped water temperature has also been measured in 29 production wells at Riskebosch. Using these observations the original temperature field could thus be reconstructed. The field is found to have a more or less stationary temperature distribution before pumping. However, with groundwater extraction the field becomes unstationary and the resultant temperature changes give a clear indication of groundwater flow and hence of salinization mechanism. Within one lithological unit (below the zone influenced by seasonal temperature variations - to a depth of about 20 meters) at places where the temperature field is un- or only slightly influenced by pumping, the temperature-depth relation is linear. In this case the heat flow by conduction follows Fourier's law:

$$q_z = -\lambda \frac{\delta T}{\delta z} \qquad (1)$$

where q_z = conductive heat flux vector (W/(m.K))

λ = thermal conductivity of the satured ground (W/(m.K))

$\frac{\delta T}{\delta z}$ = vertical temperature gradient (K/m)

The vertical temperature gradient can easily be determined from the temperature-depth curves recorded in the observation wells.

The vertical stationary heat flow through two homogeneous and isotropic layers can be described by:

$$q_z = -\lambda_1 \left(\frac{\delta T}{\delta z}\right)_1 = -\lambda_2 \left(\frac{\delta T}{\delta z}\right)_2 \qquad (2)$$

The indices 1 and 2 denote respectively the upper and lower layers. If the temperature gradient in both layers is known the ratio $\lambda_1 : \lambda_2$ can be calculated. However, complications may occur if the boundary plane between the two layers and/or the isotherms is inclined (such as near the glacial gully).

In this case the following equation is more appropriate (see also Figure 3):

$$\frac{\left(\frac{\delta T}{\delta z}\right)_1}{\left(\frac{\delta T}{\delta z}\right)_2} = R\frac{\lambda_2}{\lambda_1} \tag{3}$$

with α = angle of the boundary plane

β = angle of the lower layer isotherms

$$R = \frac{\cos\gamma_2 \cos\beta}{\cos(\alpha+\beta)\cos(\alpha-\gamma_2)} \tag{4}$$

The factor R thus determines the accuracy with which the ratio $\lambda_1 : \lambda_2$ can be determined. If $\alpha = 0°$ and $ß \leq 10°$, $R \approx 1$ and equation (2) will be applicable for the analysis of thermal conductivity.

Since the maximum slope value for the glacial gully is 25°, R will deviate significantly from 1 and hence temperature recordings from observation wells N 52 and N 61 could not be used for the determination of $\lambda_1 : \lambda_2$.

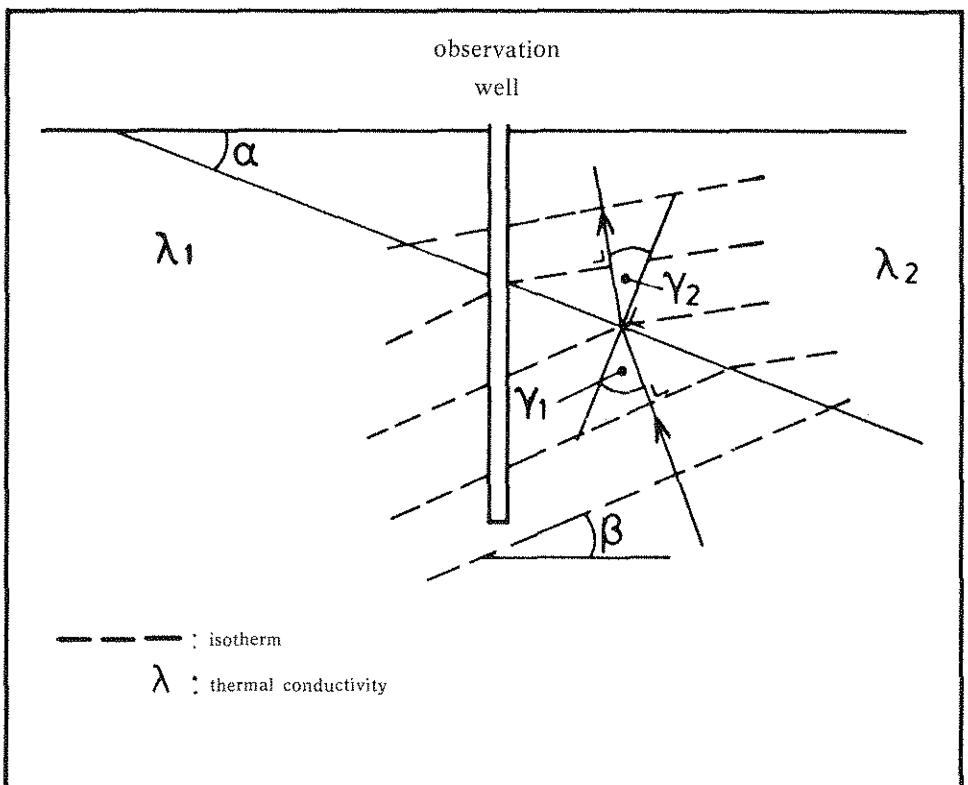

Fig. 3 – Isotherm refraction.

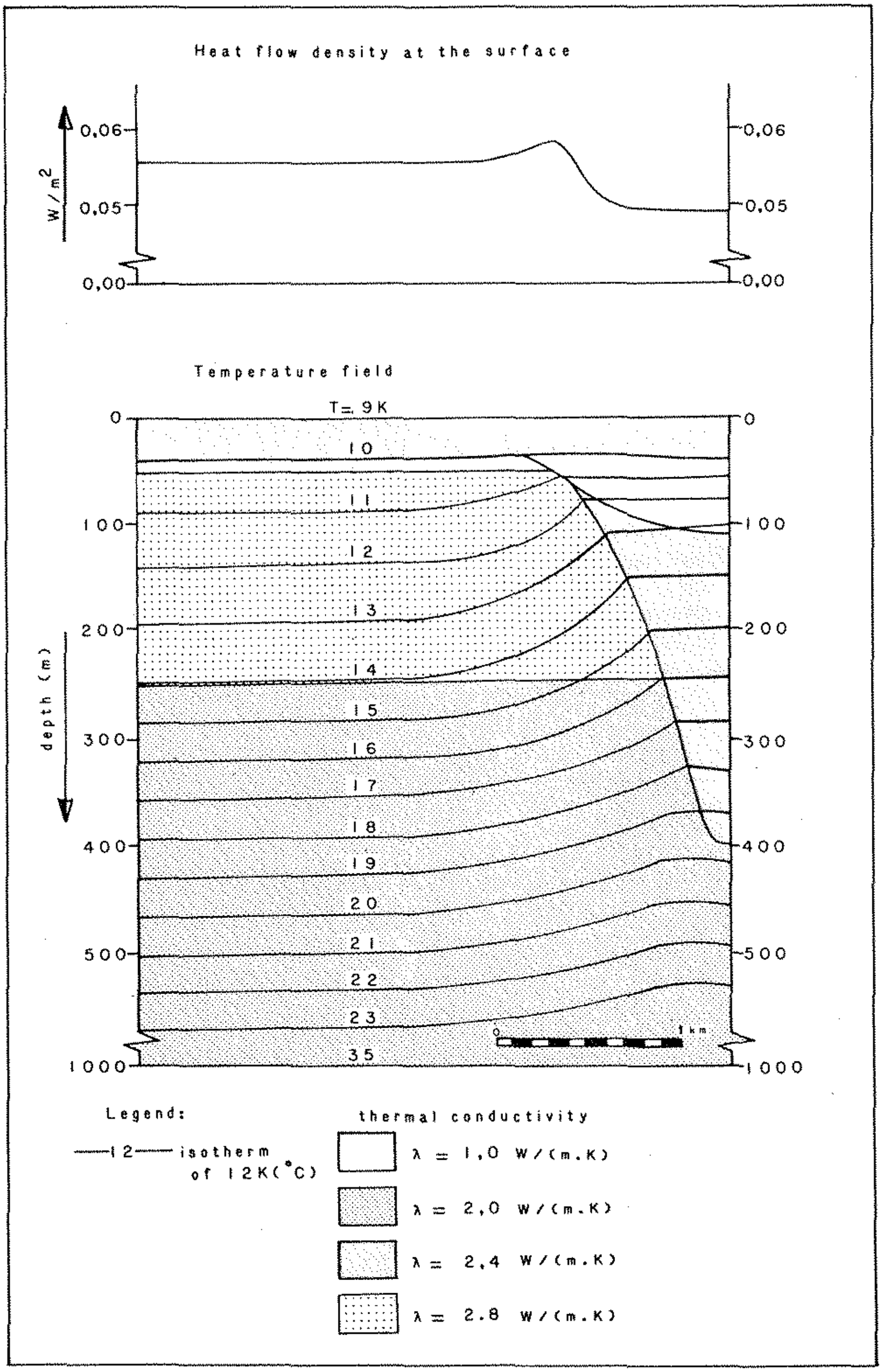

Fig. 4 – Calculated heat flow density at the surface and calculated conductive temperature field in a plane perpendicular to the glacial gully.

Thermal conductivity data, particularly for deeper deposits, are scarce in the literature and as such 2.8 W/(m.K) was taken to represent λ for the satured quartz sands of these aquifers.

Using the $\lambda_1 : \lambda_2$ ratios obtained in zones with more or less stagnant ground-water (as in the central part of the gully or at great distances from the well field) thermal conductivities have been determined for both the sandy gully deposits and the heavy clays at the top of the gully. Conductivities for covering layers east of the gully and deposits below the hydrological base have been estimated from data already published.

As a result of the above research the following thermal conductivity values have been adopted:

	λ (W/(m.K))
upper and lower aquifer	2.8
covering layers east of the gully	2.4
heavy clays at the top of the gully	1.0
sandy gully deposits	2.4
deposits below the hydrogeological base	2.0

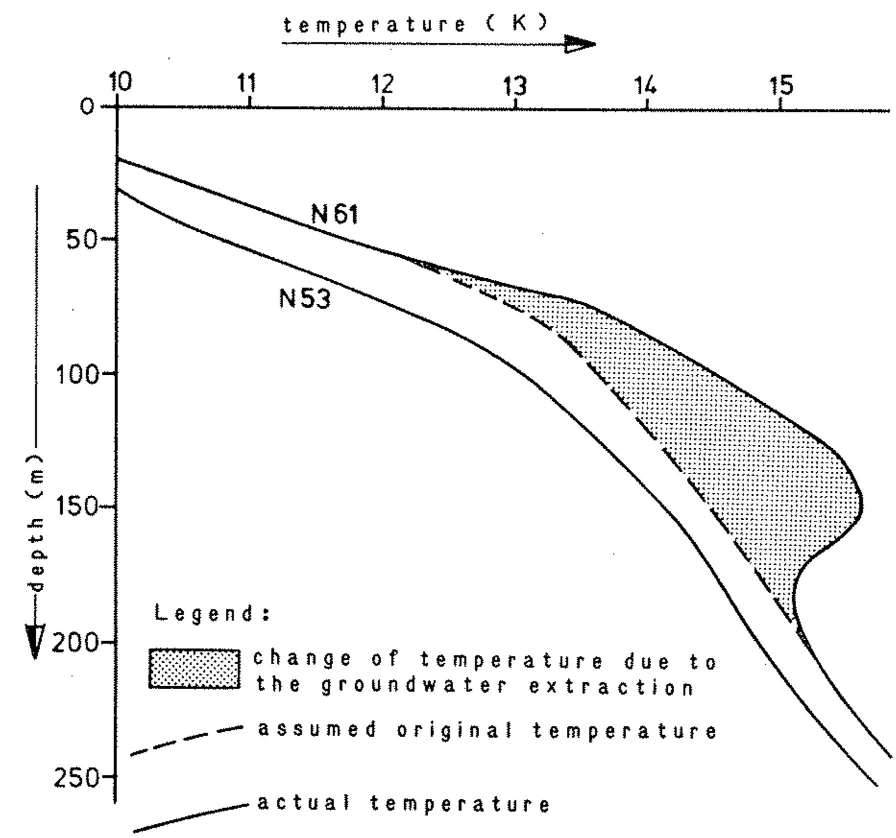

Fig. 5 – Temperature-depth curves for observation wells N 53 and N 61 and the influence of groundwater extraction for N 61.

The original conductive temperature field was calculated from these values using a finite element model for a plane perpendicular to the glacial gully (Figure 4). In this model the gully centre was taken as an axis of symmetry and it was assumed that temperature at the earth's surface is 9 K (9° C) and at a depth of 1000 m, 35 K.

The calculated field closely coincides with the original field, as illustrated by the temperature measurements in zones with stagnant groundwater (Figure 7). Near the well field and at the border of the gully differences between both fields are significant.

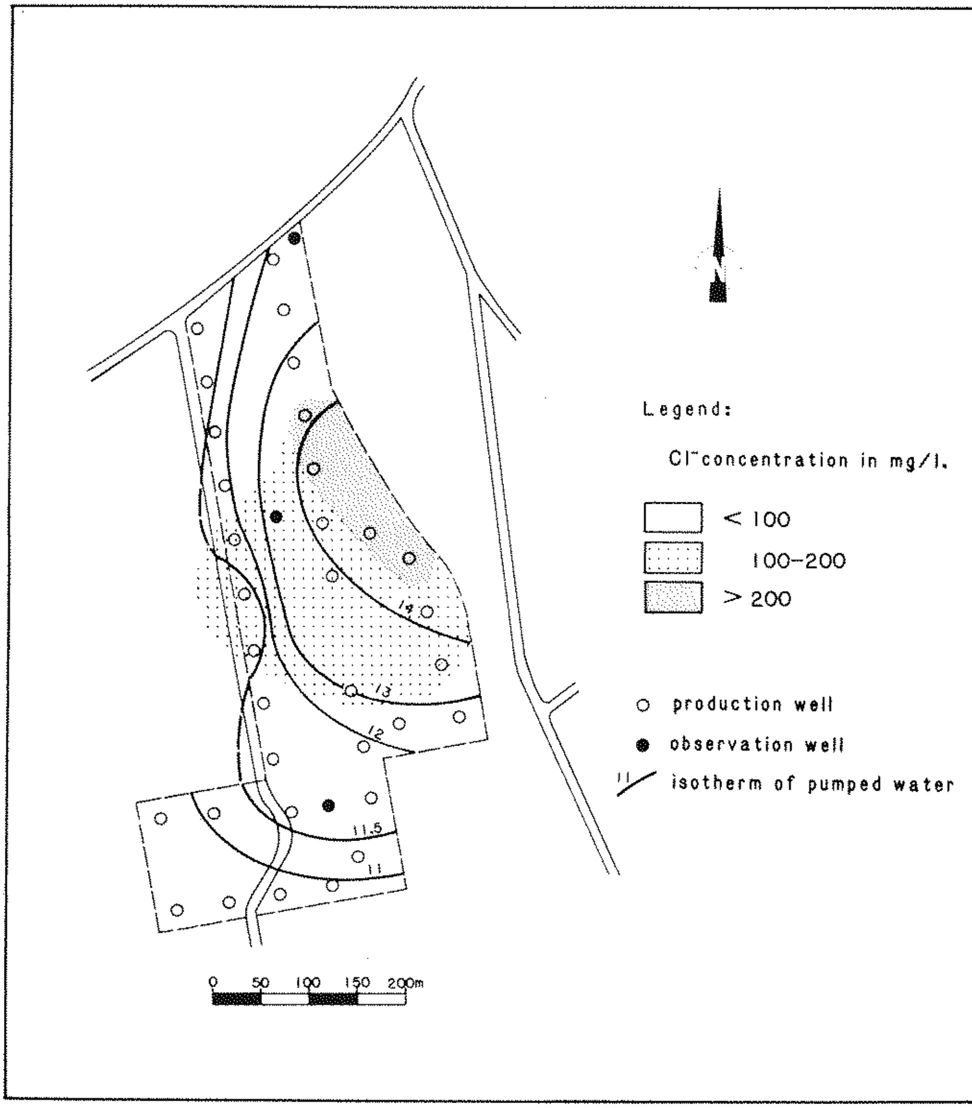

Fig. 6 - Chloride concentration and temperature of pumped water in the well field Ritskebosch.

3.3. Discussion of results

The influence of groundwater extraction on the temperature distribution of the subsoil is obvious when the temperature-depth curve recorded in observation well N 61 (located near the well field) is compared with that recorded in N 53 (located near the glacial gully more to the north, Figure 5).

Immediately above the clays at the base of the production aquifer temperatures are about 1.5° K higher than in N 61. The depth of origin for this anomalous warm water must be at least 200 m, though this should be considered a minimum value since the upward moving water loses heat to the subsoil.

A good correlation between temperature and chloride concentration is also evident. In N 53 the highest Cl^- concentration observed is 46 mg/l, while in N 61 it is 480 mg/l. This correlation also applies in general to the pumping wells of the well field as illustrated in Figure 6. However, as an exception to this rule, some wells at the eastern side of the well field produce water with a relatively high temperature and low chloride concentration. This water originates from beneath the heavy clays in the upper part of the glacial gully. Here, the water is relatively warm because of the isolating effect of clays possessing a low thermal conductivity (figure 4).

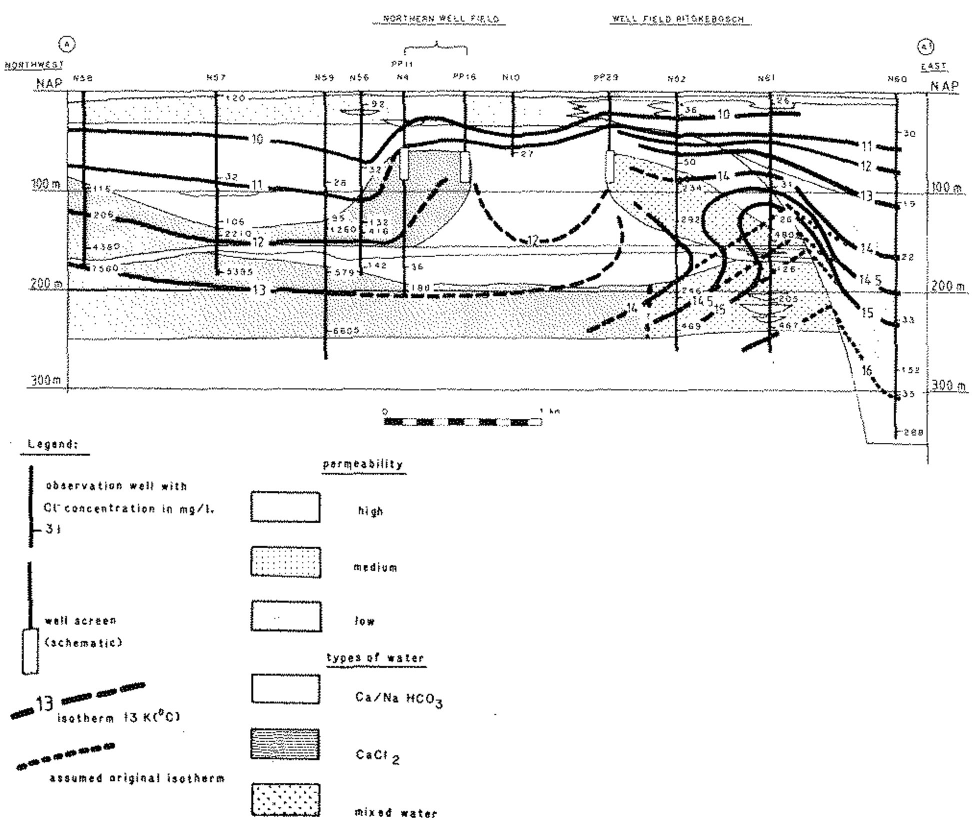

Fig. 7 – Hydrochemical and geothermal section; for location see figure 1.

The combined results of geothermal and hydrochemical data are presented in the section of figure 7. Different salinization mechanisms for the two well fields are apparent. In Ritskebosch brackish water ascends along the border of the gully where glacial erosion removed the clays at the base of the producing aquifer. No other gaps in this clay layer were located, as verified by the thin zone of fresh $CaHCO_3$-water found over a wide area beneath the clays. This water lies between brackish water occurrences in both aquifers. Furthermore, the temperature field shows no anomalies other than along the gully.

The northern well field attracts lateral brackish water from the northwest and no temperature anomaly is associated with this process.

The areal extent of brackish water in the upper aquifer is indicated in figure 1. Both brackish tongues show a chloride inversion, indicating that from surface downwards the succession fresh, brackish, fresh and salt water is found.

4. CONCLUSIONS

The temperature method combined with hydrochemical data has proved to give valuable extra information in the complicated salinization problem of the Ritskebosch well field. Measurements are neither time consuming (about 2 hours for a well of 200 m depth) nor is a large capital investment necessary - an accurate digital multimeter with a thermistor and 3 core logging cable is all that is needed (cost around 750 US $).

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