# Comparing methods for exploring the fresh/salt groundwater interface position in the Amsterdam water supply dunes

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## ABSTRACT

For the dune area of the Amsterdam Water Supply Dunes a number of methods for exploring the depth of the fresh/saline groundwater interface (FSI) in terms of chloride concentrations have been compared. Electrode cable measurements prove to be the most cost-effective and accurate method, especially once formation factors have been established for the sensor locations. EM39 logs, while susceptible for nearby metal conductors, were found insensitive for electrode cables. All methods fail when the FSI lies in aquitards, probably because of artefacts due to drilling fluids or fresh bore water entrapped in bentonite sealing. It may take several years for the FSI around new wells to recover from side effects of drilling.

## INTRODUCTION

The bulk of the drinking water for the city of Amsterdam (NL) and surroundings is produced in a large fresh water lens in the Amsterdam Water Supply Dunes (AWD). As the current annual production rate exceeds recharge from precipitation by a factor of 4 to 5, natural recharge is augmented by infiltration of pre-purified Rhine water. Sufficiently reliable mapping, tracking, and prediction of the fresh/salt interface (FSI) position is vital for proper management of this system. Several methods and combinations of them for explorating and monitoring the FSI position at borehole locations have been compared in the course of a redesign of the AWD hydrological monitoring programme (Kamps, 2010.; Nienhuis *et al*, in prep.). What usually counts is salinization risk in terms of chloride concentrations. Prediction of this risk requires FSI movement modeling which in turn requires groundwater densities. The latter can be sampled and analyzed directly or can be derived from several proxies, e.g., chloride concentrations, electrical conductivity (EC) of the groundwater (Post e.a., *in prep*.), geophysical methods, etc. Within the FSI actually two levels are distinguished: the fresh/brackish ($[Cl^-]$ = 300 mg/L) and the brackish/saline transition ($[Cl^-]$ = 10,000 mg/L), but in the scope of this paper this is disregarded.

## OVERVIEW OF USED MEASUREMENT METHODS

### *Chloride concentrations*

In the AWD individual piezometers in monitoring wells offer limited vertical resolution as they are often spaced tens of meters apart while the brackish zone thickness often amounts to 10 m. In addition the piezometer filter screen length, gravel bed and clay seals lead to groundwater samples representative of an average depth interval of several meters. While minifilters offer a finer vertical resolution, careful installation is required and potentiometric surfaces can be no more than about eight meters below surface level as sampling is done with a vacuum pump.

### *Electrical conductivity*

Electrical conductivity (EC) proves a better proxy for density than [$Cl^-$] (Post, *in prep*.; Kamps, 2010). In the AWD groundwater EC has only been measured on a regular basis since 2007, simultaneously with sampling for chloride analyses. In practice EC is used for monitoring the flushing of piezometers during sampling campaigns, as a check on $Cl^-$ analyses and to calibrate electrode cables. A properly calibrated EC-meter is vital and yields indispensable information on groundwater temperatures at depth which are needed for density calculation.

### *Geophysical logging (SN / LN / EM)*

"Short normal"(SN) and "Long normal" (LN) logs can only be made once, just after drilling and before piezometer installation. Since a few years EM-logging equipment is available that fits into 2" piezometers. This EM log has a vertical resolution on dm-scale.

### *Electrode cables*

Electrode cables (also called geohm cables) are electrode pairs (separation 0.2 m) at several depth positions (3 m apart) in the borehole wired to a multi-pin connector at surface level. Measuring the apparent resistance between the electrode pairs is straightforward, rapid and cheap, but for better interpretation the formation factors for each electrode pair are needed. These formation factors, which can only be inferred from representative measurements of local EC, have been found to lie in the range of 2 to 7 (i.e., ~0.5 magnitude), the majority between 3 and 5. As the EC variation from fresh to saline groundwater ranges across several magnitudes, electrode cable interpretation is sufficiently robust to assess the FSI position within a few meters.

### *Head measurements*

Theoretically, fresh groundwater heads measured near the top and saline groundwater heads measured near the bottom of an aquifer could be used to directly calculate an intermediate FSI position based on the Badon-Ghyben-Herzberg relation, provided the groundwater densities and temperatures are known, and a sharp FSI and equilibrium groundwater flow conditions are assumed. However, preliminary investigation in the AWD (Haas, 2006) showed that these assumption are all too often invalid. The fresh/brackish/saline zone thickness and the way its chloride concentration changes across the FSI varies considerably in lateral directions, while relatively small variations in groundwater temperatures at depth can propagate into relatively large errors in calculated FSI position.

**Table 1: Overview of methods used for FSI position exploration in the AWD**

| Method | Approximate vertical resolution[1] | Direct / indirect | Moment of use | Relative cost | Remarks |
|---|---|---|---|---|---|
| [$Cl^-$] / EC in piezometers | Order of 10s of meters | direct | anytime | Moderate | Representative of FSI only after initial effects have ceased |
| [$Cl^-$] / EC in minifilters | Order of meters | direct | Anytime | Moderate | |
| SN/LN geophysical log | Decimeters / meters | indirect | Only once just after completion of drilling | High | Interference from drilling effects |
| EM-log (EM-39) | Decimeters | indirect | Anytime | High | Reliable even in wells with electrode cables |
| Electrode cables (geohm) | Order of meters | indirect | Anytime | Cheap | Interference from drilling effects |
| Head analysis | Meters to 10s of meters | indirect | Anytime | Cheap | Vulnerable for ambiguous assumptions |

[1]*Note: Total Fresh/Brackish/Saline interface thickness in the AWD is in the order of 10 m.*

## DISCUSSION

Effects of well drilling on the local FSI position can last for several years. As an example, in Figure 1 the recovery of the FSI position in well 24H597 (inferred from electrode cable measurements) is shown to last for up to three years.

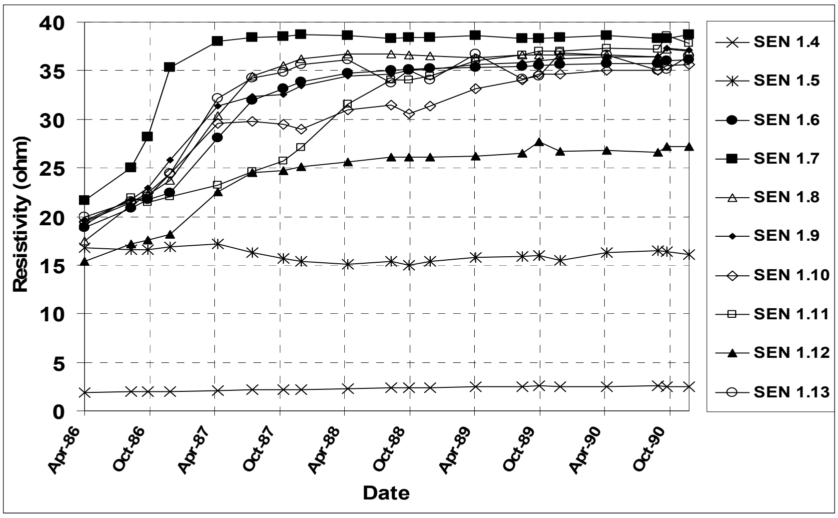


**Figure 1: Evolution of resistivity since drilling of well 24H597**

These initial effects are usually caused by slow flushing of remnant drilling fluids. In some cases large amounts of fresh groundwater had to be supplied to the open boreholes to prevent collapse. Together with the usual hydraulic conditions in the AWD (fresh water heads in shallow aquifers being several meters higher than the saline water heads in deep brackish/saline aquifers) this led to large-scale downward percolation of fresh water through the open borehole (up to several thousands of m3), leading to local displacement of saline groundwater in the lowermost aquifers. Especially FSI methods representative of small radii around the borehole can be affected and these initial effects also render SN/LN logs less useful for exploration of the FSI.

As nearby metal bodies (electrical conductors) might affect the EM-log results, in principle only boreholes without metal parts can be used for EM-logs. Comparing an EM39 log made in a specially made well without any metal parts, to one made in a well fitted with an electrode cable, show that these cables do not significantly influence the EM-logging results. As expected, EM-logs show higher conductivities near clay seals, however unexpectedly low EC-values have been found in aquitards below the FSI (Figure 2, right). We interpret this as being caused by drilling fluid, or fresh groundwater having infiltrated from higher levels during drilling (see above), that has been entrapped in the bentonite sealing of aquitards. We conclude that reliable exploration of the FSI position in aquitards based on borehole measurements is therefore probably unfeasible.

## CONCLUSIONS

Our experience and analyses show that in the AWD electrode cables by themselves are a cheap means to monitor FSI positions; simply assuming a formation factor of 4 implies an inaccuracy of the FSI position of at around 3 m. Assessing the formation factors around the electrode pairs based on e.g., minifilter sampling can help to improve vertical resolution to m-scale.

We conclude that electrode cables augmented with regular (every 5 years) EC-measurements in e.g., minifilters are the preferred means for FSI monitoring in the AWD.

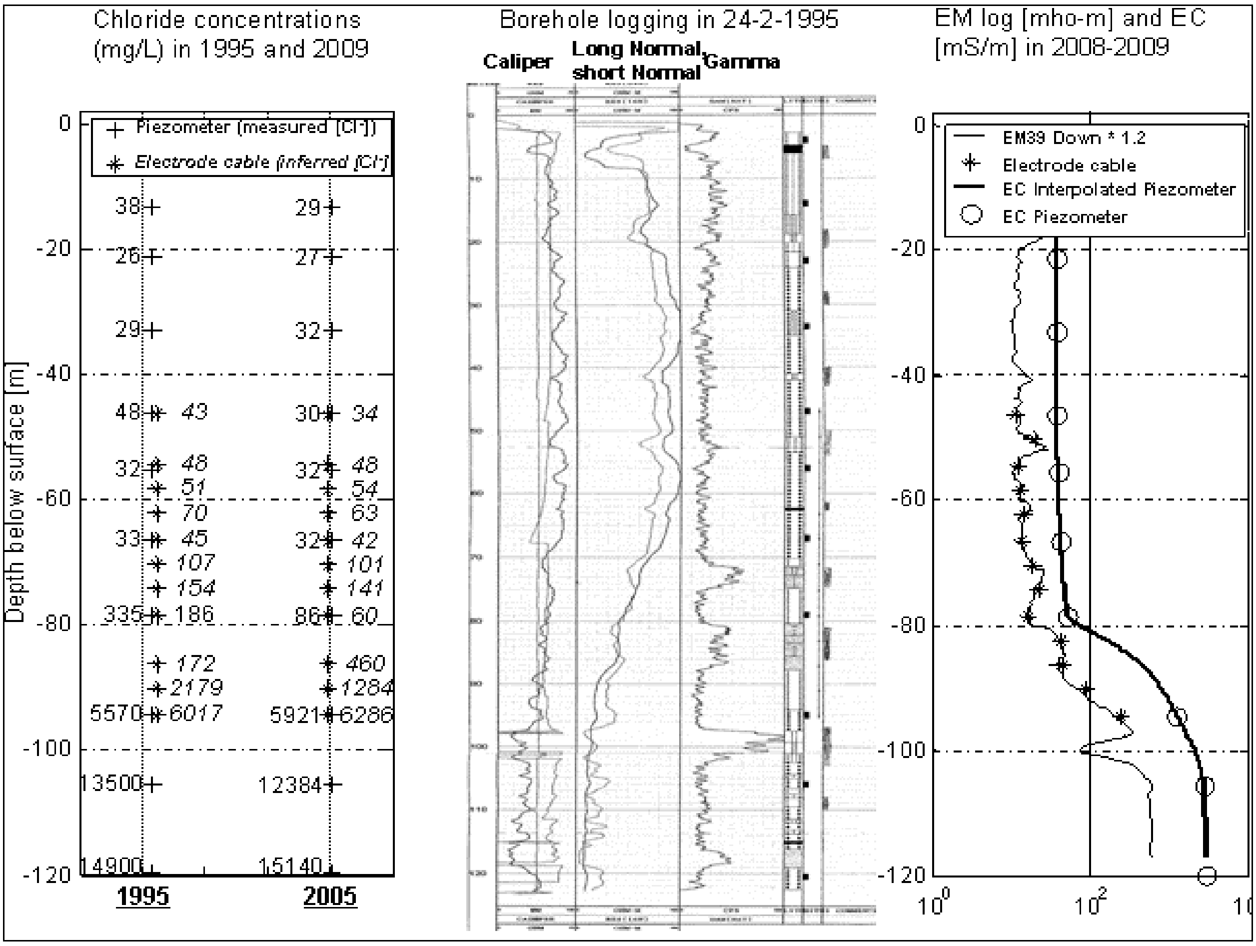


**Figure 2: Comparison of [Cl-], electrode cable (left), SN/LN and caliper/gamma logs (center), and EM-log / EC / electrode cable (right) for well 24H718**

## REFERENCES

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