

Fresh water – brackish water interface monitoring in Vitens' groundwater extraction areas

A study for optimizing Vitens' salinization monitoring strategy



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Abstract

Groundwater degradation by salinization is one of the key concerns groundwater companies have to deal with. In order to monitor saline groundwater transitions, drinking water company Vitens uses approximately 110 Permanent Electrode Cable Systems (PECS). These devices consist of seven or thirteen electrode couples separated over depth, whereby resistances measured between two electrodes correspond to the conductance of both groundwater- and soil. Consequently, by using this method, it is possible to obtain more knowledge about groundwater conductance variabilities and consecutively chloride concentration alterations (Helderman, 2016; Goes et al., 2009).

However, Vitens does not adhere a strict salinization monitoring policy yet. Current PECS datasets consist of errors and monitoring devices are not optimally used. For determining the reliability of current PECS, it is necessary to calibrate PECS with nearby chloride concentrations. Herewith, it is possible to evaluate whether PECS correctly detect alterations in groundwater conductance. In this study it is aimed to both verify current PECS and to evaluate future salinization monitoring methods.

From the data-analysis, it appeared that a significant part of the current PECS does not respond correctly on chloride concentration alterations. In general, trends between PECS resistances and chloride concentrations were absent in low chloride concentration environments ($[Cl^-] < 50 \text{ mg/l}$). More salinized environments alternately resulted in clear relationships between PECS resistances and chloride concentrations. However, prolonged periods with obvious trends between PECS resistances and chloride concentrations are absent. Current PECS are possibly influenced by local soil conductors, measured incorrectly or not sensitive enough.

Additionally, a modelling study is conducted in order to verify the abilities for salinization monitoring by using hydrological models. In combination with observation well samples, it was possible to evaluate both current salinization trends, potential salinization origins and future salinization predictions.

Another monitoring device consisting of large potentials is the EM-Slimflex logger. Past studies showed reliable relationships between EM-Slimflex measurements and chloride concentrations. Vitens owns a dense network of monitoring wells, in which EM-Slimflex loggers could be fitted. This device determines the soil resistivity by generating an electromagnetic field. Also, by conducting natural gamma radiation, it is possible to review local lithological profiles.

In conclusion, PECS are probably not the most optimal method for salinization monitoring in the entire Vitens extraction area. Groundwater salinization monitoring by using a combination between hydrological models and in-situ groundwater samples is probably more reliable and more efficient.

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List of equations

Number	Equation
1	$Ra = \frac{\Delta\rho g k H}{\mu D m}$
2	$z = \frac{\rho_f}{\rho_s - \rho_f} h$
3	$z = 40h$
4	$\rho_w = \frac{\rho_s}{F}$
5	$\rho_{w20} = \rho_{w,t} (1 + 0.226(t - 20))$
6	$[Cl^-] = \frac{((EC_{w,20} - 0.122 * [HCO_3^-]) \frac{1}{0.9446}}{0.44096}$
7	$Cl_i = 9298.6 R_i^{-1,390} + e_i$

1 Introduction

1.1 Background

Groundwater is the main drinking water source in the Netherlands. However, by minding the ongoing population growth, this already-stressed water resource has an increasing demand, forcing available groundwater amounts to deplete (Post et al., 2018). Furthermore, climate change has severe consequences for water availabilities. By focusing on the summer of 2018, which was characterized with high temperatures and dry conditions, the average water consumption in the Vitens area increased by approximately 30-40%. Consequently, in order to maintain proper water supply, Vitens was forced to extract more water than initially expected (Ten Cate, 2018).

Focusing on the Netherlands, which is largely situated below sea level, saltwater intrusion is a major concern. As described by Barlow et al. (2003), groundwater extractions near coastal regions often induce a propagation of saline water to fresh water aquifers. This subsequently results in negative effects for agricultural areas and both industrial- and domestic water sources (Oude Essink, 2001). In coastal areas, groundwater is merely extracted from aquifers which are in hydraulic connection with the sea. Besides, in the eastern part of the Netherlands, saline groundwater is present in Early Pleistocene and Tertiary marine deposits. As fresh water is composed of a smaller density than brackish water, fresh water is situated on top of brackish groundwater. Due to this, migration of brackish water towards wells may occur when fresh water supplies are depleted (Redwood, 2007).

In order to deal with the increasing consumption and potential threats, it is a prerequisite to coherently monitor and analyze groundwater quality near extraction wells. Herewith it is possible to detect contaminants and changes in groundwater quality over time. This is important for short-term safeguarding and predicting water quality changes, which is necessary for guaranteeing high quality drinking water in the future.

For monitoring the fresh water – brackish water interface near extracting wells, Vitens uses approximately 110 Permanent Electrode Cable Systems (PECS). These cables are permanently located in soil and consist of seven or thirteen electrode couples situated at different depths. By measuring the conduction between two electrodes, an indicative overview of the resistance of the formation water can be generated. However, since the measured resistance is dependent on conductors in both soil and groundwater, it is necessary to compare resistance data with chloride measurements obtained in observation well filters. Herewith, resistances obtained by PECS can be calibrated and related to groundwater.

1.2 Problem description

Although Permanent Electrode Cable Systems (PECS) can provide reliable estimates of the fresh water – brackish water interface, a proper policy is absent. This is both caused by wrong- and incomplete data-sets and the absence of a general salinization monitoring policy. There is no strict process description in which the data maintenance, requirements and responsibilities are included. As a result, little care has been taken on salinization monitoring for the past years. However, minding the increasing water consumption and potential threats in the Netherlands, a general salinization monitoring policy is useful. By strictly adhering a policy, it would be easier to observe groundwater salinization and to timely anticipate on these changes.

Nevertheless, since PECS can be valuable for estimating the fresh water – brackish water interface, it is necessary to validate, calibrate and evaluate the data. Herewith it is possible to examine the value of PECS and decide whether the investments and efforts are appropriate.

1.3 Research question

“What is the most optimal salinization monitoring policy for monitoring the fresh water – brackish water interface in Vitens’ extraction areas?”

To answer this research question, it was broken down in multiple sub-questions:

1. What is the cause of the fresh water – brackish water interface in the Netherlands?
2. What is the value of PECS?
3. Are current PECS positioned on the right location?
4. Are current PECS measured with the appropriate frequency?
5. Which alternative devices can be applied for monitoring salinization?
6. Is it possible to reliably model salinization by using groundwater models?

1.4 Hypothesis

It is hypothesized that the most optimal monitoring policy depends on Vitens’ goals. The one monitoring method might be more reliable than the other method, but also more expensive. Current PECS could be of added value, provided that a consistent policy is applied. However, as PECS are relatively time consuming because of in-situ measurements, it might be useful to evaluate alternative monitoring methods which are less time consuming and less expensive.

Hypothesis per sub-question:

1. It is hypothesized that near the coast, the fresh water – brackish water interface is especially influenced by salt water intrusion from the sea. Moving away from the coast, the fresh water – brackish water interface is dependent on ancient salt deposits.
2. It is hypothesized that PECS provide alternating results, which is caused by varying measurement policies per province, differences in measurement devices, etc.
3. If PECS have been situated in a non-critical salinization environment for many years, it could be cost-efficient to remove this location. On the other hand, if PECS have been located in brackish environments for many years, it might be more cost-efficient to remove these locations as well.
4. If PECS provide sufficiently detailed data regarding the fresh water – brackish water interface, it is hypothesized that the measurement frequency is correct. Alternatively, other measurement frequencies have to be evaluated.
5. It is hypothesized that the type of device especially depends on in-situ soil- and groundwater conditions and Vitens’ demands. Fellow drinking water companies use either PECS or alternative methods, as geo-electrical measurements and EM-39 loggers.
6. It is hypothesized that models could display reliable results of salinization developments, provided that reliable input parameters are implemented.

1.5 Objectives

The objective of this study is to provide more information about the current salinization monitoring strategy and to discuss future salinization monitoring policies. The following objectives were defined to find answers on the main research question and on the multiple sub-questions:

- Conducting a literature study in which information is gathered about PECS, the hydrogeological circumstances in which PECS are situated, the current fresh water – brackish water interface (and their potential shifts) in the Netherlands and other salinization monitoring methods.
- Calibrate PECS resistance data with chloride concentration data sampled in observation wells and try to find empirical relationships between resistance [ohm] and chloride concentrations [mg/l].
- Try to find a threshold value in ohm which is indicative for the fresh water – brackish water interface. Herewith it would be possible to interpret PECS data, instead of only visualizing trends in ohm over time.
- Analyze data and determine whether PECS locations require more or less attention.
- Discuss whether PECS measurement frequencies are correct on all locations.
- Compose a high-resolution model of a specific area in order to model the salinization interface development.
- Discuss whether PECS are the most optimal method for salinization monitoring, or whether alternative salinization monitoring methods are more suitable.

1.6 Approach

At first, a literature study is conducted in which information is gathered about both PECS, the fresh water – brackish water interface and the general hydrogeological situation in the Netherlands. Aside from this, alternative salinization monitoring methods are reviewed.

Thereafter, a data-analysis is conducted in which more information is provided about current PECS. After a short description of the spatial distribution and geohydrological conditions near PECS per province, it is analyzed whether current PECS are valuable and whether or not PECS could be a proper monitoring device in the future. Subsequently, a short discussion, conclusion and multiple recommendations are made for optimizing salinization monitoring by using PECS.

Next, a high-resolution model is composed of the Rodenmors groundwater extracting location consisting of salinized pumping wells. Herewith it is tried to evaluate possibilities of salinization monitoring by using hydrological models, elucidate in-situ salinization trends and discuss potential salinization sources. Afterwards, a discussion and conclusion are made as well as recommendations for future salinization monitoring strategies in the particular Rodenmors extraction area.

Eventually, by combining the knowledge of both the literature study, data-analysis and high-resolution model, both a final conclusion and recommendation are made regarding the current salinization monitoring strategy and general future salinization monitoring policies.

2 Literature study

In this chapter, more information is provided about the general hydrogeological situation in the Netherlands and its influence on groundwater chemistry. Apart from some main salinization contributors, other less important salinization influences are discussed. Thereafter, the Permanent Electrode Cable System (PECS) is elucidated. Besides general information about the device and measurement locations, alternative methods for measuring groundwater salinization are discussed.

2.1 Hydrogeological situation in the Netherlands

In the Netherlands, the predominant amount of drinking water is extracted from both river bank deposits, dunes and Pleistocene - Holocene deposits (Dufour, 2000). As described in De Vries (2007), groundwater is situated in fractures and pores from which the characteristics are largely determined by the geological history of the area. In the upper groundwater zone, groundwater flow is especially forced by potential energy, which is influenced by both rainfall, topography and human interventions. However, in the lower zone, groundwater becomes merely disconnected from the hydrological cycle and is primarily induced by elements of the comprehensive geological history. Here, groundwater systems are especially affected by pressure gradients forced by thermo-chemical mechanisms, tectonic influences and (paleo)-topography (De Vries, 2007).

For efficiently abstracting groundwater, it is a prerequisite to have in-depth knowledge of the hydrogeological conditions (Post et al., 2003). According to De Vries (2007) and Post (2004), a significant part of the Netherlands is situated on the south-eastern adjectice zone of the subsiding North Sea Basin. The boundaries of this basin generally coincide with the (south)-eastern geographic boundaries of the Netherlands, on which the shift starts to the high-elevated areas of the Ardennes and Rhenish Massif. In the eastern part, boundaries range between a height of 30 to 40 meters above NAP, whereas the highest elevation (322 meters above NAP) can be found in the southernmost tip in the province of Limburg. Other high-elevated areas, as the Utrechtse Heuvelrug and the Veluwe, are located in the central-eastern part of the Netherlands. These areas consist of Pleistocene ice-pushed hills with maximum elevations of approximately 107 meters above NAP.

As studied by De Vries (2007), the most dominant deposits which are engaged in the current hydrological cycle have a Pliocene - Pleistocene origin and are situated on a sequence of clayey and sandy deposits from both the Oligocene and Miocene. The Pliocene - Pleistocene deposits are characterized with medium to coarse fluvial sands and have a thickness which locally increases to more than 300 meters. Permeabilities range between 20 – 50 m/day, forcing transmissivities on specific locations to transcend 10.000 m²/day. However, as a result of multiple semi-confining layers, the Pliocene - Pleistocene deposits are characterized as multi-layer aquifers, as displayed in Figure 1. From this figure, it is possible to distinguish approximately six different aquifers, which are (partly) separated by fine-grained aquitards, for instance the Lower Pleistocene clay layer. From Figure 1 it also appears that connections between aquifers are possible. This is confirmed by the study of Post et al. (2003), who furthermore concluded that aquitards generally consist of heterogeneous hydraulic properties and alternating spatial distributions. The hydrological basis in the major part of the area is formed by Pliocene clays and locally by Early Pleistocene marine deposits (Pomper, 1983).

In the eastern part of the Netherlands, the Pleistocene aquifer is situated near the surface and thus has a phreatic character. By moving towards the west, this Pleistocene aquifer dips below the peaty and clayey Holocene layers, forcing the aquifer to be semi-confined. Holocene deposits merely consist of fluvial and estuarine strata and reach a maximum thickness of approximately 25 meters in coastal areas. A comprehensive description of the geological history of the Netherlands can be found in Dufour (2000), Post et al. (2003), Post (2004) and De Vries (2007).

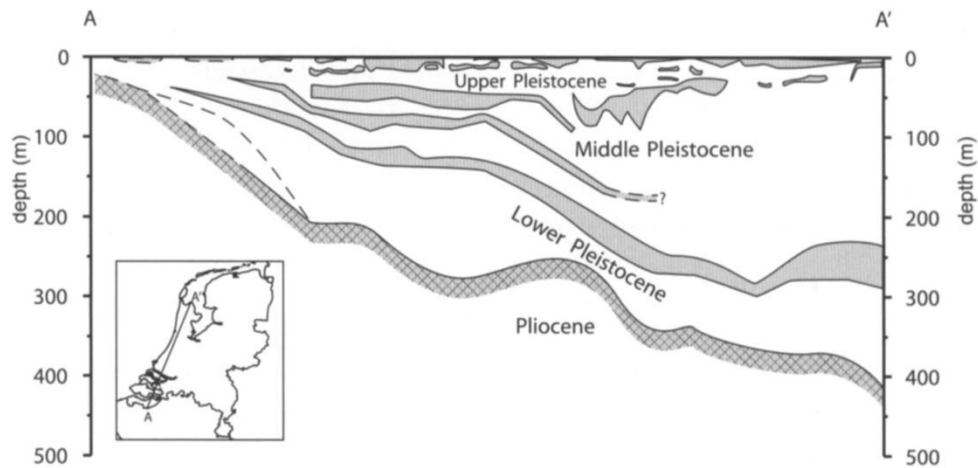


Figure 1 - Division of the subsurface in aquifers and aquitards. Cross-section of approximately 200 km from south to north (Post et al., 2003)

The Netherlands are characterized with an average annual precipitation- and evaporation rate of respectively 800 mm and 500 mm. Herein, rainfall is roughly evenly distributed over the seasons, whereas evapotranspiration has a peak during summers. In these relatively warm periods, evapotranspiration approximately equals precipitation, resulting in an annual precipitation surplus of 250 – 350 mm in winter periods (De Vries, 2007; Meinardi, 1994). Rivers as the Meuse and Rhine result in an annual inflow of approximately 2100 mm, which largely contributes to public water supply in coastal areas. A significant part of the rainfall which infiltrates in soil flows to deeper layers and is discharged to groundwater (De Vries, 2007).

Nowadays, ditches and canals artificially control groundwater levels and consequently result in a complex groundwater flow system (Post, 2004). According to De Vries (2007), the groundwater table in a large part of the Netherlands is less than two meters deep, apart from some specific locations as the Utrechtse Heuvelrug where groundwater levels are located deeper below surface level.

2.2 Origin of brackish water in the Netherlands

In order to understand the evolution of salinity distribution in the past, elaborate knowledge of hydrological processes is required (Post et al., 2003). Nevertheless, tracing the exact hydrological processes is a hard task, as today's groundwater compositions are severely affected by human interventions.

Due to the ongoing seawater encroachment in the western part of the Netherlands, groundwater in the Pleistocene aquifer near coastal areas is merely brackish. Besides, fresh groundwater reserves can be transformed to brackish groundwater due to either transgressions in the past or connate seawater. The difference is as follows: during a transgression, fresh groundwater is directly salinized by overlying seawater, whereas connate seawater salinization is induced by salt dissolution from marine deposits containing ancient seawater. In the past 2 My, glacial- and interglacial periods occurred, whereby interglacial periods inundated large parts of the present-day Netherlands (Figure 2). After the Early Pleistocene, large sea invasions furthermore occurred in the Cromerian, Holsteinian, Eemian and Holocene (De Vries, 2007; Post et al. 2003).

2.2.1 Pleistocene marine deposits

As described in Post et al. (2003), clays and fine-grained sands deposited in the Pliocene and Early Pleistocene are determined to be the oldest sources of salt. Due to upward salt transport from salt marine deposits, above-situated Pleistocene fresh water volumes undoubtedly became saline. However, as mentioned by Meinardi (1991), it is implausible that these salt-containing Pliocene - Pleistocene layers resulted in the current brackish groundwater quantities. This statement is reinforced by borehole measurements, which clearly display a chloride reversal near the interface between Pliocene/Pleistocene marine deposits and Pleistocene fluvial strata. Namely, if connate seawater from Pliocene - Pleistocene marine layers would have been the source of saline water in the Pleistocene fluvial deposits, an opposite trend was observed due to upward dissolved solute transport by diffusion (Post et al., 2003; Meinardi, 1991).

Consequently, Post et al. (2003) suggest that marine deposits dating from the Pliocene - Early Pleistocene were refreshed after deposition and eventually salinized by salts from the fluvial deposits on top. Appelo et al. (1991), who found similar results based on geochemical characteristics of sediment samples, confirm this hypothesis. Due to this process, it is assumed that significant amounts of salt have intruded Pleistocene fluvial sediments as a result of both compaction-driven flow and diffusion. Nevertheless, its contribution to the present volume of saline water is assumed to be relatively small. As mentioned in Post et al. (2003), compaction-driven flow is the consequence of compression of clastic sediments induced by sediment packing, resulting in an upward water flux. Since the combination of both compaction-driven flow and diffusion is relatively small compared to the topographically controlled horizontal advective flux in the Pleistocene aquifers, it is plausible that the horizontal groundwater flux diluted the major part of the salt water. Additionally, C-14 measurements further reinforce the assumptions of Post et al. (2003), in which marine strata from the Pliocene - Early Pleistocene became fresh after deposition and eventually salinized by salts from fluvial deposits.

2.2.2 Holocene transgressions

At the beginning of the Holocene, the North Sea gradually inundated the Netherlands (Figure 2). As a result, saline seawater was situated above fresh groundwater in the Pleistocene aquifers. Because of the density difference between fresh water ($\rho \sim 1000 \text{ kg/m}^3$) and saline water ($\rho \sim 1025 \text{ kg/m}^3$) and by assuming sufficiently high permeabilities, saline water sank into fresh water volumes due to free convection. As salt dissolutions enter aquifers by diffusion, a boundary layer starts to develop until it reaches a critical thickness. Subsequently, the boundary becomes unstable and fingers start to descend to the bottom of the aquifer (Port et al., 2003; Dufour, 2000).

The non-dimensional Rayleigh number (Ra) describes this process (Post et al., 2003):

$$Ra = \frac{\Delta\rho g k H}{\mu D_m} \quad (\text{Equation 1})$$

Whereby:

- $\Delta\rho$ = Density difference (kg/m^3)
- g = Gravitational acceleration (m/s^2)
- k = Intrinsic permeability (m^2)
- H = Height aquifer (m)
- μ = Dynamic viscosity (kg/m/s)
- D_m = Molecular diffusion coefficient (m^2/s)

According to Post et al. (2003), free convection occurs when the Rayleigh number approximately exceeds $Ra = 40$. By assuming that vertical groundwater flow velocities are generally in the order of meters per year, it will take multiple decades to salinize a highly permeable aquifer with a height of 100 meters. However, in case of very low permeable aquifers, free convection is hindered in multiple ways. For instance, low-permeable aquifers prevent brackish water to infiltrate in the aquifer. Based on this principle, it is plausible to assume that very fine-grained layers act as a protective cover for underlying sand deposits and that low-permeability layers induce retarding effects on salinization caused by free convection. Multiple studies (Pomper, 1983; Gieske, 1991; Van Dongen et al., 1982; Post et al., 2003) showed that chloride concentrations decreased significantly in low-permeable clay layers and that clay layers may contain fresh water.



Figure 2 - Interface depth between fresh water – brackish water (Dufour, 2000)

2.2.3 Alternative salinization sources

Apart from salinization by seawater intrusion, marine deposits and Holocene transgressions, groundwater can be salinized by multiple other sources (Post et al., 2003; Post, 2004):

- **Aerosols:** Atmospheric precipitation can contain enhanced chloride concentrations, mainly as a result of sea spray. Based on Post (2004) and Stuyfzand (1991), chloride concentrations in precipitation near the coastline are measured to be approximately 2 mmol/l and decrease landwards to a concentration of approximately 50 μ mol/l. Approximately 10 - 45% of the chloride concentrations measured in the study was caused by dry deposition on the rain gauge. Since chloride concentrations in precipitation are relatively low, it is assumed to be a small contributor to chloride concentrations in groundwater.
- **Evaporites:** In the eastern and north-eastern part of the Netherlands, Zechstein salt layers are detected. Deep aquifers (550 m deep) in these Zechstein areas are characterized with chloride concentrations larger than 2 mol/l. As described in Glasbergen et al. (1982), it is possible that shallow groundwater volumes which superimpose a salt dome can become saline by the process of salt dissolution.
- **Anthropogenic pollution:** An anthropogenic polluter resulting in enhanced chloride concentrations on a regional scale is agriculture. Herewith, relatively high chloride concentrations are exposed to the soil due the application of manure and fertilizers. However, studies as Broers et al. (1992), have concluded that agriculture only has a minor influence on the total volume of chloride in groundwater.
- **Evapotranspiration:** As determined by Dufour (2000), evapotranspiration in the Netherlands equals approximately two-thirds of the precipitation amount (Post et al. 2003). It is assumed that evaporation can result in high salt concentrations in both groundwater as well as in surface waters. As studied by Post (2004), highest chloride concentrations in recharge waters due to evapotranspiration are approximately 10 mm/l.
- **Hyper-filtration:** This phenomenon takes place when groundwater flows throughout a clay layer, which behaves as a semi-permeable membrane (Post et al., 2003). As a consequence of the negative surface charge of clay layers, charged solutes as chloride ions are prevented from passing. As a result, chloride concentrations on the influent side of the clay layer increase with respect to the clay layer. Nevertheless, Post et al. (2003) and Post (2004) assume that osmotic effects become exponentially small when salinity is low. Herewith, is plausible that hyper-filtration has negligible effects on salinization in the Netherlands.
- **Freezing:** Groundwater freezing causes chloride solutes to migrate. Multiple studies (Bottomley et al., 1999; Herut et al., 1992; Bein et al., 1992) have researched the influence of freezing in the formation of saline groundwaters and brines (Post et al., 2003). During glacial periods in the Pleistocene, freezing undoubtedly influenced the salinity distribution. However, the exact contribution of freezing in the past is not clear yet.

2.2.4 Hydrogeochemical analysis

As mentioned in Appelo et al. (2004), salinization results in an overall change in chemical composition of the groundwater. A standard groundwater chemical analysis requires at least information about the pH, temperature, electrical conductivity (EC), the four major cations (Na^+ , Ca^{2+} , K^+ , Mg^{2+}) and the four major anions (Cl^- , HCO_3^- , NO_3^- , SO_4^{2-}). More insight about the correlation between chemical parameters and salinity can be obtained by conducting a principal component analysis (PCA). By determining the dominance of ions in groundwater, it is possible to obtain a representation of the source. For instance, an abundance in Na^+ , Mg^{2+} , Cl^- and SO_4^{2-} is indicative for seawater, whereas an abundance in Ca^{2+} , K^+ , HCO_3^- and CO_3^{2-} is indicative for groundwater derived from a terrestrial origin. Ions as Ca^{2+} , K^+ , HCO_3^- and CO_3^{2-} are especially caused by rock-water interactions and dissolution of carbonate minerals in the aquifer (Kumar, 2016). A comprehensive explanation about correlating hydrogeochemical properties of groundwater to origins can be found in Kumar (2016).

2.3 Fresh water – brackish water interface in the Netherlands

2.3.1 Current situation

After executing both borehole measurements, geo-electric measurements and chloride observations, TNO composed a spatial distribution model of chloride concentrations in the Netherlands, as shown in Figure 3 (Stuurman et al., 2006). The fresh water – brackish water interface pattern is largely determined by Holocene transgressions as explained in Chapter 2.2. In general, it is obvious that coastal areas are characterized with a relatively shallow fresh water – brackish water interface due to both hydraulic connections with the sea and extensive polder drainages. Nevertheless, some fresh water volumes as the “Zoetwaterbel van Hoorn” are clearly visible. According to Post (2004) and Stuyfzand (1993), current seawater encroachment from the North Sea is limited to approximately 2 – 6 km from the shoreline, which is based on both hydrological calculations as well as hydrogeochemical data.

In the eastern part of the Netherlands, some shallow fresh water – brackish water interfaces are visible as well. Stuurman et al. (2006) concluded that this is caused by very impermeable marine deposits from the Tertiary, in which saline groundwater is not flushed away yet. The “Flevopolders” also consist of large fresh water volumes due to groundwater from the Veluwe. The absence of impermeable clay layers results in strong upwards directed groundwater flowpaths (Stuurman et al., 2006).

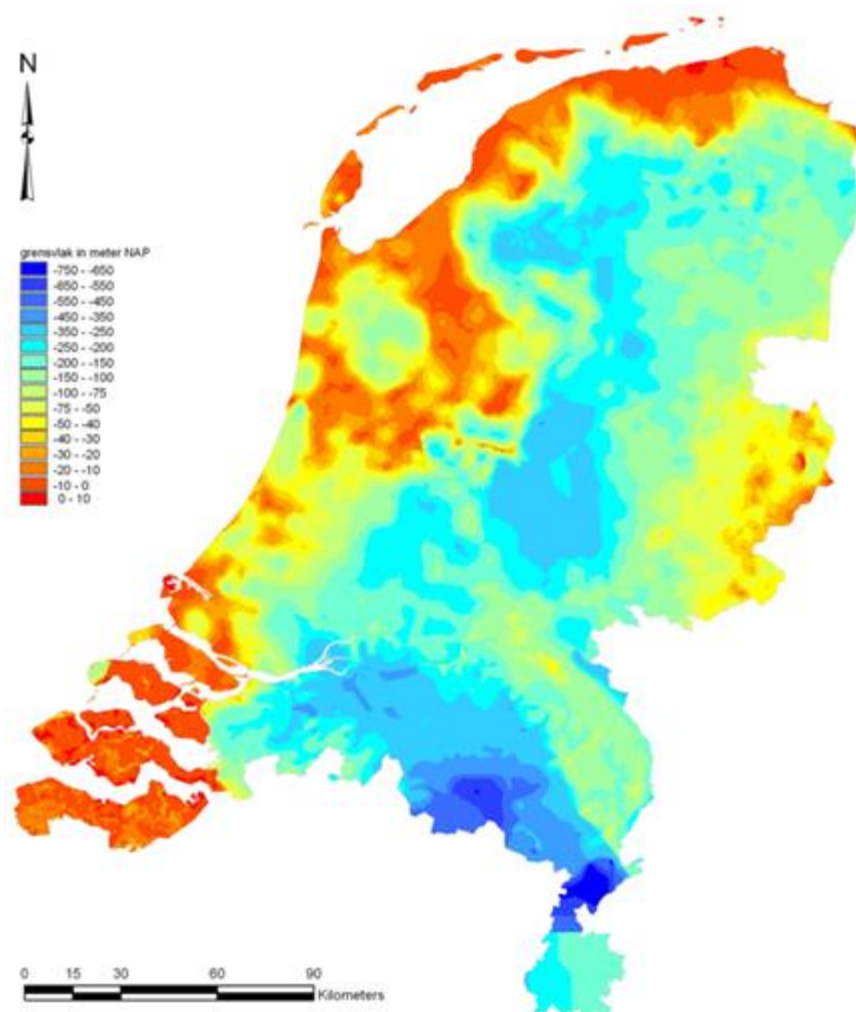


Figure 3 - Spatial distribution of the fresh water – saline water interface. The threshold value for saline water is 1000 mg/l (Stuurman et al., 2006)

As described in Barlow et al. (2003), it is possible to quantitatively approximate the depth of the fresh water – brackish water interface in coastal areas by using the Ghyben-Herzberg method. In this equation, the thickness of the freshwater zone in a coastal aquifer is relatively simple to approximate by assuming that the system consists of both hydrostatic conditions (no vertical gradients) and a sharp boundary between fresh water and salt water volumes.

The Ghyben-Herzberg relationship correlates the water table elevation to the fresh water – brackish water interface elevation and equates the height of the different water columns consisting of different densities (Equation 2) (Barlow et al., 2003).

$$z = \frac{\rho_f}{\rho_s - \rho_f} h \quad (\text{Equation 2})$$

Whereby:

- z = fresh water zone below sealevel
- h = fresh water zone above sealevel
- ρ_f = fresh water density ($\sim 1000 \text{ kg/m}^3$)
- ρ_s = salt water density ($\sim 1025 \text{ kg/m}^3$)

By inserting the densities in the formula, the equation can be simplified to Equation 3. As a result, it appears that a fresh water volume of one meter above sealevel is coherent to a fresh water volume of 40 meters depth below sea level, as schematically displayed in Figure 4.

$$z = 40h \quad (\text{Equation 3})$$

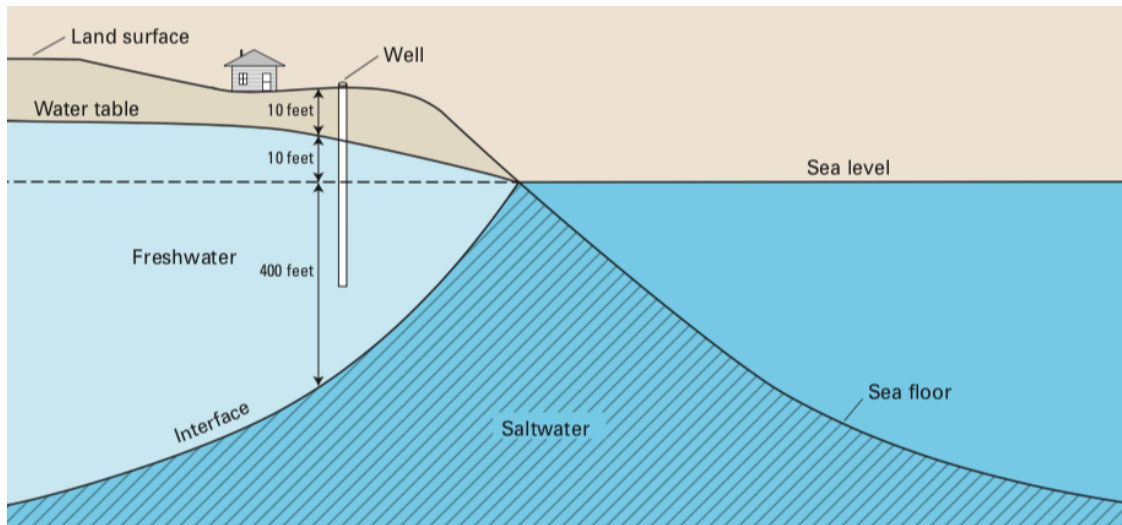


Figure 4 - Example of the application of the Ghyben-Herzberg formula (Barlow et al., 2003)

2.3.2 Fresh water – brackish water interface transitions near extraction wells

As mentioned previously, artificial activities that affect groundwater levels and eventually force saltwater to encroach in aquifers can severely affect the balance between fresh water - brackish water (Barlow et al., 2003). Hoogendoorn (2017) studied the fresh water – brackish water interface development near extraction wells and determined that the entire aquifer contributes to groundwater flow towards a well. When the fresh water – brackish water interface is located within the extracted aquifer, salinization of the well is nearly inevitable (Figure 5). Initially, a pumping well extracts fresh groundwater, but eventually the entire brackish water column is contributing to the extraction well. This phenomenon holds both in confined- and phreatic conditions. In case of isotropic and homogeneous circumstances, extracted water consists of roughly the same chloride concentrations as the aquifer.

However, since most aquifers are generally neither isotropic nor homogeneous, it is hard to model the exact salt concentration profile over depth. Some factors that contribute to the salt concentration of the extracted groundwater are the filter depth relative to the fresh water – salt water interface, the origin of the aquifer and the origin of the groundwater in the aquifer, anisotropy and porosity (Hoogendoorn, 2017).

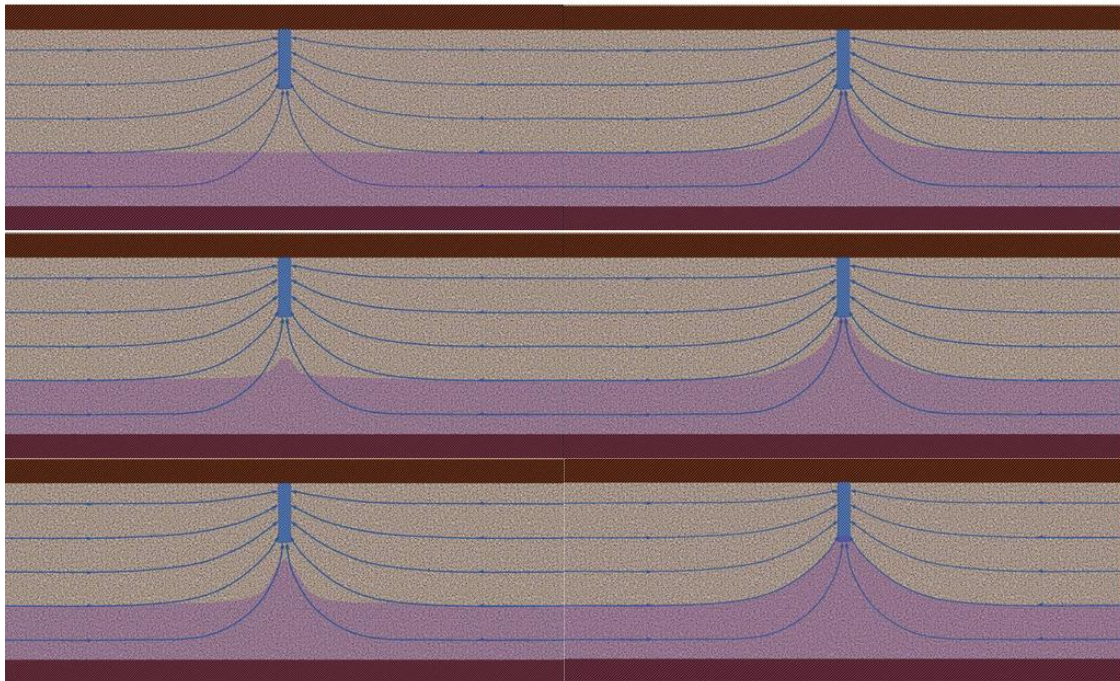


Figure 5 - Salinization interface development near extraction wells (Hoogendoorn, 2017)

Another factor which largely affects the extracted salt concentration is the (regional) groundwater flow direction. Hoogendoorn (2017) concluded that the capture zone in the aquifer decreases in case of higher groundwater flow velocities. In other words, when groundwater flow delivers more water than the amount extracted by pumping wells, a relatively small water column is sufficient. As a consequence, high groundwater flow velocities can result in salt upconing in the shadow zone of an extraction well, as visualized in Figure 6. This of course only holds in case of a relatively shallow fresh water – brackish water interface. If this interface is deeper, salt water upconing in the shadow zone is less probable.

Multiple studies, as Van Dijk et al (2017), concluded that salinization influences hydraulic conductivities of soils, resulting in alternative groundwater flow patterns. For instance, salinity induced flocculation of organic acids in peaty soils can be an explanation of altered hydraulic conductivities. Also, as a consequence of climate change, sea level rise results in larger gradients between sea level and polders, causing enhanced influxes of salt water (Stuurman et al., 2007).

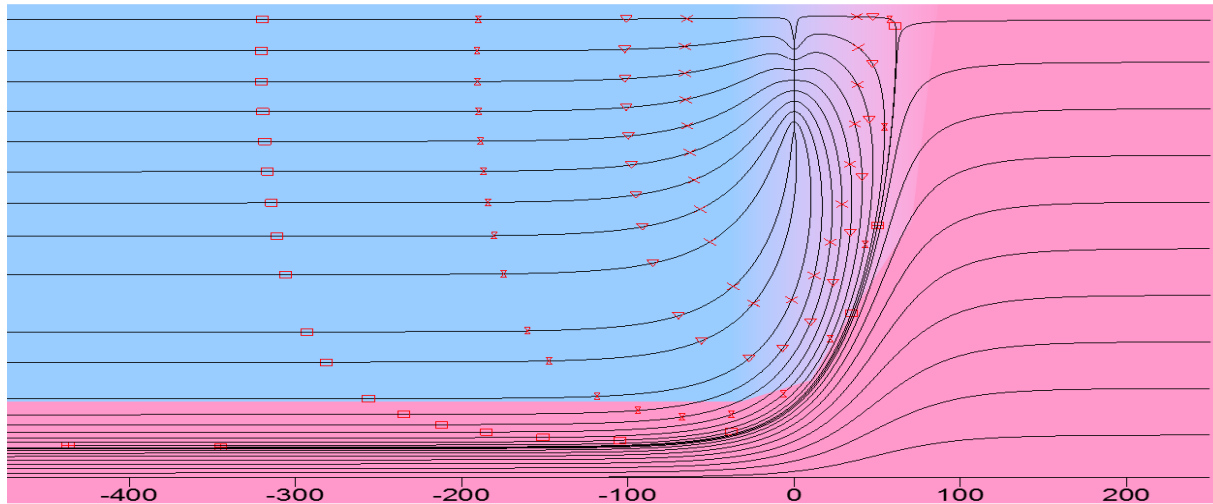


Figure 6 – Schematic visualization of salt upconing in the shadow zone of an extraction well. Blue = fresh water and pink = salt water. Groundwater flows from left to right (Hoogendoorn, 2017)

By decreasing groundwater withdrawals, the fresh water aquifer under-pressure decreases, resulting in less upconing and less salinization of fresh groundwater. Nevertheless, it has to be taken into account that groundwater salinization takes place much faster than refreshing of already salinized groundwater systems. This is partly due to the fact that density differences between fresh water and saline water are usually not large enough to quickly lower saline water interfaces (Stuurman et al., 2006). Of course, it has to be noted that the amount of upconing is dependent on multiple other factors than only the groundwater withdrawal rate, for instance the geohydrologic structure, the distance from the well to the brackish water interface and the presence of confining layers that prevent brackish water from migrating vertically (Barlow et al., 2003).

In the previous paragraph, some physical processes as free convection and compaction driven flow are evaluated. However, some other physical processes which also participate in the fresh water – brackish water interface transition are enlisted below (Stuurman et al., 2006).

- **Advective flow:** Flow as a consequence of potential energy differences.
- **Mechanical dispersion:** The extent is depending on the groundwater flow velocity. In general, the larger the flow velocity, the larger the mixture rate.
- **Molecular diffusion:** Especially relevant in stagnant situations, whereby multiple fluids consisting of different concentrations are adjacent to each other. As a consequence of particle transport from high to low concentrations, concentrations tend to level each other.
- **Osmosis:** As already explained, this process could take place when groundwater migrates throughout a clay layer which behaves as a semi-permeable membrane (Post et al., 2003; Post, 2004). As a consequence of the negative surface charge of clay layers, charged solutes as chloride ions are prevented from passing. Consecutively, groundwater chloride concentrations on the influent side of the clay layer increase with respect to the clay layer.
- **Dilution:** When fresh groundwater contacts saline deposits, groundwater becomes saline due to salt dilution.
- **Hydrothermal:** Due to high temperatures and high gas concentrations in the deep underground, is it possible for salt to rise along fractures or cracks. According Stuurman et al. (2006), multiple studies have been conducted to this subject, in which they concluded that saline hydrothermal water in the province of Noord-Brabant (The Netherlands) can rise through cracks and fractures.

2.4 Permanent Electrode Cable System (PECS)

2.4.1 General information

For monitoring the fresh water – brackish water interface, Vitens uses Permanent Electrode Cable Systems (PECS) which are characterized with an isolated cable consisting of seven or thirteen electrode couples (Figure 7¹). The distance between the electrode couples alternates between approximately three - ten meters, depending on both the in-situ geological situation and the expected fresh water – brackish water interface depth. The distance between electrodes per couple is approximately 0.2 meters (Helderman, 2016). By applying a voltage on the PECS, the conductance between specific electrodes is measured per couple. A high conductance is obtained when the resistance between electrode couples is low. Hence, fresh water (consisting of low chloride-concentrations) has a high resistance due to poor conductance capacities. On the contrary, brackish water (consisting of high chloride-concentrations) is characterized with a low resistance due to its high conductance capacities.

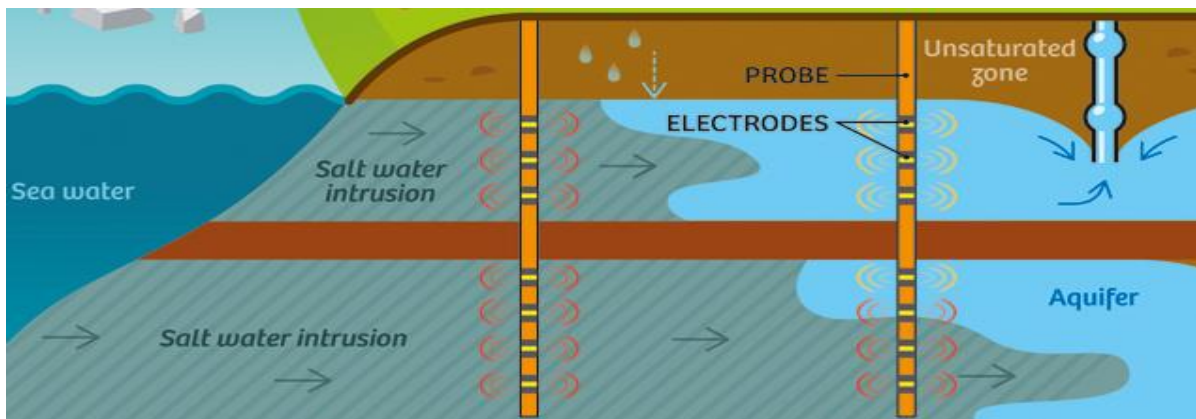


Figure 7 - Permanent Electrode Cable System (PECS) set-up (Source = Imageau.eu)

2.4.2 Geo-electrical resistivity

A conductance obtained by using PECS is not only dependent on chloride concentrations. Multiple soil properties as metals and other electricity-conducting constituents in groundwater influence measured conduction as well (Helderman, 2016). In order to relate PECS data to groundwater characteristics, it is necessary to compare PECS data with chloride data obtained in observation wells. Resistances obtained by PECS can be translated to chloride concentrations in generally two ways: theoretically and empirically.

Goes et al. (2009) describes the theoretical estimation of chloride concentrations from resistance data:

1. Estimate groundwater resistivity

Both the sediment type and electrical resistivity of groundwater influence the electrical resistivity of the subsoil. Consequently, it is possible to approximate the electrical resistivity of groundwater by using the soil resistivity and a sediment formation factor as expressed in Equation 4:

$$\rho_w = \frac{\rho_s}{F} \quad (\text{Equation 4})$$

¹ Source = <https://www.imageau.eu/solutions/securiser-exploitation-des-nappes-cotieres>

Whereby:

ρ_w = electrical resistivity of the groundwater (Ωm)
 ρ_s = soil resistivity (Ωm)
 F = formation factor (-)

The formation factor varies per type of unconsolidated sediment, as shown in Table 1. It has to be noted that Equation 4 is not representative for clayey soils. This is caused by the fact that clay is a conductive sediment. Consequently, the formation factor alternates with the electrical resistivity of groundwater (Goes et al., 2009). Furthermore, Equation 4 does not apply for layers less than 2.5 meters thick.

Table 1 – Formation factors for unconsolidated sediments in the Netherlands (Goes et al., 2009; Geirnaert and Vandenbergh, 1988; Overmeeren et al., 1991)

Lithology	Formation Factor (F)
Gravel with sand	7
Coarse sand with gravel	6
Coarse sand	5
Medium coarse sand	4
Sand with some silt	3
Silty sand	2.5 (apparent formation factor)
Strong silty sand	2
Clay	1-2 (apparent formation factor)
Peat	± 1

2. Groundwater resistivity temperature correction

As mentioned in TNO-IGG (1992) and Goes et al. (2009), the electrical resistivity of groundwater is corrected for a general temperature of 20°C by using Equation 5:

$$\rho_{w,20} = \rho_{w,t}(1 + 0.226(t - 20)) \quad (\text{Equation 5})$$

Whereby:

$\rho_{w,20}$ = electrical resistivity of groundwater at 20°C (in Ωm)
 t = temperature at depth of resistivity measurement
 $\rho_{w,t}$ = electrical resistivity of groundwater at measurement depth at temperature t (in Ωm)

3. Chloride concentration estimation

The conductance between electrodes is induced by the concentration of ions. As determined by Goes et al. (2009), low groundwater resistivity areas ($\rho_w < 3 \Omega m$) are primarily dominated by $[Na^+]$ and $[Cl^-]$. In areas with higher groundwater resistivities, other ions become important as well. For instance bicarbonate (HCO_3^-) concentrations, which are present due to $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$. Therefore, it is necessary to take account of bicarbonate concentrations by estimating chloride concentrations in groundwater. TNO-IGG (1992) generated an empirical relationship between the water resistivity (Ωm), chloride concentrations (mg/l) and bicarbonate concentrations (mg/l) as displayed in Equation 6 and Figure 8 (Goes et al., 2009):

Provided that $\rho_{w,20} < 40 \Omega m$:

$$[Cl^-] = \frac{((EC_{w,20} - 0.122 * [HCO_3^-]) \frac{1}{0.9446}}{0.44096} \quad (\text{Equation 6})$$

Whereby:

$[Cl^-]$ = chloride concentration in groundwater (mg/l)
 $[HCO_3^-]$ = bicarbonate concentration in groundwater (mg/l)
 $EC_{w,20}$ = electrical conductivity of groundwater at 20°C (mS/m)

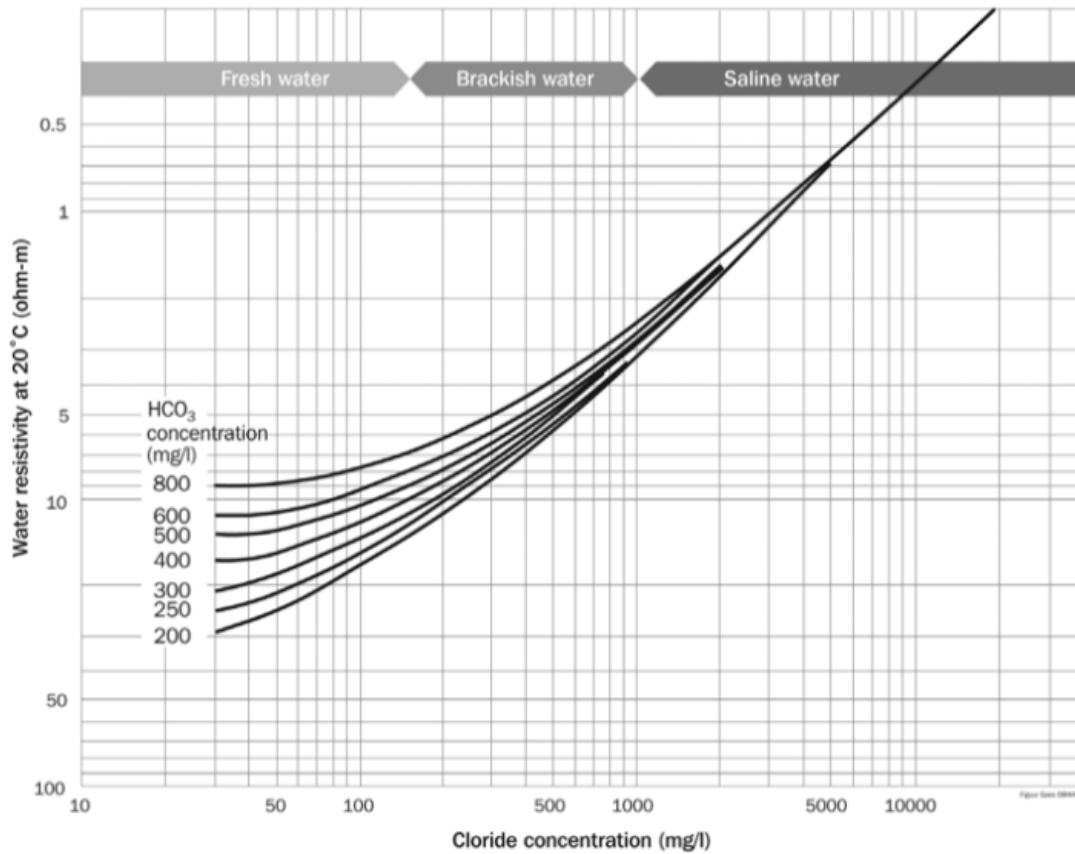


Figure 8 - Empirical relationship between the water resistivity (Ωm), chloride concentrations (mg/l) and HCO_3^- concentrations (mg/l) at a groundwater temperature of $20^\circ C$ (TNO-IGG, 1992)

Aside from the theoretical determination, it is possible to estimate relationships between chloride concentrations and resistivity by applying a statistical connection between both variables. This is less cumbersome than theoretical calculations, as variables as temperature and $[HCO_3^-]$ are not necessary. Baggelaar (2005a) conducted a study to the fresh water – brackish water interface monitoring in Boerhaar. By plotting both chloride concentrations and resistivities per specific depth in the same graph (Figure 9), Equation 7 resulted in the best fit:

$$Cl_i = 9298.6R_i^{-1,390} + e_i \quad (\text{Equation 7})$$

Whereby:

Cl_i = chloride concentration (mg/l)

R_i = Resistivity (Ω)

e_i = Model residue (mg/l)

i = index (amount of chloride – resistivity couples)

Cl [mg/l]

Chloride concentrations [mg/l] vs. resistivity [Ω]

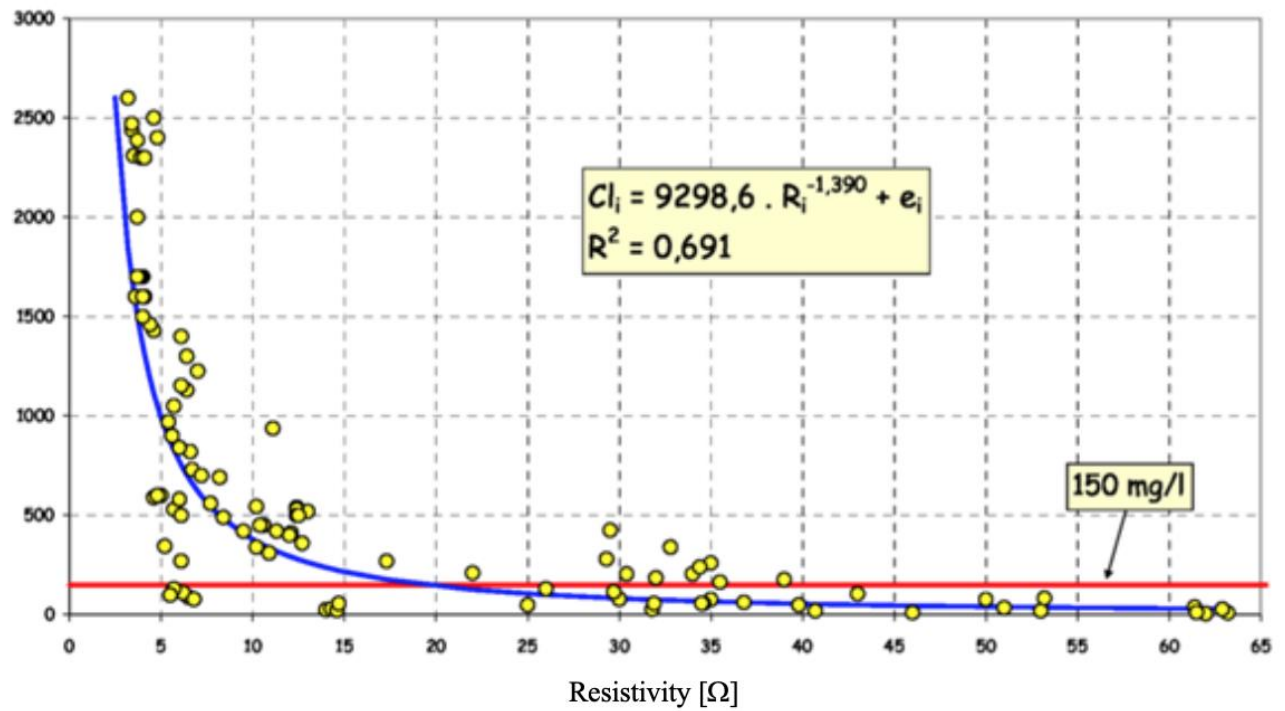


Figure 9 – Scatter diagram of chloride concentrations versus resistivity. The blue line represents the best fit. The red line represents the threshold value for brackish groundwater (Baggelaar, 2005a)

2.5 Alternative salinization monitoring methods

Nienhuis et al. (2010) conducted a research in order to verify the most optimal method for monitoring the fresh water – brackish water interface in the Amsterdam water supply dunes. In combination with information of Helderma (2016), multiple salinization monitoring methods are summarized:

- **Geophysical logging**

By conducting this method, a probe is descended in an open borehole, directly after drilling. Herewith, groundwater- and soil resistances, natural gamma radiation and electrical potential differences can be determined only once. By using this information, a reliable interpretation of the fresh water – brackish water interface can be generated as well as an overview of the lithological composition (Helderma, 2016). A disadvantage of using an open borehole is the danger of collapsing. Therefore, in the past, large volumes of fresh groundwater were supplied to open boreholes in order to prevent collapsing. This undoubtedly caused downward percolation of fresh groundwater, resulting in unreliable measurements (Nienhuis et al., 2010).

- **EM-39-logger**

This technique can be applied in already existing observation wells. However, the width of the probe has to be smaller than the width of the observation well. By using the EM-39-logger, both gamma radiation as well as formation resistances can continuously be obtained. Herewith, it is possible to monitor both the lithological composition and the fresh water – brackish water interface along the entire length of the monitoring well (Helderma, 2016). However, as alternative soil conductors as metals can affect EM-logs, it is only reliable to execute EM-logs in boreholes without conducting constituents (Nienhuis et al., 2010).

- **EM-Slimflex**

In contrast to conventional EM-39-loggers, EM-Slimflex fits in nearly all monitoring wells. Furthermore, due to its flexibility, it fits in distorted pipes. According to Deltares (2012), the EM-Slimflex device generates an electromagnetic field in a way that the soil resistivity is only measured outside the borehole. Herewith, the measured signal is not disturbed by alternative water qualities inside the borehole. In Figure 10, an example of an EM-Slimflex prototype measurement in saline conditions is shown. From this figure, relationships between EM-Slimflex measurements and chloride concentrations are evident. Also, the EM-Slimflex measurement device can be used in order to monitor groundwater contamination and natural gamma radiation, which can be used to reconstruct lithological profiles around boreholes.

- **Electrode cables**

As explained in Chapter 2.4, electrode cables consist of electrode couples located at multiple depths. By measuring the resistance between two electrodes in a couple, a quick and straightforward interpretation can be made from the fresh water – brackish water interface. However, optimal interpretations require formation factors per electrode couple, which can be determined from local EC conditions obtained in observation wells (Nienhuis et al., 2010). According to Helderma (2016), Deltares is currently developing a new type of electrode cable consisting of 96 electrode couples. Herewith it would be possible to more accurately monitor the fresh water – brackish water interface. Furthermore, Deltares is being occupied with developing an online software for visualizing electrode cable data. By applying a “stand-alone” device to electrode cables, data can be obtained without sending a mechanical in the field. Currently, a pilot is executed, and it is expected that this innovative device is ready within a few years.

- **Observation well samples**

By checking samples from observation wells in laboratories, it is possible to evaluate the chloride concentrations in high detail. However, it has to be noticed that it is hard to determine the exact fresh water – brackish water interface, as observation wells only measure chloride concentrations on specific depths. For conducting chloride concentration measurements by using observation wells, it is most optimal to use minifilters instead of piezometer filters, as minifilters often consist of a finer vertical resolution (Helderman, 2016; Nienhuis et al., 2010).

- **Geo-electric measurements**

This method is based on differences in formation resistance between soil layers. By using two electrodes positioned in the soil, a conduction is generated and measured. The potential difference between two electrodes can be used for composing a 1-D resistance profile (Helderman, 2016)

- **Head measurements**

The fresh water – brackish water interface can theoretically be determined by using the Ghyben-Herzberg relationship (Equation 2; Equation 3). When fresh groundwater heads are measured near the top of the aquifer, saline groundwater heads are obtained near the bottom of the aquifer and both groundwater densities and temperatures are known, the fresh water – brackish water interface can be approximated. However, by using this relationship, hydrostatic conditions and a sharp boundary between fresh- and brackish water are assumed, which is usually not the case (Nienhuis et al., 2010).

- **Fiberglass measurements**

Between 2015 – 2016, multiple companies have researched possibilities for measuring groundwater velocities by sending a laser beam through fiberglass cables. Herewith, it is possible to measure temperature differences alongside the cable, which are indicative for groundwater velocities. Deltares has already built a similar device in order to measure the fresh water – brackish water interface. This device consists of a special coating which transfers shrinkage and expansion due to potassium chloride towards the fiberglass cable. However, up to now, the development of this system is still ongoing (Helderman, 2016).

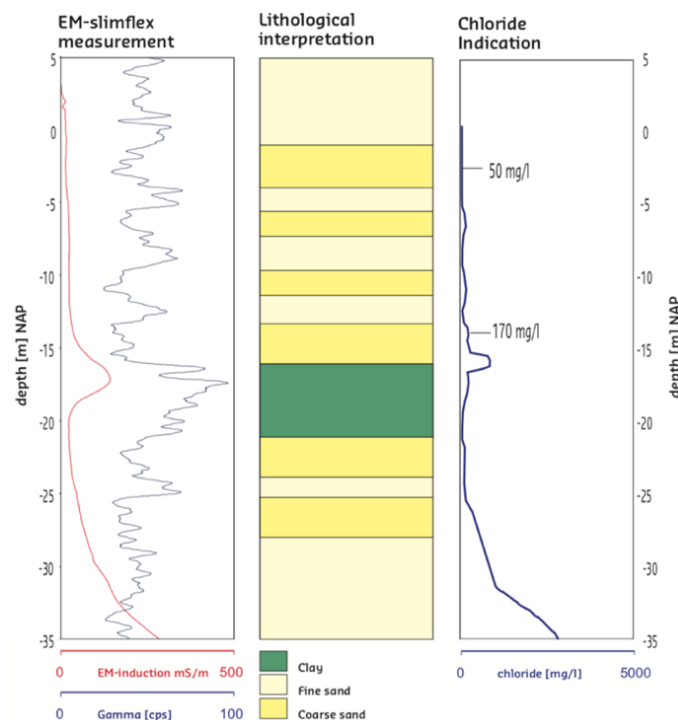


Figure 10 - EM-Slimflex prototype vs. chloride concentrations (Deltares, 2012)

2.6 Summary literature study

2.6.1 Origin fresh water – brackish water interface

Aside from coastal areas which are in hydraulic connection with the sea, salinization is furthermore caused by ancient transgressions. Based on the studies of Post et al. (2003) and De Vries (2007), it is obvious that the salinity distribution in Pleistocene aquifers is complicated. This complexity is caused by local artificially influenced flow systems and Holocene marine influences. The origin of brackish groundwater is found in Holocene transgressions, which is substantiated by both indirect demonstration (the incapability of alternative mechanisms to describe the increased groundwater salinity patterns), due to salinity inversions near the boundary between the Pliocene and Pleistocene and due to C-14 groundwater analyses. The multiple clay layers in the Pleistocene behaved as a protective layer against salinization. However, the resistance to flow and lateral continuity in most aquitards appeared to be inadequate, forcing a vertical intrusion of saline water (Post, 2004).

2.6.2 Hydrogeological conditions

As described in De Vries (2007), groundwater is predominantly present in fractures and pores from which the characteristics are largely determined by the geological history of the area. Especially deposits dating from the Pliocene – Pleistocene are a dominant groundwater source. Pliocene - Pleistocene deposits are characterized with medium to coarse fluvial sands and have a thickness which locally increases to more than 300 meters. Permeabilities generally range between 20 – 50 m/day, forcing transmissivities on specific locations to transcend 10.000 m²/day. As a consequence of multiple semi-confining layers, Pliocene - Pleistocene deposits are characterized as multi-layer aquifers. In the eastern part of the Netherlands, the Pleistocene aquifer is situated near the surface and thus has a phreatic character. By moving towards the west, this Pleistocene aquifer dips below the clayey and peaty Holocene layers, forcing aquifers to be semi-confined. The Holocene deposits merely consist of fluvial and estuarine deposits and reach a thickness of approximately 25 meters in coastal areas.

2.6.3 Current fresh water – brackish water distribution

The current salinization situation is schematically displayed in Figure 3. Herein, it is obvious that especially coastal regions are susceptible to salinization due to hydraulic connections with the sea. The depth to the fresh water – brackish water interface in these areas can be approximated by using the Ghyben-Herzberg equation (Equation 2). However, it also appears that a particular region in the eastern part of the Netherlands is characterized with a relatively shallow salinization interface, which is merely caused by local very impermeable marine deposits from the Tertiary. Factors which cause an aquifer under-pressure increase (for instance drinking water extractions, excavations and polder drainages) can severely affect the natural balance between fresh water and brackish water. However, it has to be noted that the amount of upconing is dependent on multiple factors. For instance: geohydrological structures, the distance from the well to the brackish water interface and the presence of confining layers that prevent brackish water from migrating vertically (Barlow et al., 2003).

2.6.4 Permanent Electrode Cable Systems (PECS)

The Permanent Electrode Cable System is an isolated cable consisting of seven to thirteen electrode couples. By measuring the resistance between two electrodes it is possible to approximate the fresh water – brackish water interface in soil. Vitens owns more than hundred PECS, divided over five provinces in the Netherlands. Based on literature (TNO-IGG., 1992; Goes et al., 2009) it appears that chloride concentrations can be connected to PECS resistances by using both empirical- and theoretical relationships.

2.6.5 Alternative methods for measuring the fresh water – brackish water interface

Besides PECS, other methods as EM-39 loggers, observation well samples and geophysical logging could approximate the fresh water – brackish water interface as well. Furthermore, Deltares is currently developing new methods for measuring the fresh water – brackish water interface, as EM-Slimflex and fiberglass cable measurements.

From the methods enlisted in Chapter 2.5, a few methods consist of large potentials. EM-Slimflex, for instance, fits in nearly all observation wells and generates an electromagnetic field in a way that the soil resistivity is only measured outside the borehole. Herewith, measured signals are not disturbed by alternative water qualities inside the borehole. A pilot study conducted by Deltares has already shown that EM-Slimflex results are reliable. However, in order to make a solid decision, it is important to obtain more knowledge about the specific environmental conditions in which the method has to be applied. If it is only aimed to obtain reliable estimates of chloride concentrations, samples from observations wells suit well. On the contrary, if it is aimed to create a fully autonomic measuring device for obtaining reliable estimates of brackish water interface, an EM-Slimflex would probably fit better.

3 Study area

In this chapter, more information is provided about both the spatial distribution and hydrogeological situation of PECS per province. Consecutively, information from this chapter is used in order to elucidate multiple assumptions in the data-analysis displayed in Chapter 4.

In Figure 11, the current locations of both PECS, observation wells and pumping wells are visualized. It is evident that Vitens consists of a dense network of observation wells, whereas PECS are less divided over the entire area. Upward from Chapter 3.1, a short elucidation is provided from both the hydrogeological conditions and PECS statistics per province.

It has to be noted that a separation is made between minimal- and maximal PECS electrode depths in the PECS statistical analysis. Herein, the minimal depth is defined as the deepest electrode depth while the maximum depth is defined as the shallowest electrode depth. By using statistical PECS data, it is possible to trace the dominant geohydrological formations in which PECS are situated. This is done with REGIS II v2.2 (2017), a hydrogeological subsurface model based on lithological information measured in boreholes and supplementary hydrological data as hydraulic heads².

Per province, a geohydrological cross-section is made throughout areas consisting of most PECS. Herewith, it is possible to generate a schematic overview of the geohydrological formations near PECS electrodes. Consequently, it is possible to obtain an interpretation of the general saturated transmissivities and horizontal conductivities near PECS electrodes.

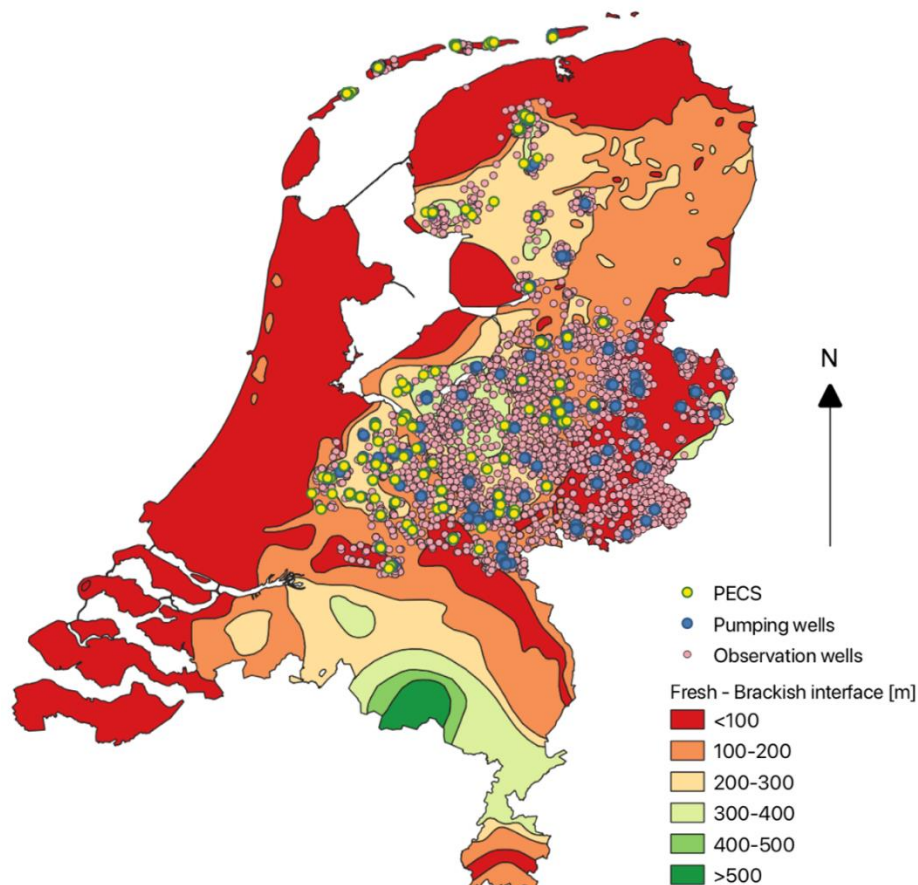


Figure 11 - Fresh water – brackish water interface depth [meters relative to NAP] in the Netherlands, based on TNO data derived in 1981.

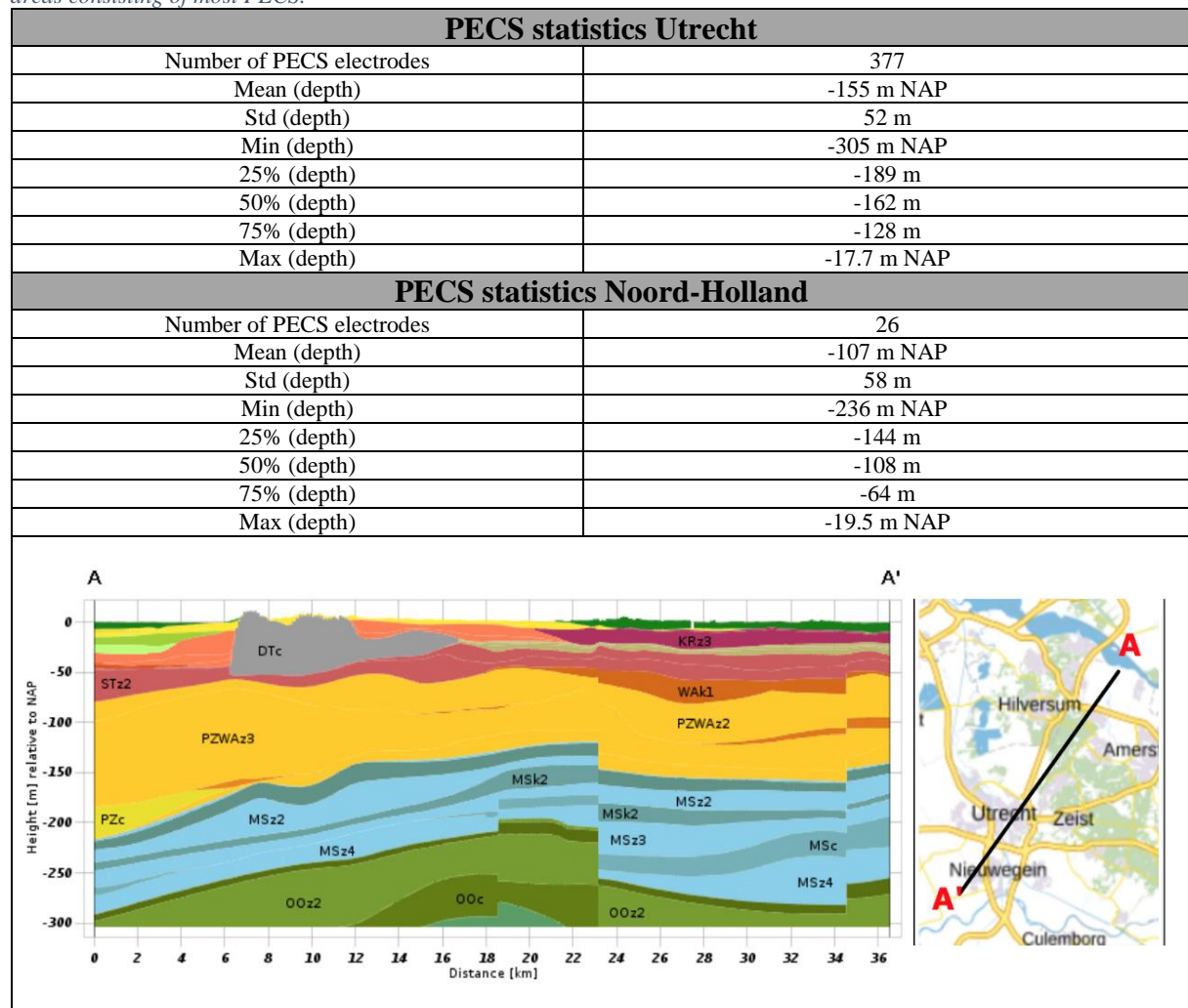
² Source = <https://www.dinoloket.nl/en/regis-ii-hydrogeological-model>

3.1 Utrecht and Noord-Holland

In the province of Utrecht, Vitens installed 31 PECS which are gradually separated over the province (based on data from 2018). Furthermore, Vitens installed two PECS in Laren, which is located in the province of Noord-Holland. From Figure 11 it is evident that the general depth of the fresh – brackish water interface ranges between approximately 100 – 300 meters below NAP. Stuurman et al. (2007) indicates that salinization has been an issue for years on particular locations in Utrecht. Especially the polder of Groot-Mijdrecht is characterized with a consistent salinization problem. Vitens does not have any extraction wells near this region. Besides, the province of Utrecht consists of thirty 100-year zones, sixteen water collection areas and fifteen groundwater protection areas. In the southern part of the province, PECS are merely situated in small water collection areas and small groundwater protection areas. In the middle of the province, larger groundwater protection areas, 100-year zones and water collection areas are situated.

Table 2 summarizes both statistical PECS data and the most dominant hydrogeological formations in which PECS are situated. PECS electrodes are generally located between 20 – 240 meters below NAP, with a mean depth at approximately 100 meters below NAP. At these depths, especially Peize and Waalre (PZWA) and Maassluis (MS) formations are relevant, consisting of large (coarse) sand units (105 – 2000 μm) which are locally intersected by alternating clay sequences. Averaged maximal horizontal conductivities range from 10 – 25 m/day in Maassluis sandy formations to 25 – 100 m/day in sandy Peize and Waalre formations (Bosch, 2003; Westerhoff et al., 2003; Huizer et al., 2003).

Table 2 - PECS statistics Utrecht and Noord-Holland (REGIS II, v2.2). Geohydrological cross-section is made throughout areas consisting of most PECS.



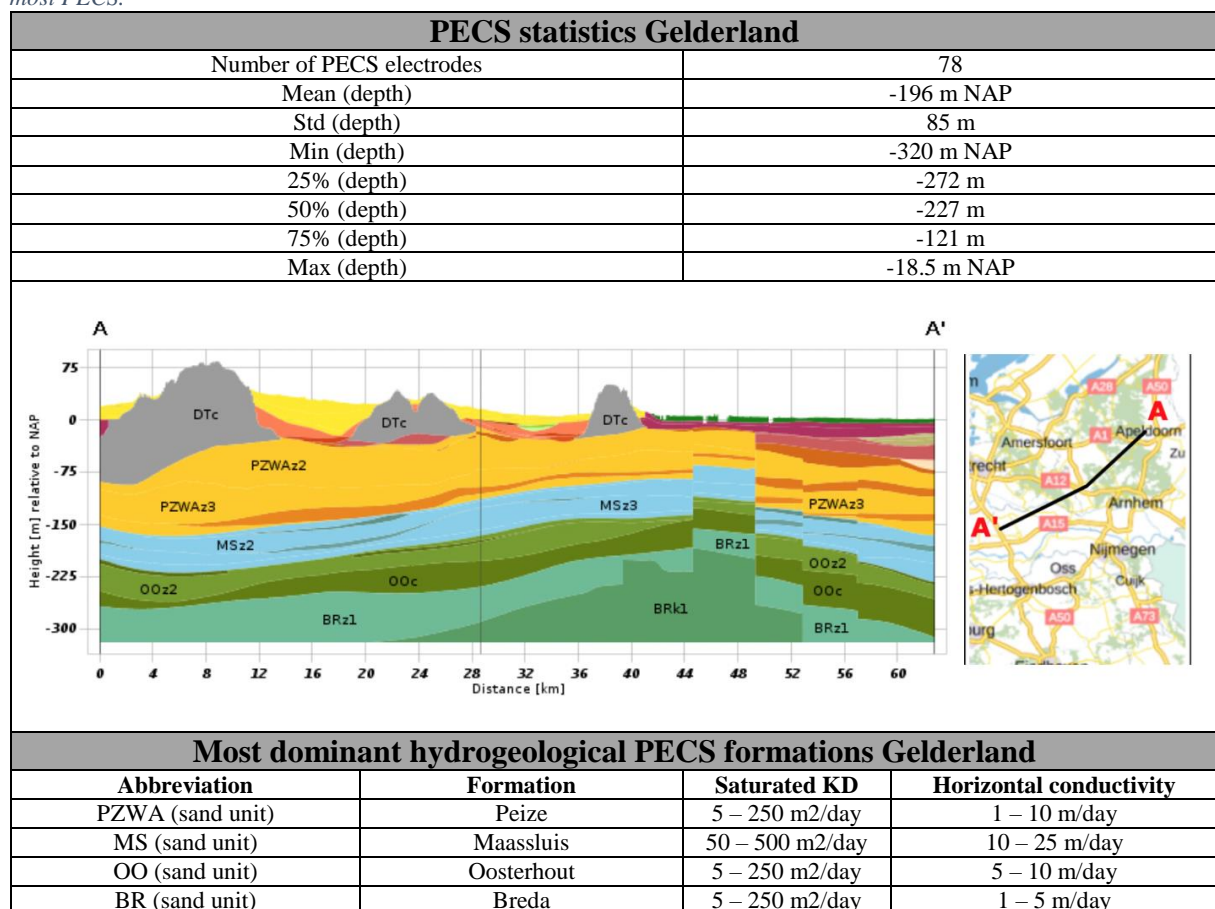
Most dominant hydrogeological PECS formations Utrecht			
Abbreviation	Formation	Saturated KD	Horizontal conductivity
PZWA (sand unit)	Peize and Waalre	>250 m ² /day	25 – 100 m/day
MS (sand unit)	Maassluis	50 – 500 m ² /day	10 – 25 m/day

3.2 Gelderland

Gelderland consists of 27 PECS, which are merely located in groundwater protection areas. According to Figure 11, the general fresh water – brackish water interface ranges between 100 – 400 meters below NAP. Most PECS are situated near the 200-meter depth boundary. Stuurman et al. (2007) mentions that potential salinization areas are primarily located in the areas near the river Rhine and IJssel. Consequently, the major part of PECS is located in these areas. Additionally, the province of Gelderland counts 35 groundwater protection areas, 49 water collection areas and approximately 62 100-year zones.

As displayed in Table 3, multiple hydrogeological formations intersect PECS. The mean PECS electrode depth in Gelderland is approximately 200 meters below NAP, with minimal- and maximal depths of 18.5 and 320 meters below NAP, respectively. Aside from the Peize and Waalre (PZWA) Formation and the Maassluis (MS) Formation, which are dominant in Utrecht, two other formations are relevant. For instance, the Oosterhout (OO) Formation, which especially consists of very fine to very coarse sand (105 – 420 μm), sandy clay and clay. As a result, maximal horizontal conductivities in the sandy Oosterhout formations range between 5 – 10 m/day. Below the Oosterhout Formation, the relatively low permeable Breda (BR) Formation is situated, which merely consists of very fine sand (105 – 150 μm) and clay. Consequently, maximum horizontal conductivities in the Breda formations differ between approximately 1 – 5 m/day (Bosch, 2003; Huizer et al., 2003; Ebbing et al., 2003; Westerhoff, 2003).

Table 3 - PECS statistics Gelderland (REGIS II, v2.2). Geohydrological cross-section is made throughout areas consisting of most PECS.

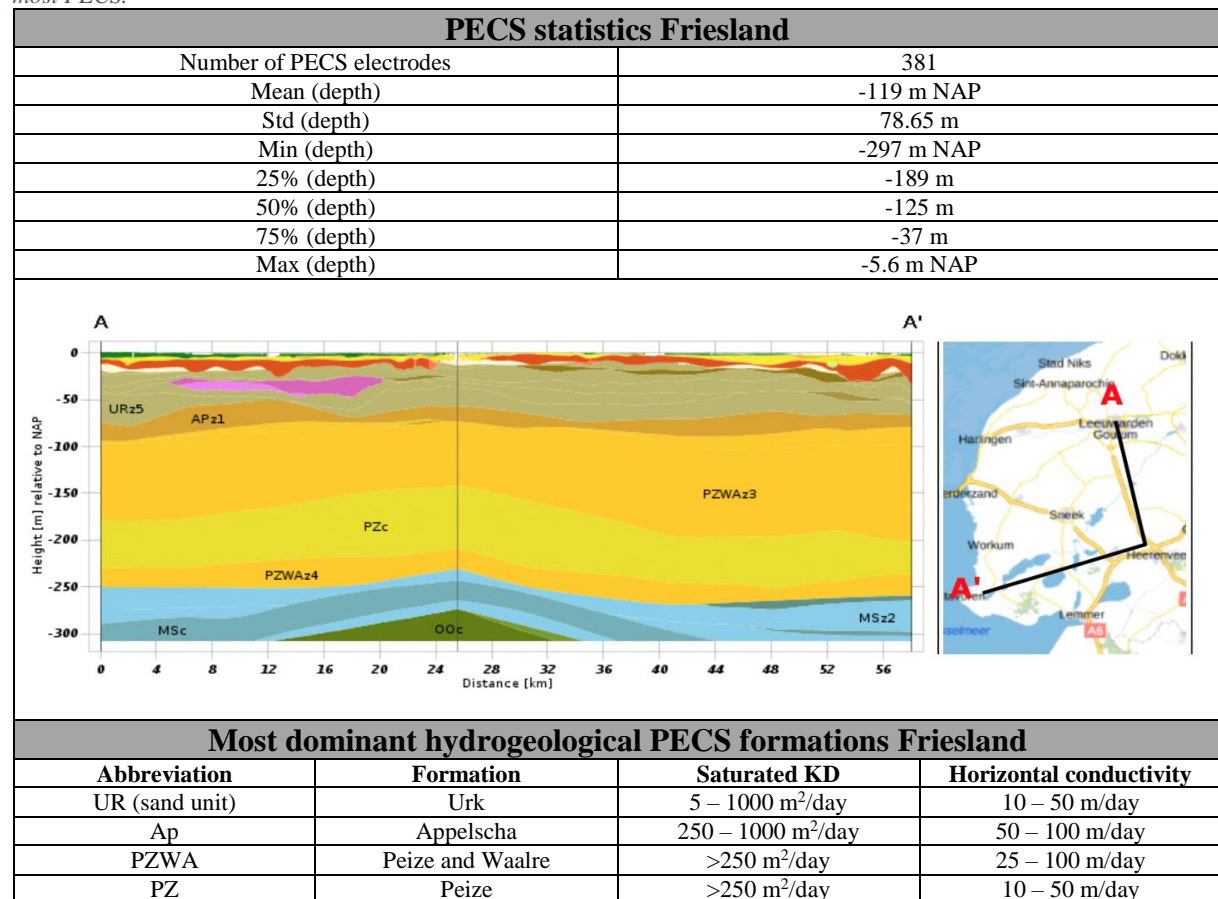


3.3 Friesland

In Friesland, Vitens installed 35 PECS. Some of these PECS are located on the Wadden Islands: Vlieland, Terschelling, Ameland and Schiermonnikoog. From Table 4 it is evident that the major part of PECS in the province of Friesland is situated at approximately 120 meters below NAP. The shallowest PECS are located at approximately 6 meters below NAP, whereas the deepest PECS are situated at approximately 300 meters below NAP. Besides, the province counts 23 water collection areas, fourteen groundwater protection areas and thirteen 100-year zones. The major part of the PECS is located in groundwater protection areas.

As displayed in Table 4, one of the shallowest large hydrogeological formations in the province of Friesland is the Urk (UR) Formation, a fluvial deposit consisting of moderately fine to very coarse sand ((150 – 2000 μm), occasional gravel deposits and alternating clay sequences. Below the Urk Formation, the Appelscha (Ap) Formation is present, which has approximately the same characteristics as the Urk Formation. Underneath, both the Peize and Waalre (PZWA) formations are located, which are elucidated before. In general, maximum horizontal conductivities range between 10 – 100 m/day (Bosch et al, 2003; Bosch, 2003; Westerhoff et al, 2003).

Table 4 - PECS statistics Friesland (REGIS II, v2.2). Geohydrological cross-section is made throughout areas consisting of most PECS.

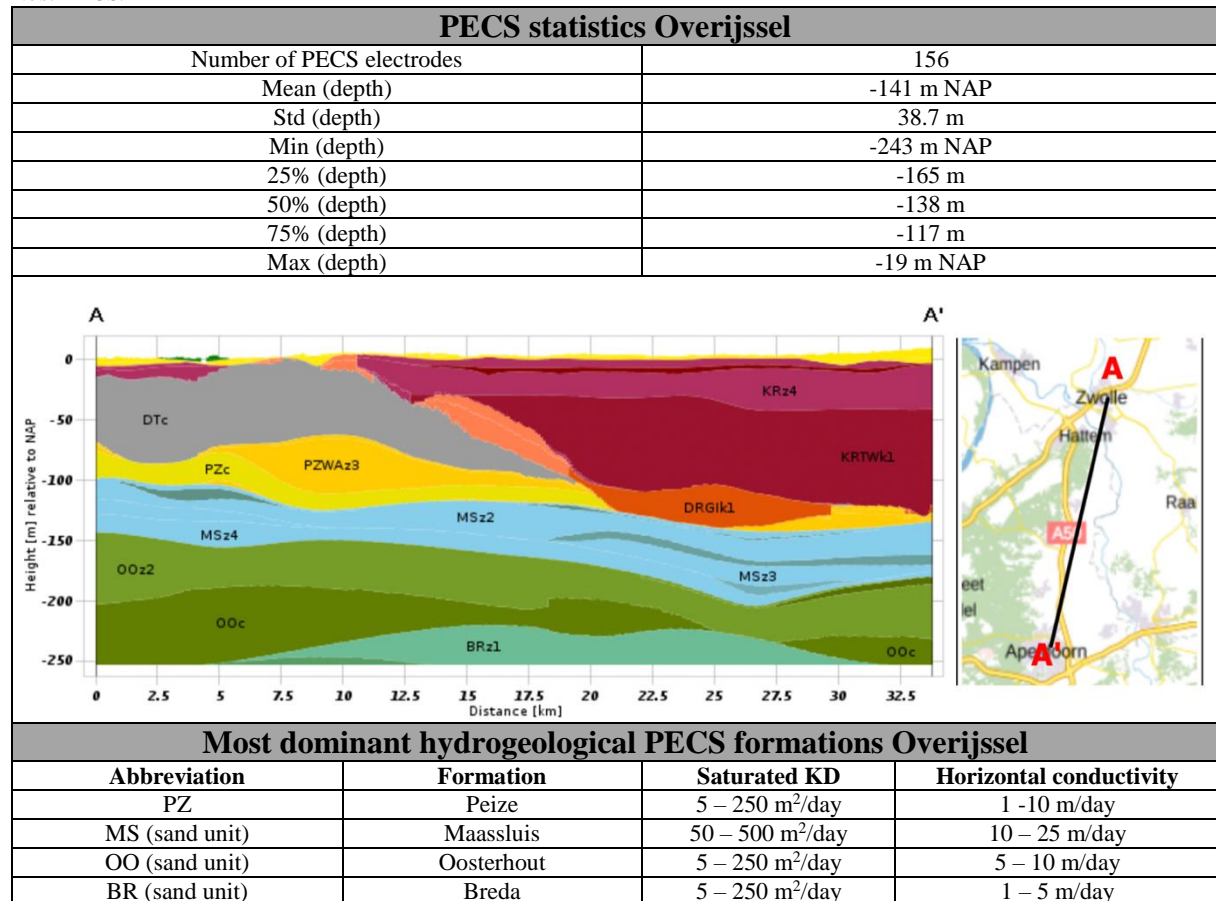


3.4 Overijssel

In the province of Overijssel, Vitens installed seventeen PECS. In 2018, none of these PECS have been measured. Stuurman et al. (2007) assumes that the largest salinization risks are located in the eastern moraine areas and in areas near river IJssel. The eastern part is susceptible due to shallow impermeable salt-containing Tertiary deposits. Some eastern parts of the province of Overijssel are characterized as inversion areas, in which brackish water is situated on top of fresh water. Up to now, the major part of the PECS is located near river IJssel, whereas no PECS are located near the eastern moraine. Besides, the province of Overijssel consists of approximately 54 water collection areas, 37 groundwater protection areas and 30 100-year zones. In this province, all PECS are situated in a groundwater protection area.

By minding Table 5, it is evident that PECS in the province of Overijssel are situated between 20 - 243 meters below NAP, with the mean depth at approximately 140 meters below NAP. Consequently, the same hydrogeological formations as Gelderland are dominant, as the Peize Formation (PZ), Maassluis Formation (MS), Oosterhout Formation (OO) and Breda Formation (BR). As a result, maximal horizontal conductivities in the province of Overijssel generally range between 1 – 25 m/day (Bosch, 2003; Huizer et al, 2003; Ebbing et al, 2003; Westerhoff, 2003).

Table 5 - PECS statistics Overijssel (REGIS II, v2.2). Geohydrological cross-section is made throughout areas consisting of most PECS.

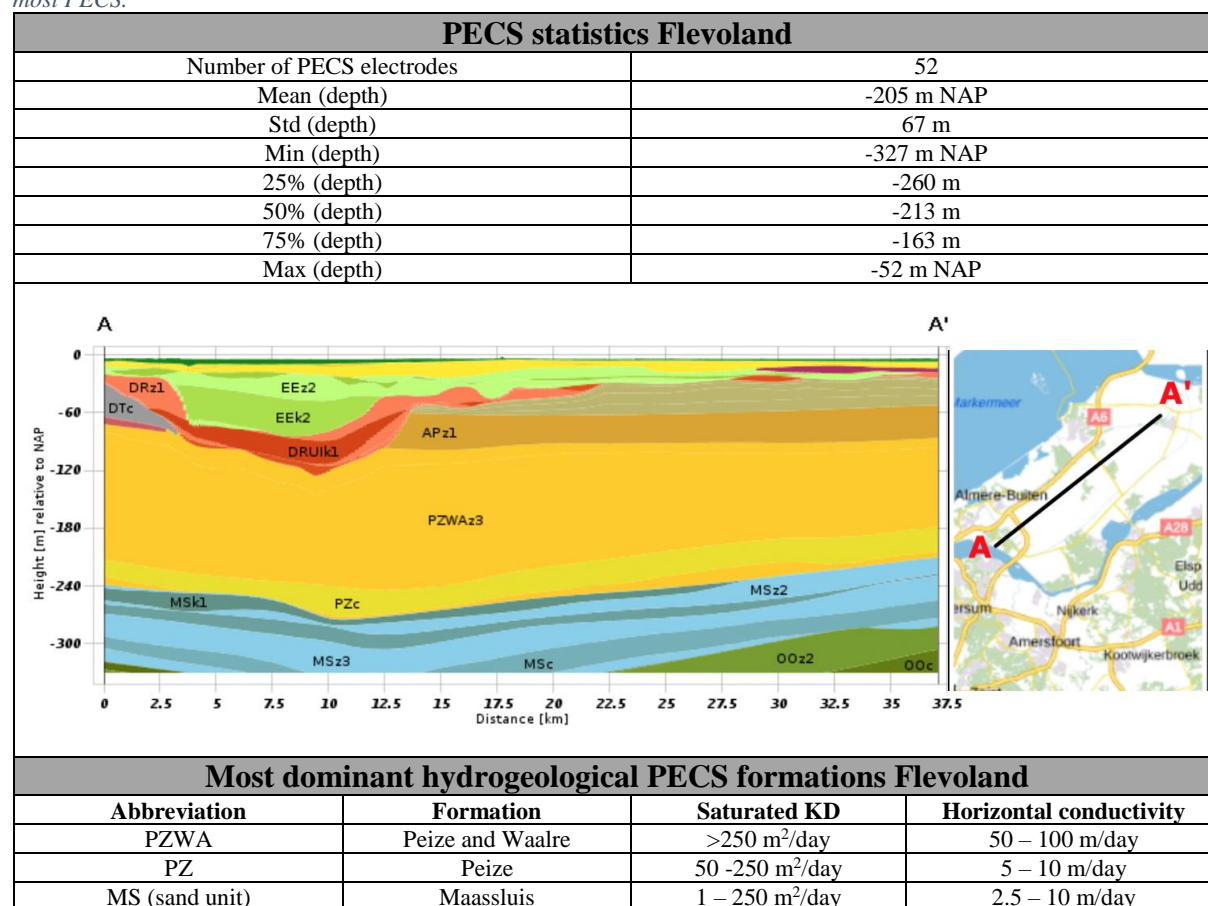


3.5 Flevoland

In Flevoland, Vitens monitors the fresh water – brackish water interface by using only five PECS. These PECS are relatively well-aligned to each other near the fresh water – brackish water interface of 300 meters below NAP (Figure 11). The south-eastern part of Flevoland is merely influenced by the Veluwe system, resulting in fresh water sources. However, in the south-western part, which is in hydraulic connection with lake IJssel, salt water sources appear. In order to monitor this fresh – brackish interface, PECS are aligned at these specific locations (Stuurman et al., 2007).

PECS in the province of Flevoland are merely situated in three different hydrogeological formations: Peize and Waalre Formation (PZWA), Peize Formation (PZ) and the Maassluis Formation (MS). The Waalre and Peize Formation consist of large (coarse) sand units (105 – 2000 μm) which are locally intersected by alternating clay sequences. Maximum horizontal conductivities in these relatively permeable formations range between 5 – 100 m/day. The Maassluis Formation, on the other hand, mainly consists of fine to moderately coarse sand (60 – 300 μm) and clay, resulting in a relatively low horizontal conductivities ranging between 2.5 – 10 m/day (Bosch, 2003; Westerhoff et al, 2003; Huizer et al. 2003).

Table 6 - PECS statistics Flevoland (REGIS II, v2.2). Geohydrological cross-section is made throughout areas consisting of most PECS.



4 Data-analysis PECS

In this chapter, current abilities of PECS are evaluated. At first, it is aimed to calibrate PECS data with chloride concentration data. This is executed per individual location and per specific depth. Thereafter, it is aimed to split irrelevant data from relevant data by applying multiple filters. The assumptions made in the data-analysis are shortly elucidated. Subsequently a discussion and conclusion are made by using both data-analysis assumptions- and results. Lastly, a recommendation is made for optimizing the current PECS salinization monitoring strategy.

4.1 Data-analysis: General filter PECS

A general filter is applied on all PECS. The purpose is to filter both relevant- and irrelevant data. In order to verify the reliability of PECS, the data-sets per location and per specific depth are compared with chloride concentration measurements, which are obtained in observation well filters. Herewith, it is necessary to couple data-sets of both PECS electrodes and observation well filters. This is conducted as displayed in the decision tree in Figure 13. Below, a short description is provided per action in the decision tree:

1. Datasets are filtered on their time-length. Some data-sets consist of a small measurement period and are therefore not suitable for conducting a proper data-analysis, whereas other PECS have already been abandoned and are therefore not relevant for further analysis. Table 7 shows the number of both PECS and chloride observations over time. Until 2014, a sufficient amount of PECS- and chloride observation data is available. Thereafter, available datasets decrease significantly: from 127 to 88 PECS in several years. Consequently, it is assumed that data-sets must contain measurements ranging to at least 2014 as this will result in the most complete data analysis.

Table 7 - Sensitivity analysis time-length PECS data

Minimal PECS timespan	Number of PECS (Total = 171)	Number of chloride observations
2013	129	2273
2014	127	2131
2015	112	1863
2016	105	1462
2017	88	296

2. Observation well locations are filtered within a horizontal radius as displayed in Figure 12. By applying this horizontal filter, it is aimed to couple PECS electrodes to observation well filters in a near distance. As shown in Chapter 3, aquifer conductivities near PECS are variable per province. Relevant hydrogeological formations in Noord-Holland, for instance, consist of higher average horizontal conductivities (± 25 m/day) than Overijssel (± 10 m/day). The delay in groundwater flow between a chloride observation well and a PECS electrode is established to be maximal one day, so it is assumed that average horizontal conductivities per province are indicative for buffer radii. Consequently, it is possible to compose a reliable relationship between PECS and chloride concentrations. Horizontal buffer distances per province are displayed in Table 8.

Table 8 – PECS horizontal buffer distances per province. Based on average Kh per province (REGIS II, v2.2)

PECS horizontal buffer distances per province						
	Utrecht	Gelderland	Overijssel	Friesland	Flevoland	Noord-Holland
Horizontal buffer [m]	25	10	10	25	15	25

3. A filter in the vertical distance is applied. Herewith, it is aimed to connect observation well filters and PECS electrodes positioned at approximately the same depth, as visualized in Figure 12. Table 9 displays the electrode distance statistics per province. In this vertical filter, the round mean electrode couple distance per province is applied as buffer in the vertical direction. For instance, the average distance between electrode couples in the province of Utrecht is 7.7 meters, resulting in a vertical buffer distance of 8 meters.

Table 9 - PECS vertical electrode distance statistics

PECS Distance between electrode couples' statistics						
	Utrecht	Gelderland	Overijssel	Friesland	Flevoland	Noord-Holland
Mean [m]	7.7	7.0	6.7	4.8	15.8	15.7
Standard deviation [m]	6.9	6.4	5.9	1.2	6.4	9.8
Minimum [m]	3	5	3	4	5	10
Maximum [m]	92	40	60	10	40	60
Vertical buffer [m]	8	7	7	5	16	16

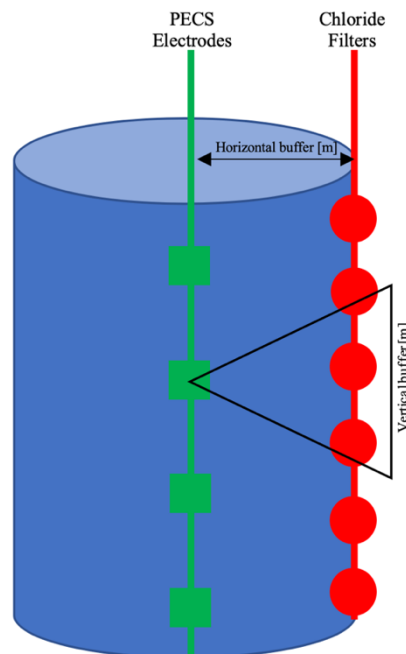


Figure 12 - Schematic overview of both the horizontal- and vertical buffer between PECS electrode cables and observation well filter

4. Eventually, PECS are categorized in three different groups: relevant data, potentially relevant data and irrelevant data. Both the relevant- and potentially relevant data are evaluated in more detail, as described in Chapter 4.2.

Relevant data: PECS consisting of a sufficient measurement extent which can be connected to observation well filters in both the horizontal- and vertical distance.

Potentially relevant data: PECS consisting of a sufficient measurement extent which cannot be connected to observation well filters in both the horizontal- and vertical distance. However, as the buffer distances are rather subjectively, PECS data is not categorized as irrelevant.

Irrelevant data: PECS consisting of an insufficient measurement extent.

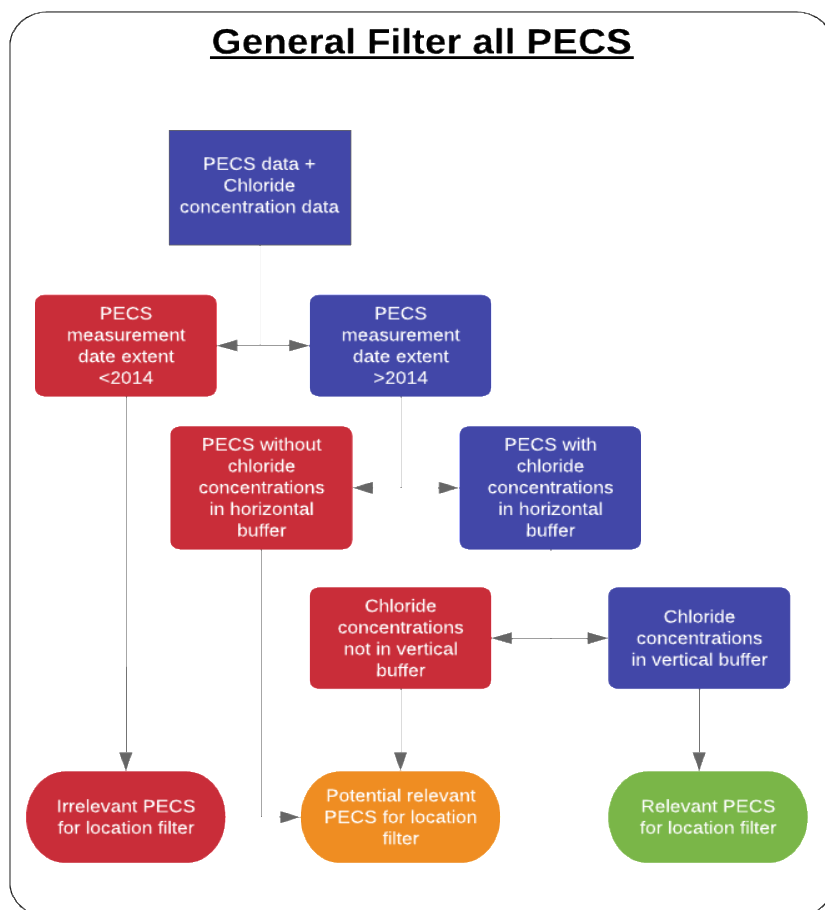


Figure 13 - Decision tree general filter PECS analysis

4.2 Data-analysis: Location filter PECS

4.2.1 Relevant PECS

Locations of relevant PECS are evaluated based on their coupled chloride concentrations. Some PECS are not located in a potential salinization area, whereas other PECS environments have already been salinized for a while. It is only possible to conduct this filter with relevant PECS, as herein it is possible to couple chloride concentrations with PECS electrodes. By applying multiple filters, as enlisted below, it is aimed to obtain more insight in PECS locations (Figure 14).

1. It is analyzed whether or not both PECS and chloride concentrations consist of an increasing or decreasing trend. It is assumed that a clear trend is absent when the chloride concentration slope and PECS slope are less than respectively 0.2 and 0.1. In case of no trend, the particular PECS is not relevant, as it does not monitor changes in chloride concentration over time.
2. Consequently, it is analyzed whether coupled chloride concentrations are sufficient or not. It is assumed that chloride concentrations below 30 mg/l are not relevant for intensive salinization monitoring. Therefore, when measured chloride concentrations in observations wells consist of a maximum average of 30 mg/l and a decreasing trend, it is assumed that these locations are not relevant for future monitoring.
3. Lastly, it is analyzed whether or not the relationship between PECS and chloride concentrations per couple is controversial. High electrode resistances are theoretically indicative for low chloride concentrations and vice versa. Consequently, a controversial trend between PECS resistances and chloride concentrations is necessary in order to determine whether the particular PECS is relevant or not. When the relationship between PECS and chloride concentrations is not controversial, it is assumed that the PECS electrodes do not respond well on chloride concentrations.

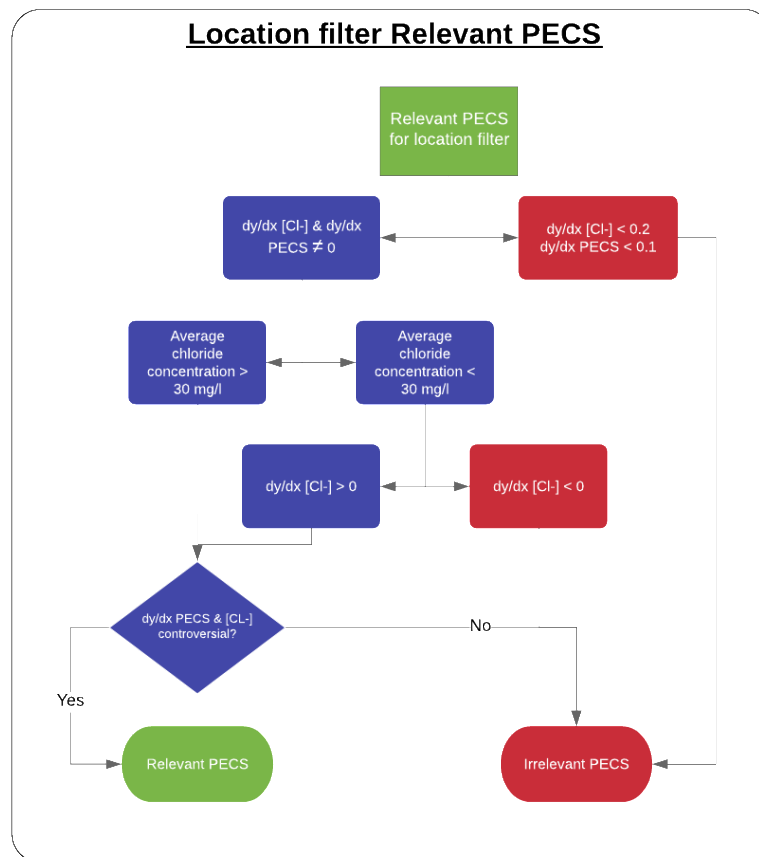


Figure 14 – Decision tree location filter “Relevant PECS”

4.2.2 Potentially relevant PECS

Besides relevant PECS, potentially relevant PECS are evaluated as well (Figure 15). PECS are categorized in this group due to assumptions made in Chapter 4.1. As these assumptions are not fully objectively, it is necessary to evaluate these PECS as well. However, since potentially relevant PECS are not correlated to chloride concentrations, it is only possible to evaluate the PECS resistance trend. It has to be noted that during this process the real abilities of potentially relevant PECS are not validated.

1. At first, it is evaluated whether PECS consist of a constant trend or not. If PECS consist of electrodes from which the trend is constant over time, it is assumed that this PECS is not situated in a salinization area.
2. Next, it is analyzed whether the PECS trend is increasing or decreasing. A decreasing trend corresponds to fresh groundwater conditions, whereas an increasing PECS trend corresponds to salinizing groundwater conditions. As a result, PECS consisting of a decreasing trend are assumed to be situated in a “(potential) salinization area” and PECS consisting of an increasing trend are assumed to be situated in a “no salinization danger area”.

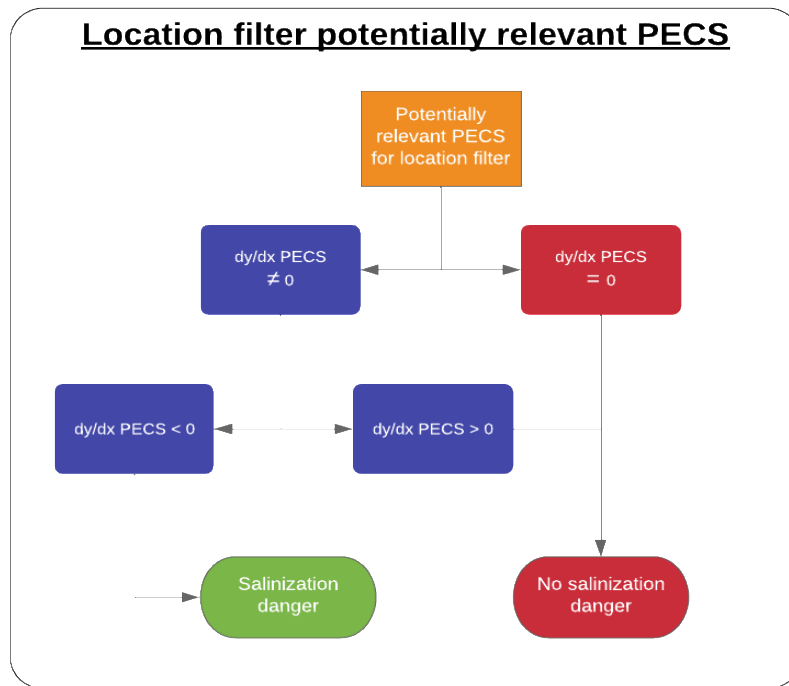


Figure 15 – Decision tree location filter “Potentially relevant PECS”

4.2.3 Location filter by using 100-year zones

Additionally, in order to evaluate the locations of PECS in more detail, a filter is conducted by using 100-year zones. These areas are generated by executing a backwards calculation from pumping well filters towards the surface during a 100-year period. Subsequently the multiple PECS (relevant, potentially relevant and irrelevant) are plotted over these areas. In case PECS are not located in a 100-year zone, PECS monitor chloride concentrations from groundwater which has to travel at least 100 years towards the pumping well.

4.3 Data-analysis: Measurement frequency PECS

Eventually an analysis is conducted on the measurement frequency, as shown in Figure 16. Herewith, it is aimed to decrease the measurement frequency where possible. In some provinces, PECS are either measured disproportionally often or too seldom. By using this analysis, it is aimed to verify whether the measurement frequencies are appropriate or not. If not, it is evaluated which measurement frequency per PECS is most optimal for future salinization monitoring.

1. A filter is applied on the current measurement frequency. It is assumed that a measurement frequency of four times per year is most optimal for relevant PECS, as herewith it is possible to quickly anticipate on broken PECS or eventual measurement errors. In case of potentially relevant PECS, it is not known which measurement frequency is required yet. The corresponding measurement frequency can be determined as soon as the PECS data is compared with chloride concentrations measured in observation wells. If there is no obvious relationship with chloride concentrations, PECS measurements are no longer necessary. However, if it appears that particular PECS consist of a clear trend with chloride concentrations, a measurement frequency of four times per year is required. Irrelevant PECS do not require further monitoring. For reliability purposes, it is visually checked whether the suggested measurement frequency per PECS is correct or not.
2. Thereafter, it is analyzed whether specific PECS consist of a municipality permission or not. If PECS consist of a municipality permission, it is not possible to alter the measurement frequency directly. Alternatively, it is possible to alter measurement frequency.
3. Besides, a small filter is applied on the irrelevant dataset. It is analyzed whether irrelevant PECS consist of a municipality permission or not. If PECS consist of a municipality permission, it is not possible to alter the measurement procedure. Irrelevant PECS appeared to be inefficient and do not have added value. It has to be discussed whether or not these PECS have to be removed.

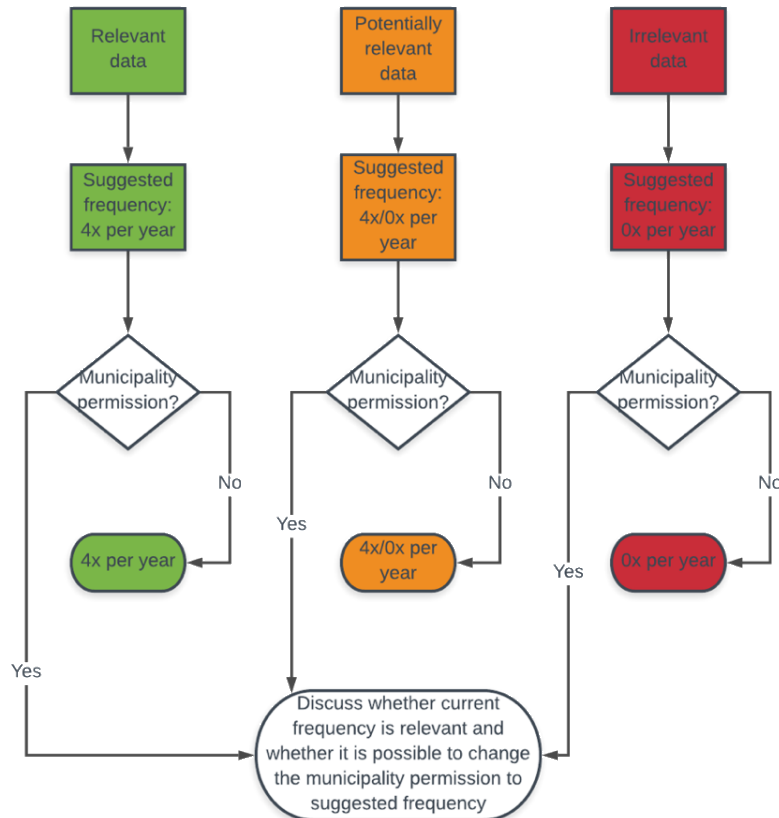


Figure 16 - Measurement frequency data analysis. It has to be noted that the suggested measurement frequency has to be checked per individual PECS and only indicates as a guideline.

4.4 Results data-analysis PECS

The results are visualized per province. It is worth mentioning that the results are generated based on assumptions made in the previous chapters. Other input parameters obviously result in alternative results. Per province, the following characteristics are discussed:

Table 10 – PECS analysis results description

1	PECS	Each PECS corresponds to a specific number, which is displayed in this column.	
2	Relevant/Irrelevant		Relevant data
			Potentially relevant data
			Irrelevant data
		Colored in red	Relevant data without a clear correlation between PECS – [Cl ⁻]
3	Cause	If PECS are potentially relevant or irrelevant, the cause is displayed.	
4	Location	Displays PECS' locations.	
5	Municipality permission	Shows whether PECS consist of a municipality permission or not.	
6	Mandatory frequency	If PECS consist of a municipality permission, the mandatory frequency is displayed.	
7	Current frequency	Displays the current measurement frequency.	
8	Suggested frequency	Displays the suggested measurement frequency as discussed in Figure 16.	
9	Number connections	Displays the total number of connections between PECS electrodes and observation well filters. It is possible that a PECS electrode is connected to multiple observation well filters. Consequently, the number of connections can be higher than 13 (maximum number of electrodes in PECS).	
10	Minimal distance pumping well [m]	Displays the minimum distance between a PECS and a pumping well.	
11	PUTCODE	Each PECS corresponds to a specific number, which is displayed in this column.	
12	Mean [Cl ⁻] [mg/l]	Displays the average chloride concentration measured near PECS.	
13	PECS' trend	Displays whether PECS consist of a constant or not a constant measured resistance.	
14	PECS Increasing/decreasing	Displays whether the trend increases or decreases.	

Per PECS it is evaluated whether it is relevant, potentially relevant or irrelevant. This is visualized by using colors. A green cell corresponds to a relevant PECS, an orange cell to a potentially relevant PECS and a red cell to an irrelevant PECS. Additionally, it appeared during the visual check that many relevant PECS do not have a clear relationship with chloride concentrations. These particular PECS are marked in red.

The results of the 100-year zone filter are visualized in Appendix A.

4.4.1 Utrecht

	PECS	Relevant/Irrelevant	Cause	Location	Municipality permission	Mandatory frequency	Current frequency	Suggested frequency	Number connections	Minimal distance pumping well [m]	PUTCODE	Mean [Cl-] [mg/l]	PECS Trend	PECS Increasing/decreasing
0	38EP0225	Relevant		Benschoten	No information	No information	2x per year, april, oktober	4x per year	16	5401	BLWP002	139,9994958		
1	31GP0200	Relevant		Linschoten	Yes	4 x per year	1x per year, april	4x per year	15	967	LIWP014	36,5992		
2	31GP0205	Relevant		Linschoten	Yes	4 x per year	1x per year, april	4x per year	15	1884	LIWP017	39,60830769		
3	31HP0697	Relevant		Leidsche Rijn	Yes	4 x per year	1x per year, oktober	4x per year	13	61	LRWP006	92,10084656		
4	32BP0258	Relevant		Eemdijk Bunschoten	Yes	4 x per year	1x per year, april	4x per year	8	630	EEWP002	9,907464789		
5	32AP0138	Relevant		Onnenkade	No	-	1x per year, oktober	4x per year	12	100	OWWP019	111,8021745		
6	32AP0335	Relevant		Lage Vuursche	No	-	1x per year, april	4x per year	6	5584	LVWP008	188,9828947		
7	32AP0336	Relevant		Soest	No	-	1x per 2 year, oktober	4x per year	7	1792	SWWP002	13,14372727		
8	32BP0210	Relevant		Amersfoort Hogeweg	No	-	2x per year, april, oktober	4x per year	4	1236	AHWP001	347,759258		
9	32CP0230	Relevant		Driebergen	No	-	1x per year, april	4x per year	13	8	DRWP003	14,57592593		
10	32CP0566	Relevant		Zeist	No	-	1x per year, oktober	4x per year	16	89	ZLWP041	81,3154		
11	32CP0568	Relevant		Beerschoten	No	-	1x per year, oktober	4x per year	14	75	BWWP061	376,2278462		
12	32DP0167	Relevant		Amersfoort Berg	No	-	1x per year, april	4x per year	12	863	ABWP001	63,91884615		
13	32BP0194	Relevant		Woudenberg	No	-	2x per year, oktober	4x per year	14	19	WOWP012	14,0295142		
14	32DP0327	Relevant		Woudenberg	No	-	2x per year, april, oktober	4x per year	18	196	WOWP032	336,2497917		
15	38EP0098	Relevant		Lopik	No	-	1x per year, april	4x per year	8	10826	UTWP002	285,0020408		
16	38FP0558	Relevant		Nieuwegein	No	-	1x per year, april	4x per year	10	414	NIWP002	114,6816532		
17	38AP0187	Relevant		Loosdrecht	No	-	1x per year, april	4x per year	4	100	LOWP001	10,84387065		
18	38AP0134	Relevant		Schaaijk	No	-	1x per 2 year, oktober	4x per year	5	4000	UTWP004	14,015		
19	39EP0145	Relevant		Veenendaal	No	-	2x per year, april, oktober	4x per year	3	16	VEWP007	722,7500575		
20	39EP0241	Relevant		Veenendaal	No	-	2x per year, april, oktober	4x per year	15	26	VEWP011	335,8470321		
21	39EP0251	Relevant		Veenendaal	No	-	1x per year, oktober	4x per year	16	272	VEWP012	51,28447552		
22	39EP0252	Relevant		Veenendaal	No	-	1x per year, oktober	4x per year	15	224	VEWP013	56,1959854		
23	39EP0254	Relevant		Rhenen	No	-	1x per year, oktober	4x per year	11	43	RHWP022	143,0252101		
24	32BP0209	Potential Relevant	No Filter Connection in Z buffer	Holk	No	-	2x per year	4x/Ox per year		2445	32BP0209	16,09512195	Not constant	Increasing
25	38FP0561	Potential Relevant	No Filter Connection in Z buffer	Nieuwegein	No	-	1x per year, april	4x/Ox per year		31	NIWP005	39,43548611		
26	38BP0142	Irrelevant	Cl- and PECS not controversial	Oudewater	No information	No information	1x per 2 year, oktober	0x per year	3	7579	UTWP001	367,7083333		
27	26DP0090	Irrelevant	Timespan not sufficient	Eemspolder, Eemdijk	Yes	4 x per year	1x per year, april	0x per year		60	EEWP005	138,1277778		
28	31GP0214	Irrelevant	Timespan not sufficient	Linschoten	Yes	4 x per year	2x per year, april, oktober	0x per year		41	LIWP018	145,7658387		
29	32CP0521	Irrelevant	Timespan not sufficient	Bunnik	No	-	1x per year, oktober	0x per year		20	BUWP012	64,16485207		
30	38FP0578	Irrelevant	Timespan not sufficient	Tull en 't Waal	No	-	1x per year, april	0x per year		50	TUWP007	960,3945946		

4.4.2 Gelderland

	PECS	Relevant/Irrelevant	Cause	Location	Municipality permission	Mandatory frequency	Current frequency	Suggested frequency	Number connections	Minimal distance pumping well [m]	PUTCODE	Mean [Cl-] [mg/l]	PECS Trend	PECS Increasing/decreasing
0	39DP0222	Relevant		Zoelen	Yes	2 x per year	1 x per year	4x per year	8	32	39DP0222	163,9214286	Not constant	Decreasing
1	39HP0165	Relevant		Druuten	No	-	1 x per year	4x per year	9	113	39HP0165	1884,690476	Not constant	Decreasing
2	40AP0397	Relevant		Fikkersdries	No	-	1 x per year	4x per year	6	2569	40AP0397	95,05833333	Not constant	Decreasing
3	32GP0137	Potential Relevant	No Filter Connection in Z buffer	Glindhorst	No information	No information	1 x per year	4x/Ox per year		4661	32GP0137		Not constant	Decreasing
4	32HP0227	Potential Relevant	No Filter Connection in Z buffer	Westeneng	No information	No information	1 x per year	4x/Ox per year		8543	32HP0227		Constant	-
5	33CP0079	Potential Relevant	No Filter Connection in Z buffer	Hoog Soeren	No information	No information	1 x per year	4x/Ox per year		3508	33CP0079		Not constant	Decreasing
6	33CP0079	Potential Relevant	No Filter Connection in Z buffer	Otterlo	No information	No information	1 x per year	4x/Ox per year		7041	33CP0079		Not constant	Increasing
7	39EP0084	Potential Relevant	No Filter Connection in Z buffer	Lienden	No information	No information	1 x per year	4x/Ox per year		2142	39EP0084	6,333333333		
8	40CP0421	Potential Relevant	No Filter Connection in Z buffer	Andelst	No information	No information	1 x per year	4x/Ox per year		2991	40CP0421		Not constant	Decreasing
9	39DP0205	Potential Relevant	No Filter Connection in Z buffer	Zoelen	Yes	2 x per year	2 x per year	4x/Ox per year		327	39DP0205	244,6287879	Not constant	Decreasing
10	40BP0349	Potential Relevant	No Filter Connection in Z buffer	Sijmons (Immerlopark, Arnhem Zuid)	Yes	1 x per year	1 x per year	4x/Ox per year		21	40BP0349	512,1	Not constant	Decreasing
11	45AP0163	Potential Relevant	No Filter Connection in Z buffer	Veldriel	Yes	2 x per year	2 x per year	4x/Ox per year		751	45AP0163	154,0975	Not constant	Decreasing
12	45AP0164	Potential Relevant	No Filter Connection in Z buffer	Veldriel	Yes	2 x per year	2 x per year	4x/Ox per year		1839	45AP0164		Not constant	Decreasing
13	27BP0255	Potential Relevant	No Filter Connection in Z buffer	Epe	No	-	1 x per year	4x/Ox per year		109	27BP0255		Not constant	Increasing
14	33CP0185	Potential Relevant	No Filter Connection in Z buffer	Twello	No	-	1 x per year	4x/Ox per year		84	33CP0185	1611,555556	Not constant	Decreasing
15	33EP0250	Potential Relevant	No Filter Connection in Z buffer	Twello	No	-	1 x per year	4x/Ox per year		456	33EP0250	718,2900901		
16	39AP0236	Potential Relevant	No Filter Connection in Z buffer	Culemborg	No	-	1 x per year	4x/Ox per year		16	39AP0236		Not constant	Decreasing
17	39CP0154	Potential Relevant	No Filter Connection in Z buffer	Kolff	No	-	1 x per year	4x/Ox per year		4	39CP0154	38,59333333	Not constant	Decreasing
18	39HP0235	Potential Relevant	No Filter Connection in Z buffer	Druuten	No	-	1 x per year	4x/Ox per year		168	39HP0235	707,2222222	Not constant	Decreasing
19	40AP0551	Potential Relevant	No Filter Connection in Z buffer	Oosterbeek	No	-	1 x per year	4x/Ox per year		10	40AP0551	481,8292683	Constant	-
20	40AP0552	Potential Relevant	No Filter Connection in Z buffer	La Cabine	No	-	1 x per year	4x/Ox per year		95	40AP0552	93,49484536	Not constant	Increasing
21	40BP0375	Irrelevant	Location - Cl < 30 mg/L + negative slope	Sijmons (Bakenhof, Arnhem zuid)	Yes	1 x per year	1 x per year	0x per year	8	1144	40BP0375	13,77083333	Not constant	Increasing
22	33CW0066	Irrelevant	Timespan not sufficient	Hoenderloo	No	-	1 x per year	0x per year		0	HOE-P00-20	77,02222222		
23	33CW0073	Irrelevant	Timespan not sufficient	Hoenderloo	No	-	1 x per year	0x per year		0	HOE-P00-22	6,6875		
24	33CW0075	Irrelevant	Timespan not sufficient	Hoenderloo	No	-	1 x per year	0x per year		0	HOE-P00-23	6,666666667		
25	33CW0080	Irrelevant	Timespan not sufficient	Hoenderloo	No	-	1 x per year	0x per year		0	HOE-P00-24			
26	39HA3161	Irrelevant	Timespan not sufficient	Beuningen	No	-	1 x per year	0x per year		7941	39HA3161	6,88		

4.4.3 Friesland

	PECS	Relevant/Irrelevant	Cause	Location	Municipality permission	Mandatory frequency	Current frequency	Suggested frequency	Number connections	Minimal distance pumping well [m]	PUTCODE	Mean [Cl-] [mg/l]	PECS Trend	PECS Increasing/decreasing
0	02CP0128	Relevant		Buren Ameland	Yes	4 x per year	4 x per year	4x per year	6	126	02CP0128	72		
1	04FP0044	Relevant		Hollum Ameland	Yes	4 x per year	4 x per year	4x per year	1	133	04FP0044	42		
2	04HP0095	Relevant		Hollum Ameland	Yes	4x per year	4x per year	4x per year	2	133	04HP0095	2090		
3	04FP0044	Relevant		Vrieland	Yes	4x per year	4x per year	4x per year	11	70	04FP0044	93		
4	04FP0045	Relevant		Vrieland	Yes	4x per year	4x per year	4x per year	1	666	04FP0045	60		
5	04FP0058	Relevant		Vrieland	Yes	4x per year	4x per year	4x per year	5	178	04FP0058	57		
6	04FP0059	Relevant		Vrieland	Yes	4x per year	4x per year	4x per year	3	135	04FP0059	7532		
7	02GP0306	Relevant		Schiernomnikooog	No	-	4x per year	4x per year	6	293	02GP0306	3201		
8	02GP0308	Relevant		Schiernomnikooog	No	-	4x per year	4x per year	13	261	02GP0308	525		
9	06DP0208	Relevant		Noardburgum	No	-	4x per year	4x per year	6	262	06DP0208	343		
10	06DP0209	Relevant		Noardburgum	No	-	4x per year	4x per year	4	258	06DP0209	3590		
11	06DP0210	Relevant		Noardburgum	No	-	4x per year	4x per year	4	1069	06DP0210	1951		
12	06DP0212	Relevant		Noardburgum	No	-	4x per year	4x per year	4	468	06DP0212	376		
13	06DP0214	Relevant		Noardburgum	No	-	4x per year	4x per year	4	782	06DP0214	10		
14	06DP0215	Relevant		Gargp	No	-	4x per year	4x per year	1	145	06DP0215	246		
15	06DP0250	Relevant		Gargp	No	-	4x per year	4x per year	2	324	06DP0250	194		
16	06DP0295	Relevant		Gargp	No	-	4x per year	4x per year	4	254	06DP0295	1344		
17	15EP0090	Relevant		Oudoga	No	-	4x per year	4x per year	4	2152	15EP0090	24		
18	15EP0091	Relevant		Oudoga	No	-	4x per year	4x per year	3	440	15EP0091	24		
19	01HP0094	Potential Relevant	No Filter Connection in Z buffer	Hollum Ameland	Yes	4 x per year	4x per year	4x/Dx per year	4	444	01HP0094	Not constant	Increasing	
20	01HP0096	Potential Relevant	No Filter Connection in Z buffer	Hollum Ameland	Yes	4 x per year	4x per year	4x/Dx per year	4	535	01HP0096	Not constant	Decreasing	
21	02CP0127	Potential Relevant	No Filter Connection in Z buffer	Buren Ameland	Yes	4 x per year	4x per year	4x/Dx per year	9	926	02CP0127	Not constant	Decreasing	
22	02CP0129	Potential Relevant	No Filter Connection in Z buffer	Buren Ameland	Yes	4 x per year	4x per year	4x/Dx per year	2	870	02CP0129	Not constant	Decreasing	
23	04FP0040	Potential Relevant	No Filter Connection in Z buffer	Vrieland	Yes	4 x per year	4x per year	4x/Dx per year	11	266	04FP0040	Not constant	Decreasing	
24	04FP0047	Potential Relevant	No Filter Connection in Z buffer	Vrieland	Yes	4 x per year	4x per year	4x/Dx per year	11	31	04FP0047	Not constant	Decreasing	
25	11EP0076	Potential Relevant	No Filter Connection in Z buffer	Nij Beets	Yes	2x per year	4x per year	4x per year	4	2219	11EP0076	Not constant	Decreasing	
26	16BP0105	Potential Relevant	No Filter Connection in Z buffer	Oldelohthade	Yes	2 x per year	No information	4x/Dx per year	4	34	16BP0105	Not constant	Decreasing	
27	11CP0090	Potential Relevant	No Filter Connection in Z buffer	Spannenburg	No	-	4x per year	4x/Dx per year	4	9574	11CP0090	Not constant	Decreasing	
28	11FP0121	Potential Relevant	No Filter Connection in Z buffer	Spannenburg	No	-	4x per year	4x/Dx per year	4	1677	11FP0121	Not constant	Increasing	
29	11FP0122	Potential Relevant	No Filter Connection in Z buffer	Spannenburg	No	-	4x per year	4x/Dx per year	4	1150	11FP0122	Not constant	Increasing	
30	04FP0025	Irrelevant	Timespan not sufficient	Vrieland	Yes	4 x per year	4x per year	0x per year	22	04FP0025	Not constant	Decreasing		
31	04FP0026	Irrelevant	Timespan not sufficient	Vrieland	Yes	4 x per year	4x per year	0x per year	22	04FP0026	Not constant	Decreasing		
32	14CP0005	Irrelevant	Timespan not sufficient	Terwischje	No	-	4x per year	0x per year	14	80540194	Not constant	Decreasing		
33	80540194	Irrelevant	Timespan not sufficient	Terwischje	No	-	4x per year	0x per year	14	80540194	Not constant	Decreasing		

4.4.4 Overijssel

	PECS	Relevant/Irrelevant	Cause	Location	Municipality permission	Mandatory frequency	Current frequency	Suggested frequency	Number connections	Minimal distance pumping well [m]	PUTCODE	Mean [Cl-] [mg/l]	PECS Trend	PECS Increasing/decreasing
0	21GP0287	Relevant		Engelse Werk	No	-	12 x per year	4x per year	5	178	21GP0287	201,8068966	Not constant	Decreasing
1	21GP0483	Relevant		Engelse Werk	No	-	12 x per year	4x per year	8	472	21GP0483	42,79009901	Not constant	Decreasing
2	21GP0502	Relevant		Engelse Werk	No	-	12 x per year	4x per year	8	38	21GP0502	597,5467742	Not constant	Decreasing
3	12CP0131	Relevant		Engelse Werk	No	-	12 x per year	4x per year	9	84	12CP0131	68,448112	Not constant	Decreasing
4	12CP0132	Relevant		Engelse Werk	No	-	12 x per year	4x per year	9	305	12CP0132	136,3328467	Not constant	Decreasing
5	12CP0133	Relevant		Engelse Werk	No	-	12 x per year	4x per year	9	421	12CP0133	145,4848485	Not constant	Decreasing
6	12CP0134	Relevant		Engelse Werk	No	-	12 x per year	4x per year	9	31	12CP0134	51,61390367	Not constant	Decreasing
7	12CP0135	Relevant		Engelse Werk	No	-	12 x per year	4x per year	9	161	12CP0135	1278,373548	Not constant	Decreasing
8	21HP0074	Potential Relevant	No Filter Connection in Z buffer	Vechterweerd	No	-	12 x per year	4x/Dx per year	526	21HP0074	Not constant	Decreasing		
9	27GP0186	Potential Relevant	No Filter Connection in Z buffer	Boerhaar	No	-	12 x per year	4x/Dx per year	69	27GP0186	Not constant	Decreasing		
10	33FP0133	Potential Relevant	No Filter Connection in Z buffer	Dortmundstraat, Deventer	No	-	12 x per year	4x/Dx per year	795	33FP0133	Not constant	Decreasing		
11	21GP0276	Irrelevant	Timespan not sufficient	Engelse Werk	No information	-	No information	0x per year	21GP0276	Not constant	Decreasing			
12	21HP0091	Irrelevant	Timespan not sufficient	Engelse Werk	No information	-	No information	0x per year	21HP0091	Not constant	Decreasing			
13	27BP0144	Irrelevant	Timespan not sufficient	Engelse Werk	No information	4x per year	0x per year	0x per year	27BP0144	559,7142857	Not constant	Decreasing		
14	28CP0155	Irrelevant	Timespan not sufficient	Engelse Werk	No information	12x per year	0x per year	0x per year	28CP0155	61,85111111	Not constant	Decreasing		
15	21BP0216	Irrelevant	Location - Cl < 30 mg/L + negative slope	St Jansklooster	Yes	2 x per year	12 x per year	0x per year	46	21BP0216	561,3725275	Not constant	Decreasing	
16	27GP0171	Irrelevant	Timespan not sufficient	Dieperveen	No	-	12 x per year	0x per year	128	27GP0171	669,7	Not constant	Decreasing	

4.4.5 Flevoland

	PECS	Relevant/Irrelevant	Cause	Location	Municipality permission	Mandatory frequency	Current frequency	Suggested frequency	Number connections	Minimal distance pumping well [m]	PUTCODE	Mean [Cl-] [mg/l]	PECS Trend	PECS Increasing/decreasing
0	26B0113	Potential Relevant	No chloride connections	Harderbroek	Yes	12x per year	12x per year	4x/Dx per year	10	7236	-	-	Not constant	Increasing
1	26B0106	Potential Relevant	No chloride connections	Spielzand	Yes	12x per year	12x per year	4x/Dx per year	10	3661	-	-	Not constant	Decreasing
2	26B0111	Potential Relevant	No chloride connections	Spielzand	Yes	12x per year	12x per year	4x/Dx per year	10	3661	-	-	Not constant	Decreasing
3	26B0112	Potential Relevant	No chloride connections	Spielzand	Yes	12x per year	12x per year	4x/Dx per year	10	3661	-	-	Not constant	Increasing
4	26E 0113	Potential Relevant	No chloride connections	Harderbroek	Yes	12x per year	12x per year	4x/Dx per year	10	3661	-	-	Not constant	Increasing

4.4.6 Noord-Holland

	PECS	Relevant/Irrelevant	Cause	Location	Municipality permission	Mandatory frequency	Current frequency	Suggested frequency	Number connections	Minimal distance pumping well [m]	PUTCODE	Mean [Cl-] [mg/l]	PECS Trend	PECS Increasing/decreasing
0	32AP0307	Relevant		Laren	No	-	1x per year	4x per year	13	88	LAWP019	68		
1	32AP0323	Relevant		Laren	No	-	1x per 2 year	4x per year	9	743	LAWP018	57		

4.5 Discussion and conclusion data-analysis PECS

During the data-analysis, several assumptions are made. The measurement extent, for instance, must contain data-sets up to and including 2014. From data provided in Table 7 it is evident that data-sets decrease significantly after 2014. As previously mentioned, this is possibly due to PECS abandoning in the meantime. However, from the results it also appeared that some PECS have been measured only once per two years and that processing PECS data can take a long period. Due to these large delays, it is not reliable to filter data with a minimal extent of for instance 2017, as this would probably result in an incomplete PECS analysis.

Other subjective input parameters are both the multiple horizontal- and vertical buffers, the minimal chloride concentration of 30 mg/l and the threshold values of 0.2 and 0.1 displayed in Chapter 4.2. Both the horizontal- and vertical buffers are based on hydrogeological interpretations from REGIS II v2.2. It has to be noted that these interpretations can differ from real in-situ soil conditions, as REGIS II v2.2 information is based on extrapolated lithological borehole information. Also, the minimal chloride concentration of 30 mg/l is subjectively and chosen in accordance with multiple hydrologists from Vitens. It is assumed that monitoring low chloride concentration environments without an increasing trend is not appropriate for intensive monitoring. Furthermore, the threshold values of 0.2 and 0.1 are based on a visual check on the resistance – chloride concentration graphs per PECS electrode.

Due to large varieties in measurement frequencies, it is recommended to measure relevant PECS four times a year and irrelevant PECS zero times per year. By measuring PECS four times per year, it is possible to quickly anticipate on broken PECS and to quickly detect measurement errors. However, it has to be noted that these measurement frequencies act as a guideline. If a particular PECS shows frequent alterations in chloride concentration over time, it might be useful to measure this PECS more than four times a year. Potentially relevant PECS have to be calibrated with chloride concentrations before they can be assigned to a particular measurement frequency.

Lastly, an analysis is conducted by using 100-year zones around pumping well locations. By using this method, it is aimed to verify whether the locations of PECS are self-evident. It has to be noted that 100-year zones are generated by using a hydrological model, which is based on rather subjective input parameters. Consequently, it only provides an interpretation of the main groundwater flow paths towards a well. Groundwater inputs from alternative directions cannot be excluded. However, if a PECS is located outside a 100-year zone, the groundwater flow delay between PECS salinization detections and extraction wells is assumed to be at least 100 years. It is doubtful whether it is relevant to monitor groundwater compositions at such large distances, as groundwater compositions can be severely modified in-between.

Nevertheless, it is worth mentioning that PECS located at large distances from pumping wells may also provide relevant information. In Flevoland, for instance, remote PECS provide relevant information about the general fresh water – brackish water boundary between the Veluwe system and lake IJssel. Or, on the Wadden Islands, where remote PECS could provide relevant information about the size of fresh water lenses.

It has to be noted that analysis outcomes undoubtedly change in case of alternative input parameters. Though, most assumptions can be substantiated by using either literature or statistical data. Hereafter, the general results per province, displayed in Chapter 4.4 and Appendix A, are shortly elucidated. An overall discussion regarding the abilities of PECS is shown in Chapter 6.

4.5.1 Utrecht

Table 11 – PECS results province of Utrecht

Province of Utrecht	
Total PECS:	31
Relevant PECS	24
Potentially relevant PECS	2
Irrelevant PECS	5

In the province of Utrecht, PECS are well separated over the province. After the 100-year zone check, it appeared that six PECS are located outside a 100-year zone: two relevant PECS, one potentially relevant PECS and three irrelevant PECS. The major part of PECS was able to correlate to chloride concentrations. Consequently, the abilities of PECS in the province of Utrecht were tested relatively well. Only two PECS (Holk and Nieuwegein) were not able to correlate with chloride concentrations, either due to the absence of electrode depth data or due to a large distance between observation wells and the PECS.

From the 24 relevant categorized PECS, it appeared that four PECS did not consist of a clear trend between PECS resistance and chloride concentrations. Moreover, PECS in Cothen and Schalkwijk are situated in low chloride concentration environments (< 30 mg/l), causing an intensive salinization monitoring policy to be irrelevant at this location.

Five PECS are categorized as irrelevant. Herein, four PECS appeared to be irrelevant due to the absence of sufficient data. These PECS are probably already abandoned and not relevant for future salinization monitoring. The other irrelevant PECS (Oudewater) did not show clear correlations between chloride and resistance. Nevertheless, due to its high chloride concentrations, it is suggested to implement an alternative salinization monitoring method.

4.5.2 Gelderland

Table 12 - PECS results province of Gelderland

Province of Gelderland	
Total PECS:	27
Relevant PECS	3
Potentially relevant PECS	18
Irrelevant PECS	6

In Gelderland, PECS are merely situated in the middle and in the western part of the province. Based on the 100-year zone filter, it is evident that six PECS are not located in a 100-year zone: one relevant PECS, four potentially relevant PECS and one irrelevant PECS. Stuurman et al. (2007) mentions that potential salinization areas are primarily located in the areas near river Rhine and river IJssel. Consequently, the major part of PECS is located in these areas. Many PECS in the province of Gelderland were not evaluated on their abilities, because of the absence of a proper calibration with chloride concentration data. Only three PECS are assumed to be relevant, whereas the remaining part either consists of an insufficient measurement extent or is not calibrated with chloride concentrations. Chloride concentration calibrations are necessary to prove whether the potentially relevant PECS in the province of Gelderland are relevant or not.

4.5.3 Friesland

Table 13 - PECS results province of Friesland

Province of Friesland	
Total PECS:	35
Relevant PECS	20
Potentially relevant PECS	11
Irrelevant PECS	4

The province of Friesland consists of many relevant PECS (20), potentially relevant PECS (11) and only a few irrelevant PECS (4). Based on the 100-year zone analysis it appeared that many PECS are situated outside a 100-year zone. However, it has to be noted that the model did not consider the Wadden Islands. Therefore, PECS located on Wadden Islands are automatically (unnecessarily) categorized outside 100-years zones.

All potentially relevant PECS require chloride concentration calibrations. During a visual check on the relevant PECS, it appeared that three PECS did not consist of a correct relationship with chloride concentrations. Also, chloride concentrations in Garyp are very low. PECS especially showed consistent relationships with chloride concentrations on the Wadden Islands, where chloride concentrations are very high ($[Cl^-] > 1000 \text{ mg/l}$). Four PECS which are assigned as irrelevant did not have sufficient data up to and including 2014. The particular PECS are probably abandoned and not relevant for future monitoring.

4.5.4 Overijssel

Table 14 - PECS results province of Overijssel

Province of Overijssel	
Total PECS:	17
Relevant PECS	8
Potentially relevant PECS	3
Irrelevant PECS	6

Stuurman et al. (2007) concludes that the largest salinization risks in the province of Overijssel are located in the eastern moraine areas and in areas near the river IJssel. This corresponds to the locations of PECS in Overijssel, which are merely situated near river IJssel, in the south-eastern part of the province. From the 100-year analysis, it is obvious that four PECS are not located in a 100-year area: one relevant PECS, one potentially relevant PECS and two irrelevant PECS.

In total, eight PECS are categorized as relevant, three as potentially relevant and six as irrelevant. Many relevant assigned PECS, however, do not consist of a clear trend with chloride concentrations. Consequently, it can be doubted whether PECS are the most efficient way to monitor salinization in the province of Overijssel. Potentially relevant PECS do not consist of a connection with chloride concentrations and irrelevant PECS either have an insufficient measurement extent or no correct relationship between chloride concentrations and PECS electrode resistances. PECS in St Jansklooster are categorized as irrelevant due to the absence of a relationship between PECS electrode resistances and chloride concentrations. However, as average chloride concentrations in this environment are higher than 30 mg/l, it is assumed that salinization monitoring is necessary.

4.5.5 Flevoland

Table 15 - PECS results province of Flevoland

Province of Flevoland	
Total PECS:	5
Relevant PECS	0
Potentially relevant PECS	5
Irrelevant PECS	0

The south-eastern part of Flevoland is merely influenced by the Veluwe system, resulting in fresh water sources. However, in the south-western part, which is in hydraulic connection with lake IJssel, salt water sources appear. In order to monitor this fresh – brackish interface, PECS are aligned at these specific locations. Due to the absence of chloride data in the province of Flevoland, no calibration can be made between PECS and chloride concentrations. Consequently, a review on the abilities of PECS in the province of Flevoland is absent. However, from the PECS trend analysis, it is evident that all PECS consist of an alternating trend. For a better understanding of this phenomenon, it is necessary to calibrate PECS with chloride concentrations from observation wells in a near distance.

Furthermore, it is notable that the PECS mandatory municipality frequency is twelve times a year. As this measurement frequency is unnecessarily high, it is recommended to downgrade this frequency to either four or zero times a year, depending on whether the PECS is categorized as relevant or irrelevant, respectively.

By minding the 100-year analysis, it is clear that most PECS in the province of Flevoland are located outside a 100-year zone. A possible explanation for this phenomenon is the characteristic fresh water – brackish water interface between the Veluwe system and lake IJssel influences.

4.5.6 Noord-Holland

Table 16 - PECS results province of Noord-Holland

Province of Noord-Holland	
Total PECS:	2
Relevant PECS	2
Potentially relevant PECS	0
Irrelevant PECS	0

The province of Noord-Holland consists of 2 PECS, both located in Laren. During the data-analysis, it was possible to connect both PECS with chloride concentrations to verify their abilities. It appeared that both PECS are relevant. Also, both PECS are located in a 100-year zone.

4.6 Recommendations current PECS salinization monitoring

From the results displayed in previous paragraphs it appeared that many PECS locations are either categorized as potentially relevant or irrelevant. A common cause of potentially relevant PECS is the absence of proper chloride concentration calibrations or the lack of electrode depth data. Also, it appeared that multiple PECS locations consist of disproportionally high obligatory measurement frequencies which have to be altered.

In Appendix B, a summary is provided with recommendations for optimizing the current PECS salinization monitoring strategy. Multiple PECS are highlighted which either require chloride concentration calibrations, electrode depth data, an alternative monitoring strategy (PECS did not consist of electrodes with correct chloride concentration calibrations) or a change in municipality permission. The recommended measurement frequency of all PECS is indicated in the results per province displayed in Chapter 4.4. In Appendix B, some PECS categorized in “*Require another monitoring strategy*” are colored in red. This means that average chloride concentrations in environments near PECS are relatively low ($[Cl^-] < 30 \text{ mg/l}$). It is doubtful whether these locations require salinization monitoring.

Furthermore, it is evident that many locations, especially in the eastern part of the Netherlands, are not monitored by using PECS. Appendix C displays a list consisting of PECS locations without PECS in a near distance of 10 kilometers. Based on current PECS data-analysis results, it is obvious that PECS are not the most efficient salinization monitoring device on many locations. Therefore, a PECS monitoring strategy is not recommended for (all) locations summarized in Appendix C. In Chapter 8, consisting of the final recommendation of this thesis, a more thorough recommendation is provided for the most optimal salinization strategies on these locations.

5 Hydrological modelling

In this chapter, more information is provided about the salinization interface development in Rodenmors, a Vitens groundwater extraction area. With this case study it is aimed to derive more insight in possibilities for salinization monitoring by using a hydrological model. After in-situ location information, the methodology is shortly elucidated after which the results, discussion and conclusion are described. Lastly, a short recommendation is composed for enhancing salinization monitoring in the particular Rodenmors area.

5.1 Problem description and study site

5.1.1 Study site

Pumping station Rodenmors is located in the eastern part of the Netherlands, near Enschede (Figure 17). The study site is characterized with agricultural landscapes, multiple rivers and canals from which the Omleidingskanaal is the nearest. As mentioned in Van den Brink et al. (2010), the Omleidingskanaal was made in order to control river Dinkel discharges for preventing floodings. Due to the soil resistivity of the canal, the river was initially characterized with both draining and infiltrating effects. However, infiltrating capacities of the Omleidingskanaal decreased over time due to silting.

In 1998, water supply plan Rodenmors was generated, which is a corporation between multiple water boards and aims to decrease land subsidence effects due to severe water extractions. In order to pump water from the Omleidingskanaal in the area and to maintain a sufficient water level in the Omleidingskanaal, several weirs and a pumping station were installed. In 2010 Royal Haskoning DHV conducted a research to the chemical composition of the Omleidingskanaal and concluded that the general quality of for instance chloride, nitrogen and sulfate was sufficient (Van den Brink et al., 2010).

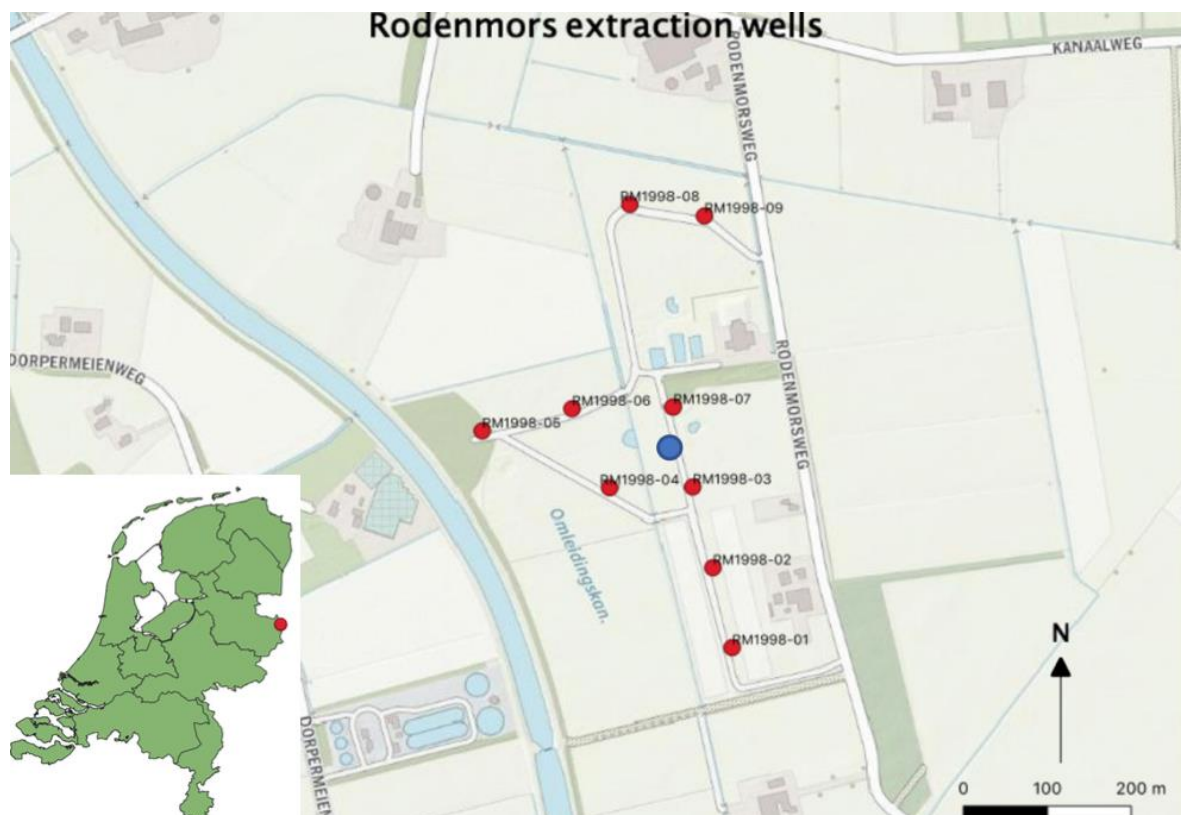


Figure 17 - Rodenmors pumping well locations (Red dots) and their identical code.

The Rodenmors extraction area consists of nine wells which have been active since 1999. All wells are located at approximately the same depth, with the top- and bottom of the filter near respectively 25 and 45 meters below NAP. In Table 17, more information is provided about the general specifications of the multiple wells in which it is evident that pumping well 5 consists of the highest average discharge per day: 648 m³/day. In contrast, pumping well 7 extracts on average 552 m³/day. In the period between 2005 – 2009, approximately 1,4 – 1,5 million m³ was extracted per year (Van den Brink et al., 2010).

Table 17 – Rodenmors pumping well characteristics

Well code	Discharge [m³/day]	Top-filter (m NAP)	Bottom-filter (m NAP)	Surface level (m NAP)
RM1998-01	-624	-24.75	-44.03	19.3
RM1998-02	-624	-24.52	-43.63	19.1
RM1998-03	-576	-24.77	-43.82	19.1
RM1998-04	-624	-24.79	-43.81	19.0
RM1998-05	-648	-29.80	-44.04	14.2
RM1998-06	-648	-25.76	-44.74	19.0
RM1998-07	-552	-22.70	-43.78	21.1
RM1998-08	-576	-25.59	-44.64	19.1
RM1998-09	-600	-23.21	-44.78	21.6
Total average	-5472	-	-	-

In 2010, engineering consultancy Royal Haskoning DHV conducted a research in the Rodenmors extraction area and concluded that the original water is characterized as anaerobe and calcareous with both low chloride- and sulfate concentrations. The occurrence of low sulfate concentrations is linked to the generation of sulfides, which bind with heavy metals. Ever since 2005, relatively high concentrations in organic pollutions have been detected, which are probably related to pesticides from agriculture. Royal Haskoning DHV assumes that aside from groundwater, infiltrated surface water is extracted as well. Consequently, effects from effluents of the nearby sewage treatment system cannot be excluded (Van den Brink et al., 2010).

5.1.2 Problem description

Since 2013, Rodenmors extraction well 5 (RM1998-05) is characterized with critical salinization phenomena, whereas all the other pumping wells do not show similar effects (Appendix D). Last observation well measurements showed a chloride concentration of more than 200 mg/l, while a chloride concentration of 150 mg/l is indicative for the fresh water – brackish water interface. Furthermore, it is expected that chloride concentrations in pumping well 5 increase to more than 300 mg/l within five years from now.

This is contradicting with the results of the study of Van den Brink et al. (2010), who concluded that the Rodenmors area is not affected by salinization influences. In order to obtain more knowledge about the groundwater flow situation and the salinization causes, a detailed groundwater flow model is made. Furthermore, it is tried to compose a salinization forecast and monitoring recommendations for the future.

5.2 Geohydrological situation

Rodenmors is situated in the basin of Nordhorn, which was abraded in the second last ice age resulting in moraines as Oostmarsum, De Lutte and Uelsen. On this location the impermeable glacial till acts as geohydrological boundary layer. Over time, the basin was filled up with abrasion material, melting water deposits, sand and clay. Groundwater generally flows from a southeastern direction towards the northwest and the phreatic groundwater level is located at approximately 0.5 – 1.5 m below surface level. Due to local surface elevation differences, groundwater levels are variable (Baggelaar, 2005b). Based on REGIS II, v2.2 it is obvious that the area is merely composed of three different formations: Bortel Formation, Drente Formation and Dongen Formation.

1. (BX) Bortel Formation (Schokker et al., 2005; REGIS II, v2.2)

From surface level till approximately 32 meters below surface level (3 meters below NAP), the Bortel formation is dominant. Within the Bortel Formation, it is possible to distinguish eight other (regional) geological formations, which are merely formed during cold periglacial conditions. The Bortel Formation is generally composed of fine to coarse sand (105 – 300 μm), silty sand, loam and some occasional traces of gravel and clay. The Bortel Formation consists of two well-defined peat-clay formations situated near 10 meters below NAP. The general horizontal hydraulic conductivity of sand units alternates between 2.5 – 10 m/d and the saturated transmissivity differs between 25 – 100 m^2/d . The Bortel sand formation is occasionally intersected by multiple Bortel clayey units, ranging between 0 – 14 meters thick, which have a vertical hydraulic conductivity ranging between approximately 0.005 – 0.01 m/d.

2. (DR) Drente Formation (Bakker et al., 2003; REGIS II, v2.2)

The Drente Formation is a 50 meters thick geological unit consisting of moderately coarse to very coarse sand (200 – 2000 μm), moderately fine sand (150 – 200 μm), clay, loam and is occasionally gravelly. The formation is characterized with an average horizontal hydraulic conductivity of approximately 10 – 25 m/d and a saturated transmissivity of approximately 250 – 1000 m^2/d . The bottom of the Drente Formation consists of the Gieten Member clayey unit, with a maximum thickness of approximately 45 meters and a vertical hydraulic conductivity ranging between 0.001 – 0.005 m/d. Aside from this clayey unit, another clayey layer is situated at approximately 30 meters below NAP called the Uitdam Member clayey unit. This clayey unit is also characterized with a vertical hydraulic conductivity ranging between 0.001 – 0.005 m/d.

3. Dongen Formation (de Lang, 2003; REGIS II, v2.2)

The Dongen Formation generally consists of clay and very fine sand (63 – 150 μm) from a marine origin. It is possible to differentiate multiple other sub-formations within the Dongen Formation: Formation of Asse, Formation of Brussel, Formation of Ieper and the Formation of Oosteind. The vertical hydraulic conductivity in the Dongen Formation ranges between 0 – 0.00005 m/d. As a result of the very low vertical hydraulic conductivity, the Dongen Formation acts as the geohydrological basis.

The study of Van den Brink et al., (2010) concluded that groundwater compositions in the sandy Bortel Formation differ from the underlying Drente Formation. As a consequence of the semi-impermeable clay-peat layers in the Bortel Formation, the Drente Formation is relatively isolated from surface influences. The groundwater composition of the underlying Drente Formation is assumed to be dominated by ancient marine influences.

5.3 Methodology hydrological modelling

5.3.1 iMOD modelling

By using iMOD it is attempted to assess a thorough understanding of the salinization causes in the Rodenmors extraction area. In order to do this, groundwater module MIPWA on iMOD is used. As quoted from Borden et al. (2016), page 54: “iMOD is an open source, easy to use graphical interface that employs an accelerated Deltares version of MODFLOW with fast, flexible and consistent sub-domain modelling techniques”. Apart from the general parameters included in the MIPWA environment (KD and K_h per province visible in Chapter 3), parameters displayed in Table 18 are used.

Table 18 - Rodenmors modelling parameters

Parameters used	
Porosity (aquifers/aquitards)	0.3
Specified fraction of total inflow to the cell	0.7
Radius wells (m)	2
Sampling (m)	0.1
Top- and bottom level start points	Aquifer 6 top- and bottom
Vertical interval number	10

By composing a groundwater model of the Rodenmors area, flowpaths per well are generated after conducting a backwards simulation. It is assumed that flowpaths per well can provide an indication of the salinization causes and salinization predictions. For instance, when the depth of the fresh water – brackish water interface is known and the groundwater propagation paths are known as well, it is possible to predict future well salinization (under the condition that the flowpaths are intersecting the fresh water – brackish water interface). Due to relatively low chloride concentration differences (300 mg/l), it is assumed that density driven flow is negligible. Consequently, only convection driven flow is assumed (Hoogendoorn, 2017).

From chloride data sampled in pumping well 5, it is evident that the threshold value of 150 mg/l (boundary fresh water – brackish water) has been intersected since 2013. Minding that pumping wells have been used since 1999, it is obvious that the wells have been salinized approximately fourteen years after their construction. In order to trace the potential polluted location, a buffer zone of fourteen years (interval between 1999 – 2013) is constructed, which displays the maximum distance of the origin of groundwater that was extracted in 2013. Also, a buffer zone corresponding to twenty years (interval between 1999 – 2019) is made, which displays the maximum distance of groundwater that is extracted nowadays.

5.3.2 Groundwater parameter analysis

In order to obtain more insight in the salinization origins, an analysis on the different groundwater parameters is conducted. This is done by a principal component analysis, in which the correlation between the multiple constituents is displayed. A broader elucidation on this subject can be found in Chapter 2.2.4. Initially, this analysis is conducted on groundwater samples from pumping well 5 and subsequently on groundwater samples measured in observation wells situated in potential salinization areas.

5.4 Results hydrological modelling

5.4.1 Groundwater flowlines

By using the MIPWA-server on IMOD, it was possible to model the groundwater pathlines in the Rodenmors area. From Figure 18, which shows a top view of the Rodenmors area, it is evident that the general groundwater flow is directed towards the north-west. However, Rodenmors well 5 is extracting groundwater from an alternative direction, as displayed in the pathlines propagating towards the red dot. The different colors in Rodenmors well 5 pathlines represent different time intervals: dark blue corresponds to the maximum distance of the origin of groundwater that was extracted in 2013, green represent the maximum distance of the origin of groundwater which is extracted nowadays and yellow displays the remainder of the groundwater pathlines.

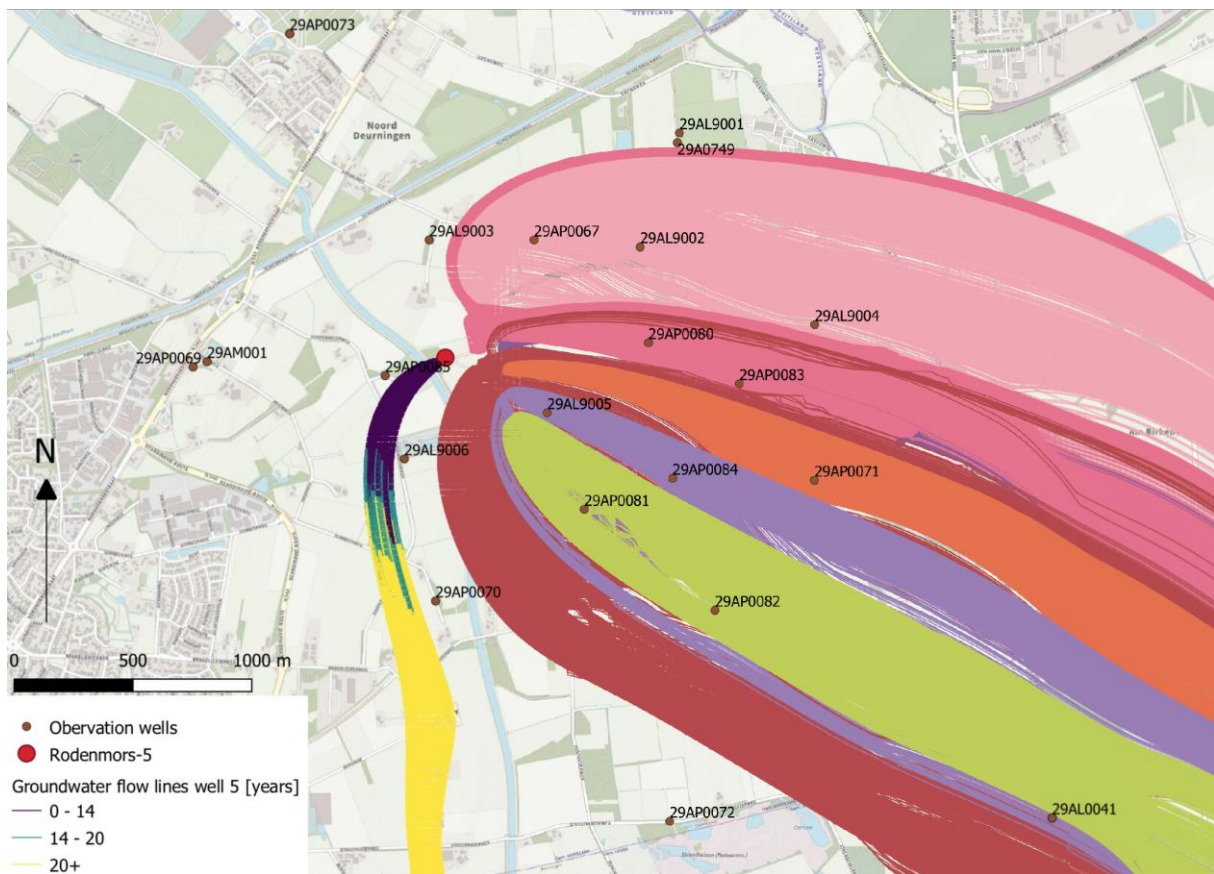


Figure 18 – iMOD groundwater pathline output. The legend corresponds to the pathlines towards Rodenmors extraction well 5.

In Figure 19, a 3D-view is displayed, in which it is obvious that pathlines in the Rodenmors area are bordered by both the geohydrological basis and the surface area. By specifically observing the groundwater pathlines towards well 5, it appears that the deepest pathlines (near the geohydrological basis) have a higher flow resistance than the upper pathlines (near the surface).

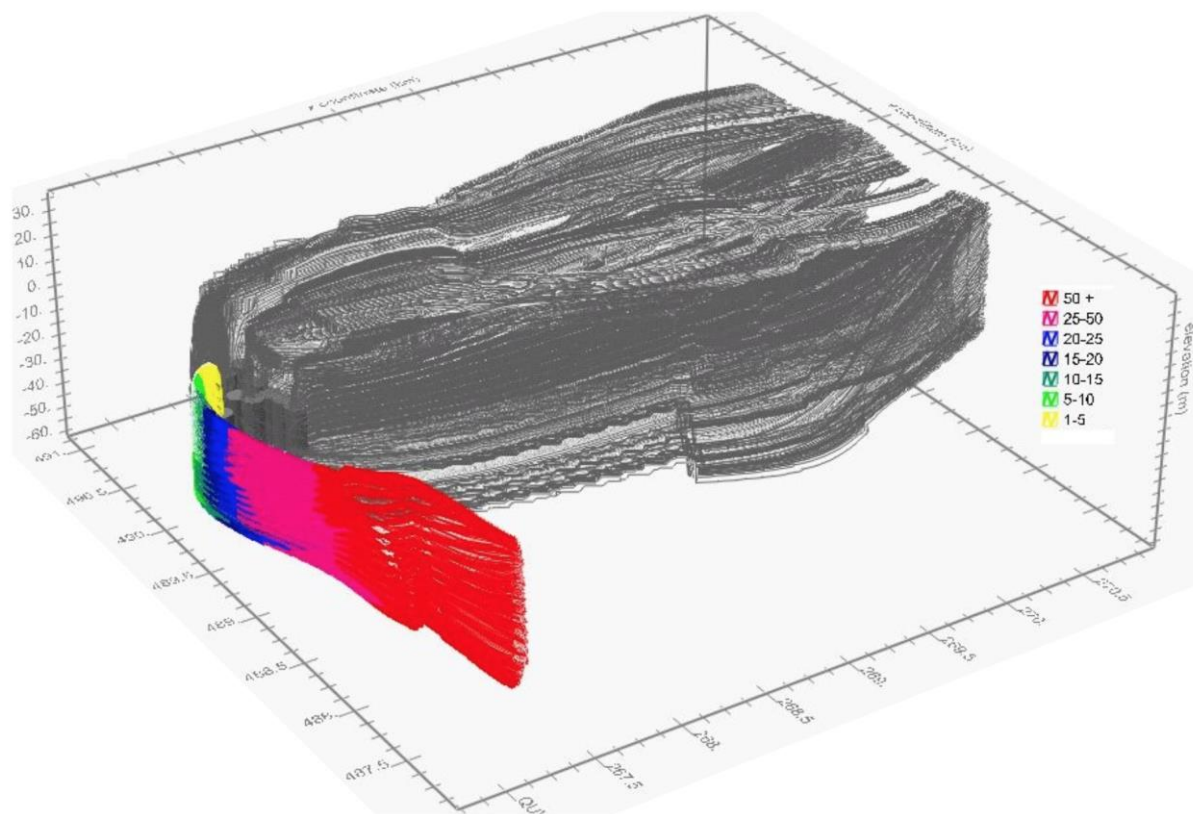


Figure 19 -3D visualization of the hydrological situation in the Rodenmors area. The colored pathlines represent pathlines towards well 5. The legend displays the travel time in years.

5.4.2 Hydrogeochemical analysis Rodenmors

In the Rodenmors area, each well is analyzed on its chemical parameters, electrical conductivity, temperature and pH. In Appendix E, a spreadsheet is visualized consisting of chemical parameter data measured in well 5 dating from 1999 to 2017. The major part of the data corresponds to chemical constituents measured in the filter between 6.4 and 21 meters depth relative to NAP. It is obvious that especially $[\text{Na}^+]$ and $[\text{Cl}^-]$ increased significantly during the past years: from 13 mg/l to 105 mg/l and 13 mg/l to 230 mg/l, respectively. By using this data, a correlation matrix is composed, in which the correlation between the major hydrogeochemical constituents of groundwater is displayed (Table 19). It has to be noted that $[\text{CO}_3^{2-}]$ was not quantified in the Rodenmors area and therefore not included in Table 19.

By mining Table 19, strong correlations between EGV – Na^+ ($r = 0.99$), EGV – Cl^- ($r = 0.99$) and Na^+ – Cl^- ($r = 0.99$) are visible. Other parameters showed less significant correlations.

Table 19 - Correlation matrix hydrogeochemical data pumping well 5

	pH[-]	EGV[mS/m]	Ca[mg/L]	Mg[mg/L]	Na[mg/L]	K[mg/L]	Cl[mg/L]	SO4[mg/L]	HCO3[mg/L]
pH[-]	1								
EGV[mS/m]	0,55	1							
Ca[mg/L]	0,01	0,22	1						
Mg[mg/L]	0,62	0,8	0,36	1					
Na[mg/L]	0,63	0,99	0,15	0,79	1				
K[mg/L]	0,84	0,71	0,18	0,81	0,75	1			
Cl[mg/L]	0,64	0,99	0,16	0,83	0,99	0,78	1		
SO4[mg/L]	-0,23	-0,7	-0,41	-0,59	-0,65	-0,49	-0,68	1	
HCO3[mg/L]	-0,64	-0,78	0,28	-0,69	-0,84	-0,71	-0,87	0,41	1

Besides, in order to trace potential salinization origins, multiple observation well parameters are evaluated. From Figure 18 it is evident that three observation wells are located near the main groundwater pathlines towards well 5, namely: 29AP0085, 29AL9006 and 29AP0070. Per location, one or multiple samples are researched from which the specifications are displayed in Table 20. It has to be noted that observation well filter depths do not correspond with pumping well filter depths. For instance, the deepest sampled observation filter is situated at 25 meters depth below surface level, whereas pumping well filters are generally situated between 40 – 60 meters depth below surface level.

Table 20 – Rodenmors observation well sample specifications. From the closest location to the one located at the greatest distance relative to well 5.

Number	Sample	Observation well	Filter depth [m] below surface level
1	V1906083652	29AP0085	6
2	V1906083653	29AP0085	15
3	V1906083654	29AL9006	3
4	V1906083655	29AP0070	12
5	V1906083656	29AP0070	25

Observation well sample analysis results are displayed in Appendix F. Among the samples, there is a significant difference in EGV (mS/m). The highest EGV (73.4 mS/m) was obtained in sample 3, which was measured near the sewage treatment system. On the contrary, the lowest EGV (34.8 mS/m) was obtained in sample 1 which is located relatively close to pumping well 5. For comparison, EGV's sampled in well 5 are currently larger than 100 mS/m.

The most obvious trends in pumping well 5 are based on both sodium- and chloride concentrations. As already mentioned, $[\text{Na}^+]$ and $[\text{Cl}^-]$ have increased significantly during the past years: from 13 mg/l to 105 mg/l and 13 mg/l to 230 mg/l, respectively. However, in the multiple samples from nearby observation wells, comparable large concentrations are not visible. $[\text{Cl}^-]$, for instance, ranged between 10 mg/l to 41 mg/l and $[\text{Na}^+]$ ranged between 6.2 mg/l and 31.5 mg/l. Both highest chloride- and sodium concentrations were obtained in sample 4.

$[\text{HCO}_3^-]$ in pumping well 5 decreased from 440 mg/l towards approximately 340 mg/l in the past fifteen years. As measured in the samples, $[\text{HCO}_3^-]$ ranged from 146 mg/l to 399 mg/l. Both the highest- and lowest concentrations were obtained near pumping well 5 in samples 1 and 2, respectively.

From Appendix F, it is evident that the multiple observation well samples consist of large differences in sulphate. Especially the relatively shallow samples (sample 1 and sample 3) consist of high sulphate concentrations ($[\text{SO}_4^{2-}] > 40$ mg/l), whereas deeper groundwater samples consist of relatively low sulphate concentrations ($[\text{SO}_4^{2-}] < 2$ mg/l). From the groundwater analysis in pumping well 5, it appears that sulphate concentrations were relatively low and consecutively more comparable to the deep groundwater samples.

5.5 Discussion and conclusion hydrological modelling

Beforehand, it was evident that pumping well 5 is threatened by severe salinization. By using a hydrological model, it was obvious that pumping well 5 extracts groundwater from an alternative direction than the other wells. In the Rodenmors area, groundwater flows from the south-east towards the north-west. Consequently, pumping well 5 is located in the shadow zone of all other pumping wells. In order to extract enough water, pumping well 5 possibly extracts the major part of its water from an alternative direction, as displayed in Figure 18 and possibly also from greater depths. A potential risk of this situation is displayed in Figure 6, in which it is shown that in the shadow zone of a pumping well, salt water upconing could occur. This phenomenon possibly also occurs in the Rodenmors area near pumping well 5. In combination with relatively high pumping discharges, groundwater from well 5 consists of high chloride concentrations.

Another obvious phenomenon can be observed by minding groundwater propagation periods towards pumping well 5, as displayed in Figure 18. Salinization in well 5 became critical approximately fourteen years after construction. By tracing groundwater back in time, it is evident that current extracted groundwater was located near a sewage water treatment system, from which effluent water generally consists of enhanced chemical concentrations. However, by minding the parameter analysis sampled in pumping well 5 (Table 19), it is evident that especially $[\text{Na}^+]$, $[\text{Cl}^-]$ and EGV are strongly correlated to each other. Other chemical constituents as $[\text{HCO}_3^-]$, $[\text{K}^+]$ and $[\text{Ca}^{2+}]$ did not show clear relationships. If chloride concentrations measured in pumping well 5 were enriched due to surface processes, chemical constituents as bicarbonate, calcium and sulphate would have been more dominant. Consequently, it is assumed that salinization by surface processes as sewage water treatment systems is not the major cause.

Additionally, Van den Brink et al. (2010) concluded that groundwater compositions in the sandy Bostel Formation differ from the underlying Drente Formation. As a consequence of the semi-impermeable clay-peat layers in the Bostel Formation, the Drente Formation is relatively isolated from surface influences. The groundwater composition of the underlying Drente Formation, from which most groundwater is extracted, is assumed to be dominated by ancient marine influences.

This assumption can be enhanced due to observation well samples measured in the extension of the salinized groundwater flow paths towards pumping well 5. From this analysis, it appeared that especially shallow observation well samples consisted of high sulphate and magnesium concentrations, which are possibly enriched due to surface interactions. Deeper observation well filters did not have comparable concentrations. Moreover, observation well samples did not show comparable EGV, $[\text{Na}^+]$ and $[\text{Cl}^-]$ as measured in pumping well 5. The deepest observation well was located at 25 meters depth below surface level, whereas pumping well filters are located between approximately 40 – 60 meters depth below surface level. As a result, it is plausible to assume that salinization of well 5 is not caused due to surface interactions, but probably due to deep salinization sources. Otherwise, pumping well samples and observation well samples would have been more comparable to each other.

As studied by Redwood (2007) and Stuurman et al. (2006), Tertiary very impermeable salt-containing marine deposits are situated in eastern parts of the Netherlands. This formation can result in occasionally shallow fresh water – brackish water interfaces, which could subsequently influence pumping well locations. Another possible deep salinization source is described in Glasbergen et al. (1982). From this study, it appears that in both eastern and north-eastern parts of the Netherlands alternating Zechstein salt layers are situated. These salt layers are especially located at 550 meters depth below surface level, in which chloride concentrations can be larger than 2 mol/l. However, by the principle of rock salt dissolution, it is possible that shallow fresh groundwater volumes are affected by these high chloride concentrations.

Although Rodenmors extraction wells are relatively shallow (between approximately 40 - 60 meters below surface level), it might be possible that salinization is caused by upconing from greater depths. The combination of the shadow zone location and relatively high pump discharges may result in upconing of deeper saline groundwater, possible derived from Tertiary marine deposits or Zechstein salt layers. However, up to now, it is not possible to assign a specific salinization source due to the lack of deep groundwater composition information. In Chapter 5.6, insight is provided about methodologies for tracing the exact salinization location and source.

When considering the salinization trend of pumping well 5, it is expected that chloride concentrations increase in the future. Currently, chloride concentrations increase approximately 15 mg/l per year in well 5. It is expected that this salinization trend will continue. Also, pumping well 6 has a slightly increasing chloride concentration trend of 3 mg/l per year. Pumping well 6 is located in the vicinity of pumping well 5, so salinization in pumping well 6 is not unthinkable. Especially in case of decreasing regional groundwater propagation velocities, it might be possible that pumping well 6 is going to be located in the shadow zone of other pumping wells zone and eventually has to extract groundwater from alternative directions. The same principle holds for pumping well 4, which is also located near pumping well 5.

Of course, it has to be noted that the hydrological model only provides an interpretation of the reality, as the model is based on both extrapolated lithological borehole information and averaged input-parameters. Consequently, groundwater pathlines as displayed in Figure 18 and Figure 19 only act as an indication. It might be possible that real groundwater pathlines differ from the modelled pathlines. Nevertheless, it is assumed that the hydrological models provide relevant interpretations. More in-situ soil information would undoubtedly reinforce model output qualities.

5.6 Recommendations Rodenmors salinization monitoring

As mentioned in the hydrological modelling study, it was possible to trace potential salinization locations and discuss eventual salinization sources. However, it was not possible to assign a specific salinization location due to the absence of sufficiently deep observation wells. The purpose of this chapter is to compose a strategy for both tracing the salinization origin and for monitoring future salinization trends.

In the Rodenmors area, pumping well filters are generally located between 40 – 60 meters depth below NAP. Furthermore, as displayed in Figure 18, it is obvious that the Rodenmors area is characterized with many observation wells, which could be used in order to monitor salinization. From the conclusions in Chapter 4, it appeared that PECS are not the most efficient and reliable method for salinization monitoring. Other methods, as EM-Slimflex loggers and hydrological models in combination with observation well samples, are supposed to be more reliable and wider applicable. However, as the abilities of EM-Slimflex loggers are not known yet, a future salinization monitoring policy by using hydrological models in combination with observation well samples has been developed.

A prerequisite for this policy is the occurrence of sufficiently deep observation wells, minimally as deep – and preferably deeper – as pumping well filters. Currently, most observation well filters are situated at a maximal depth of approximately 25 meters below NAP. Herewith, it is only possible to determine shallow and moderately deep salinization interactions, whereas deep salinization origins cannot be evaluated. In both Figure 20 and Table 21, an overview is provided about nearby observation wells consisting of filters below NAP.

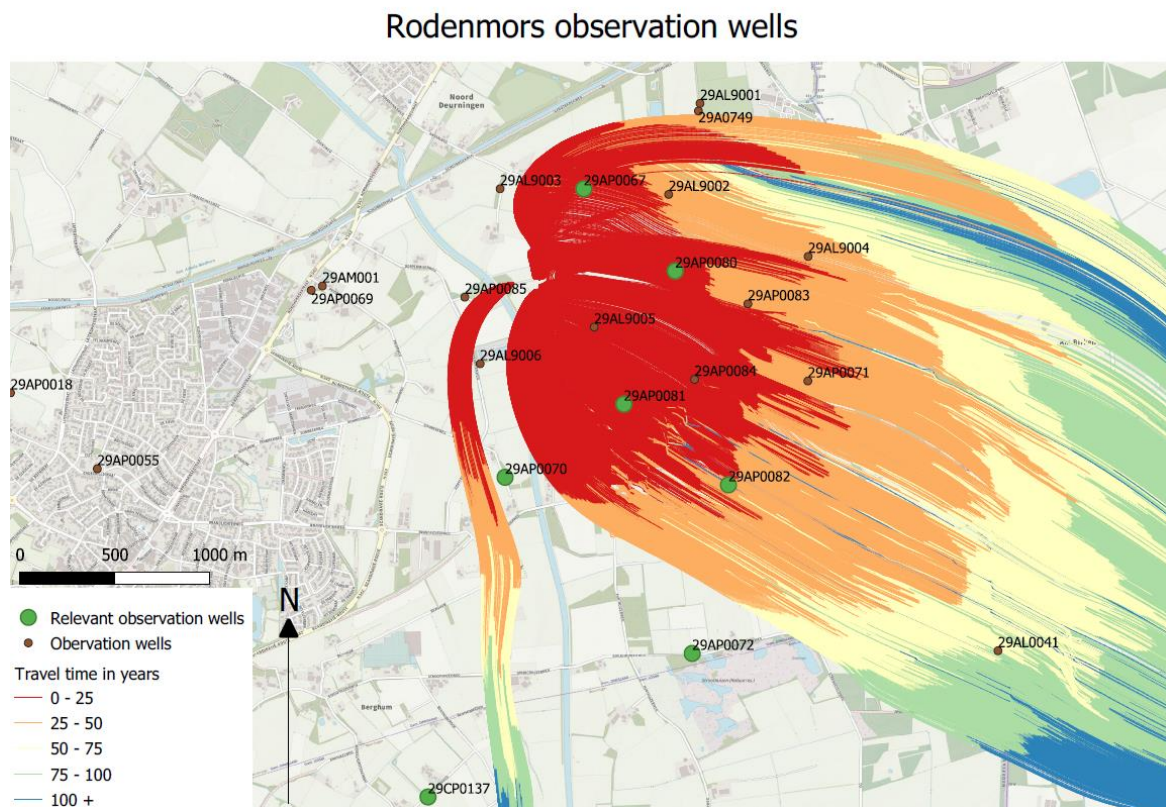


Figure 20 -Rodenmors observation well configuration. Green observation wells consist of filters below NAP.

Table 21 - Rodenmors observation well specifications

Observation well name	Number of filters	Depth bottom lowest filter [relative to NAP]
29A0081	3	-11.9m
29A0067	3	-11.2m
29A0080	2	-12.9m
29A0082	3	-16.9m
29A0070	2	-0.1m
29A0072	5	-24.1m
29C0137	6	-194.6m

Observation well 29C0137 consists of filters with a depth of maximal 194 meters below NAP and would be suitable for salinization monitoring by groundwater sampling. However, this observation well is situated at a large distance from the pumping wells. Therefore, it is suggested to drill new observation wells with filter depths reaching below pumping well filter depths close to the pumping wells. During the Rodenmors study evaluated in Chapter 5, it is obvious that the exact salinization origin location is not known yet. In order to locate new observation wells on correct locations, geophysical research is recommended. The following steps are recommended in chronological order:

1. Conduct a geophysical research

By conducting a geophysical research reaching to the geohydrological basis, more insights are obtained about the specific locations of salt layers and other lithological compositions. Currently, the location of the salinization origin from pumping well 5 is not exactly known. Obtaining more insight in this process would help for correctly switching pumping well configurations and for correctly positioning new observation wells. As described in Groen (2019), it is possible to obtain a spatial interpretation of the fresh water – brackish water interface by using TDEM- measurements (Time Domain Electro Magnetic). This inductive method is based on measuring electric resistances of multiple geologic layers up to hundreds of meters of depth. TDEM measurements are recommended on locations displayed in Figure 21. More information about TDEM-measurements can be obtained in Groen (2019).

Rodenmors TDEM-measurement locations

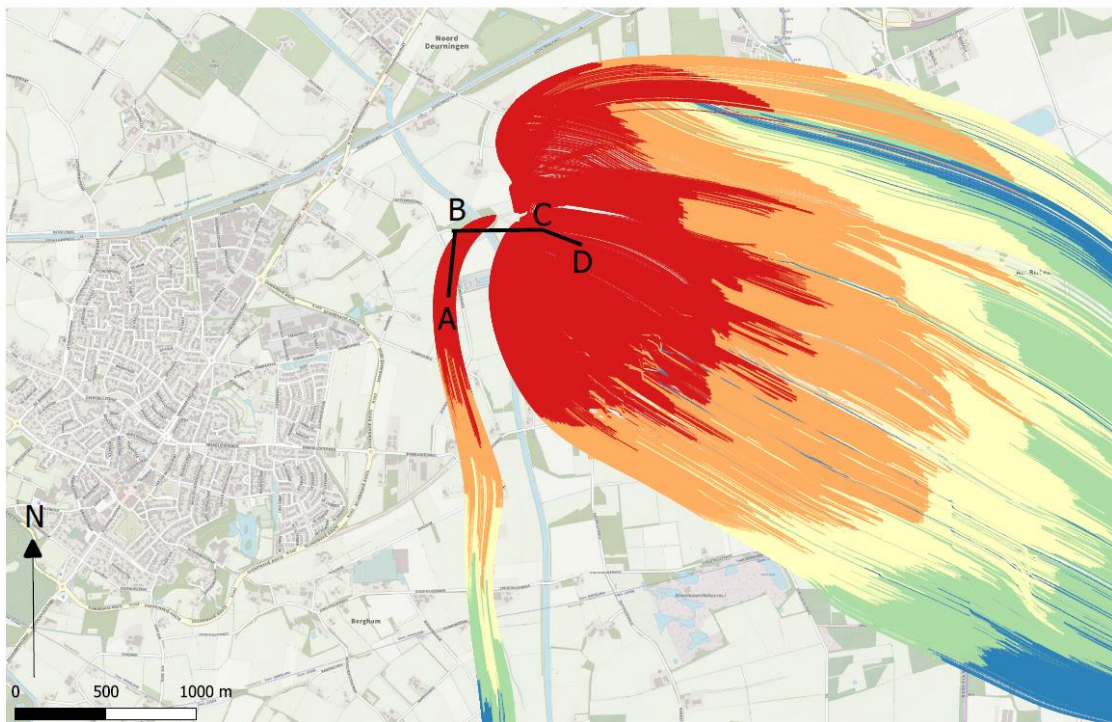


Figure 21 – Potential TDEM measurement locations (A, B, C, D) and cross-sectional areas

2. Drill observation wells

By interpreting TDEM results, more insight is obtained about lithological compositions, as for instance intersecting clay- and salt layers. Consequently, it is possible to specifically position new observation wells on correct locations. These observation wells have to reach to at least the top of the geohydrological basis, situated at approximately 50 meters below NAP.

It is recommended to position at least one observation well reaching towards the geohydrological basis near point B displayed on Figure 21. Herewith it would be possible to obtain more information about the specific salinization cause of pumping well 5. Besides, it is recommended to position at least one observation well reaching towards the geohydrological basis in the vicinity of point C/D on Figure 21. This way it would be possible to monitor eventual salinization upcoming below the other pumping wells.

3. Configure observation well filters

It is recommended to configure the observation wells as follows:

- A filter for monitoring surface interactions (~10 meters below surface level).
- A filter at approximately the same depth as the top of nearby pumping well filters (~20 meters below NAP).
- A filter at approximately the same depth as the bottom of pumping well filters (~40 meters below NAP).
- A filter at the bottom of the observation well (~50 meters below NAP).

By using the lithological information derived from TDEM-measurements, it is possible to correctly position observation well filters and avoid intersecting impermeable clay layers.

4. Measurement frequency

By minding the increasing salinization trend in pumping well 5, it is recommended to sample observation wells preferably four times a year. Herewith it is possible to quickly anticipate on critical salinization trends. Apart from new deep observation wells, observation wells indicated with green dots displayed in Figure 20 are relevant for sampling. These wells are sufficiently deep for monitoring surface – groundwater interactions.

By minding the high chloride concentrations in pumping well 5, it might be attractive to lower pump capacities. However, decreasing pump discharges in well 5 may result in salinization of the other wells. Initially, pumping salinized water decreases, but over a longer period it is assumed that other wells become salinized as well. Currently, it is assumed that pumping well 5 is sacrificing itself due to pumping salinized water away from the other wells. Therefore, it is recommended to maintain current pump discharges. Only when the exact salinization origin is known, it is possible to alter pump discharges.

6 Discussion

This chapter aims to discuss literature and compare the abilities of PECS, hydrological models in combination with observation wells and electromagnetic monitoring devices. A more elaborate discussion of the current abilities of both PECS and hydrological models can be found in Chapter 4.5 and Chapter 5.5, respectively. Appendix G contains a comparison table, wherein multiple key points per salinization monitoring device are highlighted.

6.1 Fresh water – brackish water interface

Based on Post et al. (2003), Meinardi (1991) and de Vries (2007) it is obvious that groundwater salinization is, apart from hydraulic connections with the sea, merely caused by elements of the complicated geological history. The origin of brackish groundwater is especially found in Holocene transgressions, which is substantiated due to both indirect demonstration (the incapability of alternative mechanisms to describe increased groundwater salinity patterns), due to salinity inversions near the boundary between the Pliocene and Pleistocene and due to C-14 groundwater analyses. However, as a result of local artificially induced systems, the fresh water – brackish water distribution is complex. Moreover, in the eastern part of the Netherlands, impermeable Tertiary deposits result in occasionally shallow fresh water – brackish water interfaces. On regional scales, influences as hyper-filtration, freezing, anthropogenic pollution, aerosols, evaporates and evapotranspiration can also affect fresh water compositions. By analyzing geochemical compositions of groundwater samples, it is possible to trace the origins.

As studied by Van Dijk et al. (2017), Hoogendoorn (2017) and Barlow et al. (2003), the natural balance between fresh water and brackish water can be affected by multiple processes. Especially processes inducing an under-pressure increase, as groundwater withdrawals, force the fresh water – brackish water interface to proceed upwards. Furthermore, Stuurman et al. (2007) concluded that sea level rise as a result of climate change result in larger gradients between sea level and polders, forcing enhanced salt water encroachments.

6.2 PECS abilities

In general, trends between PECS resistances and chloride concentrations were absent in low chloride concentration environments ($[Cl^-] < 50 \text{ mg/l}$). More salinized environments alternately resulted in clear relationships between PECS resistances and chloride concentrations. However, prolonged periods with obvious trends between PECS resistances and chloride concentrations are absent. PECS electrodes are possibly not sensitive enough for detecting specific chloride concentration alterations and merely serve to monitor whether chloride trends are increasing or decreasing. Besides, for conducting the most optimal calibration between PECS electrode resistances and chloride concentrations, it is necessary to measure PECS resistances and chloride concentrations at the same time. Now, PECS are merely measured in different periods than chloride concentrations, so it is only possible to compare PECS trends with chloride concentration trends.

As discussed by Helderma (2016) and Goes et al. (2009), soil conductivities are both dependent on groundwater- and soil conductors. The dependency on in-situ soil conditions is probably another reason for the inconsistency between PECS – chloride concentration correlations. For instance, clayey soils consist of higher electrical conductivities than sands, forcing the resistance to be lower. Furthermore, Post et al. (2003) concluded that chloride concentrations decrease significantly in low-permeable clay layers. Thus, when a PECS electrode is situated near a clay layer, it could display a rather distorted image of the real salinization situation.

During this study empirical relationships between chloride concentrations and PECS electrode resistances were trailed. Baggelaar (2005a), for instance, composed an empirical formula by using a statistical connection between chloride concentrations and PECS resistances. However, it was not possible to find consequent relationships between resistances and chloride concentrations. Consequently, it can be questioned whether such an empirical relationship is relevant for the Vitens area. Goes et al. (2009), on the other hand, composed a theoretical formula, consisting of both soil formation factors, soil temperatures, soil resistivity's and bicarbonate [HCO_3^-] concentrations. Though, by using these variables it is only possible to provide an assumption at a particular location and at a specific electrode depth.

Another practical disadvantage of PECS salinization monitoring is caused by the relatively high labor intensity. For consistently monitoring PECS, it is required to monitor both PECS and chloride concentrations multiple times a year. Consecutively, data needs to be validated and calibrated before it could display reliable interpretations of the fresh water – brackish water interface. Besides, as PECS consist of electrodes positioned at particular depths, it is only possible to obtain an overview of resistances at these depths. For obtaining a continuous resistance overview over depth, electrode data has to be extrapolated which could result in incorrect assumptions.

Nevertheless, according to Helderma (2016), Deltares is currently developing new PECS devices consisting of 96 electrode couples, which can be used for telemetric monitoring. Herewith it would be possible to more specifically monitor the fresh water – brackish water interface. However, as current PECS did not show consistent calibrations with chloride concentrations, it can be doubted whether the new electrodes show reliable results.

6.3 Hydrological model abilities

It is evident that the hydrological model provided more insight in the spatial salinization causes of the Rodenmors extraction area. After composing groundwater pathlines by using a hydrological model, it was possible to obtain an indication of the potential salinization origin. Of course, it has to be noted that the model only provides an indication of the potential origin as the model is dependent on averaged input parameters. By implementing more detailed in-situ subsurface information, the results would undoubtedly become more detailed. However, it is assumed that the current hydrological model is sufficient enough for providing relevant salinization information.

In addition, hydrological model results can be substantiated by using groundwater samples from nearby observation wells. However, it is a prerequisite that observation wells are at least as deep as pumping well filters. Herewith it is possible to monitor both surface- and deep salinization interactions. When the indicative salinization source is detected by using a hydrological model, the findings can be calibrated by using an in-situ groundwater parameter analysis. By combining groundwater parameter data and hydrological model results, it is possible to both detect locations of salinization origins, causes of salinization and evaluate future salinization trends.

For instance, in the Rodenmors case, observation wells provided relevant information about the depth of the salinization origin. Observation well samples near the main groundwater pathlines towards pumping well 5 did not show comparable chloride, sodium and EGV concentrations. Based on the groundwater samples from observation wells, it is evident that groundwater at deeper zones is not significantly affected by surface processes and that well salinization is probably caused by deep salt origins. More insights would have been obtained when the sampled observation wells consisted of filters at deeper depths. Now, observation well filters only reached to 25-meter depth, while pumping well filters are situated between 40 – 60 meters depth below surface level.

By using hydrological models, it is possible to obtain a continuous salinization interpretation over depth. However, a disadvantage of this salinization monitoring method is the dependence on deep observation well filters and in-situ chloride concentration samples. For reliably monitoring salinization, observation wells are required to be at least as deep as pumping wells.

Furthermore, as this method is not based on groundwater resistances, it is possible to monitor groundwater contaminations of other geochemical parameters, for instance agricultural influences on groundwater. Also, once a hydrological model is constructed, relatively little time is required for determining future salinization trends.

6.4 Electromagnetic monitoring abilities

From the study conducted by Helderma (2016) it appeared that electromagnetic devices as EM-Slimflex consist of large potentials for measuring salinization interfaces. Of course, as this measurement method is not evaluated during this thesis, the specific abilities are not known yet. Nevertheless, it is assumed that this measurement device consists of large potentials.

The EM-Slimflex device generates an electromagnetic field over the entire depth of the exterior of an observation well. This way, groundwater resistances are not affected by potentially modified groundwater parameters inside observation wells. Besides measuring groundwater resistances, this monitoring device could also monitor groundwater contaminations and reconstruct lithological profiles by using natural gamma radiation. A large disadvantage of PECS is the high sensitivity on other conducting constituents, as soil metals. It is not known whether or not EM-Slimflex devices are also sensitive for these parameters.

Another advantage of EM-Slimflex is their suitability in existing observation wells, even if they are slightly distorted. Consequently, under the condition that observation wells are sufficiently deep, it is not necessary to drill new boreholes.

Furthermore, EM-Slimflex loggers consist of possibilities for telemetric measurements. Currently, salinization monitoring in the Vitens area is especially based on in-situ measurements. By installing new methods suitable for telemetry, it is possible to decrease in-situ measurements.

6.5 Research implications

Throughout this study, multiple assumptions are made. For instance, several filter thresholds during the PECS data-analysis and input parameters for the hydrological model. The major part of the input parameters from the PECS data-analysis can be substantiated by using literature. Moreover, many assumptions are based on information derived from REGIS II, v2.2. As this lithological information is merely based on extrapolated lithological borehole information, it has to be noted that this information is not completely objective and reliable. More detailed subsurface information would undoubtedly result in more consistent and reliable model outputs.

7 Conclusion

At the start of this research a main research question was composed:

“What is the most optimal salinization monitoring policy for monitoring the fresh water – brackish water interface in Vitens’ extraction areas?”

By using multiple sub-questions, it was attempted to answer the main research question. Below, a short summary is provided per sub-question.

1. What is the cause of the fresh water – brackish water interface in the Netherlands?

Initial hypothesis: *It is hypothesized that near the coast, the fresh water – brackish water interface is especially influenced by salt water intrusion from the sea. Moving away from the coast, the fresh water – brackish water interface is dependent on ancient salt deposits.*

Aside from coastal areas which are in hydraulic connection with the sea, salinization is predominantly caused by ancient transgressions. According to Post et al. (2003), the origin of brackish groundwater is merely found in Holocene transgressions, which can be substantiated due to both indirect demonstration, salinity inversions near the Pliocene - Pleistocene boundary and due to C-14 groundwater analyses. Locally, influences as sea-spray, evapotranspiration, agriculture or large salt deposits can also alter chloride concentrations.

2. What is the value of PECS?

Initial hypothesis: *It is hypothesized that PECS provide alternating results, which is caused by varying measurement policies per province, differences in measurement devices, etc.*

The evaluation of PECS abilities differs per province. In Utrecht, for instance, the major part of PECS was able to calibrate with chloride concentrations, resulting in correct insights of current abilities of PECS. However, in Gelderland, many PECS were not able to connect to chloride concentrations. In general, trends between PECS resistances and chloride concentrations were absent in low chloride concentration environments ($[Cl^-] < 50 \text{ mg/l}$). More salinized environments alternately resulted in clear relationships between PECS resistances and chloride concentrations. However, prolonged periods with obvious trends between PECS resistances and chloride concentrations are absent. PECS electrodes are possibly not sensitive enough for detecting specific chloride concentration alterations or are strongly influenced by other conductors than chloride. Currently, PECS merely serve to monitor increasing or decreasing chloride trends. As a result, it is supposed that PECS are not the most efficient and reliable method for salinization monitoring. A more comprehensive evaluation of the current abilities of PECS would be obtained by optimizing chloride concentration connections, etc. as recommended in Chapter 8.

3. Are current PECS positioned on the right location?

Initial hypothesis: *If PECS have been situated in a non-critic salinization environment for many years, it could be cost-efficient to remove this location. On the other hand, if PECS have been located in brackish environments for many years, it might be more cost-efficient to remove these locations as well.*

Based on data-analysis results, it appeared that the major part of PECS is positioned on correct locations. This is determined by analyzing both in-situ chloride concentrations and by checking whether it is located in a 100-year zone. Nevertheless, some PECS are located in very low chloride concentration areas ($[Cl^-] < 30 \text{ mg/l}$) for a long consecutive period. Consequently, it is relevant to evaluate whether it is necessary to monitor these low chloride areas. On the other hand, it appeared that many potential salinization areas in especially the eastern part of the Netherlands are not monitored by PECS. As some of these locations are currently threatened with salinization, it is necessary to monitor these locations.

4. Are current PECS measured with the appropriate frequency?

Initial hypothesis: *If PECS provide sufficient detailed data regarding the fresh water – brackish water interface, it is hypothesized that the measurement frequency is correct. Alternatively, another measurement frequency has to be evaluated.*

Currently, PECS are measured with a large frequency variety. A large part of current PECS is measured disproportionally often. For instance, in the provinces of Flevoland and Overijssel, a measurement frequency of twelve times per year is mandatory. It is assumed that a general measurement frequency of four times per year is more efficient for relevant PECS. Herewith, it is possible to both quickly anticipate on broken PECS and to promptly detect measurement errors. Irrelevant PECS have to be removed from the measurement program and potentially relevant PECS have to be calibrated before assigning the correct measurement frequency.

5. Which alternative devices can be applied in order to monitor salinization?

Initial hypothesis: *It is hypothesized that the type of device depends especially on the situation and demands. Fellow drinking water companies use either PECS or alternative methods, as geo-electrical measurements and EM-39 loggers.*

It is assumed that electromagnetic monitoring devices consist of large potentials as these devices could be applied in existing monitoring wells and compose a continuous resistance overview over depth. Furthermore, these methods can be used in order to compose lithological overviews by using gamma radiation. This is a large advantage in contrast to for instance PECS or groundwater analysis from observation well samples.

Another method is a combination between hydrological modelling and observation well sampling. By conducting a modelling study, it is possible to obtain an interpretation of the possible groundwater flow paths. In combination with reliable groundwater parameter data from observation well monitoring, it is possible to reliably predict salinization trends in the future. Nevertheless, this method requires sufficiently deep observation wells.

6. Is it possible to reliably model salinization by using groundwater models?

Initial hypothesis: *It is hypothesized that models could display reliable results of salinization developments, provided that reliable input parameters are implemented.*

It appeared that hydraulic models can provide relevant insight in the groundwater flowpaths towards a well. Especially in combination with groundwater sampling from observation wells, this could be a proper method for detecting and predicting salinization. However, as initially hypothesized, detailed in-situ soil information is necessary in order to obtain reliable estimates. Also, it is a prerequisite that nearby observation wells consist of sufficiently deep filter depths, preferably with a minimum depth as pumping well filters. Herewith it is possible to distinguish between surface water and deep groundwater interactions.

Initially, a hypothesis was made for answering the main research question:

It is hypothesized that the most optimal monitoring policy depends on Vitens' aims. The one monitoring method might be more reliable than the other method, but also more expensive. Current PECS could be of added value, provided that a consistent policy is applied. However, as PECS are relatively time consuming because of in-situ measurements, it might be useful to evaluate alternative monitoring methods which are less time consuming and less expensive.

All in all, it is obvious that abilities of current PECS are not optimal. Most PECS do not show clear relationships with chloride concentrations, either due to conducting soil influences, low chloride concentrations, measurement errors and/or electrode sensitivity limitations. PECS are especially relevant in high chloride environments, as the Wadden Islands. In low chloride environments, PECS abilities are doubtful. As the major part of the Vitens area consists of relatively low or moderately chloride concentrations, PECS are not the most efficient and reliable monitoring device, because PECS only show whether chloride concentrations are increasing or decreasing.

It is assumed that salinization monitoring by using hydrological models in combination with observation well samples is more reliable. From this study, it appeared that hydrological models can provide relevant insight in groundwater flowpaths towards a well. Especially in combination with groundwater samples from observation wells, this could be a proper method for detecting and predicting salinization trends. However, in order to reliably monitor salinization, observation wells are required to be at least as deep as nearby pumping wells.

As the Vitens area consists of many observation wells, it might be efficient to apply electromagnetic loggers. Especially the EM-Slimflex logger seems to be an efficient salinization monitoring method. This monitoring device can be both applied for monitoring salinization and for composing lithological overviews. However, it is compulsory that observation wells are sufficiently deep and real abilities of EM-Slimflex loggers are not evaluated yet.

Consequently, it appears that the initial hypothesis is incorrect and has to be rejected. The new hypothesis is as follows:

It is hypothesized that salinization monitoring by using hydrological models in combination with observation well samples is the most optimal monitoring method. If observation wells are sufficiently deep, it would provide relevant interpretations of both salinization origins, salinization interface transitions and future salinization trends. EM-Slimflex loggers also consist of large potentials, but real abilities of these devices have to be tested first.

8 Recommendations

From Chapter 4.6 it was obvious that many pumping well locations – especially in the eastern part of the Netherlands – are not monitored by using PECS. During this study, both PECS and hydrological modelling abilities have been evaluated, as summarized in Appendix G. Furthermore, attention is paid on EM-Slimflex salinization monitoring. This chapter aims to provide more information about future salinization methods which could be applied on locations which are not monitored yet.

From Appendix C, it is obvious that groundwater extraction locations without a proper salinization monitoring policy are especially located in Overijssel and Gelderland. Based on the literature study, it is assumed that the fresh water – brackish water interface is predominantly caused by impermeable marine deposits from the Tertiary. As a result, chloride concentrations comparable with the Wadden Islands are not expected. As a consequence, PECS are not recommended as these measurement devices appeared to be unreliable and inconsistent in relatively low chloride concentration environments. Therefore, it is recommended to use hydrological models in combination with observation well samples.

Furthermore, as EM-Slimflex monitoring consists of large potentials, it is recommended to conduct a pilot-study on a location with sufficiently deep observation wells. During this pilot-study, it is important to consistently compare EM-Slimflex measurements with in-situ chloride concentrations obtained at different depths. Only if this study results in correct correlations, it is recommended to monitor salinization by using EM-Slimflex.

As both observation well samples and EM-Slimflex are dependent on sufficiently deep observation wells, drilling new observation wells is possibly unavoidable. In order to correctly position new observation wells, it is recommended to conduct a geophysical research for obtaining more insight in the in-situ lithological structure.

Although it is not recommended to install new PECS, innovative Deltares PECS might have better abilities than current PECS. Due to their high electrode couple amount, it is a more promising method than current PECS. Nevertheless, in order to test the real abilities, it is recommended to conduct a pilot study on a location with observation wells. Also, for properly installing PECS, initial geophysical research is recommended.

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July 2019

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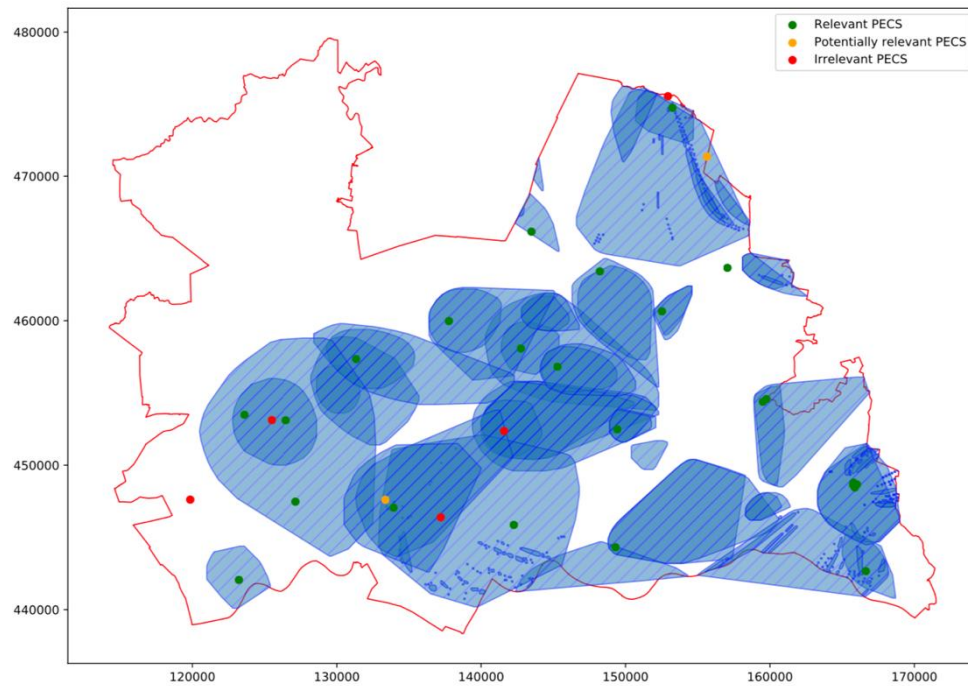
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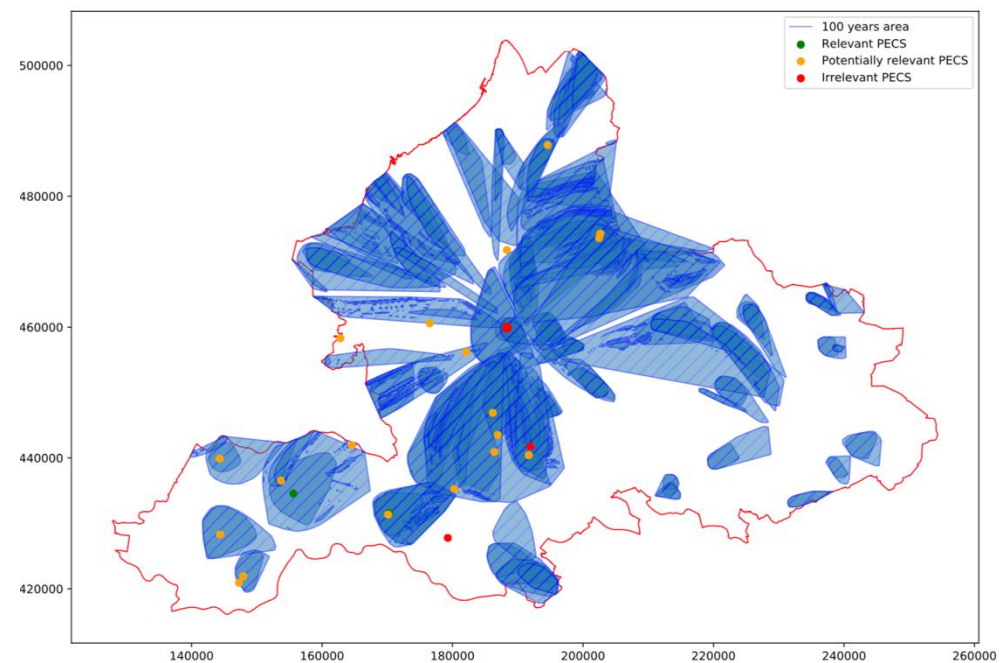
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Appendix A: Location PECS and 100 years zone per extraction location

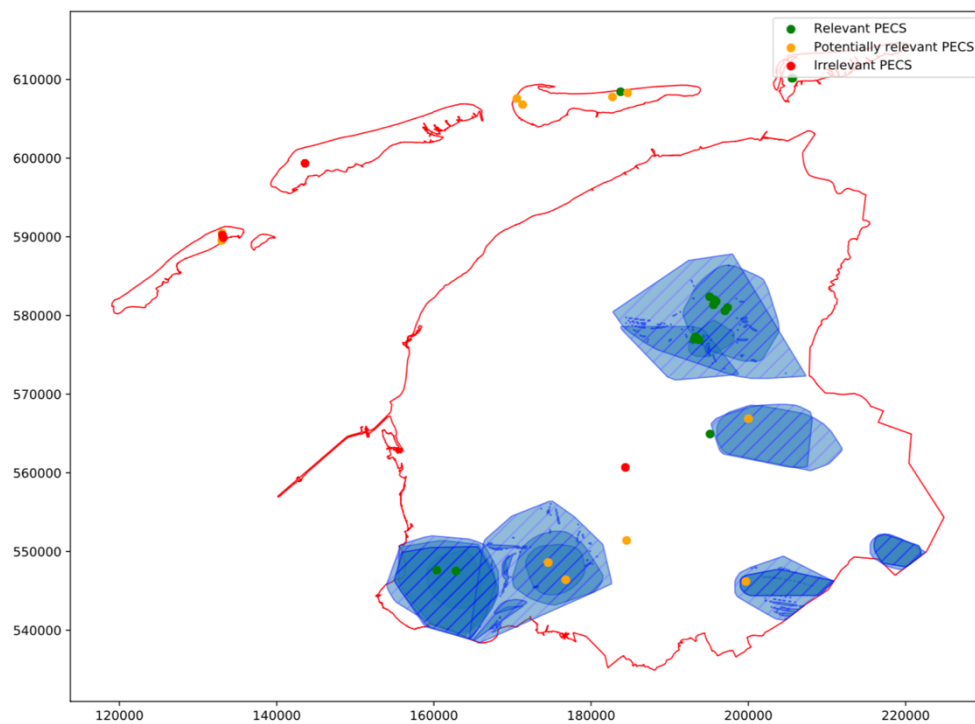
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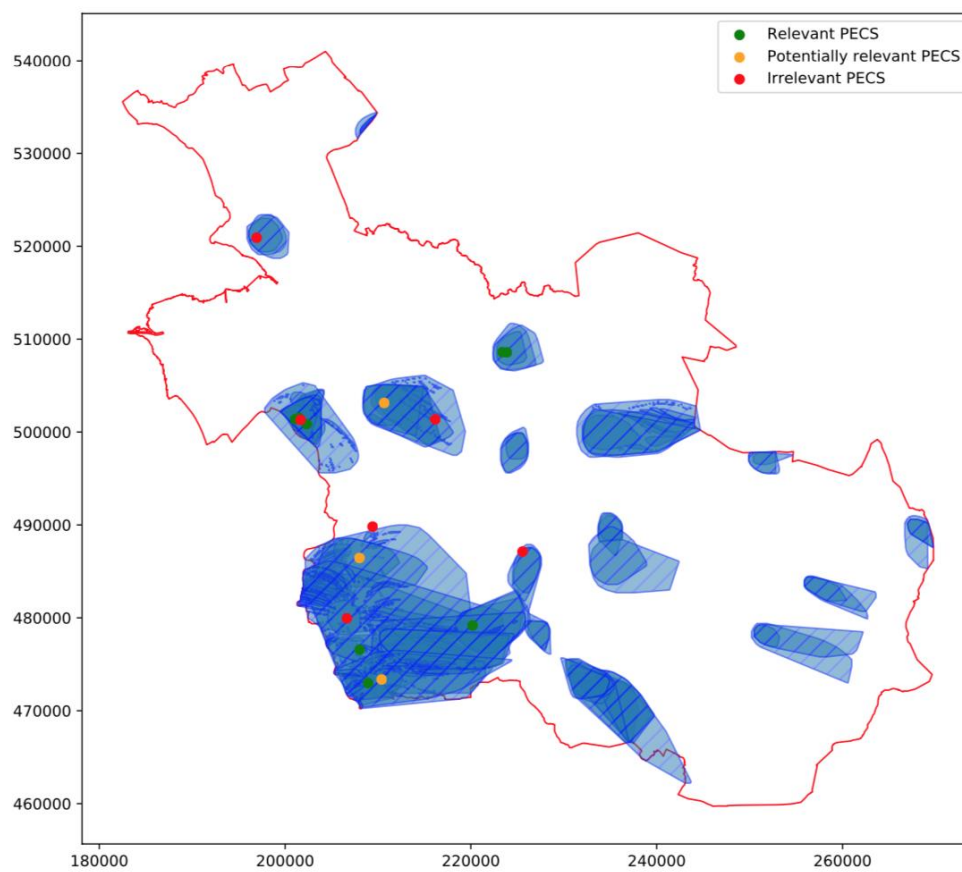
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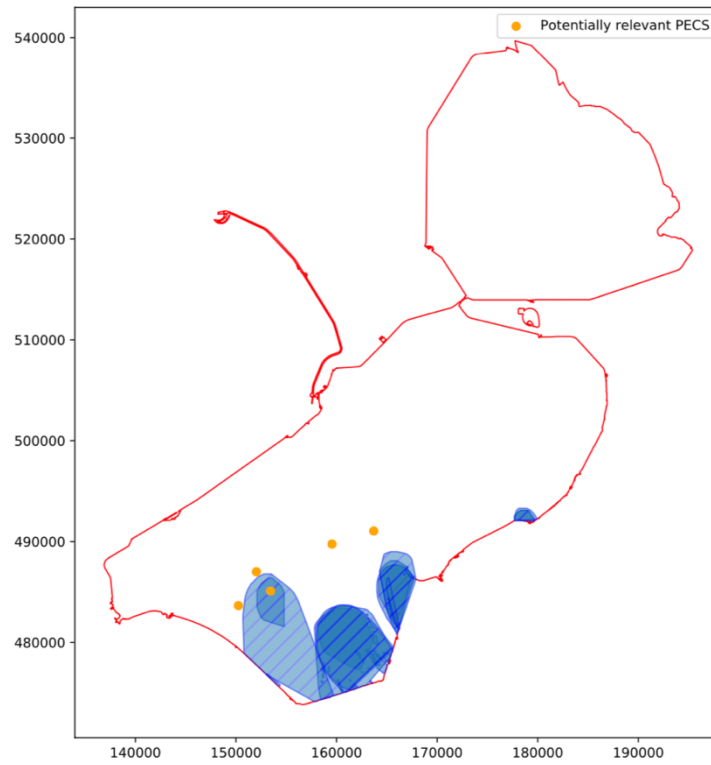
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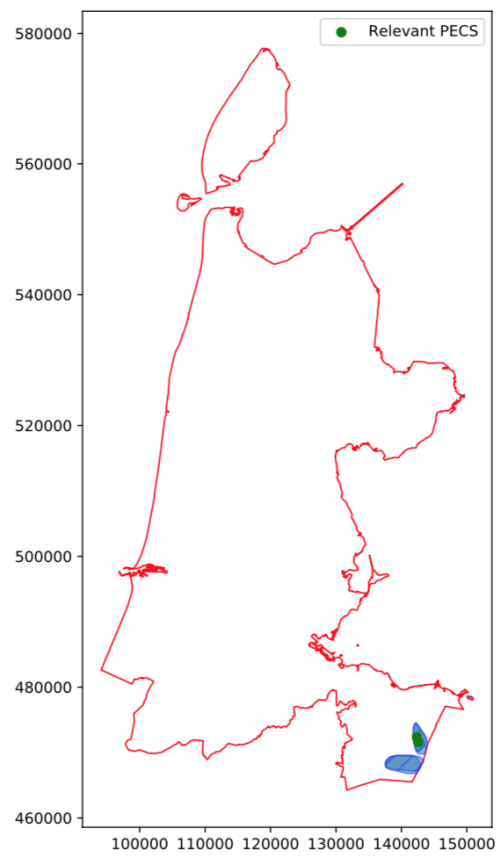
Province of Overijssel



Province of Flevoland



Province of Noord-Holland



PECS not located in 100-year zone			
PECS	Location	Province	Relevant/Irrelevant
32BP0210	Amersfoort Hogeweg	Utrecht	Relevant
32DP0167	Amersfoort Berg	Utrecht	Relevant
32BP0209	Holk	Utrecht	Potentially Relevant
38BP0142	Oudewater	Utrecht	Irrelevant
26DP0090	Eempolder, Eemdijk	Utrecht	Irrelevant
32CP0521	Bunnik	Utrecht	Irrelevant
39DP0222	Zoelen	Gelderland	Relevant
32GP0137	Glindhorst	Gelderland	Potential Relevant
33AP0192	Hoog Soeren	Gelderland	Potential Relevant
33CP0079	Otterlo	Gelderland	Potential Relevant
27BP0255	Epe	Gelderland	Potential Relevant
39HA3161	Beuningen	Gelderland	Irrelevant
02CP0128	Buren Ameland	Friesland	Relevant
11BP0084	Nij Beets	Friesland	Relevant
02GP0306	Schiermonnikoog	Friesland	Relevant
02GP0308	Schiermonnikoog	Friesland	Relevant
06DP0214	Noardburgum	Friesland	Relevant
01HP0094	Hollum Ameland	Friesland	Potential Relevant
01HP0096	Hollum Ameland	Friesland	Potential Relevant
02CP0127	Buren Ameland	Friesland	Potential Relevant
02CP0129	Buren Ameland	Friesland	Potential Relevant
04FP0040	Vlieland	Friesland	Potential Relevant
04FP0047	Vlieland	Friesland	Potential Relevant
11CP0090	Spannenburg	Friesland	Potential Relevant
04FP0025	Vlieland	Friesland	Irrelevant
04FP0026	Vlieland	Friesland	Irrelevant
11CP0095	Terschelling	Friesland	Irrelevant
B05A0194	Terwisscha	Friesland	Irrelevant
27GP0093	Ceintuurbaan, Deventer	Overijssel	Relevant
21HP0074	Vechterweerd	Overijssel	Potential Relevant
27EP0144	No information	Overijssel	Irrelevant
21BP0216	St Jansklooster	Overijssel	Irrelevant
26B0113	Harderbroek	Flevoland	Potential Relevant
26D0111	Spiekzand	Flevoland	Potential Relevant
26B0112	Spiekzand	Flevoland	Potential Relevant
26E 0113	Harderbroek	Flevoland	Potential Relevant

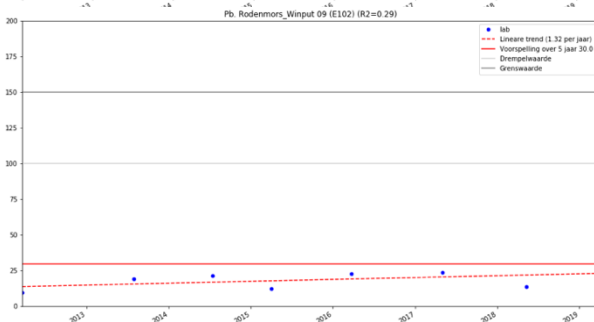
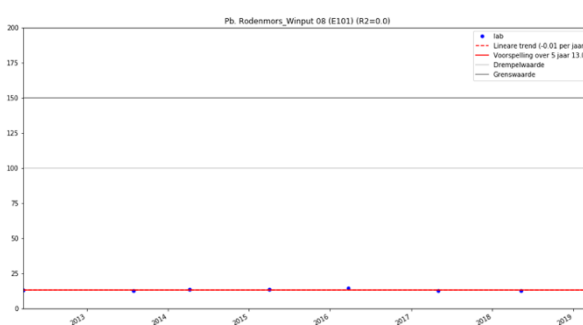
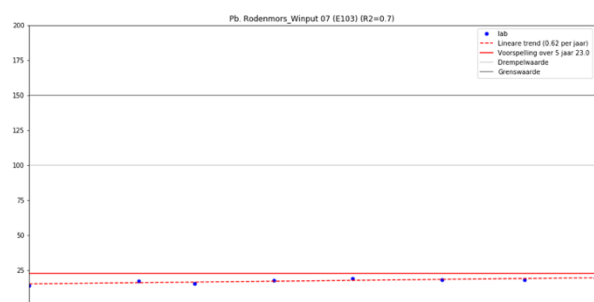
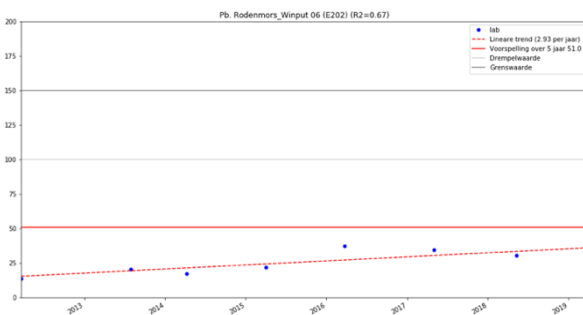
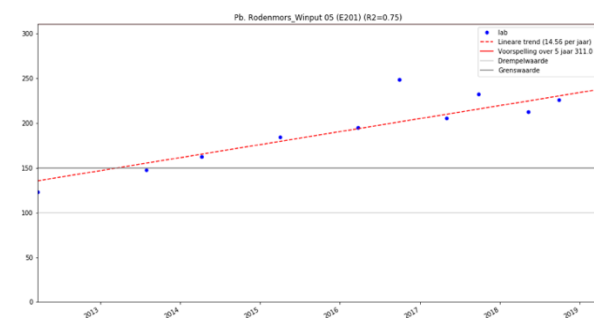
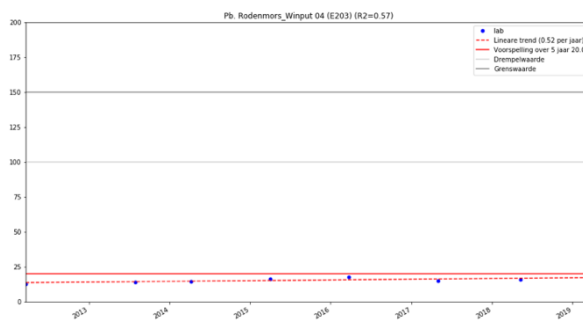
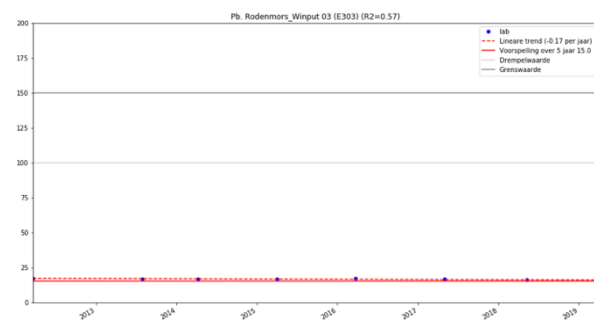
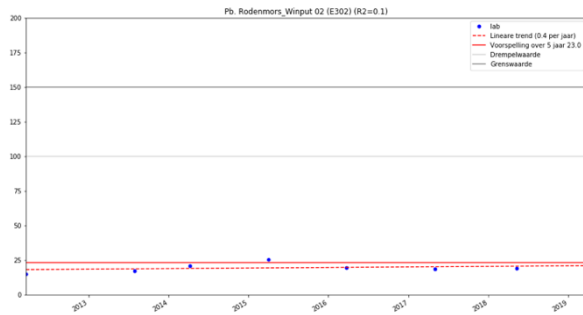
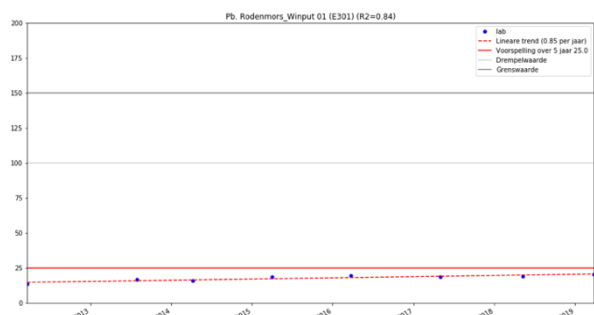
Appendix B: PECS recommendations

PECS	Location	Province	Relevant/Irrelevant	Couple to chloride concentrations	Require electrode depth data	Require another monitoring policy * In red: average [Cl ⁻] < 30 mg/l	Alternative municipality permission
31GP0200	Linschoten	Utrecht	Relevant				
31GP0205	Linschoten	Utrecht	Relevant				
31HP0697	Leidsche Rijn	Utrecht	Relevant				
32BP0258	Eemdijk Bunschoten	Utrecht	Relevant				
31HP0738	Groenekan	Utrecht	Relevant				
32DP0214	Woudenberg	Utrecht	Relevant				
39AP0187	Cothen	Utrecht	Relevant				
39AP0234	Schalkwijk	Utrecht	Relevant				
32BP0209	Holk	Utrecht	Potentially Relevant				
38FP0561	Nieuwegein	Utrecht	Potentially Relevant				
38BP0142	Oudewater	Utrecht	Irrelevant				
31GP0214	Linschoten	Utrecht	Irrelevant				
39DP0222	Zoelen	Gelderland	Relevant				
32GP0137	Glindhorst	Gelderland	Potential Relevant				
32HP0227	Westeneng	Gelderland	Potential Relevant				
33AP0192	Hoog Soeren	Gelderland	Potential Relevant				
33CP0079	Otterlo	Gelderland	Potential Relevant				
39EP0084	Lienden	Gelderland	Potential Relevant				
40CP0421	Andelst	Gelderland	Potential Relevant				
39DP0205	Zoelen	Gelderland	Potential Relevant				
40BP0349	Sijmons (Immerlopark, Arnhem Zuid)	Gelderland	Potential Relevant				
45AP0163	Velddriel	Gelderland	Potential Relevant				
45AP0164	Velddriel	Gelderland	Potential Relevant				
27BP0255	Epe	Gelderland	Potential Relevant				
33EP0185	Twello	Gelderland	Potential Relevant				
33EP0250	Twello	Gelderland	Potential Relevant				
39AP0236	Culemborg	Gelderland	Potential Relevant				
39CP0154	Kolff	Gelderland	Potential Relevant				
39HP0235	Druten	Gelderland	Potential Relevant				
40AP0551	Oosterbeek	Gelderland	Potential Relevant				
40AP0552	La Cabine	Gelderland	Potential Relevant				
40BP0375	Sijmons (Bakenhof, Arnhem zuid)	Gelderland	Irrelevant				
11BP0084	Nij Beets	Friesland	Relevant				
06DP0205	Noardburgum	Friesland	Relevant				
06DP0229	Garyp	Friesland	Relevant				
01HP0094	Hollum Ameland	Friesland	Potential Relevant				
01HP0096	Hollum Ameland	Friesland	Potential Relevant				
02CP0127	Buren Ameland	Friesland	Potential Relevant				
02CP0129	Buren Ameland	Friesland	Potential Relevant				
04FP0040	Vlieland	Friesland	Potential Relevant				
04FP0047	Vlieland	Friesland	Potential Relevant				
11EP0076	Nij Beets	Friesland	Potential Relevant				
16BP0105	Oldeholtgade	Friesland	Potential Relevant				
11CP0090	Spannenburg	Friesland	Potential Relevant				
15FP0121	Spannenburg	Friesland	Potential Relevant				
15FP0122	Spannenburg	Friesland	Potential Relevant				
04FP0025	Vlieland	Friesland	Irrelevant				
04FP0026	Vlieland	Friesland	Irrelevant				
22CP0129	Witharen	Overijssel	Relevant				
22CP0131	Witharen	Overijssel	Relevant				
27GP0093	Ceintuurbaan, Deventer	Overijssel	Relevant				
28CP0118	Espelo	Overijssel	Relevant				
33EP0181	Zutphenseweg, Deventer (zweedsestraat)	Overijssel	Relevant				
21HP0074	Vechterweerd	Overijssel	Potential Relevant				
27GP0186	Boerhaar	Overijssel	Potential Relevant				
33FP0133	Dortmundstraat, Deventer	Overijssel	Potential Relevant				
21BP0216	St Jansklooster	Overijssel	Irrelevant				
26B0113	Harderbroek	Flevoland	Potential Relevant				
26B0106	Spiekzand	Flevoland	Potential Relevant				
26D0111	Spiekzand	Flevoland	Potential Relevant				
26B0112	Spiekzand	Flevoland	Potential Relevant				
26E 0113	Harderbroek	Flevoland	Potential Relevant				

Appendix C: PECS without a monitoring policy

Potential salinization monitoring locations		
Location	Number of pumping wells	Province
Goor	9	Overijssel
Hammerflief	5	Overijssel
Hasselo	8	Overijssel
Havelterberg	22	Overijssel
Herikenberg	20	Overijssel
Hoge Hexel	10	Overijssel
Losser	3	Overijssel
Manderveen	13	Overijssel
Rodenmors	9	Overijssel
Weerselo	4	Overijssel
Wierden	27	Overijssel
Wierden ypelo	12	Overijssel
Aalten	4	Gelderland
Corle	12	Gelderland
De Muntberg	3	Gelderland
Dinxperlo	5	Gelderland
Eibergen	7	Gelderland
Haarlo	5	Gelderland
Harderwijk	15	Gelderland
Lochem	5	Gelderland
Noordijk	9	Gelderland
Putten	7	Gelderland
't Klooster	12	Gelderland
Van Heek Galgenberg	4	Gelderland
Van Heek Hettenheuvel	3	Gelderland
Van Heek Montferland	13	Gelderland
Vorden	9	Gelderland
Terwisscha	15	Friesland
Bremerberg	16	Flevoland
Harderbroek	16	Flevoland


Appendix D: Rodenmors salinization trends per well



Appendix E: Rodenmors pumping well 5 analysis

Well name	Data	Top filter	Bottom filter	pH[-]	EGV[mS/m]	Ca[mg/L]	Mg[mg/L]	Na[mg/L]	K[mg/L]	Cl[mg/L]	SO4[mg/L]	HCO3[mg/L]
		(m+NAP)	(m+NAP)									
RM1998-05.0	16-nov-1999 12:00:00	-6,44	-20,68	6,70	63,00	120,00	8,10	13,00	2,50	13,00	7,00	445,00
RM1998-05.0	15-dec-1999 12:00:00	-6,44	-20,68									
RM1998-05.0	28-feb-2000 12:00:00	-6,44	-20,68	6,65	63,00	120,00	8,70	14,00	2,50	11,00	6,00	442,00
RM1998-05.0	14-mrt-2000 12:00:00	-6,44	-20,68									
RM1998-05.0	16-jan-2001 12:00:00	-6,44	-20,68									
RM1998-05.0	07-mrt-2001 12:00:00	-6,44	-20,68	6,85	62,00	120,00	8,60	15,00	2,80	10,00	5,00	435,00
RM1998-05.0	05-mrt-2002 12:00:00	-6,44	-20,68	7,00	62,00	120,00	8,60	15,00	2,80	12,00	5,00	442,00
RM1998-05.0	27-feb-2003 12:00:00	-6,44	-20,68	6,90	61,00	120,00	8,50	16,00	3,00	14,00	5,00	432,00
RM1998-05.0	26-feb-2004 12:00:00	-6,44	-20,68	6,90	60,00	110,00	8,20	18,00	2,90	13,00	5,00	421,00
RM1998-05.0	06-apr-2005 10:32:00	-6,44	-20,68									
RM1998-05.0	06-apr-2005 10:41:00	-6,44	-20,68	7,00	58,00	120,00	9,30	21,00	3,10			408,00
RM1998-05.0	29-mrt-2006 11:44:00	-6,44	-20,68	7,05	58,70	118,00	8,76	19,20	3,10	12,00	10,00	413,00
RM1998-05.0	19-mrt-2007 13:56:00	-6,44	-20,68	6,85	58,10	106,00	8,02	19,50	2,70	19,00	10,00	392,00
RM1998-05.0	15-apr-2008 11:33:00	-6,44	-20,68	6,95	56,40	103,00	7,89	15,80	2,80	23,00	10,00	370,00
RM1998-05.0	09-sep-2009 10:55:00	-6,44	-20,68									
RM1998-05.0	09-sep-2009 10:58:00	-6,44	-20,68	6,80	70,60	113,00	8,82	30,60	3,00	75,00	2,00	373,00
RM1998-05.0	13-apr-2010 10:04:00	-6,44	-20,68	6,95	75,50	118,00	10,80	45,30	3,10	89,00	2,00	369,00
RM1998-05.0	24-feb-2011 12:00:00	-6,44	-20,68									
RM1998-05.0	25-feb-2011 12:00:00	-6,44	-20,68									
RM1998-05.0	21-apr-2011 11:49:00	-6,44	-20,68	7,05	82,50	123,00	11,10	51,30	3,30	110,00	7,60	374,00
RM1998-05.0	21-mrt-2012 09:36:00	-6,44	-20,68	7,00	83,60	119,00	9,95	54,60	3,10	125,00	2,00	367,00
RM1998-05.0	31-jul-2013 11:47:00	-6,44	-20,68	7,00	89,50	129,00	10,30	71,30	3,20	150,00	2,00	360,00
RM1998-05.0	08-apr-2014 09:37:00	-6,44	-20,68	6,99	95,50	124,00	10,40	78,20	3,30	165,00	2,00	356,00
RM1998-05.0	02-apr-2015 09:30:00	-6,44	-20,68	7,04	98,30	122,00	10,20	85,40	3,20	180,00	2,00	348,00
RM1998-05.0	23-mrt-2016 10:03:00	-6,44	-20,68	7,06	106,00	117,00	10,50	100,00	3,31	190,00	2,00	340,00
RM1998-05.0	28-sep-2016 09:25:00	-6,44	-20,68							250,00		
RM1998-05.0	02-mei-2017 11:29:00	-6,44	-20,68	7,05	107,00	117,00	9,87	105,00	3,20	210,00	2,00	336,00
RM1998-05.0	31-mei-2017 10:44:00	-6,44	-20,68									
RM1998-05.0	25-sep-2017 11:14:00	-6,44	-20,68							230,00		
RM1998-05.1	29-jul-1999 00:00:00	-7,44	-9,44	6,80	60,00	130,00	8,20	12,00	2,60	10,00	5,00	459,00
RM1998-05.2	29-jul-1999 00:00:00	-17,68	-19,68	6,85	62,00	130,00	8,70	15,00	3,00	10,00	5,00	473,00

Appendix F: Rodenmors observation well analysis



Vitens
LAAT WATER VOOR JE WERKEN

Vitens Laboratorium
Snekerterweg 61
8912 AA Leeuwarden

Analyserapport

Pagina 2 van 3


Opdrachtnr V190646374 Versie 1 Rapportage datum 25 juni 2019

Opdrachtgever	Adres	Woonplaats	Afdeling/subklient	Project	Klantreferentie
Asset Management	Oude Veerweg 1	8019 BE ZWOLLE	Asset Management	Intrekgebied Pb. Rodenmors	

Monsternr.	Adres	Monsterpunt	Klantkenmerk	Matrix	Method	Erkend	Monsternr. door
V1906083652	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0085 6 m		Grondwater	Vbens	Q	Vitens Laboratorium
V1906083653	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0085 15 m		Grondwater	Vbens	Q	Vitens Laboratorium
V1906083654	7591 NK DENEKAMP Dorpermeienweg 15	Pb. Rodenmors PB 29AL9006 3 m		Grondwater	Vbens	Q	Vitens Laboratorium
V1906083655	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0070 12 m		Grondwater	Vbens	Q	Vitens Laboratorium
V1906083656	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0070 25 m		Grondwater	Vbens	Q	Vitens Laboratorium

Monsternummer	V1906083652	V1906083653	V1906083654	V1906083655	V1906083656
Datum monsterneming	19-06-2019	19-06-2019	19-06-2019	19-06-2019	19-06-2019
Tijdstip monsterneming	12:08	11:43	09:35	10:54	10:24
Datum acceptatie	19-06-2019	19-06-2019	19-06-2019	19-06-2019	19-06-2019

Test	Testomschrijving	Einheid	Erkend	Method						
Metaal Analyses										
444	IJzer (Fe), opgelost	mg/l	Q	VL-W-ME04	1.22	4.03	13.2	4.53	6.35	
688	Calcium (Ca), opgelost	mg/l	Q	VL-W-ME04	52.0	115	111	83.2	80.3	
691	Kalium (K), opgelost	mg/l	Q	VL-W-ME04	11.9	3.58	30.4	2.41	1.63	
692	Magnesium (Mg), opgelost	mg/l	Q	VL-W-ME04	8.62	7.01	12.5	5.62	4.94	
693	Mangaan (Mn), opgelost	mg/l	Q	VL-W-ME04	0.269	0.219	0.782	0.303	0.311	
695	Natrium (Na), opgelost	mg/l	Q	VL-W-ME04	6.21	9.70	18.4	31.5	13.5	
990	Totale Hardheid, na filtratie (0,45µm)	mmol/l	Q	VL-T-AL35	1.65	3.15	3.27	2.31	2.21	
Organisch - kwantitatief										
226	Methaan, in water	µg/l	Q	VL-W-OC05	89	22000	78	2000	9700	
480	DOC	mg/l	Q	VL-W-OC02	11	8.0	11	5.9	4.8	
Monsternamen Analyses										
374	Temperatuur, in situ	°C	Q	VL-W-MN16	11.9	12.3	12.7	11.5	11.4	
375	Zuurgraad (pH), in situ	pH	Q	VL-W-MN17	6.6	6.9	6.8	7.2	7.1	
1087	Geleidingsvermogen bij 20 °C (EGV), in situ	mS/m	Q	VL-W-MN18	33.3	55.1	69.9	51.3	42.3	
1315	Pompspoort (waarnemingsfittens)			Slangenpomp	Slangenpomp	Slangenpomp	Slangenpomp	Slangenpomp	Slangenpomp	
1648	Afpomptijd	minuten		10.00	17.00	10.00	15.00	20.00		




De met 'Q' gemerkte vermeldingen zijn door de Ruik geaccrediteerd. De met 'V' gemerkte analyse(s) zijn door een ander laboratorium uitgevoerd.

Op aanvraag is een lijst met specificaties van de langzaamste analyse- en bestemmingsmethode(s) verkrijgbaar.

De datum en tijd van de start van de afzonderlijke analyses is zorgvuldig gekozen dat deze binnen de gestelde termijn vallen, anders is het resultaat vergezeld van een disclaimer.

Dit rapport mag niet anders dan in zijn geheel worden gereproduceerd zonder schriftelijke toestemming van het laboratorium.



De Ruik
Manager Laboratorium

De onderzoeksresultaten hebben uitsluitend betrekking op de begroefde monsters.

Voor meer informatie over de meest voorkomende parameters, zie: <https://www.vitens.nl/over-water/begripennlijst>

Vitens

Vitens Laboratorium

Snekerterweg 61

8912 AA Leeuwarden

LAAT WATER VOOR JE WERKEN

Analysrapport

Pagina 1 van 3

Opdrachtnr

V190646374

Versie

1

Rapportage datum

25 juni 2019

Opdrachtgever

Asset Management

Adres

Oude Veerweg 1

Woonplaats

8019 BE ZWOLLE

Afdeling/subklient

Asset Management

Project

Intrekgebied Pb. Rodenmors

Klantreferentie

Monsternr.	Adres	Monsterpunt	Klantkenmerk	Matrix	Method	Erkend	Monsternr. door
V1906083652	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0085 6 m		Grondwater	Vitens	Q	Vitens Laboratorium
V1906083653	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0085 15 m		Grondwater	Vitens	Q	Vitens Laboratorium
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V1906083655	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0070 12 m		Grondwater	Vitens	Q	Vitens Laboratorium
V1906083656	7591 ND DENEKAMP Rodenmorsweg 11	Pb. Rodenmors PB 29AP0070 25 m		Grondwater	Vitens	Q	Vitens Laboratorium

Monsternummer

V1906083652

V1906083653

V1906083654

V1906083655

V1906083656

Datum monsterneming

19-06-2019

19-06-2019

19-06-2019

19-06-2019

19-06-2019

Tijdstip monsterneming

12:08

11:43

09:35

10:54

10:24

Datum acceptatie

19-06-2019

19-06-2019

19-06-2019

19-06-2019

19-06-2019

Test	Testomschrijving	Einheid	Erkend	Method					
Anorganische Analyses									
116	Geleidingsvermogen bij 20 °C (EGV)	mS/m	Q	VL-W-AC01	34.8	57.0	73.4	52.8	43.9
118	Nitraat			VL-W-AC02					
	Nitraat	mg NO3 / l	Q		<1.0	<1.0	<1.0	<1.0	<1.0
	Nitraat-N	mg N/l	Q		<0.2	<0.2	<0.2	<0.2	<0.2
148	Koolstofdioxide	mg/l	Q	VL-W-AC01	63	83	110	38	40
150	Waterstofcarbonaat	mg/l	Q	VL-W-AC01	146	399	384	300	282
164	Chloride	mg/l	Q	VL-W-AC02	21	10	36	41	17
166	Ammonium			VL-W-AC02					
	Ammonium	mg NH4 / l	Q		0.22	2.69	1.67	0.94	0.66
	Ammonium-N	mg N/l	Q		0.17	2.09	1.30	0.73	0.52
168	Fosfaat-ortho			VL-W-AC02					
	Fosfaat-ortho-P	mg P/l	Q		0.07	0.34 ¹	0.27	0.26	0.30
	Fosfaat-ortho	mg PO4 / l	Q		0.23	1.07 ²	0.85	0.81	0.95
715	Sulfaat	mg SO4 / l	Q	VL-W-AC02	44	<2	60	2	<2
1230	Ionenbalans Berekend opgelost			VL-T-AL35					
	Negatieve ionen	meq/l			3.91	6.87	8.56	6.15	5.10
	Positieve ionen	meq/l			3.94	7.12	8.71	6.27	5.31

De met 'Q' gemerkte vermeldingen zijn door de Ruik geaccrediteerd.

De met 'V' gemerkte analyse(s) zijn door een ander laboratorium uitgevoerd.

Op aanvraag is een lijst met specificaties van de toegepaste analyse- en bestemmingsmethode(s) verkrijgbaar.

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De R. Buit Manager Laboratorium

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Voor meer informatie over de meest voorkomende parameters, zie: <https://www.vitens.nl/over-water/begripennlijst>

Appendix G: Summary monitoring devices

Monitoring device		Monitoring abilities	Spatial salinization overview	Measurement intensity	Data processing intensity	Location requirements	Remarks
PECS *Evaluated in this study	+	Only relevant in high chloride concentration environments ([Cl ⁻] > 200 mg/l)	-	-	-	-	-
	-	Temperate correlations with chloride in low chloride concentration environments ([Cl ⁻] < 200 mg/l)	Resistances are only determined at specific depths	Time intensive due to in-situ measurements of both PECS and chloride concentrations	Data validation and calibration is required	PECS require new boreholes in the vicinity of observation wells	PECS can be affected by other soil- and groundwater conductors than chloride
Hydrological models + Observation wells *Evaluated in this study	+	It is possible to both detect locations of salinization origins, causes of salinization and evaluate future salinization trends.	Groundwater pathlines provide relevant information of the spatial groundwater system.	Only requires occasional observation well samples	After construction, running hydrological models is not time intensive	Chloride measurements can be obtained in existing observation wells	Possible to monitor other groundwater parameters than only chloride
	-	Hydrological models are not 100% reliable	Groundwater samples can only be determined at specific depths	-	Constructing a hydrological model is required	Observation well filters have to be at least as deep as pumping well filters	-
EM-Slimflex *Not evaluated in this study	+	Based on literature: clear relationships with chloride concentrations	Resistances are determined over the entire depth of the observation well	Potentials for telemetric monitoring	Not known	Can be fitted in existing observation wells	Can also be used in order to monitor groundwater contamination Can be used in order to generate lithologic profiles
	-	-	-	In-situ measurement required	Not known	-	-