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HYDROGEOLOGY OF THE THERMAE BOREHOLES (VALKENBURG A/D GEUL, THE NETHERLANDS)

by

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(10 figures and 5 tables)

1. INTRODUCTION

Two aquifers have been distinguished in the three Thermae boreholes (Valkenburg a/d Geul, South-Limburg, the Netherlands). These are characterized by groundwater of different properties. The Upper Cretaceous aquifer contains a somewhat mineralized groundwater that is alimented by infiltration of meteoric water through the Quaternary and Tertiary cover. The more intensely mineralized thermal deep groundwater of Na-Cl type in the Visean carbonates circulates already for a longer period in the subsurface. This is indicated by the high mineralization and very low nitrate contents of the latter.

The differentiation in an upper, 150 m thick Cretaceous aquifer and a lower, more than 160 m thick Dinantian aquifer is produced by some 60 m thick strata which form a confining or poorly permeable layer, that hampers or even prevents the mixing of these groundwaters.

2. CRETACEOUS AQUIFER

2.1. HYDROGEOLOGICAL PROPERTIES OF STRATA

2.1.1. Aachen and Vaals Formations

The kaolinic mud-sand of the Aachen Formation and the overlying slightly sandy clays of the Vaals Formation are considered as poorly permeable to impervious strata.

2.1.2. Gulpen Formation

The base of the Gulpen Chalk may be considered as the base of the Cretaceous aquifer. The fine-grained (coarse calcisiltites) chalk has a low hydraulic conductivity. Groundwater mainly circulates through fissures in hard, cemented limestone layers which are intercalated in the otherwise soft chalk (Patijn 1966). The top of this sequence is formed by the Lichtenberg Horizon. Important circulation losses occurred at this level in Thermae 2001 and Thermae 2002 (in both cases several 100 m^3). A recharge test in Thermae 2001 revealed a hydraulic conductivity of 1.7×10^{-1} m/s for this fissured layer that presumably yielded the bulk of the groundwater in a pumping test.

2.1.3. Maastricht Formation

Two lithofacies with different hydrogeological properties are distinguished in the Maastricht Formation :
— Kunrade Chalk, and
— Maastricht Chalk.

The Kunrade Chalk is marked by a pronounced heterogeneity of the lithology consisting of alternating hard well-cemented limestone layers and soft fine-grained (coarse calcisiltites to fine calcarenites) chalk with low hydraulic conductivity. Water circulation is largely restricted to fissures in the hard limestone layers. Annual fluctuations of the groundwater level of several meters in the Ubachsberg (Heerlen) area reveal the low storativity of the Kunrade Chalk (Jongmans et al. 1941).

The Maastricht Chalk consists of more permeable, medium- to coarse-grained calcarenites which may be followed over large distances. Groundwater mainly circulates through voids, but also through fissures in hardgrounds. The mean void ratio of the «tufaceous» Maastricht Chalk is 40 % according to Jongmans et al. (1941). No literature data on the k-values of this chalk exist. The k-value may be estimated or calculated through the following parameters : capillary pressure head and apparent flow velocity.

The capillary pressure head in the coarse-grained tufaceous chalk is about 1.5 m (Jongmans et al. 1941). This would match a capillary pressure head of 0.5 to 2.0 m in silt and k-values of about 10^{-5} to 10^{-7} m/s. This comparison is acceptable since the tufaceous chalk is rather uniform as far as grain size, pore volume and permeability are concerned.

The apparent flow velocity is 0.9 to 1.4×10^{-5} m/s (Jongmans et al. 1941). This value is based on travel times of groundwater table maxima after heavy rain fall. By means of the empiric formula of Keller (1969)

$$k = \frac{\text{apparent flow velocity x void ratio}}{\text{hydraulic gradient}}$$

a mean k-value of 3.7×10^{-4} m/s has been calculated.

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2.1.4. Cenozoic

Tertiary fine-grained sands of the Tongeren Formation and Quaternary loess form the cover of the Cretaceous aquifer. These strate are some 37 m above the groundwater table in the Thermae boreholes. Because of their relatively high hydraulic conductivity these play an important role in the recharge of groundwater however. Since large quantities of rain water can easily infiltrate these sediments there is virtually no surface runoff on the Margraten Plateau south of the Thermae boreholes. This plateau is also marked by the practical absence of brooks.

2.2. GROUNDWATER RECHARGE IN SOUTH-LIMBURG

Some 35 % of the annual rain fall (mean 750 mm) infiltrates through the Cenozoic sediments (Patijn 1966). This forms the principal source for the groundwater recharge in this area.

The mean annual infiltration of some 260 mm in a drainage area of 240 km^2 yields a mean recharge of some 63 x 10^6 m^3. Therefore the Upper Cretaceous chalk forms the main groundwater reservoir in South-Limburg. Groundwater withdrawals from the bank filtrates of the Meuse Terraces form only a small portion of the total demand in South-Limburg.

The groundwater flows to the Meuse and her tributaries. In the environs of the Thermae boreholes this flow is northward in the direction of the Geul Valley.

The groundwater levels have remained about the same over long periods. The water table contour lines of Jongmans et al. (1941) and Patijn (1966) are rather similar. The most obvious differences between these maps occur around production wells which had been sunk down after 1941. This indicates that the numerous tectonic fault zones have little or no influence on the piezometric surface, and thus that these faults are permeable. This is also true for the E-W striking Klauwpijp Fault that occurs some 350 m south of Thermae 2000.

2.3. DISTRIBUTION OF GROUNDWATER IN CRETACEOUS AQUIFER

The water table of the Cretaceous aquifer in Thermae 2001 is about 59 m below the surface (+ 73 m NAP). Although three boreholes were available it resulted impossible to reconstruct the local direction since water level measurements could not be performed simultaneously in the three wells. Simultaneous water level measurements in Thermae 2001 and Thermae 2002 yielded an apparent dip of 0.6 m/100 m to the northeast for this level.

Two intervals are distinguished in the Cretaceous aquifer :

— upper interval with oxygen-rich, aerated water and relatively high groundwater movement, and

— lower interval with reducing conditions and more or less stagnant or slowly flowing water.

The transition between these two zones is rather abrupt at + 48 m NAP, where the Maastricht Chalk passes downward into the Kunrade Chalk, and this transition is marked by a color change of the sediment from ochre-yellowish to grey. Moreover pyrite crystals in the Kunrade Chalk have not been oxidized, this in contrast to those in the Maastricht Chalk where oxidation of the pyrite locally has produced a rosty-brown staining of the sediment.

2.4. AQUIFER PROPERTIES

A pumping test of the Cretaceous aquifer has been performed in Thermae 2001. This hole is meant as a freshwater production well. The drawdown curve (fig. 3a) yielded a transmissivity value of 1.13 x 10^{-3} m^2/s, the recovery curve (fig. 3b) a value of 1.06 x 10^{-3} m^2/s. The time-drawdown curve is rather irregular, presumably because of capacity fluctuations of the pump. Notwithstanding the low rate of discharge (16 m^3/h) no stationary conditions could be achieved even after a test of two days.

After completed recovery the water table was 50 cm below the level of before the test. This may be explained by a bimodal storativity (voids and fissures). In the following months the water table slowly recovered without reaching its original height.

2.5. HYDROCHEMISTRY

Table I shows the chemical analysis of the groundwater from the Cretaceous aquifer. Main elements are calcium (75 epm%) and bicarbonate (72.5 epm%). These values are representative for the Cretaceous chalk aquifer in South-Limburg. Remarkable is the high Si02 content (about 28 mg/l) that must have been derived as amorphous silica from the sediment (e.g. flint layers or silicified chalk). The low values for nitrate (19.1 mg/l) and nitrite (0.16 mg/l) point to an extremely moderate anthropogenic contamination of the groundwater. The electrical conductivity of the water (630 μS/cm) remained rather constant during the pumping test.

Table I - Hydrochemistry of the Upper Cretaceous aquifer in Thermae 2001. Data RWTH Aachen. Sampling date 17-09-1986.

temperature (°C) : 13,3
pH : 7,2
electrical conductivity (μS/cm): 630

cations				anions			
	mg/l	epm	epm%		mg/l	epm	epm%
Na^+	15,7	0,68	10,7	Cl^-	38,3	1,08	16,4
K^+	1,54	0,04	0,6	HCO_3^-	291,7	4,78	72,5
NH_4^+	0,06	0,0	0,0	NO_3^-	19,05	0,31	4,7
Ca^{2+}	95,4	4,76	75,2	NO_2^-	0,16	0,0	0,0
Mg^{2+}	10,2	0,84	13,3	SO_4^{2-}	20,0	0,42	6,4
Fe_{tot}	0,18	0,01	0,2	PO_4^{3-}	0,1	0,0	0,0
Mn_{tot}	0,1	0,0	0,0				
$\sum$	123,2	6,33	100,0	$\sum$	369,21	6,59	100,0

total hardness (°dGH): 15,7
SiO_2 (mg/l): 29,5

3. DINANTIAN AQUIFER

3.1. HYDROGEOLOGICAL PROPERTIES OF STRATA

There is no information in the literature on the hydrogeological properties of the Visean rocks in the immediate environs of Valkenburg a/d Geul, notwithstanding the rather detailed knowledge of these characteristics in the boreholes of Maastricht (Heugem and Kastanjelaan ; Bless et al. 1981, Glasbergen 1985) and Beek (Geverik ; Van Rooijen 1987). Therefore the hydrogeological classification of strata is limited to the Thermae boreholes. A more generalized description has been published by Bless et al. (1986).

The assessment of the hydrogeological rock properties - and especially of the permeability - is based on the following measurements and recordings (fig. 4) :

— recording of circulation losses,

— presence of calcite (authigenic in joints and voids)

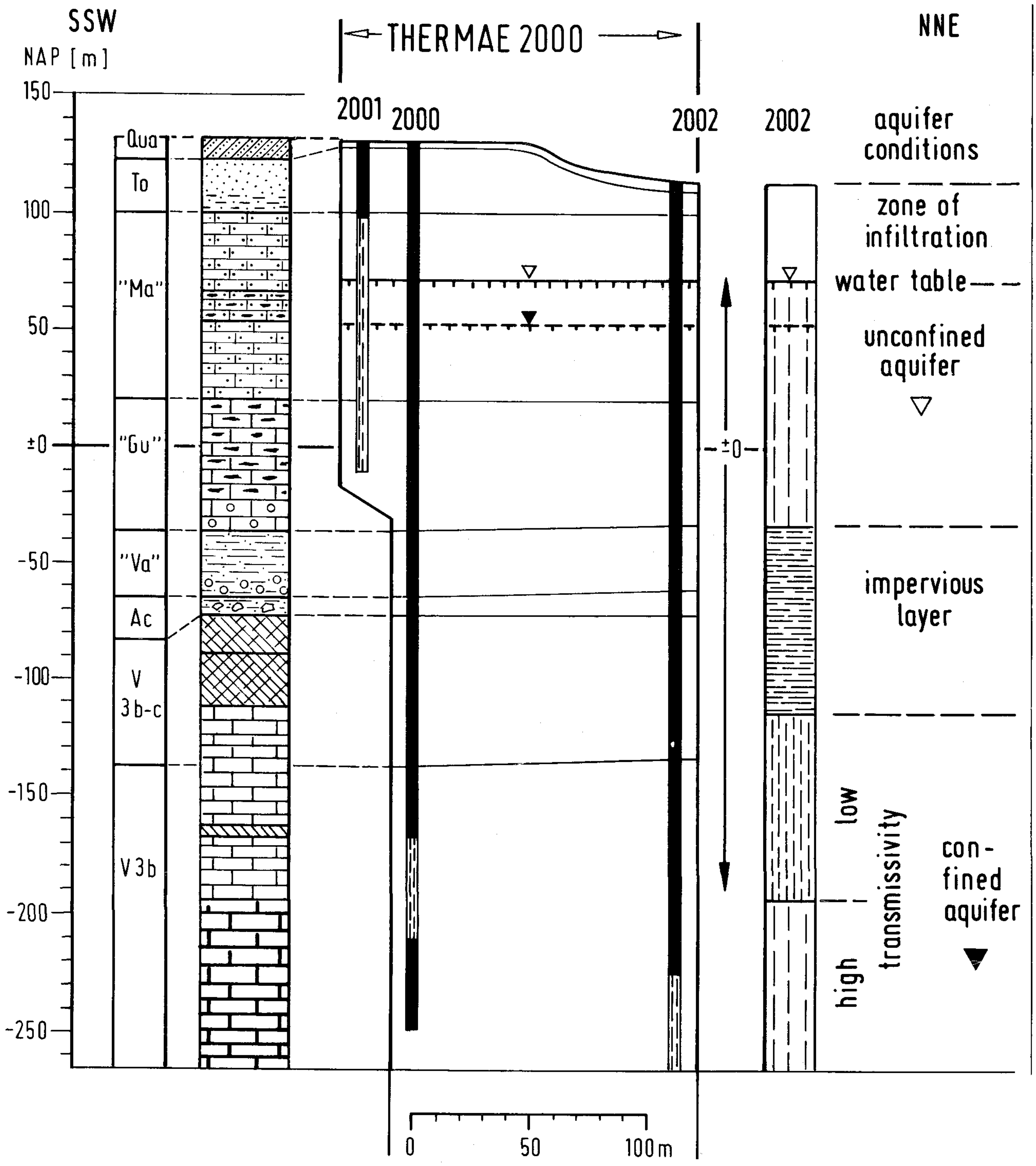

Figure 1 - Geological-hydrogeological section through the Thermae boreholes. «Ma» includes Paleocene Houthem Chalk in Thermae 2000 and Thermae 2001. «Va» includes sandy «Lower Vijlen» in Thermae 2000 and Thermae 2002.

in the cuttings,
— interpretation of temperature measurements (chapter 4), and
— electrical borehole measurements (spontaneous potential and resistivity) in Thermae 2002 between 310 and 381.5 m.

The porosity of the rocks is poor. Water circulates only in joints, fissures and karst cavities. This is suggested by circulation losses in Thermae 2000 and Thermae 2002 which are clearly limited to stratabound karstification. Three hydrogeological zones with different characteristics are distinguished. The indicated depths refer to Thermae 2002. These may be slightly different in Thermae 2000.

3.1.1. Lower zone (—267 to —197 m NAP)

This interval of limestones and partly silicified limestones is characterized by a very good hydraulic conductivity. This is shown by the fact that in this zone the most pronounced circulation losses occurred in Thermae 2000 and Thermae 2002. The SP-log of Thermae 2002 reveals three highly permeable intervals (fig. 4) : —195 to —205 m NAP, —232 to —238 m NAP, and —261 to —267 m NAP. The highest permeability may be found in the middle interval. The entire zone has been affected by karstification which is more or less stratabound since circulation losses in Thermae 2000 and Thermae 2002 occurred in the same layers. Calcite-filled joints appear to be common.

3.1.2. Middle zone (—195 to —115 m NAP)

Limestones and sometimes completely silicified limestones predominate. Minor circulation losses occurred, but cannot be correlated between the two wells. Therefore these are not stratabound as in the lower zone. Presumably groundwater only moves through joints. Karst cavities (if present) are only small and largely filled with sulfide minerals. Authigenic calcite is rare. These finds and also the results of the temperature measurements (chapter 4) indicate that the transmissivity in this zone is much lower than in the lower one.

3.1.3. Upper zone (—115 to —70 m NAP)

Black shales predominate. Between —90 and —70 m NAP these have been affected by lateritic weathering and pass upward in kaolinic paleosol. Circulation losses have not been observed. Thus this zone is assessed as only poorly pervious or rather as a confining interval. Along with the overlying, slightly sandy

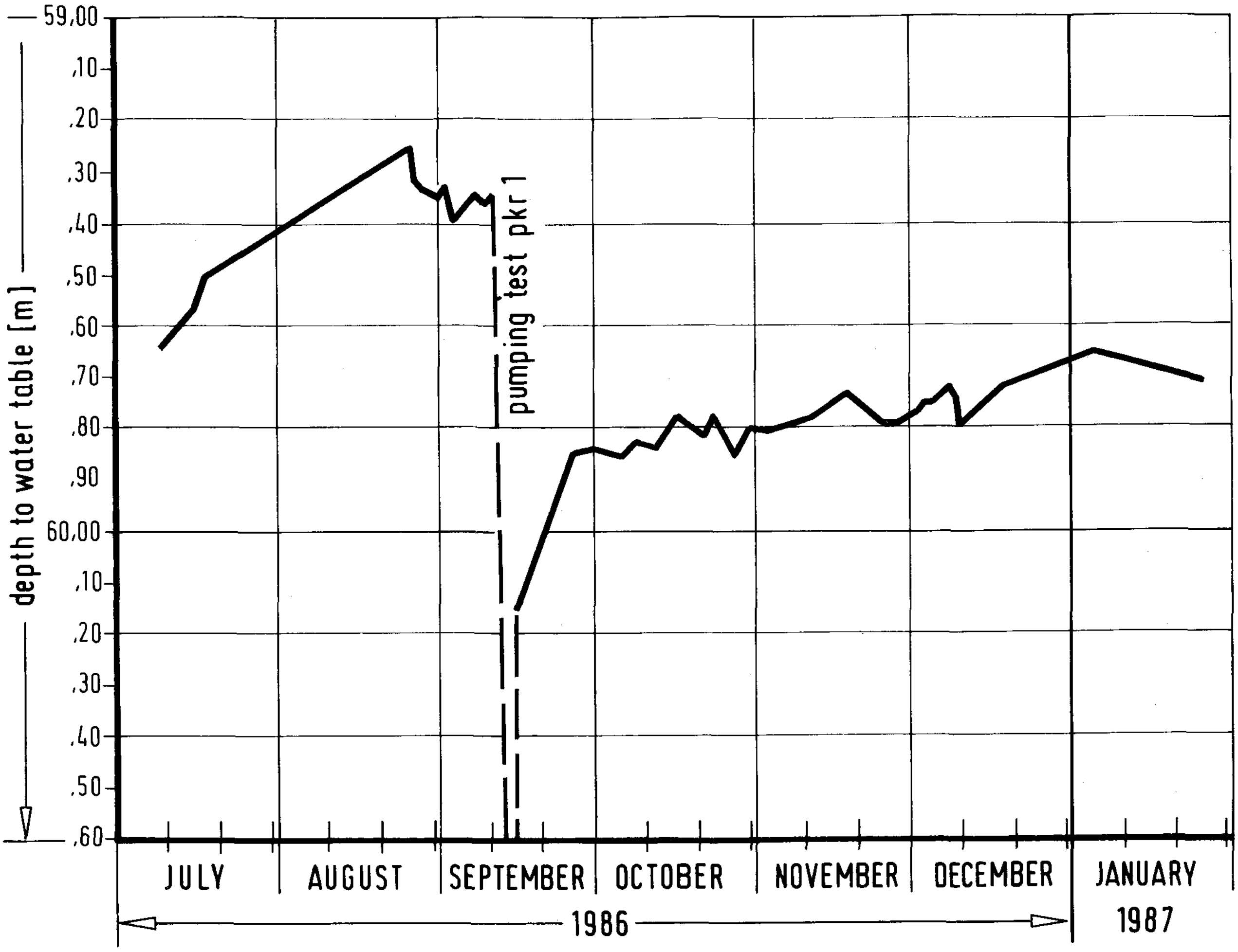

Figure 2 - Fluctuations of groundwater level of Cretaceous aquifer in Thermae 2001, measured between July 1986 and January 1987.

clays of the Aachen and Vaals Formations this upper zone separates the Dinantian and Upper Cretaceous aquifers.

3.2. HYDROGEOLOGICAL ASSESSMENT OF DINANTIAN AQUIFER

The groundwater of the Dinantian aquifer is clearly confined. Its piezometric surface is at +55 m NAP (some 125 m above the top of the aquifer). The direction of flow of the Dinantian groundwater between the two wells is to the NNE. The piezometric surface is 18 cm higher in Thermae 2000 than in Thermae 2002 (under stationary conditions). This points to a NNE flow direction with an extremely low dip of about 15 cm/100 m. This observation confirms the results of the Heugem and Kastanjelaan boreholes where the flow direction is clearly northward. And it also confirms the observation that the drainage area of the Dinantian aquifer is situated south of South-Limburg in the Herve region of Belgium.

The Dinantian groundwater level has been measured at regular intervals (in Thermae 2000 since May 1986 and in Thermae 2002 since November 1986 ; fig. 5). The piezometric surface in Thermae 2000 has been gradually lowered some 40 cm between June and December 1986, and then very slowly lowered about 10 cm more until the beginning of March 1987. A similar behaviour was noticed for the piezometric surface in Thermae 2002 since November 1986. The original difference between the groundwater tables in Thermae 2002 and Thermae 2000 was 25 cm. This difference decreased to only 1-2 cm since December 2nd 1986 as a consequence of pumping tests in Thermae 2002. The piezometric surface in Thermae 2002 did not rise again to its originally 24 cm higher level. This cannot be explained by the measurements and observations made thus far, but presumably it is produced by heterogeneity of the limestones because of differential karstification and the herewith connected variations in transmissivity and storativity. New measurements (April 1987) of the Dinantian groundwater table in Thermae 2000 and Thermae 2002 revealed a difference of 18 cm as explained above.

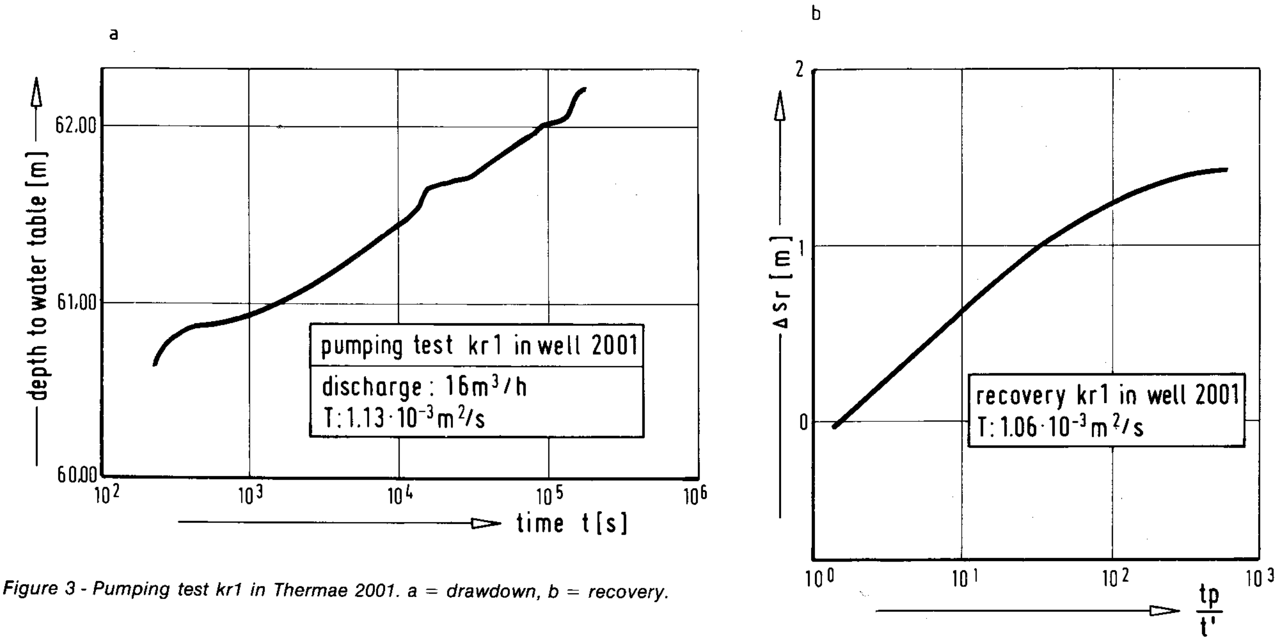

Figure 3 - Pumping test kr1 in Thermae 2001. a = drawdown, b = recovery.

3.3. AQUIFER PROPERTIES

Aquifer properties have been assessed by pumping tests and a recharge test. The usual methods have been applied for the interpretation of these tests (cf. Langguth & Voigt 1980, Kruseman & De Ridder 1970). Also stationary formulas have been used.

First of all it was established that an open connection exists between Thermae 2000 and Thermae 2002 since the water table of Thermae 2000 was influenced by the pumping test in Thermae 2002. A summary of the calculated values is presented in table IV. These indicate that the transmissivity varies between 1 x 10^{-3} m^2/s and 2 x 10^{-3} m^2/s. Noteworthy is the pumping test pc1, performed in the open hole of Thermae 2000, which yielded a value of 2 x 10^{-3} m^2/s (fig. 6). This matches a mean hydraulic conductivity for the 106 m long open hole interval of 2 x 10^{-5} m^2/s. Stationary conditions in pumping test pc1 were established after only some 300 seconds !

A pronounced, prolongated unstationary phase was observed in pumping tests with higher discharge rates (e.g. test pc3 in Thermae 2002 with Q : 48.6 m^3/h). Figure 7 shows two half-logarithmic straight lines. The first steeply rising line represents the drawdown within the well, whereas the second more slowly rising line indicates the unstationary regime of the Dinantian aquifer and allows the assessment of the transmissivity (Strayle 1983), which is about 1.24 x 10^{-3} m^2/s. This matches a k-value for a 40 m long filter of 3.1 x 10^{-5} m^2/s.

Because of the test conditions it was impossible to establish the storavity values. However a recharge test in Thermae 2002 has yielded some information. Because of the important circulation losses below

346 m some 12 m^3/h water had to be added continuously to the mud fluid. At the same time the rise of the water table in Thermae 2000 was measured. The thus calculated transmissivity of 6.04 x 10^{-3} m^2/s was four times higher than in pumping test pc3, whereas the storage coefficient was 7.09 x 10^{-3}.

3.4. HYDROCHEMISTRY

The Dinantian groundwater of Thermae 2000 and Thermae 2002 contains some 3.5 g/l (≙ 108 epm) dissolved solids. This means that it fulfils the legal conditions of the European Economic Community (EEC) and of the Netherlands for recognition as natural mineral water (Anonymous 1985).

The temperature measured at the orifice of the wells also allows to consider this as thermal water (tables II and III).The principal cation is sodium (> 80 epm%), whereas chloride is the dominant anion (about 80 epm%). Therefore - in agreement with common usage - this is a Na-Cl-thermal water. Important cations are also calcium (11 epm%) and magnesium (6 epm%), whereas bicarbonate (15 epm%) and sulfate (6 epm%) should be mentioned among the anions. However these values are below the limit of 20 epm% for characterization of the mineral water.

The iron contents (0.5 mg/l) is low. Remarkable is the relatively high ammonium content (3.4 mg/l) that may be of geogenic origin. Presumably the organic-rich

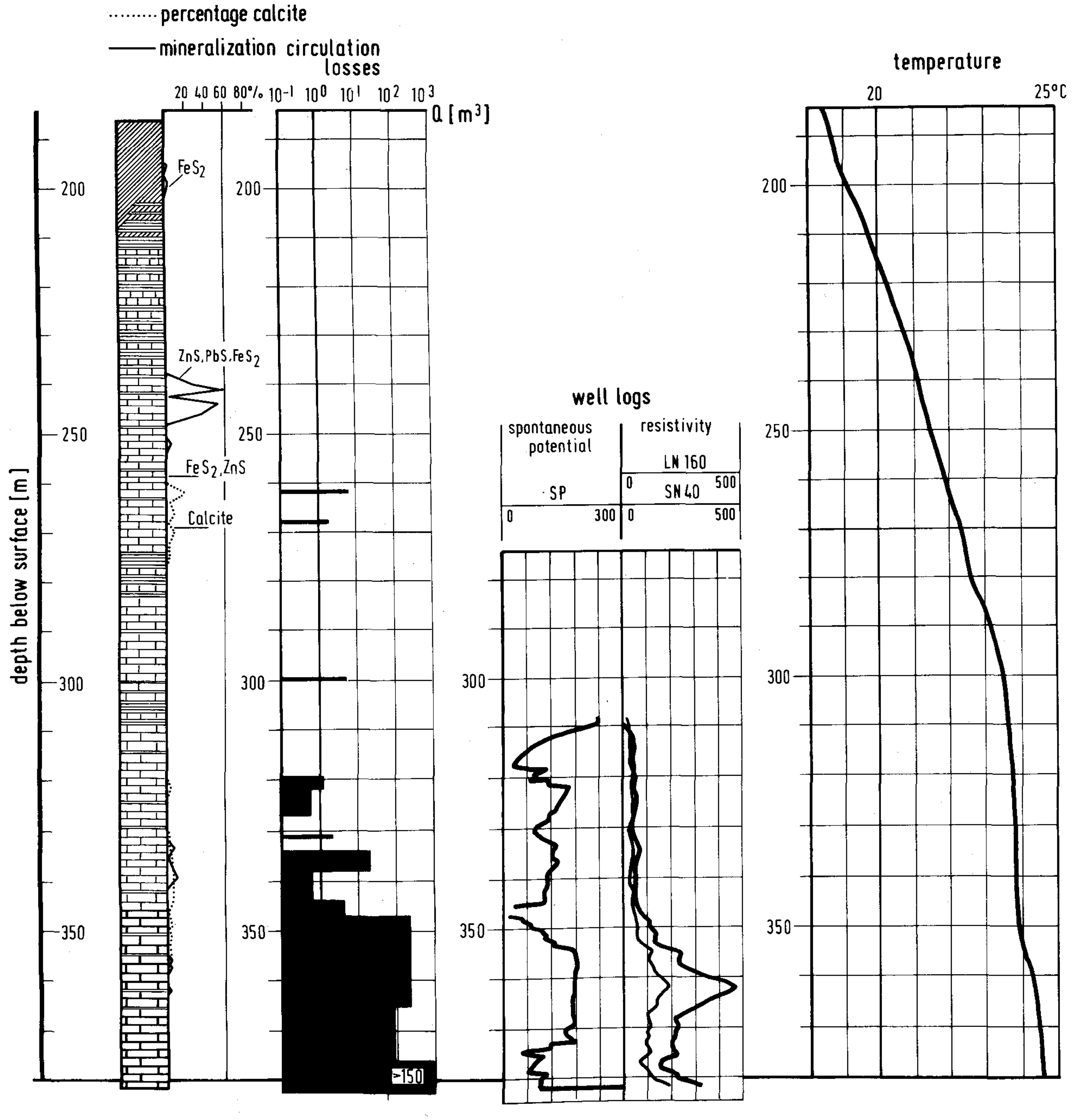

Figure 4 - Relationship between parameters used for qualitive assessment of permeability in the Dinantian rocks.

Dinantian shales and limestones (Bless et al. 1981) form the source for the ammonium. Oxidized nitrogen compounds occurring as nitrate and nitrite are rare. Along with the low oxygen content (1 mg/l) these indicate reducing conditions of the water.

The fluoride content (2.0 mg/l ; Bless et al. 1986) is above the Dutch (1 mg/l) and German (1.5 mg/l) characterization limits. Therefore the mineral water might be denominated as fluoride-containing.

Fluctuations in the temperature and conductivity during pumping test pc4 are shown in figure 8. The temperature remained virtually constant. Temperature rised from 24.3°C in the beginning (March 5th 1987) to 24.4°C after three days pumpage. It stayed at this value until the end of the test on March 20th 1987. At the beginning of the pumping test the conductivity was 4810 μS/cm. This value slightly decreased with some small fluctuations until it stabilized after three days at 4650 μS/cm. Most likely, later fluctuations of some 70 μS/cm are due to the apparatus used and to temperature variations.

Table II - Hydrochemistry of the Dinantian aquifer in Thermae 2002. Data RWTH Aachen. Sampling date 4-12-1986.

temperature (°C) : 23,5
pH : 6,8
electrical conductivity (μS/cm) : 5280

cations				anions			
	mg/l	epm	epm%		mg/l	epm	epm%
Na^+	1014	44,11	81,82	Cl^-	1499	42,27	78,80
K^+	49	1,25	2,32	HCO_3^-	497	8,14	15,18
NH_4^+	3,1	0,17	0,32	NO_3^-	0,1	0,0	0,0
Ca^{2+}	112	5,99	11,11	NO_2^-	0,03	0,0	0,0
Mg^{2+}	29	2,38	4,41	SO_4^{2-}	155	3,23	6,02
Fe_{tot}	0,33	0,01	0,02	PO_4^{3-}	n.a.		
Mn_{tot}	n.a.						
Σ	1207,4	53,91	100	Σ	2151,1	53,64	100

total hardness (°dGH) : 22,5
SiO_2 (mg/l) : 10,9

4. TEMPERATURE MEASUREMENTS IN THERMAE 2002

A temperature survey in a borehole may be helpful for the hydrogeological interpretation. Drilling activities change the original temperature of the rocks. However, according to Kappelmeyer (1985) the original temperature is restored after some two months. Figure 9 shows the temperature profile in Thermae 2002, measured 63 days after completion of the well. It reveals between 65 m (piezometric surface of Dinantian groundwater) and 290 m a temperature rise from 13.0 to 23.2°C. This corresponds with a relatively high mean gradient of 4.57°C/100 m. Between 290 m and 310 m the temperature gradient slowly decreases until it amounts only some 1.18°C/100 m between 310 and 381.5 m (total depth). The temperature at total depth is 24.5°C.

The temperature curve in figure 9 suggests fast ascendant movement of warm water from deeper sources. The rather high thermal gradient in the impervious or less permeable strata above the karstified zone is caused by the piling effect of these strata.

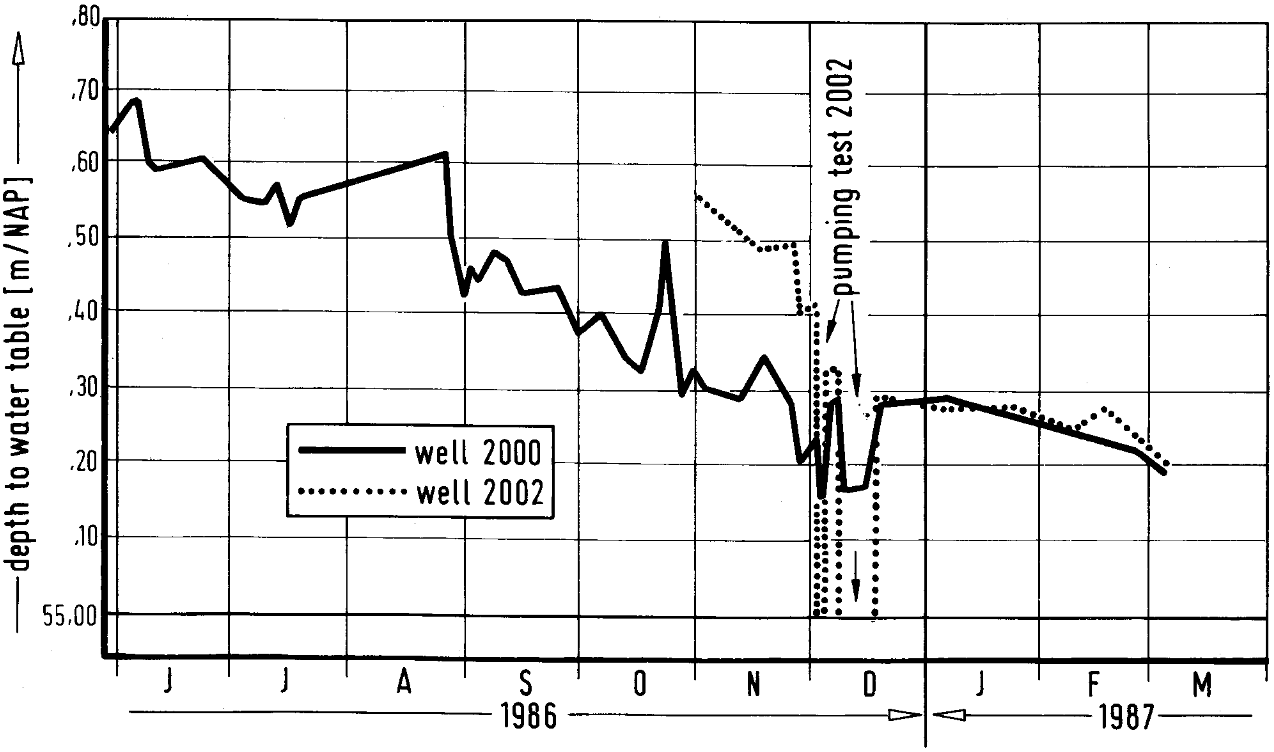

Figure 5 - Fluctuations of groundwater level of Dinantian aquifer in Thermae 2000 and Thermae 2002.

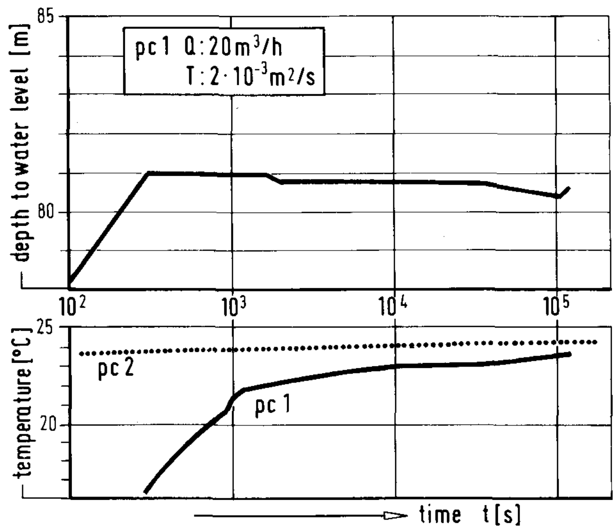

Figure 6 - Pumping test pc1 in Thermae 2000 and fluctuations of discharged water in pc1 and pc2.

This results in an apparently anomalous temperature which according to the thermal gradient of 3°C/100 m in South-Limburg (Sadée 1975) should be found at a depth of 500 m below the surface. The low temperature gradient below 310 m matches the interval with maximum circulation losses where the SP log points to a highly permeable zone within the Dinantian limestones.

The temperature profile of Thermae 2002 has been disturbed by the circulating mud fluid during drilling. This produced relative heating in the upper portion of the hole and cooling in the lower part. Figure 10 shows three temperature curves of Thermae 2002 which have been measured respectively 4 days (t1), 18 days (t2) and 63 days (t3 ; cf. also fig. 9) after finishing drilling and pumping tests.

Profile t1 in figure 10 clearly indicates that the rather cool mud fluid has deeply penetrated the karstified zone between 300 and 350 m. The increase of the temperature between 350 m and total depth is explained by the fact that in that interval the time available for this cooling effect was much shorter.

The recovery of the temperature to original rock temperature is shown especially well in the interval below 300 m in the profiles t1, t2 and t3.

5. COMPARISON OF HYDRAULIC REGIMES IN THE CRETACEOUS AND DINANTIAN AQUIFERS

For the exploitation of the wells it is vital to know whether there exist any hydraulic connections between the Cretaceous aquifer and the Dinantian one. Therefore the following parameters are used :
— assessment of the permeability of the various lithologies,
— results of pumping tests, and
— measurements of tritium contents.

The strata separating these aquifers have been described in detail in chapters 2.1 and 3.1. The slightly sandy clays of the Aachen and Vaals Formations and the kaolinic paleosol plus the Dinantian black shales have been interpreted as an aquitard. The thickness of this interval is more or less the same in Thermae

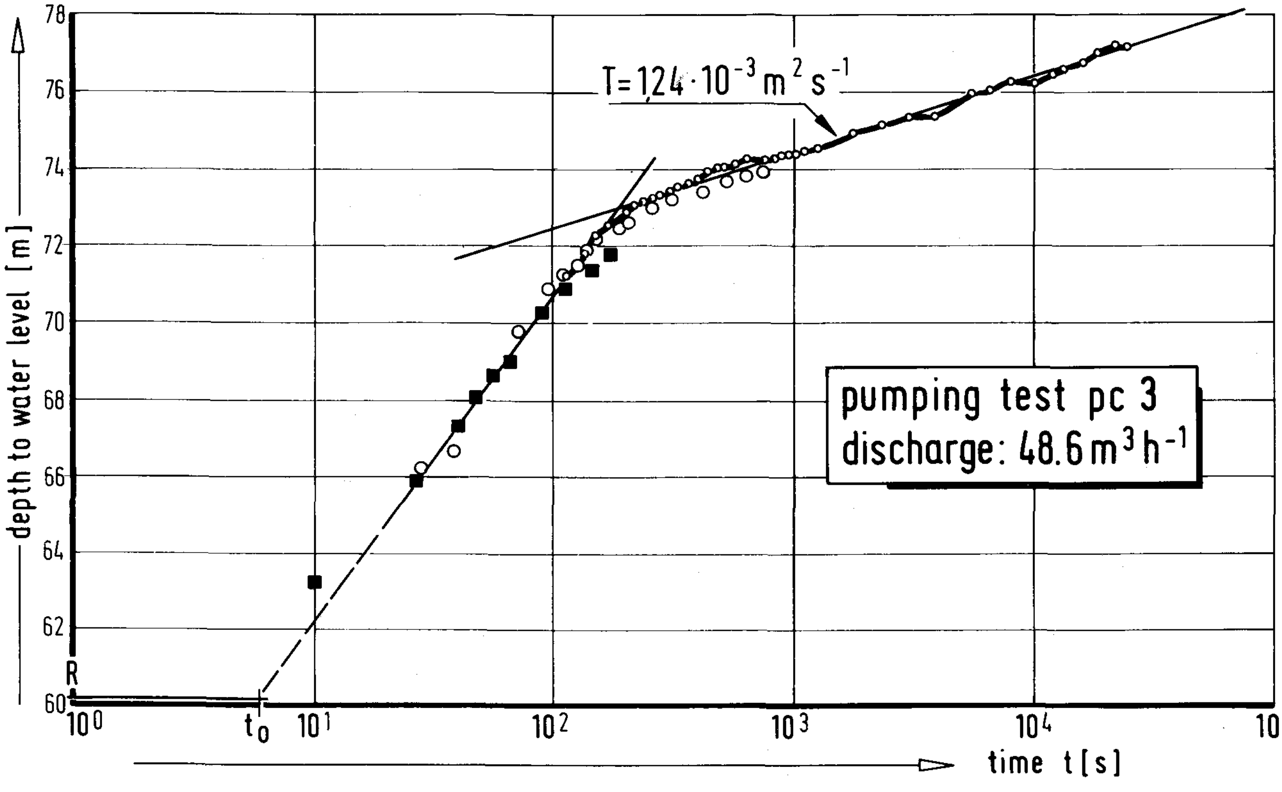

Figure 7 - Pumping test pc3 in Thermae 2002.

Table III - Hydrochemistry of the Dinantian aquifer in Thermae 2002. Data Institut Fresenius, Taunusstein. Sampling date 18-03-1987. Nitrite, dissolved oxygen and phenols were not detectable. Microbiological examinations did not yield any colonies after 20 and 44 hours on gelatin (20° C) and agar (20° C and 37° C). Tests for Escherichia coli, coliforms, faecal streptococci, Pseudomonas aeruginosa (in 250 ml) and sulfite reducing spore forming anaerobes (in 50 ml) were all negative. Fresenius' assessment is that «the tested samples are unobjectionable. They are also in accordance with paragraph 4, sect. 1 and 2 of the mineral- and table-water regulation of the Federal Republic of Germany».

Temperature of the water	24.5 °C
pH-value during the sampling and 24.5°C water temperature	7.25
Electrical conductivity (25°C)	5.80 mS/cm
Redox potential during the sampling and 24.5°C water temperature (Pt//Ag/AgCl-Electr.)	- 175 mV

	Mass concentration mg/l	Equivalent concentration meq/l	Equivalent percentage %
Cations			
Lithium (Li^+)	1.80	0.2594	0.45
Sodium (Na^+)	1083	47.11	82.10
Potassium (K^+)	49.7	1.271	2.21
Ammonium (NH_4^+)	3.6	0.1996	0.35
Magnesium (Mg^{2+})	37.1	3.053	5.32
Calcium (Ca^{2+})	107	5.339	9.30
Strontium (Sr^{2+})	6.2	0.1415	0.25
Barium (Ba^{2+})	0.061	0.0009	-
Manganese (Mn^{2+})	0.058	0.0021	-
Iron (Fe^{2+})	0.15	0.0054	0.01
Total		57.38	100
Anions			
Fluoride (F^-)	2.00	0.1053	0.18
Chloride (Cl^-)	1622	45.75	79.67
Iodid (I^-)	0.1	0.0008	-
Nitrate (NO_3^-)	0.77	0.0124	0.02
Sulphate (SO_4^{2-})	155	3.227	5.62
Hydrogenphosphate (HPO_4^{2-})	0.05	0.0010	-
Hydrogencarbonate (HCO_3^-)	508	8.33	14.51
Total	3577	57.43	100
Undissociated Substances			
Silic acid (meta) (H_2SiO_3)	15.1	0.193	
Boric acid (HBO_2)	4.7	0.107	
Total	3597		
Gaseous Substances			
Free dissolved carbon dioxide (CO_2)	51	1.16 = 25.8 ml at 0°C and 1013 hPa	

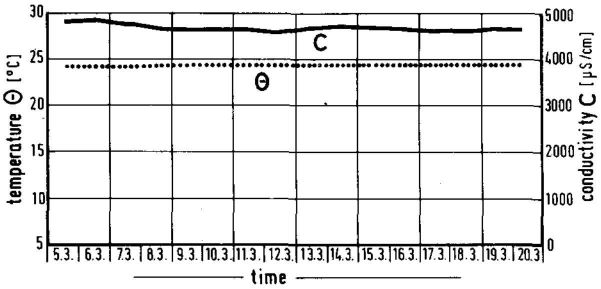

Figure 8 - Variation in temperature and electrical conductivity of discharged water from Thermae 2002 during pumping test pc4 between March 5th and March 20th 1987.

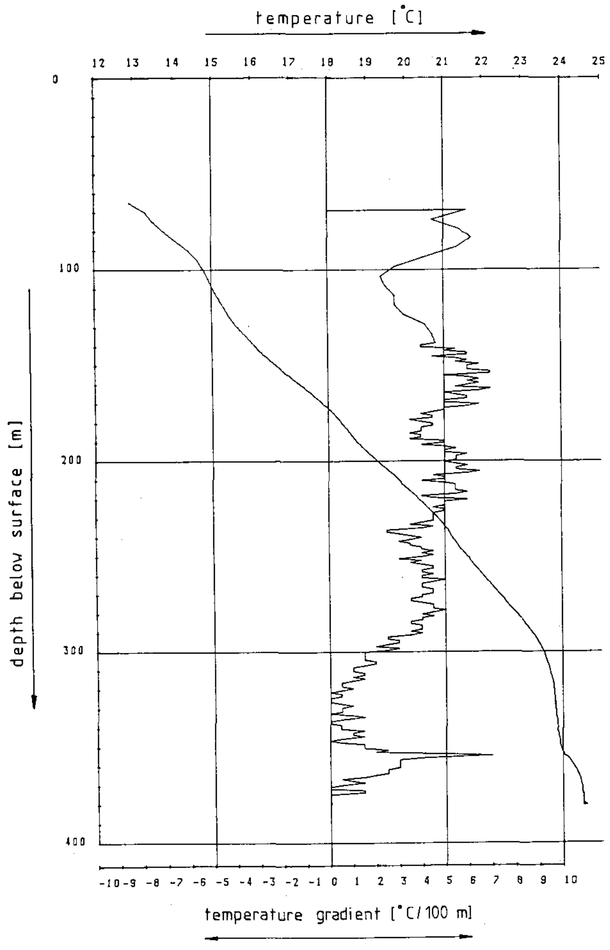

Figure 9 - Temperature log of Thermae 2002 measured 63 days after finishing drilling and pumping tests.

2000 and Thermae 2002 (cf. fig. 1). Wedging of these strata may only occur at some distance from the Thermae boreholes.

During pumping tests in Thermae 2002 the groundwater table of the Cretaceous aquifer in Thermae 2001 has been frequently measured. No measurable drawdown could be recognized.

During pumping test pc4 in Thermae 2002 three samples have been taken at different moments for ana-

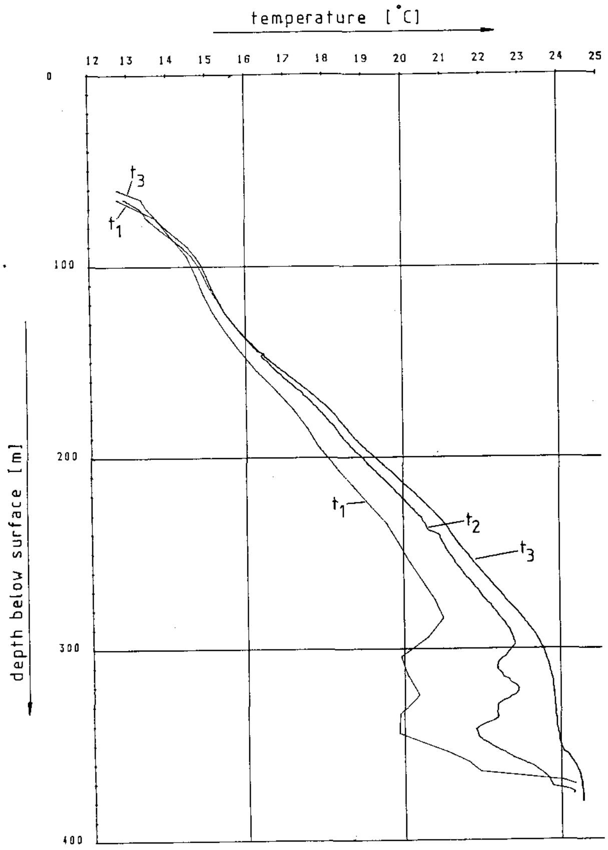

Figure 10 - Temperature profiles of Thermae 2002 measured at different moments after finishing drilling and pumping tests. t1 = 4 days, t2 = 18 days, t3 = 63 days.

Table IV - Aquifer properties of the Dinantian limestones in Thermae 2002. Data RWTH Aachen.

no. of test p=pumping r=recharge	well	Q	T	S	fig.
		m^3/h	m^2/s		
pc1	2000	20,0	$1,98 \times 10^{-3}$	-	6
pc2	2000	20,0	-	-	-
pc3	2002	48,6	$1,24 \times 10^{-3}$	-	7
pc4	2002	29,7	$1,69 \times 10^{-3}$	-	-
rc1	2002	12,0	$6,04 \times 10^{-3}$	$7,09 \times 10^{-3}$	-

Table V - Preliminar results of analysis of tritium and $\delta^{18}O$ in water from the Cretaceous aquifer in Thermae 2001 and from the Dinantian aquifer in Thermae 2002. The (low) tritium content in samples 2002-1 to 2002-3 is probably due to important circulation losses during drilling.

sample number	aquifer	Q	tritium content	$\delta^{18}O$
2001-1	Cretaceous	--	11.8 ±1.8 TU	--
2002-1	Dinantian	290 m^3	2.7 ±1.3 TU	--
2002-2	Dinantian	3360 m^3	3.0 ±1.3 TU	-8.6 ‰
2002-3	Dinantian	8740 m^3	2.1 ±1.4 TU	-8.57‰

lysis of their tritium contents. Also a sample from the Cretaceous aquifer has been taken. The samples have been analized in the Hydro-Isotop-Labor in Attenkirchen (near München). For the theoretical basis underlying the interpretation of isotope analysis the reader is referred to Moser & Rauert (1980). The results are shown in table V. As expected the water from the Cretaceous aquifer contains some tritium. This means that the groundwater in this aquifer has been mixed with water that infiltrated during the past 50 years. The confined Dinantian aquifer has yielded very low tritium values. These are probably due to the important circulation losses during the drilling which deeply penetrated the karstic fissures (cf. also interpretation of temperature profiles). If this interpretation is correct the tritium will gradually disappear after further pumping.

Summarizing the above observations we must conclude that there exists an hydraulic seal (aquiclude) between the Cretaceous and Dinantian aquifers in the environs of the Thermae boreholes.

6. CONCLUSIONS

Two aquifers have been recognized in the Thermae boreholes. The upper one is largely restricted to the Upper Cretaceous chalk and contains weakly mineralized groundwater. The deeper aquifer is formed by the Dinantian limestones. The mineralization of this water is higher (3.5 g/l TDS). According to the regulations of the Netherlands and the European Economic Community this is considered as a mineral water. The principal constituents are Na^+ and Cl^- (both about 80 epm%). Because of the temperature of 24.4°C at the orifice of the well this is also a thermal water.

The two aquifers are separated by an about 60 m thick sequence of slightly sandy clays at the base of the Cretaceous and a kaolinic paleosol and black shales on top of the Dinantian. The lithology of this sequence, pumping tests and tritium analysis of the groundwater from both aquifers indicates that this interval forms an aquiclude in the environs of the Thermae boreholes.

Permeability in the Dinantian aquifer is only high in the lower portion (below —197 m NAP) of the wells. This is established by the high transmissivity (1 to 2 x 10^{-3} m^2/s) of that interval, that has been caused by the karstification of the Dinantian limestones.

The temperature at total depth (381.5 m) is 24.5°C in Thermae 2002. This temperature would have been expected at a depth of 500 m bore depth because of the normally occurring temperature gradient of 3°C/100 m. Ascendance of warm water from that depth of about 500 m has caused the apparent thermal anomaly in the Thermae boreholes.

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