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RECENT DEVELOPMENTS OF PHYSICAL INVESTIGATIONS IN BOREHOLES AND WELLS

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ABSTRACT

Well logging methods and physical borehole investigations have come into use for geohydrological reconnaissance in The Netherlands in recent years.

In open uncased boreholes the following features are logged: spontaneous potential, resistivity, natural gamma radiation and diameter; interpretation methods are given in short. Reference is made to investigation methods in observation and discharging wells.

Permanent electrode systems can be used for monitoring ground-water salinity.

INTRODUCTION

Around 1962, physical well-logging techniques appeared on the scene in geohydrological exploration in The Netherlands. Since 1966, when rotary methods for drilling reconnaissance holes were first introduced for geohydrological exploration in The Netherlands, these techniques have developed rapidly. At the present moment measurements of the following properties in uncased holes are standard practice:

a) the spontaneous potential (S.P.)
b) the electrical resistivity in "normal" configuration (SN, LN)
c) the intensity of the natural gamma radiation
d) the diameter of the borehole

The nature of the formations encountered in the geohydrological exploration of the Netherlands have determined the methods chosen. These formations consist of unconsolidated sediments, principally of tertiary and quaternary age.

In completed boreholes, i.e. in holes provided with screens and tubes, the following features can be logged:

a) the intensity of the natural gamma radiation, to check clay plugs opposite perforated clay layers
b) the temperature gradient in the screens and tubes of observation wells, to detect the vertical ground-water flow (downward or upward)
c) the water conductivity to determine the salinity in discharging wells which are gradually beginning to yield water with a higher chloride content as a result of the rising interface between fresh and saline water
d) the flow velocity (vertical component) in discharging wells
e) the electrical resistivity to trace and locate damage to (plastic) tubes

Furthermore, permanent electrode systems are currently being placed in many observation wells to permit changes in the salinity of the ground-water to be followed as a function of time.

The various methods and the results they have yielded will be discussed below.

MEASUREMENTS IN UNCASED BOREHOLES

The measurements in open holes mentioned in the

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introduction are always done in combination. Their objective is:

1) to obtain information regarding the lithology and stratigraphy of the perforated strata;
2) to aquire data on the quality of the aquifers encountered.

The reason for the measurements is the poor quality of the soil samples obtained from the mud if the straight flush rotary method is used.

The spontaneous potential

The spontaneous potential changes which are found in the borehole are generated by the difference in salt concentration between the drilling fluid and the pore water in the formations. Opposite a clean (clay-free) sandbed a diffusion potential arises while a membrane potential is built up opposite a clay layer. In the first place, therefore, the S.P. permits a differentiation between sand strata and clay and peat strata. Under favourable conditions it is theoretically possible for the salinity of the formation water to be computed.

The prevalent conditions, however, are unfavourable: the drilled deposits generally contain fresh water, and the drilling fluid is generally also fresh. Consequently the S.P. curve is often of poor quality. Calculations of the salinity of the formation water have not lead to acceptable results up till now.

The resistivity

The electrical resistivity R_f, which can be found by means of departure curves (Schlumberger, 1955) for a given formation from the SN and LN curves, depends on the resistivity of the pore water R_l and the formation factor F, expressing among other things the porosity of the deposit:

$$R_f = F \times R_l$$

The formation factor of the sediments in the fresh water zone has proven to be a function of grain size. From a series of resistivity measurements in carefully sampled cased percussion borings and resistivity determinations of water samples obtained from piezometers in these borings, the relations given in table 1 have been found.

sediment	F
clay, peat	$\leqslant 1$
clayey sand	2,5
fine sand, clean	3,5
coarse sand	5,0
coarse sand with gravel	6,5
coarse sand with much fine and coarse gravel	7,5

TABLE 1

The formation factor of peat and clay deposits increases as the salinity of the pore water rises. At a salinity equal to that of sea-water there is no longer a significant difference between the formation factor of medium size sandbeds and peat or clay layers.

About the pore water resistivity (the reciprocal value of the conductivity) the following can be remarked. The determination of water resistivity (or conductivity) is standard practice when analyzing ground-water samples. Nevertheless it is the hardness (for instance expressed in German degrees, $^{\circ}$D) that attracts the attention in fresh water areas and the chloride content in brackish and salt water areas in practice.

Walter (1967) and Jeurissen (1971) have shown that, at least in several regions in The Netherlands, there is a relation between the conductivity and the total hardness of the fresh groundwater. This enables the calculation of the total hardness once the ground-water resistivity has been derived. The results obtained by Jeurissen are shown in fig. 1.

A sufficiently accurate derivation of the chloride content of the groundwater from the water resistivity is also possible in most cases. The water occurring at a certain level in a transition zone can be considered as a mixture of the fresh water at the top of the zone and the saline water below, which has a composition equal or similar to that of seawater.

If the fresh water contains virtually exclusively bicarbonates and if the bicarbonate content of the water in the transition zone is not or hardly dependent on the chloride concentration (both these conditions are met in many regions), the water at a certain depth may be regarded as dilute sea-water with a certain bicarbonate content.

The conductivity K_c of ground-water with a chloride concentration can therefore be written as follows:

$$K_c = K_z + K_h$$

where:

K_z = conductivity of dilute sea-water with chloride content c

K_h = conductivity due to bicarbonate content h

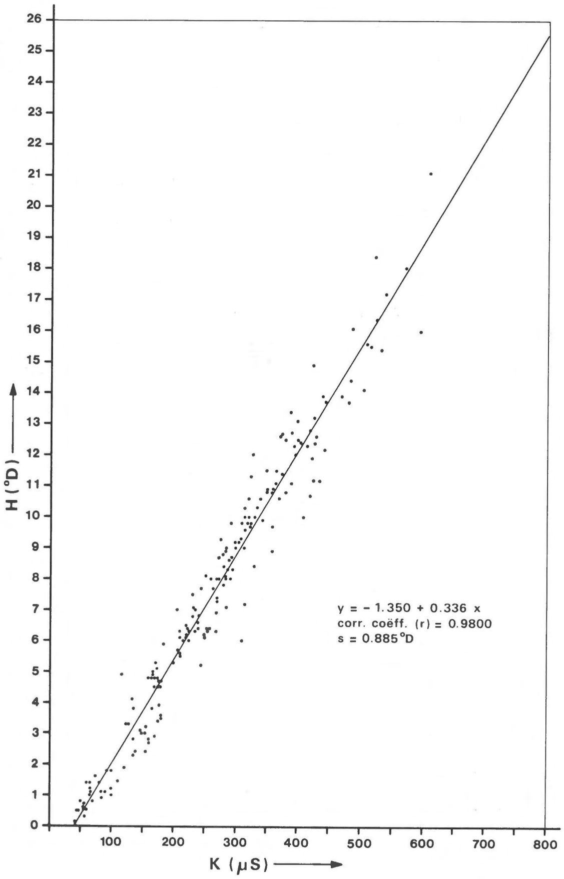

Fig. 1
Relation between electrical conductivity and total hardness of the ground-water in Twente and Salland (Teurissen; 1971).

In fig. 2 the correlation between resistivity and chloride content is shown for certain bicarbonate concentrations. The graph was constructed from precise determinations obtained from mixtures of sea-water and distilled water (Thomas, Thompson and Utterback, 1934) and from a number of ground-water samples with varying bicarbonate content and with a low chloride content (approx. 50 ppm).

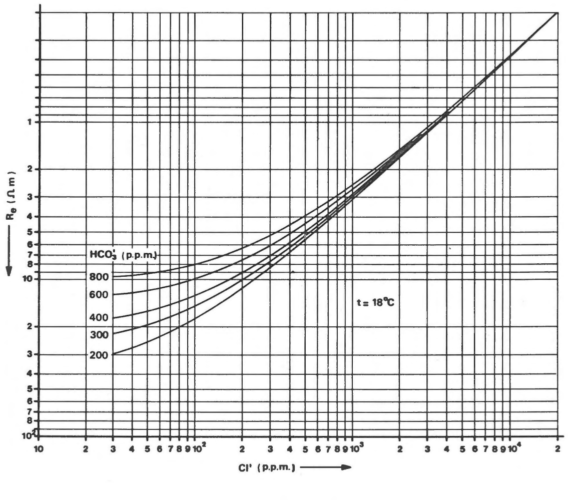

Fig. 2
Relation between resistivity and chloride content of ground-water with a varying HCO'_3-concentration.

The natural gamma radiation

The natural gamma radiation logged in a borehole is due to the presence of radioactive elements, which occur in low concentrations in virtually all minerals. Important contributions to the total intensity measured in boreholes are provided by elements of the uranium-radium and thorium series and the K^{40} isotope, which accounts for approx. 0.01% of the total potassium content. Sand and peat formation generally have a very low radioactivity; clay formations are relatively highly radioactive. The lowest intensity found in The Netherlands for tertiary and quaternary deposits was measured in the miocene lignite sands in Limburg. These sands consist almost entirely of quartz. The highest intensity was found for glauconitic tertiary clay. In fig. 3 the intensities

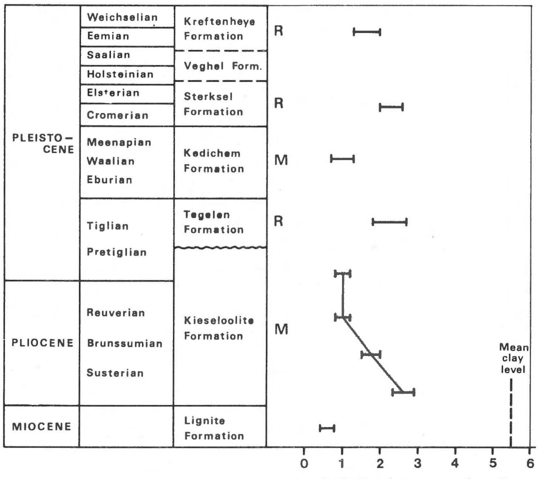

Fig. 3
Intensity of natural gamma radiation measured in tertiary and quaternary fluvial sands in the SE-Netherlands; R = Rhine; M = Maas.

found for a number of fluvial deposits in various boreholes in the S.E. region of The Netherlands are shown in diagram form. A scintillometer with a thallium-activated sodium iodide crystal was used in these measurements. The results should be regarded as provisional. It has been found that the intensity of the natural gamma radiation in the kieseloölite sands in the Susterian stage (Late Pliocene) is almost twice as high as in the Reuverian stage (Early Pliocene). Of the pleistocene sands the Rhine sands seem to have a higher intensity than those of the Maas. In the northern Netherlands the sands of north-eastern provenance also have a lower intensity than the Rhine sands. This shows that in some instances the gamma curve gives indications as to the lithostratigraphy. The grain size of the sand appears to have very little effect on the radiation intensity. The gamma curve is of extreme importance in the brackish and saline zone.

The diameter of the borehole

A proper evaluation of the gamma curve is only possible when a caliper log is available.

The interpretation procedure

Immediately after the running of the logs a provisional interpretation is made, giving:

a) the depths of interfaces between aquifers, clay and peat layers;
b) the base of the fresh water zone;
c) a rough picture of the total hardness of the ground-water in the perforated aquifers.

The provisional interpretation enables the installation of piezometer screens at the proper depths and the re-sealing of clay layers. For the definite interpretation of the measurements all available information is used: the description of the formation samples extracted from the mud and the conductivity determinations of the water samples if screens have been installed.

Examples

In figs. 4 and 5 the results of the measurements in two reconnaisance holes are shown.

Fig. 4 refers to a borehole in the central part of the country. The configuration is rather simple. The sand deposits between 80 m and 185 m have a rather homogeneous resistivity, pointing to a a homogeneous grain size and water conductivity (thus: hardness). The grain size can be deduced from the samples collected from the mud and from the formation factor if a water sample can be taken for the determination of the water resistivity. The sand strata down to a depth of 80 m have a less homogeneous and somewhat lower resistivity. The hardness of the water is higher and the grain size shows changes.

Fig. 5 refers to a hole in the same area. The situation is somewhat more complicated than in the case described above. The top of the transition zone between fresh and saline water can be located at a depth of ca. 115 m. At a depth of about 130 m a chloride content of 200 ppm is to be expected; the 1000 ppm chloride limit is likely to be at a depth of 200 m.

MEASUREMENTS IN COMPLETED BOREHOLES

Inspection of clay seals

When completing a borehole in which one or more screens are placed, the perforated clay strata are generally re-sealed by introducing clay plugs. By measuring the intensity of the natural gamma radiation in a tube, which for that purpose must have a diameter of at least 5 cm, the clay plugs can be

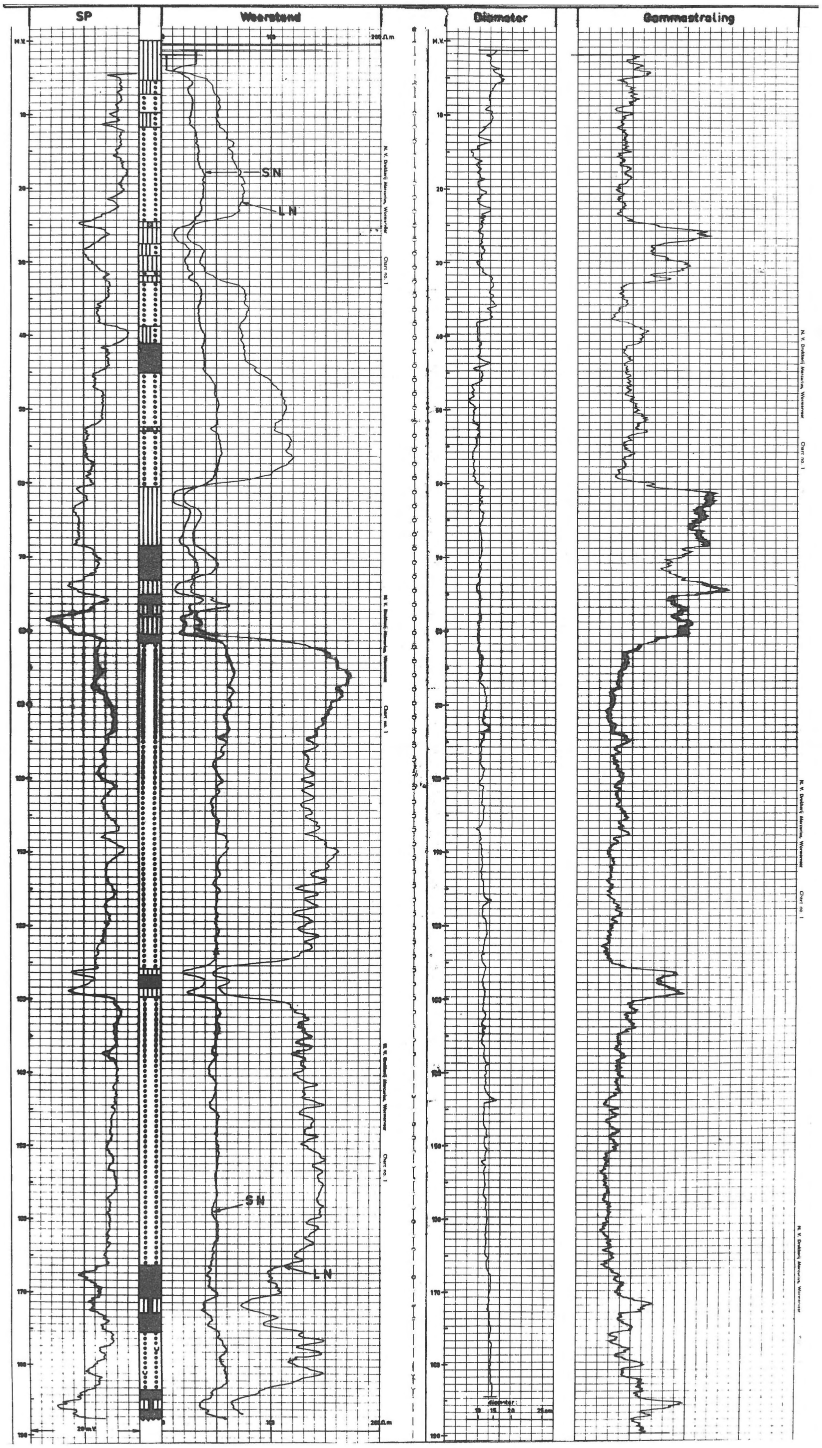

Fig. 4
S.P., resistivity, gamma and caliper logs of a hole in the central part of The Netherlands – first example.

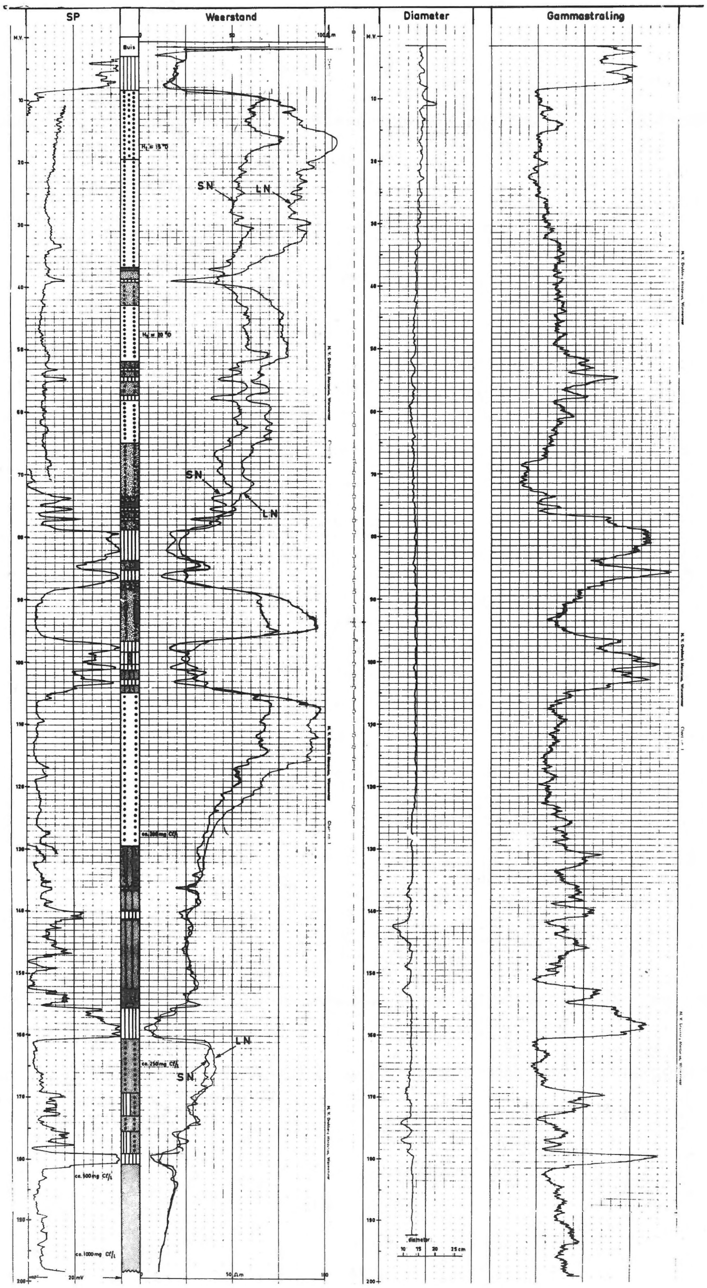

Fig. 5
S.P., resistivity, gamma and caliper logs of a hole in the central part of The Netherlands – second example.

checked. The absorption of the sand and clay layers is such that about 90% of the radiation measured originates from a volume with a radius of about 30 cm around the detector. This enables the clay plugs to be distinguished from the clay layers. In fig. 6 two logs of the natural gamma radiation in a borehole are shown. The first log was made in the open hole; the second was recorded in the tube after completion of the hole. The figure is taken from Csonka et al. (1971).

Temperature logs in observation wells

Temperature logs can aid in investigating whether vertical ground-water flow is present at the location of the well. Relatively high temperatures indicate possible upward flow (seepage) while relatively low temperatures generally indicate infiltration. Some results of a comprehensive temperature investigation performed in The Netherlands have been published by Csonka (1969).

Conductivity logs in discharging wells

In recent years a number of discharging wells in various areas in The Netherlands have shown an increase in the chloride content of the water. This is due in most cases to rising saline ground-water. When taking measures against this salination it is important to know in what section of the screen the salt water is intruding and what the chloride content of this water is. The measurements are carried out with a conductivity cell provided with four electrodes: two current electrodes and two measuring electrodes. The diameter of the probe is about 2 cm. Conductivity logs should be combined with flow measurements to obtain a complete picture.

Flow measurements in discharging wells

Flowmeter data give an insight into:

a) the condition of a well directly after completion
b) the effectiveness of well development
c) the sections responsible in the event of production fall-off in course of time

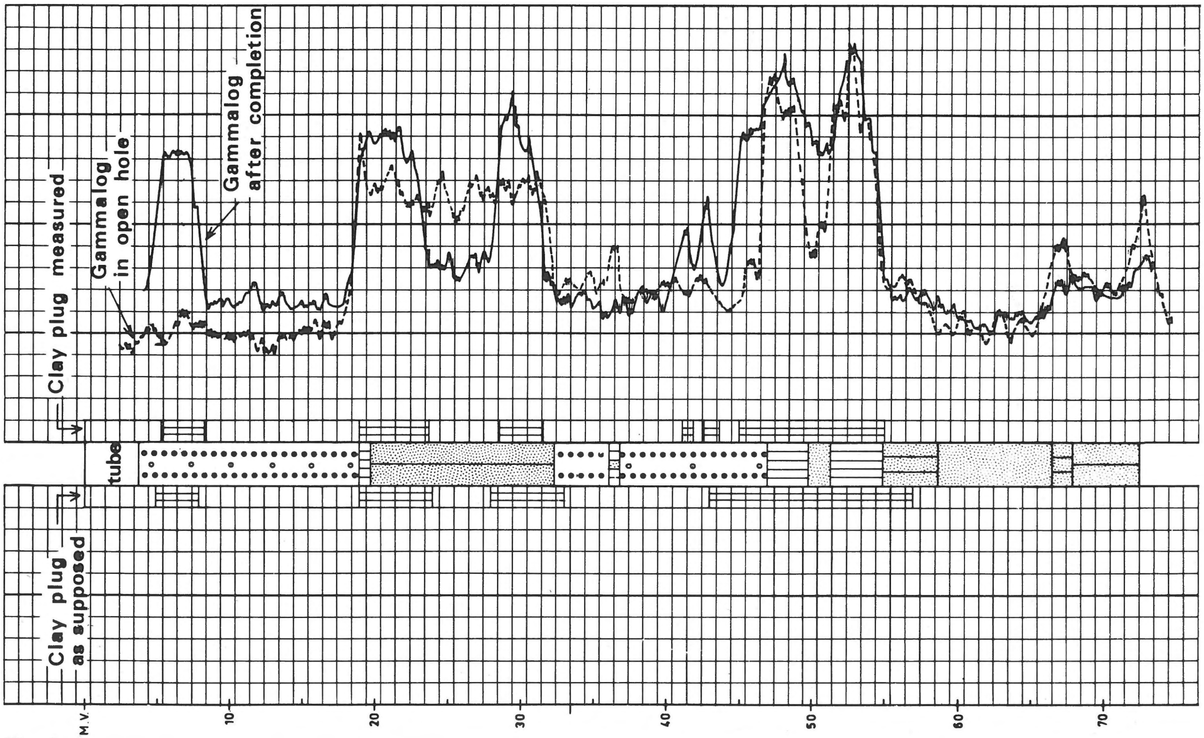

Fig. 6
Gamma logs before and after completion of well (Csonka c.s.; 1971).

d) the optimum dimensions for the screens of new wells in the same production area.

The device used is of the impeller type; its diameter is approx. 5 cm.

Detection of damage to plastic tubes

This logging is done using a cable which is provided with one or more electrodes. A lower electrical resistivity is registered in the immediate vicinity of a crack or hole.

PERMANENT ELECTRODE SYSTEMS

During recent years permanent electrode systems have been placed in holes or laid horizontally at a certain depth in order to allow fluctuations in the salinity of the ground-water to be followed as a function of time.

An electrode system consists of a 14-strand or 26-strand cable onto which a number of helical electrodes are attached in pairs. The distance between the electrodes forming one detector pair is generally 15 cm. The distance between the pairs varies as the situation requires. One electrode of a pair acts as current electrode, the other as measuring electrode. The return-current electrode and the reference measuring electrode are placed at a wide distance apart on the surface or elsewhere. This implies the use of the fourpoint configuration. Measurements can be done with adapted four-terminal resistivity meters. A series of observations takes only five minutes to complete.

The distance between the electrodes of one pair is so selected that the difference in the composition of the material used to fill up the hole with respect to the formation has a negligible effect on the measurement results. When the mud filtrate has disappeared after some time from the adjacent portion of the formation, the resistivity obtained is virtually the formation resistivity. This process takes some months in coarse deposits; in fine clayey deposits it may take some years. The observations are interpreted as follows.

From the formation resistivity measured, the electrical resistivity of the pore water is calculated by means of an estimated or measured value for the formation factor. On the basis of the chemical analyses available, one of the curves shown in fig. 2 is selected; these curves give the correlation between the electrical resistivity and the chloride content of the ground-water for various bicarbonate concentrations.

Salinity inspection by means of a permanent electrode system is an inexpensive alternative to the conventional procedure, in which water samples through screens are taken and analysed.

The advantages of a permanent system are:

a) the number of detection points which can be set up in a 10-15 cm diameter borehole is virtually unlimited
b) inspection is also possible in semi-impervious formations
c) the procedure takes very little time
d) the local conditions are not affected

Some results obtained with a permanent electrode system near an injection well will now be discussed briefly. A system was placed at a short distance from an injection well in the transition zone from fresh to saline water. Soon afterwards the injection of (fresh) water was commenced. The results of the measurements at the beginning of the test and after ½, 1½, 2½ and 11½ weeks respectively are shown in fig. 7.

Among other things the following may be observed:

a) at the three uppermost detection points resistivity increases somewhat at first and subsequently falls to below its initial value. This may be explained as follows. First, the original formation water passes, expelling the water remaining from the drilling operations. The formation water has a slightly higher resistivity. The original formation water is followed by the injected water, which has a lower resistivity than the formation water;
b) at the deeper detection points expulsion of the brackish or saline water by fresh formation water, followed by expulsion.

CONCLUSION

Present-day knowledge and equipment for logging boreholes goes a long way towards meeting the demands of geohydrological investigations. One important problem which has not yet been overcome, however, is the determination of the coarseness and permeability of the sands. In the first place more should be known of the relation between grain size, porosity, formation factor and permeability. Laboratory research in this field is currently being carried out.

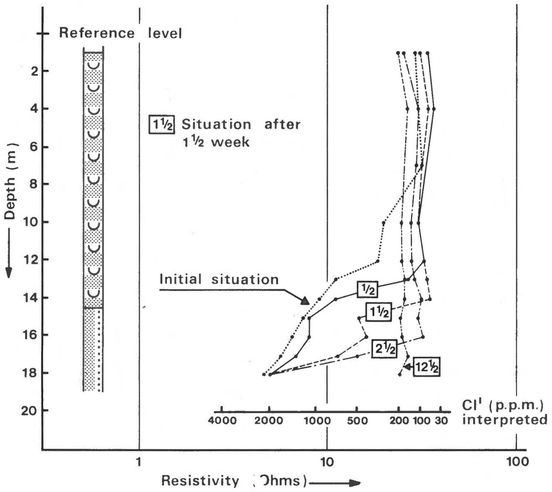

Fig. 7
Permanent electrode system near injection well.

Spectral analysis of the natural gamma radiation may contribute towards finding a solution to this problem. Research on this aspect is in progress in The Netherlands.

REFERENCES

Csonka, J. (1969) – The use of geothermic measurements for groundwater seepage problems in polder areas, Proceedings and Informations nr. 16 of the Committee for Hydrological Research TNO.

Csonka, J., P.G. van Dongen, G.F.J. Jeurissen and F. Walter (1971) – Fysische metingen in afgewerkte boringen, Dienst Grondwaterverkenning TNO, Verslag over het jaar 1970.

Jeurissen, G.F.J. (1971) – Rapport inzake een geo-elektrisch onderzoek van Salland, report nr. 70, Dienst Grondwaterverkenning TNO (in preparation).

Schlumberger Well Surveying Corporation (1955) – Resistivity departure curves, doc. nr. 7.

Thomas, B.D., Th.G. Thompson and C.L. Utterback (1934) – The electrical conductivity of sea water, J. Cons. Perm. Int. Pour l'Expl. de la Mer, Vol. 9.

Walter, F. (1967) – Elektrische boorgatmetingen, Water 51, nr. 2.