

## GEOHYDROLOGICAL INVESTIGATIONS WITH A VIEW TO GROUNDWATER CATCHMENT A CASE HISTORY

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### ABSTRACT

With the intention to give an impression of the usually applied geohydrological procedures for the foundation of a pumping station in the Netherlands, the investigations for the well field at Beerschoten (provincie of Utrecht, The Netherlands) are reviewed.

The area concerned is located on the western slope of ice pushed hills forming the Utrecht Ridge. The subsoil consists predominantly of Pleistocene sandy deposits of fluvial origin, with local loam layers. The groundwater has a suitable quality for the preparation of drinking water and requires only a simple treatment. From a pumping test it appeared that the studied area is situated in the transition zone between a recharge and a discharge area and that loam layers delay the propagation of drawdowns from the pumped aquifer to the phreatic surface. The transmissivity of the aquifer from which the water will be withdrawn amounts to 3500 m<sup>2</sup>/day.

On the base of subsequent studies carried out by means of a mathematical method and electrical model tests a prediction of the consequences of the withdrawal for the groundwater table has been given. Several relatively simple statistical methods are described, from which it appears that in spite of a certain lack of appropriate data the prediction given was reasonably reliable and also that after adjustments for several external influences the actual consequences of the withdrawal could be very well determined.

As in many other cases, the practical sustained yield in this area depends merely on the drawdowns due to the withdrawal and on the decrease of underground flow to ditches. From the point of view of water resources management the survey forms an example of a case where a series of multi-purpose investigations should serve to arrive at an optimum exploitation of the groundwater.

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## 1. INTRODUCTION

The relatively limited groundwater resources in the Netherlands on the one hand and the increasing demands for water for domestic, industrial and agricultural purposes on the other hand, compel thorough investigation before founding or extending a well field.

For groundwater extractions by water companies a licence is required; the request to the Ministry of Public Health has to be accompanied by an advice of the CoGroWa<sup>2)</sup> concerning the consequences of the proposed withdrawal for the groundwater table. In an earlier stage the Government Institute for Drinking Water Supply (Rijksinstituut voor Drinkwatervoorziening, R.I.D.) is often requested by the water company concerned, to carry out geohydrological investigations and to make an estimate of the possible yield of the well field and the resulting drawdowns in the neighbourhood. Often there is a lack of appropriate data whereas possibilities for extensive field investigations and the application of advanced geohydrological methods are mostly limited.

The intention of this article is to give by means of a case history an impression of the usually followed procedure for the foundation of a new pumping station, which in most cases leads to relatively good results. In general the procedure is as follows. After the water company has selected a well situated area preliminary investigations in the form of test-drillings will be carried out; screens will be placed so that water level measurements can be performed and water samples can be taken. Geophysical borehole logging will often provide additional valuable information; geo-electrical investigations will be carried out if the fresh-salt water interface is relatively near to the surface. After positive results of the preliminary investigations a pumping test will be held in order to determine the soil and formation constants, and to get an impression of the geohydrological regime. With the available results a prediction as good as possible will be given of the consequences of withdrawal and the range of the influence by means of calculation methods or analogue model tests. An estimate will be made of the possible yield of the pumping station, for which the drawdown of the

water table and the decreased discharge of brooks and rivers will in many cases be the determining factor. In order to be able to check the predictions and to register the consequences of the extraction, observation wells will often be placed.

In this paper the investigations for the pumping station at Beerschoten (provincie of Utrecht, The Netherlands; report R.I.D. 1958) will serve as an example of the above mentioned approach, firstly because of the many observation wells available and investigations at a later stage, enabling to check the prognoses afterwards. Secondly this pumping station may serve as a good example for the many complications a water company may encounter, in the efforts to provide a sufficient amount of water of good quality.

## 2. LOCATION AND DESCRIPTION OF THE AREA

The pumping station of Beerschoten is one of the well fields of the Water Company "Midden Nederland" which provides the water supply in the western part of the province of Utrecht. As a result of the rapid population growth of the city of Utrecht, the increasing water use, the expansion of many industries and the wish to be armed against possible emergencies, the Company became aware of the need for larger quantities of drinking water at the end of the forties.

The attention of the Company was drawn to the estate of Beerschoten which is situated east of the city of Utrecht within the municipal limits of De Bilt (fig. 1). The estate is part of a natural reserve, securing a safe water supply from a hygienic point of view. Other advantages were its location near the city of Utrecht and its proximity to an existing 700 mm watermain between Utrecht and the pumping station of Soestduinen which mainly served Utrecht up to that moment and which was maximally loaded. The permission of the land proprietors was obtained to extract water and a small piece of land for the actual pumping station could be purchased. It was then decided to have an investigation programme carried out by the Geohydrological Department of the Government Institute for Drinking Water Supply.

The area concerned covers approximately 2500 hectares and is part of a rural region, which is predominantly made up of woods and some meadows and arable land (fig. 2) and which in the south is

<sup>2)</sup> A Commission which advises, by enforcement of the Groundwater law, to water companies in the Netherlands.

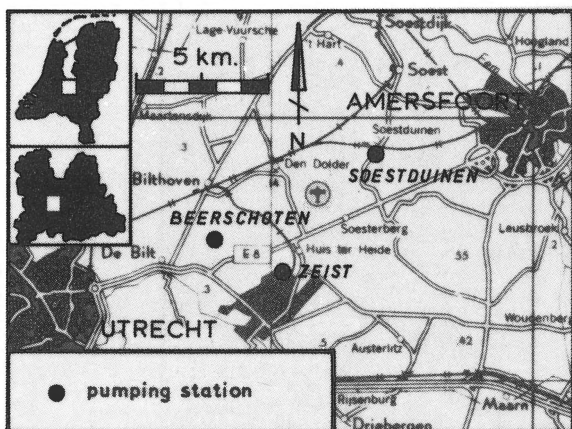


Fig. 1  
Localitv map of the central part of the province of Utrecht.

bounded by the polder district "Biltsche en Zeister Grift" (Rijkswaterstaat, 1968). The property of the Water Company is situated in the nature reserve "De Pan".

From a geomorphological point of view the area forms the transition between the ice pushed hills forming the Utrecht Ridge and the Pleistocene basin west of it. The general slope of the land surface is from east to west, in the eastern part approximately 1 : 400, in the western part approximately 1 : 1600; the altitude varying between 2 m and 5 m above sea level respectively.

The water regime of the region is affected by the Utrecht Ridge. Rain water infiltrates in the higher areas of the Ridge and flows through the sub-surface to the lower parts, at a gradient in westerly direction to the region concerned. In the lower parts the groundwater seeps to the surface and forms brooks. The surface water is discharged through open water to the "Biltsche en Zeistergrift", an artificial waterway (fig. 3). The C.O.L.N.-investigations (Van der Voort & Vrijhof, 1958) have made clear that the depth of the phreatic level in the north-eastern part of the area is more than 2.00 m below ground level. From a report of the Stichting Bodemkartering (1970) appears that in the south-west the average highest (winter) level is approximately 0.80-1.50 m below ground surface and the average lowest (summer) level > 1.50 m. At the southern side of the Biltsche en Zeistergrift, the phreatic level can rise till 0.40 m below ground level.



Fig. 2  
Scenery near the estate of Beerschooten.

### 3. PRELIMINARY HYDROGEOLOGICAL INVESTIGATIONS

#### 3.1 *Quality of the groundwater*

In 1951 four test wells were drilled out to approximately 100 m below ground level (nos. I/66, II/67, III/68 and IV/74 in fig. 9). From different depths several water samples were taken which were analyzed in the Waterworks Laboratory "Mid'en Nederland" (Van de Grient, 1963). Some of the results are schematically drawn in fig. 4.

From the analysis it appears that roughly speaking the water from corresponding depths had an analogous quality. With increasing depth, total and carbonate hardness rose (although not higher than 6°D) and the percentage of aggressive free carbon dioxide decreased. As the water did not contain any carbonates, the carbonate hardness was caused by biocarbonates; sulphates caused noncarbonates hardness. Sodium hydrocarbonates were not present. The chloride content was low: less than 30 mg/l. No sulfides and nitrates were found.

With a view to drinking water purposes the iron content of the water from most screens proved to be too high (the recommendations of the Netherlands Water Works Association are: less than 0.1 mg/l and preferably less than 0.05 mg/l). The manganese content amounted up to 0.38 mg/l (recommendations: less than 0.05 mg/l or rather: not present). Consequently removal of iron and manganese would be necessary.

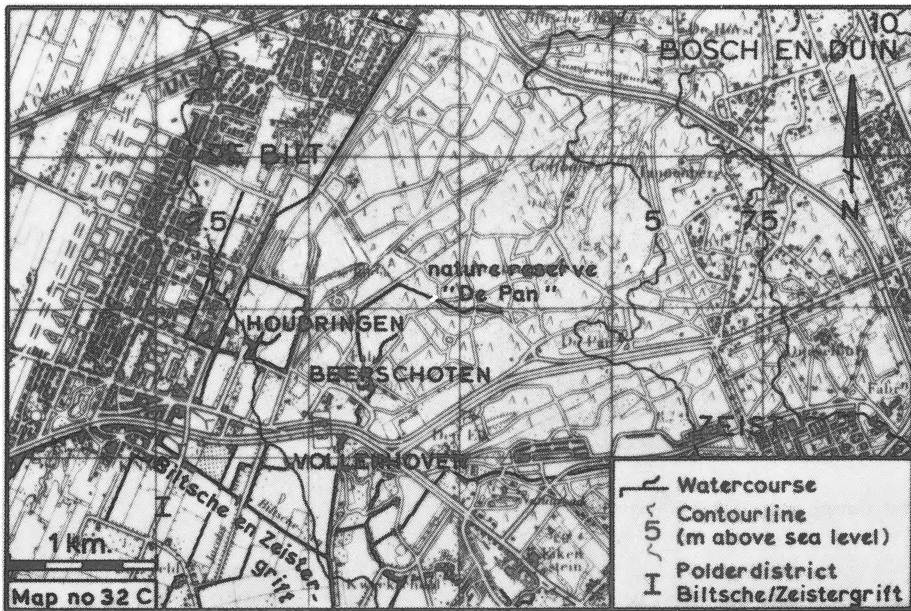


Fig. 3  
Map of the rural area between De Bilt and Zeist, with the estates of Houdringen, Beerschoten and Vollenhoven.

It seemed justifiable to conclude from the water analyses and the data of the drillings that a large amount of water of suitable quality could be withdrawn from a depth of 60-100 m below ground level. It was now necessary to investigate the influence of a possible withdrawal on the groundwater level in the neighbourhood.

### 3.2. Hydrological situation

In 1956, 23 groundwater observation wells with shallow filters, forming 4 rows in a crosswise net over the area, and a water level gauge in the Biltsche en Zeistergrift were installed (fig. 5). The observations would serve to get an impression of the hydrological situation and of the lowering of the groundwater table as a consequence of pumping. Based on the average value of the observations in 1957, a contour map of the phreatic surface could be drawn (fig. 6) which serves as an example for the situation before groundwater extraction at Beerschoten. It appears that the natural slope of the groundwater is approximately 1 : 2000, with a direction from north-east to south-west.

By applying Darcy's law, a rough calculation of subsurface inflow and outflow of groundwater across

the boundaries of the area of approximately 25 km<sup>2</sup> can be made with the aid of the map. The calculated groundwater inflow and outflow (with an estimated transmissivity of 4000 m<sup>2</sup>/day) give a loss of about  $4 \times 10^6$  m<sup>3</sup>/year. If surface flow is not considered and a natural groundwater recharge by rainfall of 350 mm/year ( $8$  to  $9 \times 10^6$  m<sup>3</sup>/year) is being assumed the net inflow into the area amounts to approximately  $4$  to  $5 \times 10^6$  m<sup>3</sup>/year, which comes to the half of the effective precipitation.

The observations of 7 wells during 1956 and 1957 are drawn in fig. 7 together with the precipitation during that period, measured at the station of the Royal Netherlands Meteorological Institute (KNMI) at De Bilt (K.N.M.I. No. 117). In the second part of 1956 and in 1957 (with an extraordinary high precipitation in September), the seasonal fluctuations were approximately 0.20-0.40 m and 0.60-0.90 m respectively. It further appears that the piezometers in the higher areas (nos. 3 and 10) react later on a rain-shower after a dry period than those in the lower areas (no. 18) and that the fluctuations in the different piezometers are rather irregular. From the hydrological sections through the area, showing the average water table observations during 1957 and the values of August 14 and December 13, 1957 (fig. 8),

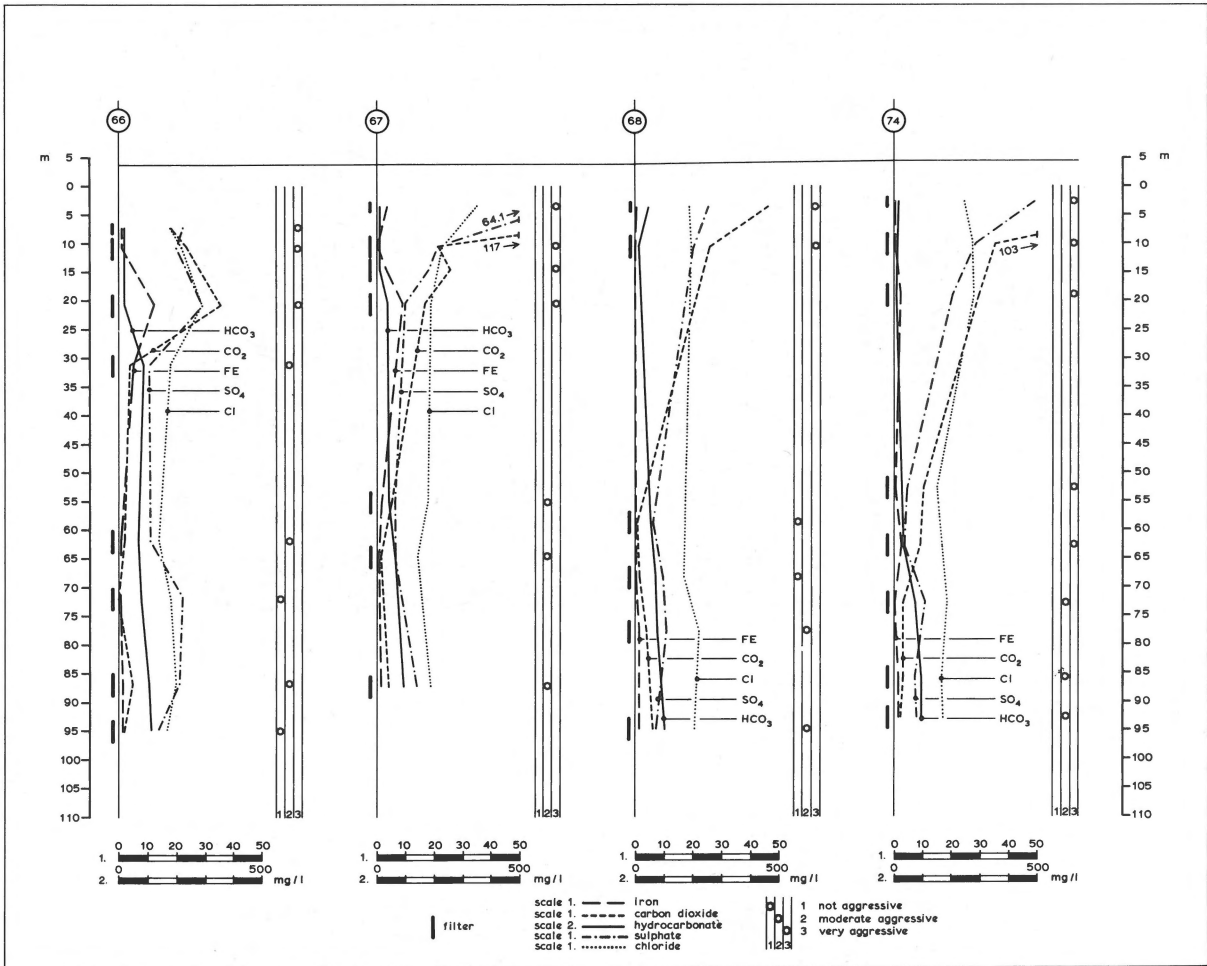


Fig. 4 Schematical reproduction of chemical watersample analyses in test drillings. I/66, II/67, III/68 and IV/74 (locations on fig. 9).

it becomes evident that in the higher areas the fluctuations are somewhat larger than in the lower areas (except in piezometer 16). In the north-eastern part the water table depth is more than 6 m, decreasing to less than 1 m in the south-west. It seems that the Biltse en Zeistergrift has a draining effect during the winterperiod, which might also be true for the ditches in the surroundings of piezometer 7.

Considering the depth of the groundwater table and the seasonal fluctuations, it appeared from these preliminary investigations that no damage to the vegetation would be caused as a result of a lowering of the water table of some dozens of centimeters. The most sensitive parts would be the low lands along the

north-western and south-western border of the area. It was therefore decided that the well field should be located as far as possible in a north-easterly direction. An additional advantage would then be that its influence on open water courses and pools would be restricted.

### 3.3 Geology

In 1957 five new wells were drilled by the cable tool-percussion method (nos. V to IX on fig. 9). The soil samples were lithologically described and stratigraphically interpreted; at a later stage heavy-mineral analyses have been made. The results of these and

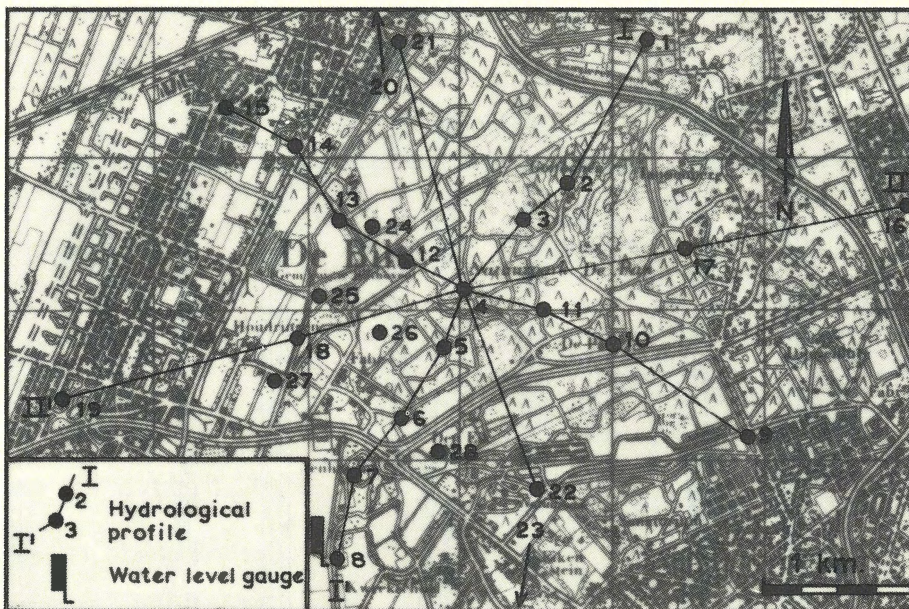


Fig. 5  
Location of groundwater observation wells and water level gauge (the wells 24-28 were installed in 1959).

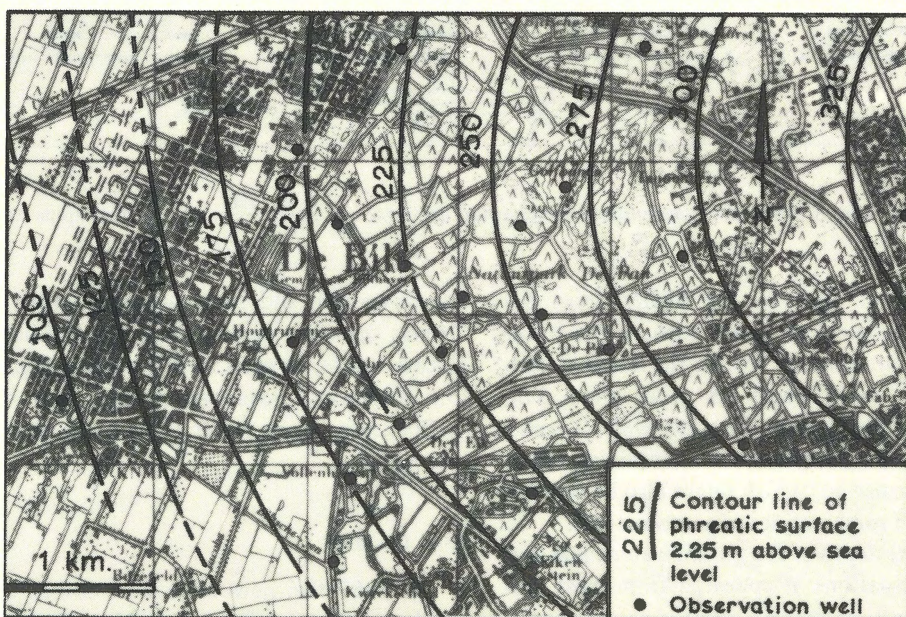


Fig. 6  
Contour map of the phreatic water according to the average situation in 1957.

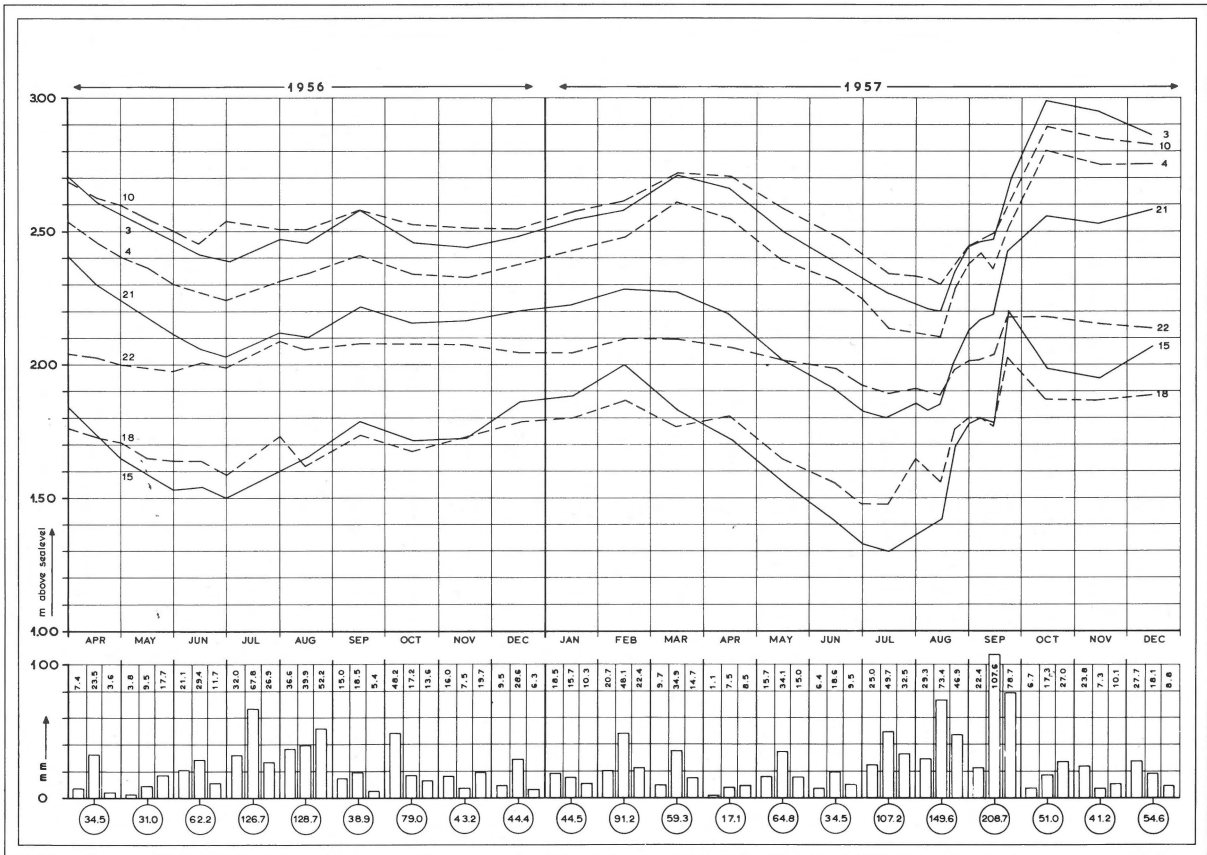


Fig. 7 Hydrographs of the observation wells 3, 4, 10, 15, 18, 21 and 22 (location see fig. 5) and decade and monthly precipitation, measured at De Bilt.

earlier investigations have been completed for this article with the data of later drillings and are represented in three geological cross sections through the area (figs. 10 and 11). The drillings in this area have contributed much to a better understanding of the geological history of the central part of the Netherlands, which may be summarized as follows (report R.G.D.-1970).

A transgression during the transition from the Pliocene to the Pleistocene period caused the sedimentation of fine to moderately coarse, shell bearing sands with local clay layers (Icenian). After a drop of the sea level, the river Rhine deposited the Tegelen formation, also consisting of alternating fine to moderately coarse sands with clayey layers. The fluvial formation of Harderwijk (from eastern origin), Kedichem (Rhine deposit), Enschede (eastern

and Rhine) and Sterksel, Urk and Kreftenheye (all Rhine deposits) were successively laid down. Part of the Kedichem and Sterksel formations were made up of clay and clayey fine sands; the other formations consist mainly of coarse grained, gravel bearing sands.

During the Saalian the Utrecht Ridge was formed which is built up of pushed material of the Urk, Sterksel and Enschede formations, and local clay layers. During the Weichselian period the area was covered by fine wind blown sands (Twente formation). During the Holocene, peat and clay deposits were formed in the western part of the region.

The formations in the subsurface of the investigated area can be read from the profiles. At the surface are dry, partly pushed and blown Pleistocene layers. After crossing the motorway De Bilt-Zeist in southern direction, the first Holocene

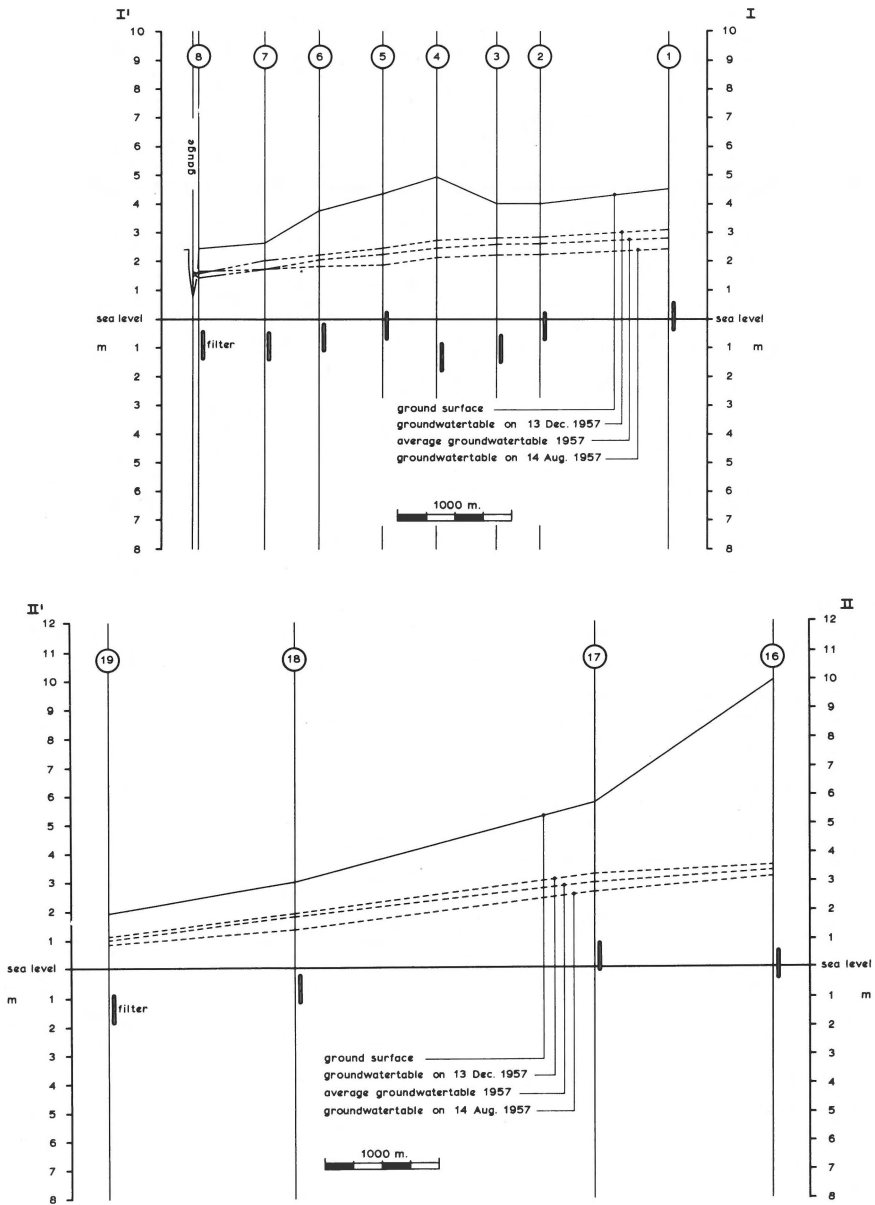


Fig. 8  
Hydrological profiles I – I' and II – II' (see fig. 5) showing groundwater table fluctuations in 1957.

clay layers (at this point having a thickness of 0.1 m) appear.

From a lithological point of view the subsurface of the area consists predominantly of moderately fine and coarse grained sands. In the Sterksel formation, primarily at a depth of approximately 30 to 50 m below sea-level, this complex is interrupted at about

50 m by fine sands with clay and loam layers, and with peat zones and fragments. Between 70 and 90 m some loamy and clayey layers are present in the Harderwijk formation. Both the Tegelen formation and the Icenian are built up of mainly fine sands with clay.

From a geohydrological viewpoint, the entire

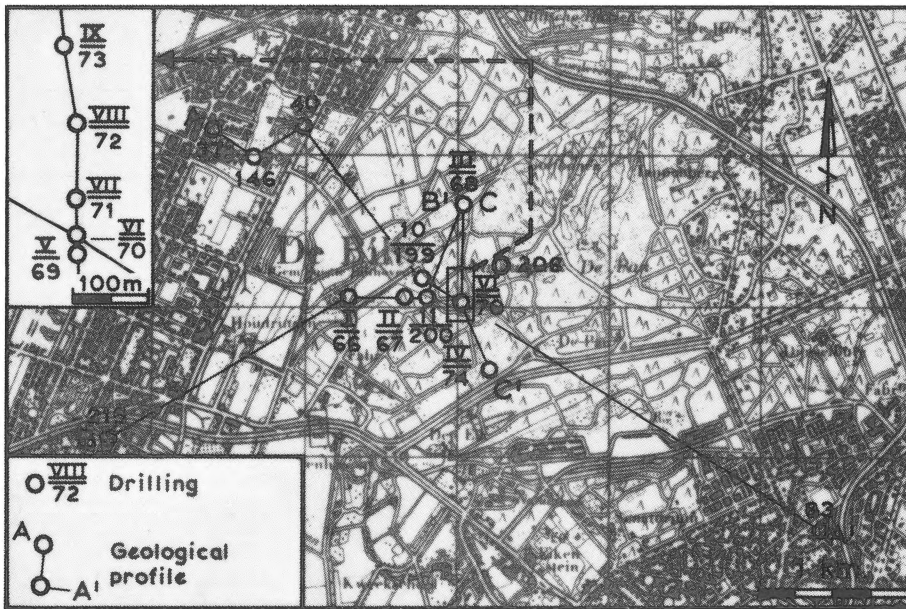


Fig. 9  
Location of drillings. For geological cross sections A-A' and B-B' refer to fig. 10, for C-C' (with part of it on inset) to fig. 11.

sedimentary complex should be considered as one aquifer. At about 100-110 m below sea level a semi-permeable base is formed by the Tegelen formation and the Icenian. The various loam layers, especially in the Sterksel formation, may be regarded as a zone of resistance to vertical flow (see also fig. 4). However, the entire water bearing stratum can be expected to finally react on pumping as an unconfined aquifer. In the south-eastern part of the region, the presence of semi-permeable beds of the Holocene will transform the group of water bearing formations into a leaky aquifer system.

#### 4. PUMPING TEST

##### 4.1 Preparations

The capacity of the pumping station was planned at 500 m<sup>3</sup>/h. A pumping test would be necessary in order to be able to predict the consequences of the extraction for the groundwater table and for the drainage to the nearby ditches. One of the five new drillings (no. VI) was completed as a pumping well; a 6" pumping screen was installed at a depth of 49 to 69 m below sea level. The four other drillings at

distances of 25, 50, 150 and 250 m from the pumping well were constructed as observation wells and provided with four 2" piezometers, with screens having a length of 1 m each at depths of approximately 80 m, 55 m, 25 m and 0 m below sea level (as indicated on fig. 11).

The groundwater was regarded to be in a phreatic state. The permeability and the storage coefficient of the subsurface were expected to be high and so it would probably be necessary to carry out a pumping test of long duration (longer than 1 month). Only then could reliable data be collected to determine the expected future decline of the water table as a result of pumping. The pumping test was held from July 9, 1957, 8.00 a.m. until September 19, 1957, 8.00 a.m. The constant discharge amounted to 100 m<sup>3</sup>/h.

##### 4.2 Drawdown after 24 hours

The hydraulic heads at the beginning of the pumping test and the drawdowns in the observation wells are mentioned in table I; the observations of well V are drawn in fig. 12, together with the amount of precipitation during the indicated periods. Just before pumping the heads in piezometers of each well were equal (except in well no. VIII).

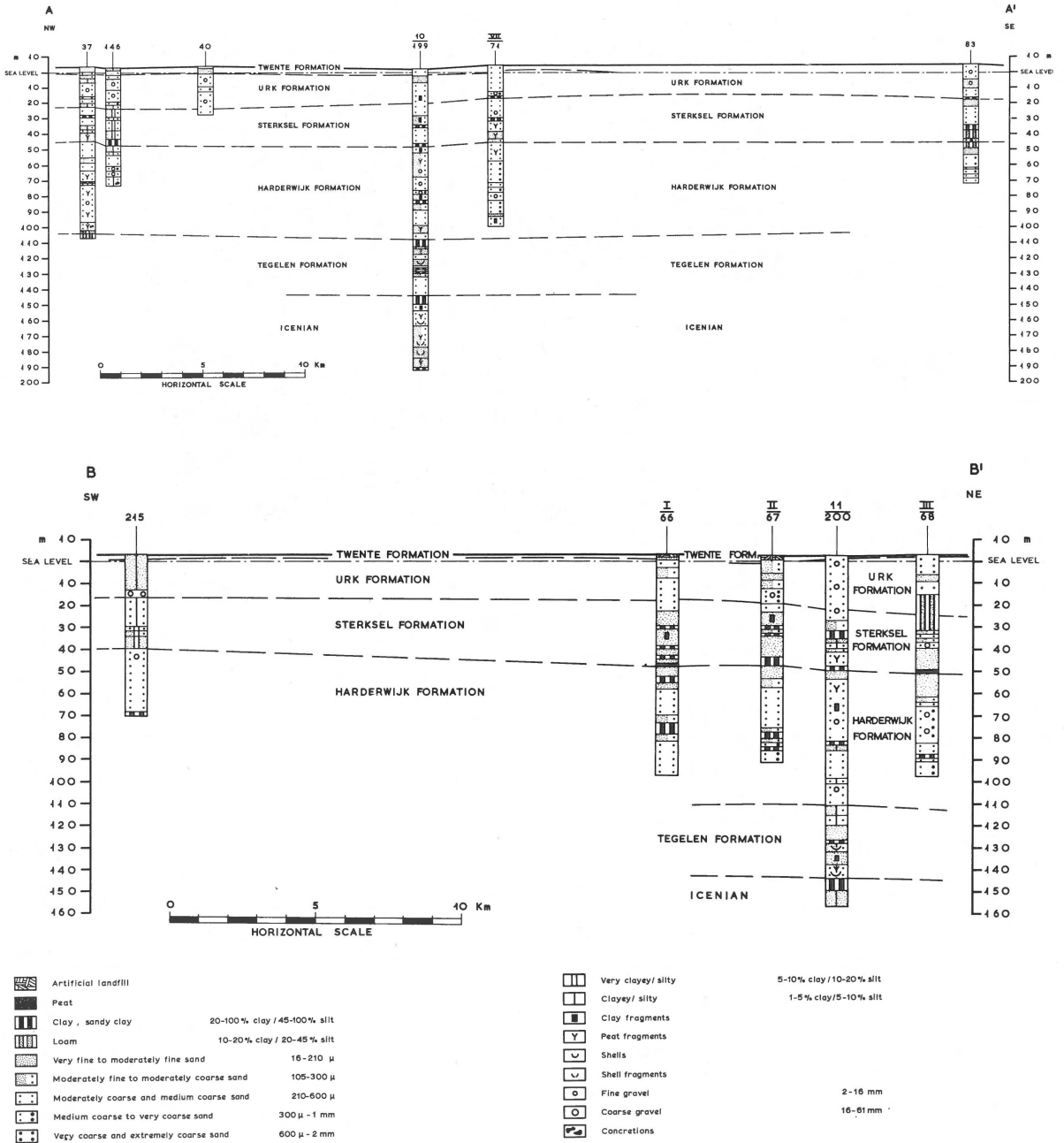


Fig. 10 Section A-A' en B-B' of Quaternary strata east of De Bilt (locations are indicated on fig. 9).

TABLE I  
Drawdown in the observation wells during the first 24 hours of the pumping test

Observation well	Lower end screen in m $\pm$ sealevel	Head in m $\pm$ sealevel		Drawdown in m	Distance to pumping well in m
		9 July 8.00 a.m.	10 July 8.00 a.m.		
		VI (pumping well)	69.00 -		
V piezometer 1	83.00 -	2.08 +	1.90 +	0.18	25
piezometer 2	53.00 -	2.08 +	1.75 +	0.33	
piezometer 3	23.00 -	2.08 +	2.03 +	0.05	
piezometer 4	0.50 -	2.08 +	2.04 +	0.04	
VII piezometer 1	82.50 -	2.11 +	1.95 +	0.16	50
piezometer 2	52.50 -	2.11 +	1.91 +	0.20	
piezometer 3	22.50 -	2.11 +	2.08 +	0.03	
piezometer 4	0.25 -	2.10 +	2.09 +	0.01	
VIII piezometer 1	75.50 -	2.12 +	2.04 +	0.08	150
piezometer 2	51.50 -	2.12 +	2.03 +	0.09	
piezometer 3	20.25 -	2.07 +	2.03 +	0.04	
piezometer 4	0.25 -	2.08 +	2.05 +	0.03	
IX piezometer 1	79.75 -	2.13 +	2.07 +	0.06	250
piezometer 2	50.75 -	2.13 +	2.08 +	0.05	
piezometer 3	23.75 -	2.13 +	2.10 +	0.03	
piezometer 4	1.25 -	2.14 +	2.12 +	0.02	
4	1.75 -	2.22 +	2.19 +	0.03	160
5	0.75 -	1.96 +	1.95 +	0.01	350
12	2.00 -	1.92 +	1.91 +	0.01	580
6	1.25 -	1.79 +	1.76 +	0.03	870
1	0.25 -	2.59 +	2.57 +	0.02	2100
9	0.25 +	2.64 +	2.63 +	0.01	2100
15	1.50 -	1.33 +	1.31 +	0.02	2100

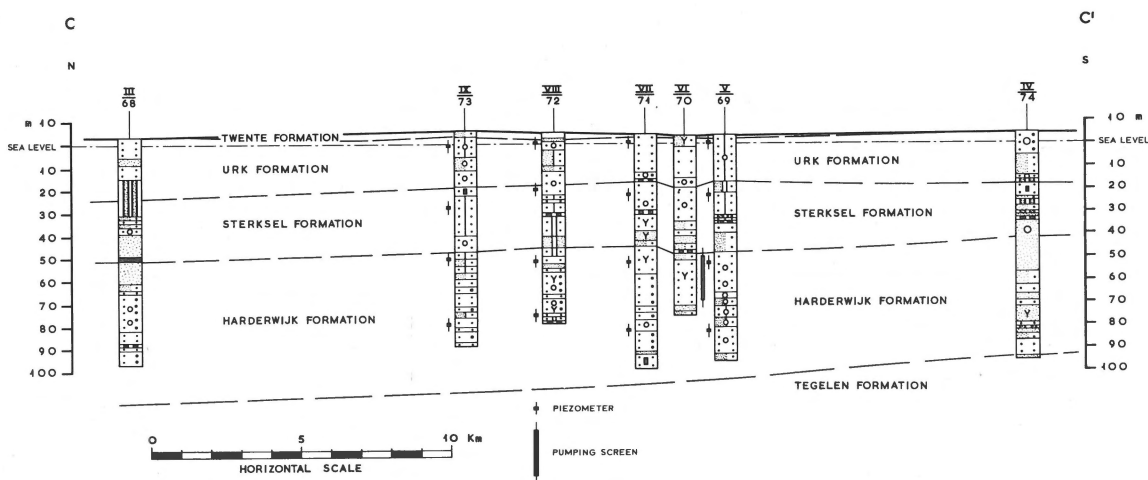


Fig. 11  
Geological cross section C-C' through the well field (location on fig. 9).

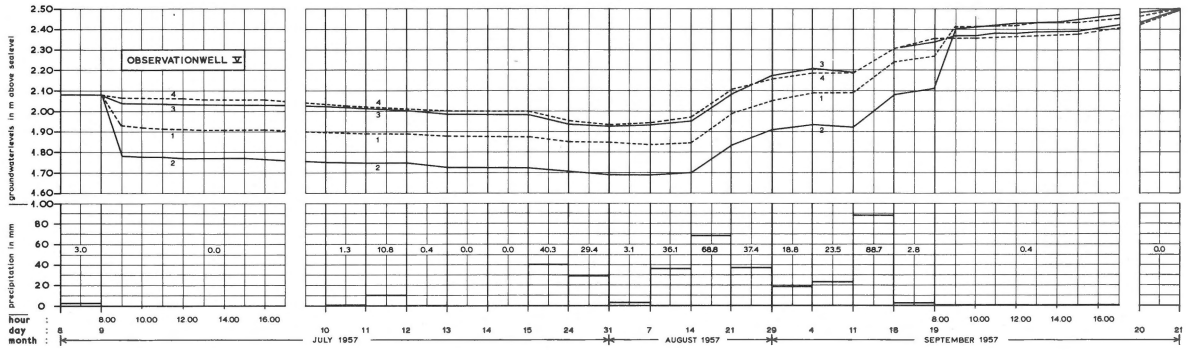


Fig. 12  
Hydrograph of observation well V during the pumping test and precipitation totals measured during the indicated intervals at De Bilt.

During pumping a drawdown in all piezometers appeared; After 24 hours in the piezometers no. 2 — with screens at the same depth as the pumping screen — a considerable drawdown, in the deep piezometers no. 1, a smaller drawdowns was measured. In the shallow piezometers 3 and 4 a slight drawdown was registered. The difference in drawdown in the piezometers no. 1 and 2 decreased with increasing distance. Obviously this difference is a result of the partial penetration of the pumping screen.

The fact that the drawdown in the shallow piezometers after 24 hours was only small, must be attributed to the semi-pervious layers in the Sterksel formation at approximately 30 m below sea level. These layers prevent a transmission of a decrease of the head within short time. It is even questionable whether the measured drawdowns in the shallow piezometers were a result of pumping, as remote shallow wells showed a slight head loss due to a natural lowering of the water table.

#### 4.3 The further course of the pumping test

During the second part of the pumping test a gradual lowering of the groundwater potential took place until August 14, 1957. Under the influence of the precipitation during this summer (see fig. 12) a general rise occurred after that date. On September 19, a higher level was measured in all wells (except the pumping well) in comparison to the beginning of the test. The transmission of the head loss during the pumping test can be read from table II.

It appears from the table that during the period of

declining groundwater levels, the head loss in the shallow piezometers no. 3 and 4 is larger than in the deep piezometers nos. 1 and 2. During the period of rising levels, the rise of head in the shallow piezometers was smaller than in the deep piezometers (see also fig. 12). Consequently the difference in hydraulic head between shallow and deep piezometers decreased gradually during this period. This and the fact that the level in the deep piezometers after stopping the pumping on September 19, rises above the level in the shallow piezometers, shows that the shallow groundwater underwent a lowering because of the extraction.

Theoretically it can be expected that the head loss of the deep groundwater will be followed by an equal lowering of the phreatic water table. In an infiltration area where discharge of precipitation excess mainly occurs through the aquifer, the difference in hydraulic head between the deep groundwater below and the shallow groundwater above the semi-pervious layer, will be determined by the over-pressure which is necessary to let the water pass through the layer. If a decrease of the pressure potential of the deep groundwater occurs, the difference in head will not alter as the decrease does not cause a change in the precipitation excess.

In the area concerned there was no difference in heads between the deep and the shallow water at the start of the pumping test, although the test showed the presence of semi-pervious layers. The reason for this must be that the area is situated in the transition zone between a recharge and a discharge area.

TABLE II

Groundwater fluctuations in the observation wells during the pumping test from 10 July to 19 September 1957.

Observation well	Head in m + sealevel			Drawdown in m from 10 July - 14 Aug.	Rise in m from 14 Aug. - 19 Sept.
	10 July	14 Aug.	19 Sept.		
V piezometer 1	1.90	1.85	2.27	0.05	0.42
piezometer 2	1.75	1.70	2.11	0.05	0.41
piezometer 3	2.03	1.96	2.34	0.07	0.38
piezometer 4	2.04	1.97	2.36	0.07	0.39
VII piezometer 1	1.95	1.90	2.32	0.05	0.42
piezometer 2	1.91	1.86	2.28	0.05	0.42
piezometer 3	2.08	2.02	2.40	0.06	0.38
piezometer 4	2.09	2.03	2.39	0.06	0.36
VIII piezometer 1	2.04	1.98	2.40	0.06	0.42
piezometer 2	2.03	1.98	2.41	0.05	0.43
piezometer 3	2.03	1.97	2.38	0.06	0.41
piezometer 4	2.05	1.98	2.40	0.07	0.42
IX piezometer 1	2.07	2.02	2.41	0.05	0.39
piezometer 2	2.08	2.02	2.45	0.06	0.43
piezometer 3	2.10	2.03	2.46	0.07	0.43
piezometer 4	2.12	2.04	2.48	0.08	0.44

#### 4.4 Recovery test

The pumping test was stopped on September 19, at 8.00 a.m. Taking into account a natural rise of the groundwater table of 0.03 m, the rise of head during 24 hours was equal to the loss of head during the first 24 hours of the pumping test (see table I).

#### 4.5 Calculation of soil and formation constants

The transmissivity and the leakage factor of the deep aquifer under the semi-pervious layer are calculated, making use of the drawdowns in the piezometers nos. 2 after 24 hours pumping, when a steady state situation was reached (see also fig. 12; calculations with later data are hampered by fluctuations due to natural circumstances). As mentioned before, the data resulting from the recovery test coincide with those of the pumping test.

As the deep aquifer can be regarded as semi-confined, and the phreatic surface remained practically constant during pumping, the method of De Glee can be applied (K r u s e m a n & d e R i d d e r, 1970). The data of the piezometers nos. 2 of the wells VII, VIII and IX were used (certainly the drawdown in the latter two wells will not have been affected by the partial penetration). The drawdowns as mentioned in table I, plotted versus the corresponding distances

and superimposed on the De Glee type curve give a point with coordinates  $s = 11,0$  and  $r = 260$ ;  $s$  is substituted into De Glee's formula

$$s = \frac{Q}{2\pi kD} K_0 \left( \frac{r}{L} \right) \quad (1)$$

where  $s =$  steady state drawdown in m in a piezometer at distance  $r$  in m from the pumped well

$Q =$  discharge of the pumped well in  $m^3/day$   
 $kD =$  coefficient of transmissibility (product of the permeability coefficient  $k$  and the thickness  $D$  of the water bearing formation)

$L = \sqrt{kDc} =$  leakage factor in m

$c =$  hydraulic resistance of the semi-pervious layer in days (quotient of the thickness  $D$  and the permeability coefficient  $k$  of the semi-pervious layer)

$K_0 =$  modified Bessel function of zero order and of the second kind

The results are :  $kD = 3500 m^2/day$   
 $L = 260 m$

It is now possible to determine the drawdown in each desired point. The calculated drawdown curve is

shown on fig. 13. As formula (1) only holds for fully penetrating wells, the actual drawdowns in the

vicinity of the pumping well will be larger than the calculated ones.

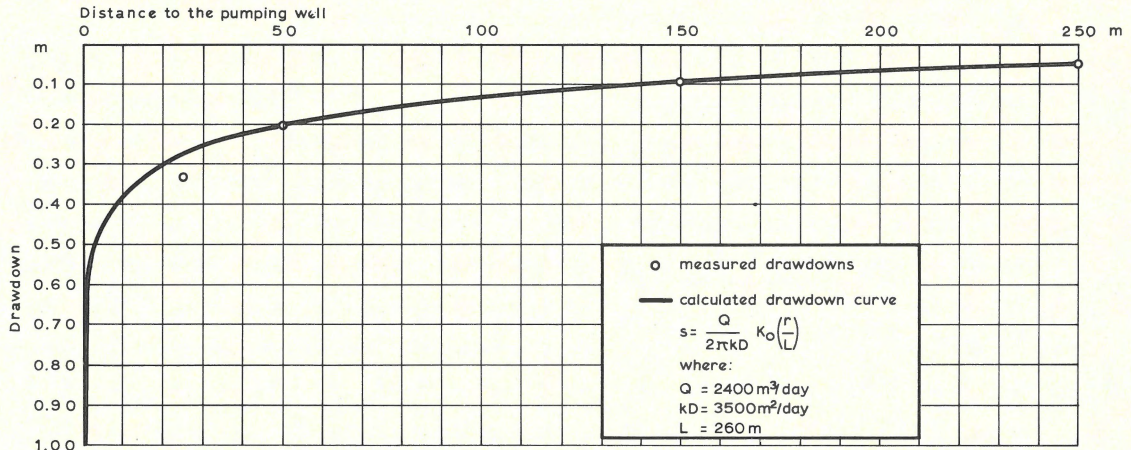


Fig. 13  
Calculated drawdown curve for a fully penetrating well (for symbols see text).

### 5. PREDICTION OF THE CONSEQUENCES OF FUTURE EXTRACTION

#### 5.1 Mathematical method

Assuming that in the long run the lowering of the shallow groundwater table will equal the loss of head of the groundwater in the deep aquifer, from which the water will be pumped, the presence of the semi-pervious layer at a depth of about 30 m will not be taken into consideration in the following calculations.

For the coefficient of transmissivity of the deep aquifer 3500 m<sup>2</sup>/day was found. The kD-value of the sand layer above the semi-pervious layer will be at least 500 m<sup>2</sup>/day. The transmissivity of the entire aquifer is therefore supposed to be 4000 m<sup>2</sup>/day. The capacity of the pumping station is planned at 500 m<sup>3</sup>/hour. The average daily production will then be approximately 8000 m<sup>3</sup>/day, with a maximum of 12,000 m<sup>3</sup>/day. In the summer season an average amount of approximately 10,000 m<sup>3</sup>/day is assumed and will be used in further calculations.

The drawdowns in the area can be calculated with the help of a mathematical method of solution, assuming two boundaries with a fixed potential, more

or less coinciding with water courses and polder boundaries (fig. 14). Beyond these boundaries no drawdown of the phreatic level due to pumping is to be expected. The system of two line sources and a sink, making use of the method of images, can be applied (Verruijt, 1970; Dietz, 1943). The drawdown *s* in a point (*x*, *y*) with the sink at the point *x* = *p* and *y* = *q*, can be expressed by

$$s = \frac{Q}{4\pi kD} \ln \left[ \frac{(x + p)^2 + (y - q)^2}{(x - p)^2 + (y - q)^2} \right]$$

$$\frac{(x - p)^2 + (y + q)^2}{(x + p)^2 + (y + q)^2} \quad (2)$$

where Q = 10,000 m<sup>3</sup>/day and kD = 4000 m<sup>2</sup>/day, and the boundaries form the *x* and *y* axes.

The result of the calculations is drawn in fig. 14. The actual drawdown can be expected to be somewhat smaller, as the assumed boundaries might be situated slightly nearer to the well. Moreover the semi-pervious layer at 30 m depth will reduce the transmission of drawdowns from the pumped aquifer to the phreatic level. This means that the calculation of the drawdowns should be based rather on the average daily extraction over the year than on the

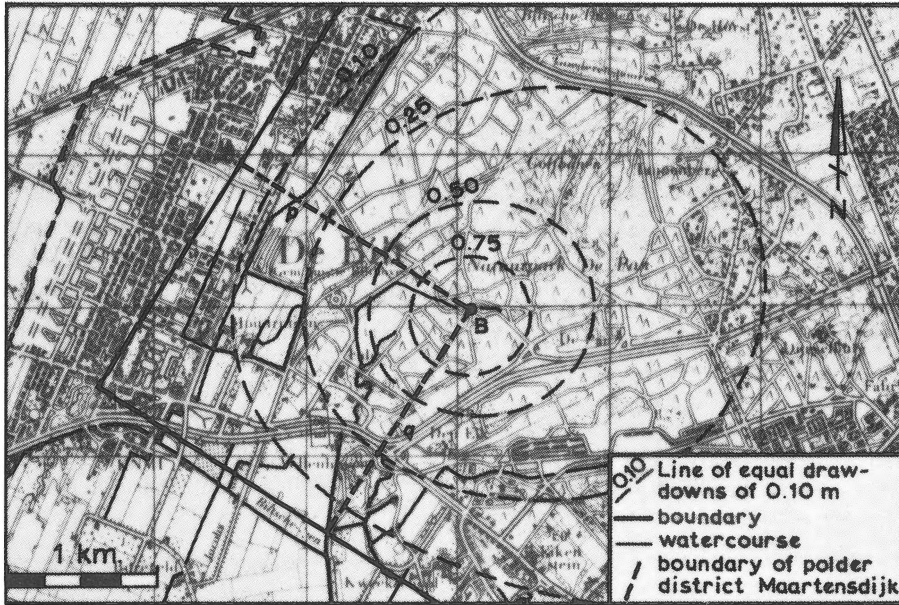


Fig. 14  
Map of predicted maximum drawdowns of the water table, in consequence of a water captation of  $10,000 \text{ m}^3/\text{day}$  in the centre of extraction B. Determination by means of a mathematical method (for further explanations see text).

average summer production. For safety reasons, however, the advise given has been based on the above mentioned findings.

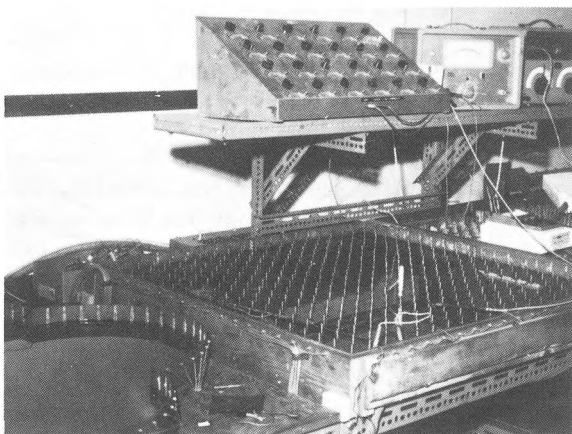


Fig. 15  
Requisites of the electrolytic analogue. In clockwise direction from top left: supply distributor, voltmeter, pulse generator, ammeter, tank with electrolyte for the actual model, extra tank for transformed area beyond the model boundaries.

## 5.2 Model tests

In order to refine the results of the mathematical approach, also a series of electrical model tests by means of an electrolytic analogue were carried out. As in the previous method the same values for the amount of extraction and the transmissivity – converted into the appropriate units – were used. The electrical potentials in and around the pumping well were measured and after conversion resulted in the values of the drawdowns. A picture of the model and the requisite apparatuses is given in the figures 15 and 16 (de Jong, 1962). The first model test served as a check of the mathematical model and was carried out with the same boundary conditions. As could be expected the same result was obtained. As shifting of the boundaries is quite easy in models of this kind, several cases with different configurations were simulated and measured.

In another test additional boundaries were simulated along open water at the northern side of the topographic divide of the Utrecht Ridge and along open water in the surroundings of Amersfoort, all at distances between 6 and 12 kms from the planned pumping station (fig. 17). Finally the north-west/

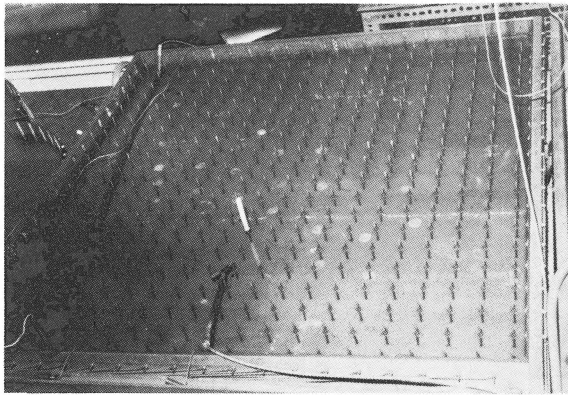


Fig. 16  
Electrical model with boundaries NE-SW (left) and NW-SE (bottom). Topographic scale 1 : 12,500. In the centre the simulated pumping well and a probe.

south-east boundary was shifted a little nearer to the pumping well (Report R.I.D., 1970-1). Figure 18 shows the model, while the result of the test is visualized in fig. 19. This configuration of the draw-downs and especially the lines of small drawdowns may approximate better the situation to be expected than the one of the mathematical method as allowance was made for all possible boundaries without safety margins.



Fig. 17  
Map indicating open water courses in the central part of the province of Utrecht.

## 6. THE ACTUAL CONSEQUENCES OF THE GROUNDWATER WITHDRAWAL

### 6.1 Preliminary studies

In March 1958 the licence for the groundwater withdrawal was applied for and was granted in March 1960. The actual extraction was started in June 1962 and was brought into full capacity in December 1963, according to the licence to a maximum of 12,000 m<sup>3</sup>/day, 350,000 m<sup>3</sup>/month and 4,000,000 m<sup>3</sup>/year. The withdrawal takes place at a depth between 53 and 73 m below ground level and is situated a few hundred meters north-west of the observation wells.

In connection with a possible further extension of the withdrawal a study of the influence on the

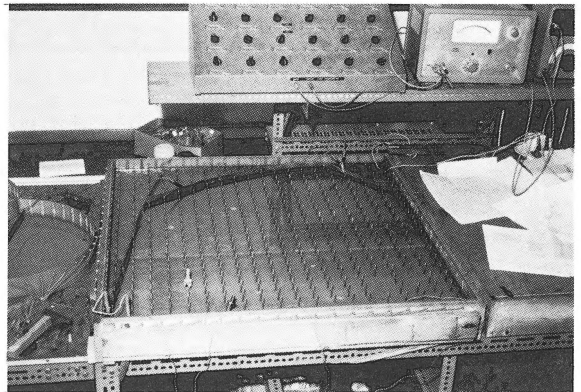


Fig. 18  
Electrical model, topographic scale 1 : 6,250 with boundaries at three sides. Below left the pumping well.

groundwater levels in the region was carried out by the CoGroWa in 1968. This study was based on the data from the shallow observation wells, completed with those of a number of fire wells.

It appeared that the natural differences in groundwater levels between wet periods (spring 1958, '61, '62, '66) and dry periods (period winter 1959 to 1960 and 1967) in the high regions can amount to more than one meter. In the lower regions the water is drained by ditches and the fluctuation is therefore approximately 0.60 m. The rises and drops of the groundwater table in the high and low lands are not synchronic and are of different size. In the low

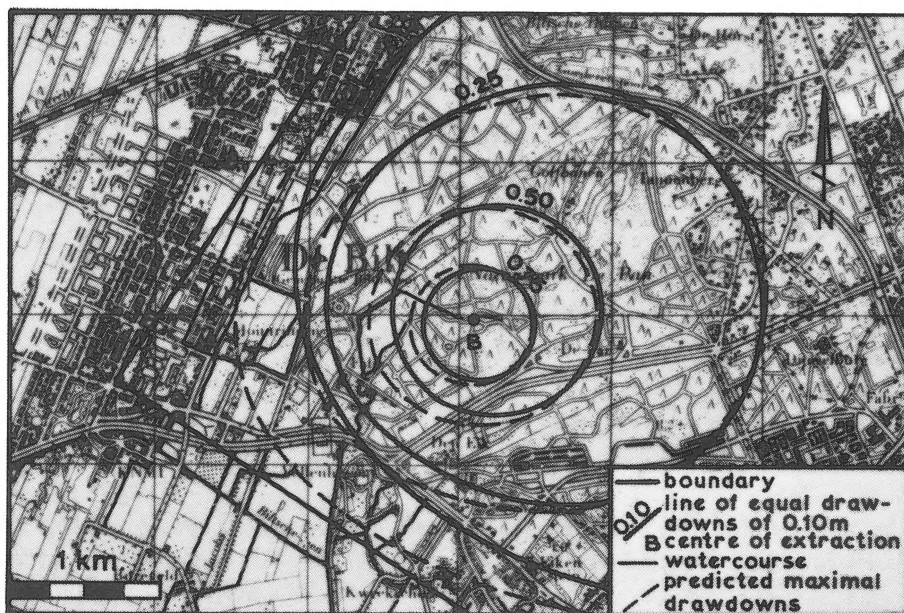


Fig. 19  
Map showing lines of equal drawdowns, as a consequence of an extraction of  $10,000 \text{ m}^3/\text{day}$ , by a transmissivity of  $4000 \text{ m}^2/\text{day}$ , and boundaries as on fig. 17. Determination by means of an electrical model. The dotted lines represent the predicted maximum drawdowns determined by the mathematical method (fig. 14).

lands the rise because of rain after a dry period begins earlier than on the woody hills. Moreover the difference in groundwater levels in the high and the low lands after a dry period is less than after a wet period. These aspects, confirmed by what can be read from fig. 7, made an analysis of the groundwater levels rather complicated.

TABLE III  
Amount of annual and seasonal precipitation from 1957-1969 measured by the KNMI at De Bilt (ref. 6).

Year	Totals mm	Winter mm	Summer mm
1957	924	362	582
1958	829	364	432
1959	539	364	200
1960	928	320	401
1961	912	573	425
1962	765	488	363
1963	777	309	494
1964	748	269	385
1965	1160	464	643
1966	1143	558	569
1967	856	510	354
1968	863	491	547
1969	748	306	456

A first impression of the actual consequences of the extraction was found by comparing the average April and August groundwater levels over a series of years before and after the beginning of the extraction. Data were used of the years 1957, 1958, 1961, 1962 and 1964, 1965, 1967 respectively; the dry period 1959-1960 and the wet year 1966 were left out of consideration (table III). The actual lowerings of the water table appeared to be smaller than the predicted ones. In the western part of the area, the effect of the captation seemed to spread further than it was expected. The picture, however, was confused by drawdowns due to extractions elsewhere, by differences in rainfall amount and distribution in the two periods and by a small shift of the centre of extraction as compared with the one during the pumping test.

Several alternative methods were tried out by the author in order to arrive at a more complete view of the actual drawdowns. The presence of a programmable calculator at the Institute made it possible to carry out many comparisons of the average relative data of several observation wells, one in the area of supposed influence and one outside that area. It is

TABLE IV

Amount of precipitation during 1956-1958 and 1967-1969, measured by the KNMI at De Bilt (ref. 6).

year	month(s)	mm/month	mm/season	mm/season	mm/month	month(s)	year
1956	Apr.-Sep.		422	354		Apr.-Sep.	1967
1956/57	Oct.-Mar.		362	491		Oct.-Mar.	1967/68
1957	Apr.-Sep.		582	547		Apr.-Sep.	1968
1957	Oct.	51			87	Oct.	1968
	Nov.	41			48	Nov.	
	Dec.	55	(147)	(161)	26	Dec.	
1958	Jan.	111			45	Jan.	1969
	Feb.	73			52	Feb.	
	Mar.	<u>33</u>	364	306	<u>48</u>	Mar.	
1958	Apr.	<u>53</u>			<u>74</u>	Apr.	
	May	66			85	May	
	Jun.	64			42	Jun.	
	Jul.	<u>80</u>	263	247	<u>46</u>	Jul.	

illustrative for the diversity of landscapes within the area that it proved impossible to find acceptable correlations.

### 6.2 Comparison of groundwater levels after periods with corresponding precipitation

In the following approach one date before and one after the beginning of the withdrawal were chosen which followed after series of seasons during which the precipitation was of comparable order of magnitude and followed by months in which the amount and the distribution of the precipitation were more or less the same. The periods preceding July 1958 and July 1969 met the requirements; the amounts of precipitation measured during the seasons and months prior to these dates are indicated on table IV. As only potential evaporation data were available, which cannot be used in regions with low water tables, the study has been based on precipitation figures only. The errors thus introduced are not considerable, as evaporation fluctuations throughout the year are not very large and in most cases much less than fluctuations in precipitation.

The groundwater levels in the observation wells of July 1958 were compared with those of July 1969. The differences thus found (in all wells drawdowns appeared) can be regarded as to represent the drawdowns concerned.

Unfortunately by the middle of February 1969 a dewatering of a construction site for an underpass of the road De Bilt-Zeist was started approximately 0.5 km south-west of observation well 28, which resulted in a considerable lowering of the ground-

water table in the neighbourhood. The analysis of the consequences of this dewatering which reached as far as well no. 5 in northern direction, is beyond the scope of this review. Lines of equal drawdowns, available from other investigations, were used to adjust the drawdowns caused by the extraction at Beerschoten.

During the considered period lowerings of the water table were also caused as a result of pumping for industrial purposes in the north-western part of the area while the pumping station at Zeist increased its withdrawal. Adjustments for all these influences were made; the drawdown pattern thus found is visualized in fig. 20.

A disadvantage of the chosen period is the fact that during the last months before the measuring, an average difference of precipitation amount of 16 mm occurred. This means theoretically, reckoning with a specific yield of 10%, a possible difference in groundwater level of 16 cm. The actual recharge of the groundwater will be much less as due to evapotranspiration and drainage by ditches, only part of the precipitation will reach the groundwater. This is also evident from the figs. 7 and 12.

An advantage of the period considered, is the fact that drawdowns are determined for a summer situation, which in view of agricultural interests is the limiting situation for the permissible lowering of the water table. In this respect the result of the described method can be compared with the predicted lowering of the water table, determined by the mathematical method, as this was also based on a summer situation. Indeed the configuration and the extent of the

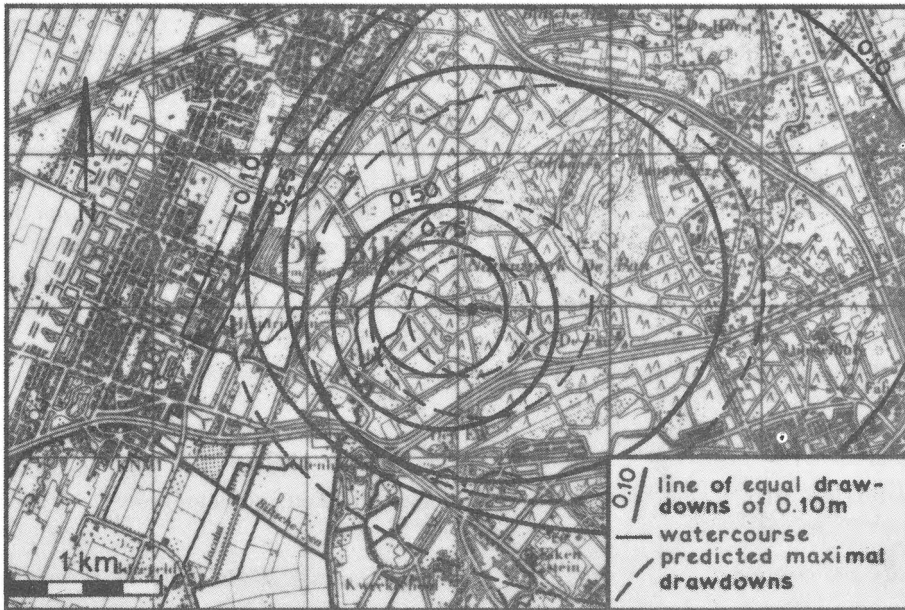


Fig. 20  
Map showing lines of equal actual drawdowns, based on a comparison of average groundwater levels in July 1958 and July 1969.

drawdowns appear to correspond with the prediction. As already stated, the centre of extraction during the actual groundwater captation was situated more to the north-west in comparison with the centre of withdrawal during the pumping test. As the latter point was used in the prediction methods, the curves are shifted somewhat to the north-west.

The average difference in groundwater levels between winter situations was also determined, namely those of December 1957 and 1968. The configuration of the drawdown lines thus obtained was comparable to that on the previous map. Due to the fact that in a winter season the ditches contain more water, which results in a better recharge of the aquifer, the drawdowns were slightly less. A map of the average (adjusted) drawdowns during the year, based on data of the two previous maps has been given in figure 21.

### 6.3 Comparison of groundwater level differences

Apart from valuable information in respect of the foregoing approaches, the GoGroWa kindly placed the results of another recent method at the author's disposal. Considered were data of observation wells,

located along four rows from the wells 1, 9, 16 and 20, through the centre of extraction. The average groundwater levels in two wells situated closely together, measured during the period before the withdrawal were compared. The same was done with data of the same wells during the years after the beginning of the withdrawal. The increase of the two differences is the increase of the average level difference in the two wells as the result of the withdrawal.

The same procedure was followed with the next pair of wells. The sum of the two increases thus found, is the total increase of level difference between the first and the third well. Assuming that no drawdown in the first well occurred, these figures represent total drawdowns. By repeating this procedure several times in the direction of the centre of extraction, total drawdowns for all wells considered were found. The reason for choosing pairs of wells situated closely together, is to avoid irregularities as a result of the different landscapes and circumstances within the area.

The check on this method is the drawdown in the central wells which, following the procedure along the rows, must always appear approximately to be the same. This was indeed the case (deviation less

than 0,05 m, with a drawdown in the central wells of 0,80 m). Further the drawdown at the other end of the row should be zero. Taking into account adjustments for groundwater extractions elsewhere, this also appeared to be so. The result of this approach, which must be regarded as the average drawdown configuration, is given in figure 22.

This configuration and that of figure 21 show a striking similarity. The drawdowns, found through two completely different methods, must be conceived as the actual average lowering of the water table as a consequence of the extraction at Beerschoten.

## 7. FURTHER DEVELOPMENTS

### 7.1 Water quality and treatment

After the beginning of the withdrawal, chemical analyses of the raw water were regularly carried out. Except for some slight alterations the same chemical properties as before the extraction were found. As it was stated in Chapter 3.1 the analyses of the water samples taken then, showed that total and carbonate

hardness rose and that the percentage of aggressive free carbon dioxide and in some cases also the iron content decreased with increasing depth. When the figures of the analyses of 1971 are considered and compared with the ones found before the withdrawal, a slight tendency can be observed of a decrease in total and carbonate hardness and an increase in iron content and possibly in aggressive free carbon dioxide. The obvious conclusion is that this might be caused by the fact that at least part of the water originates from shallower layers.

The water treatment at the new pumping station (fig. 23) could, because of the good quality of the raw water, be restricted to aeration (the oxygen content is smaller than 1 mg/l) and subsequent rapid sand filtration and lime feeding.

### 7.2 Extension of the withdrawal

Already before the actual beginning of the withdrawal, the Water Company became aware that a further extension of the capacity of the pumping station would soon be necessary. The increase of the capacity of the surrounding pumping stations, the limit of which is determined because of geohydro-

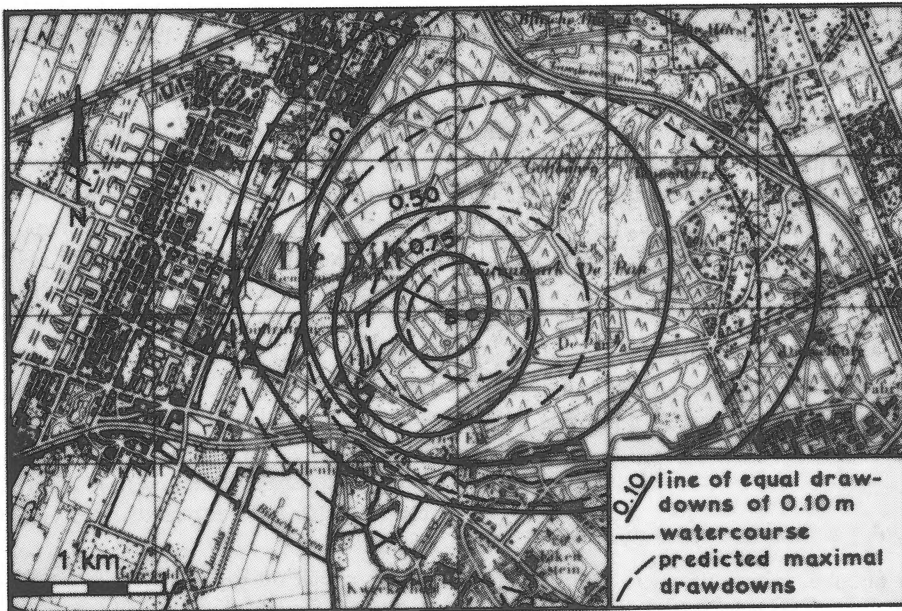


Fig. 21  
Average drawdown configuration.

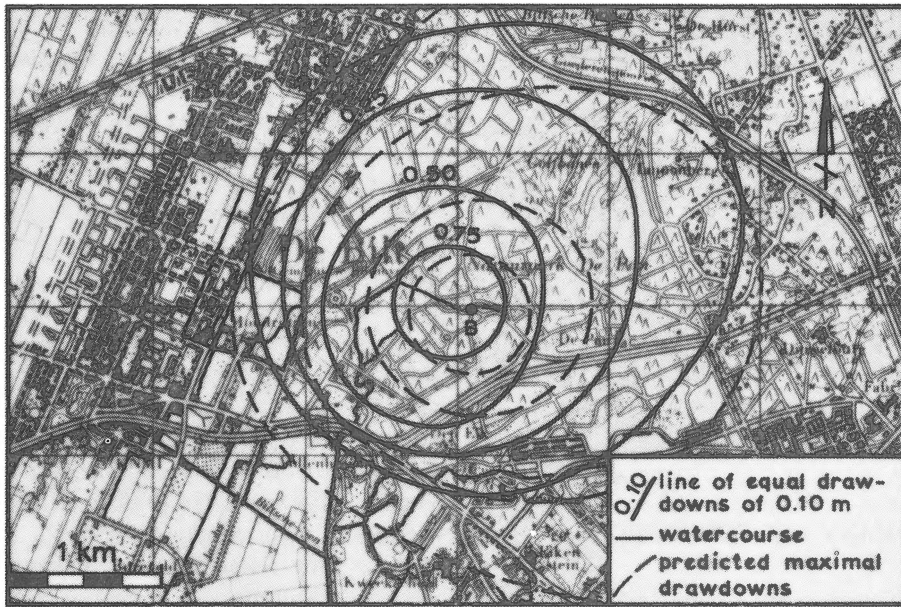


Fig. 22  
Map of equal actual drawdowns, based on determinations of drawdown differences by the CoGroWa.

logical and planological reasons (R.I.D., 1970-2), would not be sufficient to cover the increasing demand for water in the city of Utrecht. At an early stage of the discussions and based on the above mentioned experiences, the suggestion was made to extract part of the water from deep layers, in order to avoid a noticeable influence on the groundwater table and the water level in the ditches, for agricultural and environmental reasons.



Fig. 23  
The pumping station of "Beerschoten".

By means of a reverse rotary air lift drilling method, 3 deep test holes of a depth of 160 to 190 m below ground level were drilled (nos. 199, 200 and 206 on figs. 9 and 10). From a subsequent pumping test it appeared that the well yield was limited and that only a small amount of water could be withdrawn from the Icenian aquifer.

The chemical properties of the deep water came up to the expectations. The value of total and carbonate hardness (bicarbonates) was twice as high as in the shallower layers and a considerably lower iron and manganese content were found. Also the chloride content was somewhat lower. Filtration tests were started in order to determine the future treatment (fig. 24).

A licence for a withdrawal of 2,000,000 m<sup>3</sup>/year from the deep situated layers and of another 2,000,000 m<sup>3</sup>/year from the already exploited layers was applied for in 1965. Several investigations concerning the possible consequences, as stated in Chapter 6, were carried out by the CoGroWa and the Government Institute. The licence was obtained in 1971, but objections of parties concerned still have to be studied before the extended withdrawal can actually commence.



Fig. 24  
Test filter for treatment of deep groundwater.

## 8. SUMMARY AND CONCLUSIONS

In the foregoing chapters an impression is given of the course of a geohydrological investigation connected with watersupply in the Netherlands. From this case history it appears that in spite of a certain lack of appropriate data, yet reasonably reliable predictions could be made with the available procedures. In the present case it also turned out to be possible to find methods by which the consequences of the extraction could be traced. The data of the observation wells formed an indispensable basis for these and subsequent investigations.

The geohydrological investigations carried out can be divided into two stages: 1) the determination of soil and formation constants and the analysis of the geohydrological regime, by means of a pumping test and 2) the prediction of the drawdowns as a consequence of pumping, by means of a calculation method and a model.

It appears from this and other cases that the practical sustained yield – the amount of water which can be withdrawn annually without producing undesirable effects (Walton, 1970) – is dependent on the drawdowns due to extractions, the decrease of underground flow to ditches and rivers, and the possibility of drawing water of different quality. In the future more attention will have to be paid to the relation between groundwater and surface water (drainage patterns, recharge and interflow) and to chemical properties of the groundwater.

The bacteriological and hygienic reliability and the

permanent availability in spite of seasonal influences give groundwater, as a resource for drinking water supply, a great advantage in comparison with surface water. The simple treatment system which can generally be applied, the low temperature and the slight quality fluctuations make it even more advantageous.

While the geohydrological problems in the Netherlands are on the one hand becoming more and more complicated, the inventory of water supplies and the optimum location of well fields will on the other hand have to be studied with more exactness, as fresh groundwater is getting scarcer and scarcer. As it can be gathered from the masterplan drawn up by the R.I.D. (R.I.D., 1971) further research programmes will have to be carried out in order to create the possibilities to meet the growing demand of reliable water. The water supply for domestic and industrial purposes, for water discharge and quality control, and for agriculture and recreation will have to be considered in connection with each other, in order to arrive at an optimum exploitation of the groundwater. It is a favourable development that a number of institutions in the Netherlands working in fields related to groundwater hydrology have taken the task upon themselves to cooperatively carry out geohydrological surveys, of which this case history forms an example.

## ACKNOWLEDGEMENTS

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