LABORATORIUM VOOR TOEGEPASTE GEOLOGIE EN HYDROGEOLOGIE

GROUNDWATER INVESTIGATION

LANDFALL INTERCONNECTOR PIPELINE

BACTON - ZEEBRUGGE

PHASE II

RIJKSUNIVERSITEIT
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CONTENT

1 INTRODUCTION

By order of Haecon nv the Laboratory of Applied Geology and Hydrogeology (LTGH) of the University of Ghent carried out a hydrogeological investigation near the landfall point of the Gas interconnector pipeline Bacton-Zeebrugge.

The investigation consisted of:

- drilling at three locations
- geophysical well logging in three boreholes
- construction of observation wells in the boreholes
- measuring groundwater levels and direction of the groundwater flow
- sampling and analysis of ground- and surface water (pond)

The investigation started on April the 18th.

2 SITE DESCRIPTION

The landfall of the gas interconnector pipeline Bacton-Zeebrugge is planned west of the Harbour near "De Fonteintjes". The projected trajectory from the low water line to the reception terminal is shown on figure 1, an orthofotoplan of the region, on which also the location of the drilling sites (SB1, SB2 and SB3) is marked.

The drilling site one lies on the beach, 50 m north of the seawall, near the end of the "Zeedijk". Site two lies just south of the pond, approximately 200 m west of the "Londenstraat". Site three is at the centre of resistivity sounding four (see report TGO 94/01 February 1994, Vermoortel et al.).

3 FIELD WORK

Information about the lithology and the groundwater quality is provided by installing three observation wells. In the boreholes geophysical logs were made, the boreholes were then equipped as observation wells with a one- or two-metre screen. Samples were taken from these observation wells.

3.1 Drilling and sampling

3.1.1 Principle

Drillings was done by the direct rotary method (DR-method). Circulating fluid is pumped down the drill pipe and returns via the annular space between the pipe and hole carrying the sediment to the surface. The mud is picked up by the pump after dropping the bulk of its load and again pumped down the pipe.

The drilling fluid is a mixture of fresh water, sediment and an additive. The drilling fluid has different purposes:

- relief of the vertical axis stress in the formation immediately below the bit
- removing the sediment beneath the bit and transport to the surface
- maintaining the hole stability
- cooling the bit
- preventing fluid entry from the porous sediment penetrated
- reducing the drilling fluid losses into permeable formations

A biodegradable additive has been used. It heightens the viscosity of the drilling fluid and decomposes after a period through enzymatic action.

With the DR-method samples are collected at regular intervals. Because of the shallow depth of the drillings (max. 30 m) the time-lag between the actual cutting of a given bed at the depth and the collection of the sample at the surface is not too great. This allows a crude description of the lithology.

3.1.2 Drilling

For this study five holes were drilled, one on the beach and two at the other sites.
The drilling sites are numbered SB1 (beach), SB2 (pond) and SB3 (Koninklijke Baan); F1 for the deep and F2 for the shallower ones.

3.2 Monitoring well design

All boreholes were equipped with a piezometer (or screen -F). The deep one (F1) was placed in that part of the aquifer that contained salt ground water (estimated from a crude interpretation of the resistivity logs) and the second one (F2), shallower, was placed in the zone of the highest resistivity values (less salty ground water). Near the Koninklijke Baan (site three; SB3F1 and SB3F2) and the water pond (site two SB2F1 and SB2F2), the piezometers were installed in separate boreholes. At the beach, both piezometers (SB1F1 and SB1F2) were put in the same borehole.

The annular space around screen and casing has been filled with calibrated sand (0.7 to 1.25 mm), depending on the lithology; clay plugs were installed.

Well screen length, screen slot opening, filter pack design, casing and screen diameter, well screen level (in m*) and other data are given in table 1.

* all levels are expressed in metres versus the datum level of the National Geographic Institute.

3.3 Geophysical well logging

Application of the DR-drilling method hampers an accurate description of the perforated strata because of the inappropriate quality of formation samples obtained from the drilling mud. Geophysical well logging provides information on the lithology, the stratigraphy and the physico-chemical properties of the liquid filling the pores of the perforated formations. The following combination of log methods for the deep boreholes (SB1F1, SB2F1 and SB3F1) was used; spontaneous potential (SP), formation resistivity (RES), natural gamma radiation (GAM), hole diameter (CAL) and single point resistance (PW). All variables were recorded continuously as a function of probe depth with an upwards moving probe. The logs of SB1, SB2 and SB3 are given in figure 2 to 4.

Natural gamma logging
The gamma-ray log is used in a qualitative way to distinguish sand from clay beds. In general, low cps (counts per seconds) values are typical for sand (and peat), high for clay. The presence of glauconite, occuring in many tertiary sand formations, may result in higher cps values, thus obscuring the boundaries between sand and clay strata.

Resistivity logging
In each borehole a long normal and a short normal resistivity logging was made. In the former the distance between the electrodes is 1 m; in the latter it is 0.25 m. Measurements with the short normal device are largely influenced by the drilling mud and the invaded zone; therefore they do not yield the true resistivity of the sediment. However, because of the small electrode spacing and interval of measurement, they accurately locate the lithological (or water quality) boundaries. Measurements with the long normal device penetrate deeper into the formation because of the larger spacing. They provide values of the true formation resistivity.

In aquifers containing salt water, as in the case of the investigated area, resistivity differences due to lithological variations are negligible compared to those due to variations in salt content. The salt content (TDS - total dissolved solids) can be derived from the resistivity log. In the zones with fresh water the resistivity log can also yield information about the lithology.

Point resistance logging
Because the true resistance of the sediments cannot be obtained with this method, they are not suited for quantitative analysis. They can be used for the lithological interpretation in fresh water aquifers and for the water quality determination in aquifers containing salt water.

Self-Potential (or SP) logging
This log records the difference between the natural potential between a reference electrode at the surface and an electrode in the borehole. The clay line is chosen as a reference level, in nearly all cases only a qualitative evaluation can be made. If the formation water is much more saline than the mud, the SP-log will be more negative in

the sands than in the clays; there is no absolute scale. They are mainly used for a lithological interpretation. The importance of the SP curve lies in its capability to detect thin clay lenses and its effectiveness within the salt water zone where the resistivity log no longer allows the differentiation between sand and clay beds.

Caliper logging
The recording of the diameter of the hole is used for the identification of the lithology, as a guide to well construction and to correct the interpretation of other logs for hole diameter effects.

3.4 Leveling

The level of the top of the piezometers (z-coordinate in m TAW) was determined by Haecon NV (table 1).

3.5 Water sampling

From each piezometer a water sample was analyzed for the parameters: pH, conductivity, Na, K, Ca, Mg, Fe, Mn, NH_4, Cl, SO_4, NO_3, NO_2, HCO_3, CO_3, PO_4 and total hardness. The sum of cations and anions gives the TDS or Total Dissolved Solids, a parameter for the salinity.

The water from the pond was also analyzed for the same set of parameters.

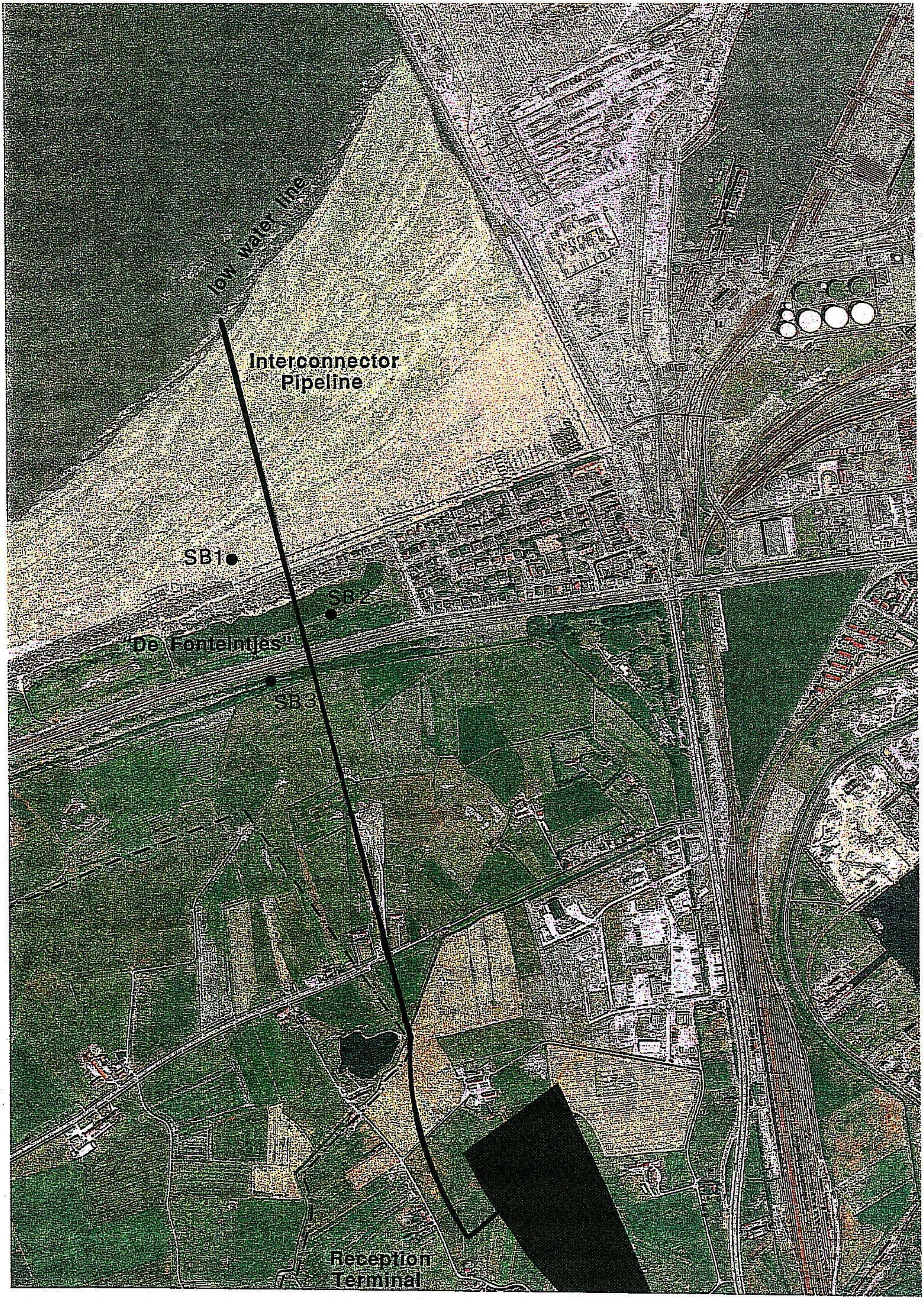

Figure 1 - Drilling sites and projected trajectory

well	screen length in m	screen diameter in m	screen slot opening in mm	casing diameter in m	level top filter in m TAW	level base filter in m TAW	level top piezometer in m TAW	calibrated sand from / to in m	clay plug from / to in m	drilling depth in m
SB1F1	2.2	0.58/0.63	0.3	0.63	-13.56	-15.76	+5.76	22.0 - 16.2 12.2 - 8.2	16.2 - 12.2 8.2 - 1.3	22.0
SB1F2	1	0.38/0.40	0.3	0.40	-4.06	-5.06	+5.76			
SB2F2	2	0.58/0.63	0.3	0.63	-15.93	-17.93	+8.07	28.0 - 15.0	15.0 - 1.0	28.0
SB2F2	2	0.58/0.63	0.3	0.63	-5.46	-7.46	+8.04	15.5 - 10.3	10.3 - 6.5	15.5
SB3F1	2	0.58/0.63	0.3	0.63	-14.98	-16.98	+5.02	25.6 - 16.0	16.0 - 10.0	25.6
SB3F2	2	0.58/0.63	0.3	0.63	-4.88	-6.88	+5.12	12.5 - 8.6	8.6 - 3.0	12.5

Table 1 Monitoring well design.

4 RESULTS AND DISCUSION

4.1 Geology

In the following tables (numbers 2, 3 and 4), the lithology of the three sites is given, based only on the description of the DR-drilling samples.

The regional correlation between the drilling data and the geology of Zeebrugge (DEPRET M., 1981) is given by the attribute K (1 through 10) or T5 (K for Quaternary deposits, T for Tertiary deposits).

Drilling site 1 - beach		SB1F1
Depth from/to in m Level from/to	material	interpretation (Depret M., 1981)
0.0 - 4.4 +5.56 - +1.16	light brown fine to medium sand, rich in shell fragments	beach sand
4.4 - 5.4 +1.16 - +0.16	as before but light gray color	beach sand
5.4 - 6.4 +0.16 - -0.84	dark brown peat, no individual plant structures, loamy	K7
6.4 - 9.0 -0.84 - 3.44	dark brown peat, no structure, thin intercallations of loam and sand beds	K5.1
9.0 - 9.6 -3.44 - -4.04	dark gray loam, slightly sandy	K
9.6 - 22.0 -4.04 - -16.44	light gray, fine to medium sand, shell fragments	K4.1, K3 and K2.1
end 22.0 m, level -16.44		

Table 2 Lithology at drilling site 1.

Drilling site 2 - pond		SB2F1
depth from/to level from/to	material	interpretation
0.0 - 1.5 +8.1 - +6.6	sand, stones,	K 10
1.5 - 7.0 +6.6 - +1.1	light gray brown, heavy clay, compact	K 8.3
7.0 - 9.3 +1.1 - -1.2	loamy sand	K
9.3 - 10.0 -1.2 - -1.9	compact clay layer	K
10.0 - 12.0 -1.9 - -3.9	light gray fine to medium sand	K
12.0 - 12.4 -3.9 - -4.3	compact clay layer	K
12.4 - 15.8 -4.3 - -7.7	loamy sand	K 4.1
15.8 - 25.0 -7.7 - 16.9	fine to medium sand, no shell fragments	K 2.1
25.0 - 27.0 -16.9 - -18.9	coarse sand and gravel, abundant in shell fragments	K 1
27.0 - 28.0 -18.9 - -19.9	dark green, glauconitic slightly sandy clay to clay	T 5
	end 28.0 m, level -19.9	

Table 3 Lithology at drilling site 2.

Drilling site 3 - Koninklijke Baan		SB3F1
depth from/to in m level from/to	sediment	interpretation
0.0 - 2.0 +5.2 - +3.2	sand, stones,	K 10
2.0 - 2.6 +3.2 - +2.6	compact, massive clay	K 8.3
2.6 - 5.5 +2.6 - -0.3	loamy, clayey sand	K 8.1
5.5 - 8.0 -0.3 - -2.8	peat, thin loam and clay beds	K 7 (peat) and K 5
8.0 - 12.0 -2.8 - -6.8	fine sand with thin loam beds	K 4.1 (sand) K 4.2 (loam beds)
12.0 - 20.0 -6.8 - -14.8	fine to medium sand	K 2.1
20.0 - 20.4 -14.8 - 15.2	dark gray loam	K 2.2
20.4 - 21.0 -15.2 - -15.8	fine to medium sand	K 2.1
21.0 - 24.3 -15.8 - -19.1	coarse sand and gravel, abundant in shell fragments	K 1
24.3 - 25.5 -19.1 - -20.3	dark green, glauconitic sandy clay, gravel	T 5
end 25.5 m, level -20.3		

Table 4 Lithology at drilling site 3.

The geological cross section (Fig. 5) between SB1 (beach) and SB3 (Koninklijke Baan), parallel to the projected trajectory summarizes the results obtained by the different methods: field observations, sediment sampling (DR-drilling method), drilling speed log, geophysical well logging and the information of the earlier study (TGO 94/01; February 1994, Vermoortel et al.).

From top to bottom (from young too old) seven distinct lithological units can be distinguished;

- beach and dune sand
- heavy surface clay K8.3
- peat K7
- loam, peat, clay, sand complex K5
- fine sand K2.1
- coarse sand and gravel with abundant shell fragments K1
- glauconitic sandy clay T5

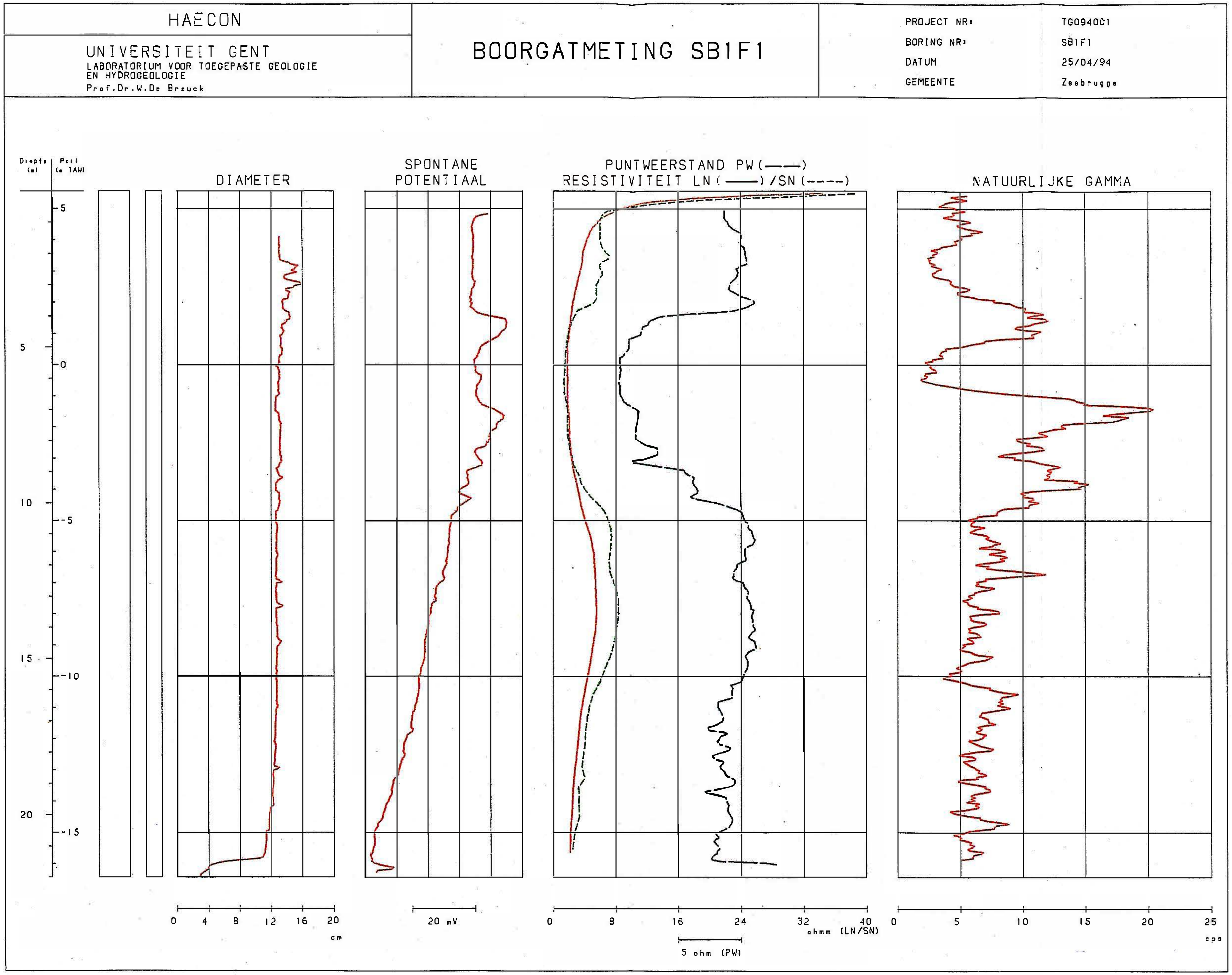

Figure 2 - Geophysical well logging - SB1

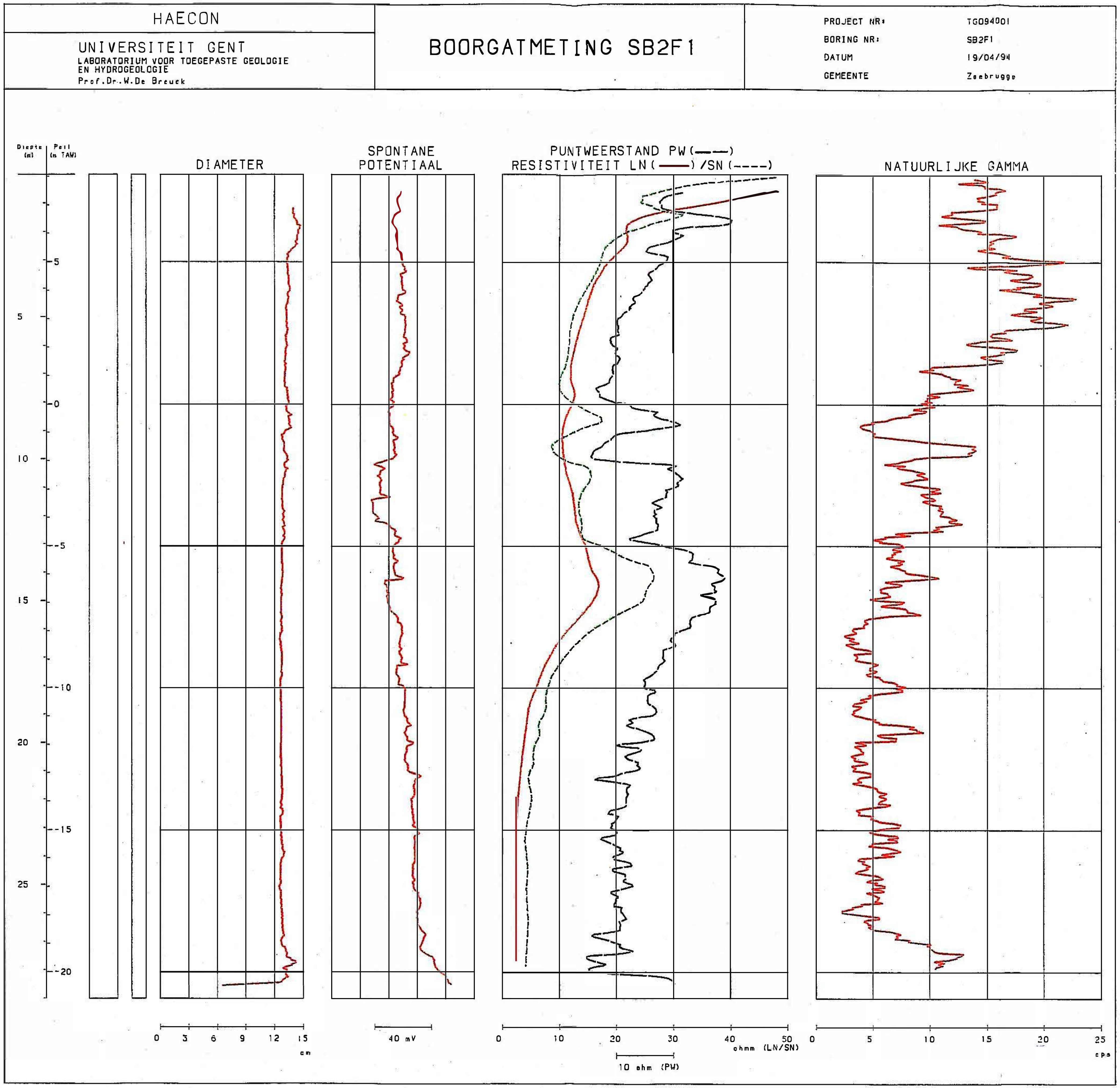

Figure 3 - Geophysical well logging - SB2

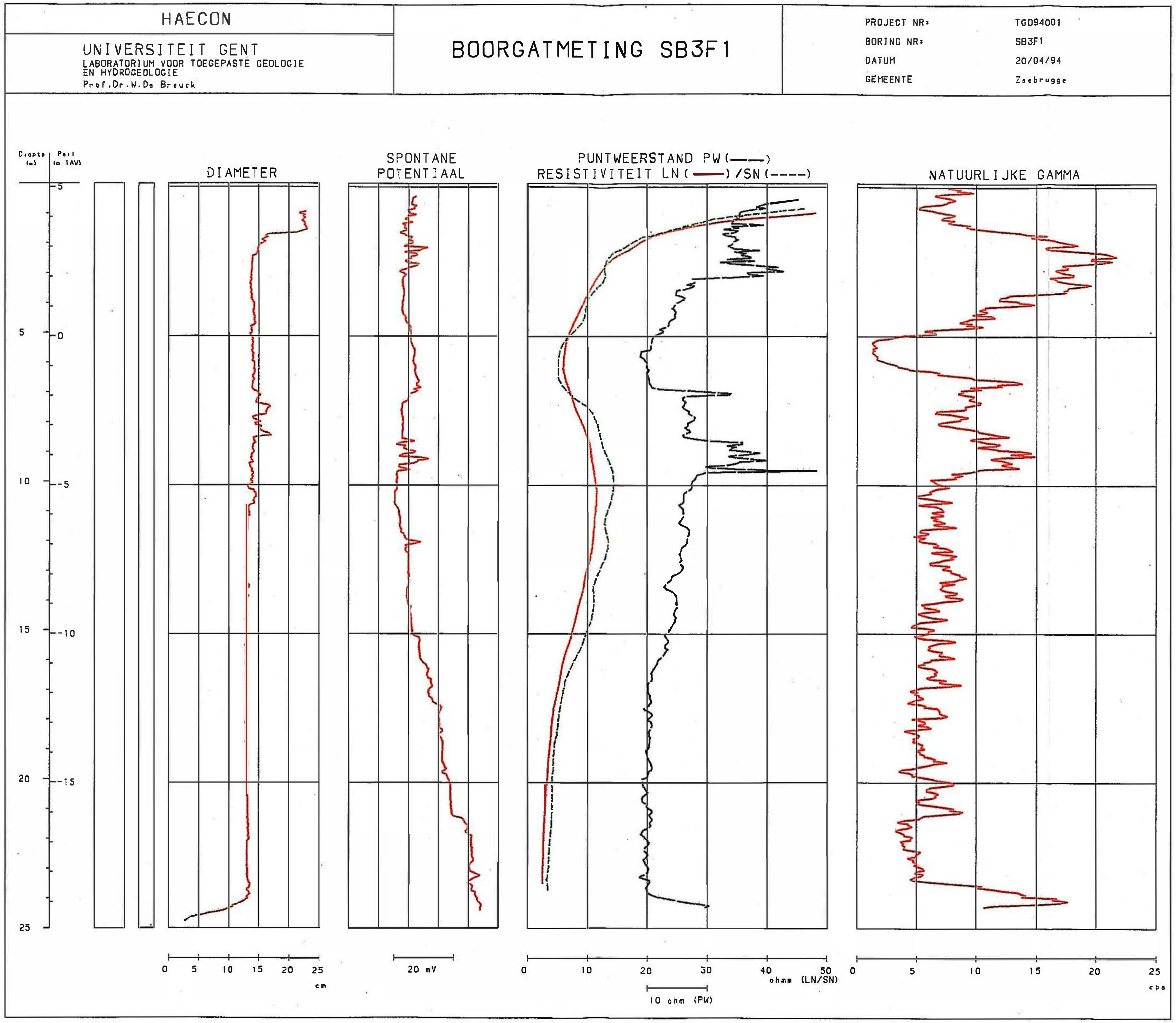

Figure 4 - Geophysical well logging - SB3

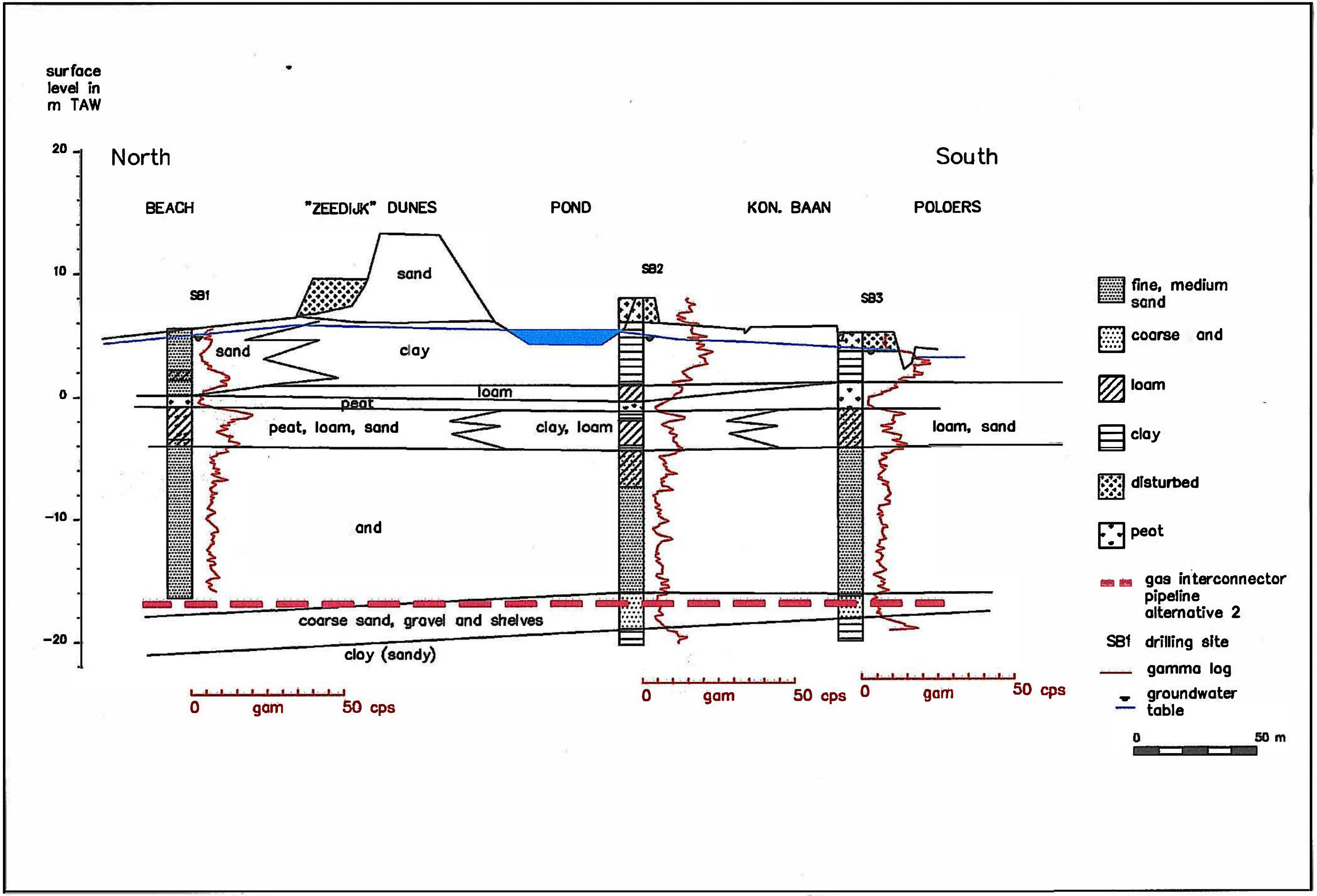

Figure 5 Geologicol cross section through the investigated area.

Dune and beach sand
The layer above level +6 1 is mainly made up by windblown sand, forming small dunes (up to level +20) between the beach and the pond. More to the south the sands only form a very thin cover.

Heavy surface clay
Below the dune sand or below the human influenced topzone lies unit K8.3. The layer of mainly heavy clay with intercalations of loam and sand lies between +6 and level 0. The base of the clay is loamy. The layer was not found at site 1 (eroded by the sea); it is replaced by beach sand. The K8 units are of Holocene age and correspond to the "Duinkirk deposits".

Peat
Below the surface clay or beach sand lies a uniform peat layer. It forms a 0.5 m (site 1 and 2) to 3 m (site 3) thick layer, of dark brown peat in a far stage of decomposition. No individual plant fragments could be distinguished. The lower 0.1 to 0.4 m appeares a black, strongly decomposed amorphous mass. The peat layer corresponds to unit K7; surface peat (Depret M, 1981), of Holocene age.

Peat/clay/loam/sand complex
Under the peat lies a complex zone. At site 1 the layer is formed by the alternation of thin layers of peat, loam and sand, totalling a thickness of more than 3 m. At site 2 the complex is formed by 3 m of heavy clay and loam. At site 3 it is mainly composed by loam and sand beds with a total thickness of 4 m.

This fourth zone, characterized by lateral lithological variations, corresponds to unit K5 (Depret M, 1981). A peat-loam-sand complex with a thickness of 5 to 8 m near Zeebrugge. It is made up by horizontal sand beds (K5.2) separated by loam and/or peat beds (K5.1). The top of K5 is loamy. K5 is of Pleistocene age and belongs to mid- and late-Weichselian "Maldegem deposits" and "Eeklo deposits".

Fine sand
From about -4 down to - 16 a uniform very fine to fine sand layer with small shell fragments occur. At site 2 the upper 3 m are slightly loamy. Occasionally very thin loamy or clayey beds occur. This zone corresponds to the unit K2, which can be up to 15 m thick. It is mainly composed by fine and medium sand with some shells. Occasionally thin beds of loam or clay occur. The sand corresponds to the K 2.1; the clay and loam intercalations to K 2.2. K2 is of Eemian age; they are termed as "Moerkerke deposits".

Coarse sand and gravel
Below K 2.1, toward the base of the Quaternary deposits very coarse sand, gravel and shell fragments occur. This is unit K 1 (up to 2 m thick), of Eemian age; and it belongs to the "Kaprijke deposits".

(Sandy) clay
The top of the Tertiary lies between level -18 (site 3) and -20 (site 2). The sediments belong to unit T5; it is made by dark green, slightly glauconitic, clay with very fine sand. The top contains coarse fragments (up to several cm). This unit was not attained at site 1. The clay layer T5 is approximately 1 to 3.5 m thick.

Below T5, but not attained by the drillings, lies T4; it is formed by dark green, slightly glauconitic, slightly clayey very fine sand. The unit is between 2 and 4 m thick and contains several discontinuous sandstone levels.

Stratigraphically T4 and T5 are a part of the Member of Oedelem (Formation of den Hoorn).

Table 5 schematizes the lithology in the investigation area "De Fonteintjes".

level between ... and ..	sediment	interpretation
+14 - +6	dune/beach sand	
+6 - 0	clay	K8
0 - -1	peat	K7
-1 - -4	peat/clay/sand/loam	K5
-4 - -16	fine to medium sand	K2
-16 - -18	course sand and gravel	K1
-18 - ...	sandy clay to clay	T5

Table 5 Schematized lithostratigraphy in the investigation area ("De Fonteintjes").

4.2 Water quality

The geophysical logs were roughly interpreted in the field to obtain the necessary information for the proper installation of the well screen (6 screens in total) and the plugging of clay layers. The location of the aquifer was determined and the pore water salinity estimated.

4.2.1 Water samples

After ample resting time, the monitoring wells were pumped clean and a ground water sample from each well was taken for analysis.

Only the parameters that influence the water salinity were analized. The sum of cations and anions in mg/l is related to the salinity, given by the TDS or total dissolved solids. The relation between TDS, salinity and water type (De Moor and De Breuck, 1969) is given in table 14.

Another way to express the salinity uses the classification of Stuyfzand (Stuyfzand, 1986). The interpretation of the analytical data results in a water type; the different types express different salinities.

In the following tables (6 to 12) the analytical data of six ground water samples (one for each piezometer) and one surface water (pond) are given.

SB1F1 ground water analysis					
Conduct. µS/cm					22300.00
pH					7.32
Tot. hardness °F					358.68
cations	mg/l	meq/l	anions	mg/l	meq/l
Na^+	4655.00	202.391	Cl^-	8537.00	240.750
K^+	201.00	5.141	SO_4^{2-}	1119.10	23.315
Ca^{2+}	307.69	15.361	NO_3^{2-}	8.40	0.135
Mg^{2+}	632.00	51.974	NO_2^{2-}	0.01	0.000
$Fe^{3+/2+}$	1.12	0.041	HCO_3^-	1022.36	16.76
Mn^{2+}	0.17	0.006	PO_4^{3-}	3.15	0.099
NH_4^+	2.83	0.157	CO_3^{2-}	0.00	0.000
sum	5799.81	275.071	sum	10690.02	281.060
error %					1.08
TDS mg/l					16489.83
class					S - moderate salt

Table 6 Ion balance and salinity for sample SB1F1

SB1F2 ground water analysis					
Conduct. µS/cm					7990.00
pH					7.21
Tot. hardness °F					126.27
cations	mg/l	meq/l	anions	mg/l	meq/l
Na^+	1472.00	64.000	Cl^-	2552.00	71.968
K^+	99.20	2.537	SO_4^{2-}	60.51	1.261
Ca^{2+}	109.30	5.457	NO_3^{2-}	5.00	0.081
Mg^{2+}	203.50	16.735	NO_2^{2-}	0.00	0.000
$Fe^{3+/2+}$	0.19	0.007	HCO_3^-	1056.52	17.320
Mn^{2+}	0.06	0.002	PO_4^{3-}	6.47	0.204
NH_4^+	12.00	0.665	CO_3^{2-}	0.00	0.000
sum	**1916.25**	89.404	sum	**3680.50**	90.834
error %					0.79
TDS					5596.75
class					B - brackish

Table 7 Ion balance and salinity for sample SB1F2.

SB2F1 ground water analyses					
Conduct. µS/cm					28900.00
pH					6.93
Tot. hardness °F					468.64
cations	mg/l	meq/l	anions	mg/l	meq/l
Na^+	6725.00	292.391	Cl^-	12287.00	346.503
K^+	259.90	6.648	SO_4^{2-}	463.62	9.659
Ca^{2+}	412.96	20.617	NO_3^{2-}	39.00	0.629
Mg^{2+}	872.00	71.711	NO_2^{2-}	0.00	0.000
$Fe^{3+/2+}$	0.50	0.018	HCO_3^-	2309.46	37.860
Mn^{2+}	0.09	0.003	PO_4^{3-}	4.46	0.141
NH_4^+	11.90	0.660	CO_3^{2-}	0.00	0.000
sum	**8282.35**	392.048	sum	**15103.54**	394.792
error %					0.35
TDS					23385.89
class					S - moderate salt

Table 8 Ion balance and salinity for sample SB2F1

SB2F2 ground water analysis					
Conduct. µS/cm					2990.00
pH					7.49
Tot. hardness °F					30.20
cations	mg/l	meq/l	anions	mg/l	meq/l
Na^+	387.50	16.848	Cl^-	365.00	10.293
K^+	55.10	1.409	SO_4^{2-}	11.11	0.231
Ca^{2+}	36.63	1.779	NO_3^{2-}	4.70	0.076
Mg^{2+}	45.50	3.742	NO_2^{2-}	0.00	0.000
$Fe^{3+/2+}$	1.30	0.047	HCO_3^-	866.20	14.200
Mn^{2+}	0.16	0.006	PO_4^{3-}	7.24	0.229
NH_4^+	9.00	0.499	CO_3^{2-}	0.00	0.000
sum	**534.19**	24.330	sum	**1254.25**	25.029
error %					1.42
TDS					1788.44
class					A - moderate brackish

Table 9 Ion balance and salinity for sample SB2F2.

SB3F1 ground water analysis					
Conduct. µS/cm					21600.00
pH					7.24
Tot. hardness °F					338.61
cations	mg/l	meq/l	anions	mg/l	meq/l
Na^+	4825.00	209.783	Cl^-	8617.00	243.006
K^+	202.90	5.190	SO_4^{2-}	1043.74	21.745
Ca^{2+}	380.57	19.000	NO_3^{2-}	10.00	0.161
Mg^{2+}	566.00	46.546	NO_2^{2-}	0.00	0.000
$Fe^{3+/2+}$	1.41	0.051	HCO_3^-	1038.22	17.020
Mn^{2+}	0.24	0.009	PO_4^{3-}	2.08	0.066
NH_4^+	4.60	0.255	CO_3^{2-}	0.00	0.000
sum	**5980.72**	280.833	sum	**10711.04**	281.998
error %					0.21
TDS					16691.76
class					S - moderate salt

Table 10 Ion balance and salinity for sample SB3F1

SB3F2 ground water analysis					
Conduct. µS/cm					3780.00
pH					7.63
Tot. hardness °F					49.41
cations	mg/l	meq/l	anions	mg/l	meq/l
Na^+	649.50	28.239	Cl^-	784.00	22.109
K^+	73.70	1.885	SO_4^{2-}	6.17	0.129
Ca^{2+}	55.06	2.749	NO_3^{2-}	4.70	0.076
Mg^{2+}	85.50	7.031	NO_2^{2-}	0.00	0.000
$Fe^{3+/2+}$	0.42	0.015	HCO_3^-	1111.42	18.220
Mn^{2+}	0.04	0.001	PO_4^{3-}	5.39	0.170
NH_4^+	8.20	0.455	CO_3^{2-}	0.00	0.000
sum	**872.42**	40.376	sum	**1811.58**	40.704
error %					0.41
TDS					2684.10
class					A - moderate brackish

Table 11 Ion balance ans salinity for sample SB3F2.

surface water analysis					
Conduct. µS/cm					681.00
pH					8.57
Tot. hardness °F					20.12
cations	mg/l	meq/l	anions	mg/l	meq/l
Na^+	61.60	2.678	Cl^-	115.80	3.266
K^+	13.35	0.341	SO_4^{2-}	17.36	0.362
Ca^{2+}	52.63	2.628	NO_3^{2-}	2.30	0.037
Mg^{2+}	13.60	1.118	NO_2^{2-}	0.01	0.000
$Fe^{3+/2+}$	0.31	0.011	HCO_3^-	148.84	2.440
Mn^{2+}	0.03	0.001	PO_4^{3-}	0.19	0.006
NH_4^+	0.08	0.004	CO_3^{2-}	26.40	0.880
sum	**141.60**	6.782	sum	**310.90**	6.991
error %					1.51
TDS					452.50
class					V - moderate fresh

Table 12 Ion balance and salinity for surface water sample.

Table 13 summarizes the TDS and conductivity results.

sample	TDS mg/l	conductivity (room temp.) µS/cm	class *	type **
SB1F1	16490	22300	S moderate salt	Bs8-$NaCl^{o}$ brackish-salt
SB1F2	5597	7990	B brackish	Bs6-$NaCl^{+}$ brackish-salt
SB2F1	23386	28900	S moderate salt	S8-$NaCl^{o}$ salt
SB2F2	1788	2990	A moderate brackish	B4-$NaHCO_3^{+}$ brackish
SB3F1	16692	21600	S moderate salt	Bs8-$NaCl^{o}$ brackish-salt
SB3F2	2684	3780	B brackish	B5-$NaCl^{+}$ brackish
pond	452	681	V moderate fresh	F3-$CaHCO_3^{o}$ fresh

* **De Moor and De Breuck 1969**
** **Stuyfzand, 1986**

The groundwater of all three deep wells is moderatly salt (TDS between 12800 and 25600 mg/l) according to the classification De Moor and De Breuck and moderatly brackish (site 2 and 3) or brackish (site 1) for the shallow wells. According to the Stuyfzand classification the groundwater of all wells is brackish to salt and the water of the pond is fresh.

In the latter classification, the suffix "-" points to a (former) salt water intrusion, the extention "+" to a (former) fresh-water encroachment and the suffix "0" to a equilibrium. The deep aquifer (F1) is in equilibrium, while the shallow zone (F2) is characterized by a (former) fresh-water encroachment.

TDS-values and the Stuyfzand water type are indicated on figure 7 for the different samples.

4.2.2 Resisivity profile.

4.2.2.1 Theory

De Moor and De Breuck, 1969 defined nine water types based on the TDS. The pore water resistivity and sediment resistivity can be used to determine the water type with this classification. The relation is given in the following formulas.

$$TDS = (\frac{10000}{\rho_w})$$

and

$$\rho_{sed'} = F * \rho_w$$

with F= formation factor, chosen as 3.2

The classification is given in the following table (number 14).

resistivity group	water quality	TDS in mg/l	pore water resistivity in ohm.m	sediment resistivity in ohm.m
G	very fresh	<200	50	>160
W	fresh	200-400	50-25	160-80
V	moderate fresh	400-800	25-12.5	80-40
F	weak fresh	800-1600	12.5-6.25	40-20
A	moderate brackish	1600-3200	6.25-3.12	20-10
B	brackish	3200-6400	3.12-1.56	10-5
C	very brackish	6400-12800	1.56-0.78	5-2.5
S	moderate salt	12800-25600	0.78-0.39	2.5-1.25
Z	salt	>25600	<0.39	<1.25

Table 14 Relation between TDS, pore water - and sediment resistivity and ground water salinity according to De Moor and De Breuck, 1969.

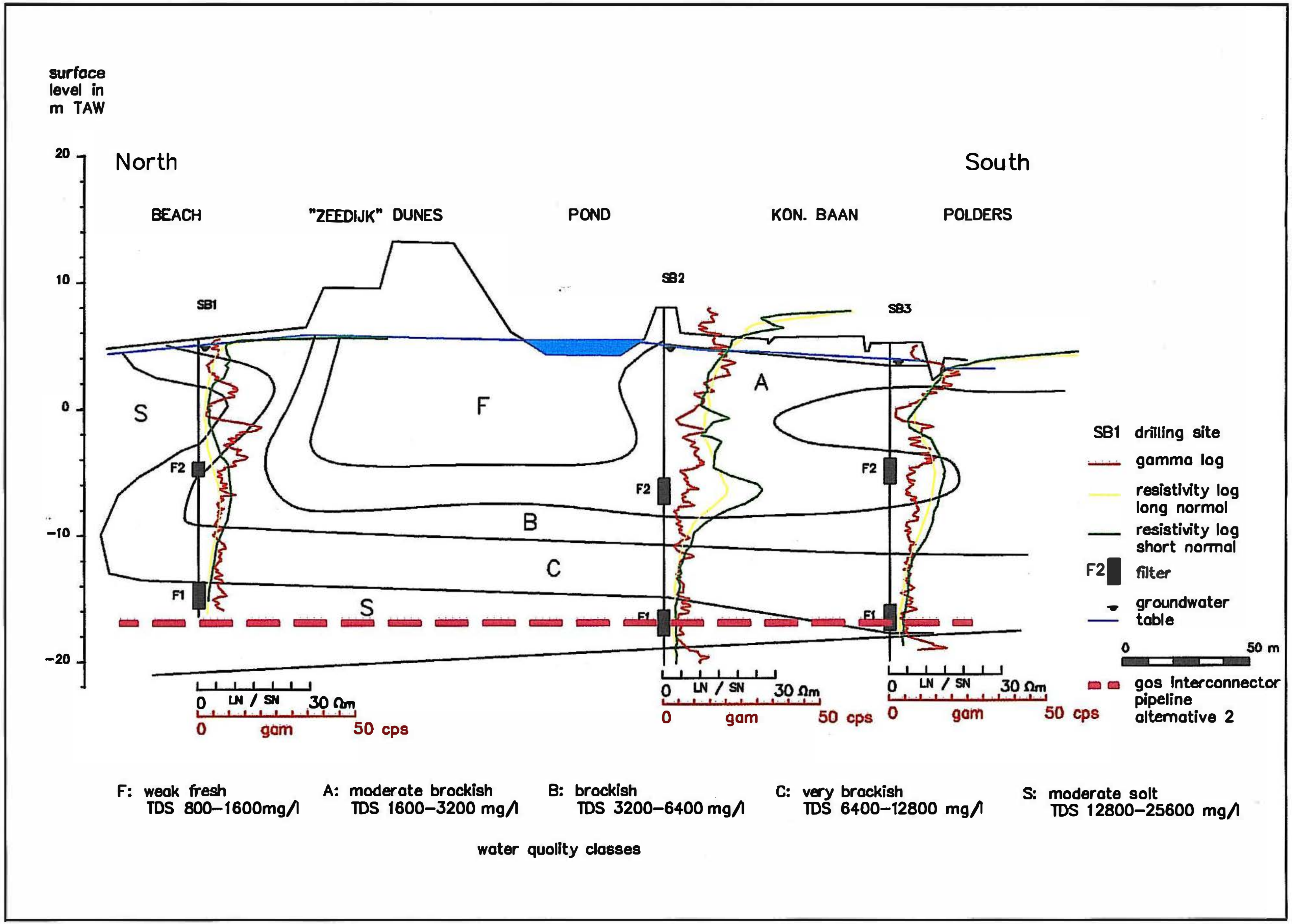

Figure 6 Resistivity profile through the investigated area.

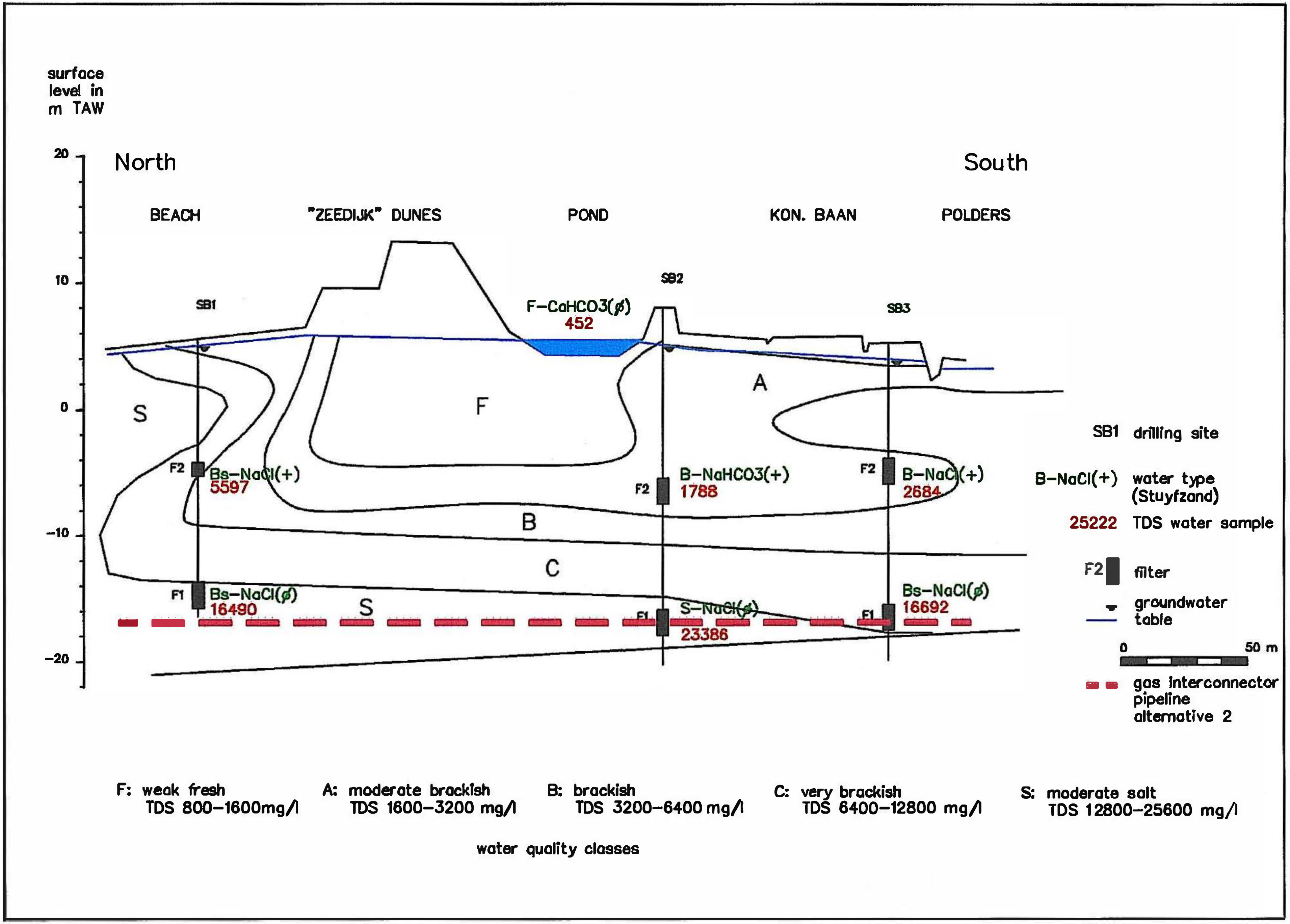

Figure 7 Water type, TDS value and resistivity profile.

4.2.2.2 Results

Since the LN resistivity log is more representative for the true sediment resistivity value, this log is used rather than the short normal. The TDS and thus the ground water salinity with depth is derived from the LN log for each site. The points of equal resistivity (class limits) are connected resulting in the resistivity or water quality cross section (Fig. 6 and 7).

The cross section shows the dominance of salt to brackish ground water in most places. Under the pond and the dune belt lies a limited (in depth) zone with fresh to moderately fresh ground water. The groundwater below level -10 is very brackish or even saline.

The pore water in the sand layer below the peat/loam/clay/sand complex is brackish to salt. The salinity increases towards the sea. Below the beach the salt- / fresh-water interface is at shallow depth, with a very small zone between -2 and -10 that is less salty (with still high TDS levels). Towards the polders, the salt pore water lies very close to the surface. In the nature reserve "De Fonteintjes", the pore water of the upper layers is moderately fresh (possibly fresh in the upper metres); (fig. 6 and 7).

The analytical data (water samples) confirm the measured resistivities of the groundwater and the resistivity profile.

Since only one value for formation factor (3.2) is used, despite differences in lithology, the actual salinity may be slightly different from the one indicated in the figures. This might be the case for the peat layer and for the very fine deposits (clay layer). This deviation is however very small for sand layers and especially in those filled with brackish to salt ground water. Correction for the formation factor could only lead to a reduction of the fresh water zone below the dunes and the pond and an increase in the salt or brackish groundwater zone.

4.3 Groundwater flow

4.3.1. Principle

In the observation wells groundwater levels were measured. Before the measurements the wells were pumped so that the whole water column in the well had the same quality and the same density. The depth of the ground water (in m versus the top of the well tube) gives the hydraulic head for the piezometer in m.by subtracting the depth from the level of the measuring point (top piezometer).

For the determination of the ground water flow, only the data at sites 2 and 3 and the surface water are used; site 1 is too much influenced by the tidal movements.

4.3.2 Vertical groundwater flow.

The vertical groundwater flow is given by the difference in hydraulic head between the upper and the lower screen. When the head of the upper filter (F2) is higher than that of the lower (F1), there is a downward movement; in the opposite case, the groundwater flows upward.

The change in water quality (salinity) between F1 and F2 influences the hydraulic head, therefore the head values have to be corrected for the salt content. From the resistivity of the water in the well the density can be deduced from the relation between the resistivity and the TDS and the density of the water. Once the density of the water column and the location of the screen are known, one can deduce from the measured hydraulic head the fresh water head.

In both cases the measured hydraulic head of F2 is slightly higher than that of F1. Thus one may assume a slightly downward groundwater flow, from the top (less salty) towards the bottom (salty) of the aquifer. The head difference is 0.21 m.

filter	TDS in mg/l	measured head in m TAW	fresh water head in m TAW
SB1F1	16490	+3.45	+3,68
SB1F2	5597	+3.41	+3,44
SB2F1	23386	+2.83	+3,18
SB2F2	1788	+3.04	+3,05
SB3F1	16692	+2.87	+3,11
SB3F2	2684	+3.01	+3,03

Table 15 Measured and corrected hydraulic head.

After correction the head difference between F2 and F1 is about 0.1 m for site 1, 0.5 m for site 2 and 0.3 m for site 3. In all three cases the vertical groundwater flow is downward.

The differences in fresh-water head between site 2 and 3 are too small to be significant and do not allow any conclusions about the horizontal groundwater flow.

4.3.3 Conclusion

At the three sites there is a small downward groundwater flow. Between site 2 and 3 there seems to be no horizontal ground waterflow.

Since only a single set of data was used, these conclusions should be used with the greatest caution. Regular measurements of water levels and the TDS for the different wells (and further tests - pumping, modelling) are necessary to determine both horizontal and vertical groundwater movements.

5 EVALUATION OF ALTERNATIVES

The projected trajectory indicated in the figures is only one of three possible alternatives for the connection low water line - reception terminal.

Two sites have been chosen for the transect low water line - Koninklijke Baan. Location 1 follows the Londenstraat, for this location two alternatives exist: 1a and 1b. Alternative 1a uses the directional drilling method under the Londenstraat for the construction, alternative 1b is a standard cut and cover method with jackings under the roads. Location 2 (alternative 2) is the one that has been indicated on figures 1,5,6 and 7. It also uses the directional drilling method between the low water line and the Koninklijke Baan. In both alternative 1a and 2, the pipeline lies between 30 and 23 m depth, corresponding to level -17 m.

From a hydrogeological and especially groundwater quality point of view, the constructi-on in depth, that is around level -17 (or at least below -10) is to be prefered over the cut and cover method. With the directional drilling in depth, the pipeline will be constucted in a very brackish to salty ground water zone. The pipeline trajectory nowhere crosses a zone with fresh or moderately fresh groundwater. The small fresh water reservoir in the upper layer could become contaminated with the cut and cover method. With the directional drilling method both locations (alternative 1a and 2) are equally suited.

6 CONCLUSION

Field investigations for the construction of the Interconnector Pipeline Bacton-Zeebrugge between the landfall point and the Reception Terminal were focused on a small area between the low water line and the Koninklijke Baan, better known as "De Fonteintjes".

Since the construction of a pipeline (cut and cover method or directional drilling) through a biologically important zone might disturb the fresh-water lens below the pond and the dune belt more information about the quality of the groundwater was needed.

Reverse-circulation rotary drillings with geophysical loggings have been made. Observation wells were installed in the boreholes. In these wells groundwater has been sampled and analyzed.

Water levels were measured and hydraulic heads were calculated.

The lithological cross section shows that between -4 and the Tertiary substratum (at -18) only present; occasionally thin clay or loam lenses occur. Near the bottom the sand is coarser; it also contains many shell fragments.

Above the sand lies a complex of peat, loam and sand (site 1); clay and loam (site 2) or loam and sand (site 3). This unit is some 4 m thick. On top of it lies 0.5 to 3 m peat. Above the peat and up to level +6 (surface) mainly clay and loam occur. At the beach the clay was eroded and replaced by sand. A pond is located in a small dune belt.

The resistivity loggings confirmed by the water analyses disclose the presence of only a very small lens of fresh to moderately fresh groundwater. Below level -10 the groundwater is very brackish to moderately salt. In site 1 the brackish to salt groundwater is found near the surface. There is no fresh-water lens under the beach.

In alternative 2, the pipeline will be constructed with the directional drilling method in the sand layer at level -17, below the loam/peat/clay/sand complex (Fig. 5, 6 and 7). At that depth the groundwater is moderately salt, containing 12800 to 25600 mg/l salt. With the cut and cover method the risk for contamination is higher because there, the pipeline would be constructed in the upper part of the aquifer, where water of moderately quality (weak fresh or possibly fresh) is present, at least in part of the transect (below the dunes and water pond.

The directional drilling method for the construction of the pipeline is to be preferred over the cut and cover method, since the latter will cut through a section of the fresh groundwater zone (to a depth of about 5m). Precautions would have to be taken to preserve the quality of the water in the pond and the fresh water lens and to maintain the level in the pond. The former method will have no influence on the quality and the level of the pond since the borehole will be cut entirely in the salt-water zone below the -10 level.

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APPENDIX

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Krijgslaan 281 - S8, 9000 Gent tel. 09/2644647 fax. 09/2644988
Gas Interconnector Pipeline Bacton-Zeebrugge - TGO 94/01 - phase II drilling
Contact P. Vermoortel Y 09/2644645

PROJECT: 94/01
NR DRILLING: SB1F1&F2
DATE: 25 april 1994
DESCRIPTION BY: Y. Vermoortel
DRILLING FIRM: LTGH
MATERIAL: SPOBO1
NGI map: 5/5
MUNICIPAL: Zeebrugge - BRUGGE
LAMBERT X: Y: Z: +5.56 m TAW
surface
DRILLING METHOD: Direct rotary
DIAMETER DRILL BIT: 125 mm
TYPE FLUSHING: water

FILTER	DTS	DBS	LTC	LGW	AQ
F1 F2	19.3 9.8	21.5 10.8	+5.76 +5.76	+3.45 +3.41	1 1

DTS: Depth to top screen
DBS: Depth to base screen
LTC: Level in m of measuring point for groundwater
LGW: Level groundwater
AQ: Type aquifer
1: unconfined 2: other

Several screens in one bore hole: Yes No

Type well tube: PVC 63/58 mm (F1) PVC 40 mm (F2)
well screen: PVC 63/58 mm (F1) PVC 40 mm (F2)
connections: limed

Filterslots: type: horizontal sawcuts
size: 0.3 mm

Casing: calibrated sand 0.7 to 1.25 mm
from 22.0 to 16.2
from 12.2 to 8.2

Clay plugs: type: compactonit pellets
from 16.2 to 12.2
from 8.2 to 1.3

Completion: surface

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Contact P. Vermoortel Y 09/2644645

PROJECT: 94/01
NR DRILLING: SB2F1
DATE: 19 april 1994
DESCRIPTION BY: Y. Vermoortel
DRILLING FIRM: LTGH
MATERIAL: SPOBO1
NGI map: 5/5
MUNICIPAL: Zeebrugge - BRUGGE
LAMBERT X: Y: Z: +8.10 m TAW surface
DRILLING METHOD: Direct rotary
DIAMETER DRILL BIT: 125 mm
TYPE FLUSHING: water

FILTER	DTS	DBS	LTC	LGW	AQ
F1	24	26	+ 8.07	+2.83	1

DTS: Depth to top screen
DBS: Depth to base screen
LTC: Level in m of measuring point for groundwater
LGW: Level groundwater
AQ: Type aquifer
1: unconfined 2: other

Several screens in one bore hole: Yes No

Type well tube: PVC 63/58 mm
well screen: PVC 63/58 mm
connections: limed

Filterslots: type: horizontal sawcuts
size: 0.3 mm

Casing: calibrated sand 0.7 to 1.25 mm
from 28 to 15
from to

Clay plugs: type: compactonit pellets
from 15 to 1
from to

Completion: below surface

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Gas Interconnector Pipeline Bacton-Zeebrugge - TGO 94/01 - phase II drilling
Contact P. Vermoortel Y 09/2644645

PROJECT: 94/01
NR DRILLING: SB2F2
DATE: 22 april 1994
DESCRIPTION BY: Y. Vermoortel
DRILLING FIRM: LTGH
MATERIAL: SPOBO1
NGI map: 5/5
MUNICIPAL: Zeebrugge - BRUGGE
LAMBERT X: Y: Z: +8.10 m TAW
surface
DRILLING METHOD: Direct rotary
DIAMETER DRILL BIT: 125 mm
TYPE FLUSHING: water

FILTER	DTS	DBS	LTC	LGW	AQ
F2	13.5	15.5	+8.04	+3.04	1

DTS: Depth to top screen
DBS: Depth to base screen
LTC: Level in m of measuring point for groundwater
LGW: Level groundwater
AQ: Type aquifer
1: unconfined 2: other

Several screens in one bore hole: Yes No

Type well tube PVC 63/58 mm
well screen: PVC 63/58 mm
connections: limed

Filterslots: type: horizontal sawcuts
size: 0.3 mm

Casing: calibrated sand 0.7 to 1.25 mm
from 15.5 to 10.3
from to

Clay plugs: type: compactonit pellets
from 10.3 to 6.5
from to

Completion: below surface

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Gas Interconnector Pipeline Bacton-Zeebrugge - TGO 94/01 - phase II drilling
Contact P. Vermoortel Y 09/2644645

PROJECT: 94/01
NR DRILLING: SB3F1
DATE: 20 april 1994
DESCRIPTION BY: Y. Vermoortel
DRILLING FIRM: LTGH
MATERIAL: SPOBO1
NGI map: 5/5
MUNICIPAL: Zeebrugge - BRUGGE
LAMBERT X: Y: Z: +5.20 m TAW
surface
DRILLING METHOD: Direct rotary
DIAMETER DRILL BIT: 125 mm
TYPE FLUSHING: water

FILTER	DTS	DBS	LTC	LGW	AQ
F1	20	22	+5.02	+2.87	1

DTS: Depth to top screen
DBS: Depth to base screen
LTC: Level in m of measuring point for groundwater
LGW: Level groundwater
AQ: Type aquifer
1: unconfined 2: other

Several screens in one bore hole: Yes No

Type well tube: PVC 63/58 mm
well screen: PVC 63/58 mm
connections: limed

Filterslots: type: horizontal sawcuts
size: 0.3 mm

Casing: calibrated sand 0.7 to 1.25 mm
from 25.6 to 16
from to

Clay plugs: type: compactonit pellets
from 16 to 10
from to

Completion: below surface

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Contact P. Vermoortel Y 09/2644645

PROJECT: 94/01
NR DRILLING: SB3F2
DATE: 21 april 1994
DESCRIPTION BY: Y. Vermoortel
DRILLING FIRM: LTGH
MATERIAL: SPOBO1
NGI map: 5/5
MUNICIPAL: Zeebrugge
LAMBERT X: Y: Z: +5.20 m TAW
surface
DRILLING METHOD: Direct rotary
DIAMETER DRILL BIT: 125 mm
TYPE FLUSHING: water

FILTER	DTS	DBS	LTC	LGW	AQ
F2	10	12	+5.12	+3.01	1

DTS: Depth to top screen
DBS: Depth to base screen
LTC: Level in m of measuring point for groundwater
LGW: Level groundwater
AQ: Type aquifer
1: unconfined 2: other

Several screens in one bore hole: Yes No

Type well tube: PVC 63/58 mm
well screen: PVC 63/58 mm
connections: limed

Filterslots: type: horizontal sawcuts
size: 0.3 mm

Casing: calibrated sand 0.7 to 1.25 mm
from 12.5 to 8.6
from to

Clay plugs: type: compactonit pellets
from 8.6 to 3.0
from to

Completion: surface