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The origin of groundwater in Carboniferous and Devonian aquifers at Maastricht

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Abstract

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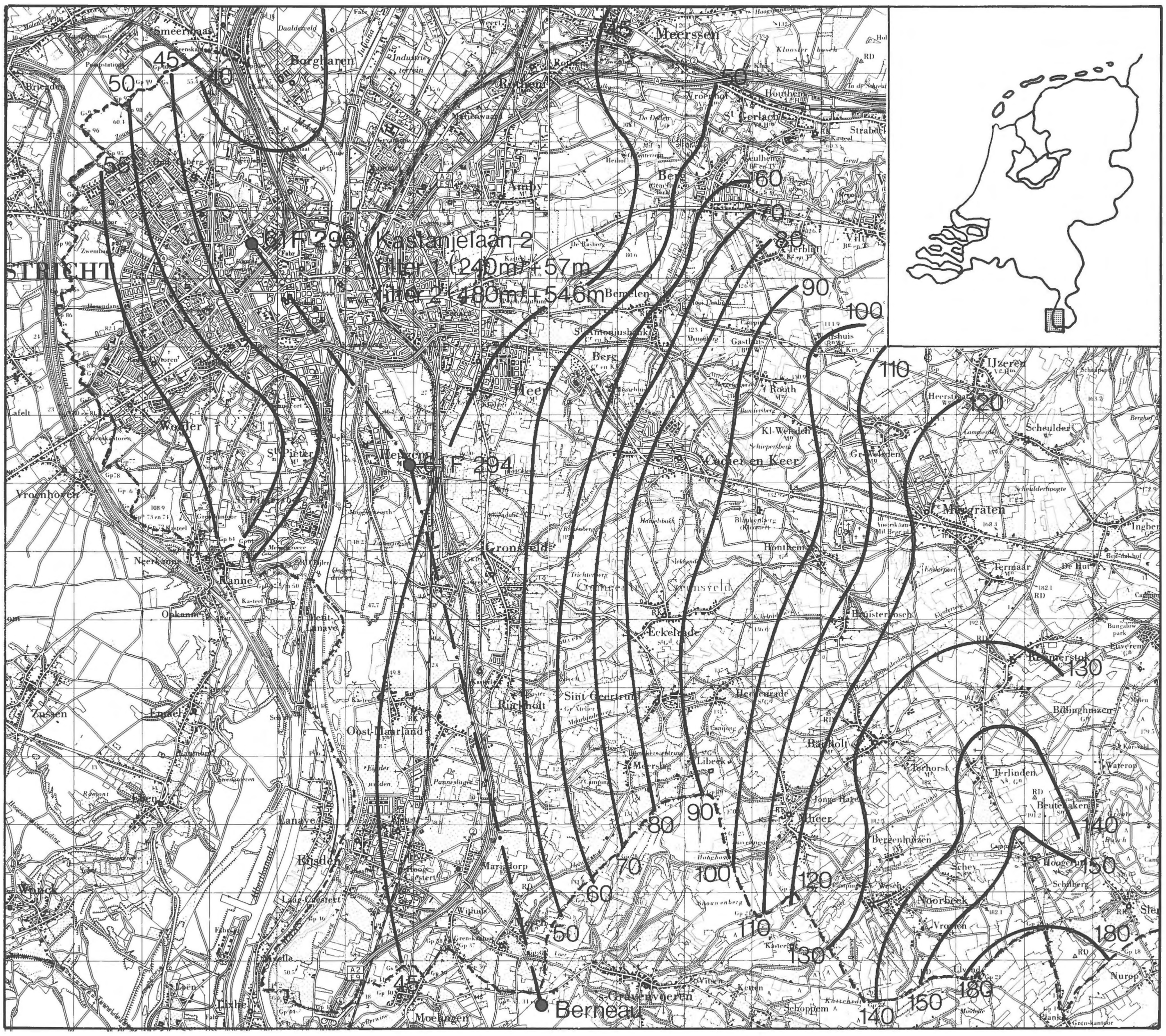
Two approximately 500 m deep boreholes were drilled in Maastricht (The Netherlands) and in one piezometers were placed at respectively 240 and 480 m depth. From the piezometric heads, which are several metres above ground level, and the existing groundwater contour maps of the area no firm conclusions concerning the groundwater origin can be drawn.

However, oxygen-18 and carbon-14 isotope analyses of the groundwater indicate a meteoric source. The calculated subsurface migration times suggest infiltration in the Middle-Weichselian for water from the upper piezometer and an Early-Weichselian age for water from the lower piezometer. Ionic ratios for bromide and chloride indicate that both groundwater types are influenced by salts dissolved from the rock matrix. Dissolved salts are supposed to be taken up by diffusive transport from pores with stagnant water into the cracks where the main groundwater flow takes place. Well tests performed on both piezometers yielded hydraulic conductivity. It is concluded that the flow velocities in the upper and lower layers are different. However, the area of origin of the groundwater found in both screens could be the same, taking into account the differences in conductivity and piezometric head.

Introduction

The provincial authorities of Limburg had two approximately 500 m deep boreholes drilled in Maastricht at the locations Heugem and Kastanjelaan. The locations are indicated in Figure 1. In the period 1927-1929 a well was drilled to 330 m depth. A description of this well and the quality of the groundwater encountered was published by Jongmans & Driessen (1932). Water from this borehole was bottled and sold as mineral water for some time. The main purpose of the recent drillings was the exploration for mineral water. Also a better understanding of the underground geological structure would be achieved. Both boreholes are extensively described geologically by Bless et al. (1981). They also reported water analyses of both locations. An interpretation of the water quality in view of the origin of the water is lacking, however.

Zuurdeeg (1981) considered the origin of the water, as well as its 'mineral' water characteristics. This last aspect will not be dealt with here. According to *Zuurdeeg* the water originates from infiltrated precipitation in the Land of Herve,



cross-section fig. 4
piezometric head in m above Dutch Datum Level (N.A.P.)

Fig. 1. Groundwater contours around Maastricht for the Cretaceous aquifer (after Van der Heijde et al., 1980).

which lies between the Voerstreek and Verviers (Belgium). The Paleozoic rock there is covered locally by Upper Cretaceous sands. The isotope oxygen-18 content mentioned supports this hypothesis. Analyses carried out at the University of Utrecht resulted in a value of −8 to −9 ‰ (SMOW). In comparison the same author mentioned a value of −8.1 ‰ for present well water from the Ardennes. His theory is that the water encountered dissolved rock salt during its passage from the infiltration area to Maastricht. Furthermore he referred to the Na/Cl ratio of 1.01 (concentrations in mmol/l) for a sample of the borehole Kastanjelaan (460 - 480 m) taken shortly after completion of the borehole. This is indeed close to the ratio which will appear when rock salt (NaCl) dissolves. This is also found elsewhere in the Netherlands e.g. in the deep groundwater at Nieuweschans, that almost certainly contains dissolved rock salt (Glasbergen 1982). Generally speaking, no conclusions can be drawn from the Na/Cl ratio alone. Also ion exchange often causes shifts in this ratio. Caution is necessary in using the ^{18}O data to draw inferences about the supposed area of origin. Due to the long underground residence time one should not compare them with the recent ^{18}O value, but with a value corrected for climatic changes in the past. This correction becomes possible by using the ^{14}C data as well. This is a point of further elaboration in this article.

Mapping of the groundwater

On September 21, 1984 the piezometric head of the shallow screen (230 - 240 m depth) (Kastanjelaan) was 5.2 m above ground level and of the deep screen (460 - 480 m depth) 2.9 m above ground level. These heads suggest infiltration in higher lying areas. Vertical groundwater movement is strongly impeded by the presence of several almost impermeable strata.

Looking at the groundwater contours (Fig. 1) of the area, it is obvious that the river Meuse has a strong draining influence on the groundwater in the shallow Cretaceous aquifer. Groundwater flow is consequently directed toward the Meuse. The shallow aquifer contours are based on observation wells in Cretaceous rock. From this map it can be concluded that at the east side of the river Meuse at Maastricht the groundwater in the Cretaceous aquifer originates from the southeastern border area with Belgium, whereas the groundwater at the westbank of the Meuse at Maastricht may have an origin in the topographically high-lying area southwest of Maastricht. From the geohydrological map of Belgium (Gulinck 1962) it follows that the watershed between the Meuse basin and the Scheldt basin lies not far west of Maastricht.

However, outside the Meuse valley the topographic height of the area southwest of Maastricht is 100 m or more lower than southeast of Maastricht over the Belgium border. For this reason and also regarding the piezometric head, which in both piezometers is above the level in the Cretaceous aquifer, it is very well possible that the groundwater in both piezometers at the Kastanjelaan borehole on the west bank originates from the southeast, provided that it is separated from the overlying shallow Cretaceous aquifer by a layer of very low permeability. Indications for such a layer have been found in the form of a plastic clay layer both at Heugen and Kastanjelaan boreholes at the base of the Vaals Formation, just at the top of the Dinantian rock.

Because the hydrological data do not lead to a uniform conclusion about the area of origin, we will firstly regard the water composition. After that an attempt will be made to indicate the relation between quality and origin.

Interpretation of the water quality in the deep screen of the borehole Kastanjelaan

On 5 November 1981 samples were taken by the RIVM from the borehole Kastanjelaan. At 480 m (screen 2), in the Upper Devonian, the chloride content was 5300 mg/l and the sodium content 3600 mg/l (see Table 1). The Na/Cl ratio in mmol/l is 1.05, that is slightly higher than the ratio for seawater. The oxygen-18 value analysed (−8.20 ‰ SMOW) can be considered to be rather low compared with the chloride content. When seawater mixes with water originating from precipitation the ^{18}O value related to SMOW of the mixture is determined by the relation:

$$\delta^{18} = \frac{19300-[Cl]}{19300}\,\delta_f^{18}$$

where: [Cl] = chloride concentration of the original seawater in mg/l and $\delta_f^{18} = {}^{18}O$ of the precipitation in ‰ SMOW. With the analysis carried out by the Isotope Physics Laboratory of the University of Groningen the ^{18}O value given by Zuurdeeg (1981) was confirmed namely −8.26 ‰. From the formula given before it follows that $\delta_f^{18} = -11.4$ ‰.

The ^{14}C analysis indicates a very low level of 3.0% (modern carbon). The exact relationship between the ^{14}C values and the age of the groundwater is still a matter of dispute. A rough indication can be given, however. For the water of the deep screen a rough estimate of the age is 25 000 years. This means that the water could have infiltrated during the very cold period in the Middle-Weichselian between approximately 30 000 and 15 000 years ago. In the then prevailing climatic condi-

Table 1. Wateranalyses boring Kastanjelaan (lab. of anorganic chemistry of the 'Rijksinstituut voor Volksgezondheid en Milieuhygiëne').

Depth	230-240 m	460-480 m	
Conductivity	360	1400	mS/m
pH	7.33	7.10	
Cl^-	984	5300	mg/l
SO_4^{2-}	118	390	mg/l
SO_2	36	83	mg/l
HCO_3^-	595	852	mg/l
PO_4^{3-}	0.01	0.02	mg/l
NH_4^+	1.9	6.6	mg/l
Ca^{2+}	61	170	mg/l
Mg^{2+}	29	82	mg/l
tot.hardn.	3.87	7.71	mmol/l
Ba	100	160	µg/l
Cu	1.0	7.0	µg/l
Zn	10	< 10	µg/l
Cd	0.2	0.2	µg/l
Hg	0.2	0.1	µg/l
Pb	2.0	2.0	µg/l
As	< 0.5	5.0	µg/l
Cr	0.5	0.5	µg/l
Mn	0.06	0.2	mg/l
Fe	0.6	1.6	mg/l
Co	< 0.5	2.4	µg/l
Ni	1.0	5.0	µg/l
Li	1.35	5.30	mg/l
Na	750	3600	mg/l
K	41	100	mg/l
Br*	1.78 ± 0.4	8.73 ± 0.12	mg/l
I*	0.091 ± 0.008	0.203 ± 0.006	mg/l
^{18}O**	-8.90	-8.20	‰SMOW
^{2}H**	-58.0	-56.2	‰SMOW
^{3}H**	< 1.4	< 2	TU
^{14}C**	0.4 ± 0.1	3.0 ± 0.1	%
^{13}C**		-4.78	‰

* analyses Netherlands Energy Research Foundation

** analyses Isotope Physics Laboratory, University of Groningen

tions the ^{18}O value of the precipitation must have been lower than at present in the ara involved.

From research at various locations around the world a relation between temperature and ^{18}O value has been established (see for instance: Brown et al. 1972). With isotope research in the province of Groningen (The Netherlands) a connection could be made with climatic developments in the past (Glasbergen & Mook 1982). Other analyses of groundwater dated between 20 000 and 45 000 years (Glasbergen 1984) point to ^{18}O values of only 1 to 2% lower than the present ones. It can therefore be stated that the correction of ^{18}O value for chloride content as carried out previously leads to too low values. This problem can be avoided if one assumes that the chloride for the greater part originated from dissolution of rock salt.

The water-bearing strata at both piezometers can be regarded as a system where groundwater flow occurs in interconnected cracks and fissures. The remaining pores contain stagnant water that could have a completely different composition. In these pores remnants of solid rock salt might be present, which serve as a source of dissolved sodiumchloride. Transport of ions between the flowing water and the stagnant pore water takes place by diffusion.

Also the ratio between the concentrations of ions in solution can sometimes give indications of its origin. From the Br/Cl ratio, which is 16.5×10^{-4} at a depth of 460 - 480 m, the following comparisons can be made. In fresh, brackish or salt water of meteoric or marine origin this ratio lies between 25×10^{-4} and 50×10^{-4}. In water in which rock salt has been dissolved the ratio can decrease to 1×10^{-4}

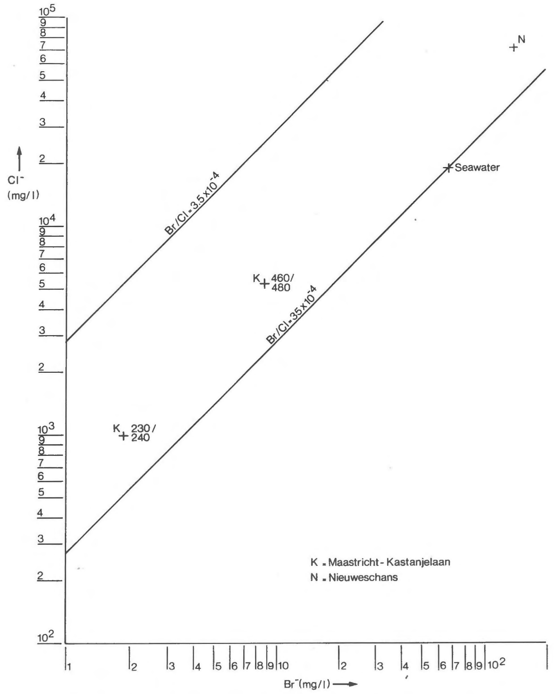


Fig. 2. Relations between chloride and bromide; a decreasing ratio indicates presence of more dissolved evaporites.

to 3×10^{-4}. In Figure 2 the concentration of Br is given versus that of Cl. A line showing the dilution of seawater with fresh water is drawn also. Besides the ratios for the two samples at different depths at Kastanjelaan, the value of the extremely saline water of borehole Nieuweschans is also given. The chloride content indicates that the water of Nieuweschans is certainly influenced by dissolved salt. All the points in this graph lie above the seawater-line. Thus the groundwater at the Kastanjelaan borehole is probably influenced by dissolving salts as well. However, the dissolved salts at Nieuweschans are of Zechstein origin as follows from the geohydrological situation.

Groundwater flow

Bless et al. (1981) mentioned porosity and permeability values derived from well logs and core research. The average porosity for the stretch between 460 and 480 m is 0.6% and the permeability 1 milli Darcy (mD) or approximately 10^{-3} m/d. Because permeability tests on small samples are often not representative for water-bearing strata, well tests have been performed. The flow rate of the deep well screen has been measured at the outflow point of the well at surface level. With a valve the well is closed and subsequently opened after having placed a transparent tube vertically above the well. From the plot of the piezometric head in the tube as a function of time since opening the valve the transmissivity can be calculated using Theis' method (Fig. 3). The flow rate is 1.15×10^{-4} m^3/s and the calculated transmissivity $T= 3.1\times10^{-6}$ m^2/s. The average hydraulic conductivity over the screen stretch is $3.1\times10^{-6}/20=1.55\times10^{-7}$ m/s, which is comparable to 16.1 mD. The difference with the above mentioned results from core tests is probably caused by the predominate effect of cracks on the conductivity.

From Darcy's law the following relation can be derived between the ^{14}C age (T), the distance to the infiltration area (L), the porosity (n), the hydraulic head difference (Δh_2) and the hydraulic conductivity (k): $Tk/n = L^2/\Delta h_2$. Using the welltest data and other data given for T and n and assuming L =

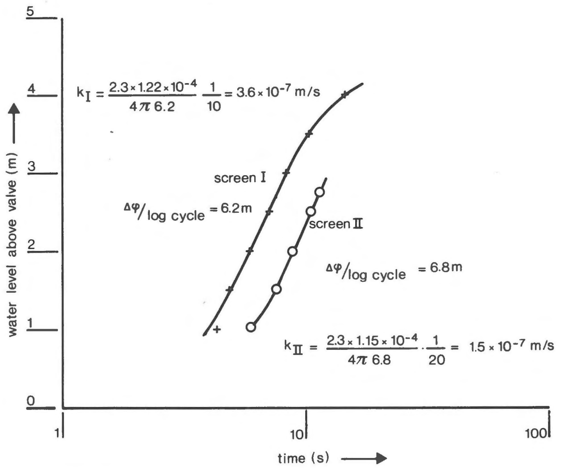


Fig. 3. Well-test data of the Kastanjelaan borehole; time and waterlevel shown after opening of the valve.

10^4 m it is calculated that $\Delta h_2 = 5$ m. This implies that in a potential infiltration area the piezometric head is about 8 m higher than at the Kastanjelaan borehole, because the well itself shows a head of 2.9 m aboven surface.

Interpretation of the water quality in the shallow screen of the well Kastanjelaan

The sample of 240 m depth (Dinantian) is investigated for isotopes as well : $\delta^{18}O = -8.9$ ‰ and ^{14}C = 0.4 ± 0.1%. This water contains the lowest ^{14}C content ever measured in the Netherlands and could be 40 000 to 50 000 year old. $\delta^{18}O$ is somewhat lower than in the deeper sample. This could indicate infiltration in a colder period in the earliest Middle-Weichselian.

The Na/Cl ratio for this sample is 1.18, which is higher than in seawater or dissolved rock salt. This is however a frequently occurring phenomenon in areas where infiltrating precipitation percolates through an originally marine sediment. Through ion exchange Na from the sediment will be released and replaced by Ca. Also in the analyses mentioned by Kimpe (1963) for Carboniferous water the Na/Cl ratio is often higher than 1.

The Br/Cl ratio is 18.1×10^{-4} and that is thus somewhat higher than in the deepest screen. For the screen at 240 m as well as the screen at 480 m it can be concluded from the oxygen-18 and deuterium relation, that no extreme evaporation has taken place during infiltration. The analyses of both groundwater samples as given in table 1 show a great resemblance in composition. The parameters related to the assumed dissolution of evaporites increase with depth by about a factor 5 for Cl^-, Br^-, Na^+, and Li^+ and by about a factor 3 for SO_4^{2-}, Ca^{2+}, and Mg^{2+}. The groundwater quality in both screens seems to point to the same origin, whereby the deepest water has been able to take up more dissolved salts.

It is of interest how far the preliminary indication about the origin is supported by the collected geohydrological data. Using the same method as described for the shallow screen the hydraulic conductivity has been determined with a well test at 3.6×10^{-7} m/s. The flow rate was 1.22×10^{-4} m^3/s. Taking for T a value of 45 000 a and for n 1% and assuming $L = 10^4$ m, it can be calculated that $\Delta h_1 = 2$ m. The porosity is put at 1%, because Bless et al. (1981) found the porosity, derived from the formation density compensated log, to be relatively high in the stretch 218 to 235 m. The piezometric head of this screen is 5.2 m above ground level, which leads to a head of more than 7 m in a potential infiltration area. This figure does not deviate much from the calculated piezometric head for the deep screen of the Kastanjelaan borehole and supports also the indications about an identical origin of the groundwater found at both screens derived from the water quality.

A comparison with the analyses of Heugem

The water analysis presented by Bless et al. (1981) for the Heugem borehole (402-502.7 m) showed that the chloride content is greater than 800 mg/l. Regarding the Br/Cl ratio of 16×10^{-4} and the water composition in general it could be stated that the water of the Heugem borehole, just as that of the Kastanjelaan borehole, is influenced by diffusive supply or dissolution of salts.

The fracture zone, which according to Bless et al. (1981) is probably present between Heugem and Kastanjelaan (Fig. 4), could lead to flow of water with a relatively low chloride content, as present between 400 and 500 m at Heugem, to shallower depths at the Kastanjelaan borehole. Groundwater following the deepest flow lines could take up more salts which contain relatively more sodiumchloride. The concentrations of dissolved salts increase with depth while the Br/Cl ratio remains the same.

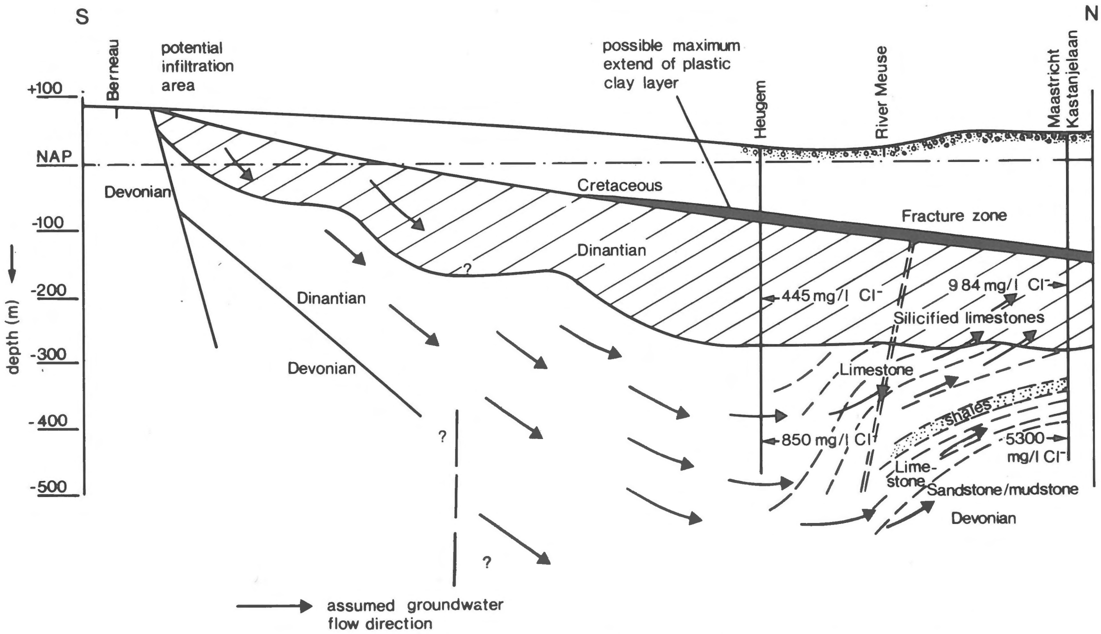


Fig. 4. Simplified cross-section Berneau-Maastricht, showing the assumed flow system (with data taken from Bless et al., 1981).

Unfortunately the borehole Heugem is no longer accessible for sampling, so that no isotope analyses can be carried out to verify the age and oxygen-18 value.

Conclusions

Summarizing, it can be assumed that the groundwater from both screens in the Kastanjelaan borehole in the Dinantian and Devonian aquifers could have the same origin in a southeastern infiltration area. The available geohydrological data support the indications derived from the Carbon-14 and Oxygen-18 analyses about the postulated origin. The groundwater of the Kastanjelaan borehole (230-240 m) and the Heugem borehole (400-500 m) might have the same origin.

The main water movement in the deep aquifers in the surroundings of Maastricht will take place through cracks in the rock. From stagnant water in other pores, dissolved salts will slowly enter the main flow due to diffusion. The water composition, as analysed at Kastanjelaan, strongly indicates that it consists of infiltrating rain water, which has been in passage for some tens of thousands of years, during which time salts were dissolved to high concentrations. The highest concentrations have been found at the greater depth. The mechanisms presented to explain dissolved salts in the groundwater support the suggestion given by Bless et al. (1983) concerning the presence of rock salt southeast of Maastricht.

It is worth mentioning that the sample of 230-240 m (Kastanjelaan) has the lowest carbon-14 content observed up till now in the Netherlands. The quality of this water cannot be explained by local upward flow from greater depth, but must be a result of more or less horizontal flow more slowly than in the deeper stratum.

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