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PUMPING TESTS AND HYDROGEOLOGICAL INVESTIGATIONS OF AN ARTESIAN AQUIFER NEAR HORSENS, DENMARK

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In the Egebjerg area, near Horsens, several aquifers consisting of glacial outwash material deposited in a glacial eroded buried valley in the Tertiary formation have been encountered.

The lowest of these, which is the main productive aquifer, and which has leaky artesian conditions, has been investigated. The thickness of this aquifer varies from 10-40 m. The lower confining bed consists of boulder clay or meltwater clay underlain by boulder clay. The upper confining bed, where leakage occurs, consists of meltwater clay with thickness from 0 to 5 m. The upper meltwater deposits include a sequence of interglacial lake deposits and several layers or laminae of clay, which separate this water-bearing material into more aquifers with watertable or artesian conditions. In the eastern part of the area boulder clay deposits are found at the top of the sequence.

The Theis modified non-equilibrium equation and its derived formula for the non-steady-state leaky artesian case have been used to determine aquifer properties from pumping test data. By means of Jacob's method and a logarithmic method, well characteristics are determined graphically. Barometric efficiency, reverse fluctuations, and boundary conditions are recorded and discussed.

As a result of an increasing demand for ground water for public use the Municipal Water Supply Department of Horsens requested the Hydrogeological Department of the Geological Survey of Denmark to make an investigation in the area of Egebjerg, where a new water plant would be built if sufficient ground water was available. The purpose of the investigation was therefore to determine whether the aquifer is able to yield the required quantity of water.

The investigations included a geoelectrical survey and pumping tests. The pumping test procedure used has been practised in different areas with fair results by the Geological Survey of Denmark since 1967.

In September 1968 the Geological Survey of Denmark began investigations in the area; and in cooperation with the Municipal Water Supply Department of Horsens a pumping test programme on existing wells was carried out by the writers. A geoelectrical survey was carried out by Niels Viggo Jessen from the Geological Survey of Denmark.

DRILLING OF WELLS

The drilling of boreholes, necessary for supplying the town with water, started early in 1965. Up to now 12 boreholes (Horsens Municipal, file Nos. 51-62) have been drilled. Fig. 1 shows the position of the wells. All boreholes except No. 54 are constructed as wells. For drilling, the cable tool technique has been used. Selected data about constructed wells, reported by the driller, are shown in Table 1.

WITHDRAWAL FROM THE AREA

Pumping from the Egebjerg area increased with the number of wells, and in 1966 Wells 51, 52, 53, 55, 56, 57, 59, and 60 were discharging. On account of small capacity, Well 58 has not been included. Yields and specific capacities of discharged wells are shown in Table 2. The quantity of water pumped from the wells during 1966, 1967, and the first half of 1968 was approximately 330 m^3/h or 2.8 million m^3 per year. In the second half of 1968 the new Wells 61 and 62 increased the total capacity to 420 m^3/h or 3.6 million m^3 per year, but up to now these two wells have not been used for water supply. The future water demand of the town is estimated to be 750 m^3/h or 6.6 million m^3 per year, which is nearly twice as much as is pumped today.

Before the beginning of the investigation, in September 1968, Wells 52 and 53 were shut down on account of their relatively small capacities.

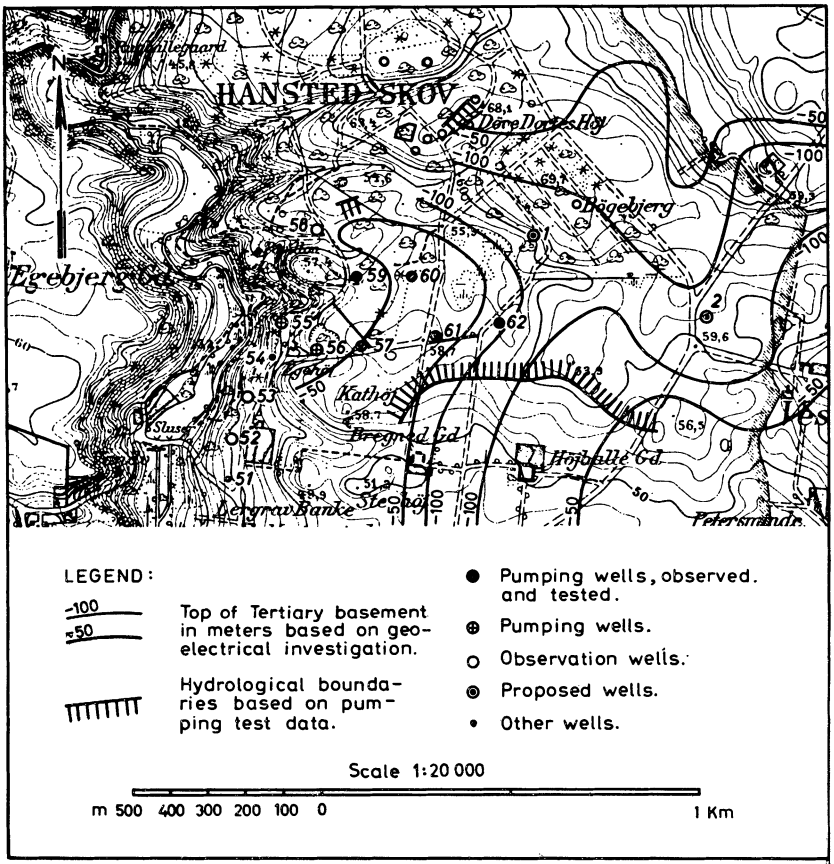

Fig. 1.

Egebjerg area, Horsens, Denmark. Investigation map. (Segment of M. 2812 on the scale of 1:20.000.) Copyright Geodetic Institute.

GEOLOGY AND HYDROGEOLOGY OF THE AREA

The investigated area (see Fig. 1) is located 5 km north of the town Horsens, East Jutland. This part of Denmark was covered by three glaciations during the Quaternary. A great number of tunnel valleys divide the eastern part of Jutland into several moraine plateaus. The investigated area is situated on such a plateau. A small stream has cut a narrow valley in the plateau just west of

Table 1.
Selected data about wells in Egebjerg area, Horsens, Denmark

Horsens Municipal file No.	D.G.U. file No.	Diameter (inches)		Top of casing (m)	Ground level (m)	Aquifer (m)				Screen (m)			Bottom of well (m)
		Temporary casing	Casing & screen			Top	Bottom	Thick-ness	Piez. surface	Top	Bottom	Length	
52			10	+30.65	+31.51	+15.01	— 4.51	11.50	+16.76	— 7.51	+ 4.51	3.00	—12.49
53		14 (–12.6)	10	+32.51	+33.27	+ 8.65	—12.60	21.25	+16.57	— 4.60	—12.60	8.00	—51.10
		12 (–51.1)											
54				+37.80	+36.86	+18.86	+12.36	6.50		+17.36	+15.36	2.00	— 7.64
55		14	10	+41.49	+42.43	+12.90	— 2.10	15.00	+23.08	+10.90	+ 4.90	6.00	— 9.10
56		14	10	+46.61	+47.51	+11.01	— 6.99	18.00	+23.11	+ 3.51	— 6.49	10.00	—11.79
57		14	10	+57.60	+58.31	+ 5.31	—10.69	16.00	+27.06	— 0.69	—10.69	10.00	—11.69
58		14	10	+48.08	+47.86	+39.36	+ 6.86	32.50	+25.06	+12.36	+ 7.36	5.00	— 2.14
59		14 (– 6.5)	10	+54.74	+55.50	+21.00	— 3.50	24.50	+25.80	+ 6.50	— 3.50	10.00	—30.00
		12 (–30.0)											
60		14	10	+54.36	+56.90	+ 8.40	— 6.10	14.50	+27.90	+ 3.90	— 6.10	10.00	—12.10
61	107.517	14	10	+58.57	+58.43	— 1.17	—22.57	21.50	+24.03	— 7.57	—22.57	15.00	—36.57
						—29.57	—34.07	4.50		—30.57	—34.57	4.00	
62	107.553	14	12	+58.39	+57.33	— 1.67	—10.67	9.00	+26.83	— 1.67	—14.67	13.00	—80.67
						—19.67	—43.17	23.50		—19.67	—37.17	17.50	

Table 2.
Yields and specific capacities of discharged wells, in Egebjerg area

Horsens Mun. file No.	Well finished (year)	Yield (m^3/h)	Specific capacity (m^3 per h/m)	Discharged wells for water supply during pumping test investigation
51	–	–	–	+
52	1965	18	2.0	—
53	1965	37	3.9	—
54	1965	–	–	—
55	1965	35	4.1	+
56	1965	48	3.8	+
57	1965	62	9.8	+
58	1965	13	2.2	—
59	1965	67	14.4	+
60	1965	69	13.6	+
61	1968	67	6.3	—
62	1968	72	6.1	—

the well field. The bottom of the valley is about 10-15 m, and the elevation of the plateau is about 30 to 60 m above sea-level.

Knowledge of the geology of the area is based on previous geological investigations (Harder 1908, Jessen & Milthers 1928, Milthers 1948), on driller's logs from the 12 boreholes drilled by Erik Mortensen, Lund, and on samples from Wells 61 and 62. The top of the Tertiary bedrock as determined from the results of the geoelectrical survey is indicated by the contours on the map, Fig. 1. The agreement of the drilling data and geoelectrical data seems to be rather good.

Fig. 2 shows a compilation of well records, except for Well 58, and the top of the Tertiary bedrock, as based on the geoelectrical measurements. It appears from the block diagram that Tertiary deposits are encountered in Wells 53 and 62, where the deposits consist of plastic clay or clayey marl of Eocene-Upper Oligocene age, Littlebelt Clay, and Søvind Marl, respectively. The strata above the Tertiary belong to the Quaternary and include a sequence of boulder clay, meltwater sand and gravel, meltwater clay, and silt as well as lake deposits of interglacial age, interbedded in the glacio-fluvial sands and gravels. The lower part of the Quaternary is composed of glacial drift, mostly boulder clay, with subordinate beds or lenses of meltwater deposits without aquifers of impor-

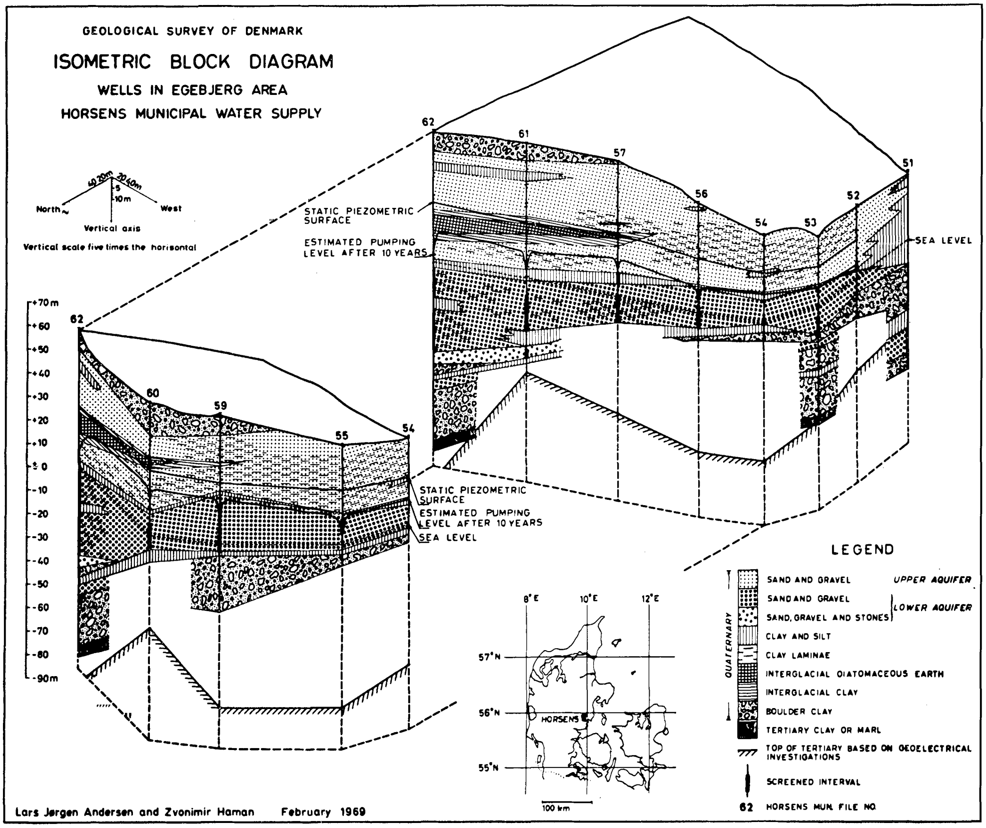

Fig. 2.

Isometric block diagram based on well records, Egebjerg area, Horsens, Denmark.

tance. Above the boulder clay is a meltwater sequence of fine to medium sand with sporadic gravel. At the bottom of this meltwater sequence, coarse material of sand, gravel, and stone has been locally encountered (see Fig. 2, Wells 61 and 62). The sand and gravel deposits compose the main aquifer. The total thickness is about 40 m in NE, decreasing to about 10 m in SW. This aquifer is mostly covered by the bed of meltwater clay, partly silty, with a thickness of from 5 to 0 m in a SW direction. Above this semi-confining bed, an upper melt-water sand layer is found. Its total thickness, including interglacial lake deposits, is about 45 m. From below, the interglacial sequence comprises some metres of dark, silty clay, about 10 m of diatomaceous earth, followed by some metres of dark silty clay. The thickness of the lake deposits decreases to the west; and west of the Wells 56 and 55, no lake deposits have been encountered. The age of these deposits has not been determined. However, from the stratigraphic position between two beds of boulder clay, it may be concluded that they are of interglacial age. The clay and the diatomaceous earth both have a high moisture content, and they are highly compressible. Furthermore, clay beds with a thickness of a few metres have been recorded in the upper meltwater sequence, and clay lenses or clay laminae are widely distributed here. Boulder clay up to 10 m thick covers the eastern part of the investigated area. Erosion in Late-glacial and Post-glacial time has possibly removed the boulder clay together with some part of the upper aquifer in the western section of the area, where the ground surface slopes rather steeply down to a small stream.

The interglacial deposits, the clay beds and clay laminae of low permeability, divide the meltwater sequence in separate aquifers. The aquifer below the interglacial deposits is confined, and the aquifers above are perched with water tables above the piezometric surface of the deeper groundwater reservoir.

This geological sequence opens possibilities to barometric efficiency and leakage into the main aquifer. Both phenomena have been observed and taken into consideration during the pumping tests and the analysis of data.

PUMPING TEST PROCEDURE

The pumping tests in the Egebjerg area have been impeded by the fluctuations of the piezometric surface produced by the cyclic pumping from the wells, which supply the town with water. Before the pumping tests could be started, it was therefore necessary to establish a dynamic equilibrium by continuous constant pumping from each well, started in August 1968. An automatic water-level recorder combined with a barograph was installed in Well 61 for registration of water level and atmospheric pressure. About one month later, the fluctuations of the piezometric surface in Well 61 corresponded to the changes of atmospheric pressure, which means that dynamic equilibrium had been approached. To get an impression of the interferences among the wells, preliminary investigation was done by shutting down the wells one by one, and all wells were shut down for 37 hours. The total recovery was measured and correlated with the original static piezometric surface, measured at that time when the wells were drilled. However, the shut-down period was too short to reach the original piezometric surface. Therefore, there are discrepancies among the recorded data and the driller's data for all wells. However, the differences were smaller in Wells 61 and 62 owing to the fact that the driller's data were influenced by the existing pumping before drilling of these two wells.

Due to the fact that pumping from all existing wells, but one, was necessary to supply the town with water, the general procedure for the pumping test of each well was as follows, (1) the well chosen for the pumping test was shut down, (2) the discharges of all other pumping wells were maintained constant, (3) the recovery rate of the water levels in the stopped well and in the surrounding discharge and observation wells was measured, (4) when the water-level fluctuations in the wells were caused only by changes in atmospheric pressure the tested well was pumped again, (5) the capacity of the well and the drawdowns in all wells were observed, taking care that the discharge from all wells was maintained constant at all times. The duration of the different pumping tests and the discharge capacities are given in Table 3.

In all discharging wells the water levels were measured by electrical tape instruments with an accuracy of 1 cm, and during all tests four automatic water-level recorders of type R 16, manufactured by A. Ott, were used in different wells. The measuring point was everywhere the top of the casing. The discharge capacities during the pumping test were measured as a unit volume of water through a flow meter, and the flow time was registered by a stopwatch. The discharged water was pumped through pipelines to the town or into storage to prevent reinfiltration of water into the aquifer.

Table 3.
Pumping tests, duration, and discharge

Horsens Municipal file No.	Constant discharge rate pumping test			Step-drawdown pumping test		
	Date	Duration (hrs)	Discharge (m^3/sec)	Date	Number of steps	Duration (hrs)
60	22/9 – 23/9	24	1.92×10^{-2}	–	–	–
59	1/10 – 3/10	56	1.86×10^{-2}	–	–	–
57	7/10 – 10/10	68	1.71×10^{-2}	13/10	4	4
61	19/10 – 23/10	94	1.85×10^{-2}	16/10	4	4.25
60	24/10 – 5/11	293	1.92×10^{-2}	23/10	4	4
62	2/12 – 13/12	263	2.05×10^{-2}	29/11	5	5.25

HYDRAULIC CHARACTERISTICS OF THE AQUIFER

Barometric efficiency

Prominent changes in air pressure are compared with the changes in the water level during the period of equilibrium and used for computation of the barometric efficiency of each well. Fig. 3 shows as an example computation of the barometric efficiency for Well 62. The following equation is used:

$$BE = \frac{\Delta W}{\Delta P} \cdot 100 \text{ per cent} \qquad (1)$$

BE ≡ barometric efficiency, in per cent

ΔW ≡ change in water level resulting from a change in atmospheric pressure, in cm

ΔP ≡ change in atmospheric pressure, in cm of water

Table 4 gives BE-values for the respective wells.

Drawdown data are adjusted for barometric efficiency according to atmospheric pressure changes during the pumping test by means of the following equation:

$$\pm \Delta W = \frac{(BE)\, \Delta P}{100} \text{ cm} \qquad (2)$$

where symbols are defined as previously.

The barometric efficiency (BE) can be referred to elasticity of the aquifer and the water and to the competence of the confining bed to resist pressure

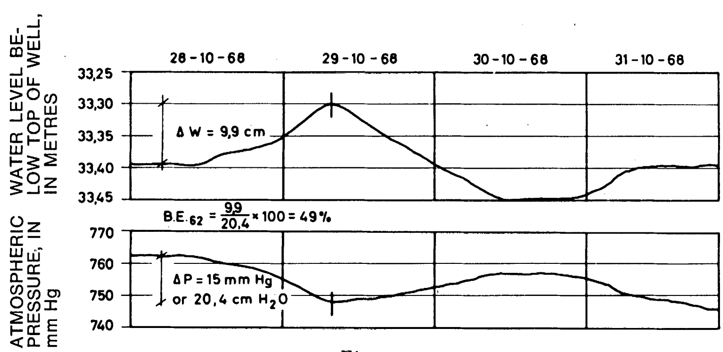

Fig. 3.

Hydrograph of Well 62, atmospheric pressure and barometric efficiency (BE).

Table 4.
Barometric efficiency (BE) in wells, Egebjerg area, Horsens, Denmark

Horsens Mun. well file No.	52	53	55	56	57	59	60	61	62
Barometric efficiency, in %	25	30	40	46	70	47	50	60	45

changes (Jacob 1940). The barometric efficiency can be referred also to the leakage from the confining bed. The BE-value will decrease with increasing aquifer elasticity and increasing leakage. Furthermore, the BE-value will increase with increasing competence of the confining bed. In cases of influence from leakage or competence of the confining bed, the barometric efficiency does not fully represent the aquifer properties. The variations in the determined BE-values (see Table 4) can possibly be explained by the above-mentioned parameters. However, the influence from each of them has, for the time being, not been outlined.

Reverse fluctuations

Reverse fluctuations of water level have been observed both in the pumping wells and the observation wells. In the pumping wells the drawdown ceased after some minutes of pumping, and the water level even rose during a few minutes before the drawdown rate increased again. In the observation wells the same phenomena were observed, but the duration increased with the distance to the pumping well. The mentioned duration period in the observation wells is defined as the time from the start of pumping until the water level fell below static level. Therefore, the total duration of the reverse fluctuations is much larger than this value, but the influence of the reverse fluctuations is too difficult to separate in combination with drawdown, recovery, and leakage; therefore, the absolute duration period of the reverse fluctuations has not been measurable. Table 5 gives the relative duration and magnitude of reverse fluctuations in the respective observation wells during the pumping tests. Reverse fluctuations were earlier described by several authors (Thompson 1936, Andreasen

Table 5.
Relative duration and magnitude of reverse fluctuations during pumping tests

Pumping test, Well	Duration (min) and magnitude (cm) for observation Well																	
	52		53		55		56		57		59		60		61		62	
	min	cm	min	cm	min	cm	min	cm	min	cm	min	cm	min	cm	min	cm	min	cm
57					400	13	12	4			200	17						
59	3360	5	360	+	93	13	406	15	408	19								
60	17580	25	17580	60	365	13	190	20	90	22	75	20	+					
61			30	+	150	2					6	1			+	+		
62					316	2	30	1	20	2	90	2						

Table 6.

Data from pumping test on Well 61 and observation wells between 13^{00} on 19 October, and 11^{00} on 23 October 1968, Egebjerg area, Horsens, Denmark

Time (min)	Well 61				Well 62		Well 57		Well 60		Well 56		Well 53	
	Drawdown (m)		Discharge		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)	
	*	**	l	sec	*	**	*	**	*	**	*	**	*	**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.25	7.555													
0.50	8.505													
0.70	8.875													
1	9.015													
1.25	9.085													
1.50	9.120		100	5.2										
2	9.185		100	5.2										
2.5	9.285		100	5.2										
3	9.255		100	5.5			0.01							
3.5	9.210													
4	9.145		100	5.4			0.02							
4.5	9.135													
5	9.170		200	10.9										
5.5	9.195		100	5.5										
6	9.225		200	10.9			0.05							
6.5	9.245		200	10.8					0.055					
7	9.260		200	10.8										

7.5	9.295			0.004				
8	9.310				0.075			
8.5	9.285							
9	9.325	200	10.8					
9.5	9.385	100	5.4					
10	9.410	100	5.5		0.095			
10.5	9.430	1000	54.2			0.097		
11				0.014				
12	9.460	1000	54.0		0.115			
14	9.495	1100	59.2		0.135	0.127		
15				0.029				0.001
16	9.530	1000	54.0		0.155			
17								
18	9.555	500	27.0		0.170	0.150		
19				0.044				
20	9.580	1000	54.0		0.180			
21.5						0.169		
22.5				0.059				
23							0.030	
25	9.620	1000	54.3		0.210			
27							0.045	
29						0.195		
30	9.660	1500	81.1	0.099	0.235			0.000
32							0.055	

(Table 6, *continued)*

Time (min)	Well 61				Well 62		Well 57		Well 60		Well 56		Well 53	
	Drawdown (m)		Discharge		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)	
	*	**	1	sec	*	**	*	**	*	**	*	**	*	**
36.5									0.207					
37.5					0.127									
40	9.695		1000	54.2			0.255							
43											0.06			
44									0.217					
45					0.164								0.002	
50	9.720						0.265							
55											0.065			
59									0.232					
60	9.760		1000	54.0	0.211		0.275						0.004	
75					0.249		0.275		0.241					
78	9.775		1000	54.2										
90	9.785		1000	54.3	0.273		0.280		0.246				0.008	
97											0.070			
120	9.815		1000	54.2	0.307		0.300		0.251				0.010	
126											0.075			
150	9.845		1000	54.2	0.323		0.335		0.259					
156											0.080			

180	9.860	1000	54.2	0.334				0.262				0.013	
195						0.340							
200										0.090			
236												0.017	
240	9.880	1000	54.2	0.349				0.270					
245						0.345							
252										0.100			
300				0.359				0.279	0.278			0.023	
375										0.130	0.127		
377						0.380	0.376						
382	9.935	1000	54.2										
420				0.374	0.371			0.295	0.292			0.029	0.027
500										0.115	0.111		
505						0.345	0.338						
510	9.935	1000	54.1										
540								0.300	0.297			0.037	0.035
660				0.387	0.384			0.305	0.302			0.033	
680										0.135	0.131		
690						0.375	0.369						
700	9.970	1000	54.2										
900				0.389	0.388								
1020								0.315	0.317			0.037	
1165										0.155	0.157		

(Table 6, *continued*)

Time (min)	Well 61				Well 62		Well 57		Well 60		Well 56		Well 53	
	Drawdown (m)		Discharge		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)	
	*	**	1	sec	*	**	*	**	*	**	*	**	*	**
1170	10.015		1000	54.2			0.385	0.388						
1380					0.379	0.391			0.317	0.329			0.043	0.051
1517											0.175	0.199		
1520							0.400	0.436						
1525	10.060		1000	54.1										
1740					0.347	0.387			0.315	0.356			0.045	0.069
1905	10.070	10.067	1000	54.1										
1908											0.185	0.226		
1910							0.390	0.452						
2100					0.339	0.385			0.322	0.370				
2140													0.051	0.082
2460					0.339	0.389								
2500													0.055	0.088
2596											0.205	0.255		
2600							0.400	0.476						
2605	10.105	10.108	1000	54.0										
2820					0.364	0.412			0.368	0.421				
2860													0.065	0.097

2985							0.405	0.489			0.195	0.245		
2990	10.110	10.154	1000	54.2										
3180					0.377	0.424			0.380	0.438				
3220													0.071	0.102
3350											0.220	0.265		
3355	10.150	10.188	1000	54.2			0.410	0.479						
3540					0.404	0.447			0.395	0.443				
3580													0.077	0.106
3900					0.404	0.449			0.395	0.445			0.081	0.111
4037											0.255	0.301		
4040							0.45	0.52						
4050	10.195	10.243	1000	54.2										
4260					0.413	0.460			0.406	0.458				
4300													0.090	0.121
4430							0.435	0.513			0.245	0.296		
4485	10.205	10.253	1000	54.2										
4515									0.394	0.452				
4620					0.417	0.469								
4660			1000	54.2									0.093	0.128
4800									0.404	0.464				
4815							0.440	0.524			0.255	0.310		
4820	10.200	10.251	1000	54.2										
4980					0.424	0.479								
5020													0.097	0.134

(Table 6, *continued)*

Time (min)	Well 61				Well 62		Well 57		Well 60		Wel 56		Well 53	
	Drawdown (m)		Disharge		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)		Drawdown (m)	
	*	**	1	sec	*	**	*	**	*	**	*	**	*	**
5340					0.418	0.481								
5380													0.100	0.142
5470							0.475	0.575						
5530											0.295	0.361		
5538	10.240	10.306	1000	54.2										
5575									0.414	0.489				
5640					0.421	0.488								
5670									0.434	0.509				
5680													0.110	0.155

* Measured values.
** Values adjusted for barometric efficiency.

& Brookhart 1963) in connection with wells tapping two or more separate aquifers. The reverse fluctuations described here appeared in the main aquifer. A possible explanation of reverse fluctuations in this aquifer may therefore be due to the presence of thin clay lenses or widely distributed clay laminae in the aquifer.

Adequate explanation of this phenomenon does not exist at this time. A tentative explanation is that changes of the water level during stop or start of pumping imply re-arrangement in the aquifer skeleton and that the reverse fluctuations last until the skeleton reaches a new equilibrium. An adequate solution of this problem can also make possible application of such data for calculation of the hydraulic properties of aquifers.

Transmissivity (T), storage coefficient (S), and vertical permeability (P')

Data adjusted for barometric efficiency and without visible reverse fluctuations have been used for construction of the time-drawdown and distance-drawdown graphs. As an example, data from Table 6 are plotted on semi-logarithmic (Fig. 4 and 5) and logarithmic paper (Fig. 6 and 7) to illustrate the graphical solution.

For the semi-logarithmic time-drawdown graphs, Jacob's method has been used,

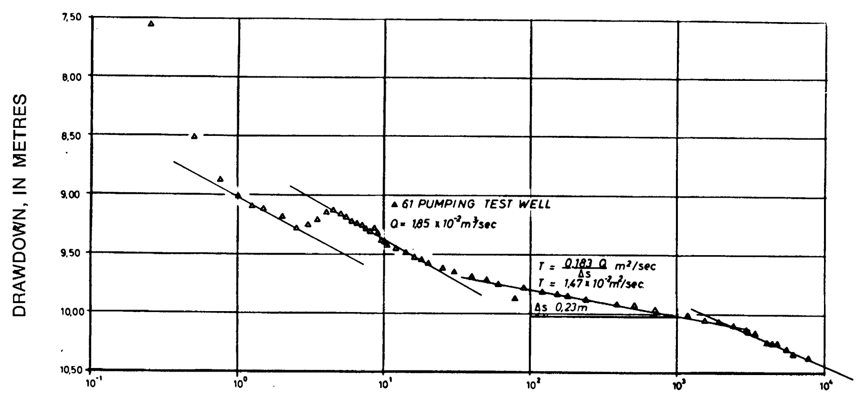

Fig. 4.
Time-drawdown graph for Well 61. Semilogarithmic plot.

7*

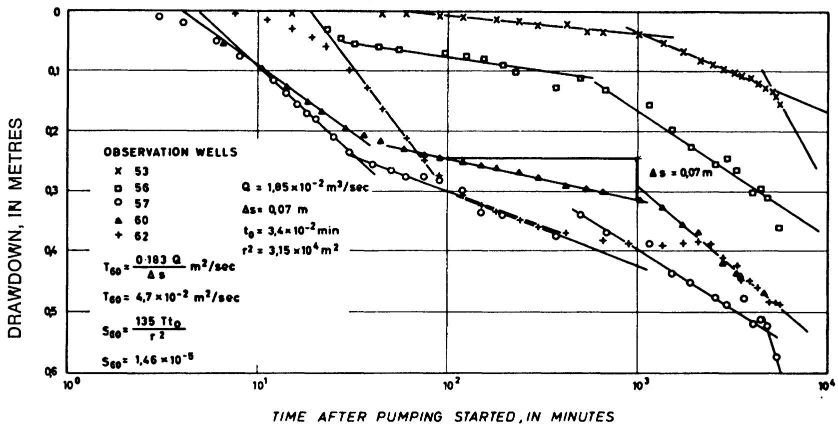

Fig. 5.

Time-drawdown graphs for selected observation wells used in test on Well 61. Semi-logarithmic plot.

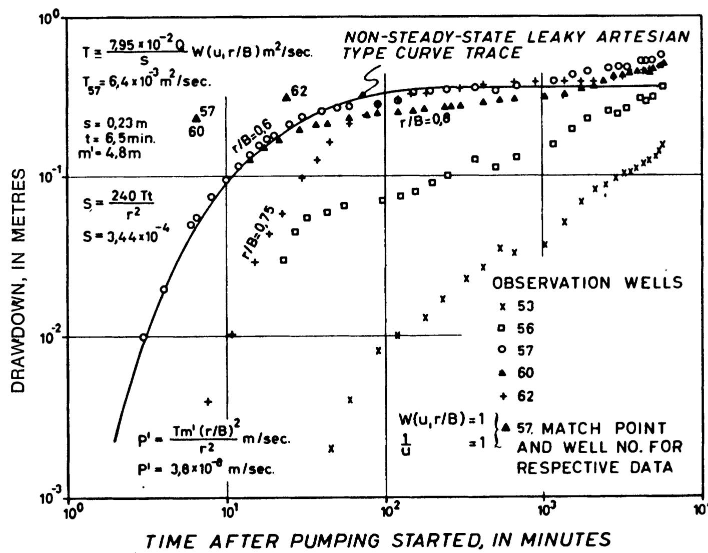

Fig. 6.

Time-drawdown graphs for selected observation wells used in test on Well 61. Logarithmic plot.

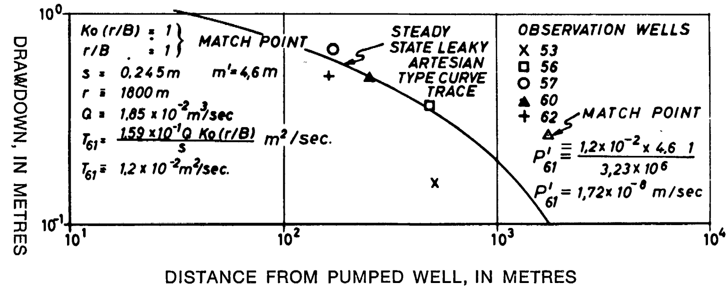

Fig. 7.

Distance-drawdown graph for observation wells used in test on Well 61. Logarithmic plot.

$$T = \frac{0{,}183\,Q}{\Delta s}\ \mathrm{m^2/sec} \tag{3}$$

$$S = \frac{135\,T\,t_0}{r^2} \tag{4}$$

where:

- $T \equiv$ coefficient of transmissivity, in m^2/sec
- $S \equiv$ coefficient of storage, dimensionless
- $Q \equiv$ discharge, in m^3/sec
- $\Delta s \equiv$ drawdown difference per log cycle, in m
- $t_0 \equiv$ intercept on zero-drawdown axis, in min
- $r \equiv$ distance from pumping well to observation point, in m.

For the logarithmic time-drawdown graphs the non-steady-state leaky artesion graphical method (Hantush 1956, Walton 1960) has been used.

$$T = \frac{7{,}95 \times 10^{-2}\,Q}{s}\ W(u,\ r/B)\ \mathrm{m^2/sec} \tag{5}$$

$$S = \frac{240\,Tt}{r^2} \tag{6}$$

$$P' \equiv \frac{T\,m'\,(r/B)^2}{r^2}\ \mathrm{m/sec}$$

where:

- $W(u,\ r/B) \equiv$ well function for leaky artesian aquifer
- $m' \equiv$ thickness of confining bed through which leakage occurs, in m

B $\equiv$ leakage factor, in m

s $\equiv$ drawdown in observation point, in m

and other symbols as previously defined.

For the distance-drawdown graphs the steady-state leaky artesian method (Jacob 1946a) has been used.

$$T = \frac{1.59 \times 10^{-1} Q}{s} K_0 (r/B) \text{ m}^2/\text{sec} \tag{8}$$

$$P' \equiv \frac{T m' (r/B)^2}{r^2} \text{ m/sec} \tag{9}$$

where:

$K_0 (r/B)$ $\equiv$ modified Bessel function of the second kind and zero order, all other symbols are as previously defined.

It should be mentioned that the artesian aquifer is assumed to conform the assumptions under which the theory has been developed, (Theis 1935). However, in the case discussed here, the artesian aquifer does not fulfil the assumption of infinity in its extension. The limitation of the aquifer will be discussed later on.

Calculated values of the coefficients T, S, and P′ are given in Table 7.

Values of the transmissivity coefficients calculated by means of Jacob's method are tabulated so that the first value is calculated from the first straight-line of the time-drawdown data plot and so on. In general, it is possible to distinguish three different T-values.

The first T-values are smaller if no leakage or reverse fluctuations appeared instantaneously after pumping started. The second, higher, T-values comprise the influence of leakage and reverse fluctuations, which produce a decrease in the time-drawdown rate. The third T-values are again smaller, and include the influence of the negative boundaries, which produce an increase in the time-drawdown rate.

The comparison among the average T-values given in Table 8 shows in general an increasing tendency in the values of transmissivity, where Wells 56, 59, 60, 61, and 62 are situated. The highest average value is from Well 60, and the smallest value is from Well 57. A high transmissivity is also found for Well 53. This agrees with the aquifer thickness and extension as shown on the block diagram, Fig. 2. Also, the increasing depth to the Tertiary bedrock as determined by the geoelectrical investigations shows that the aquifer thickness increases around the mentioned wells and, moreover, the aquifer seems to extend to the NE.

Two explanations for high T-value of Well 53 are possible. In this well the

Table 7.

Values of transmissivity (T), storage coefficient (S), and vertical permeability of confining bed (P′)

Pumping well	Observation well 53	56	57	59	60	61	62
Transmissivity coefficient (T) (m^2/sec)							
57	316×10^{-2}*	1.03×10^{-2}*	5.90×10^{-3}*		2.20×10^{-2}*	9.06×10^{-3}*	3.40×10^{-2}*
	5.30×10^{-2}	1.25×10^{-2}	5.50×10^{-3}		3.26×10^{-2}	1.16×10^{-2}	3.86×10^{-2}
	3.64×10^{-2}		7.85×10^{-3}		4.90×10^{-2}	2.85×10^{-2}	6.95×10^{-2}
	2.33×10^{-2}				2.48×10^{-2}	2.60×10^{-2}	1.98×10^{-2}
59				2.83×10^{-2}	1.23×10^{-1}*	7.40×10^{-2}*	
				1.20×10^{-2}	1.47×10^{-1}	6.80×10^{-2}	
				7.50×10^{-3}	9.70×10^{-2}	1.53×10^{-1}	
						6.18×10^{-2}	
60						2.04×10^{-2}*	
					5.30×10^{-3}	1.91×10^{-2}*	1.70×10^{-2}*
					2.20×10^{-2}	$.195 \times 10^{-2}$	2.99×10^{-2}
					1.52×10^{-2}	2.42×10^{-2}	6.30×10^{-3}
					3.50×10^{-2}	4.66×10^{-3}	
61	4.83×10^{-2}	4.20×10^{-2}	6.40×10^{-3}*		6.40×10^{-3}	1.20×10^{-2}	4.75×10^{-3}*
	2.18×10^{-2}	1.27×10^{-2}	1.16×10^{-2}		1.56×10^{-2}	4.85×10^{-3}	6.00×10^{-3}
			2.82×10^{-2}		4.70×10^{-2}	1.47×10^{-2}	2.86×10^{-2}
			1.38×10^{-2}		1.28×10^{-2}	6.25×10^{-3}	1.28×10^{-2}

(Table 7, *continued*)

Pumping well	53	56	57	59	60	61	62
62		4.40×10^{-2}*	2.10×10^{-2}*	2.80×10^{-2}	2.30×10^{-2}*	9.93×10^{-3}	5.40×10^{-3}*
		4.63×10^{-2}	3.52×10^{-2}	4.57×10^{-2}	3.80×10^{-2}	1.29×10^{-2}	6.10×10^{-3}
		9.90×10^{-3}	6.10×10^{-3}	1.25×10^{-2}		3.42×10^{-2}	9.60×10^{-3}
						1.60×10^{-2}	6.70×10^{-3}
Storage coefficient (S)							
57	1.30×10^{-3}*	9.99×10^{-4}*			3.28×10^{-4}*	2.87×10^{-4}*	1.43×10^{-3}*
	9.1×10^{-4}	6.7×10^{-4}			2.96×10^{-4}	2.18×10^{-4}	1.09×10^{-3}
	1.34×10^{-3}				1.05×10^{-4}	3.7×10^{-5}	5.05×10^{-4}
	2.8×10^{-3}				2.32×10^{-3}	4.46×10^{-5}	1.65×10^{-3}
59					1.45×10^{-2}*	1.38×10^{-3}*	
					2.72×10^{-4}	3.42×10^{-3}	
					1.4×10^{-3}	1.47×10^{-3}	
						3.5×10^{-3}	
60						2.02×10^{-4}*	
						2.9×10^{-4}*	1.24×10^{-3}*
						1.97×10^{-2}	7.32×10^{-4}
						2.07×10^{-4}	2.26×10^{-2}
						2.16×10^{-4}	
61	1.76×10^{-3}	8.5×10^{-5}	3.44×10^{-4}*		3.17×10^{-4}*		9.85×10^{-4}*
	2.6×10^{-2}	2.74×10^{-3}	2.62×10^{-4}		1.54×10^{-4}		5.3×10^{-4}
			2.7×10^{-5}		1.46×10^{-5}		3.4×10^{-5}
			6.15×10^{-4}				4.9×10^{-3}

62	1.4×10^{-3}*	1.1×10^{-3}*	7.7×10^{-3}*	7.1×10^{-4}*	6.2×10^{-4}*	
	9.2×10^{-4}	8.8×10^{-4}	4.95×10^{-3}	9.4×10^{-4}	3.32×10^{-4}	
					3.2×10^{-3}	
Vertical permeability coefficient (P') (m/sec)						
57	2.42×10^{-8}*	2.46×10^{-7}*		3.8×10^{-8}*	1.44×10^{-7}*	
60				6.26×10^{-8}*	2.8×10^{-7}*	9.3×10^{-8}*
61		3.8×10^{-7}*		1.95×10^{-7}*	1.72×10^{-8}*	3.8×10^{-7}*
62	8.4×10^{-8}*	3.5×10^{-8}*		2.1×10^{-8}*	1.6×10^{-7}*	1.2×10^{-7}*

* Values determined by type curve method

Table 8.
Average values of transmissivity (T) and storage (S) coefficients

	Method	Well file no.						
		53	56	57	59	60	61	62
Transmissivity (m^2/sec)								
Observation wells	Log-log	3.16×10^{-2}	2.70×10^{-2}	1.10×10^{-2}	2.80×10^{-2}	4.60×10^{-2}	2.50×10^{-2}	1.50×10^{-2}
	Jacob	3.70×10^{-2}	2.50×10^{-2}	1.90×10^{-2}	2.90×10^{-2}	5.00×10^{-2}	3.70×10^{-2}	2.70×10^{-2}
Pumping wells	Jacob and Log-log			6.70×10^{-3}	1.60×10^{-2}	2.20×10^{-2}	8.60×10^{-3}	7.80×10^{-3}
Storage coeff.								
Observation wells	Jacob and Log-log	1.32×10^{-3}	1.36×10^{-3}	3.31×10^{-4}	6.32×10^{-4}	3.48×10^{-4}	7.21×10^{-4}	7.54×10^{-4}

reverse fluctuations have been observed over a long time and are of a high magnitude (see Table 5), therefore the average T-value may be influenced by this phenomenon. A similar influence of the reverse fluctuations in Well 52 made it impossible to use data for computation of the aquifer properties from this well. Another explanation is that the aquifer in this section is relatively thick and that the very thin confining bed or its disappearance actually means an established connection with the upper aquifer.

For the computation of the future drawdown in the aquifer two sets of transmissivity values have been used. For the drawdown interference among the wells the average value of transmissivity from observation wells, calculated by both methods, has been used as a representative value of the aquifer properties. The value of transmissivity determined from the pumping wells does not represent the true aquifer properties because of well losses are also included. However, from these values only values influenced by the boundary effect have been used for the determination of the future drawdown in the pumping wells.

Values of the storage coefficient (S) calculated by means of the two mentioned methods are different. Concordance among the values calculated by the type curve method and Jacob's method exists only for the values in which no influences of boundaries are included. These are in the range from 0.0002 to 0.002, representing artesian conditions. Elsewhere (Wells 53, 60, and 62) the occurrence of appreciably higher S-values, in the range of 0.01, is due to boundary influence on the time-drawdown rate. In this case, t_0 interception value on the zero-drawdown axis is big. Where t_0 is smaller, due to a big decrease in the time-drawdown rate on account of leakage, the S-values are in the range of 0.00001. For the computation of the future drawdowns only the average S-values without boundary influence have been used.

The decrease of the time-drawdown rate on the semi-logarithmic graphs and the deviation from the non-equilibrium type of curve (Fig. 6 and 7) can be interpreted as influence of either leakage or reverse fluctuations. By means of the respective r/B-values and equations (7) and (9) the vertical permeability values (P′) are computed (Table 7). Analysis of their relative magnitude shows an increasing tendency for the aquifer section around Wells 57, 60, 61, and 62, indicating in this way an increase of leakage through the semi-confining overlying bed in these areas. The increasing amount of the leakage also influences an increase in the T-values as mentioned before, and the magnitude of the influence is governed by the thickness and texture of the confining bed.

Compared with the features of the aquifer shown on Fig. 2, the variations of the P′-values seems to coincide with the variations in the thickness of the confining bed. However, it is necessary to emphasize that the undeterminable rate of influence due to reverse fluctuations can lead to erroneous conclusions about the leakage magnitude. Data from Wells 53 and 59 plotted on logarithmic paper do not show particular r/B-values, which means that no leakage is present in this section of the aquifer.

HYDROLOGICAL BOUNDARIES

The time-drawdown rate indicates the existence of negative hydrological boundaries in the aquifer. Distances from respective wells to the boundaries have been determined by means of the image well theory (Ferris 1948) and the equation:

$$\frac{r_0^2}{t_0} = \frac{r_1^2}{t_1} = \frac{r_2^2}{t_2} \equiv K \tag{10}$$

where:

t_0 is as previously described

and

$r_0 \equiv$ distance from pumped well to observation well, in m

$r_1, r_2 \equiv$ distances from respective image wells to observation wells, in m

$t_1, t_2 \equiv$ time, from which influence from boundary is recorded in the respective observation wells, in minutes

$K \equiv$ constant

Calculated distances to the hydrological boundaries are given in Table 9.

Depending on the duration of the tests several boundaries are determined. During all tests the first boundary is indicated as an increase in the time-drawdown rate within 800 minutes after pumping started. Calculated distances from the respective wells to this boundary (Table 9) are within 200-700 m and coincide in relation to the different pumping wells. From the knowledge about the hydrogeology of the aquifer this boundary is determined as the southern boundary.

The second boundary effect appears from 1000 to 2500 minutes after pumping started, as an increase of the drawdown rate, and the third boundary effect has been registered during the tests of Wells 60, 61, and 62 of long duration (Table 3, and Fig. 5) as an abrupt change in the drawdown rate 6000 minutes after pumping started.

The last two boundary effects are interpreted as a northern discontinuous boundary. Because of insufficient knowledge about the distribution of the aquifer in this direction it has not been possible to trace the further extension of this boundary.

Some of the time-drawdown data also showed slight changes in the rate during the pumping tests. The local small clay lenses or widely distributed clay laminae can presumably produce such an effect. This was particularly the case for the data from Wells 57 and 59.

DETERMINATION OF WELL CHARACTERISTICS

Data from step-drawdown pumping test performed on Wells 57, 60, 61, and 62 (Table 3) have been used for the determination of well losses and formation losses. As an example, data from the test on Well 61 are tabulated (see Table 10) and plotted on the arithmetic coordinate paper (Fig. 8) to illustrate graphical procedure.

For determination of the well characteristics graphical methods and the following equations have been used (Jacob 1946b, Rorabaugh 1953):

where

$$s_w = BQ + CQ^2 \text{ (Jacob's method)} \tag{11}$$

$$s_w \equiv BQ + CQ^n \text{ (Logarithmic method)} \tag{12}$$

$s_w \equiv$ drawdown in the pumping well, in m

$B =$ aquifer loss factor, sec/m^2

$C \equiv$ "well loss" constant, sec^2/m^5

$Q \equiv$ discharge in m^3/sec

$n \equiv$ exponent

Graphical solutions of well losses and formation losses based on data from Table 11 are shown for both methods on Figs. 9a-d and 10a-d.

The analysis of the drawdown data shows that for the highest discharge during the last steps the time-drawdown rate is higher than expected. This can be attributed to the boundary influence, therefore the plotted points from the last step on the graphical solution do not fall on the required straight line drawn through the plotted points from earlier steps.

Examination of the equations representing well characteristics indicates that differences in the formation factors (B), determined by both methods, are negligible. However, differences in the well loss constants (C) vary appreciably. In general, well loss constants determined by the logarithmic method are higher, because the exponent exceeds the second power. Computed drawdowns by both

Table 9.
Estimated distances to hydrological boundaries

	Pumping well	Observation well								
		52	53	55	56	57	59	60	61	62
Distance to southern hydrological boundary (in metres)	57		850			325 170 300 210		425	300	400
	59						260 430	1000	270	
	60							270 185	75	740
	61		965		2950	225		250	600 150 200 240 200	200
	62								330	150

Distance to northern hydrological boundary (in metres)	57	2030		1350 700 1250 800		2125	1450	775
	59				650 570	2150	680	
	60					430 3000	4900	
	61	2100	8950	1625		1710	6250 1500 1950 2400 1000	935

Table 10.
Data from step-drawdown test on Well 61, between 12^{50}–18^{05} on 16 October 1968

Time (min)	I. Step			II. Step			III. Step			IV. Step		
	Drawdown	Discharge		Drawdown	Discharge		Drawdown	Discharge		Drawdown	Discharge	
	m	l	sec	m	l	sec	m	l	sec	m	l	sec
0	0	0										
0.24	2.060	50		4.870	100	9.0	7.105	100	6.5	9.160	100	5.4
0.50	2.520	50	8.2	5.200	100	9.0	7.450	100	6.6	9.380	100	5.6
1	2.570	50	8.2	5.235			7.480	100	6.8	9.410	100	5.4
1.25	2.630	100	16.8	5.270			7.515	200	13.5	9.430	400	21.8
1.5	2.665	100	16.2	5.310			7.530	200	13.5	9.445	100	5.5
2	2.695	100	16.8	5.345	100	9.0	7.560	500	33.7	9.465		
3	2.720	100	16.7	5.395	200	18.2	7.600	1000	67.2	9.490	500	27.4
4	2.750	100	17.0	5.425	400	36.2	7.630	500	33.5	9.505	1000	54.8
5	2.780	500	84.3	5.450			7.635	500	34.0	9.525	100	5.5
6	2.800	100	16.9	5.505	1000	90.4	7.650	500	33.7	9.535	1000	55
7	2.815			5.525			7.665			9.545		
8	2.825	500	83.9	5.550			7.675			9.555	1000	54.7
9	2.835	100	16.9	5.560			7.690			9.565	1000	54.8

10	2.845	500	84.2	5.575	1000	90.2	7.695	500	33.5	9.570	500	27.6
12	2.850	500	84.2	5.595	500	45.0	7.715	500	33.5	9.580	500	27.6
14	2.865	500	84.8	5.610	500	44.9	7.695	500	33.9	9.595	500	27.6
16	2.875	500	84.8	5.630	500	44.6	7.710	500	33.8	9.600	500	27.8
18	2.885	500	85.0	5.640	500	45.0	7.725	500	34.1	9.610	500	27.5
20	2.845	500	85.8	5.650	500	45.2	7.745	500	33.8	9.620	500	27.5
25	2.825	1000	174.0	5.670	1000	90.0	7.770	1000	67.2	9.635	1000	55.1
30	2.820	1000	176.0	5.685	1000	90.1	7.780	1000	67.1			
35										9.640	1000	55.0
40	2.830	1000	176.2	5.715	1000	89.9	7.810	1000	67.1			
45										9.655	1000	54.9
50	2.835	1000	175.8	5.745	1000	90.0	7.865	1000	66.8			
60	2.845	1000	175.8	5.750	1000	89.6	7.875	1000	66.9	9.675	1000	55.0
75	2.825	1000	178.4	5.770	1000	89.5	7.890	500	33.0			
90	2.820	100	18.3	5.790	100	9.2						

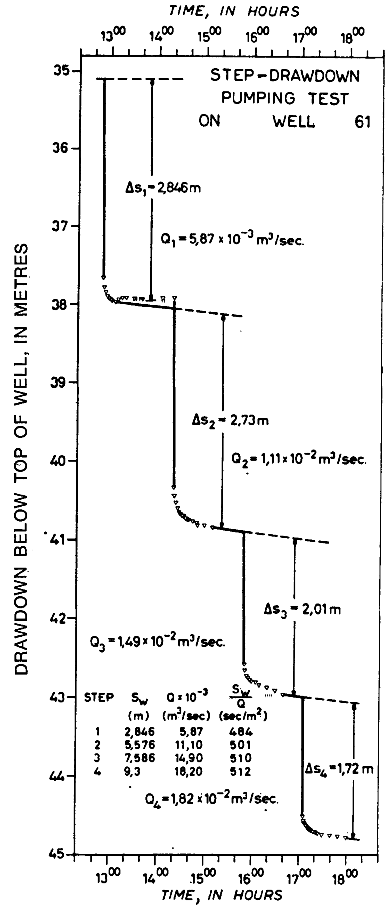

Fig. 8.
Step-drawdown graph from test on Well 61.

methods for one day after pumping started are correlated with the measured data. Results of the computation are given in Table 12.

For the computation the Theis simplified equation has been used.

$$s_w = \frac{7.95 \times 10^{-2}\, Q}{T}\left[2.3 \log \frac{4\,Tt}{r_w^2 S} - 0.577\right] + CQ^n$$

Table 11.
Selected data from step-drawdown tests for graphical solution of well characteristics

Step	s_W Drawdown (m) 1 hour after each step started, for Well:				$Q \times 10^{-2}$ Pumping rate (m^3/sec) for Well:				s_W/Q (sec/m^2) for Well:			
	57	60	61	62	57	60	61	62	57	60	61	62
1	1.73	1.14	2.85	2.20	0.536	0.482	0.587	0.408	324	236.5	484	539
2	2.89	1.97	5.58	4.18	0.88	0.831	1.11	0.77	327	237	501	544
3	4.46	3.41	7.59	6.46	1.34	1.36	1.49	1.18	333	250.5	510	547
4	5.56	4.66	9.31	7.92	1.64	1.92	1.82	1.40	339	243	512	565
5				11.18				2.05				545

8*

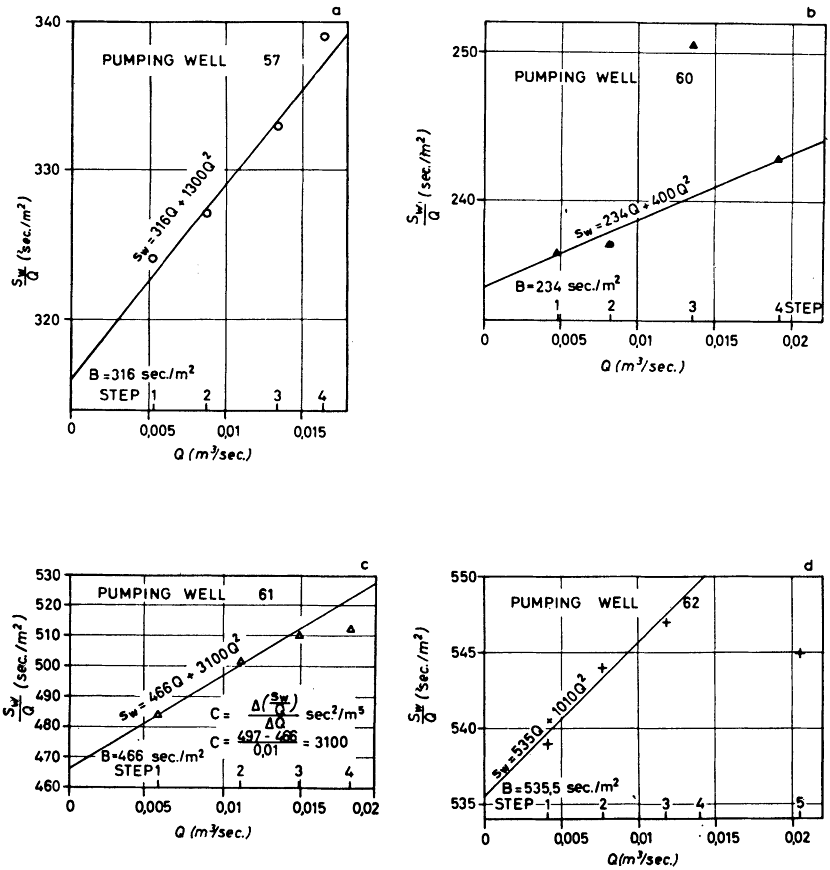

Fig. 9a-d.
Graphical solution for determination of well losses for Wells 57, 60, 61, and 62. Arithmetic plot.

where

$r_w \equiv$ effective radius of the well, which in this case, because of the small pumping rate, is replaced with actual radius of the well signified with $r_n \equiv 0.125$ m

and all other symbols are as previously defined.

The comparison of the calculated and measured data shows that the logarithmic method better conforms with the actual data except for Well 61. Further-

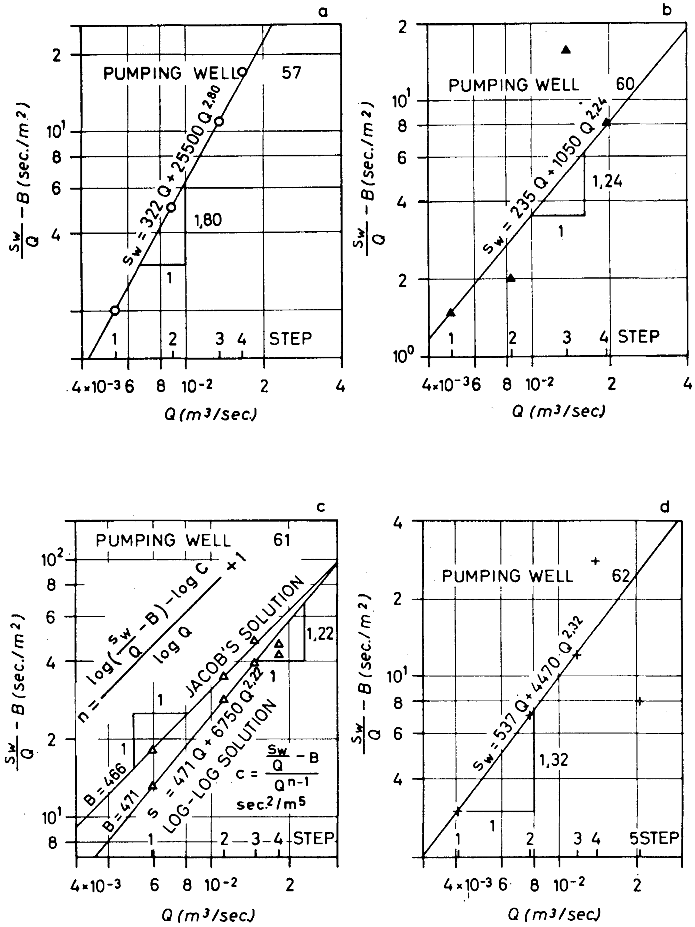

Fig. 10a-d.
Graphical solution for determination of well losses for Wells 57, 60, 61, and 62. Logarithmic method.

more, the logarithmic method also gives smaller well losses, but not appreciably smaller than Jacob's method. Well losses do not exceed 5 per cent for the logarithmic method and 12 per cent for Jacob's method in relation to the total calculated drawdown for discharge rate of approximately $2.0 \times 10^{-2} m^3$/sec.

However, the calculated drawdowns by both methods are 14 and 12 per cent

Table 12.
Comparison of measured and calculated values of drawdowns in wells 24 hours after pumping started

Well	Measured drawdown (m)	Jacob's method			Logarithmic method		
		BQ (m)	CQ^2 (m)	s_w (m)	BQ (m)	CQ^n (m)	s_w (m)
57	6.30	6.63	0.35	6.98	6.70	0.26	6.96
60	5.04	5.58	0.17	5.75	5.59	0.07	5.66
61	10.06	9.10	1.04	10.14	9.15	0.52	9.67
62	11.77	10.62	0.42	11.04	10.64	0.54	11.18

higher than the drawdown in Wells 57 and 60, respectively. Jacob's method also gives a slightly higher value for Well 61, whereas the logarithmic method gives a 4 per cent smaller value for the same well. Both methods give approximately a 6 per cent smaller value for Well 62.

In spite of influence from leakage, reverse fluctuations, and hydrological boundaries the graphical solution by both methods represents well characteristics with sufficient accuracy for practical purposes.

The approximately 50 per cent higher formation losses for Wells 61 and 62 than for Wells 57 and 60 can be attributed to the existence of small clay laminae, which obstruct flow of water into the well. This assumption seems to be reasonable according to the lithological composition of the aquifer around these wells. Well losses have almost the same range for all tested wells and are negligible. With increase of the pumping rate a turbulent zone develops around the wells and the well losses also increase. The calculated values for well losses do not include an increase of the well loss due to incrustation of the well screen. This factor can increase the well losses remarkably and produce higher future drawdown than here estimated.

THE FUTURE DRAWDOWN

The future drawdown in the different wells is calculated without consideration to influence from any kind of recharge into the artesian aquifer. As recharge exists, the future drawdown will be smaller than the calculated values by con-

Table 13.
Estimated drawdowns after 1 year, 5, and 10 years of pumping

Horsens Municipal file No.	Drawdown (m) after		
	1 year	5 years	10 years
52	7.39	8.91	9.51
53	7.69	9.19	9.78
55	20.14	21.57	22.23
56	19.40	20.86	21.48
57	14.36	15.78	16.39
59	15.52	17.05	17.69
60	14.54	16.16	16.83
61	20.42	21.84	22.46
62	20.30	21.79	22.46
Proposed Well 1	20.10	21.56	22.24
Proposed Well 2	19.06	20.54	21.23

tinuous pumping with 570 m^3/h during 1, 5, and 10 years. The calculated values of the drawdown are presented in Table 13.

To reach the above-mentioned discharge two wells (Fig. 2) are proposed on the basis of the results from the pumping tests and the hydrogeological and geoelectrical investigations. The aquifer properties and discharge determined for Well 62 are attributed to both of the new wells. For the computation of the drawdown two sets of T- and S-values are used, as discussed in the section on hydraulic properties of the aquifer (see also Table 8).

In order to estimate the total drawdown in the well, two components are considered: the drawdown in each well caused by its own pumping and the interference in each well caused by the pumping of the other wells.

Computed drawdown for 10 years shown on Fig. 2 indicates that no critical drawdown will appear in the section where the aquifer is thickest. As calculated, critical drawdown will appear in the pumping Wells 55, 56, 59.

No registration of the static piezometric surface was done before the start of drilling in 1965, and it is possible that the reported values are too low. Therefore, plotted values of the future drawdowns from that piezometric level will present a too low position. This seems also to be the explanation of the peculiar problem seen in the plotted values of the future pumping level in Fig. 2. Wells 61 and 62 were completed after $2^1/_2$ years of pumping from the area, and, therefore, the reported piezometric surface has already been influenced. That explains why the hydraulic gradient slopes against these two wells, whereas the original static piezometric level should have been in a higher position than recorded.

A reasonable explanation of the critical drawdown is that the step-drawdown test was not performed on these wells, and therefore the well characteristics are not determined. Due to this, the self-drawdowns based only on the specific capacity data can be too big.

However, the computation of the future drawdown in the aquifer indicates that no greater excess in discharge will be able to withdraw from the investigated part of the aquifer. Furthermore, to provide a sufficient quantity of water for the water supply, in the rate of 750 m^3/h, further investigations and development of the aquifer and pumping sites are necessary. The pumping test results indicate that increase of the aquifer properties takes place in northeastern direction. Hydrogeological and geoelectrical interpretations also suggest increasing thickness of the Quaternary glacial deposits and sand deposits in the same direction. Therefore the development of the aquifer is scheduled according to these results.

CONCLUSIONS

The semi-confined aquifer of the Quaternary outwash sand and gravel deposits in the Egebjerg area, north of Horsens, has been investigated by several methods. The analysis of the pumping test data shows that continuous withdrawal of 570 m^3/h during a period of 10 years will be possible without critical drawdown in all wells, except for Wells 55, 56, and 59. The drawdowns in these wells are based on insufficient and, possibly, pessimistic data. The drawdowns are, therefore, probably overestimated. Furthermore, the results indicate possibilities of an extension of the aquifer in a northeastern direction. Withdrawal of a quantity of 750 m^3/h requires further investigations.

The analysis of the pumping test data indicates an increase of transmissivity in the aquifer section, where Wells 59, 60, 61, and 62 are situated. Both methods by which the well characteristics have been determined show rather good agreement with the measured data after one day of pumping. This agreement is obtained by using values of transmissivity influenced by the existing boundaries and uninfluenced storage coefficients. This procedure should imply that the future drawdown will correspond to the calculated drawdown with sufficient accuracy for practical purposes.

By continuous recording of all water level fluctuations it has been possible to distinguish and select data which approximate the assumptions for their analysis with methods by which the calculations of the different aquifer parameters are possible. The leakage values can be too high on account of their appearance with the reverse fluctuations. When the reverse fluctuations have a high magnitude and a long duration, data from the pumping test are not yet usable for determination of the hydraulic properties of the aquifer.

The results of these investigations show that the aquifer test methods employed indicate good applicability for practical purposes, even in aquifers of a complex hydrogeological composition.

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