PUMPING BRACKISH GROUNDWATER TO PREPARE DRINKING WATER AND KEEP SALINIZING WELLS FRESH: A FEASIBILITY STUDY

Ir. J.W. KOOIMAN✉, P. J. STUYFZAND, C. MAAS and J.W.N.M. KAPPELHOF

Kiwa Water Research, PO Box 1072, 3430 BB Nieuwegein, Netherlands,
E-mails: jan.willem.kooiman@kiwa.nl;
pieter.stuyfzand@kiwa.nl;
kees.maas@kiwa.nl;
joost.kappelhof@kiwa.nl

Abstract

Rapid technological improvements in membrane technology have made the production of fresh drinking water from brackish groundwater more economically viable. Currently, 525 Mm^3/yr of fresh water can be produced from purely brackish water in The Netherlands; with 375 Mm^3/yr from the western, salinized parts, and 150 Mm^3/yr from below Lake Yssel. This is about half the present volume of fresh water used in The Netherlands annually. Some restrictions for using this source are mentioned, concerning geohydrology and groundwater quality. In the last 30 years a significant amount of well fields have been threatened by brackish water upconing. To preserve these well fields, fresh and brackish groundwater are recovered separately, thus keeping the brackish groundwater away from the fresh well. The risk of brackish upconing was assessed by a new risk-index SAPORE (SAlinizaton POtential for water REsources). Forty-three well fields with an aggregate drinking water production of 150 Mm^3/yr were classified as 'high risk'. The overall conclusion is that exploiting brackish water is no longer a ubiquitous problem, but challenges do persist. Huge amounts of good quality brackish water can be used, and many desalinizing well fields can be made sustainable concerning salinization.

Keywords: brackish groundwater, pumping groundwater, salinization, risk assessment, fresh holder

Introduction

Rapid technological improvements in membrane technology have made the production of fresh drinking water from brackish groundwater more economically viable. We propose two ways to use brackish groundwater through reverse osmosis:

✉ Corresponding author

a) as 100% direct water source;
b) as a partial source (<50%) to preserve those well fields which are threatened by the upconing of brackish or saline water. The latter case is called the 'Fresh Holder' and was first presented at SWIM-17, in 2002 (Grakist et al, 2002).

The use of brackish groundwater (chloride 300-10,000 mg/L) also has important advantages. The world-wide reserves are large, the quality is generally unimpeachable regarding the microbiology and presence of organic pollutants, and pumping creates less environmental impacts. Disadvantages include the relatively high energy consumption of the membranes and the necessity to discharge the membrane 'disposal', with high chloride-contents, to surface water or by deep well infiltration in the saline aquifers (Stuyfzand, 2003a, 2003b).

The principle of Brackish Groundwater Abstraction, as presented at the previous SWIM is outlined here as a reminder. We will then describe the occurrence of brackish water in The Netherlands. In the following paragraphs two methods of using brackish groundwater are presented. Finally, in the last paragraphs, some non-hydrological feasibility aspects concerning the abstraction of brackish groundwater are discussed.

The principle

Figure 1 shows the operational principles in three figures. On the left a salinizing well, threatened by upconing of brackish water. In the middle a solution for this well: The Fresh Holder. In this case, fresh and brackish groundwater are recovered separately. By this partial abstraction of brackish water below the fresh filter screen, we can keep the fresh screen fresh. On the right, the brackish water well: 100% brackish water, no fresh water abstraction.

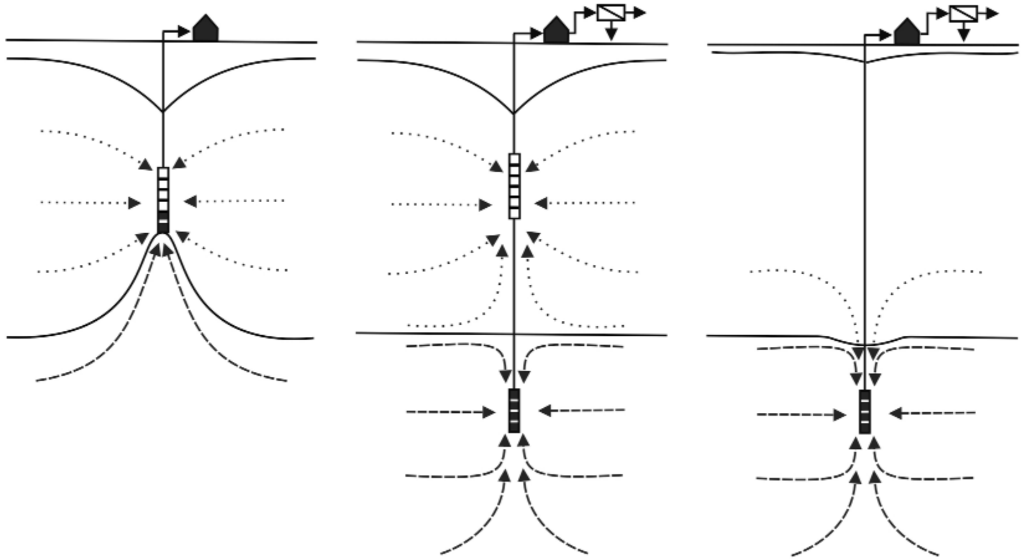


Figure 1. Schematic presentation of a salinizing well, the fresh-holder and a brackish well.

The membranes can be applied without any pretreatment of the anaerobic brackish water (Figure 2). The need for chemicals to prevent the membranes from fouling is minimized by choosing a low recovery rate (50%). This results in a moderately brackish concentrate, with minimal additions, to be disposed of.

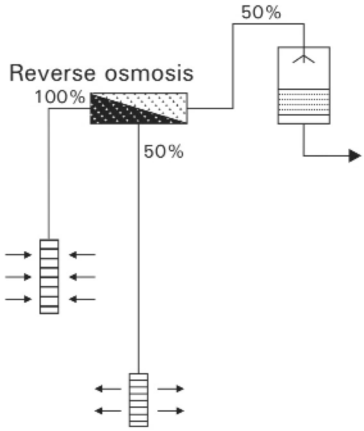


Figure 2. The pretreatment of the brackish groundwater with membranes

The occurrence of brackish groundwater in the netherlands

Figure 3 shows a map with the depth of the fresh-brackish interface (chloride content 150 mg/l) in The Netherlands and a West-East cross-section. It is worth to notice that the vertical scale is a few hundreds of meters, while the horizontal scale extends over some 300 km, so in reality the fresh/brackish water lens is like a pancake.

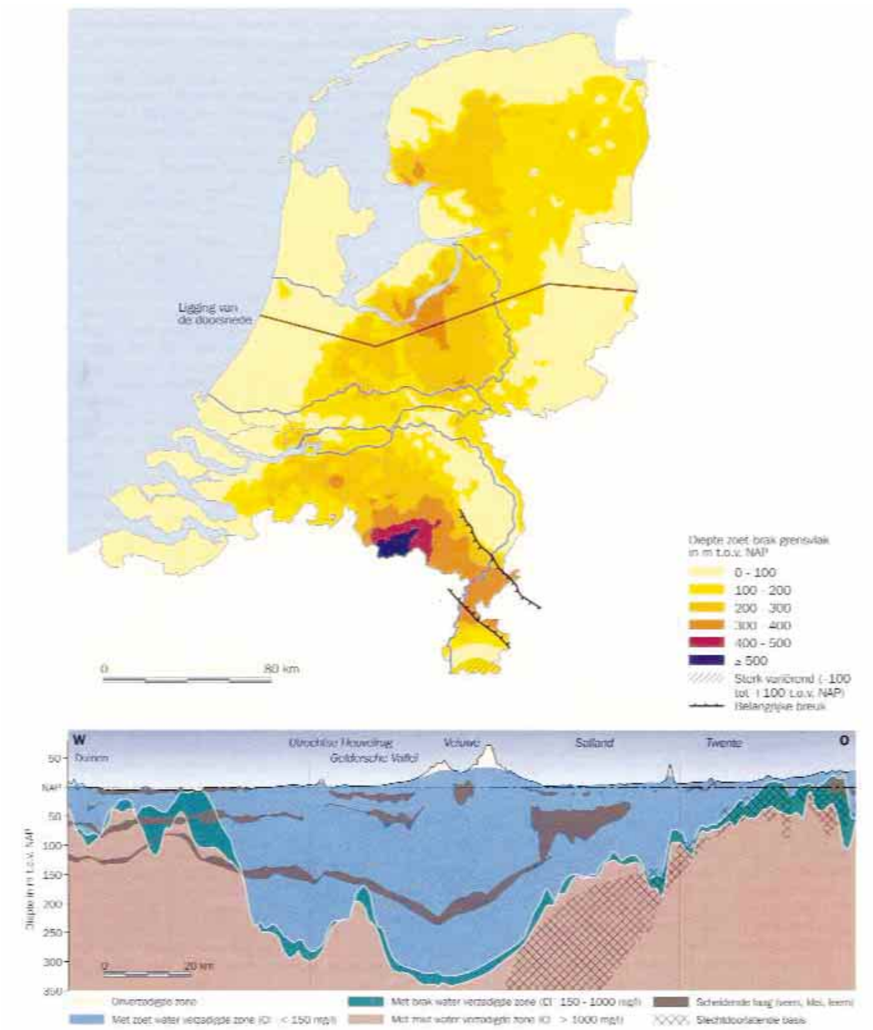
Relatively small depths are found in the western and northern parts, roughly along the North Sea coast, and in a small part along the east boundary. The thickness of the brackish zone varies from 5 to 500 m. The thinnest (5-20 m) sections were found along the coast (1,5–5 km inwards), due to seawater intrusion, where salt water is found at relatively small depths. At other places, further land inwards, the thickness reaches more than 60 m, and at some places, it extents to more than 100 m. Nowadays there are too many uncertainties concerning the small area along the east boundary. The use of brackish groundwater in The Netherlands is thus restricted to the western and northern parts.

BrackIsh water as a 100% source

The amount of brackish groundwater available

In the 'fresh' part of The Netherlands (some two-third of the total area, in the eastern and southern parts, as shown in Figure 3), groundwater abstraction is limited to some 40 mm/yr. Extrapolation of this amount to include the brackish part, predicts a maximum availability of 500 Mm^3/yr of brackish groundwater. Restrictions are due to the chloride content (<8000 mg/L). Figure 4 gives the average chloride content from the upper part (10 meter) of the abstraction aquifer, which shows that 25% of the 'brackish' area is not feasible. Therefore, the real amount of brackish water to be used for drinking water purposes reduces to 375 Mm^3/yr, with an economic value of 450 million Euros/yr.

Groundwater below Lake Yssel, a former sea branch located in the middle-north of The Netherlands, is brackish. Nowadays no abstraction takes place, but in the near future, technical improvements in abstraction technology, e.g. horizontal directional drilling (HDD), will probably provide the possibility. Because no or very small negative environmental effects will occur, a 'double' amount of groundwater



Translation of texts in Dutch:

– Ligging van de doorsnede	– Cross-section West-East
– Diepte zoet-brak grensvlak in m t.o.v. NAP	– Depth fresh-brackish interface in m-MSL
– Onverzadigde zone	– Unsaturated zone
– Met brak water verzadigde zone	– Zone saturated with brackish water
– Scheidende laag (veen, klei, leem)	– Separating layer (peat, clay, loam)
– Met zoet water verzadigde zone	– Zone saturated with fresh water
– Met zout water verzadigde zone	– Zone saturated with salt water
– Slechtdoorlatende basis	– Semi-confining basis

Figure 3. Depth of the fresh-brackish interface: map of The Netherlands and W-E cross-section (source: NITG-TNO Dutch Institute of Applied Geosciences)

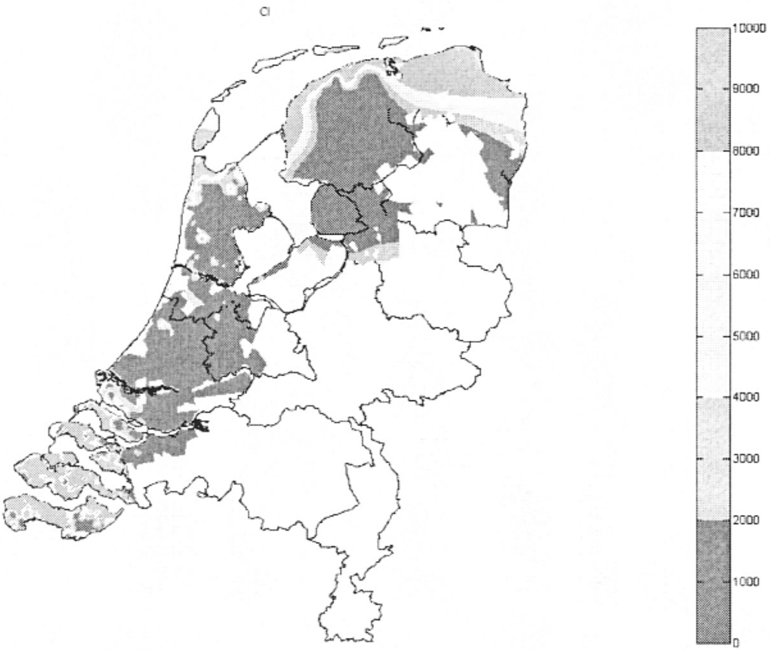


Figure 4. Average chloride content from the upper part (10- meter) of the abstraction aquifer (Pleistocene aquifer)

(~ 80 mm/yr) can be abstracted, providing a yearly yield of 150 Mm^3, representing an economic value of some 180 million Euros/yr.

The total amount of brackish water which can be directly (100%) used for drinking water purposes, in the western, salinized parts of the Netherlands and in aquifers below Lake Yssel, is estimated at 525 Mm^3/yr. This is about half the present volume of fresh groundwater used annually (1100 Mm^3/yr).

Conditions

Not all brackish water bodies seem favourable for exploitation. Brackish groundwater can be used for drinking water purposes under the following conditions:

1. The depth of the aquifer is not too deep (e.g. < 300 m) for economical reasons.
2. The gradient in the chloride content is small (e.g. <10 mg chloride $L^{-1}m^{-1}$).
3. The hydraulic conductivity (K_h) and the thickness (D) of the aquifer are high enough (e.g. K_hD > 200 m^2/day).
4. The chloride content is favourable (results and costs) for optimum membrane purification (< 8000 mg/L preventing problems in membrane purification).
5. Also the concentrations of other ions are favourable concerning risks on scaling of membranes with for instance barium sulphate, carbonate, phosphate or silicate minerals.
6. The abstraction must be sustainable: no salinization or 'sweetening' of groundwater, no well clogging or corrosion should be produced.

The favourable regions

It is difficult to find locations which fulfil all conditions, so compromises are necessary. A rough screening of the possible areas results in three regions relatively favourable (Figure 5):

a. The Rhine/Meuse estuary, from 60-300 m.b.s.l.
b. Lake Yssel, from 100-250 m.b.s.l.
c. The eastern polder area of the province of South-Holland, from 30-120 m.b.s.l.

Figure 5. Three regions in The Netherlands relatively favourable for the use of brackish water

Brackish water as a partial source (Fresh holder)

The risk of brackish water upconing is always an important threat for an important number of (drinking water) well fields in The Netherlands. In the last 30 years a significant number of well fields have been abandoned or replaced due to severe salinization, and another relevant number of well fields present a high risk of suffering sooner or later from brackish water upconing. By means of a desk-study, using a large number of groundwater quality-data, the extent of the problem is estimated. Therefore the database of Stuyfzand (1996), presented at the SWIM-14, was extended with more and more recent data.

Risk-index

The risk of brackish water upconing was assessed by a new risk-index 'SAPORE' (Salinization Potential for water REsources). 'Sapore' means taste (Italian), since salt gives water a typical taste.

This index is based on 7 sub-indices, each varying between –2 and +3 (see Table 1):

$SAPORE = 2{,}646\ (MAX+TREND+POS+SAL_{MAR}+SAL_{CONT}+BEX+SAL_{RISK})\ /\ N^{1/2}$

where:

MAX = Maximum chloride content of the raw water in the year 2000 is critical. Value is +3 as Cl>300 mg/L, etc.

TREND = Current trend in salinity of the water pumped in the period 1970-1992. A positive trend gives a value of +1.

POS = The position of the pumping wells relative to the fresh/brackish interface (150 mg/L). Less than 10 meters between filter screen and interface gives a POS-value of +2, etc.

SAL_{MAR} = The origin of the salt incursion in 1992 is maritime (Stuyfzand, 1996). If yes, the value is +2.

SAL_{CONT} = The origin of the salt incursion in 1992 is continental (Stuyfzand, 1996). If yes, the value is -2.

BEX = The base exchange index (BEX, indicating either freshening or salinization).

SAL_{RISK} = A relatively rapid increase of chloride contents in the period 1992-2000 (>8 mg/L or >20%). If yes, the value is +1.

N = The number of considered indices. By lacking data in several situations it was impossible to calculate a value for all seven sub–indices.

The factor $2{,}646=\sqrt{7}$ is necessary to make the index SAPORE less dependant on the number of measured sub-indices (N). The possible values of the seven sub-indices are given in Table 1. Different options of SAPORE are tested. The version in this article gives the best fit between the calculated risk and the actual salinization.

Table 1. Brief explanation of the seven sub-indices of SAPORE, and their possible values

Code in SAPORE	Betekenis subindex	-2	-1	0	+1	+2	+3
MAX	MAXimum Cl-content in 2000 is critical (> 300 mg/l)			<100	100-200	200-300	>300
TREND	TREND in Cl-content during 1970-1992		decrease	non	increase		
POS	POSition filter screens relative to fresh/brackish interface		>50 m	20-50 m	10-20 m	<10 m	
SAL_{MAR}	origin of SALt incursion is MARitime			NO		YES	
SAL_{CONT}	origin of SALt incursion is CONTinental	YES		NO			
BEX	Base EXchange index			NO	YES		
SAL_{RISK}	Relatively rapid increase of chloride content during 1992-2000			NO	YES		

Risk Assessment

SAPORE is calculated for all 370 well fields (active or abandoned) in The Netherlands, which gives values between '9' (very high salinization risk) and '-4' (no risk). The twenty highest ranking well fields are given in Table 2.

Values '>2' indicate a higher risk on maritime salt incursion. High risks results for 43 of them, together delivering 150 Mm^3/yr of groundwater for drinking water. Their loss will endanger drinking water supply in certain regions.

Between 1880-2000, twenty well fields were closed due to salinization, together representing an amount of 15 Mm^3/year. Between 1940-1978, nine dune areas changed from groundwater extraction to Artificial Recharge with a loss of 40 Mm^3/yr of fresh groundwater.

Table 2. Twenty well fields in The Netherlands with the highest 'SAPORE'-values

Company 2002	WELL FIELD	Cl 1992	Cl-max 2000	SAPORE
Vitens	DIEPENVEEN	185	710	9.0
Vitens	CEINTUURBAAAN (DEVENTER)	132	290	8.0
Vitens	NOORDBERGUM: MIX (Jhr.v.'s-Gravesande)	88	130	7.0
Brab.Water	NULAND: MIX	88	300	7.0
Vitens	ZUTPHENSEWEG (DEVENTER)	108	195	6.0
Vitens	TWELLO	52	161	6.0
WG	DE PUNT	45	425	5.9
PWN	BERGEN: MIX	75	99	5.0
WG	HAREN	71	180	4.0
Vitens	WEERSELO	41	50	4.0
Vitens	LOSSER: MIX	30	33	4.0
Brab.Water	GENDEREN	27	32	4.0
WML	HANIK-ARCEN	43	87	4.0
Vitens	VAN VERSCHUER (LIENDEN)	44		4.0
DZH	LANGEVELD	114		4.0
WG	DE GROEVE	42	69	3.0
Vitens	BUREN (AMELAND)	77	88	3.0
Vitens	NIJVERDAL	17	67	3.0
Vitens	NOORDIJKERVELD	24	35	3.0
Hydron	HOOGEWEG (AMERSFOORT)	240	140	3.0

Pumping stations with a high 'SAPORE' can be preserved by proper use of the 'Fresh Holder' (Grakist et al., 2002). In The Netherlands the total amount of brackish water which has to be recovered for 'fresh-holder-purposes' depends on the total fresh abstraction capacity and the geohydrological conditions, e.g. the chloride contents of 'fresh' and 'brackish' groundwater, and environmental effects. Supposing a 20% brackish groundwater percentage in all 'high risk' well fields, results in a total amount of brackish groundwater of 18-40 Mm^3/yr.

Important non-hydrological Feasibility aspects of brackish groundwater abstraction for drinking water

Considering the feasibility of using brackish groundwater, more aspects have to be taken into account, which in a real feasibility-study must be calculated in more detail. We mention some points shortly:

– **Legislation** (very important).
It is important to get the right licences for groundwater abstraction, for both fresh and brackish groundwater. Using the Fresh Holder you have to imagine that the total abstraction capacity is higher than the amount of fresh water which is needed. It is important to realize that the government at this time is not familiar with brackish water abstractions, therefore it is necessary investigate the 'brain-washing' of the responsible officials. More critical, is the license to discharge the membrane concentrate with very high chloride concentrations. Deep well infiltration in salty aquifers mostly require special licences which necessitate profound (geohydrological) studies. Discharge in surface water depends on whether it is seawater or fresh water. In The Netherlands the legislative aspect is of high importance, because if no licences are given it will stop the development of this new technique. Sometimes we have to distinguish between pilot studies and real production locations, with different governmental procedures.

– **Costs.**
This is of course a very important point. Cost calculations have to be made for the specific situation. Besides costs for recovery, groundwater tax, treatment and discharge, also the suitability of the 'brackish' system in the existing 'fresh' system is important. For a traditional fresh groundwater plant, the treatment costs amounts to € 0,15 (groundwater tax) + € 0,21 (different treatment steps) = € 0,36/m^3. Using brackish groundwater the costs will be € 0,23 (reverse osmosis) + € 0,04 (post treatment) = € 0,27/m^3.

– **Environmental aspects.**
The usual environmental effects when using a groundwater well field must be considered. We can distinguish between more global effects, as calculated with the Life-Cycle-Analysis methodology (LCA), the effects on agriculture and nature, and effects of discharging the membrane concentrate. For all these effects, the normal calculation procedures can be used.

– **Sustainability and energy**
In general the sustainability of brackish groundwater well fields is comparable to the well-known fresh well fields. The specific sustainability highly depends on the specific location, and has to be calculated

for the specific circumstances. Environmental effects can be less than anticipated, because of the greater abstraction depth. Using the Fresh Holder makes well fields more sustainable concerning the chloride contents. Energy consumption, especially for membranes, is an important issue. Therefore special systems for regaining energy will be used to decrease costs.

The use of sustainable energy production significantly influences the LCA results. Only when sustainable energy sources are used (solar, wind, nuclear), brackish water desalination will be advantageous compared to fresh groundwater.

Future developments: pilot studies

Desk studies in the last few years have indicated that using brackish groundwater as a source of drinking water or as Fresh Holder seems feasible. Remaining questions have to be answered by carrying out pilot-studies for a real situation. Especially the legislative aspects need a concrete project to discuss the necessary licences. In 2004 pilot locations will be selected by two or three water companies, with experiments following in 2005-2006.

Using brackish groundwater as a source for drinking water as well as abstraction of brackish groundwater for keeping wells fresh can, in principle, be applied world-wide. There are no special restrictions. If it is feasible or cost-effective depends on local and regional circumstances, which have to be taken into account at every place. Water quality and the geohydrological system are essential parameters, if it is in The Netherlands or any other region in the world. Strict anaerobic conditions are necessary to be able to apply RO (Reverse Osmosis) on raw water. Salinity must be les than 15.000 ppm, since energy consumption and thereby, costs and environmental impact increase with salinity. The hydraulic conductivity of the aquifer must be large enough to limit the number of wells. During the extraction period a stable level of salinity is necessary (variation less than 5% per year). Other conditions have been previously mentioned.

The possibility of using brackish groundwater as a source for drinking water depends on the water quality in relation to the membranes used, and on the possibilities to remove the membrane concentrate. The key issue is whether the water company is capable to run a membrane system, which is technologically complex, in a proper way. This generally depends on the local standard of technology. The same holds for the Fresh Holder.

Conclusions

- Brackish groundwater is no longer a problem at all sites, but employing feasible exploitation methods remains a challenge.
- Brackish groundwater is an extensive unexploited source.
- Many salinizing well fields can be made sustainable.

Acknowledgements

The research project 'Brackish Groundwater' is part of the Joint Research Programme (BTO) of the Dutch Waterworks, which is carried out by Kiwa.

References

GRAKIST, G., C. MAAS, W. ROSBERGEN and J. KAPPELHOF. (2002). Keeping our wells fresh. *Proceedings of the 17th Salt Water Intrusion Meeting*, Delft, 337-340.

STUYFZAND, P.J. (1996). Salinization of drinking water in the Netherlands: anamnesis, diagnosis and remediation. *Proceedings 14th SWIM*, Malmö, Geological Survey Sweden, Uppsala: 168-177.

STUYFZAND, P.J. (2003a). Voorkomen, Kwaliteit en Winbaarheid van Brak Grondwater voor de Nederlandse Drinkwatervoorziening (in Dutch). Kiwa-report BTO 2002.152, March 2003.

STUYFZAND, P.J. (2003b). Verziltingsrisico van de Nederlandse Puttenvelden voor de Drinkwatervoorziening door Brakwateropkegeling (in Dutch). Kiwa-report BTO 2002.153, March 2003.