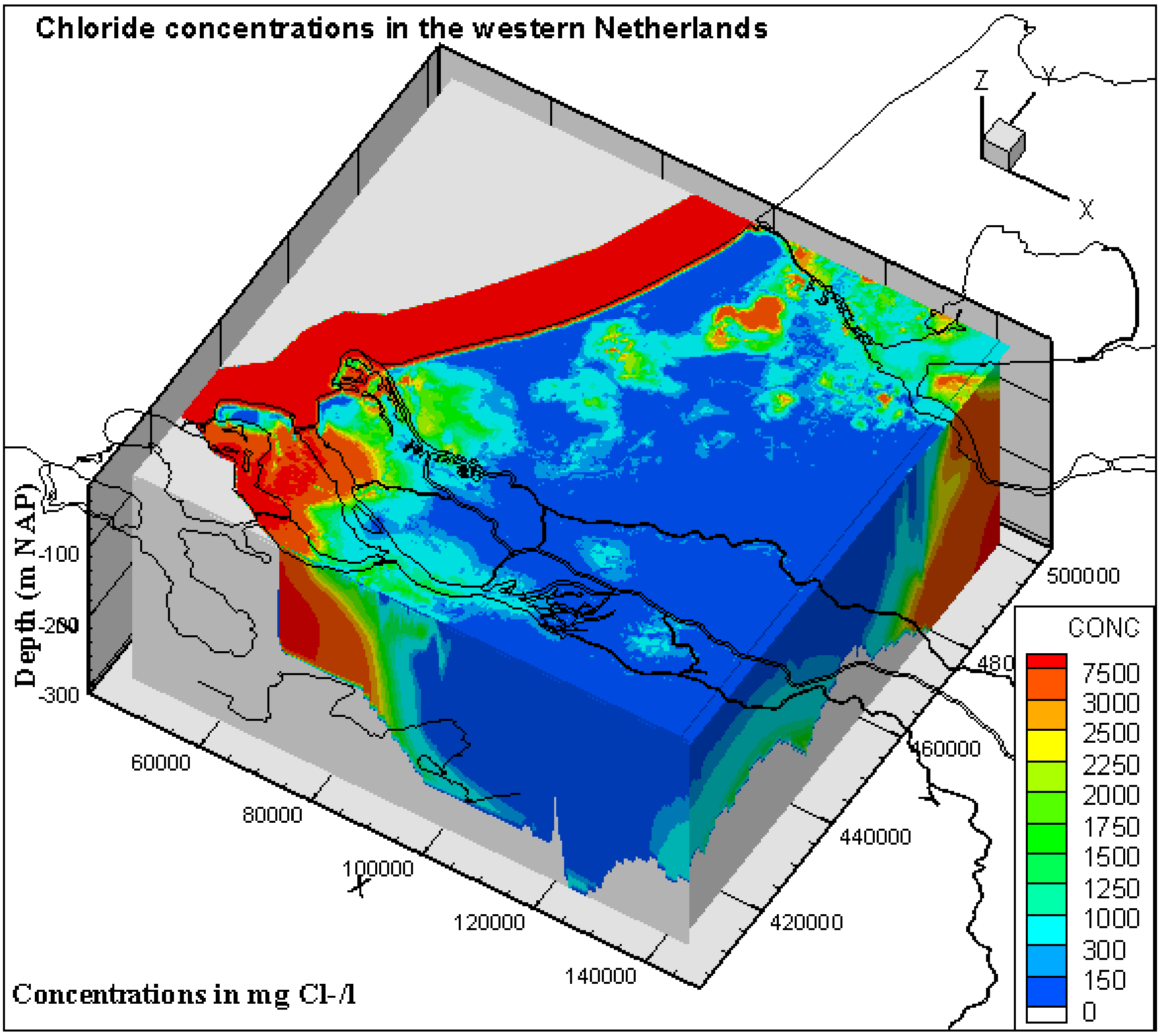
Universiteit Utrecht

Deltares
Enabling Delta Life

Master's Thesis
Master Water Science and Management

Saline groundwater extraction as a measure to increase the freshwater availability

A case study for the western parts of the Netherlands



The salt distribution within the Zuid-Holland model visualized.

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Abstract

Autonomous salinization threatens freshwater availability in deltaic and areas and is expected to increase by future sea level rise and soil subsidence. To preserve freshwater volumes and prevent increased agricultural damages mitigation measures needed to be taken. Saline groundwater extractions lower the saline groundwater interface and fresh water can percolate deeper into the subsoil, increasing the fresh water availability. The extracted water can be purified using reverse osmosis and be used as drinking water. This research investigated the geo-hydrological properties required to increase freshwater availability by applying saline groundwater extraction as a socio-economic mitigation measure for salinization.

Within the Zuid-Holland model different extraction scenarios were tested per polder area, to investigate the geo-hydrological properties. The agricultural damages and the phreatic water level decline were calculated with the WAOR and LHM model. To improve the freshwater availability extraction wells should be placed within saline seepage areas; to prevent saline seepage from bypassing the wells a high well density is needed. The extraction wells should be placed on the brackish-saline interface to prevent saline water from up-coning in the brackish groundwater. To prevent the area of dewatering and soil subsidence, no large phreatic water level decline should occur. A thick confining layer with a hydraulic resistance of at least 2000 days prevents this To obey the Dutch law a groundwater protection zone should be created which prevents pesticides from diminishing the water quality of the upper aquifer. The costs for drinking water production from the extracted groundwater (€0.93) are higher than conventional drinking water production methods therefore a division of costs between the stakeholders is needed.

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1. Introduction

1.1 Background

Low-lying delta areas are attractive living areas caused by their abundance of food and the high accessibility. These areas depend on freshwater for domestic, agricultural and industrial processes. They are dependent on precipitation, surface water, and shallow groundwater since the deep groundwater is often saline due to seawater intrusion, saline seepage, marine transgressions and sea spray (Stuyfzand and Stuurman, 1994). These mechanisms also threaten the shallow groundwater. The pressures on the deltaic fresh groundwater reserves are expected to increase with future sea level rise and land subsidence (De Louw, 2013).

This research focusses on the Dutch delta since an abundance of geo-hydrological data (REGIS and GEOTOP) is available. Geo-hydrological studies have been executed since 1889 (Badon Ghijben & Drabbe, 1889). As the Dutch delta obtains important economic activities, lies largely below mean sea level and would be flooded without dykes, it faces currently problems (flooding and salinization) which will be future problems for other deltaic areas (Oude Essink et al., 2010) as the Mekong, Ganges, Mississippi and the Po (Barlow & Reichard, 2010; Bobba, 2002; Custodio, 2010; Giambastiani, Antonellini, Oude Essink, & Stuurman, 2007; Meisler, Leahy, & Knobel, 1984; Ranjan, Kazama, & Sawamoto, 2006). In 2016 Deltares, KWR, Arcadis & Allied Waters started the COastal Aquifer STorage And Recovery project (COASTAR) in the Netherlands to increase the freshwater availability in the future. The aim of COASTAR is to use underground techniques for drought control and to create a robust freshwater provision (Stofberg et al., 2018). The project incorporates different sectors as drinking water, industry, agriculture and the urban areas. The project is financed by the province of Zuid-Holland and the drinking water company Dunea. This research is done within the COASTAR project.

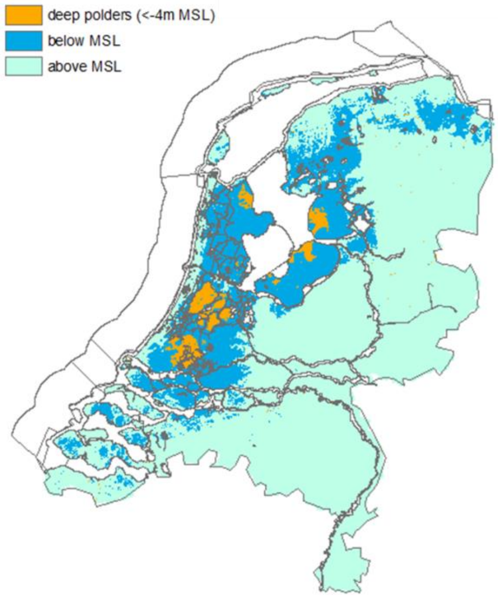

Figure 1: Areas below mean sea level in the Netherlands.

In the Netherlands about 25% of the land is below sea level; polders mainly exist in the northern and western parts of the country. A polder is according to the Koenen dictionary (2006) a terrain enclosed by dikes or quays, to block outside water and to extract inside water. Reclaimed lake or sea polders can be as deep as 5 metres below sea-level (figure 1). Areas surrounding the deep polder have a higher phreatic water level than the deep polders. The water level tries to reach equilibrium. In the higher areas the hydraulic heads are lower than the phreatic water level causing infiltration, while in deep polders the hydraulic head exceeds the phreatic water level causing a seepage flux (De Louw, et al., 2010). To keep the deep polders dry and applicable for agriculture the Dutch water authorities lower the surface water levels artificially by water pump stations. The water is pumped into so-called boezems, a temporary storage channel for freshwater (figure 2).

The seepage flux originates from marine sediments, which were deposed between 5500 BC and 3850 BC in which the coastal parts of the Netherlands were still under the tidal influence of the North Sea (Delsman et al., 2013). Therefore the seepage is saline and causing autonomous salinization. Besides anthropogenic processes, autonomous salinization can also be caused by natural processes like soil subsidence (Oude Essink & Van Baaren, 2009).

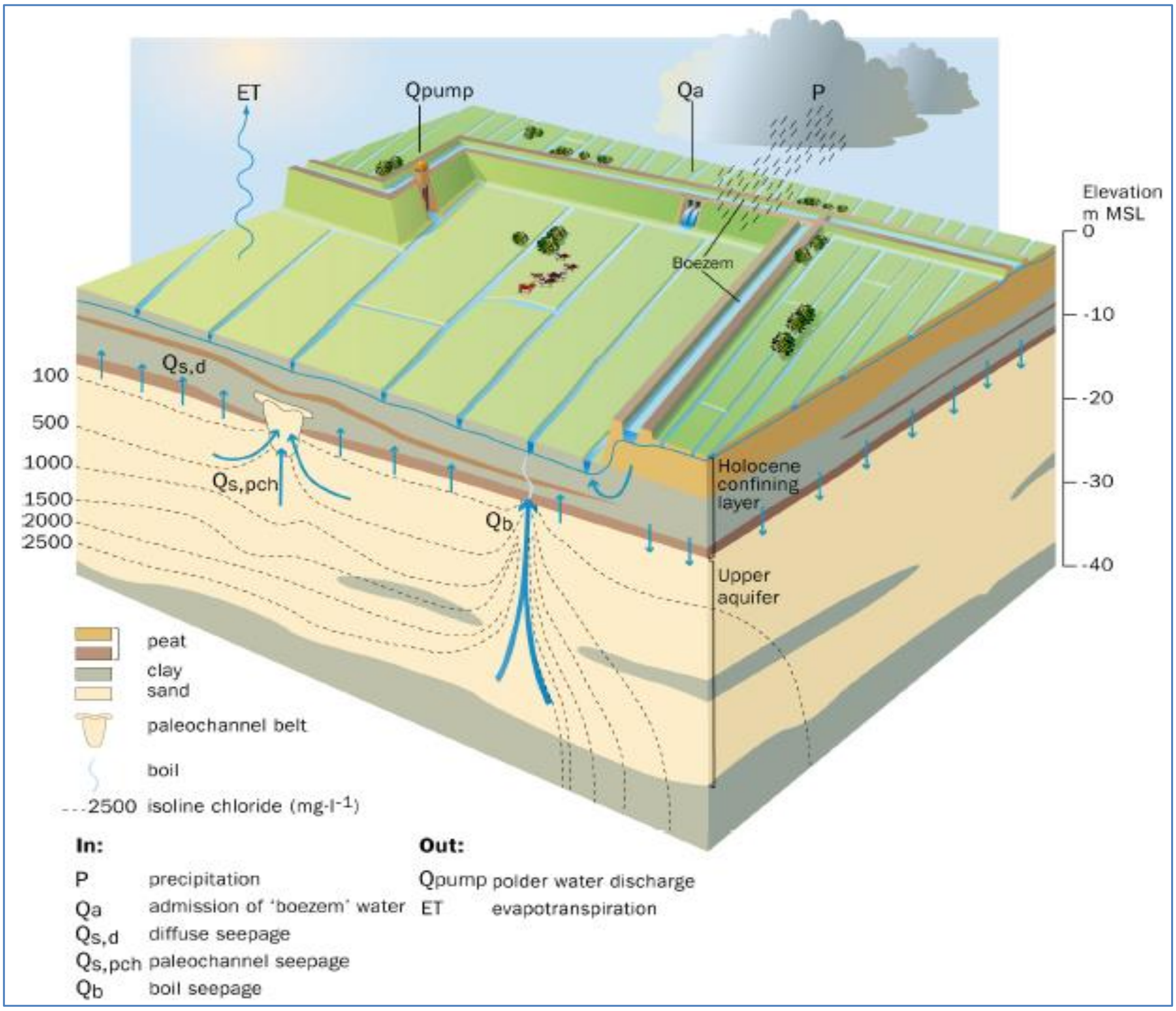

Figure 2: A typical deep polder setting in the Netherlands (De Louw et al., 2010).

1.2 Problem definition

It is expected that the Dutch population will increase to 18.4 million inhabitants in 2050 (CBS, 2017). The population growth will increase the water demand for the Dutch delta and increase the pollution pressure on the freshwater system. The drinking water companies of Dunea, Groningen, PWN and Vitens already stated that their current drinking water production methods will not cover the future needs and they search for new water sources for drinking water production (Zwolsman, 2017). Greenhouse businesses are using reverse osmosis (RO) technologies to make freshwater from brackish (150-1000 mgl^{-1} Cl^{-}) / saline (>1000 mgl^{-1} Cl^{-}) groundwater. RO is a technique which filters water using membranes and high pressure. It results in demi-water and a by-product, often called brine. The demi-water can be transformed into drinking water. The by-product needs to be processed. The brine can be injected back into to the subsoil in a deeper layer, brought to a waste water treatment plant (WWTP) or can be brought to sea. The RO costs have declined the last decennia and make saline groundwater a more applicable drinking water source.

The autonomous salinization process and climate change will also increase the freshwater demand for agriculture. Salt loads larger than >1000 kg^{-1} ha^{-1} y^{-1} Cl^{-} are already present in polders below -5m metre (Oude Essink et al., 2010). High salt concentrations have a negative impact on agriculture in these polders. The maximum salt norm for agriculture is 500 mgl^{-1} Cl^{-} (Stuyt, Bakel, & Massop, 2011; Stuyt, Blom-Zandstra & Kselink, 2016). Some agricultural sectors like tree nurseries (150 mgl^{-1} Cl^{-}) and greenhouse horticulture (75 mgl^{-1} Cl^{-}), however, are even more sensitive to saline environments and therefore have a lower maximum salt tolerance (Stuyt et al., 2013).To make the brackish to saline areas more applicable for agriculture the water authorities dilute the salt concentrations by adding freshwater from the boezem (Van Rees Vellinga, Toussaint, & Wit, 1981).

Adding water by inlets and extracting water by water pump stations is called flushing and is mainly necessary during dry summers. The water inlets are also used for managing the surface water levels during dry periods, keeping nutrients and pesticides out of natural areas, stopping subsidence and sustaining the dikes and agriculture (Van Rees Vellinga et al., 1981; Stuyt et al., 2012). The strategy of using surface water to solve groundwater related problems is commonly implemented in the Netherlands (Stuyt et al., 2011). However, flushing is not always done efficiently. For example, the water authority of Rijnland (HHR) uses 30-40 million m^3 water for flushing in an average year (Stuyt et al., 2011). Inlets are often permanently opened and therefore flushing also occurs in winter when the salt concentrations are low due to precipitation. To pump water back into the boezem electricity is needed. Clean water from the boezem is mixed with the saline water and pesticides of the polder before it is pumped back into the boezem. Flushing therefore lowers the water quality of the boezem. Secondly, the added freshwater does not reach the entire polder, but it takes the fastest route from the inlet to the extraction point (Hakkenes, 2015; Delsman, 2015).

Figure 3: The water inlets of Gouda and Bodegraven within the water authority of Rijnland (HHR, 2009).

During dry summers, like 2011, not enough freshwater was accessible for flushing, resulting in agricultural damages. These droughts occur on average once every 10 years, but with climate change, it is expected to occur every 2 years (Delsman, 2015). The flushing of brackish areas increases the salinity of the boezems and causes agricultural damages in areas depending on freshwater from the boezem inlets. The boezem of Rijnland crosses multiple polders with salt seepage before it enters the sensitive tree nursery area of Boskoop (near Bodegraven) and the flower bulb fields of the Bollenstrook between Haarlem and Katwijk (figure 3). During the dry summer of 1989, the agricultural damages caused by salinity in the Rijnland area still had an estimated value of € 25 million (Stuyt et al., 2012). Flushing is therefore not the most sustainable and socio-economic solution for salinization.

The Dutch government signed in 2017 the Waterakkoord Klimaatbestendige Water Aanvoer Midden-Holland (KWA, 2017), which states that three new boezems will be created for bringing freshwater from the eastern to this western part of the Netherlands. The KWA used when the flow capacity of the Rhine drops below 1100 m^3/s. The inlet at Gouda will close to prevent salt sea water from entering the area; and consequently, a different water source is necessary (KWA, 2017). The agreement is an extension of the already existing KWA at Bodegraven (figure 3), which cannot provide enough water to sustain all relevant functions within Rijnland during droughts (Stuyt et al., 2012). The KWA may solve the problem for Rijnland, however, it is a regional solution and not widely applicable, further on it does not solve the source problem. Would a more economical and efficient solution be to prevent the brackish groundwater seepage from entering the surface water system?

1.3 Previous research

In Oude Essink (2001) six mitigation options for saline seepage are named: ‘’(1) Instalment of a freshwater injection barrier through injection or infiltration of freshwater near the shoreline; (2) extraction of saline and brackish groundwater; (3) modifying pumping practice through reduction of withdrawal rates or adequate relocation of extraction wells (4); land reclamation and creating a foreland where a freshwater body may develop which could delay the inflow of saline groundwater; (5) increase of recharge in upland areas to enlarge the outflow of fresh groundwater through the coastal aquifer and to reduce the length of the salt water wedge and (6) the creation of physical barriers such as sheet piles, clay trenches or injection of chemicals’’.
Multiple geo-hydrological studies investigated the effects of salinization. Oude Essink et al. (2010) studied the effects of saline groundwater seepage in some low lying areas (including the Noordplas polder and its surroundings). De Louw et al., (2011) made a water balance model with salt concentrations for the same polder. The COASTAR project has done extended research on temporary freshwater storage in the subsurface since 2016. One of their interests is saline water extraction as a possible drinking water source and as a mitigation option for salinization.

Oude Essink (2001) expected that when groundwater seepage is extracted, the fall of hydraulic heads will prevent the saline seepage to enter the upper aquifer. Therefore, freshwater can percolate deeper into the subsoil and generates a larger freshwater volume. However, quantification and qualification of the effects of brackish groundwater extraction on water quality, seepage and infiltration fluxes, hydraulic heads and hydraulic soil failure of the confining layer is not yet done. Also, the socio-economic aspects needed to make the brackish groundwater extraction feasible are largely unknown.

1.4 Objective

This research will focus on saline groundwater extractions within the province of Zuid-Holland. The aim of this research is to analyze the required geo-hydrologic and socio-economic properties needed to extract saline groundwater as a drinking water source, but also as a mitigation measure for salinization. The effects on water quality in and around the deep polders will be estimated. Water quality is a rather extended subject, therefore, will this research be focussing on the chloride concentrations and will not deal with other nutrients like nitrate. The geo-hydrologic sub-questions of this research are:

1. Which geo-hydrologic conditions does an area need to have to facilitate saline groundwater extraction as an effective mitigation option for salinization?
2. How much groundwater can be extracted and what will be the effects of the extraction on surface and groundwater water quality (saline seepage), hydraulic heads and hydraulic soil failure risk of the area and its surroundings? Is it sustainable?
3. What are the effects of the water injections and which geo-hydrological conditions are necessary for it?

The socio-economic questions of this research are:

1. What can be done with the brackish groundwater once it is extracted?
2. Is it possible for drinking water companies, farmers or industry to use this brackish groundwater for drinking water and under what conditions (quantity and quality)?
3. Which stakeholders are influenced by the brackish groundwater extraction and to what extent?
4. Will it fit into the Dutch Delta Program? What are the boundaries set by Dutch and European law (Kader Richtlijn Water) on this subject?

The main research question in this research is:

Which geo-hydrological properties are required to increase freshwater availability by applying saline groundwater extraction as a socio-economic mitigation measure for salinization?

2. Methods

2.1. Study areas

In this study, five different study areas are explored. The research will start with the case study in the Noordplas polder but is extended to the: Zuidplaspolder, Meerpolder, Polder Groot-Mijdrecht, Middelburg-Tempel polder and the dune area of Zuid-Holland (figure 4). The polder areas are all deep polders with brackish water in the first aquifer. All these polders suffer from salinization and become mores saline in 2100. The dune areas are chosen due to their proximity close to drinking water production plants. The dunes, however, also have brackish / saline groundwater surrounding their fresh groundwater reserves.

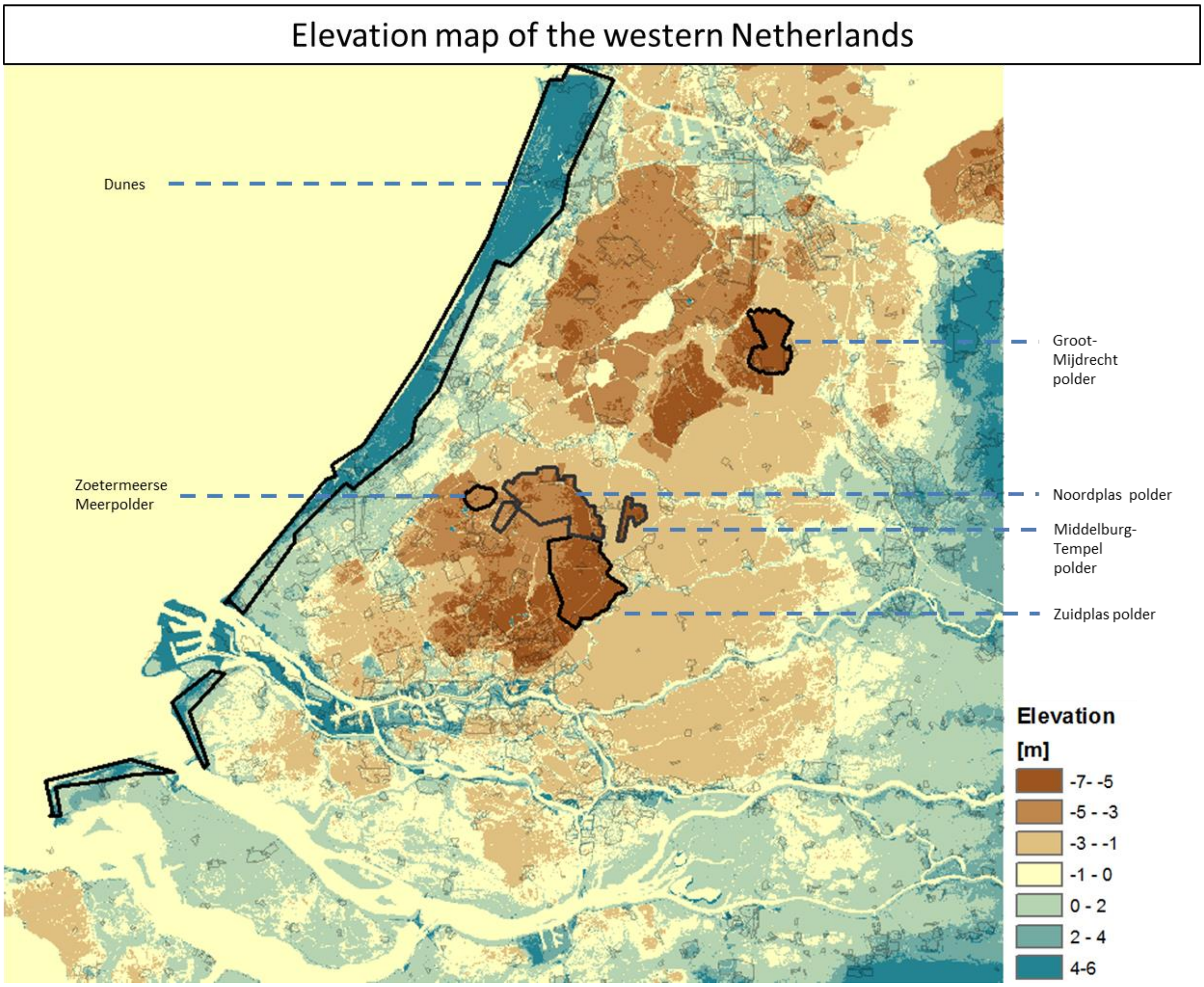

Figure 4: Elevation map of the western Netherlands based on NHI data, research areas marked.

2.1.1 *Noordplas polder*

The Noordplas polder is a deep polder between Alphen aan den Rijn and Zoetermeer. The average depth of the polder is -5 m mean sea level. The water level is about -6.1 m mean sea level. The polder was a former lake called Noordplas. The lake was reclaimed during 1750-1850 AD (Schutz, 1992). It covers an area of 37 km^2 of which 86% contains agricultural lands and 14% urban (De Louw et al, 2011). The south of the polder the nature project Bentwoud is realized by Rijkswaterstaat. The chloride concentrations in the surface water of the polder vary between 100 and 800 mgl^{-1} Cl^- (figure 5). On yearly basis 12 million kilograms of chloride are transported from the polder; this amounts to 7.9% of the total salt transport in Rijnland (De Louw et al., 2004).

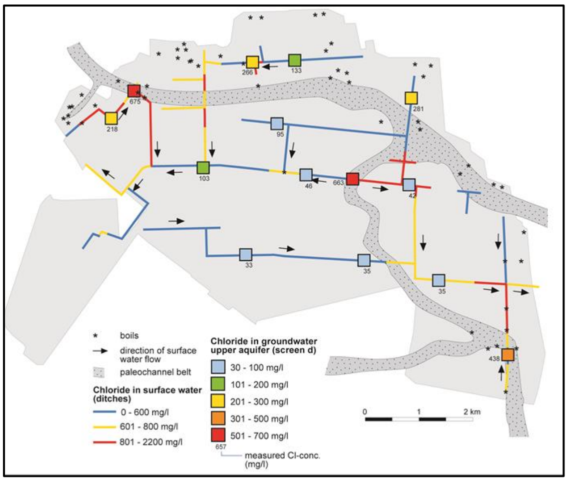

Figure 5: The Noordplas polder with both the paleo channel and the surface water concentration described (De Louw et al., 2014).

To lower the salt concentrations the water authority decided to heighten the surface water levels in 2007 despite the complaints of local farmers (Omroep West, 2007). The water level change did not stop the saline seepage, therefore, more research on saline seepage was done at the polder in 2010 (De Louw et al., 2010). In 2017 the drinking water company Dunea started the research for the potential of drinking water production here (Zwolsman, 2017).

2.1.2 *Middelburg-Tempel polder*

The Middelburg-Tempel polder is a low lying polder between Gouda and Boskoop. The Middelburg polder was reclaimed in 1861 (HHR, 1978a) and the Tempel polder was reclaimed in 1875 (HHR, 1978b). The combined polder has a depth between -3 and -5.6 NAP (AHN, 2018). The polder experiences land subsidence, a large salt load and it suffers from hydraulic soil failure (HHR, 2018). These disadvantages are expected to increase with future soil subsidence. The province of Zuid-Holland in cooperation with the water authority came up with the plan to flood the polder partly. However this plan turned out to have a negative hydrologic influence on the surroundings of the polder (TNO, 2006). Field research is done to come up with a water management plan for the future (HHR, 2018).

2.1.3 *Zuidplas polder*

The Zuidplas polder is a low lying polder between Gouda and Rotterdam. The polder was Lake Zuidplas until it was reclaimed between 1828 and 1839 (Knoester, 2010). The polder is the deepest polder of the Netherlands with an elevation of 6.76 m below NAP. The polder is part of the water authority: Hoogheemraadschap van Schieland en de Krimpenerwaard (HSK). The polder pumps water into the Hollandse IJssel and into the Gouwe before it enters the area of the water authority of Rijnland. Within the polder, the seepage flux and hydraulic soil failure cause problems in the south and eastern parts of the polder (Westera, Casimi & Kwadijk, 2006).

2.1.4 Zoetermeerse Meerpolder

The Zoetermeerse Meerpolder is the oldest reclaimed lake of the Netherlands, it was reclaimed in 1614 and has an area of 540 hectare. (Schultz, 1992). The polder is located between Leiden and Zoetermeer. The polder is mainly used as grassland.

2.1.5 Groot-Mijdrecht polder

The Groot-Mijdrecht polder is a south of Amsterdam in the province Utrecht (figure 4). The polder is reclaimed in 1877 (Schultz, 1992) and has an average depth of -6m NAP (Hoekwater, 1901). According to the Zuid-Holland model, no freshwater volume is present in the polder. In 2012 the province of South Holland, decided to flood the polder partly to stop the salinization and soil subsidence in the polder. The flooded part is changed into a nature area (Natuurmonumenten, n.d.).

2.1.6 Dune areas

The Dutch dunes are found on the west coast of the Netherlands (figure 4) and form a natural barrier against flooding from the sea. During the Subatlanticum (900 BC-present) sea transgression occurred and sand of old dunes was eroded and the current dunes were formed (Wilderom & Burger, 1984). The new dunes are higher than the old dunes. The dune area is characterized by both fresh water from precipitation and saline water from the North Sea. Freshwater is stored in the dunes for drinking water production by the drinking water companies of Dunea and Waternet.

2.2. Approach and models

Within this research three models were used to estimate the effect of the groundwater extractions.

2.2.1 Zuid-Holland Model (PZH-model)

The Zuid-Holland model is within this study used to calculate the geo-hydrologic effects of the groundwater extractions. The PZH-model takes into account variable-density groundwater flow model and coupled salt transport for the Dutch province of Zuid-Holland (Minnema et al., 2004). The variable-density groundwater flow module considers the REgional Geohydrologic Information System (REGIS) of TNO-NITG. The model is stationary for flow and transient for salt transport and is calibrated with hydraulic heads from the period 1993-2002. The model is built to calculate the effects on the different aquifers and does, therefore, not include a top layer (Minnema et al., 2004). Representers, functions which describe the relationship between spatial variation and model parameters (Valstar, 2001), are used to calibrate the model. With the use of these representers, the transmissivity of the aquifers and hydraulic resistance of aquitards are estimated (figure 6). The measured hydraulic heads are corrected for density differences to fresh water heads (Minnema et al., 2004). To calculate the groundwater flux water these fresh water heads (density equivalent water heads) are used. The mean squared error between the measured and modeled values is 0.17 m. The salt transport module is based on density differences caused by variation in the chloride concentrations.

The model is constructed with the MOCDENS3D code, which considers density variations within the flow calculations (Oude Essink, 1998). The model exists of 5,920,000 cells of 250 metres by 250 metres, located in 370 rows, 400 columns, and 40 layers. The upper 20 layers have a thickness of 5 metres, while the lower 20 layers have a thickness of 10 metres. The transport of salt is modeled with 8 particles per grid cell. The model predicts the flow based on different chloride concentrations (Minnema et al., 2004).

Within this research the extraction and injection wells are placed within the PZH-model. The model was run from 2000 until 2100 to give an estimation of the effects of the groundwater extractions and injections. To calculate the concentration and fluxes of the injection the following formulas are used. In which Qs are the fluxes of the extraction and injection [L^3/T], C is the concentration of the extraction and injection [M/V].

$$\% \, Recovery = \frac{\text{Permeate Flux}}{\text{Feed Flux}} * 100\ \% \qquad [1]$$

$$\sum_{1}^{n} Q(in) = \sum_{1}^{n} Q(out) * \% \, Recovery \qquad [2]$$

$$C\ (in) = \sum_{1}^{n} C(out) * \frac{1}{n} \qquad [3]$$

The efficiency of RO-systems is expressed in recovery. The ratio between the extracted groundwater and the final product (demi-water) is between 50% and 85% (Puretec Industrial Water, 2018). Within the COASTAR project, a recovery of 50% is assumed. The concentration of the extraction is influenced by the concentration of the injection, therefore, iteration is necessary. To improve the results during this research one iteration step is done.

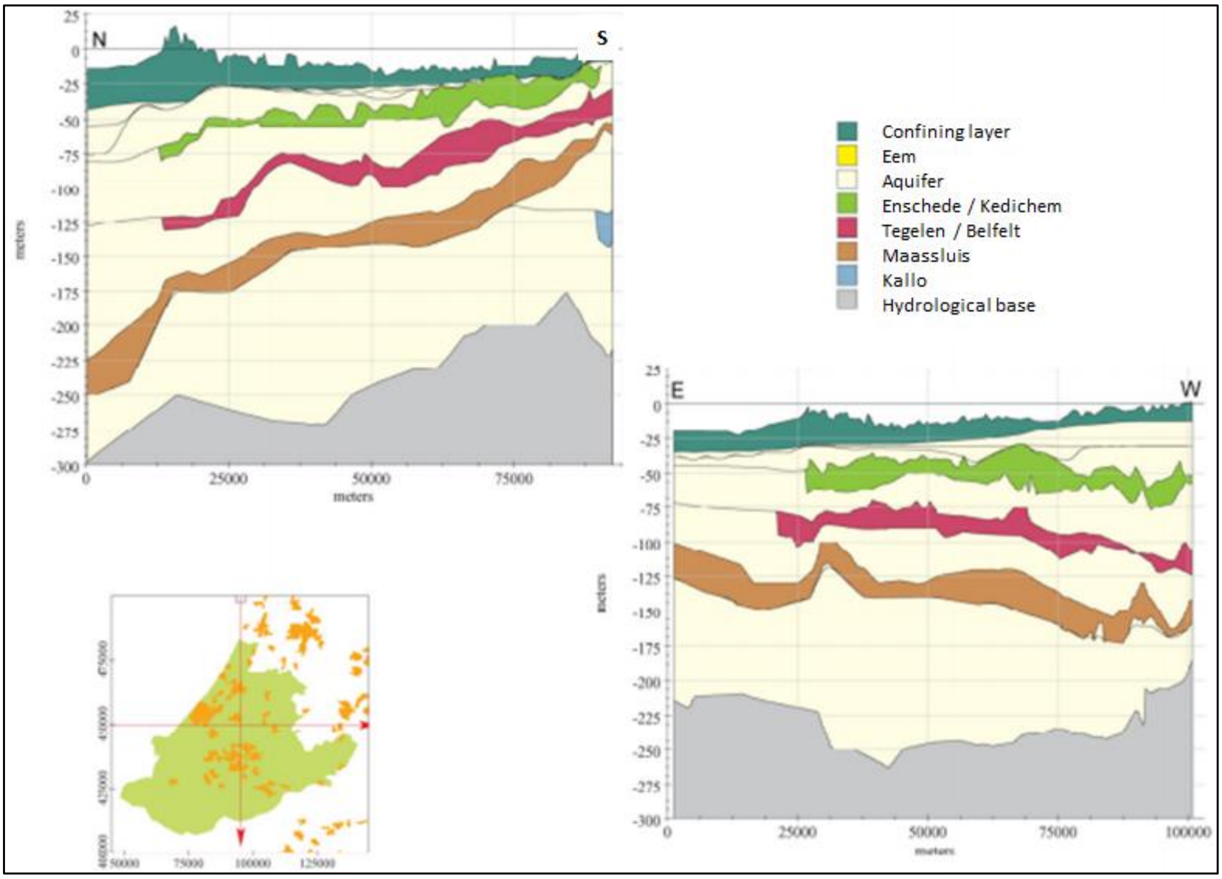

Figure 6: The geohydrology as within the Zuid-Holland model (REGIS) (Minnema et al., 2004).

2.2.2 WAOR model

The Water Allocation and Optimisation Rijnland (WAOR) model is used to estimate agricultural damages per scenario within the water authority of Rijnland. The WAOR is an updated version of the €ureyeopener (EEO) model (Stuyt et al., 2013). It is an Excel-based model for the area of Rijnland. The model generates a water balance for a selected number of sub-regions of the area. The updated instrument uses Landelijk Hydrologisch model (LHM) data of the growing season for different years, which includes meteorological data (Verkaik et al., 2010). The WAOR model can be used to indicate the effect of certain actions on the water system of water authority of Rijnland.

The improvement of the WAOR compared to the EEO is the implementation of climate models and water reduction options (Erkelens, 2016). It is possible to run the model with the old and new KWA which changes the flux direction between the polders. Within this research, the model will be used with the old KWA (mixed water inlet), which means that water from both Bodegraven and Gouda can be used. The old KWA will be used if the chloride concentration of the Hollandse IJssel becomes too high. The WAOR was run with no climate scenarios and water reduction methods. Also the pumping costs at the water inlet of Gouda were not taken into account in this research. In figure 7 the set-up of the WAOR model is shown when the water inlet of Gouda is used. The WAOR needs as input variables the boil and drainage concentrations and the boil, drainage and infiltration fluxes. Boils are small vents with high discharge rates and therefore cause a strong up-coning of deeper and more saline groundwater (De Louw et al., 2011).

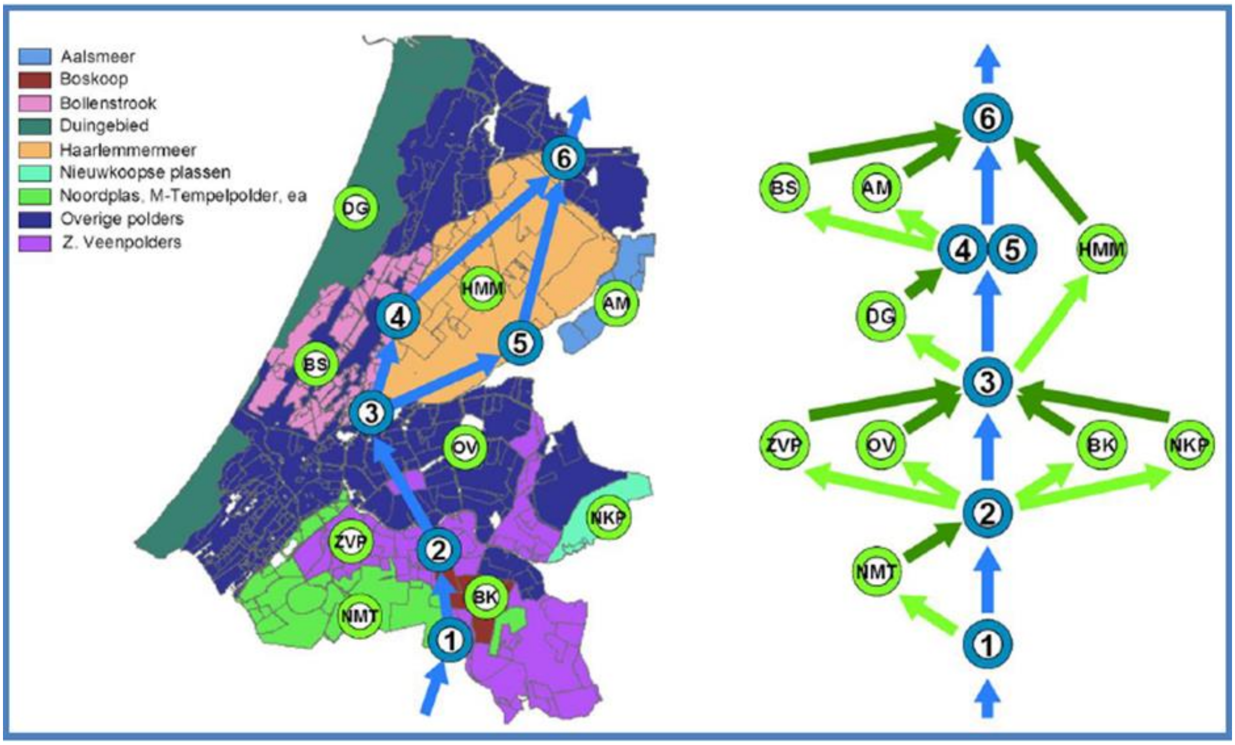

Figure 7: The boezem of the water authority of Rijnland with the deep Noordplas, Tempel and Haarlemmermeer polders and the low salt-tolerance areas of Aalsmeer, Boskoop and the Bollenstrook (Stuyt et al., 2012) The water balance is based on the situation with only water intake from Gouda.

The drainage seepage flux consists both of diffuse seepage and seepage through paleo channels. This flux is together with the infiltration flux calculated by the PZH-model.
The average concentration of layer 1 (-2.5 until -7.5 m NAP) is calculated for the drainage flux, while the average concentration of model layer 8 (-37.5 until -42.5 m NAP) is calculated for the boil flux. These values were taken since they give similar values for the Noordplas polder as De Louw, et al., (2011).

The boil flux is not implemented in the model. To estimate the boil flux the approach of Erkens et al., 2018 was used starting with a derivative of Darcy’s law (Hendriks, 2010):

$$Qseep = Kv * \frac{A}{d} * (hp - \varphi z) \qquad [4]$$

In which Kv is the vertical hydraulic conductivity of the confining layer [L/T], A is the area of the polder [L^2], d is the thickness of the confining layer [L] while hp is the phreatic water level of the polder [L] and φz is the hydraulic head of the aquifer below the confining layer [L]. Kv, d and A are properties of the area, which remain constant in this approach. Formula 4 can, therefore, be rewritten. So the seepage flux is directly proportional to the change in head difference:

$$\frac{Qseep(t)}{Qseep\ (t+1)} = \frac{hp - \varphi z(t)}{hp - \varphi z(t+1)} \qquad [5]$$

This formula can be used to estimate the seepage flux of a boil. The hydraulic heads are calculated by the PZH-model and differ per scenario. The phreatic water level is kept constant by the water authorities and is estimated with the lowest water level map (figure 8). Data of the reference boil flux is only available for the Noordplas polder (De Louw, et al., 2011) and the polder Groot-Mijdrecht (Zaadnoordijk, et al., 2009). Therefore, the reference seepage flux per boil in the Noordplas is used is considered representative for the boil fluxes in the other deep polder areas. The boil flux per boil is multiplied by the area with a risk of hydraulic soil failure (A) to obtain the total seepage flux for the polder ($Qboilpolder$) using formula 6:

$$Qboilpolder = Qboil * A\ [I \leq 1.1] \qquad [6]$$

Where I is the hydraulic soil failure risk [-] .Hydraulic soil failure is defined as ‘loss of grain contact in the ground as a consequence of water overpressure; in the case of a cohesive covering soil layer, this leads to uplifting and cracking; in the case of a non-cohesive soil layer to heave’ (RWS, 1999). The concept is further explained in section 2.3.

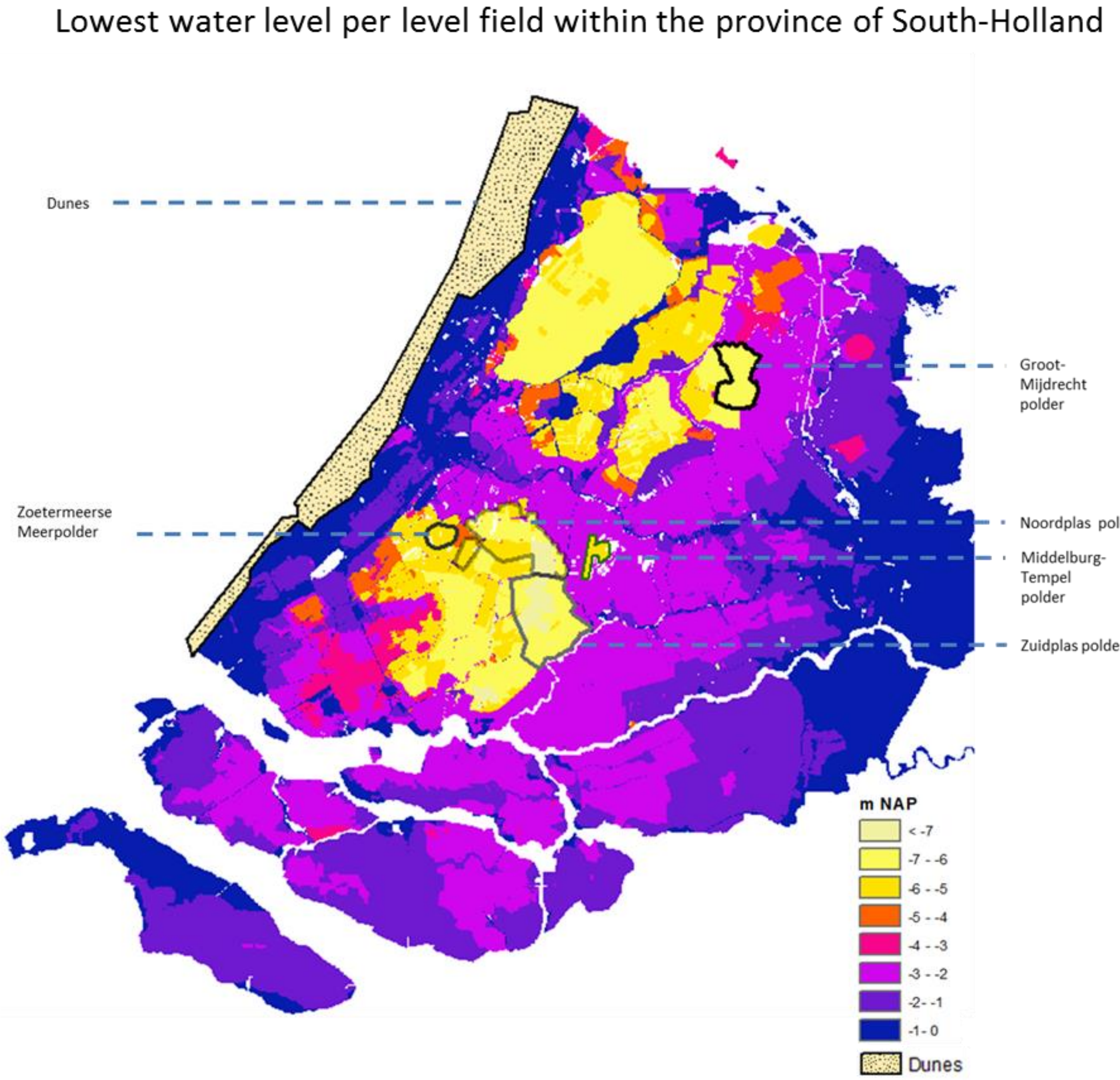

Figure 8: The lowest maintained water level (hp) map of the province of Zuid-Holland, with the research areas marked. The map is generated with data from the water authorities of Rijnland, De Stichtse Rijnlanden, Amstel, Gooi en Vecht, Schieland & Krimpenerwaard, Hollandse Delta, and Delfland.

2.2.3. Landelijk Hydrologisch Model (LHM)

The LHM is used in this research to calculate the phreatic water level decline. The LHM is developed by the research institutes Deltares and Alterra with the cooperation of Rijkswaterstaat and the water boards (De Lange et al., 2014). It consists of five different models: the distribution network, the regional sub-catchments, the local surface waters, the unsaturated zone and the groundwater system (figure 9). The LHM is used for national model-based solutions to surface water and groundwater issues and therefore, it is a good way to characterize polders in the Netherlands (De Lange et al., 2014).

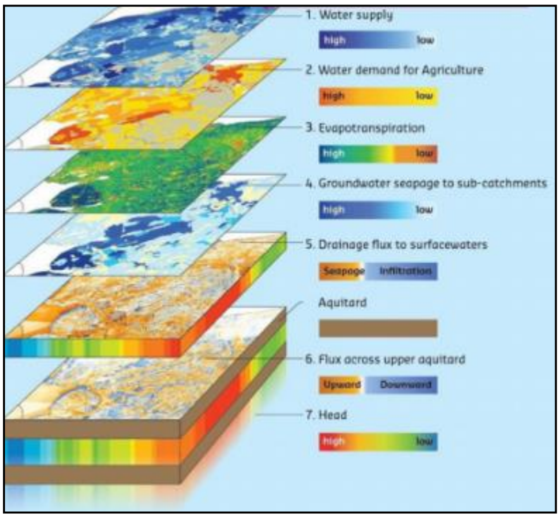

Figure 9. A visualisation of the LHM model (De Lange et al., 2014).

The groundwater model uses a grid of 250*250 metre cells and is based on REGIS. An advantage compared to the PZH-model is that within the water calculations boils are taken into account and phreatic water levels are calculated. However a significant disadvantage compared to the PZH-model is that the model does not correct for density differences between fresh and salt water (Erkens et al., 2018). Within this study, the model runs one time with the maximum extractions per polder for a period of 10 years (1996-2006). It is used to estimate the maximum phreatic groundwater level decline.

2.2.4 Stakeholder analysis

Within this research a literature study is done to analyse the interests, concerns and responsibilities for every involved stakeholder. The goal of this analysis is to optimize the scenarios so the positive effects for the stakeholders are optimized and the negative effects are diminished.

2.3 Theory

The groundwater extractions are expected to lower the seepage flux and let water percolate deeper into the subsoil, reducing the salinization process. Salinization is measured in salt load. The formula of Oude Essink & Van Baaren (2009) is used:

$$Sl = C(aqf) * Qseep \qquad [7]$$

The salt load Sl [M/L^2/T] of a polder is calculated by multiplying the seepage flux through the confining layer $Qseep$ [V/T] with the concentration below the confining layer $C(aqf)$ [M/V]. To indicate the effect of the fresh water availability the volumes of fresh water (<150 mgl^{-1} Cl), brackish water (between 150 and 1000 mgl^{-1} Cl) and saline water (> 1000 mgl^{-1} Cl) are calculated.

To estimate if the extracted water is influenced by the injected water, the travel time between the extraction and injection wells is calculated using this formula:

$$Ttravel = \frac{d(r)}{v(z)} \qquad [9]$$

In which $Ttravel$ is the travel time [T], $d(r)$ is the thickness of the resistance layer [L] and v_z is the effective velocity in the z-direction [L/T].

The hydraulic heads are expected to fall, and, therefore, both the seepage flux as the hydraulic soil failure risk is expected to decline. Hydraulic soil failure is the working mechanism for the creation of boils. For calculating hydraulic soil failure risk index the approach of Erkens et al., (2018) was used. Boils occur when the hydraulic heads are higher than the phreatic water level and if the pressure heads in the first aquifer are larger than the gravity pressure of the confining layer.

The formula used for hydraulic soil failure is (Oldhoff, 2013):

$$\frac{\gamma(conf) - \gamma(gw)}{\gamma(gw) * (\varphi z - hp)} d = I \qquad [10]$$

In which $\gamma(conf)$ and $\gamma(gw)$ are the wet volumetric weight of the confining layer and the groundwater [L^3/M]. The index number I has according to the NEN6740 a critical value of 1.1. A lower index number creates a risk of hydraulic soil failure (Kremer et al., 2001). The depth of the confining layer is defined by locations wherever the top layer has a resistance [c] of 500 days or more. The approach only uses soil pressure and water pressure, so no soil cohesion is taken into account. Therefore, no distinguish between the difference between heave, uplifting and cracking is made (Erkens et al., 2018).

3. *Results.*

3.1 Autonomous salinization.

Within in this subchapter the autonomous salinization process is explained, within this research the autonomous salinization process is referred to as 000. In Appendix I all figures are available in larger format as well a time series of the autonomous salinization in steps of 25 years. In figure 10 the seepage fluxes are shown for the investigated area. The investigated deep polders are surrounded by higher polders. Within these higher areas infiltration occurs, while in the deep polders seepage occurs. The water authority keeps the phreatic water levels constant within polders, so the seepage and infiltration fluxes are not changed in reference situation between 2000 and 2100.

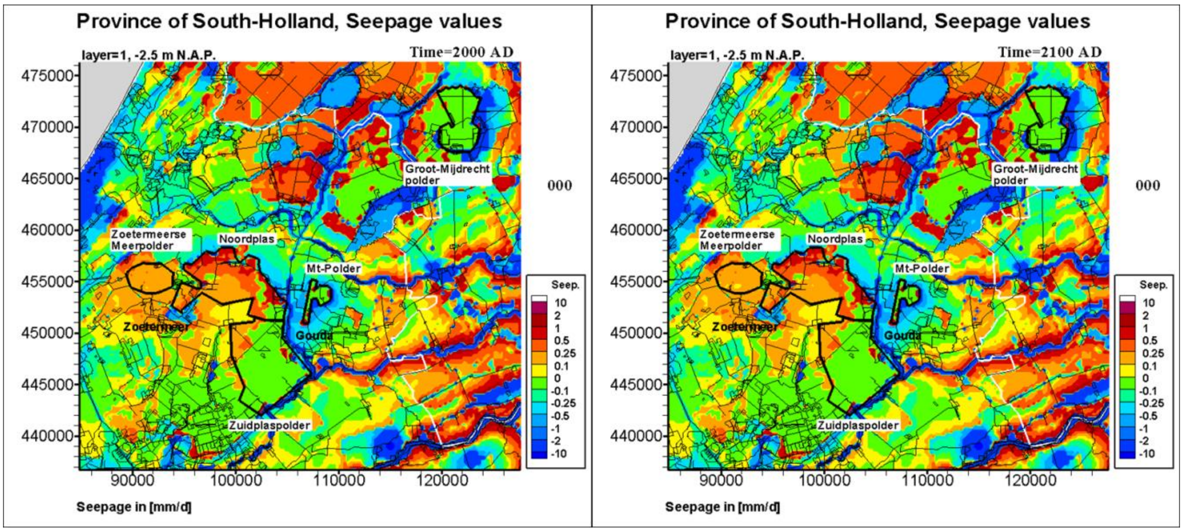

Figure 10: The seepage values of the research area stay constant between 2000 and 2100.

The infiltration flux brings fresh water into the subsoil. Therefore, a low chloride concentration is visible in infiltration areas and seepage areas close to infiltration areas. Seepage areas further from the infiltration areas bring saline water from a deeper aquifer to the surface. The autonomous salinization process between 2000 and 2100 shows an increase in chloride concentration in the deep polders, while the freshwater is concentrated in or close to infiltration areas (figure 11).

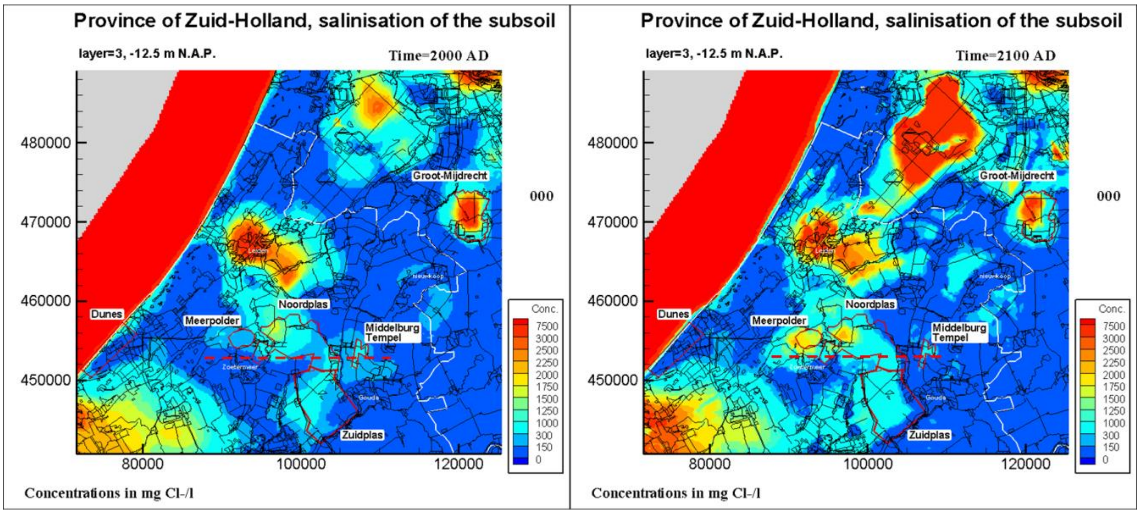

Figure 11: The concentrations of the research area increase between 2000 and 2100.

In **figure 12** a cross-section of the brackish areas of Noordplas and MT-polder is shown. The cross-section is set a south of the Zoetermeerse Meerpolder. Every polder is distinguishable by up-coning of saline and brackish water. While the up-coning in the Noordplas and MT-polder is not visible at -12.5 m NAP (figure 11), it still visible between the -80 and -40 metres below NAP.

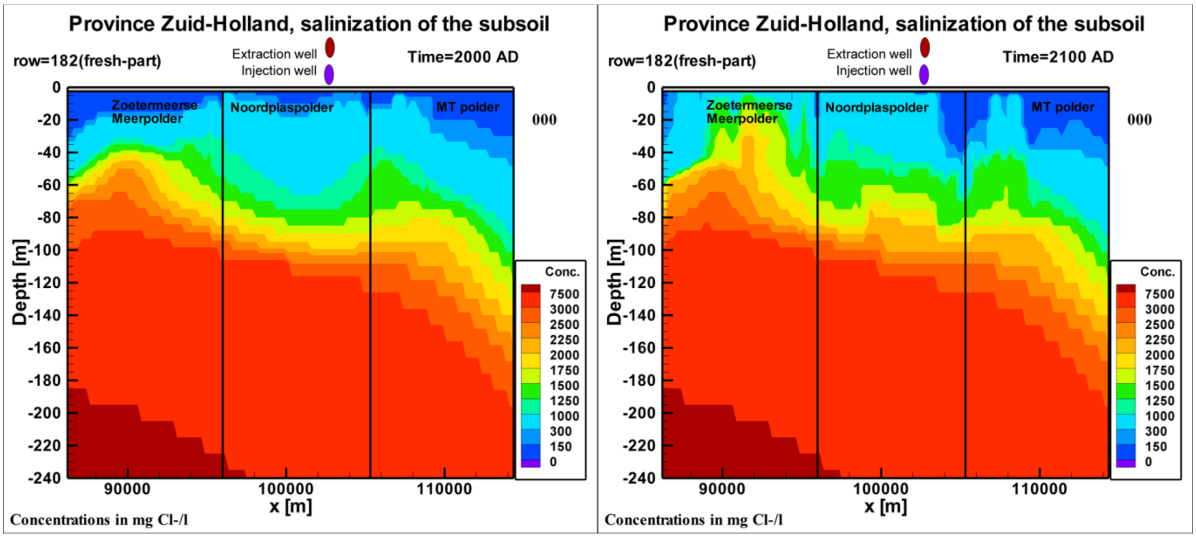

Figure 12: Cross-sections of the dotted line (**figure 11**). Up-coning of saline and brackish water is visible in the deep polders.

The salt load at -2.5 m NAP is shown in figure 13. The highest salt loads can be found in the eastern parts of the Noordplas. In 2100 the salt load has increased in the eastern part of the Noordplas polder and the salt load increased in the Zoetermeerse Meerpolder is clearly visible. The seepage brings more saline water to the surface in these areas. The MT and the Groot Mijdrecht polder do not show much increase in salt load.

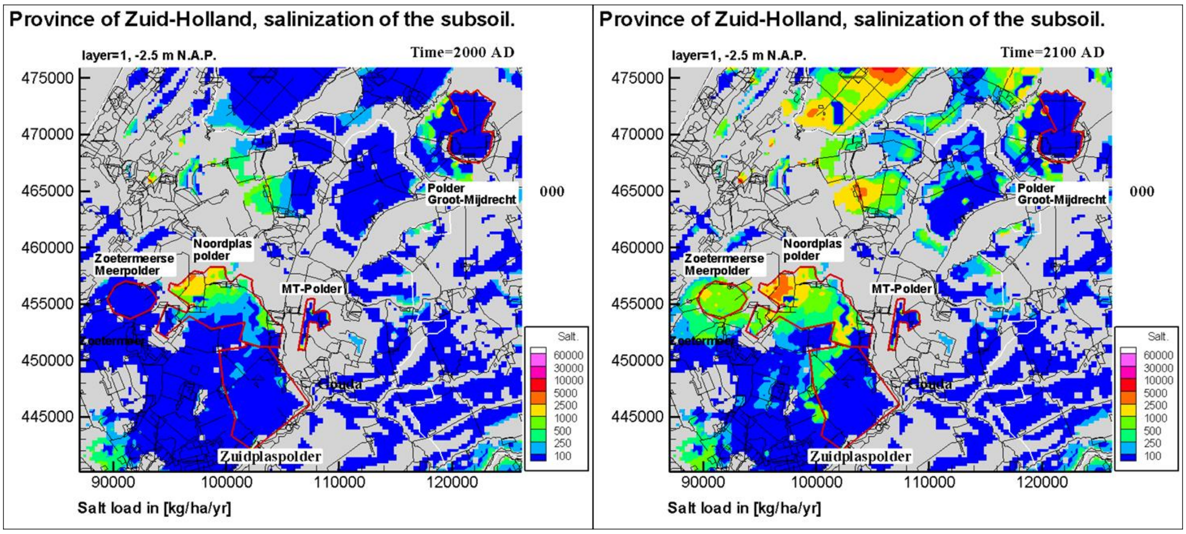

Figure 13: The Autonomous salinization process, the salt load increases between 2000 and 2100.

3.2 Wells

Within this subsection the location of the wells is explored. This research started with a reference case of 8 million m^3y^{-1} water extraction in the Noordplas polder to investigate the ideal depth of the extraction wells. Afterwards injections wells are also implemented with an injection of 4 m^3y^{-1} water to find the best spatial locations of the wells. After which the ideal extraction rate is investigated.

3.2.1 Depth of the wells.

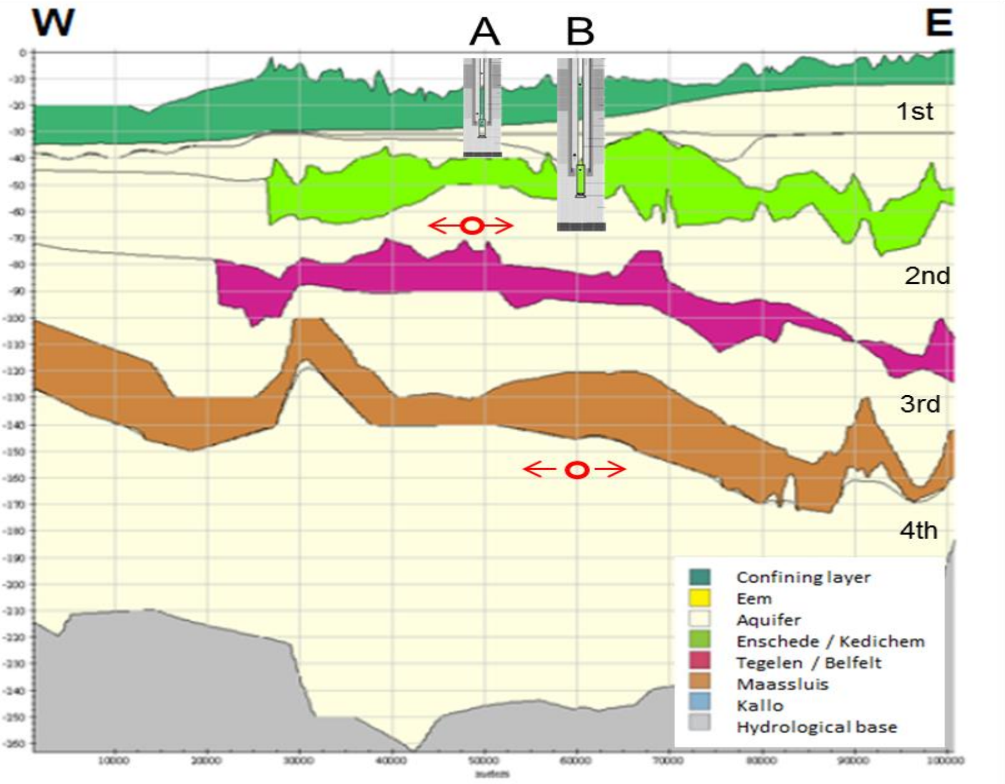

Figure 14: Option A extracts in the first aquifer, while option B extracts from the second aquifer. The injection wells are placed in the second aquifer (scenario A) and the fourth aquifer (scenario B) (Minnema et al., 2004).

To estimate the depth of the extraction wells two options were considered (figure 14). In option A water is extracted from the upper aquifer, while in option B groundwater is extracted from the second aquifer. The extraction wells are repositioned for clay layers since water can only be extracted from aquifers. The saline water volumes for both options A, B and the reference situation are shown in figure 15.

Extractions in the upper aquifer (option A) show an increase or small decline of the saline water volume, while extractions in the second aquifer show a larger decline of saline water volumes. The formation of Kedichem/ Enschede which divides the first with the second aquifer consists of both clay and sand layers. Extractions above this formation cause, therefore, saline groundwater seepage to bypass the aquitard through the sand layers. To prevent this bypassing the wells need to be placed only in the saline seepage areas. Wells further away from this area cause vertical flow in the upper aquifer from the saline seepage areas to the extraction wells, increasing the saline water volumes.

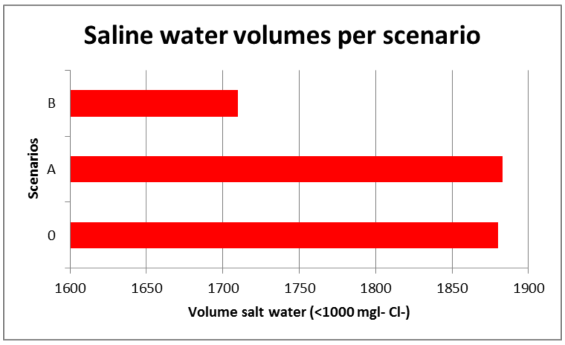

Figure 15: The salt water volume in 2100 for the reference situation, scenario A and B for the Noordplas polder. No water is injected in this setting

Option B is closer to the brackish-saline water interface, up-coning of saline water causes, therefore, a smaller increase in saline water volumes. To prevent saline seepage water from entering the upper aquifer still a high well density is necessary. This research focusses therefore on option B If vertical flow occurs from the saline seepage areas to the extraction wells in the second aquifer; less saline water enters the upper aquifer and the saline water volumes declines.

The depth of the extraction wells was investigated for every area and they were all placed in the second aquifer (47 and 92 metre below NAP) between the formation of Enschede/Kedichem and Tegelen/Belfeld. The injection wells are located at a depth in which the chloride concentration was lower than the injected concentration (figure 14). They were located in the fourth aquifer between 145 and 235 metre below NAP. In Appendix II a table with the extraction and injections depths can be found.

3.2.2 Spatial distribution of the wells.

In this subchapter the location of the wells is investigated. Wells were placed both in the eastern part as in the western part of the polder (figure 16), this was done to see the effects of the location of the wells and because the drinking water company Dunea was interested in the effects of extractions with a lower chloride concentration. The east scenario replaced the brackish water with fresh water, while the west scenarios replace the saline water in the first aquifer with brackish water (table 17). The scenarios show similar decline in drainage seepage, while the volume saline water and the drainage salt load declines the most in the west scenario.

The extracted concentration of the eastern scenario is 500 mgl^{-1} Cl lower than the western scenario. The costs of drinking water production with RO increase with a higher chloride concentration (Al-Karaghouli & Kazmerski, 2012).

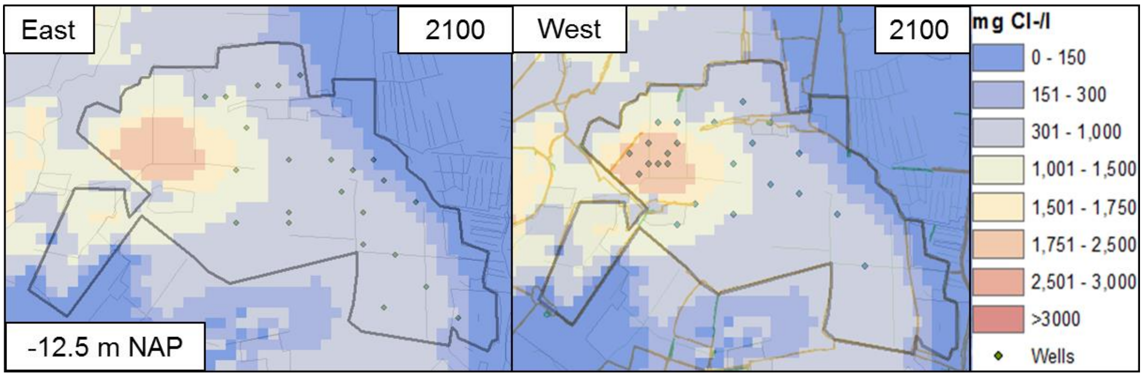

Figure 16: The wells located in the saline west of the polder and the brackish east of the polder. Concentrations of the first aquifer are shown as it would be in the year 2100 without extractions.

Scenarios 2050	Drainage seepage	Fresh water	Brackish water	Salt water	Drainage salt load	Extracted Concentration
	m^3/day	Millon m^3	Million m^3	Millon m^3	tonyr-1 Cl-	mgl-1 Cl-
0	-16500	20	425	1840	-4500	-
east	-11300	30	435	1820	-2800	1900
west	-11500	25	455	1805	-2100	2600

Table 17: The data of reference, eastern scenario and scenario 001 compared for the year 2050.

Investigating the scenarios a decision should be made:

- *East scenario: Extracted water with a low concentration and therefore lower drinking water production costs.*
- *West scenario: Extracted water with a higher salt concentration, which lower the salt load the most.*

The east scenario is most favourable for the drinking water company, since purifying water with RO is already more expensive compared to conventional purify methods (Stofberg et al., 2018). The west scenario is favourable for the water authority. A lower salt load lowers the need of flushing. Within this research the western scenario is chosen, the location of the wells is optimized, so the salt load decline is maximized. However, the extracted concentration of 6000 mgl^{-1} Cl^{-} is used as boundary criteria. In figure 18 the locations of the wells in all scenarios are shown to optimize the decline in salt load.

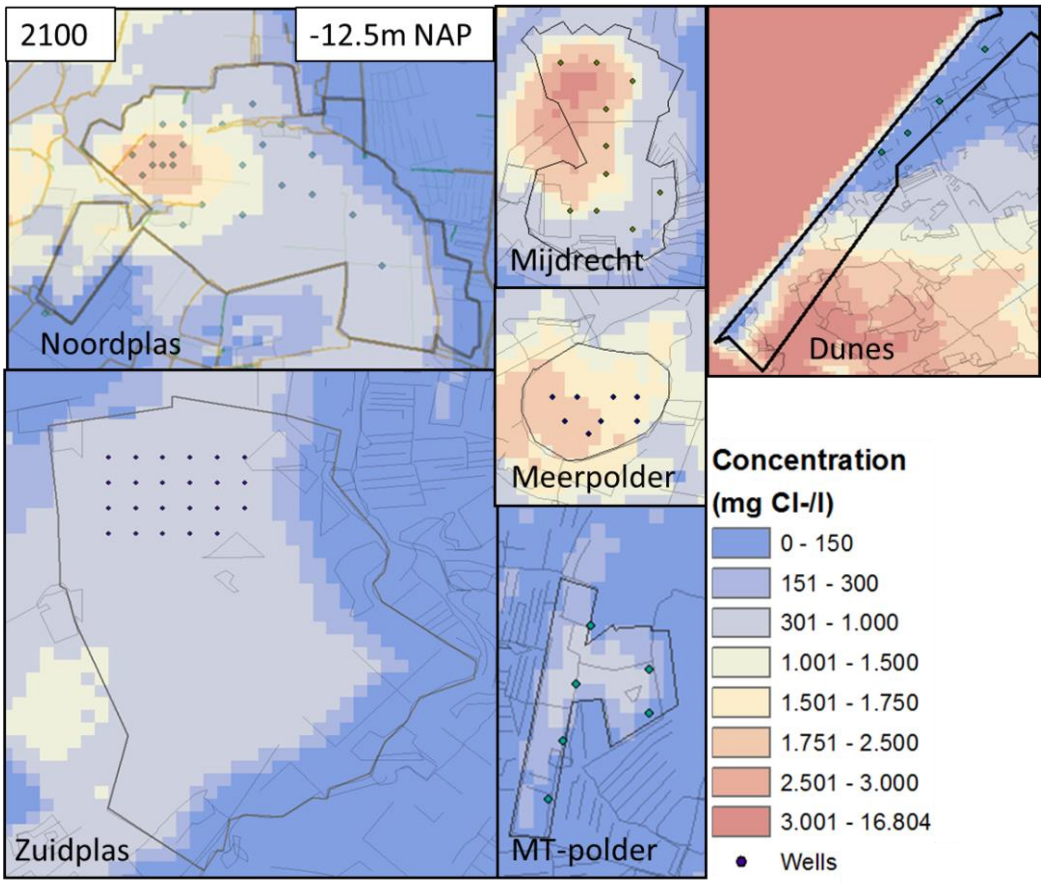

Figure 18: The location of the wells. The concentration of the upper aquifer for a model simulation of the year 2100 is plotted.

3.2.3 The extraction and injection rates of the wells.

To investigate how much water can be extracted; different extraction and injection rates were tested within different areas. In the Noordplas polder 8 million m^3y^{-1} is extracted, since this was the number in which COASTAR calculated the costs. In the other polders the extraction rates are chosen to optimize the salt load decline. Injections wells are placed if there was an aquitard below the extraction wells. In the scenarios of the Groot-Mijdrecht polder no continuous aquitard was below the extraction wells. Within the dune area no injection wells were placed since the brine can be taken to sea. In the other areas, scenarios with and without injections are tested to see the influence of the injections. Within table 19 the investigated scenarios are shown. To find out how much can be extracted; the effects of the extractions are investigated. All the effects will be explained for the Noordplas polder, while the effects specific to the other researched areas will be explained in their subsections. Figures for these areas can be found in Appendix III-VII.

Areas /scenarios	Q(out) Extracted water *(million m3/y)*	Q(in) Injected water *(million m3/y)*	C(out) Extracted *(mgl-1 Cl-)*	C(in) Injected *(mgl-1 Cl-)*
Initial sitation				
000	0	0	0	0
Noordplas				
001	8	4	2600	6000
002	8	0	2100	-
003	16	8	3000	6000
MT-polder				
101	5	2.5	1600	3000
102	5	0	1200	-
Zuidplas				
201	8	4	1800	3400
202	8	0	1200	-
Zoetermeerse Meerpolder				
301	3.5	1.75	3600	7400
302	3.5	0	2800	-
Groot-Mijdrecht				
401*	6.6	0	2600	-
402*	6.6	0	3100	-
Dunes				
501	1.5	0	1900	-
**scenarios differ in depth 401 (-62.5- -92.5m NAP) & 402 (-92.5 - -125m NAP)*				

Table 19: The investigated scenarios per polder, with different extraction and injection rates.

3.3. Noordplas polder

3.3.1. Water quality

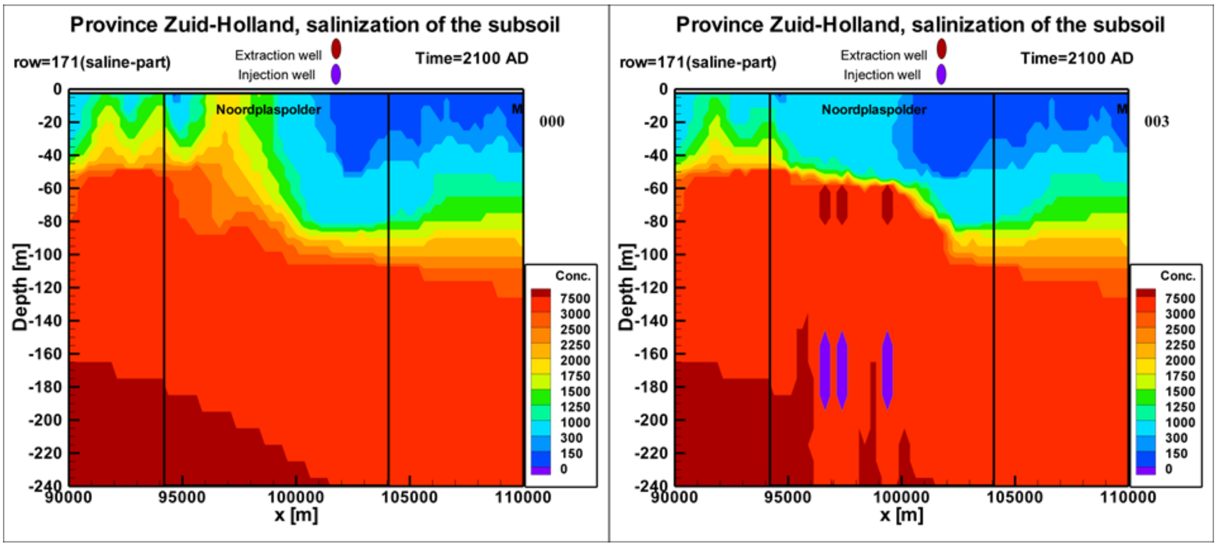

Figure 20: West-east cross-sections of the Noordplas polder. On the left, the autonomous salinization process is visualized while in the right scenario 003 is visualized. Fresh water is dark blue, brackish water light-blue and salt water consists of the other colours. Cross-sections are marked in figure 24.

Groundwater extractions lower the salt concentration of the upper aquifer. The brackish or saline water above the extraction wells is extracted and fresh surface water can percolate deeper into the soil. Groundwater extractions also cause up-coning of deep saline water (>7500 m mgl^{-1} Cl^{-}) visible in figure 20 between -140 and -240 metres below NAP. Both the fresh-brackish water interface and the brackish-saline groundwater interface move down deeper in the system. Therefore, the fresh and brackish groundwater volumes increase and the saline water volumes decline. Scenario 003 lowers the fresh-brackish groundwater interface the most and generates, therefore, the largest increase in freshwater volume (figure 21).

By both lowering the freshwater interface and moving up the salt water interface, the extraction wells tend to move to an equilibrium in which both the fresh and saline water are on the same depth as the extraction well.

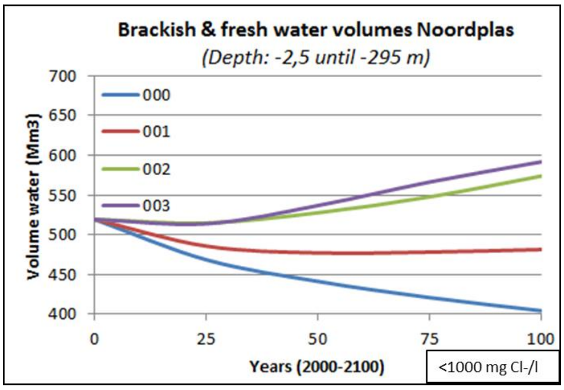

Figure 21: The development of the water volumes with a concentration below 1000 mgl^{-1} Cl^{-} for the years 2000 until 2100.

The creation of this equilibrium, however, causes the salt concentration of the extracted water to increase. The extracted concentration is calculated with observation wells (figure 22). All scenarios seem to stabilize after 175 years, however, scenarios 001 and 003 with both injection and extraction wells extract more saline water than the scenario 002 with only extraction wells.

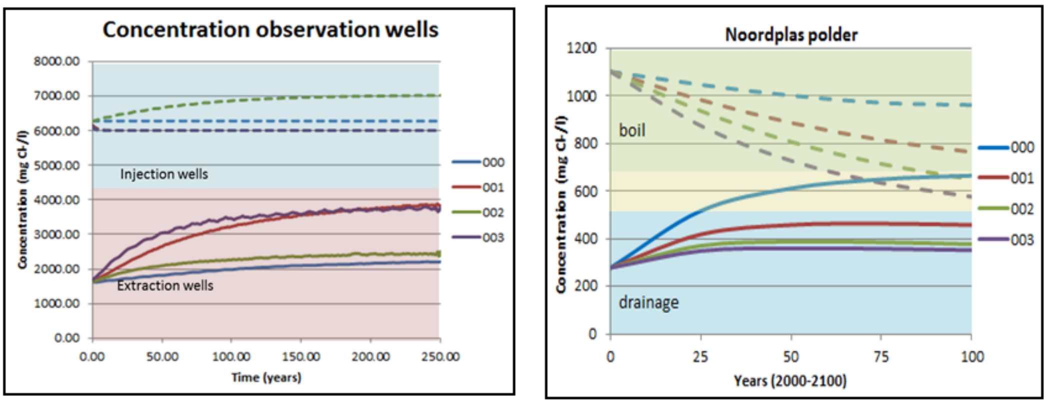

Figure 22: The concentrations of the observation wells, the boil and drainage seepage. The observation wells are located at the locations of the injection and extraction wells, this is also done for scenario 000 and 002 for comparison. The extracted concentration increases while the concentration of the boil and drainage seepage decreases.

The injection wells lower the salt concentration at the injection depth to the salt concentration of the injected brine (6000 mgl^{-1} Cl^{-}). The salt concentration of scenario 002 (with no injections) increases at the depth of the injection well. This indicates that the extractions are noticeable to a depth of -150 metres NAP.

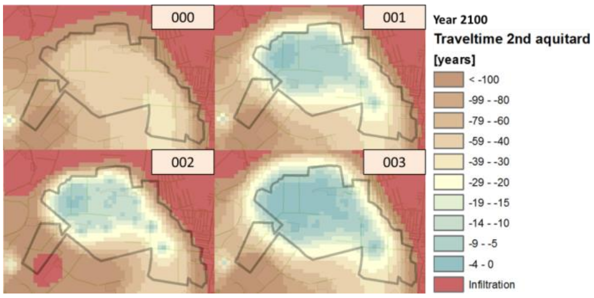

Figure 23: The travel time of the seepage flux through the formation of Tegelen/Belfeld (-82.5m and -97.5m NAP).

The travel time through the aquitard gives an estimation of the time it takes for the seepage flux to flow through the aquitard (figure 23). In the reference situation, the travel time is between the 40 and 80 years. The travel time decreases to 15 years (without injections) or even 5 years (with injections). This indicates that traces of the injected brine can be found back in the extracted water within a time range of 5 to 15 years depending on the scenario. This explains the increase of the salt concentration within the extracted water of figure 22.

The source area of the boils (-40 metres NAP) receives more freshwater, therefore the concentration of the boil fluxes lowers. The drainage concentrations still increases due to the autonomous salinization process, however this increase is much lower in the scenarios with groundwater extractions. The concentration difference between the boil and the drainage concentration becomes smaller if water is extracted (figure 22).

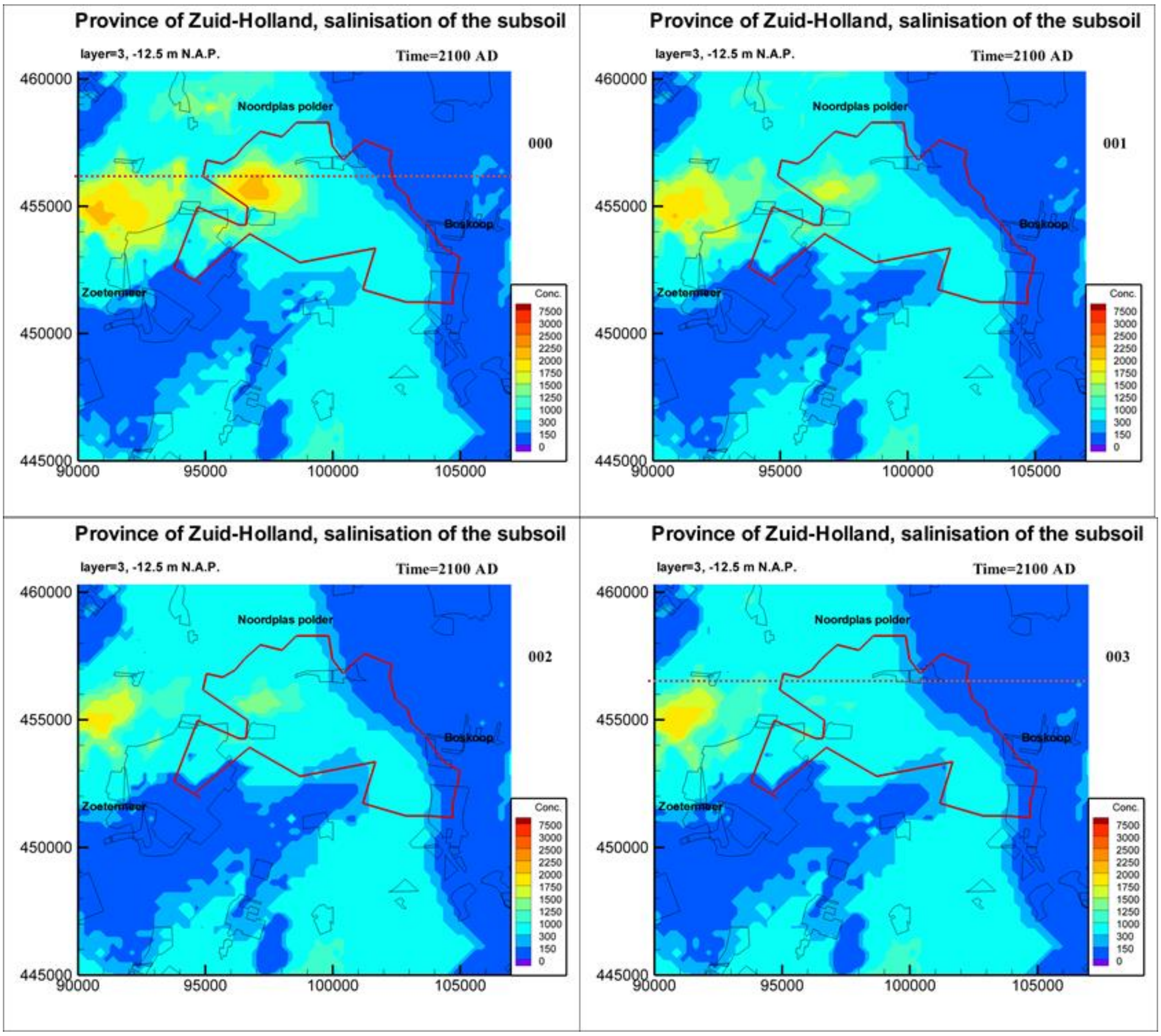

Figure 24: The salt concentrations below the confining layer (-12.5 m) visualized per scenario in 2100, noticeable is that the groundwater extraction influences also areas outside the Noordplas polder. The dotted line indicates the cross-sections of **figure 16**.

In **figure 24** the spatial distribution of the salt concentration of the upper aquifer is visualized. For all scenarios, the area in which the chloride concentration is above the 1500 mgl^{-1} Cl^{-} is lowered as is the concentration of the most saline area compared to scenario 000. The largest influence is visible in the western area of the Noordplas polder also the brackish eastern part of the polder shows a lowering salt concentration. The saline areas in the west change into brackish areas while the brackish areas in the eastern part change into fresh areas.. If more water is extracted the chloride concentration lowers more, therefore, scenario 003 shows the largest decline in chloride concentration

3.3.2 Seepage and infiltration fluxes

Groundwater extractions reduce the seepage flux and cause freshwater to infiltrate into the subsurface, therefore the infiltration flux increases (figure 25). Within this research fluxes out of the subsoil are considered negative and fluxes into the subsoil are considered positive. Both the seepages decreases and the infiltration fluxes increase, the polder continues however to be a net seepage area. In figure 26 the spatial distribution of the diffuse and paleo channel seepage and infiltration fluxes is visualized. It is visible that most of the increased infiltration occurs outside the Noordplas polder. Especially the higher areas in the north and east of the polder show an increase in infiltration, while in the polder itself only some decrease in seepage is visible. Figure 25 gives a good indication of the division of fluxes within the Noordplas polder, it does not take the increased infiltration outside the polder into account.

More extraction generates more infiltration. In scenario 003 even infiltration occurs within the polder. Scenario 001 and 002 have the same extraction rate but scenario 002 shows lower seepage values. Brine injections cause therefore higher seepage values. However the extraction rate has a larger influence since scenario 003 and 002 have the same net extraction (extraction –injection) rate, but scenario 003 indicates a stronger decline in seepage values.

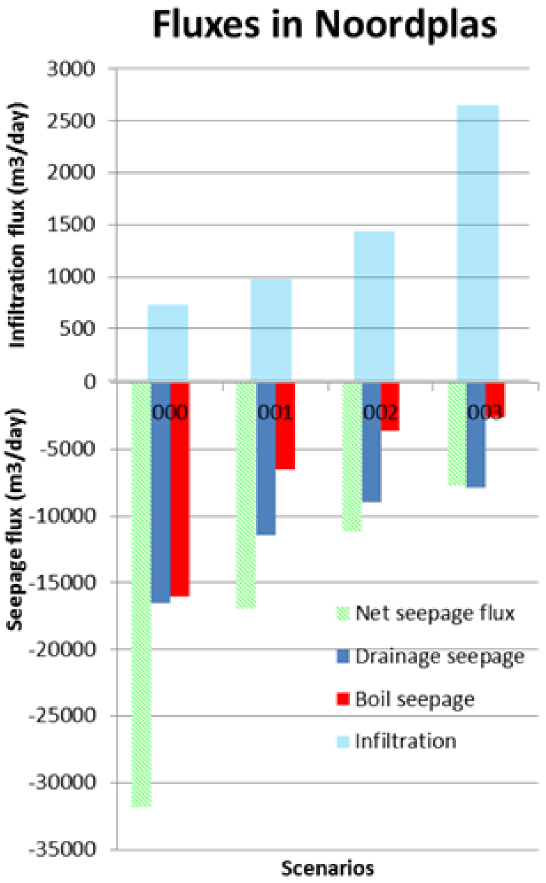

Figure 25: The drainage seepage, boil seepage and infiltration fluxes of the Noordplas area in 2100. The net flux is the sum of the boil and diffuse seepage and is corrected for the infiltration flux.

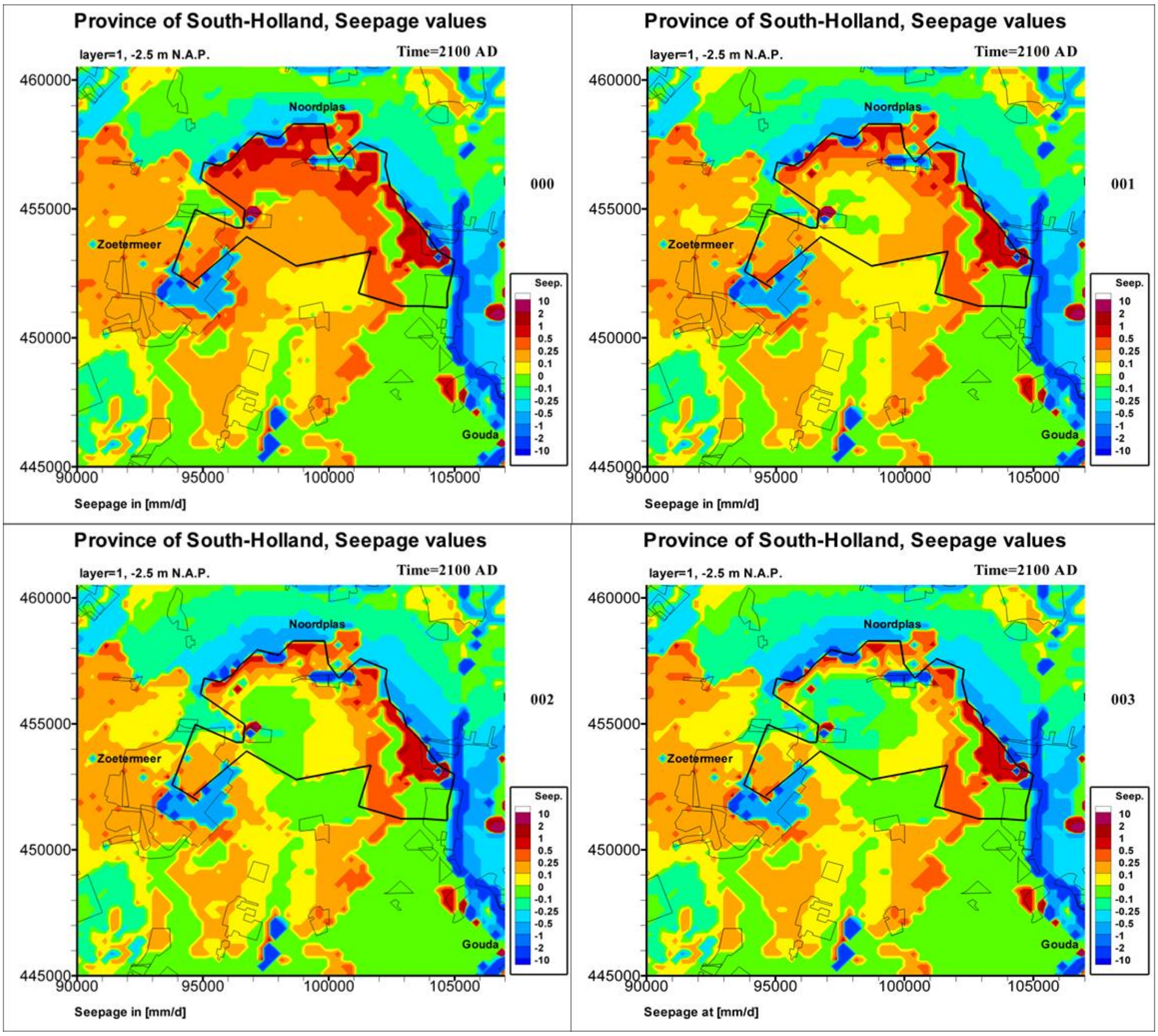

Figure 26: The spatial allocation of the seepage and infiltration fluxes through the Holocene confining layer in the Noordplas polder per scenario in 2100.

3.3.3 Salt load.

When the seepage fluxes and the concentrations change the salt load also changed (figure 27). In the original situation, the salt load was 10000 tons chloride per year in the year 2000. Due to the direct change in seepage, the salt load directly decreases 50% to 20% of the reference situation. In figure 28 the spatial distribution of the salt load is visualized. The location of the wells and the extraction rate are the prevalent parameters; most of the wells are located in the western part of the polder therefore the largest salt load decline is visible there. The salt load decline increases when the extraction rate increases. Therefore scenario 003 shows the largest reduction in salt load and scenario 001 the lowest. In scenario 002 and 003, the salt load completely disappears in the western part of the polder as well as in the areas south of the Noordplas polder.

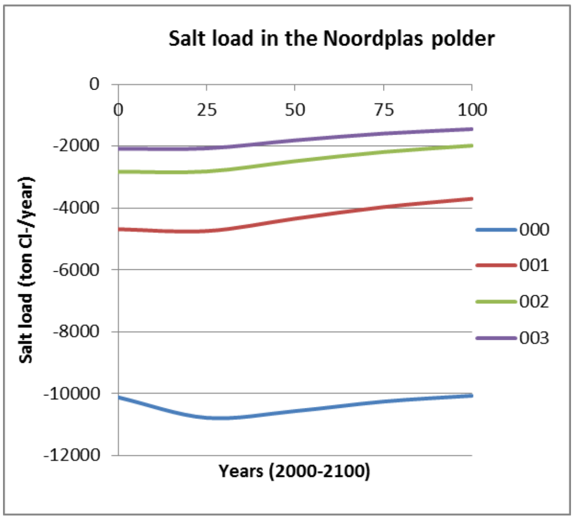

Figure 27: The total salt load (diffuse, paleo channel and boil) decline over 100 years per scenario.

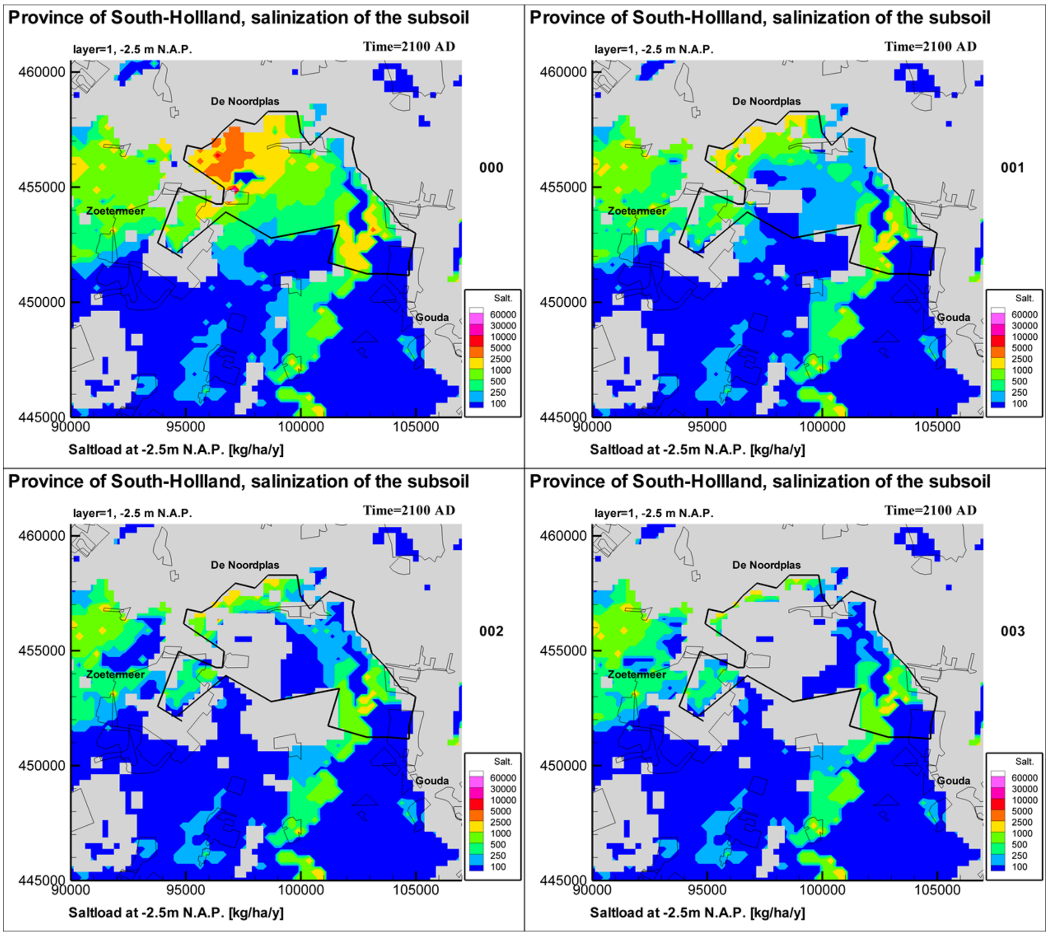

Figure 28: The drainage salt load distribution within the Noordplas polder in 2100 per scenario. Areas without salt load are shown in grey colour.

3.3.4 Hydraulic heads and hydraulic soil failure

The groundwater extraction causes piezometric heads to fall, therefore the difference between the hydraulic head and the phreatic water level decline. As visualized in figure 29, the hydraulic heads in the upper aquifer drop in every scenario.

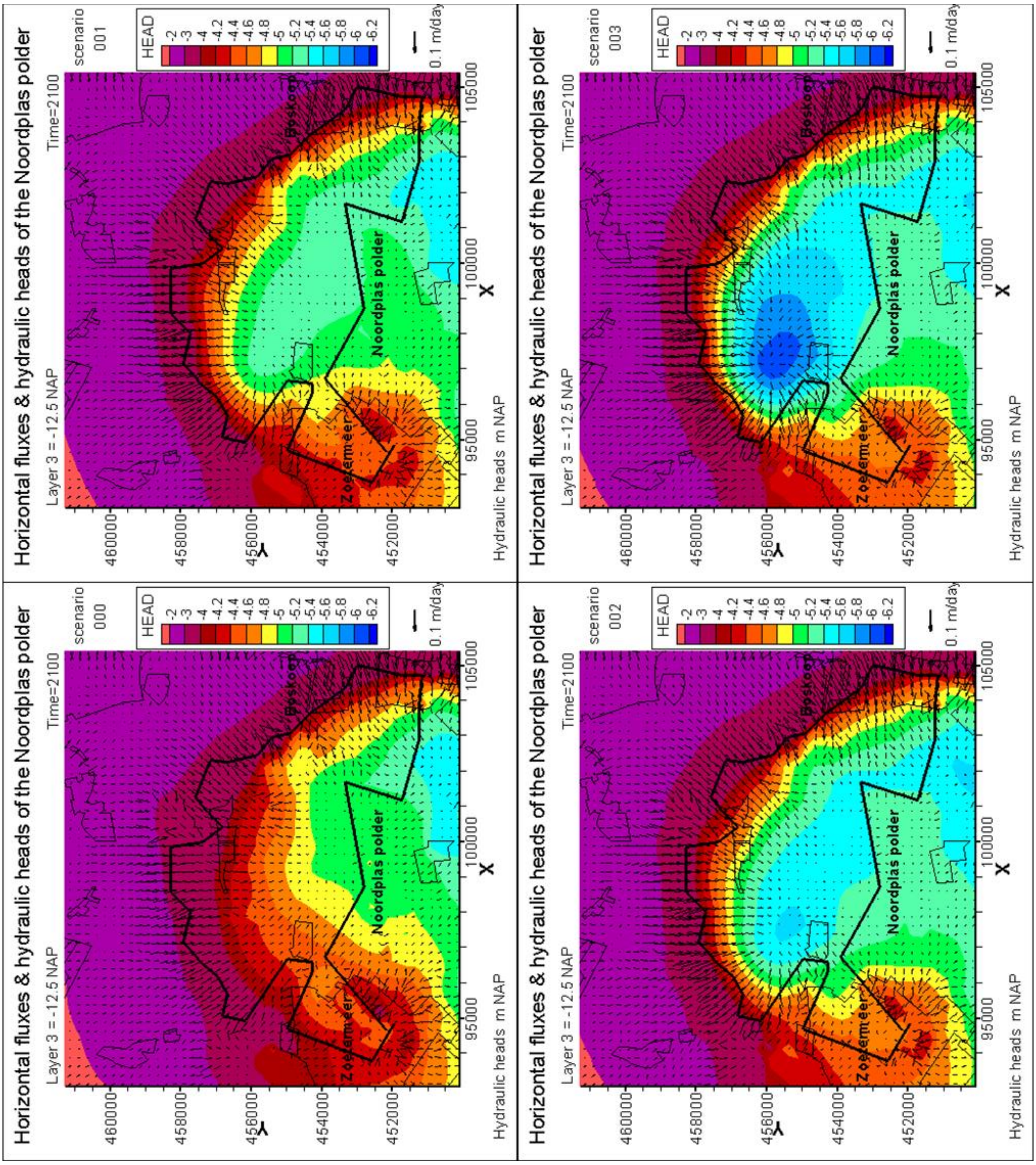

Figure 29: The hydraulic head below the confining layer in the first aquifer (12.5 m NAP). The horizontal fluxes are shown with vectors.

Scenario 001 drops between the 0 and 0.5 metre, while scenario 002 shows a head decline of 1.2 metres. Therefore injections seem to have a large effect on the hydraulic head decline and cause a smaller head decline. Scenario 003, however, shows a head decline with a maximum of 2 metres. Extraction wells have more effects than injections since they are located closer to the upper aquifer and their extraction rate is higher than the injection rate of the injection wells.

The difference in the hydraulic head causes lateral fluxes to flow from areas with a high hydraulic head to areas with a low hydraulic head. In the reference situation, the highest fluxes are located at infiltration areas at the edges of the polder (figure 30). The fluxes at the infiltration areas increase when the hydraulic heads are lowered. The infiltration area in the northern part of the polder reaches effective velocities up to 0.2 m/day. The area with an effective velocity of 0.2 m/day increases when more water is extracted. The the fluxes are pointed to the extraction wells, while no increased groundwater flow is visible there. Influence of the extractions on the horizontal fluxes is visible up to a maximum of two kilometres outside of the Noordplas polder.

The lowered hydraulic head has a positive effect on the hydraulic soil failure (table 31). If the hydraulic head in the upper aquifer declines the relative pressure of the confining layer increases and therefore the hydraulic soil failure risk lowers. It is worth noticing hydraulic soil failure occurs more often in the bottom of ditches than on land. Due to the coarse 250 by 250-metre cells, the calculated head is not representative for the ditches in the Noordplas polder. Therefore, the hydraulic soil failure risk for ditches is not calculated.

Hydraulic soil failure areas	
Noordplas scenarios 2100	Risk index [<1.1] [ha^2]
000	54
001	27
002	18
003	15

Table 31: The hydraulic soil failure risk areas on land, per scenario with a risk index of 1.1 and lower within the Noordplas polder.

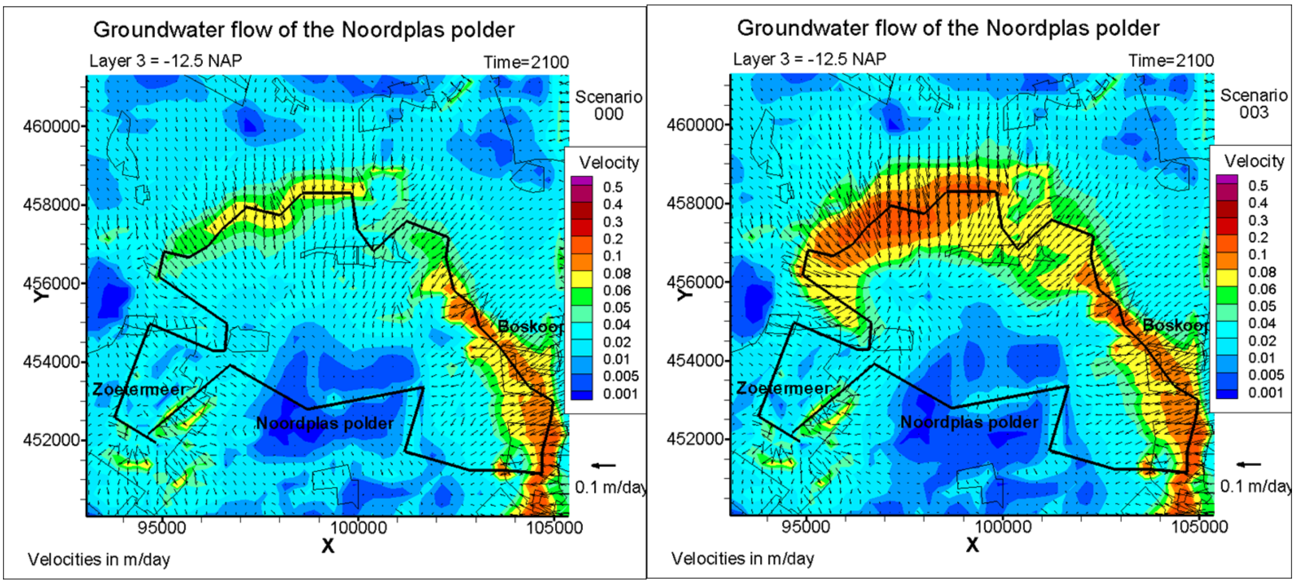

Figure 30: The velocities before and after the groundwater extractions scenarios 000 and 003.

3.4 Other areas

Within this subsection, the results of the other areas are presented. Only issues which were absent in the Noordplas polder scenarios but are prevalent in these areas are explained in detail. More figures and data can be found in Appendix III-VII.

3.4.1. The Middelburg-Tempel polder scenarios

The MT-polder has a large boil seepage flux. The locations of the boils are represented in the hydraulic soil failure index (figure 32). The eastern and northern parts consist mainly of areas with a hydraulic soil failure risk index below 1.1. The extractions lower the risk of hydraulic soil failure in the middle of the polder, the edges of the polder, do not show improvements.

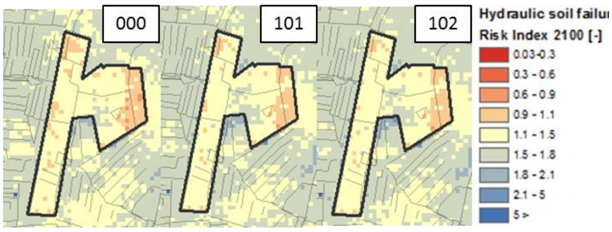

Figure 32 The hydraulic soil failure risk on land for the MT polder per scenario in 2100.

The reason for the small improvement in hydraulic soil failure area is visible in figure 33. The largest head decline is visible in the second aquifer. Aquifers are distinguishable from aquitards looking at the direction of the water flow. Within aquifers, the water flow is mostly horizontal, while in the aquitards only vertical flow is visible. Flow within aquifers is much faster than flow in aquitards.

The water extraction causes the effective horizontal groundwater velocity in the second aquifer to increase up to 0.4 m/day close to the well and 0.1 m/day up to 2000 metres from the well. More groundwater is extracted in horizontal directions within the aquifer than in vertical directions through the aquitard. In the confining layer, a seepage flux is still visible, while the first aquitard infiltrates. Therefore the seepage flux is fed by infiltration fluxes within the edges of the polder or the horizontal flow within the upper aquifer.

The brine injections cause a water flux pointed away from the injection well. Most of this effective groundwater flow is horizontal but also increased effective vertical flow is visible. The influence of the injection is visible until 4000 metres in the horizontal direction from the injection well. A sandy opening in the aquitard, a so-called window, is visible, but it is outside the influence of the injection and extraction well. Therefore no shortcuts through the window are visible, while an infiltration flux through the window is visible

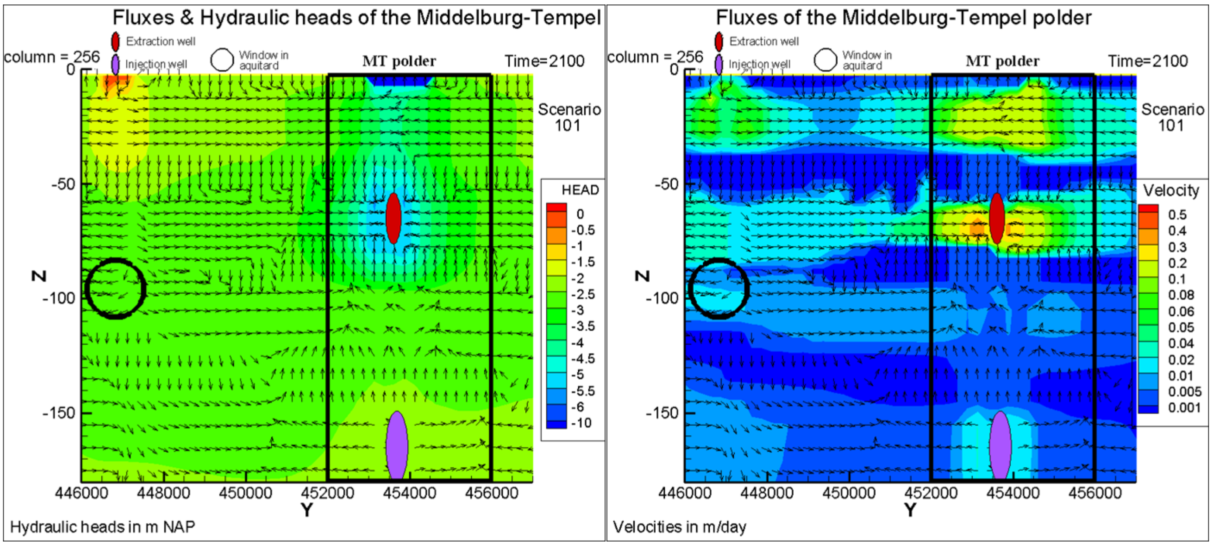

Figure 33 Fluxes and hydraulic heads at the MT polder. The vectors indicate only the direction of the groundwater flow; the velocity map shows the effective velocities. Effective horizontal velocities are visible in aquifers, while effective vertical velocities are visible in aquitards.

3.4.2 Zuidplas polder scenarios

For the Zuidplas polder the wells were relocated at the salt-brackish interface. This prevented saline up-coning in a brackish aquifer. In the adjusted scenario saline up-coning still exists but it enters an already saline area (figure 34). The relocation of the wells prevented the decline of the brackish ground water volume. In figure 34 also a small increase in fresh water volume is visible above the wells.

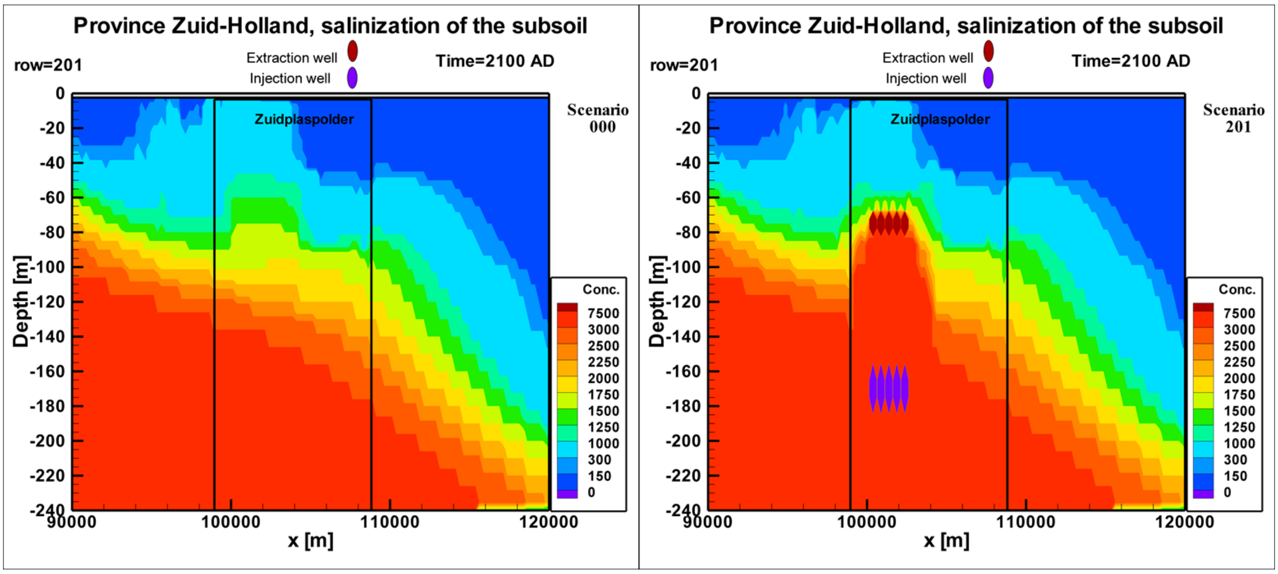

Figure 34 The effects of the groundwater extractions in the Zuidplas polder visualized, up-coning of saline groundwater under the extraction wells is visible.

3.4.3 Zoetermeerse Meerpolder scenarios

Within figure 35 the effects of the extractions within the Zoetermeerse Meerpolder are visible. In the reference situation, no fresh or brackish water volumes exist in the polder in 2100. The groundwater extractions cause the saline water interface to be lowered by 40 metres and prevent the up-coning of the saline water within the first aquifer. Strong up-coning of saline water above the 7500 mgl^{-1} Cl^- is however also visible below the wells. Scenario 301 (with injections) shows more saline up-coning compared to scenario 302 (without extractions). The injection wells create an overpressure which results in more saline seepage in the deeper aquifers. In figure 36 the concentration of the extracted water is shown. The concentrations of the extracted water is 4000 mgl^{-1} Cl^- after 100 years, so below the drinking water criteria of 6000 mgl^{-1} Cl^-.

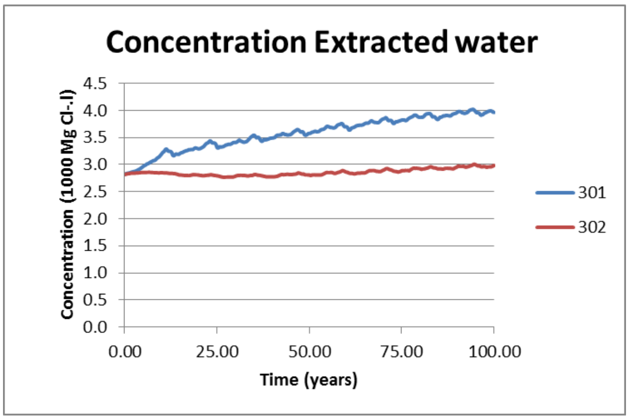

Figure 36. The concentration of the extracted water of the Zoetermeerse Meerpolder per scenarios plotted. Scenario 301 with injections increase while scenario 302 without injections stabilizes.

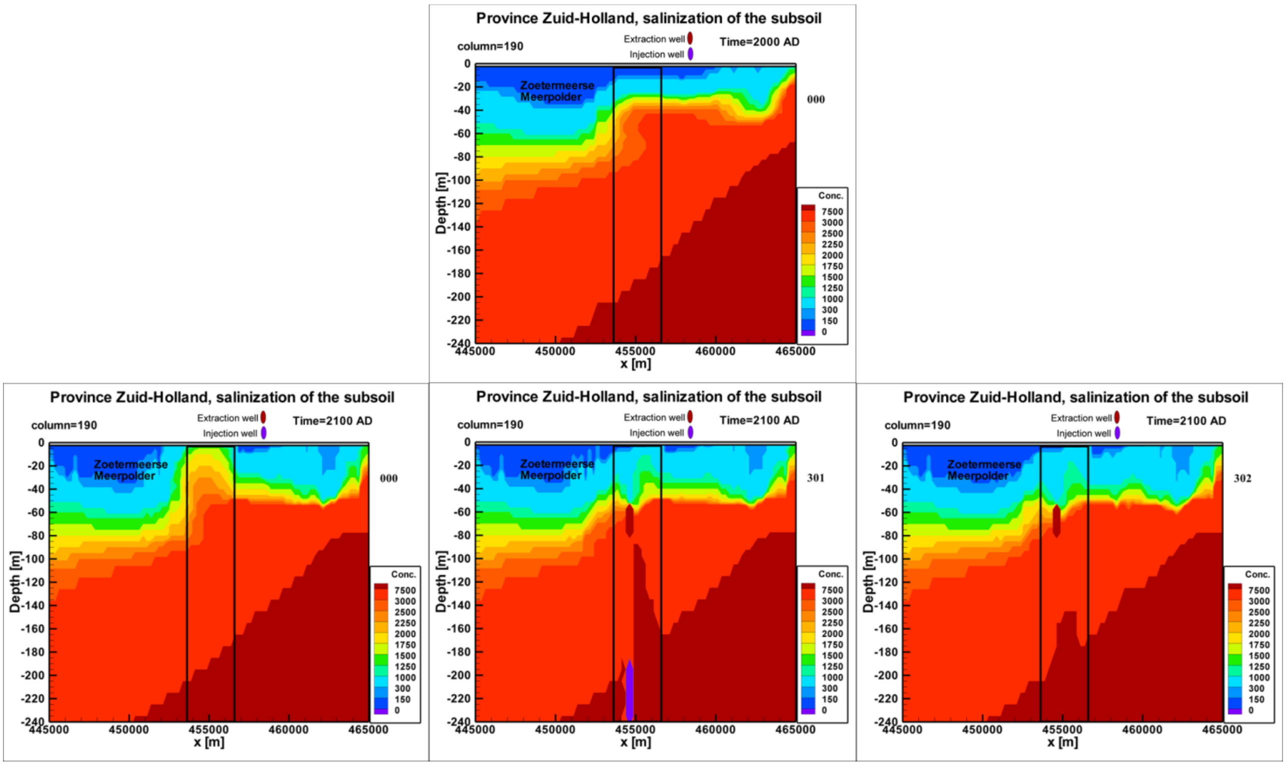

Figure 35 Cross-sections of the Zoetermeerse Meerpolder scenarios, saline up-coning is visible, but the saline water above the wells is almost completely changed in fresh water.

3.4.4 Groot-Mijdrecht polder scenarios

The Groot-Mijdrecht has almost no fresh water volume and has large hydraulic soil failure area (Appendix VI). Within the polder, two scenarios were run on different depths, to estimate the influence of the well depth (figure 37). Within the polder no continuous aquitard is present since the resistance layer consists of both sand and clay.

In the reference situation, a fresh groundwater lens was prevalent at -80 metres NAP within the polder. Between 2000 and 2100, the fresh groundwater volume is mixed with the saline seepage and carried to the surface in the reference situation. In the scenarios with extraction, the freshwater volume is mixed with the saline water at the original depth and is not carried to the surface. The deep scenario 402 extracts less of the freshwater volume and generates, therefore, more brackish groundwater volume compared to 401 (figure 38). The extraction scenarios increase the freshwater volume, however less than 1 million m^3 of freshwater is generated.

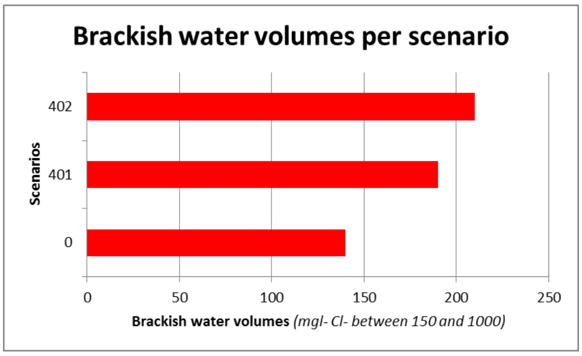

Figure 38: The brackish groundwater volumes in 2100 per scenario.

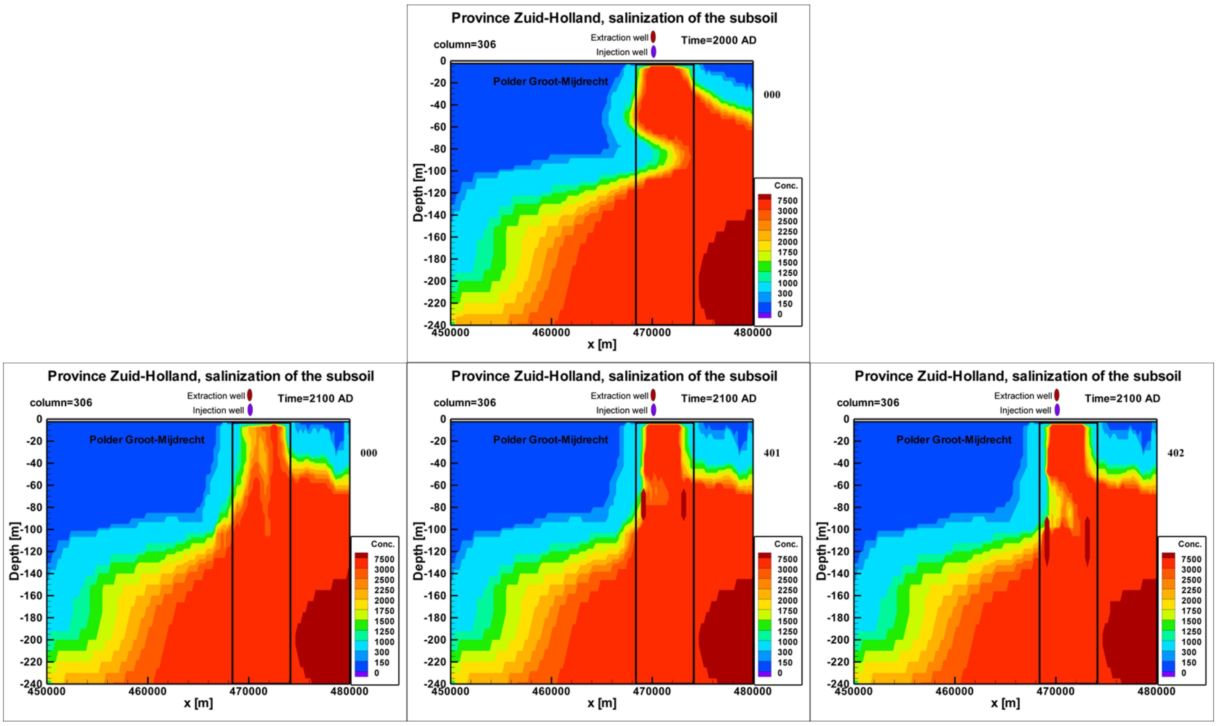

Figure 37. The development of the salt concentration within the Groot Mijdrecht polder compared to the reference situation in 2000 and in 2100.

3.4.5 Dune area scenario

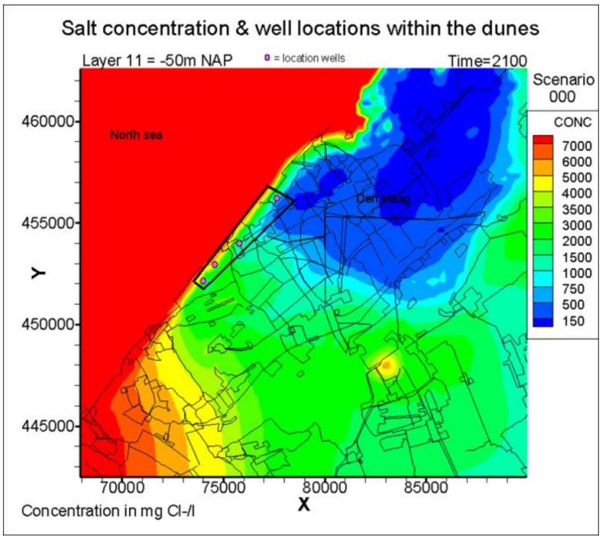

Figure 39. The salt concentrations and location of the wells within the investigated part of the dune area.

Within the dune area, one extraction scenario without injection was investegated since the proximity of the sea the injection can be taken to sea. The locations of the wells need to be placed carefully since freshwater lenses and saline seawater (>7000 mgl^{-1} Cl^{-}) are both present at the same depth. (figure 39). Therefore, only a small subsection of the dunes was explored.

If fresh groundwater is extracted the freshwater lenses decrease and will be replaced by saline water, while if sea water is extracted it is too saline for being a cost-efficient drinking water source. The wells should, therefore, be located in the brackish groundwater zone between the fresh and saline water volume.

The effects of the groundwater extractions are minimal. The brackish groundwater volumes increase with 3 million m^3 water after 100 years of extraction (figure 40). The concentration of the extracted water varies over time. Starting with 3000 mgl^{-1} Cl^{-} it lowers rapidly to 2000 mgl^{-1} Cl^{-} and decreases slowly over time with an amplitude of 500 mgl^{-1} Cl^{-} This amplitude indicates density differences, if the water concentration is lowered it is pushed back up by the brackish water surrounded causing the concentration instability. Numerical instabilities within the PZH-model can also be the cause (subsection 4.6).

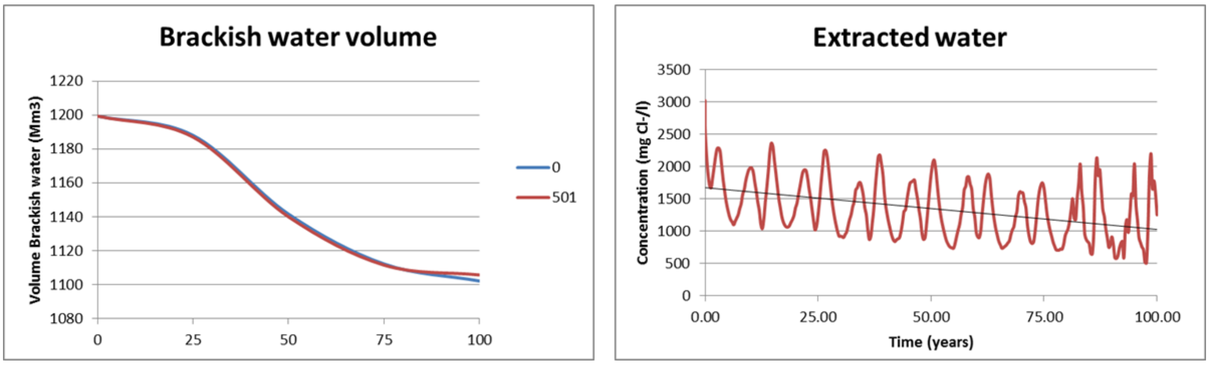

Figure 40 the brackish groundwater volume of the dunes (left) and the concentration of the extracted water (right).

3.5. Estimation of agricultural damages.

Within the reference situation the agricultural damages in the area of the water authority of Rijnland are in a dry year around the €20 million euro and in a wet year around the €10 million euro. To calculate the agricultural damages for the other scenarios five input values are needed per given colour area (figure 41). These input values are infiltration flux, boil and drainage seepage fluxes and boil and drainage concentrations. In this study, the input values of the southern deep polders (green area in the red circle) are changed per scenario. A sensitivity analysis for the parameter is done (Appendix VIII). Agricultural damages are calculated for the total area of Rijnland. A wet year and a dry were plotted. 1975 is chosen as a relative wet year, while 1976 as a dry year since it is one of the driest years within the data of the WAOR. In the reference situation, the agricultural damages are around the 20 million euro for a dry year and 10 million euro for a wet year. All scenarios show a decrease in agricultural damages compared to the reference situation. The scenarios 002 and 003 for the Noordplas polders generate the most decline in agricultural damages €1.5 million in a wet year and €3 million in a dry year. While the scenarios are extracted within different polders, they still show a general lowering trend.

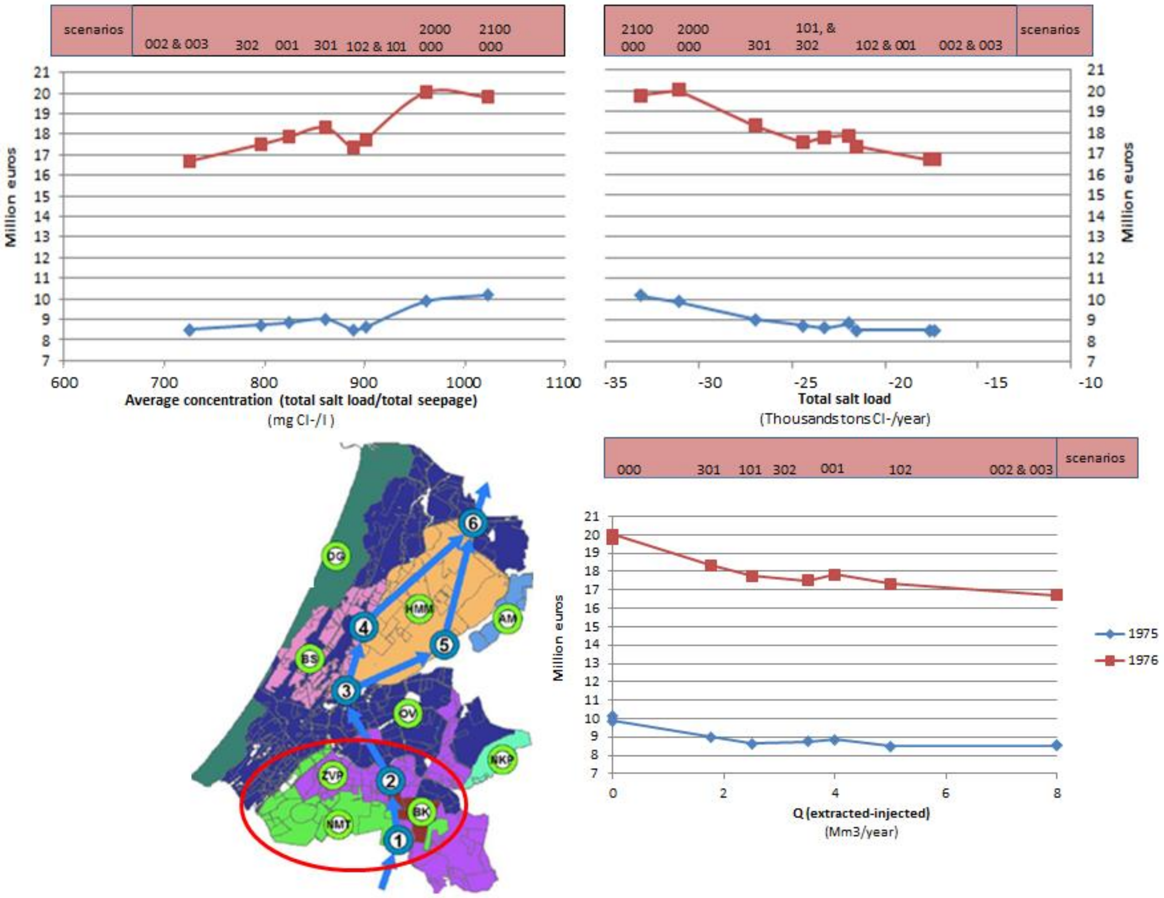

Figure 41 The average concentration, the total salt load and the net extraction rate for the deep polders in the green area in the red circle are plotted with the agricultural damages of the total area of Rijnland. The different scenarios for 2100 are plotted on graphs.

3.6. Effects on the phreatic water level.

The phreatic water level decline is important to prevent polders from dewatering and soil subsidence. Polders often have low summer water levels and high winter water levels. To estimate the water level decline both in winter and summer, the average general low groundwater level (GLG) and the average general high groundwater level (GHG) were calculated for the period 1996 until 2006. These GLG and GHG are compared to the reference situation to generate a delta GLG and delta GHG (figure 42). The risk for dewatering and soil subsidence is larger when the phreatic water level is lower; therefore the delta GLG is more important than the delta GHG.

The change in GLG and GHG are only given for extraction rates. No injection wells are placed to calculate the phreatic water level drop. Interference between the polders is visible. The polders: Zoetermeerse Meerpolder, Middelburg-Tempel polder, and Groot-Mijdrecht polder show a phreatic water level of 0.2 metres within the polder itself. Within the Zuidplas polder, there is a GLG decline of more than 0.8 metre and in the Noordplas polder if 0.48 metres. The phreatic water level is influenced by the hydraulic head, therefore, it is expected that scenarios with more extractions show a larger phreatic water level decline. Injections will, however, lower the phreatic water level decline.

Phreatic water level decline is also visible in infiltration areas outside the polders. For example, in the Boskoop area in the northeast of the Zuidplas polder, no extractions are placed but still a phreatic water decline is visible. These phreatic water level declines outside the extraction areas match with low resistance values of the confining layer (**figure 43**). A resistance of around 2000 days does not generate a phreatic water level decline. Areas with a seepage flux have a hydraulic head which exceeds the phreatic water level. Head decline will, therefore, lead to less phreatic water decline at those places. For example, the Middelburg-Tempel polder has both extraction wells and a small resistance but almost none phreatic water level decline is visible in the polder.

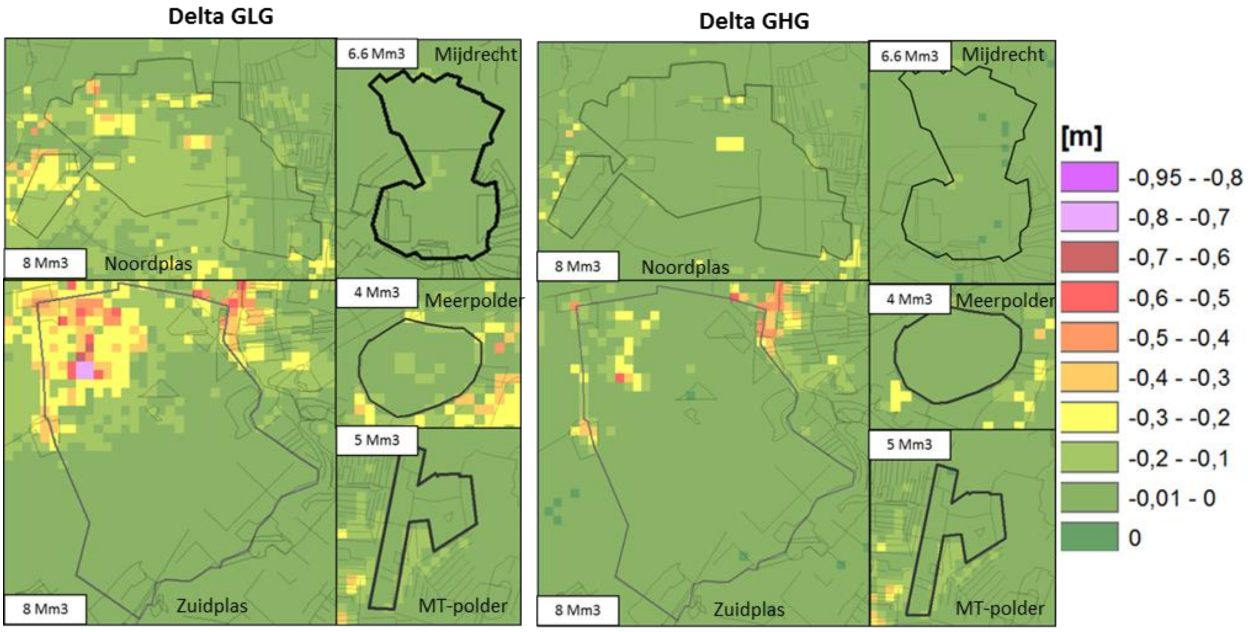

Figure 42: The average change of the GLG and GHG per scenario compared to the reference situation.

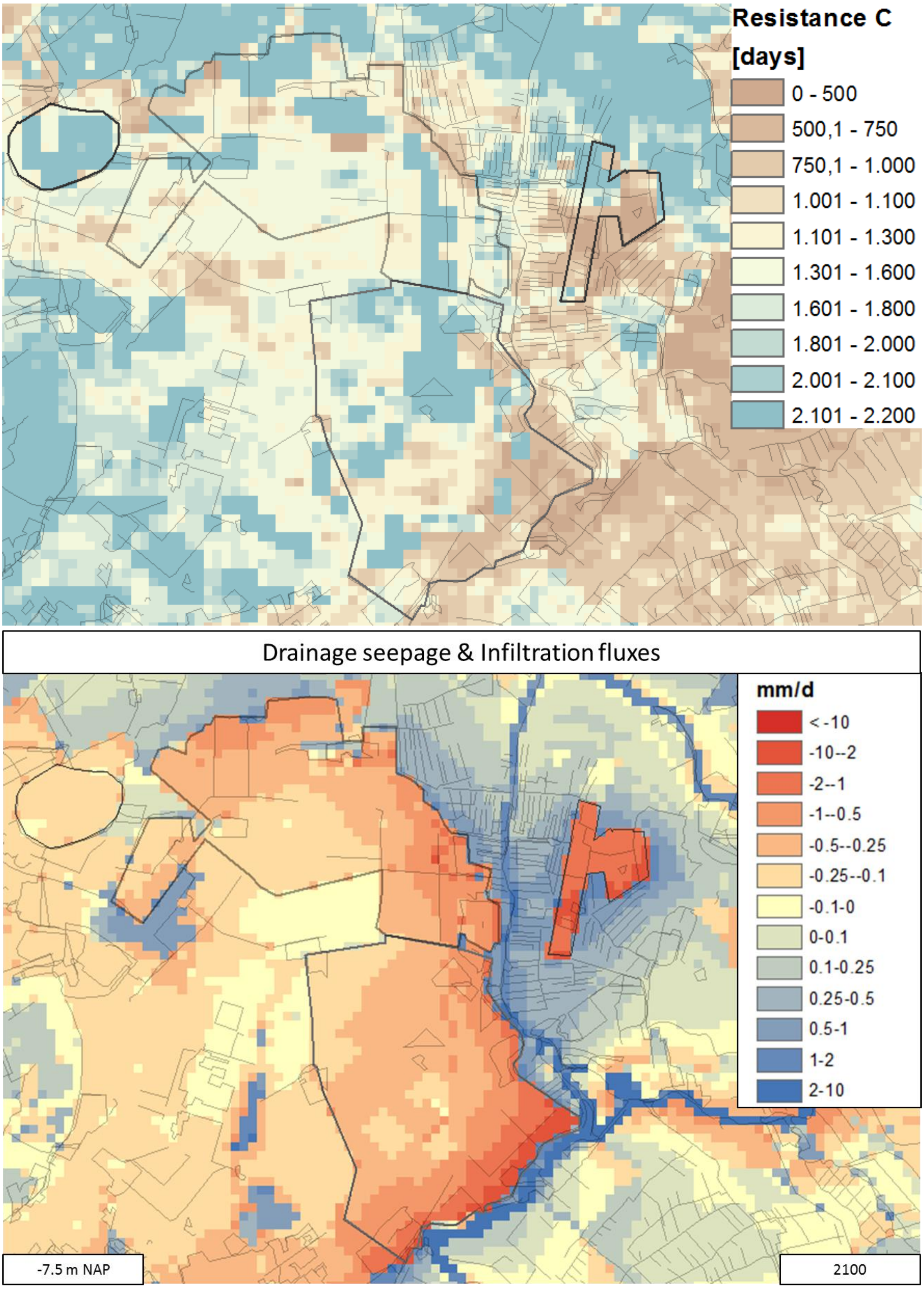

Figure 43. The resistance [c] of the confining layer (in the LHM model) and the diffuse seepage fluxes within PZH-model for the reference situation in 2100.

3.7. Stakeholder involvement.

The groundwater extraction influences different stakeholders. The responsibilities and the interests of every stakeholder are explained in this section and summarized in table 44.

-The drinking water companies.

The goal of the drinking water companies is to provide drinking water for now and in the future, for a reasonable price. The water demand is expected to increase in the future and the dunes have reached their maximum inlet capacity during winter (Zwolsman, 2017). Their interests are mainly focused on the quantity of the extracted water and the price of it. Using reverse osmosis this water is turned into drinking water. However, since the price of RO is influenced by the quality of the water (Al-Karaghouli & Kazmerski, 2012), the interest of the water company is also on the salt concentration of the extracted water**.** The generated brine may be used as a resource in the future.

-Water Authorities

The water authorities are responsible for both surface and groundwater. Their tasks consist of operational groundwater management, water level management, spatial planning and small groundwater extractions (below 150.000 m3/year), which are not used for drinking water production (Provincie Utrecht, 2009). The water authority transports water into the polders to sustain the water level and water is also used by the water authority for flushing deep saline polder (Van Rees Vellinga et al., 1981; Stuyt et al., 2012). Therefore the water authority has a main interest in both the seepage and infiltration flux and the salt load of the deep polders.

-Province

The provinces in the Netherlands are responsible for the groundwater extraction larger than 150.000 m^3 per year or groundwater extraction used for public drinking water supply (Provincie Utrecht, 2009). The provinces provide permits for these extractions. An advisory committee investigates the effects of the groundwater extractions and they estimate the size of the damages caused by the groundwater extractions. The provinces are responsible for water quality and strategic and operational groundwater management. The province is therefore mainly interested in the volume of the fresh, brackish and saline groundwater.

-Local farmers and nature conservationists

The local farmers and nature conservationists need fresh surface water during summer to water their plants. If the surface water is too saline agricultural damages will occur. Therefore, they are interested in the estimated agricultural damages. Plants take up water from the unsaturated zone. If the phreatic water level drops, dewatering can occur and plants are not able to take up water. This is harmful to farmers and the nature conservationist. The local land users have therefore an interest in the influence of the extractions on the phreatic water level. The farmers and nature conservationists have also a main interest in the hydraulic soil failure area. If the area with a risk of hydraulic soil failure decreases, due to groundwater extraction, the subsoil becomes less fragile. The subsoil can more easily be used for ploughing or as a building ground. The existing boil flux will also decrease by the lowered hydraulic heads.

Stakeholders:	Drinking water company			Water Authority		Province		Local farmers / Nature conservatists			
2100 values	Drinking water (Mm3 /y)	Extraced / Injected water (Mm3/y)	Concentration extracted water 2050 (mgl-1 Cl-)	Seepage - infiltration (m3/day)	Total Saltload (tons Cl- /year)	Fresh water (Mm3)	Brackish water (Mm3)	Agricultural damages Rijnland (wet year) (M€)	Agricultural damages Rijnland (dry year) (M€)	Maxixum delta GLG (m)	Hydraulic soil failure area (ha)
Noordplas											
000	0	0	-	-31,500	-10,100	40	370	9.9	20	0	54
001	4	8/4	2600	-16,900	-3,700	55	430	8.3	16.3	nd	27
002	4	8/0	2100	-11,100	-2,000	70	510	8.1	15.5	0.48	18
003	8	16/8	3000	-7,800	-1,500	75	520	8.0	15.3	nd	15
MT polder											
000	0	0	-	-48,900	-10,700	10	60	9.9	20	0	113
101	2.5	5/2.5	1600	-31,800	-1,800	50	45	8.6	17.8	nd	79
102	2.5	5/0	1200	-28,800	-1,400	60	50	8.5	17.3	0.1	75
Zuidplas											
000	0	0	-	-34,600	-4,700	110	670	-	-	0	33
201	4	8/4	1800	-26,400	-2,700	135	680	-	-	nd	31
202	4	8/0	1200	-21,500	-1,900	170	780	-	-	0.8	28
Zoetermeerse Meerpolder											
000	0	0	-	-850	-500	0	0	9.9	20	0	0
301	1.75	3.5/1.75	3600	-150	-100	7	25	9	18.3	nd	0
302	1.75	3.5/0	2800	-100	-50	8	30	8.7	17.5	0	0
Groot Mijdrecht											
000	0	0	-	-112,700	-56,300	0	140	-	-	0	697
401	3.3	6.6/0	2600	-84,000	-41,100	0.4	190	-	-	0.1	579
402	3.3	6.6/0	3100	-88,200	-44,800	0.4	210	-	-	nd	601
Dunes											
000	0	0	-	209,700	-3,000	2600	1100	9.9	20	0	0
501	1.5	1.5/0	1900	217,000	-3,000	2600	1100	9.9	20	nd	0

Table 44: Table with stakeholder and their main interests. The seepage and salt load are adjusted for boils.

Within table 44 the effects of the groundwater extractions are summarized for every stakeholder. Within the Noordplas scenario 003 decreases the salt load the most and has overall positive effects for the stakeholders. However, the phreatic water level decline will be significant in this scenario since scenario 002 has a maximum phreatic water level decline of 0.48 metre. Within the MT-polder the salt load was in the reference situation larger than the Noordplas, while the MT-polder has a smaller surface area. The concentration of the extracted water is relative low.

Within the Zuidplas polder the extraction have positive effects on the salt load but cause a large phreatic water level decline. Within the Zoetermeerse Meerpolder groundwater extractions generate fresh and saline water volumes which are absent in the reference situation. The Groot-Mijdrecht polder has also no freshwater volume in the reference situation, while extractions improve the situation for all stakeholders; the large hydraulic soil failure area and the high salt load of the polder are still a concern. Within the dune scenarios the infiltration flux increases when water is extracted but no other clear effects are visible. Detailed data for the given scenarios can be in Appendix VII.

4. Discussion

4.1 Effects of groundwater extractions

To estimate the relationship between the extraction rate and the seepage flux the data was analysed. To adjust for the injection rates the injected rate was subtracted from the extraction rate (figure 45). The drainage flux and the infiltration flux show linear trends with the net extraction rate. If the linear trend is followed, around 30 million m^3 water needs to be extracted to bring the drainage flux back to zero. 30 million m^3 water is also the net seepage flux in the reference situation. If 30 million m^3 is extracted, the infiltration flux will be 4.2 million $m^3 y^{-1}$ water. The salt load is also depended on the seepage fluxes; therefore, it shows also a linear trend. The concentration of boils and drainage do not show a clear trend.

A polynomial trend can be seen for difference in phreatic water level and hydraulic head compared to the individual boil flux for every polder **(figure 46).** The quadratic relation occurs since both the area with a risk of hydraulic soil failure and the seepage flux per well depend on difference between the hydraulic head and phreatic water level. To calculate the total boil flux for a polder, the seepage flux per boil is multiplied by the risk area (chapter 2) and causing therefore the quadratic relation visible in figure 46.

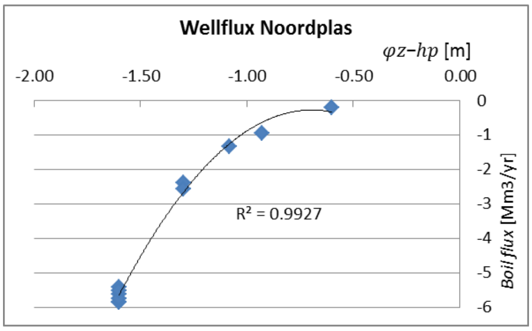

Figure 46. The quadratic relation between the difference between ($\varphi z - hp$) and the boil flux within the Noordplas polder is shown.

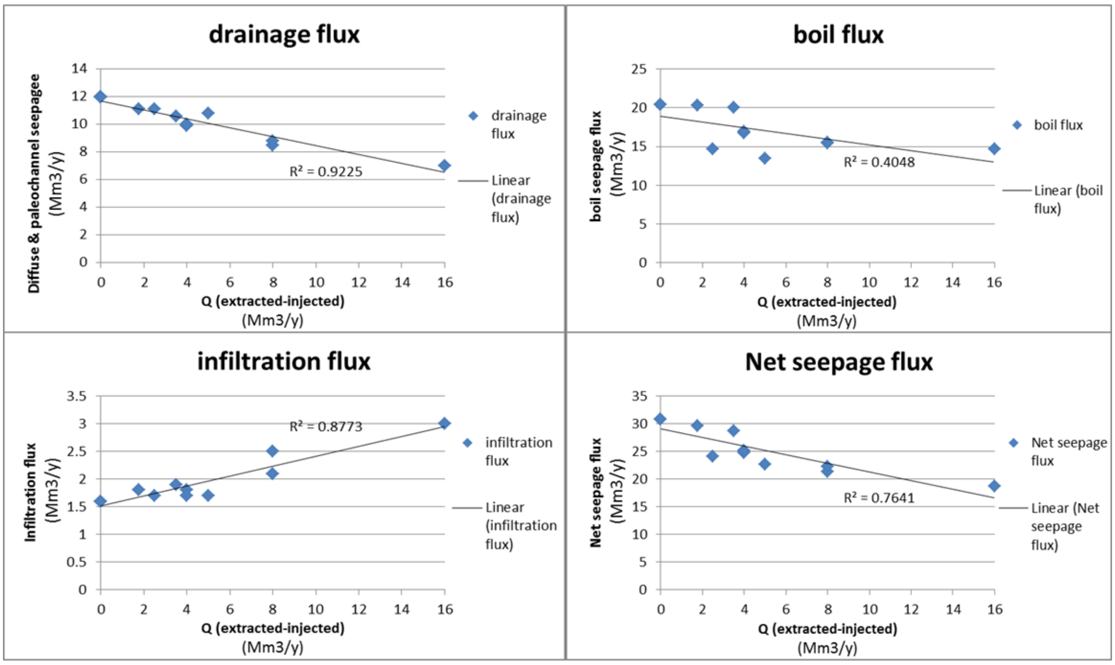

Figure 45. The correlation between the net extraction rate and the seepage and boil fluxes in the southern deep polder area of Rijnland (figure 41). Linear relationships are visible.

The groundwater extractions cause the hydraulic heads to drop between 1 and 2 metres around the extractions wells, while brine injections cause a local hydraulic head increase of 0.5 metres. A lowered head in the upper aquifer lowers the risk areas for a hydraulic soil failure. The head difference causes fluxes to move from the injection wells to the extraction wells. In scenario 101 flow velocities within the aquifers reach up to 0.4 m/day and the effect of the extraction is noticeable up to 3 kilometres from the wells. Brine injections increase the velocity up to 0.02 m/day and are only visible up to 1 kilometre from the injection point. Fluxes through the deeper aquitards are much smaller with a maximum of 0.005 m/day. The travel time through the aquitard decreases and traces of the brine injections and saline up-coning can be found back in the extracted water within 5 to 15 years.

The groundwater extractions cause the infiltration flux of existing infiltration areas to increase and travel through the first aquifer to the location of the extraction wells. The seepage flux within the polder is lowered, but no large infiltration occurs within the polder. The infiltration fluxes cause freshening of aquifers above the extraction wells, while saline up-coning is visible below the extraction wells. The concentration of the extracted water increases but reaches equilibrium before 6000 mgl^{-1} Cl^{-} within the Noordplas scenarios. The salt load also reaches equilibrium when the extracted water concentration stabilizes after 150 until 175 years.

4.2

4.3 *Boundaries within the Dutch and European law*

Within this subsection the boundaries set within the Dutch and European law are analysed, so the scenarios can be implemented in the future. Within the Kaderrichtlijn Water (KRW) it is stated that from 2015 onwards, a decline of the water quality within the groundwater bodies should be stopped and negative trends should be turned. It also states that good quality of groundwater bodies needs to be reached and contained (Rijksoverheid, n.d.). Salinization can be seen as a negative trend and a decline of water quality.

Within the Dutch delta programme, the Deltaplan Zoetwater was launched. This plan has the aim to increase freshwater availability for different stakeholders. The plan focusses on gaining insights of the water availability and on a robust and efficient freshwater supply. One of the focus areas is Boskoop (Deltacommissaris, n.d.). Groundwater extractions in the Noordplas, Zuidplas and MT-polder improve the water quality of the boezem and have positive effects on the fresh water availability at Boskoop.

The Drinkwaterwet is the law which controls drinking water production. At the moment surface and groundwater can be used for drinking water production if it can be purified in an easy way (Versteegh et al., 2010). To make this possible water protection zones are commonly applied. This law is expected to be changed when RO systems are used for drinking water production at a large scale (Zwolsman, personal communication April 20, 2018).

Brine injections are forbidden, but a transition time until 2022 is present (Zuurbier et al., 2015). In the absence of alternatives it is expected the transition time will be extended. Van Mook et al. (2015) concluded no good alternatives for brine injections are yet available. It is possible to get a groundwater injection license if the conditions of figure 47 are met (Pelamonia & Keessen, 2013).

Boundaries within the Dutch law for brine injections

-1. The chloride concentration of the brine is lower than the chloride concentration within the injections points.

-2. For other substances than chloride, no norms should be exceeded.

-3. There must be an aquitard between the extraction and injection locations.

-4. Monitoring needs to take place.

-5. The injections should be energy efficient.

-6. Brackish groundwater volume should not decline.

-7. No soil subsidence should occur.

Figure 47: Conditions for brine injections within the Dutch law (Pelamonia & Keessen, 2013).

4.4 Alternatives for brine

RO is used to purify the extracted groundwater for drinking water use; therefore a solution for the produced brine needs to be found. As said in the previous subchapter, Van Mook et al. (2015) concluded no good alternatives for brine injections are yet available. Three different brine solutions were used in the costs analysis for the Noordplas and Solleveld area (Stofberg et al., 2018) (table 48). Solleveld is an area in the dunes close to Den Haag. The brine can be injected deeper into the subsoil, brought to a waste water treatment plant (WWTP) or taken to sea.

Areas ->	Noordplas	Solleveld
Brine solutions	*(costs / m^3)*	
Brine injections	€0.93	€0.95
Brine to WWTP	€1.22	€1.07
Brine to sea	€1.24	€0.96

Table 48: The cheapest scenario for every brine solution shown. A concentration of 1500 mgl^{-1} Cl^{-} for the extracted water is used to calculate the costs (Stofberg et al., 2018).

The cheapest option is to inject the brine into the deeper subsoil. For the Noordplas scenario brine needed to be injected below -145 metres NAP, to inject in a higher chloride concentration than the brine. If the RO recovery rate increases, less brine is produced but with a higher concentration. Therefore, the injections must be placed deeper into the subsoil. If brine is diluted before it is injected, a lower injection depth can be used. If brine has a lower salt concentration than the deep aquifer, it will lower the chloride concentration in the deep aquifer. However, concentrations of other substances like phosphor may increase in the aquifer (Faneca et al., 2012).

To take brine to sea is a cheap solution for areas close to the sea like Solleveld. However, for polders further land inwards like the Noordplas polder this solution asks for higher investments and the costs rise. Brine can only be taken to the sea if the concentration of the brine is lower than the concentration of the seawater (Koffeman et al., 2010).

Taking water to a wastewater treatment plant involves higher costs compared to the other scenarios. Not all wastewater treatment plants can process saline water since biological degradation rates of organic compounds decrease with increasing salt concentration (Kargi & Dencir, 1997).

4.4. Management implications

Management implications for the groundwater extractions will be explained in this chapter. Which concerns are there and what needs to be implemented to comply with the law? In an ideal situation, where would the extraction wells be placed? Which geo-hydrologic conditions does an area need to have in order to facilitate groundwater extraction as an effective mitigation option for salinization?

-1. Extraction wells need to be placed within the in saline seepage areas. If the extraction wells are up to two kilometres away from the seepage areas a vertical flow through the aquifer can occur and causing the saline water volumes to increase. In seepage areas a high well density is needed to prevent the saline seepage from bypassing the wells. Seepage areas have a hydraulic head which exceeds the phreatic water level. The phreatic water level is, therefore, less sensitive to a decline in hydraulic head within these areas.

-2. To prevent soil subsidence and dewatering only a small phreatic water level decline is possible. Extraction areas should, therefore, have a thick confining layer. A resistance [c] of around 2000 days does not show any phreatic water level decline in the investigated scenarios.

-3. To prevent pesticides from diminishing the water quality of the upper aquifer a groundwater protection zone should be created within a range of around two kilometres from the extraction wells. Within this groundwater protection zone the infiltration rate increases and more water needs to be let in to prevent dewatering, droughts and soil subsidence.

-4. Areas close to the sea are applicable for groundwater extractions. The brine can be taken to sea and does not have to be injected. Therefore the extractions are not bounded to the transition time until 2022. If brine is injected it need to be injected within an aquifer which has a lower chloride concentration than the brine itself. The concentration of the other substances within the brine should not exceed norms.

-5. To prevent interference between the injection and the extraction wells a thick continuous aquitard should be located between them. The aquitard also lowers the extracted concentration of become to saline by salt up-coning. No openings within the aquitard should, therefore, be present to prevent the saline up-coning of bypassing the aquitard.

-6. The extractions wells should be placed on the brackish-saline interface or within the upper saline water, to prevent up-coning of saline water. Up-coning of saline water makes temporary groundwater extraction impossible, since the up-coned water will be brought to the surface by the seepage when the extractions are stopped.

-7. The salt concentration within the three-dimensional plane should be within the same order of concentration, to prevent fresh water lenses to be replaced by the surrounding saline water. This forms a risk in the dune areas.

-8. The costs for groundwater extraction and purifying with RO are higher than conventional drinking water production methods. The costs of RO increases if the chloride concentration increases, within this research the boundary criteria of 6000 mgl^{-1}Cl^{-} was used. The costs for the production of drinking water from saline groundwater are affordable for the industry, but it is too high for drinking water companies (table 48). The extraction wells should be located in areas with or nearby areas sensitive to salinization, the water authority has then lower costs since less flushing occurs and local landowners have less agricultural damages. A division of costs between these stakeholders and the drinking water company is, therefore, may be possible.

Taking the concerns, criteria, and effects of the groundwater extraction into account what are the best scenarios? Figure 49 gives an estimation of the optimal extraction rates for every investigated area. Within the Groot-Mijdrecht polder no injections are possible due to the porous aquitard and in the dunes a good alternative is available. For the other polders brine is injected.

If the given amount is extracted, the practice can be endured within the near-future, and is, therefore, sustainable. For the Noordplas 8 million m^{3}y^{-1} water can be extracted, but some wells need to be relocated to prevent the phreatic water level from declining 40 centimetres. For the Meerpolder and Middelburg-Tempel polder, 3.5 and 5 million m^3 can be extracted, while in the Zuidplas polder, around 3 million m^{3}y^{-1} water can be extracted. The extraction of 8 million m^{3}y^{-1} water caused a phreatic water level decline of 1 metre. The Groot-Mijdrecht polder did not reach limitations, and more water than 6.6 million m^{3}y^{-1} could be extracted to lower the salt load more.

Wihtin the dunes a small area was investigated due to the complex situation, but the whole dune area has potential. The Haarlemmermeer polder has similar characteristics as the researched polders and therefore has also a potential for groundwater extractions.

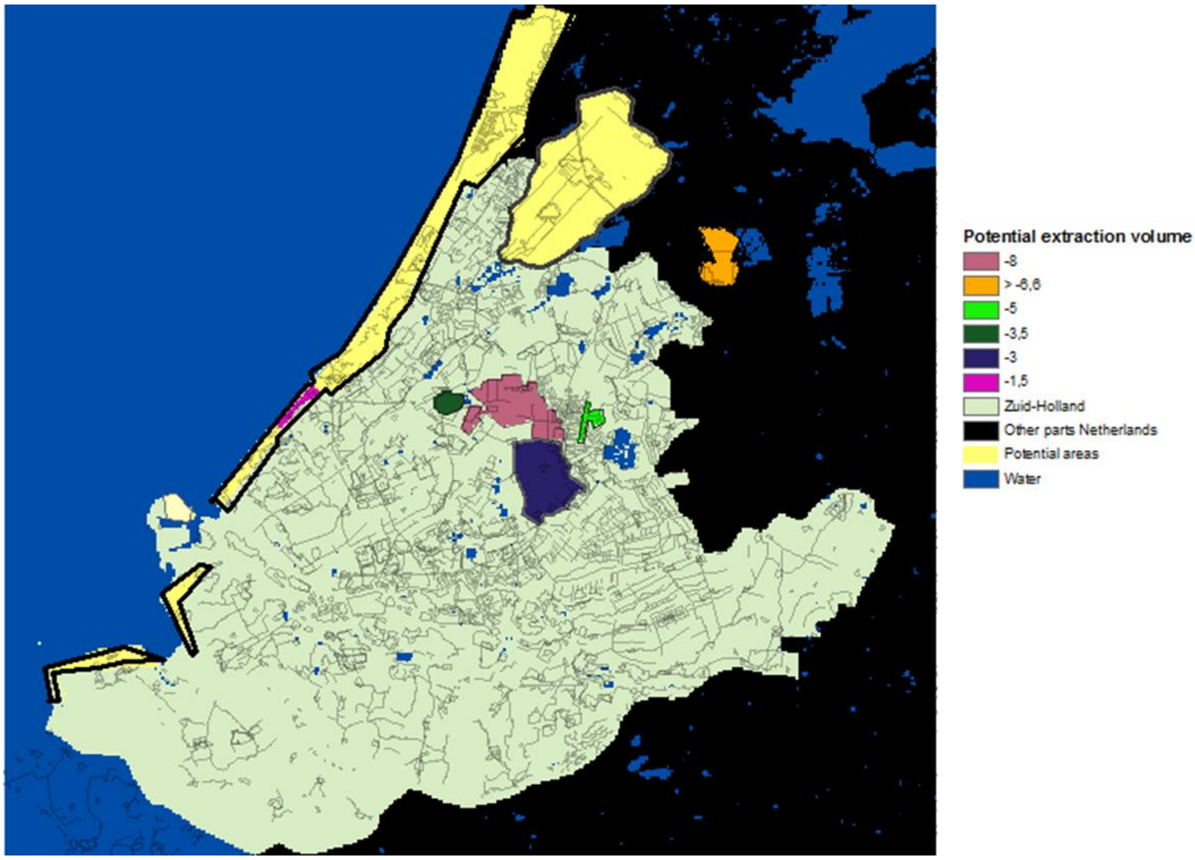

Figure 49. The location of the extraction areas within Zuid-Holland and their sustainable extractions per year.

4.5. Compared to previous research

Values Noordplas	Q boil (m3/day)	Q drainage (m3/day)	Q total (m3/day)	C boil (mg Cl-/l)	C drainage (mg Cl-./l)	Saltload boil (tons/year)	Saltload drainage (tons/year)	Saltload total (m3/day)
measured values 2010	-16,000	-15,300	-31,300	1310	465	-7,700	-2,600	-10,300
calculated values 2000	-16,000	-16,600	-32,600	1130	575	-6,600	-3,500	-10,100
% difference	0%	-8%	-4%	14%	-24%	14%	-35%	2%

Table 50 Calculated results, compared with measured results by De Louw, et al., 2011. The total seepage flux and the total salt load gave good estimations of the real situation.

Within figure 50 the calculated results of this study are compared to the measured results of previous study by De Louw et al., (2011). The boil flux of that study was taken as a reference point and shows no difference. The diffuse and paleo channel seepage, however, are underestimated by the PZH-model. A reason for this can be found in the paleo channels. Paleo channels are visible within the model, but they are not present at all location due to the coarse grid. De Louw, et al., (2011) names 1100 as average boil concentration. However, 1300 (the median) was used to calculate the salt load. The model gives a good estimation for the boil flux, the total seepage flux, and the total salt load, while the concentrations and the separate boil and drainage salt loads divert much from the measured results. In figure 51 the hydraulic soil failure map is compared to the map with wells from the water authority. The hydraulic soil failure risk map shows similar location as the boil, however not all boils are visible at the hydraulic soil failure risk map. This can be caused by local geological differences within the confining layer as well as local distortions in the hydraulic head.

This research shows of similar results with the other COASTAR paper Stofberg et al., (2018), which investigated the effect of saline groundwater extractions on the salt load of the Noordplas polder. This research however, gives improved salt load declines since the locations of the wells are optimized and gives a more in depth quantification and qualification of saline groundwater extraction.

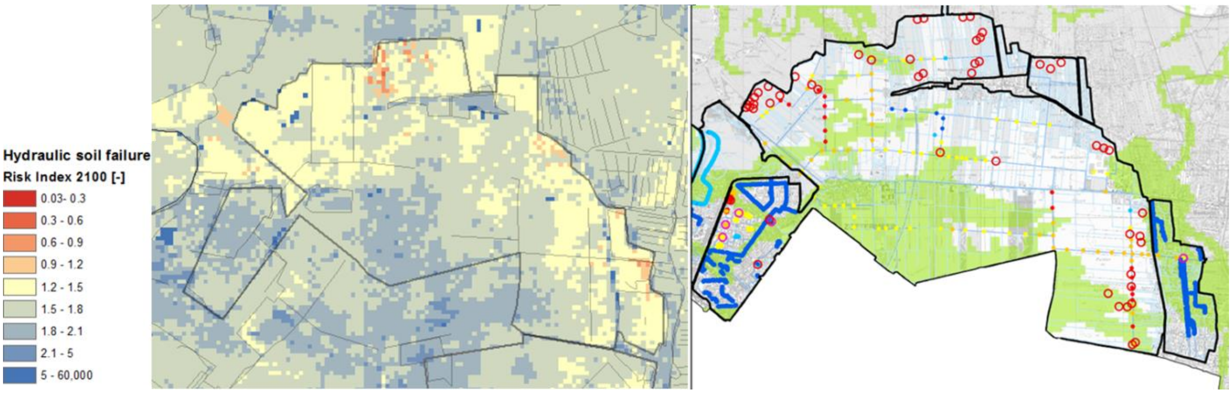

Figure 51: Map of hydraulic soil failure (left) and a map of boils within the Noordplas (right) (HHR, nd). The maps show similarities, while not all boils are visible in the hydraulic soil risk map.

4.6 Model and research restrictions

The used models have some restrictions. The PZH-model does not have a dynamic top system. It can, therefore, not be used to calculate phreatic water level decline. Both the PZH and the LHM model use a large grid size with cells of 250 by 250 metres. It cannot represent local geology as paleo channels or head difference near small ditches. The phreatic water level decline will have more local variety in reality.

The PZH-model is based on the old REGIS, while REGIS II is available with updated geology. GEOTOP can also be implemented in the upper 50 metres of the model. Deeper salt and geology input is needed to better calibrate deeper extraction and injections. In most scenarios the injected water influences the extracted water, iteration could, therefore, give significantly different results.
To give the correct injection concentration, iteration between the extracted and injected concentration is needed.

The PZH-model does not include boil fluxes. Therefore the boil flux needed to be estimated for the area with a hydraulic soil risk. However, as visible in figure 51, a hydraulic soil failure map is not the same as a boil map. If a boil is created the local hydraulic heads change, the risk of a hydraulic soil failure lowers around the boil. Therefore, the implementation of boils within the PZH-model is highly recommended for further research.

The PZH-model gives some rapid changes in salt concentrations, salinization, and water volumes. Most of the salinization occurs within the first 25 years of the model; afterwards the autonomous salinization process slows down. This can be seen in Appendix I. The PZH-model is therefore, may be not in balance with its input data.

The PZH-model may be shows numerical instabilities within the dune scenario. Minnema et al. (2004) stated that ‘inversions in fresh and salt can easily be introduced [..]. Such mistakes generate unrealistic large fluctuations within the vertical ground water velocity.’ These density inversions are may be the reason for the fluctuations within the concentration in the dune scenarios.

4.7 Future research.

The PZH-model was run without soil subsidence or sea level rise, while both will increase salinization within the future. The effects of these factors in combination with the groundwater extractions need further research.

Within the WAOR model only the southern deep polders of Rijnland are taken into account. The PZH-model generated however different fluxes and concentration compared to the 2013 situation in the WAOR. The data for the other polder areas was therefore, not adjusted, which can be done in future research. The WAOR can be run with different climate scenarios, different years and pumping costs for Gouda. The costs of the groundwater extractions and the prevention of agricultural damages can be compared to the new KWA solutions. Which solution is more profitable?

This research focussed on the extraction of saline groundwater, while another idea is to capture saline seepage with horizontal wells. The effects of this practice cannot be estimated with the PZH-model but are worth investigating in the future. It may causes less saline up-coning.

More research must be done at boils. The current formula created by Erkens et al., (2018) is theoretical and not proven. A physical formula to predict a boil flux should help to understand and prevent boils. More measurements should be made, to quantify the fluxes and concentrations of the boils.

This research showed the potential of groundwater extractions as a mitigation option for salinization within the province of Zuid-Holland. There is also potential in other parts of the Netherlands with deep polders, as in Noord-Holland, but also in saline deltaic areas worldwide as in the Nile delta.

5. Conclusion

The research question of this research was:
Which geo-hydrological properties are required to increase freshwater availability by applying saline groundwater extraction as a socio-economic mitigation measure for salinization?

Saline groundwater is extracted and fresh water can percolate deeper into the subsoil increasing the fresh water availability. To improve the freshwater availability extraction wells should be placed within saline seepage areas. A high well density is necessary to prevent the saline seepage from bypassing the wells. The extraction wells should be placed on the brackish-saline interface to prevent saline water from up-coning in the brackish groundwater. No freshwater lenses should be close to extraction wells to prevent the fresh water volumes being replaced by saline water.

To prevent the area of dewatering and soil subsidence, no phreatic water level decline should occur. Extraction wells should therefore be placed within areas with a thick confining layer with a resistance of at least 2000 days.

Groundwater extractions lower the seepage fluxes but also generate an infiltration flux. To prevent pesticides from diminishing the water quality of the upper aquifer a groundwater protection zone should be created within a range of around two kilometres from the extraction wells.

If the saline groundwater is purified with reverse osmosis; the generated brine should not be injected. In areas close to the sea; the brine can be taken to sea. If brine still needs to be injected; it should be in an aquifer which has a lower chloride concentration than the brine itself. To prevent interference between the injection and the extraction wells a thick continuous aquitard should be located between them.

The costs for drinking water production from the extracted groundwater (€0.93) are higher than conventional drinking water production methods. If the wells are located in an agricultural area with a small salt-tolerance a division of costs is may be possible.

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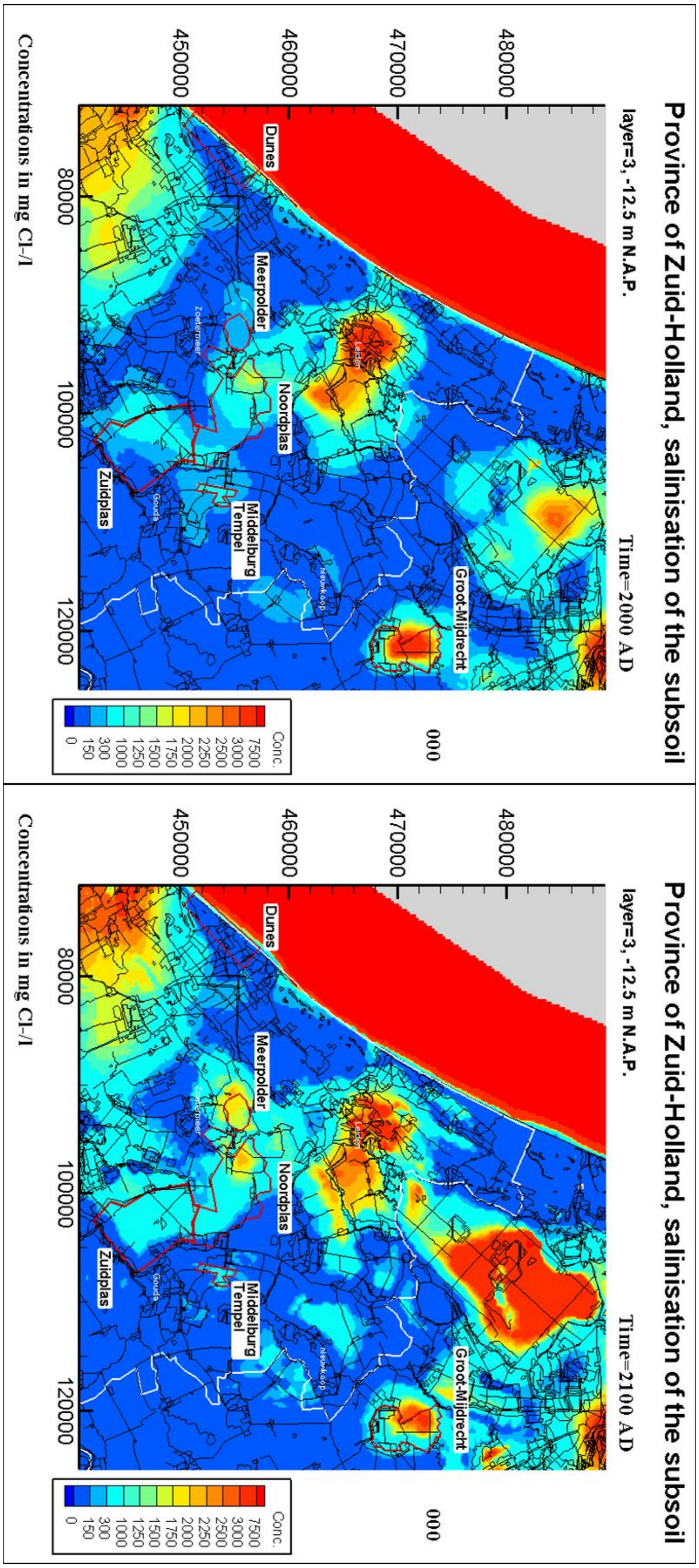
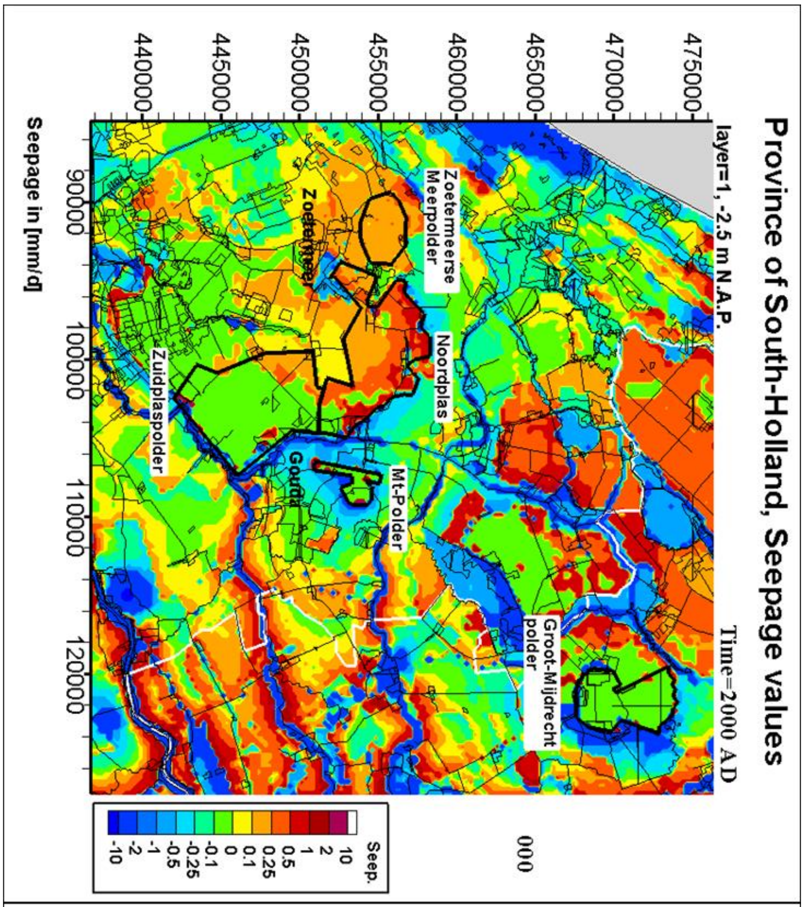
Appendix I: Autonomous salinization




Province of South-Holland, Seepage values
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Time=2000 AD
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470000
465000
460000
455000
450000
445000
440000
90000
100000
110000
120000
Zoetermeerse Meerpolder
Zoetermeer
Noordplas
Zuidplaspolder
Gouda
Mt-Polder
Groot-Mijdrecht polder
000
Seep.
10
2
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0.1
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-0.1
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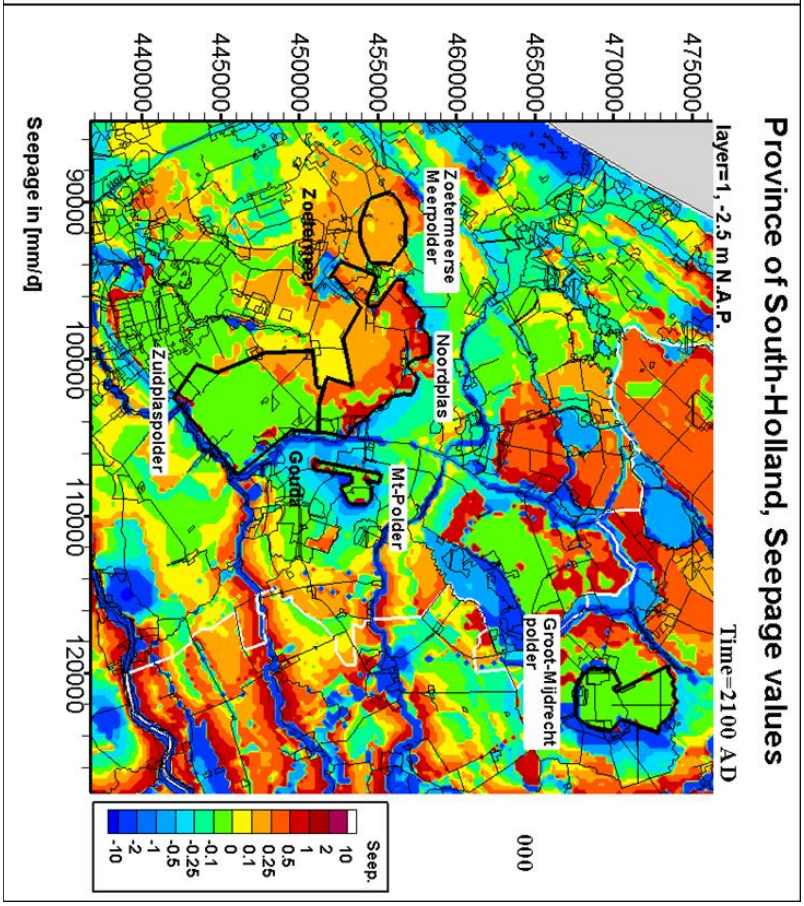
-0.5
-1
-2
-10
Seepage in [mm/d]


Province of South-Holland, Seepage values
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Time=2100 AD
475000
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465000
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455000
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445000
440000
90000
100000
110000
120000
Zoetermeerse Meerpolder
Zoetermeer
Noordplas
Zuidplaspolder
Gouda
Mt-Polder
Groot-Mijdrecht polder
000
Seep.
10
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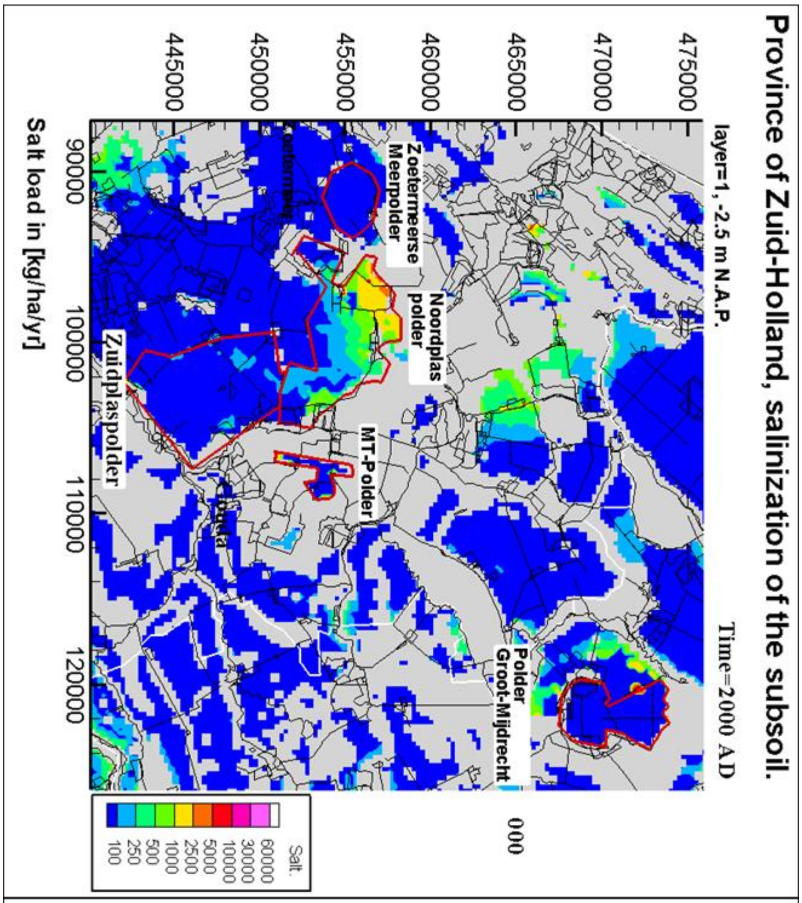
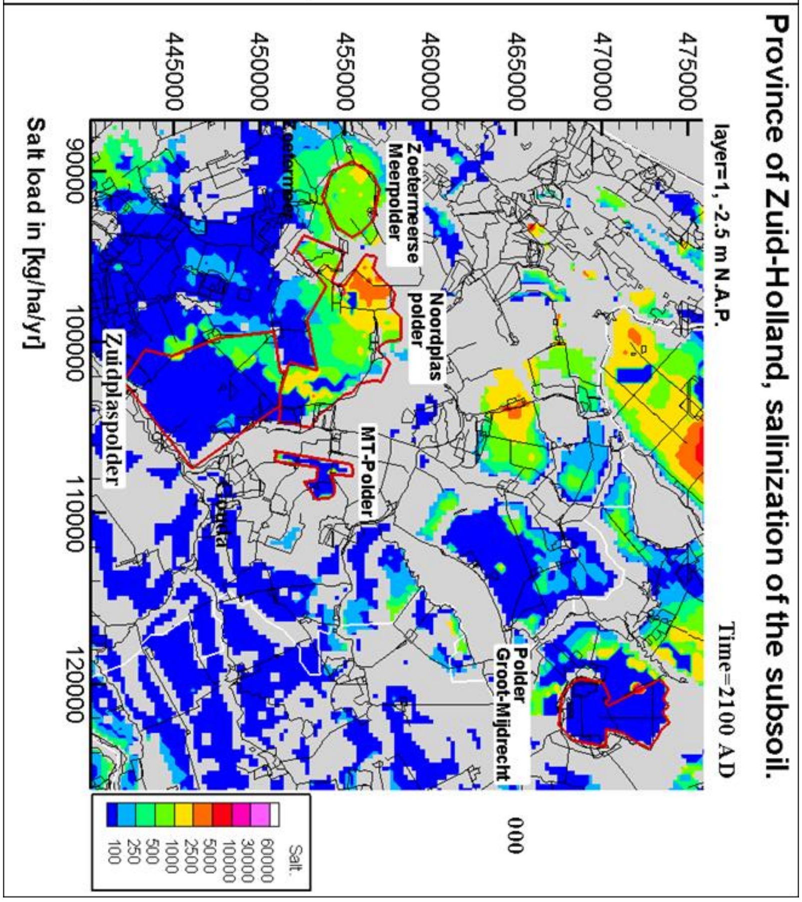
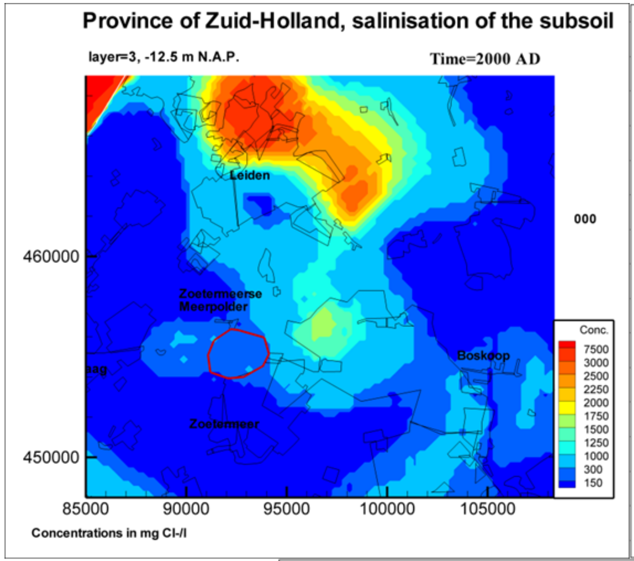
1
0.5
0.25
0.1
0
-0.1
-0.25
-0.5
-1
-2
-10
Seepage in [mm/d]

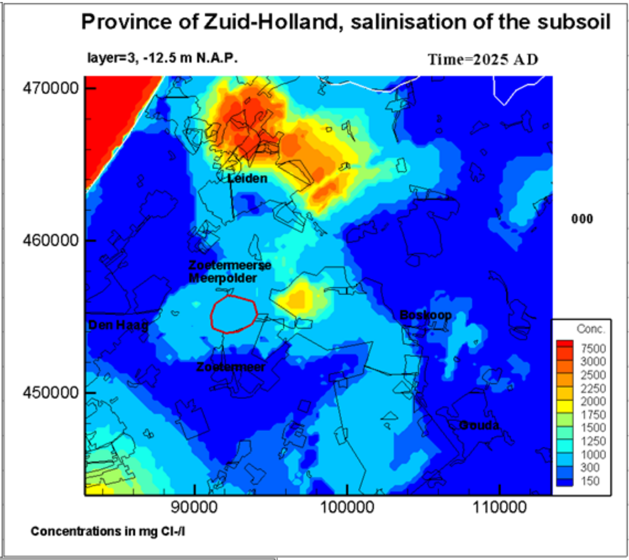


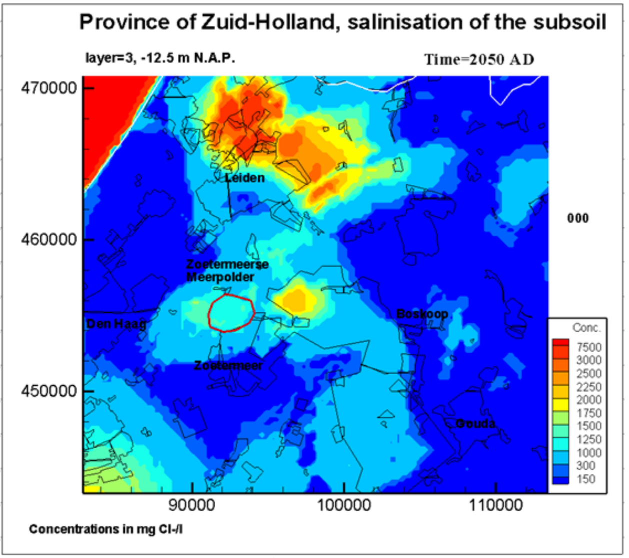
Province of Zuid-Holland, salinization of the subsoil.

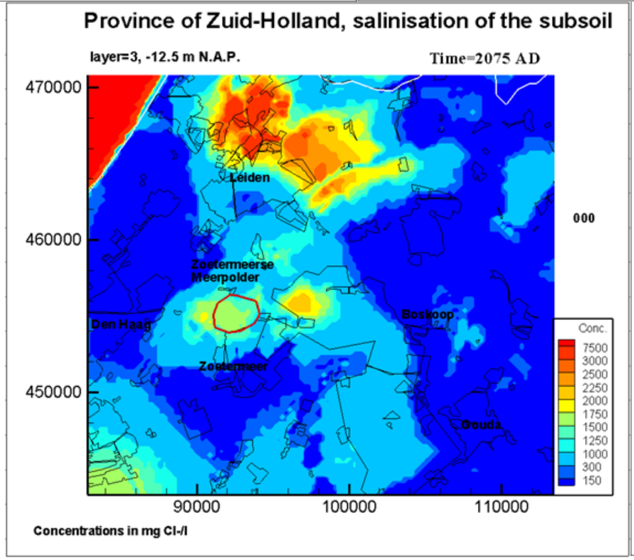


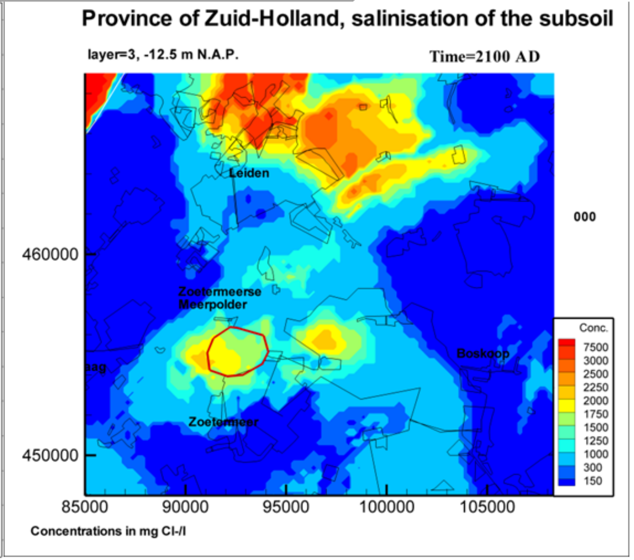
Province of Zuid-Holland, salinization of the subsoil.


Province of Zuid-Holland, salinisation of the subsoil


Province of Zuid-Holland, salinisation of the subsoil


Province of Zuid-Holland, salinisation of the subsoil


Province of Zuid-Holland, salinisation of the subsoil

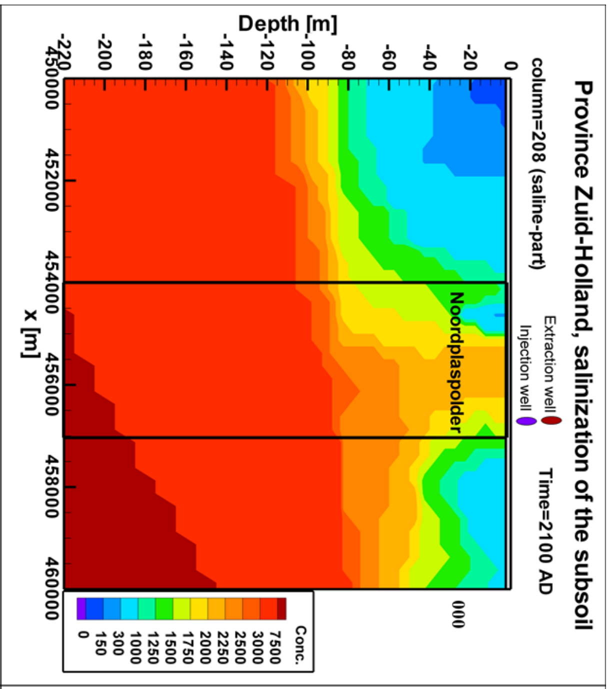

Province of Zuid-Holland, salinisation of the subsoil

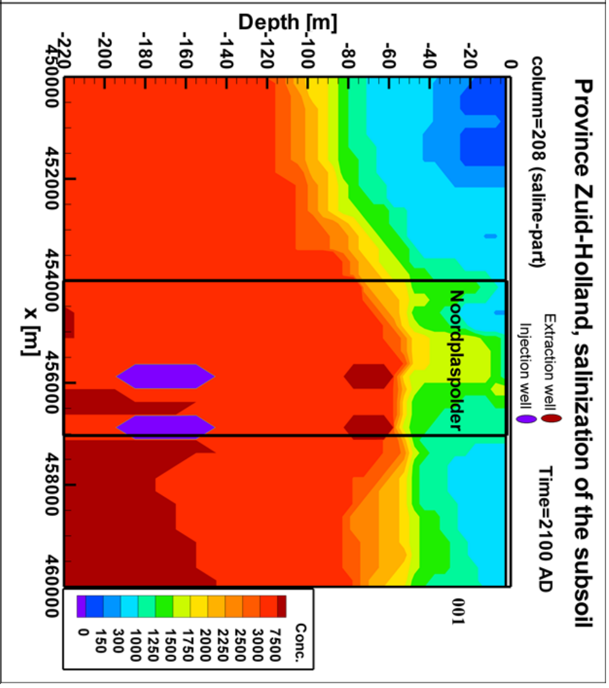
Appendix II: Depth of the wells

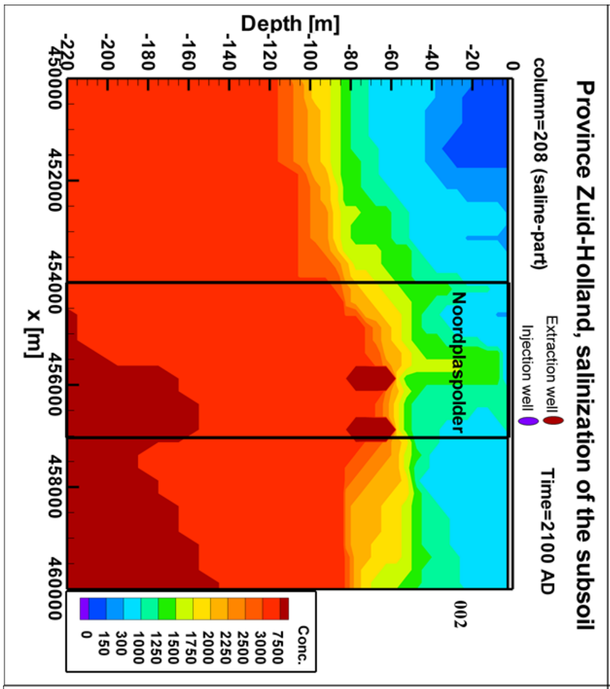
2050 scenarios	Extraction				Injection			
Areas:	Q	concentration	wells	depth	Q	concentration	wells	depth
Noordplas	*(Mm3/y)*	*(mgl-1 Cl-)*	*(n)*	*(m below NAP)*	*(Mm^3/y)*	*(mgl-1 Cl-)*	*(n)*	*(m below NAP)*
001	8	2600	23	62.5-82.5	4	6000	23	155-195
002	8	2100	23	62.5-82.5	0	-	0	-
003	16	3000	23	62.5-82.5	8	6000	23	155-195
MT-polder								
101	5	1600	6	57.5-72.5	2.5	3000	6	145-185
102	5	1200	6	57.5-72.5	0	-	0	-
Zuidplas								
201	8	1800	23	72.5-82.5	4	3400	23	165-185
202	8	1200	23	72.5-82.5	0	-	0	-
Zoetermeerse Meerpolder								
301	3.5	3600	7	57.5-82.5	1.75	7400	7	195-235
302	3.5	2800	7	57.5-82.5	0	-	0	-
Groot-Mijdrecht								
401	6.6	2600	10	62.5-92.5	0	-	0	-
402	6.6	3100	10	92.5-125	0	-	0	-
Dunes								
501	1.5	1900	4	47.5-52.5	0	-	0	-

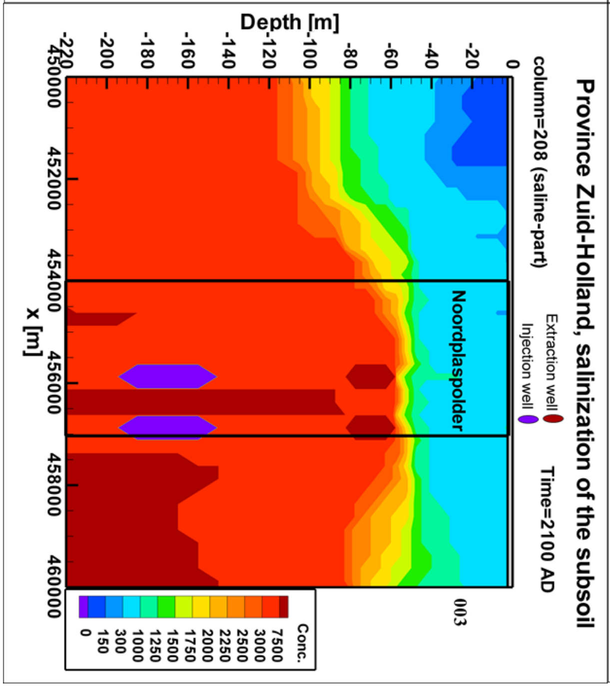
Appendix III Concentration per scenario

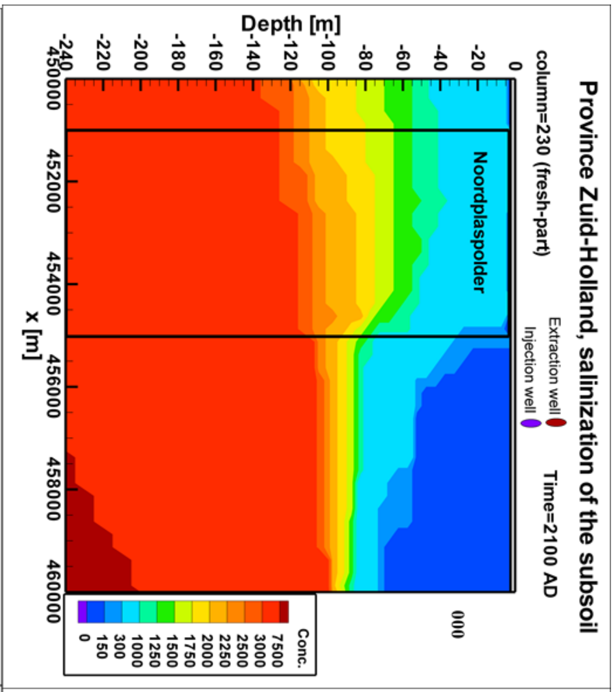
Noordplas polder scenarios

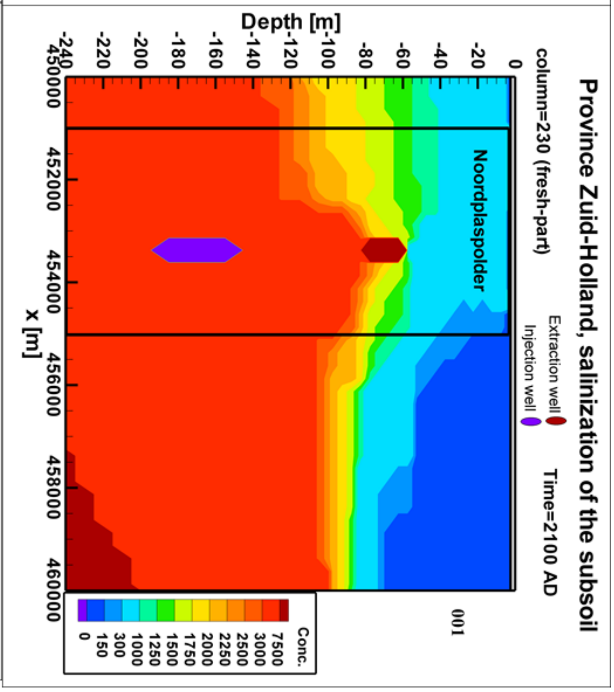


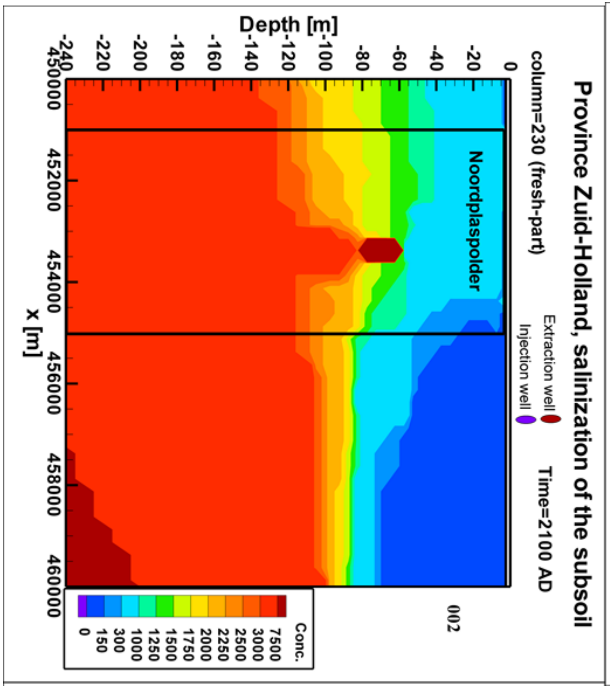


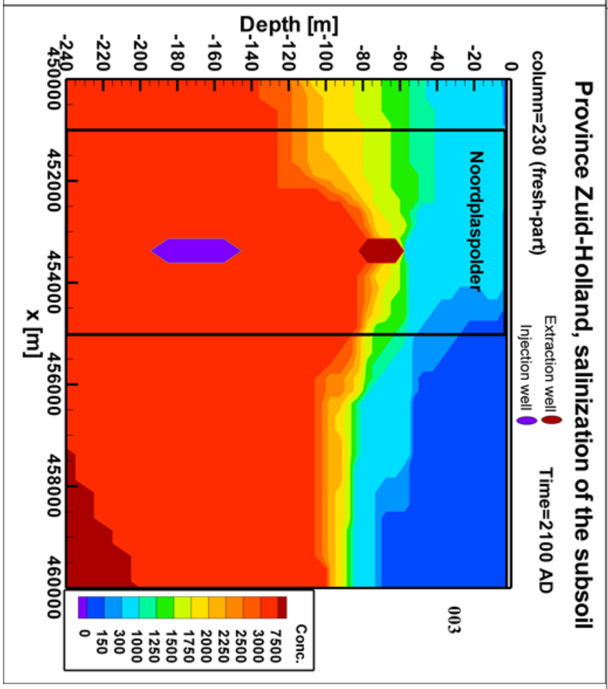




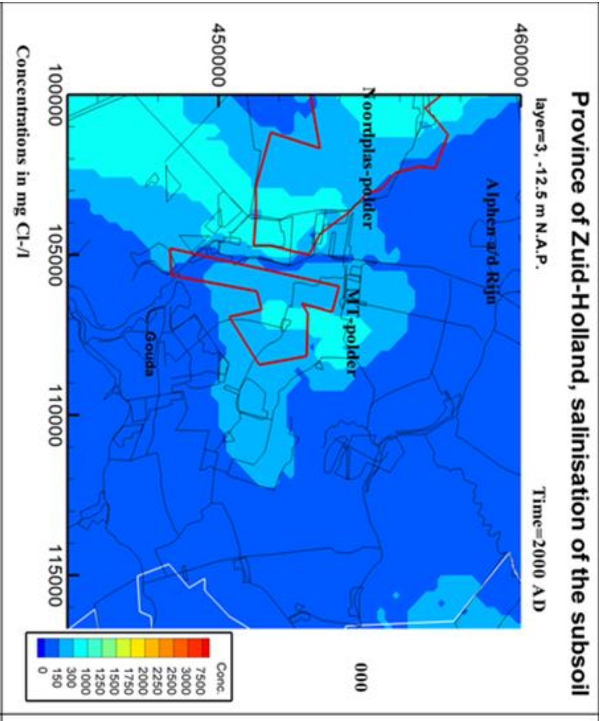

Province Zuid-Holland, salinization of the subsoil
column=230 (fresh-part)
Extraction well
Injection well
Time=2100 AD
000
Noordplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
450000
452000
454000
456000
458000
460000
x [m]
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

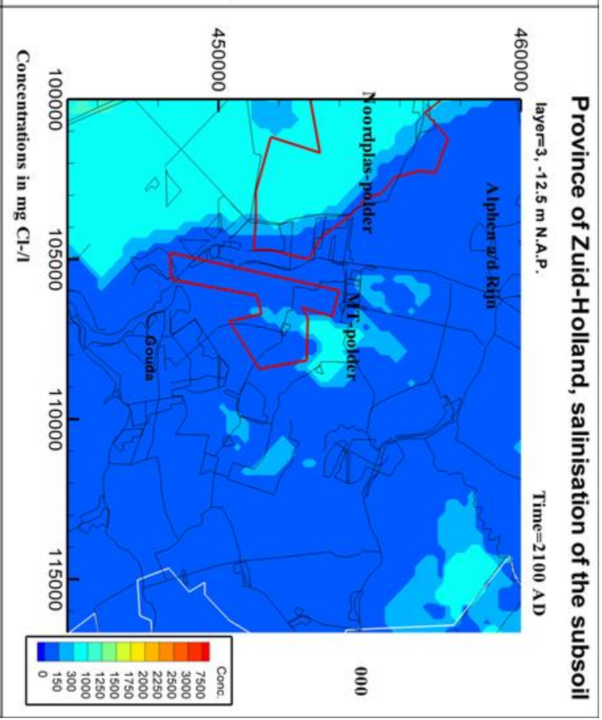

Province Zuid-Holland, salinization of the subsoil
column=230 (fresh-part)
Extraction well
Injection well
Time=2100 AD
001
Noordplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
450000
452000
454000
456000
458000
460000
x [m]
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

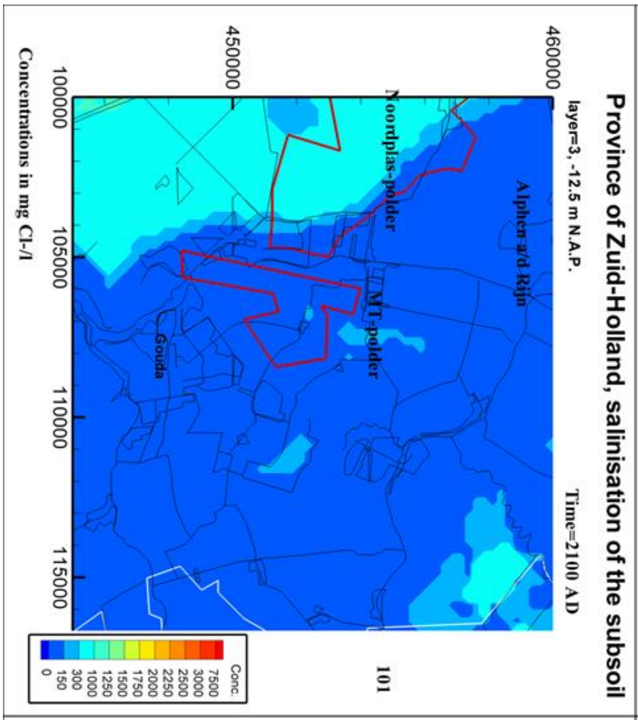

Province Zuid-Holland, salinization of the subsoil
column=230 (fresh-part)
Extraction well
Injection well
Time=2100 AD
002
Noordplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
450000
452000
454000
456000
458000
460000
x [m]
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

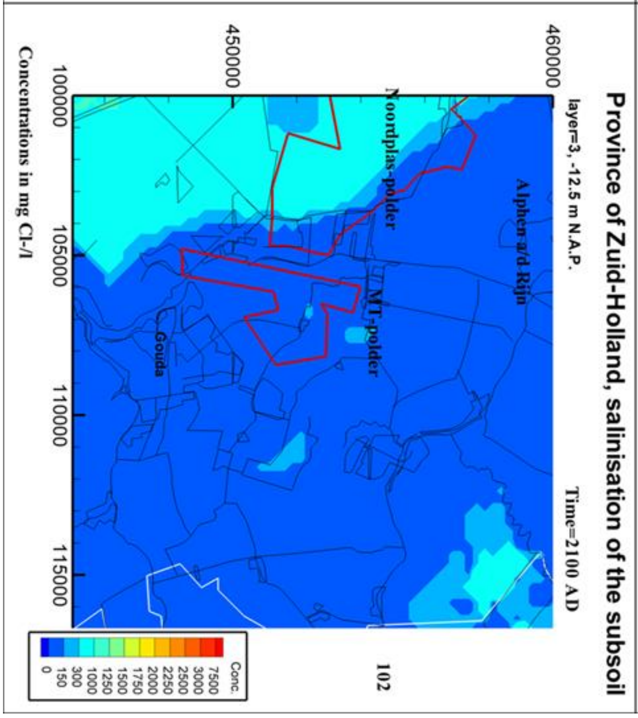

Province Zuid-Holland, salinization of the subsoil
column=230 (fresh-part)
Extraction well
Injection well
Time=2100 AD
003
Noordplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
450000
452000
454000
456000
458000
460000
x [m]
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

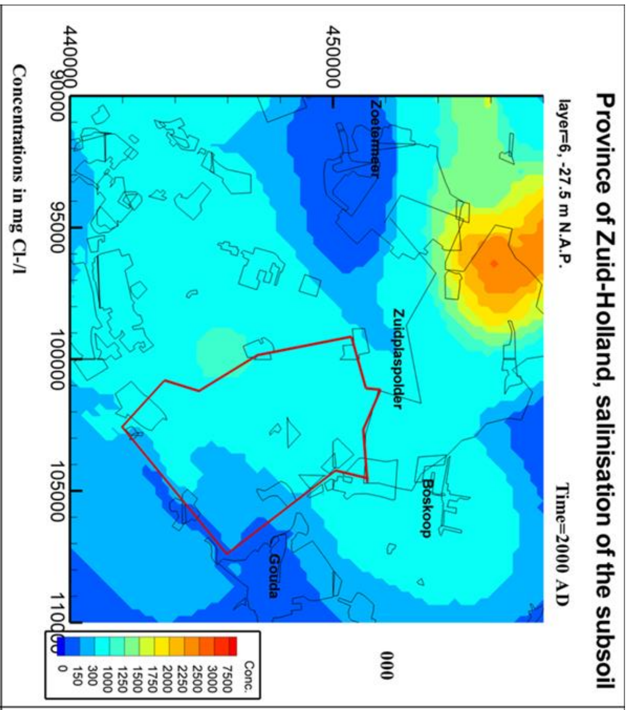
Middelburg-Tempel polder scenarios

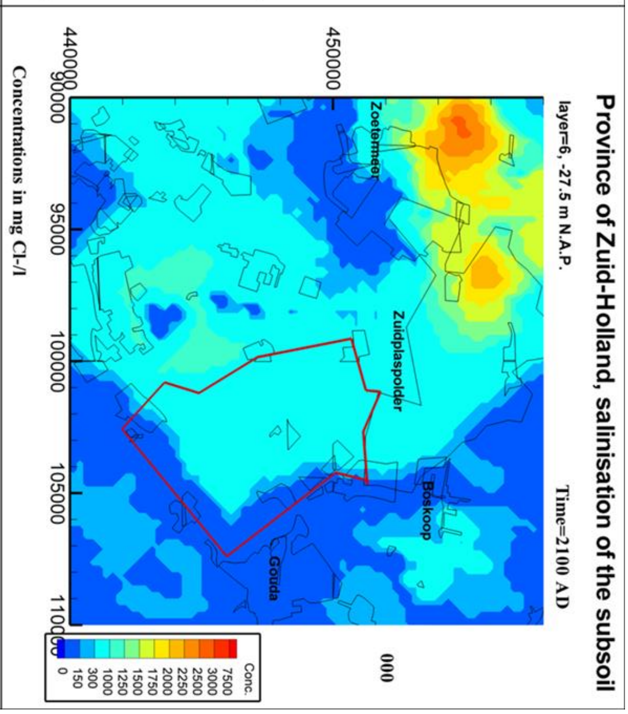


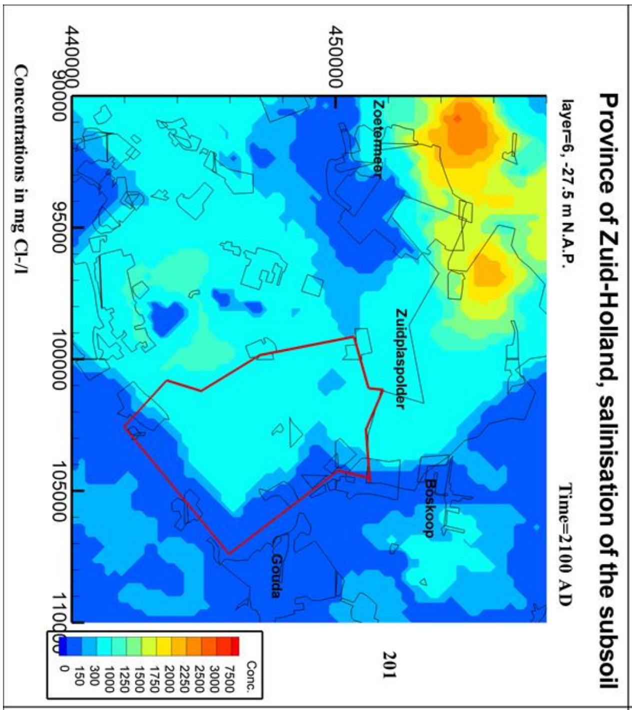


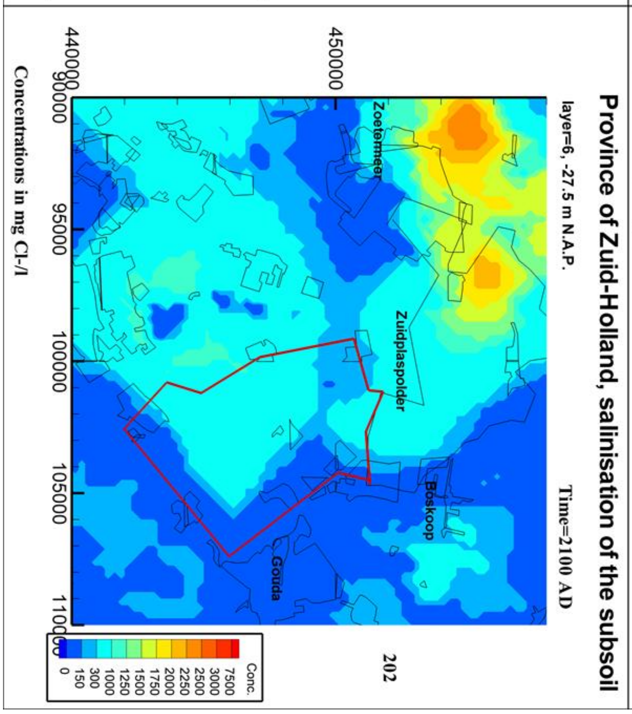


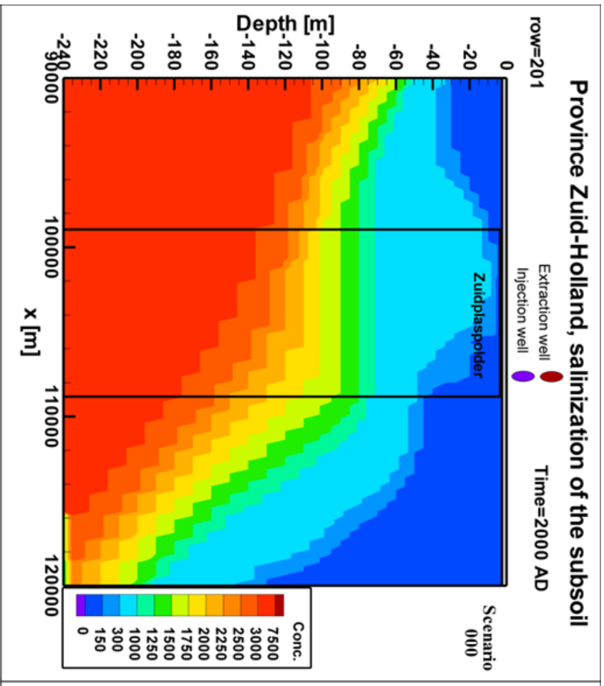


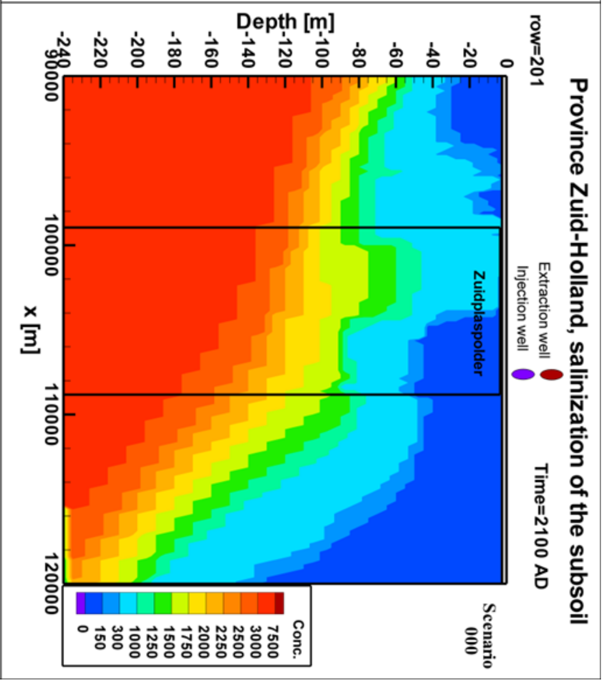

Province of Zuid-Holland, salinisation of the subsoil
layer=6, -27.5 m N.A.P.
Time=2000 AD
000
Zoetermeer
Zuidplaspolder
Boskoop
Gouda
440000
450000
90000
95000
100000
105000
110000
Concentrations in mg Cl-/l
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

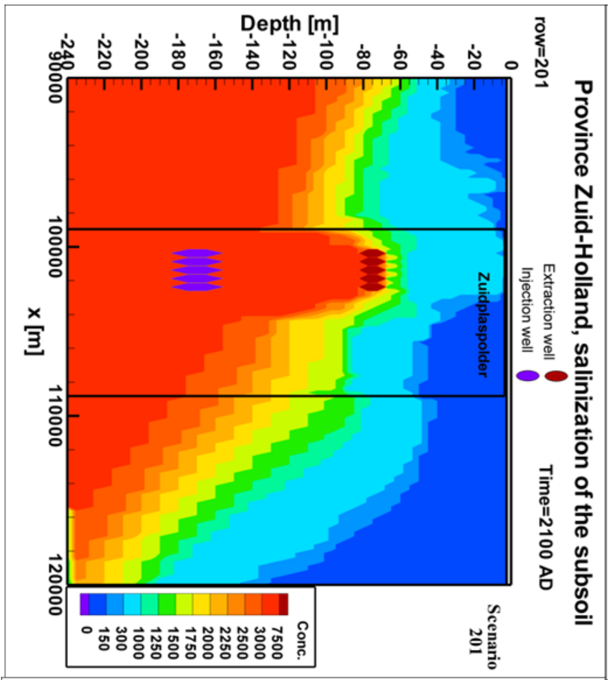

Province of Zuid-Holland, salinisation of the subsoil
layer=6, -27.5 m N.A.P.
Time=2100 AD
000
Zoetermeer
Zuidplaspolder
Boskoop
Gouda
440000
450000
90000
95000
100000
105000
110000
Concentrations in mg Cl-/l
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

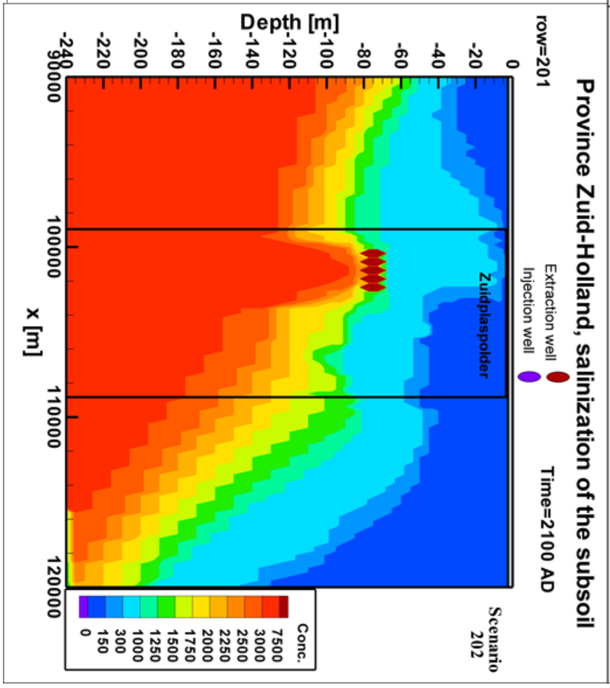

Province of Zuid-Holland, salinisation of the subsoil
layer=6, -27.5 m N.A.P.
Time=2100 AD
201
Zoetermeer
Zuidplaspolder
Boskoop
Gouda
440000
450000
90000
95000
100000
105000
110000
Concentrations in mg Cl-/l
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0


Province of Zuid-Holland, salinisation of the subsoil
layer=6, -27.5 m N.A.P.
Time=2100 AD
202
Zoetermeer
Zuidplaspolder
Boskoop
Gouda
440000
450000
90000
95000
100000
105000
110000
Concentrations in mg Cl-/l
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

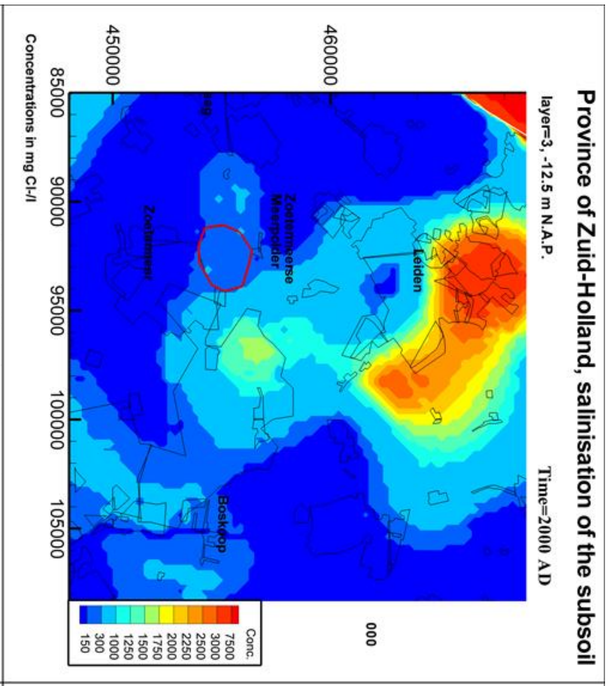

Province Zuid-Holland, salinization of the subsoil
row=201
Time=2000 AD
Scenario 000
Extraction well
Injection well
Zuidplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
x [m]
90000
100000
110000
120000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

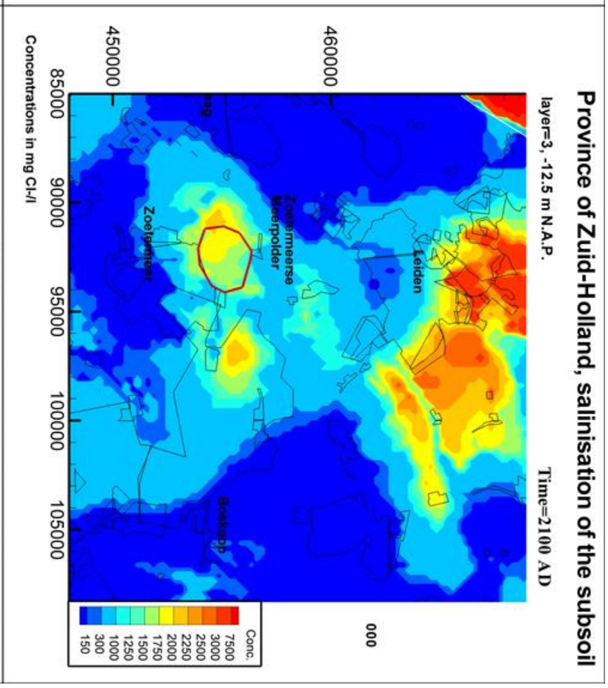

Province Zuid-Holland, salinization of the subsoil
row=201
Time=2100 AD
Scenario 000
Extraction well
Injection well
Zuidplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
x [m]
90000
100000
110000
120000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

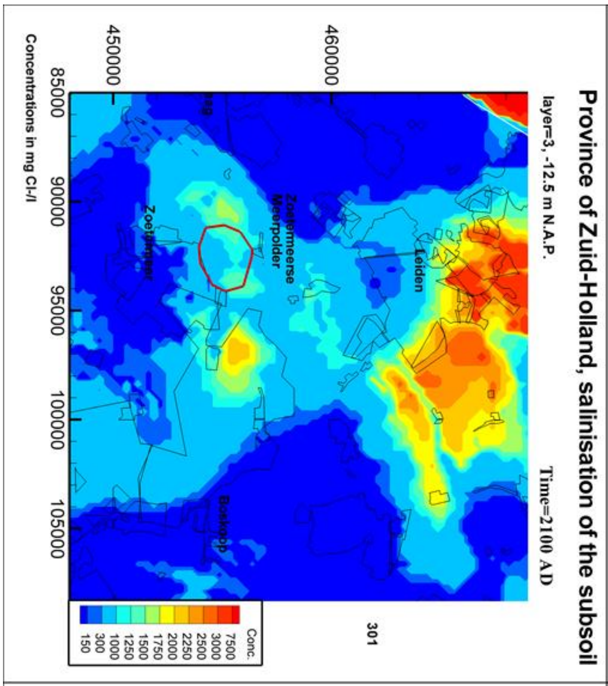

Province Zuid-Holland, salinization of the subsoil
row=201
Time=2100 AD
Scenario 201
Extraction well
Injection well
Zuidplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
x [m]
90000
100000
110000
120000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

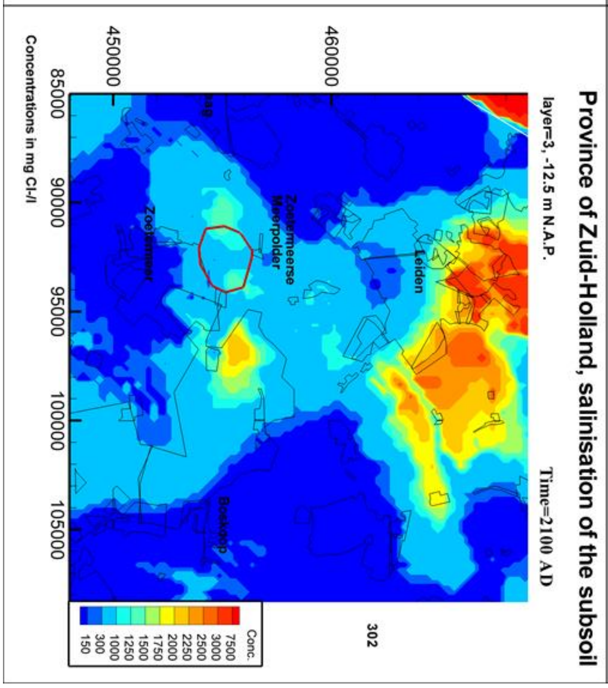

Province Zuid-Holland, salinization of the subsoil
row=201
Time=2100 AD
Scenario 202
Extraction well
Injection well
Zuidplaspolder
Depth [m]
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
x [m]
90000
100000
110000
120000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

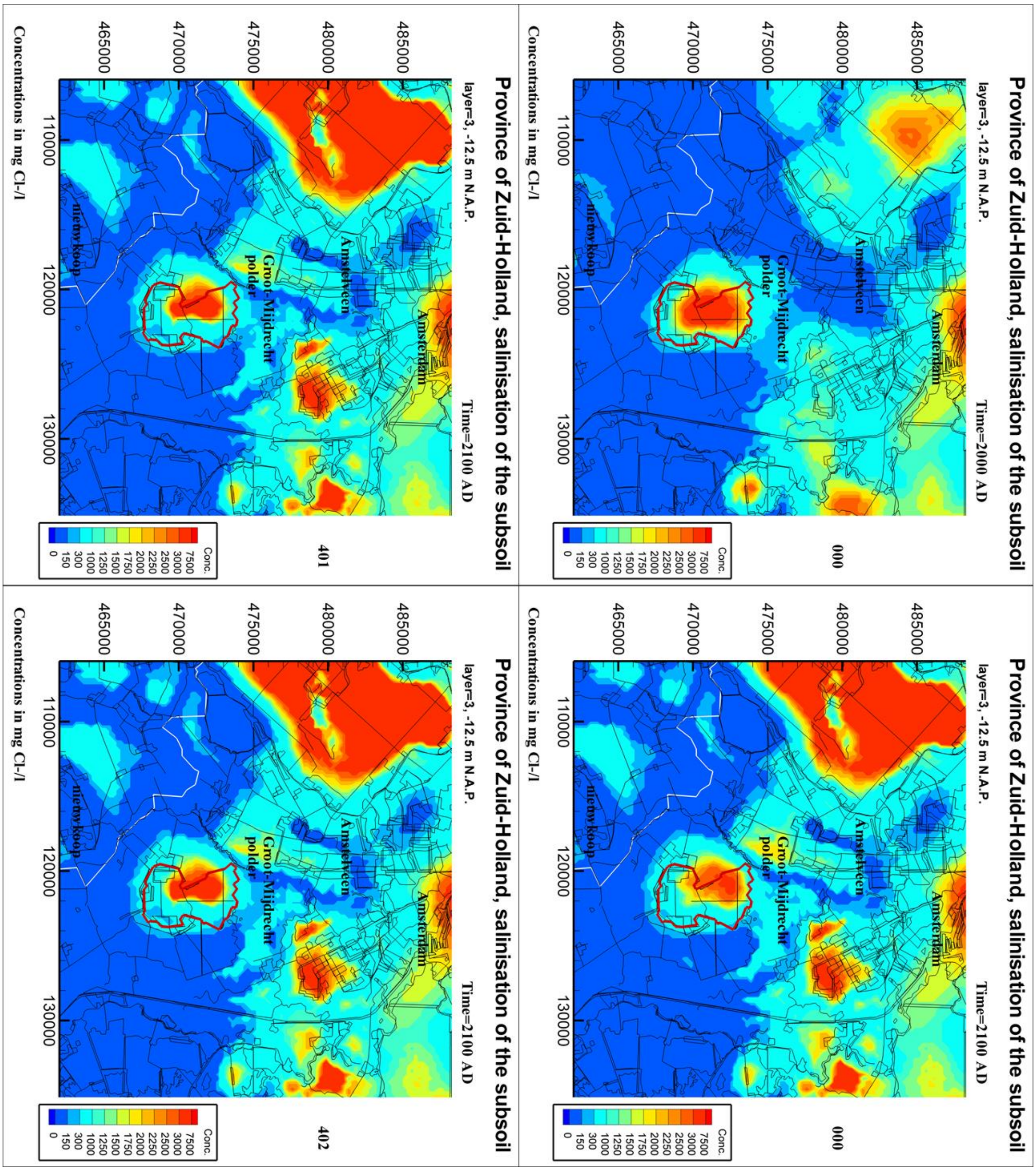
Zoetermeerse Meerpolder scenarios



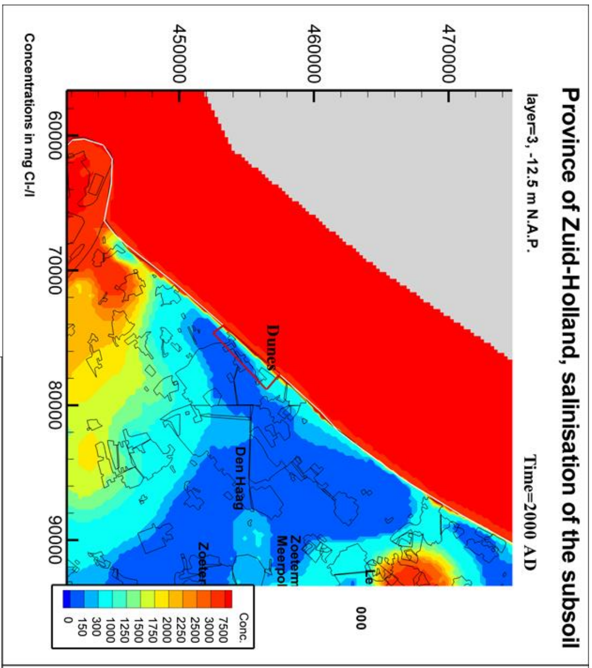


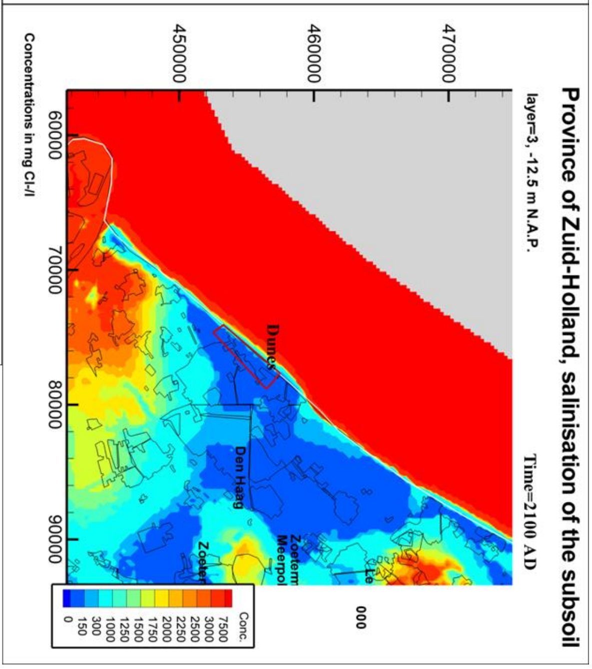


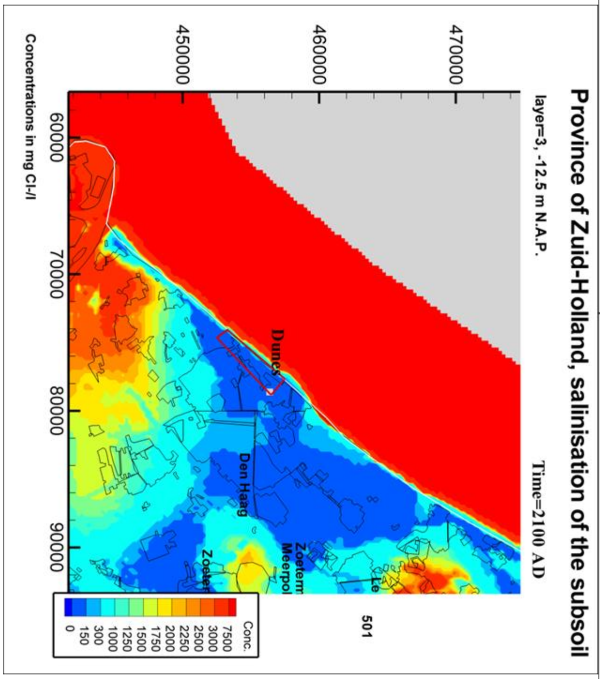


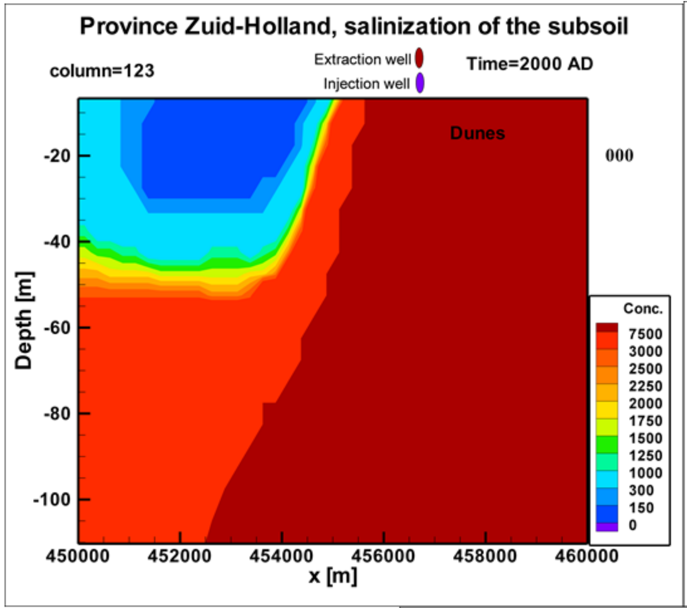

Province of Zuid-Holland, salinisation of the subsoil
layer=3, -12.5 m N.A.P.
Time=2000 AD
000
Province of Zuid-Holland, salinisation of the subsoil
layer=3, -12.5 m N.A.P.
Time=2100 AD
000
Province of Zuid-Holland, salinisation of the subsoil
layer=3, -12.5 m N.A.P.
Time=2100 AD
401
Province of Zuid-Holland, salinisation of the subsoil
layer=3, -12.5 m N.A.P.
Time=2100 AD
402
Amsterdam
Amstelveen
Groot-Mijdrecht polder
nieuwkoop
485000
480000
475000
470000
465000
110000
120000
130000
Concentrations in mg Cl-/l
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

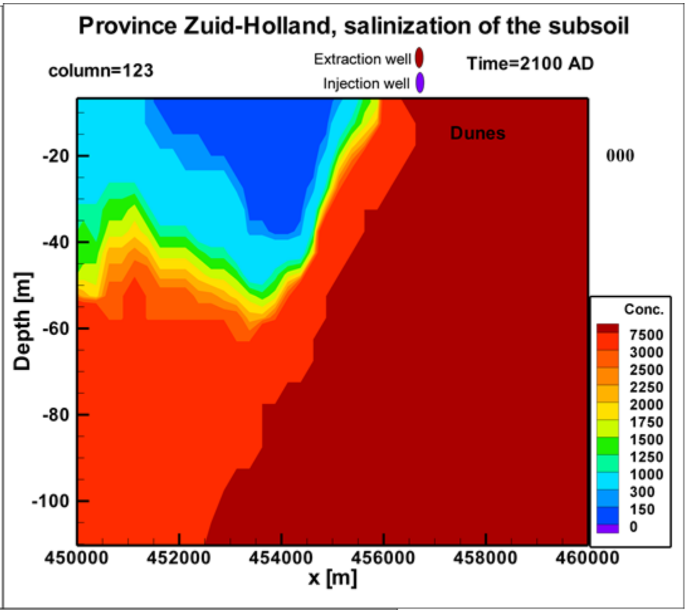
Dune scenarios

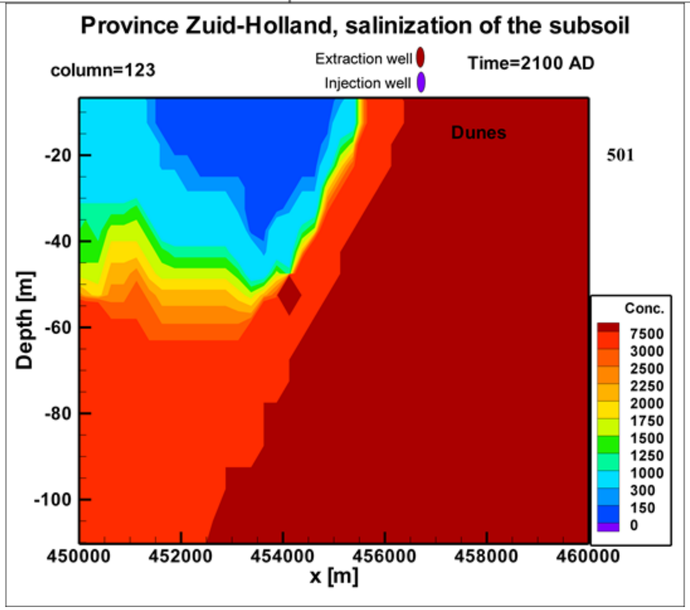


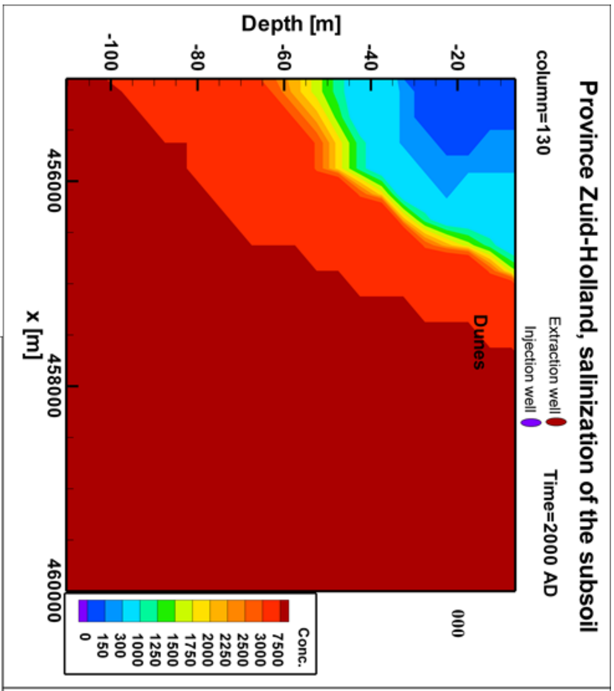


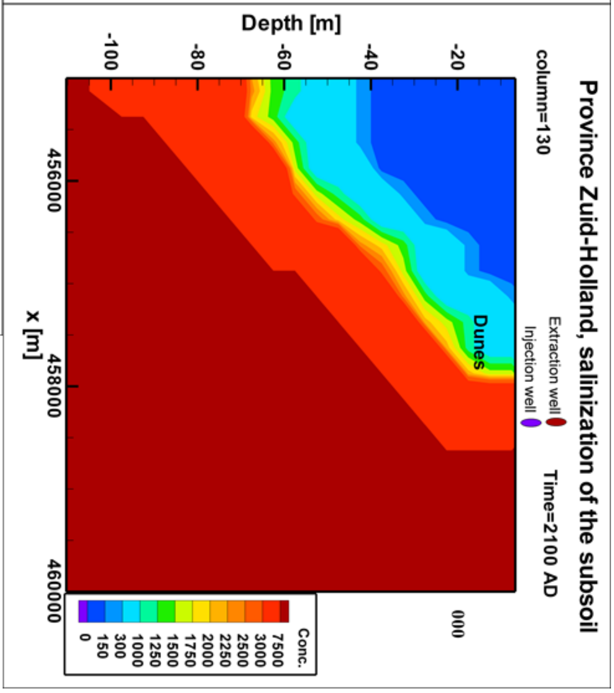


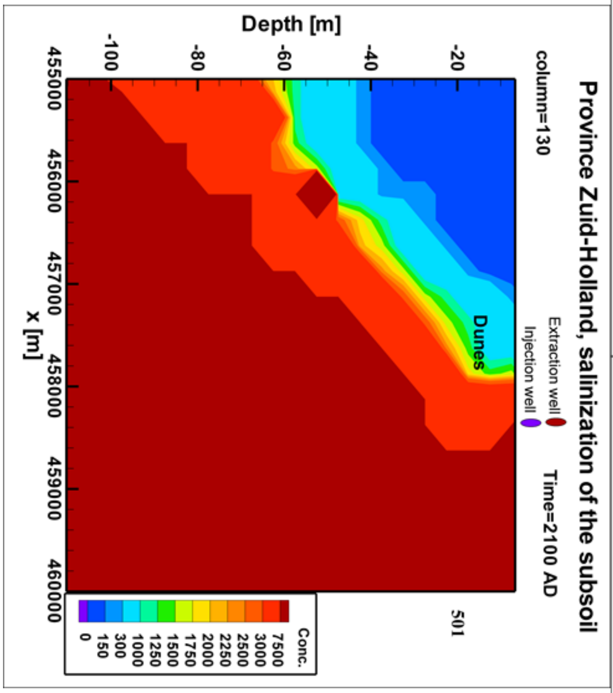

Province Zuid-Holland, salinization of the subsoil
column=123
Extraction well
Injection well
Time=2000 AD
Dunes
000
Depth [m]
-20
-40
-60
-80
-100
x [m]
450000
452000
454000
456000
458000
460000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0


Province Zuid-Holland, salinization of the subsoil
column=123
Extraction well
Injection well
Time=2100 AD
Dunes
000
Depth [m]
-20
-40
-60
-80
-100
x [m]
450000
452000
454000
456000
458000
460000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0


Province Zuid-Holland, salinization of the subsoil
column=123
Extraction well
Injection well
Time=2100 AD
Dunes
501
Depth [m]
-20
-40
-60
-80
-100
x [m]
450000
452000
454000
456000
458000
460000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0


Province Zuid-Holland, salinization of the subsoil
column=130
Time=2000 AD
Extraction well
Injection well
Dunes
000
Depth [m]
-20
-40
-60
-80
-100
x [m]
456000
458000
460000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0


Province Zuid-Holland, salinization of the subsoil
column=130
Time=2100 AD
Extraction well
Injection well
Dunes
000
Depth [m]
-20
-40
-60
-80
-100
x [m]
456000
458000
460000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

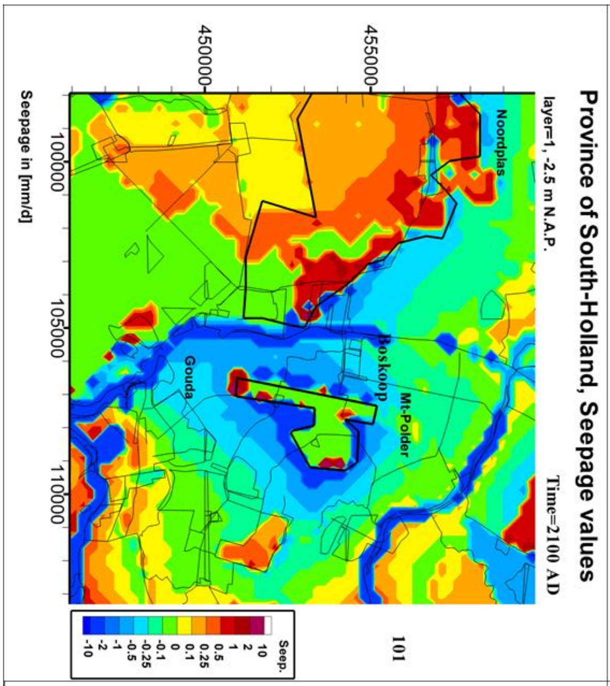

Province Zuid-Holland, salinization of the subsoil
column=130
Time=2100 AD
Extraction well
Injection well
Dunes
501
Depth [m]
-20
-40
-60
-80
-100
x [m]
455000
456000
457000
458000
459000
460000
Conc.
7500
3000
2500
2250
2000
1750
1500
1250
1000
300
150
0

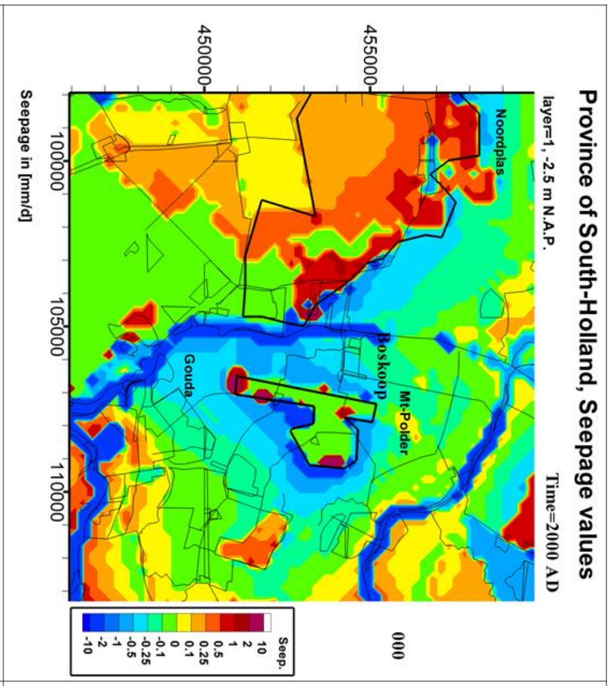
Universiteit Utrecht

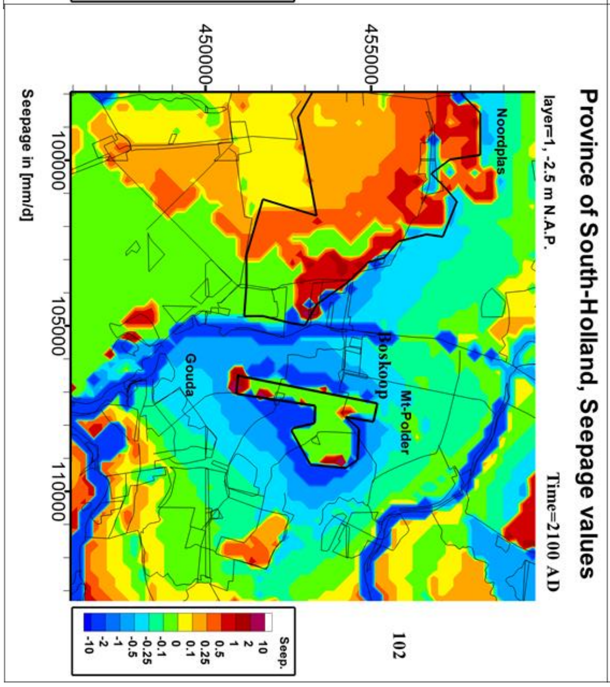
Deltares

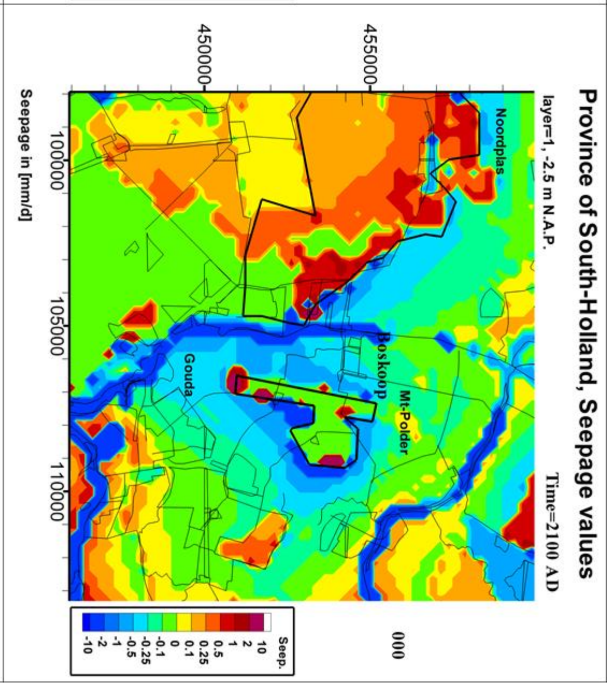
Appendix IV: Seepage values

Middelburg-Tempelpolder scenarios

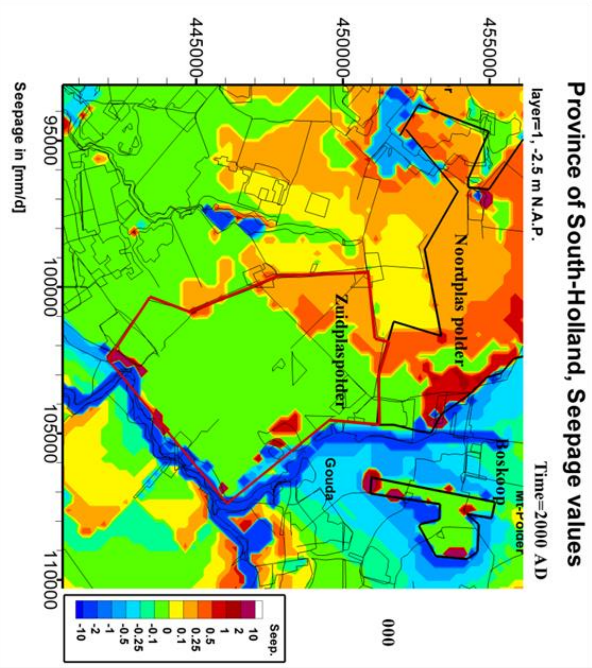


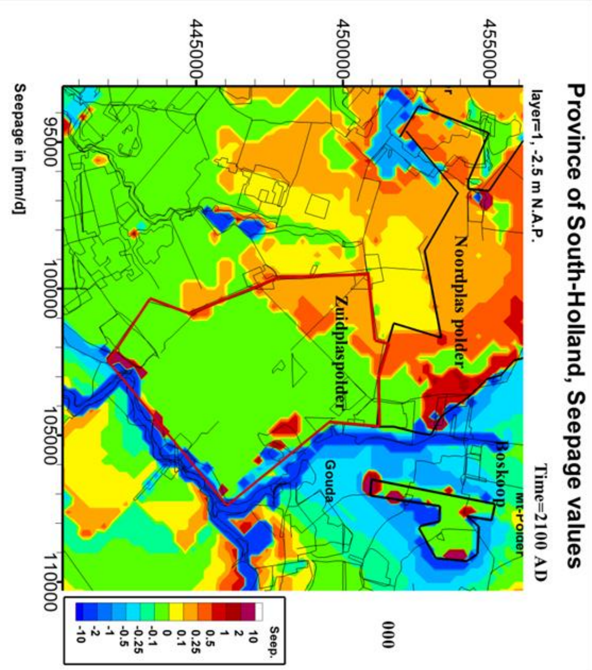


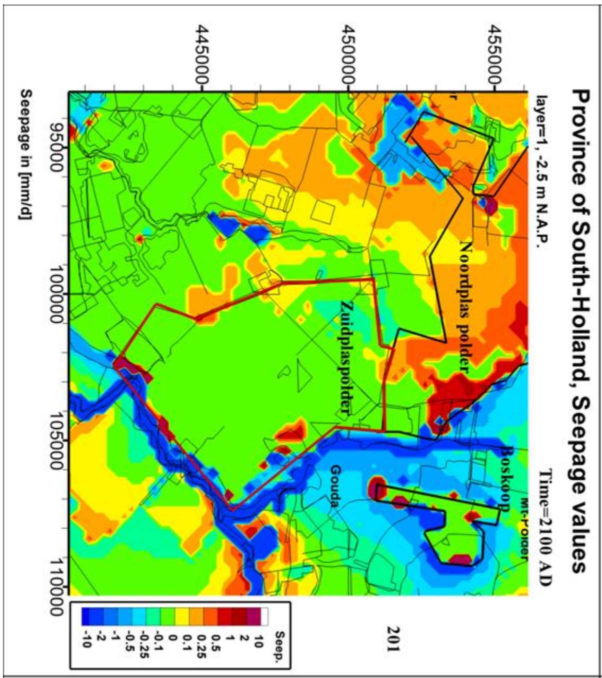


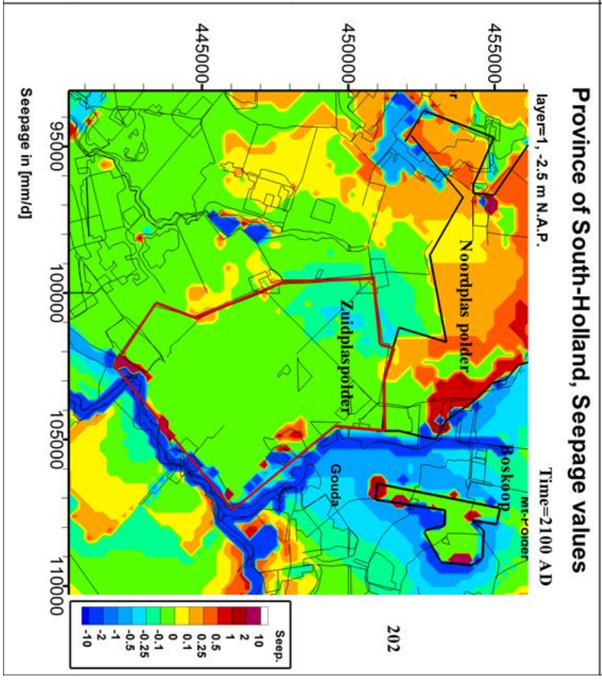


Zuidplas polder scenarios

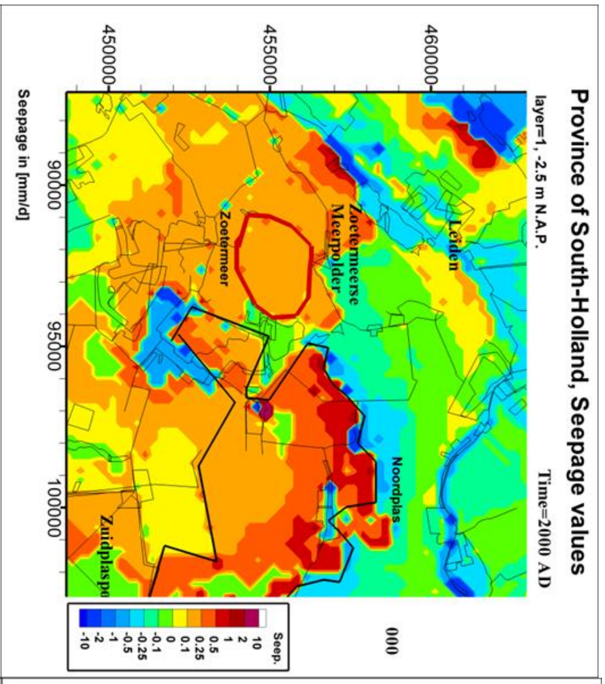


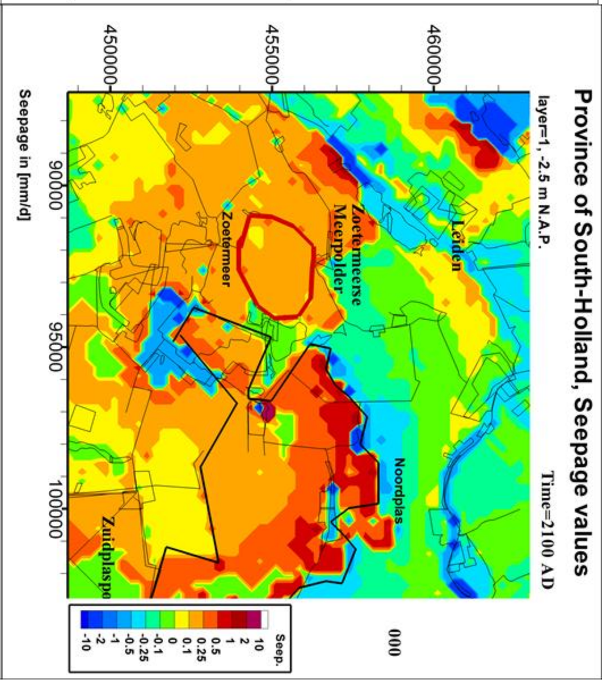


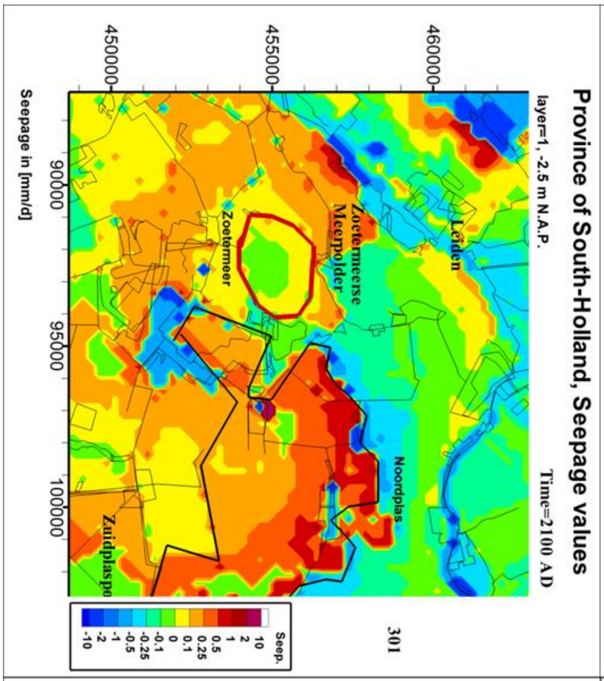


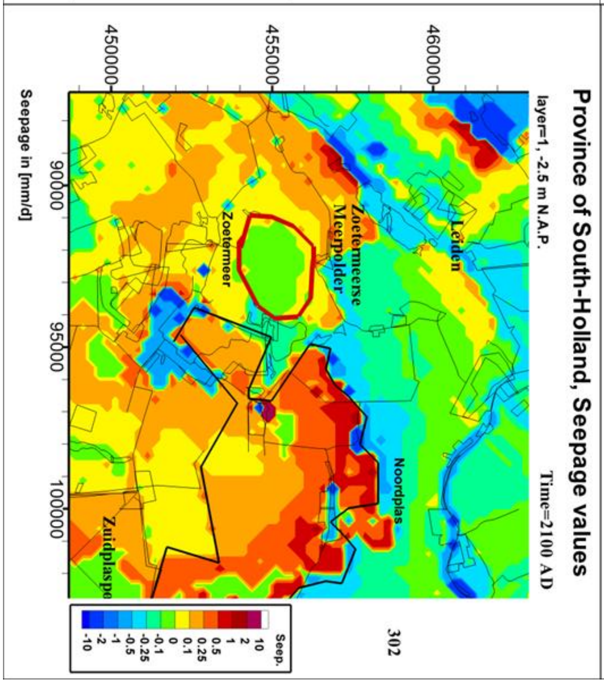


Zoetermeerse Meerpolder scenarios

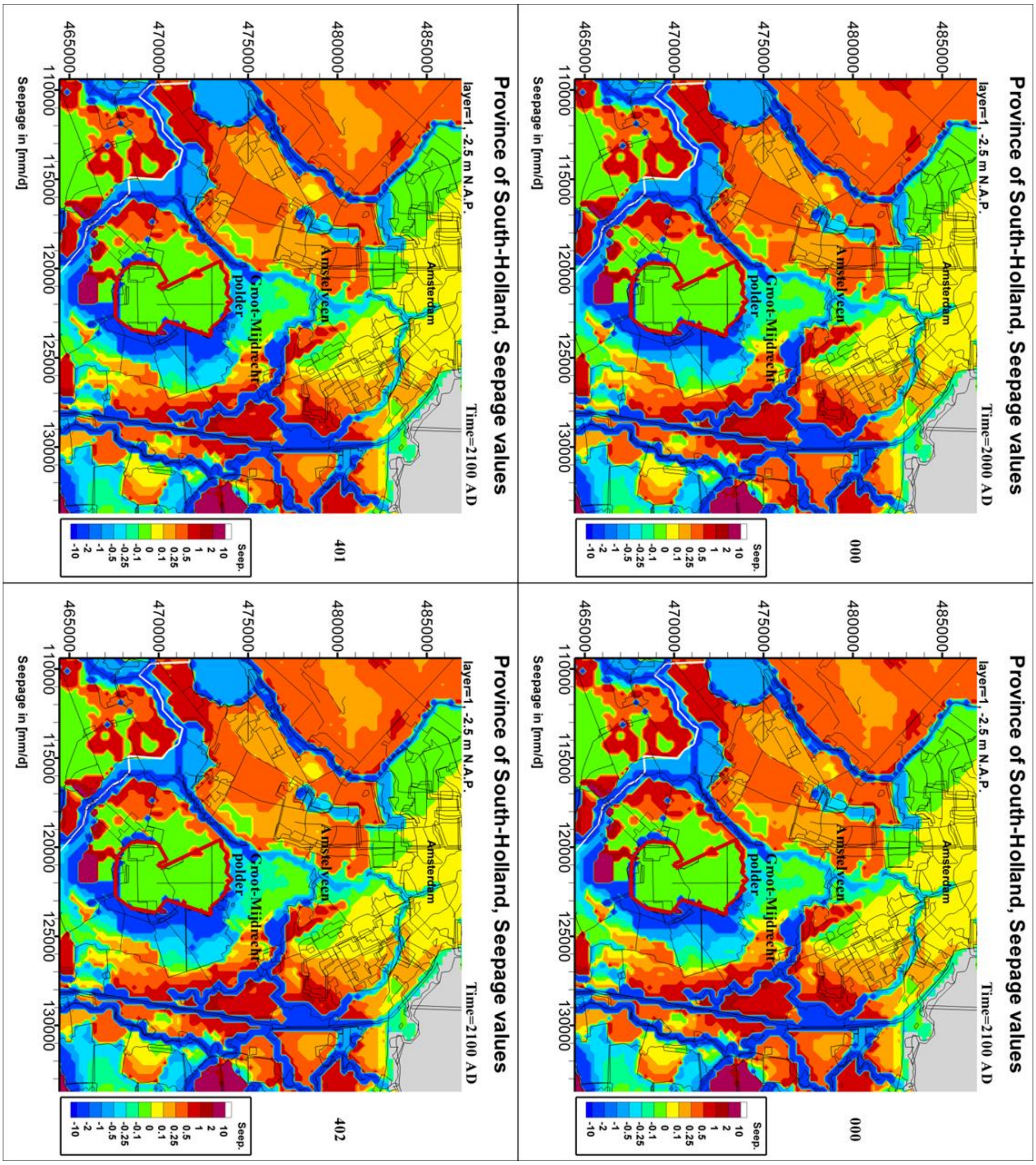




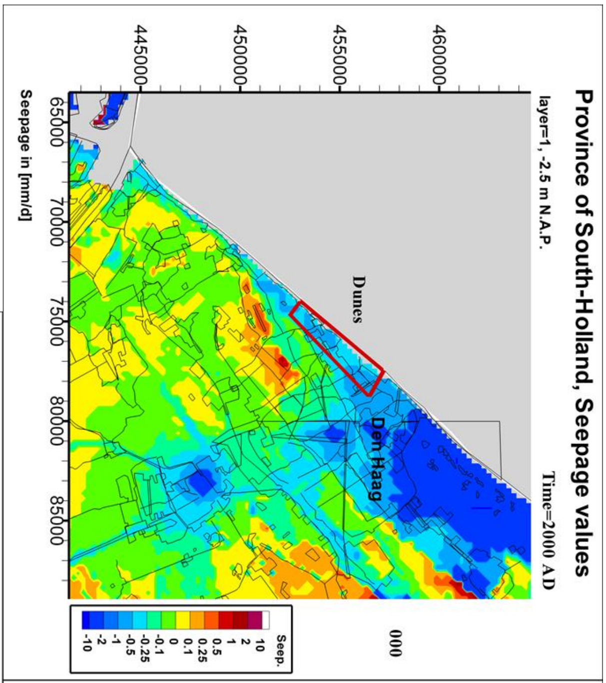


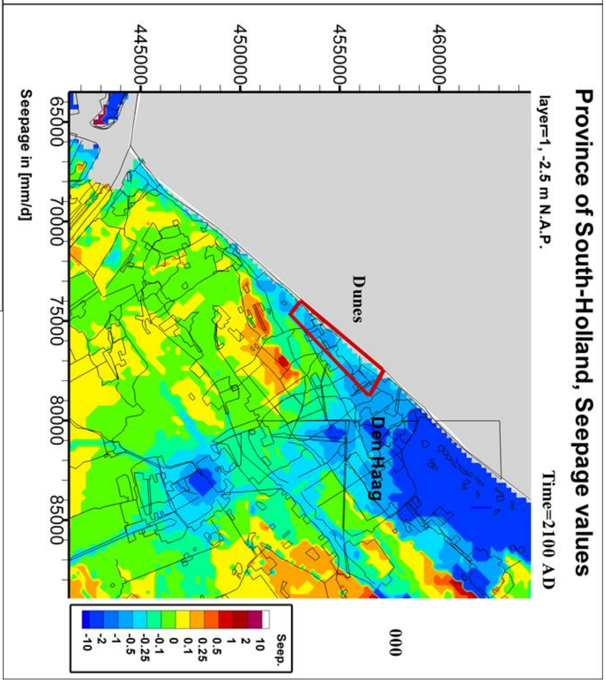


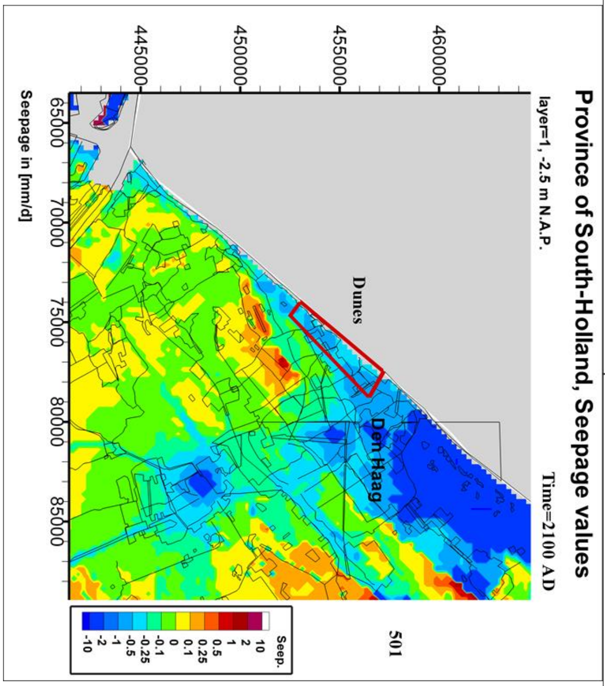
Groot-Mijdrecht polder scenarios



Dune scenarios

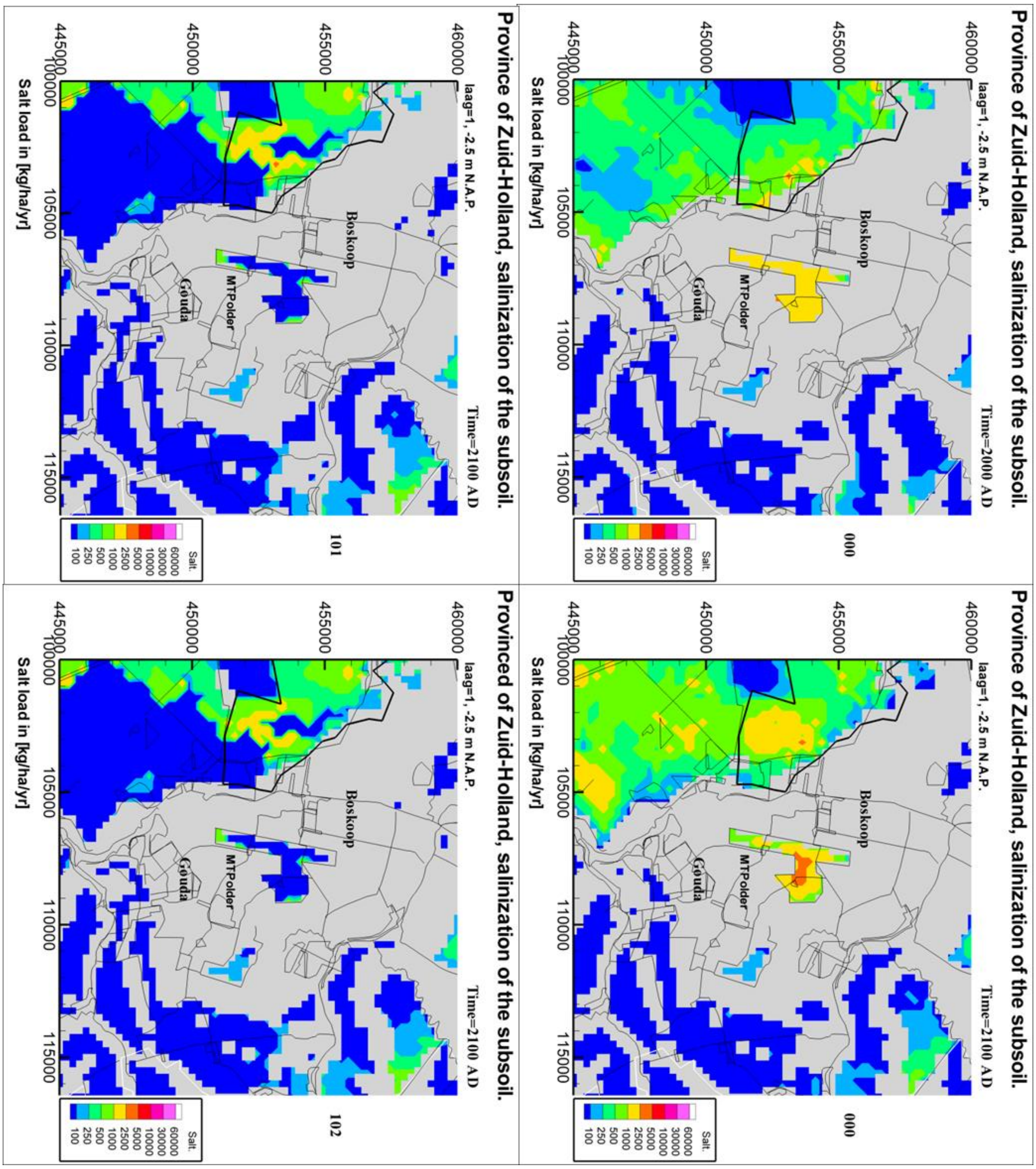


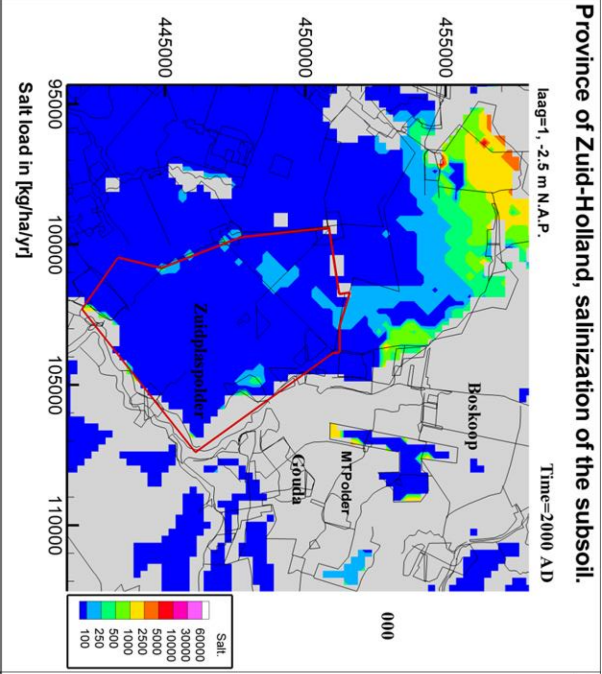


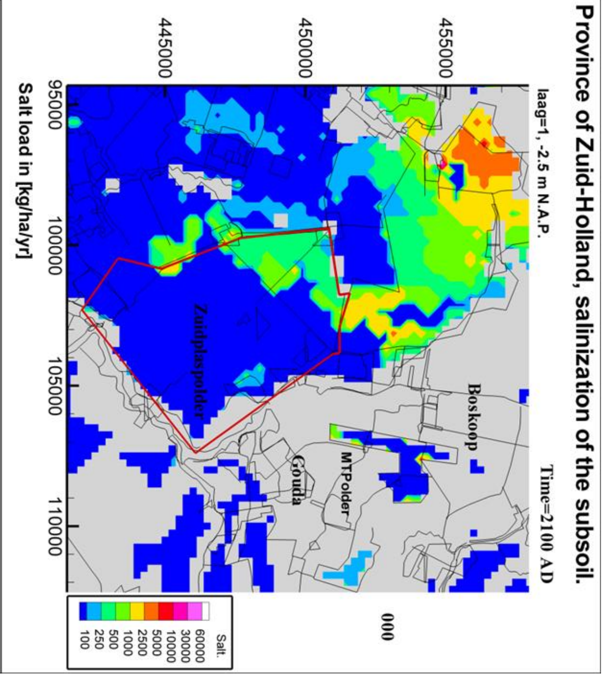


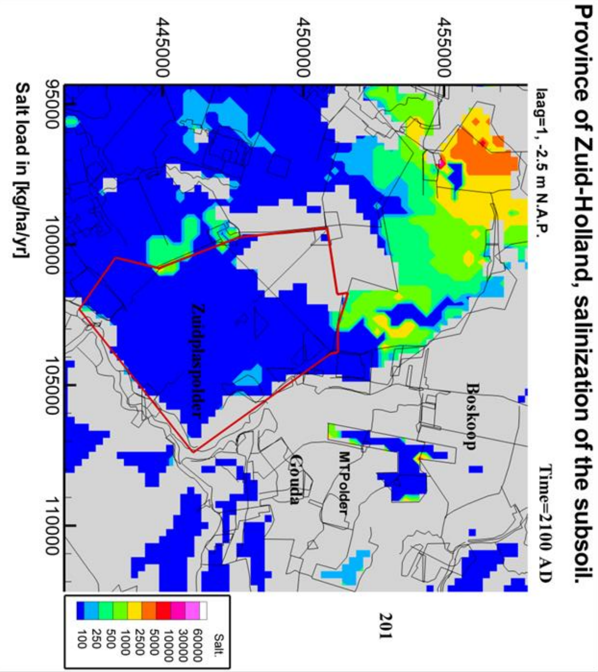
Appendix V: Salt load.

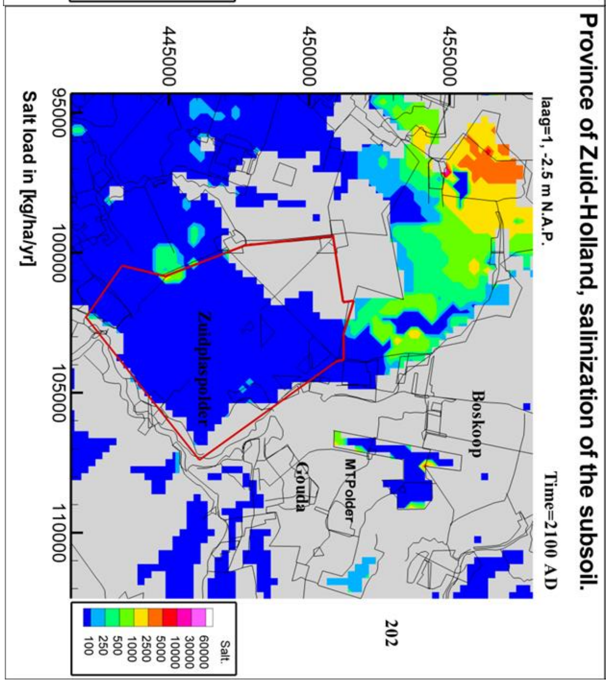
Middelburg-Tempel polder scenarios

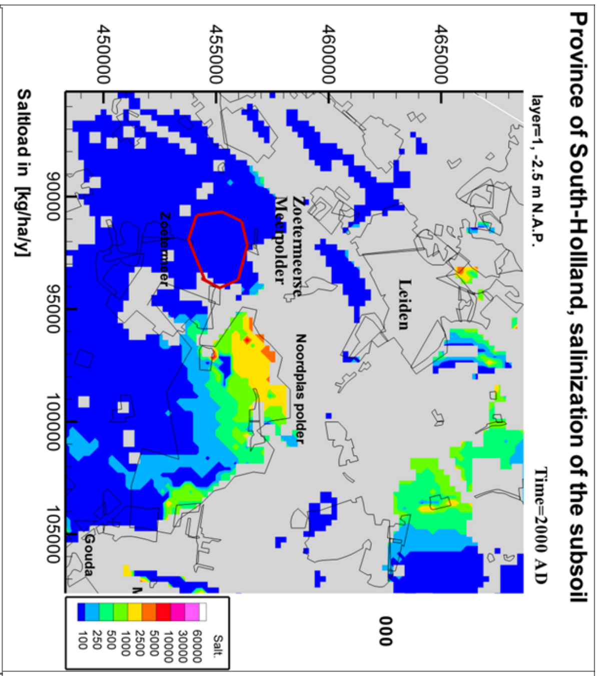


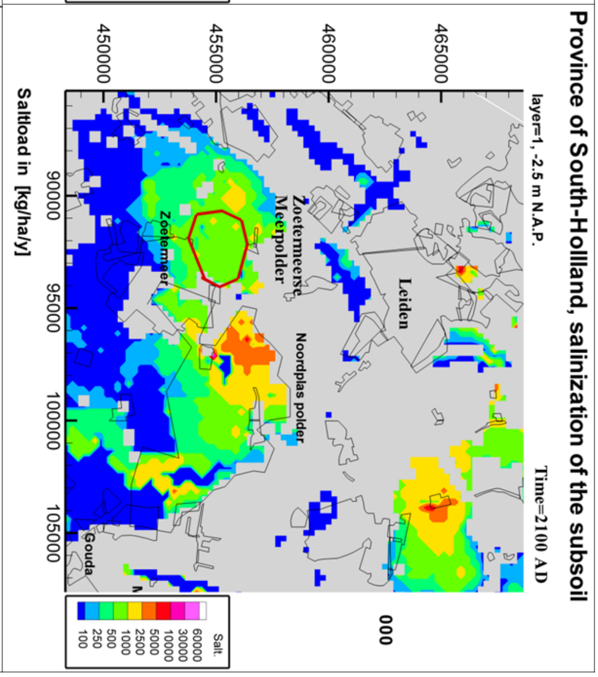

Province of Zuid-Holland, salinization of the subsoil.
laag=1, -2.5 m N.A.P.
Time=2000 AD
000
455000
450000
445000
95000
100000
105000
110000
Salt load in [kg/ha/yr]
Boskoop
MTPolder
Gouda
Zuidplaspolder
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

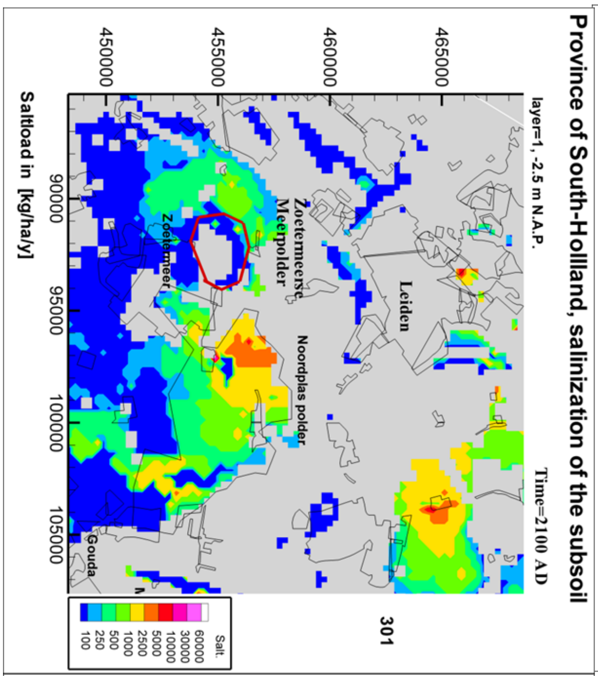

Province of Zuid-Holland, salinization of the subsoil.
laag=1, -2.5 m N.A.P.
Time=2100 AD
000
455000
450000
445000
95000
100000
105000
110000
Salt load in [kg/ha/yr]
Boskoop
MTPolder
Gouda
Zuidplaspolder
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

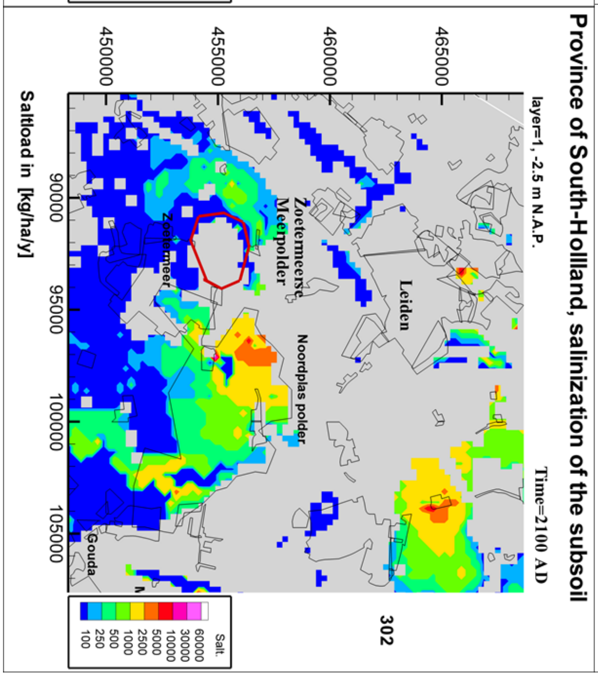

Province of Zuid-Holland, salinization of the subsoil.
laag=1, -2.5 m N.A.P.
Time=2100 AD
201
455000
450000
445000
95000
100000
105000
110000
Salt load in [kg/ha/yr]
Boskoop
MTPolder
Gouda
Zuidplaspolder
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

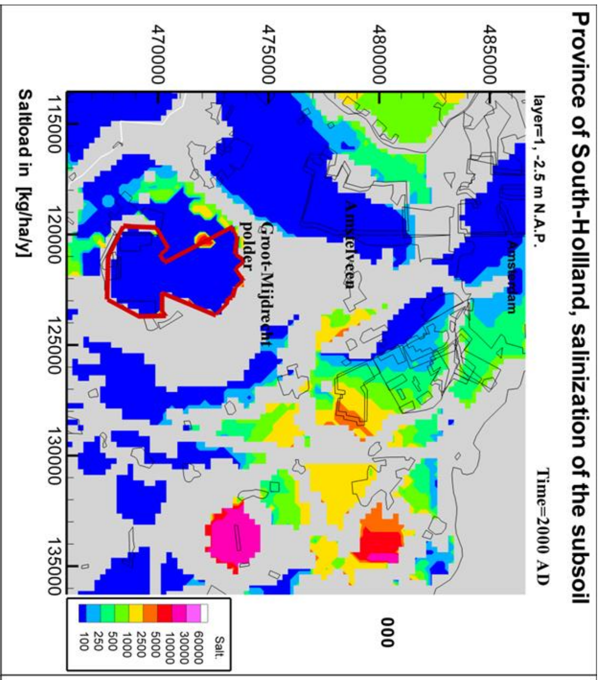

Province of Zuid-Holland, salinization of the subsoil.
laag=1, -2.5 m N.A.P.
Time=2100 AD
202
455000
450000
445000
95000
100000
105000
110000
Salt load in [kg/ha/yr]
Boskoop
MTPolder
Gouda
Zuidplaspolder
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

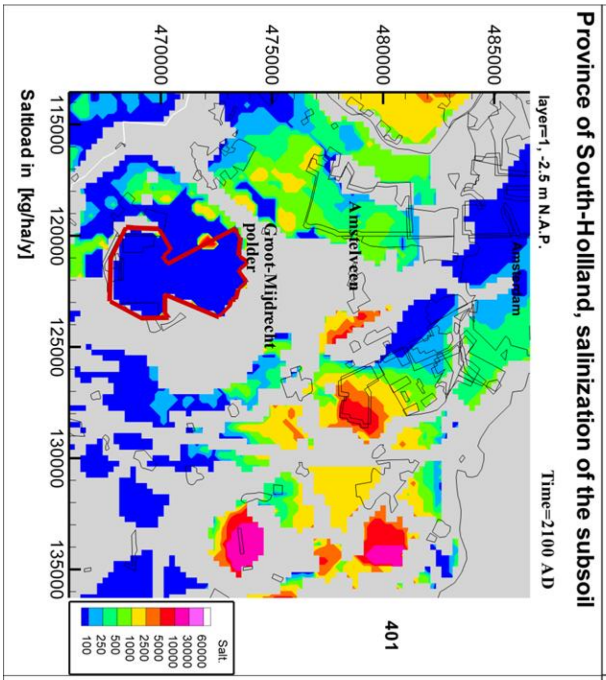

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2000 AD
000
Leiden
Zoetermeerse Meerpolder
Noordplas polder
Zoetermeer
Gouda
465000
460000
455000
450000
90000
95000
100000
105000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

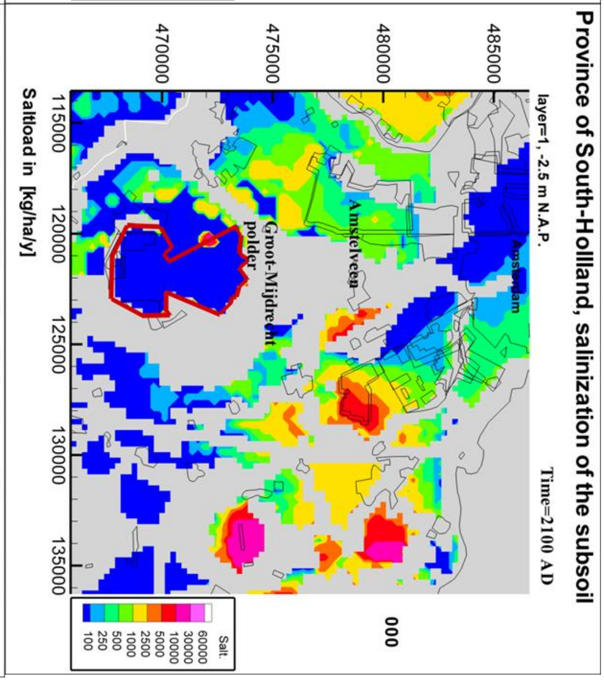

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
000
Leiden
Zoetermeerse Meerpolder
Noordplas polder
Zoetermeer
Gouda
465000
460000
455000
450000
90000
95000
100000
105000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

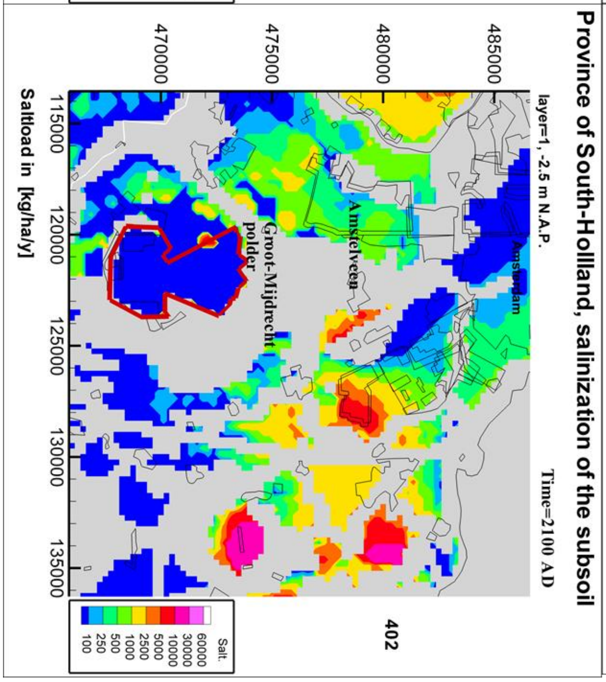

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
301
Leiden
Zoetermeerse Meerpolder
Noordplas polder
Zoetermeer
Gouda
465000
460000
455000
450000
90000
95000
100000
105000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

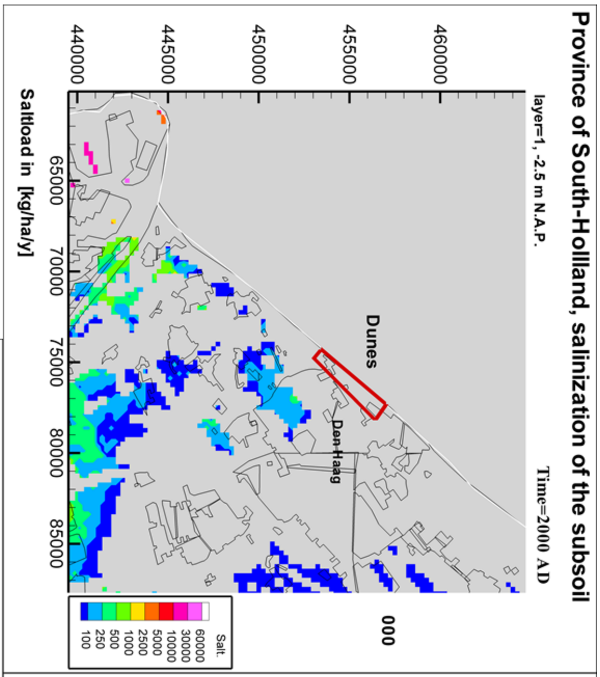

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
302
Leiden
Zoetermeerse Meerpolder
Noordplas polder
Zoetermeer
Gouda
465000
460000
455000
450000
90000
95000
100000
105000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

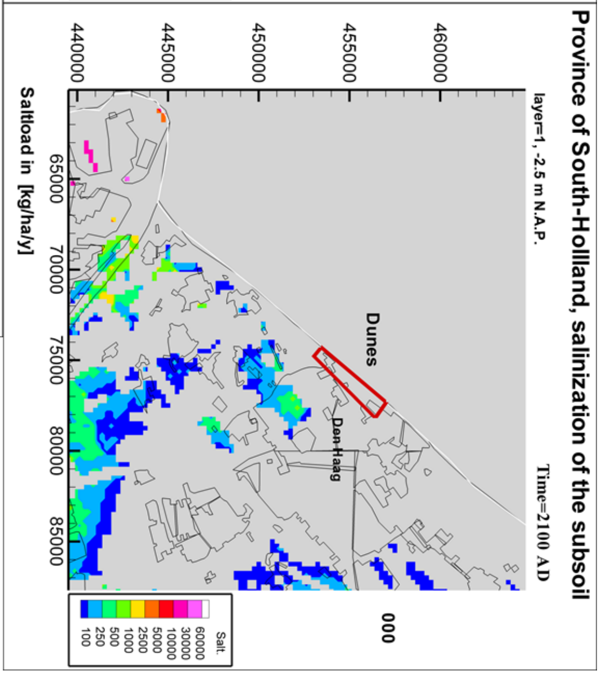

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2000 AD
Amsterdam
Amstelveen
Groot-Mijdrecht polder
485000
480000
475000
470000
115000
120000
125000
130000
135000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100
000

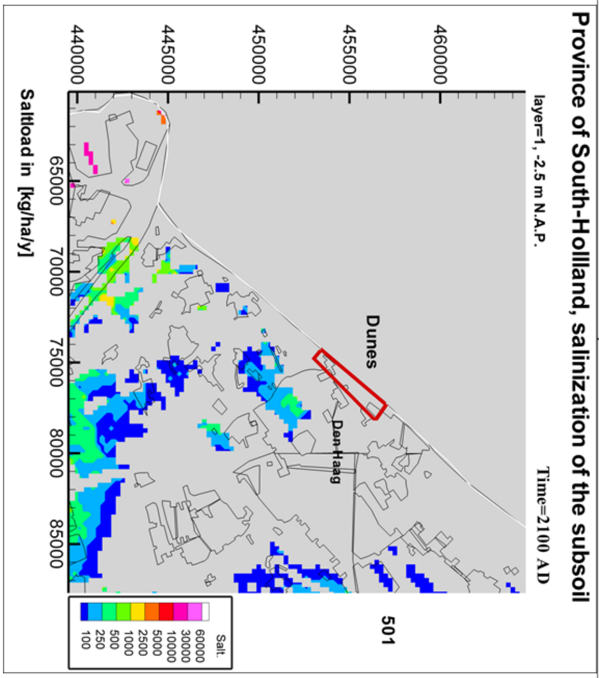

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
Amsterdam
Amstelveen
Groot-Mijdrecht polder
485000
480000
475000
470000
115000
120000
125000
130000
135000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100
401


Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
Amsterdam
Amstelveen
Groot-Mijdrecht polder
485000
480000
475000
470000
115000
120000
125000
130000
135000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100
000


Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
Amsterdam
Amstelveen
Groot-Mijdrecht polder
485000
480000
475000
470000
115000
120000
125000
130000
135000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100
402

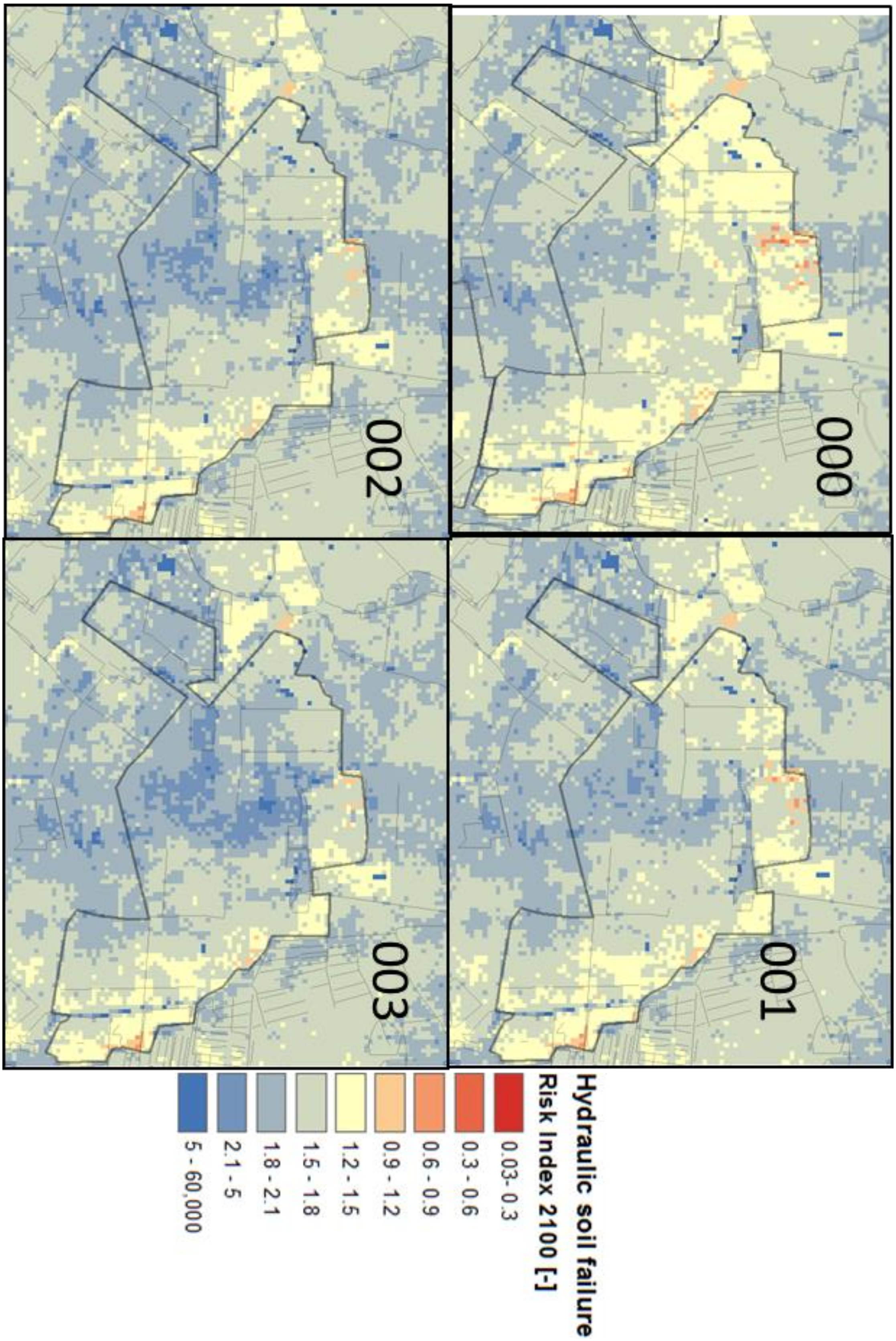

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2000 AD
000
Dunes
Den Haag
460000
455000
450000
445000
440000
65000
70000
75000
80000
85000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

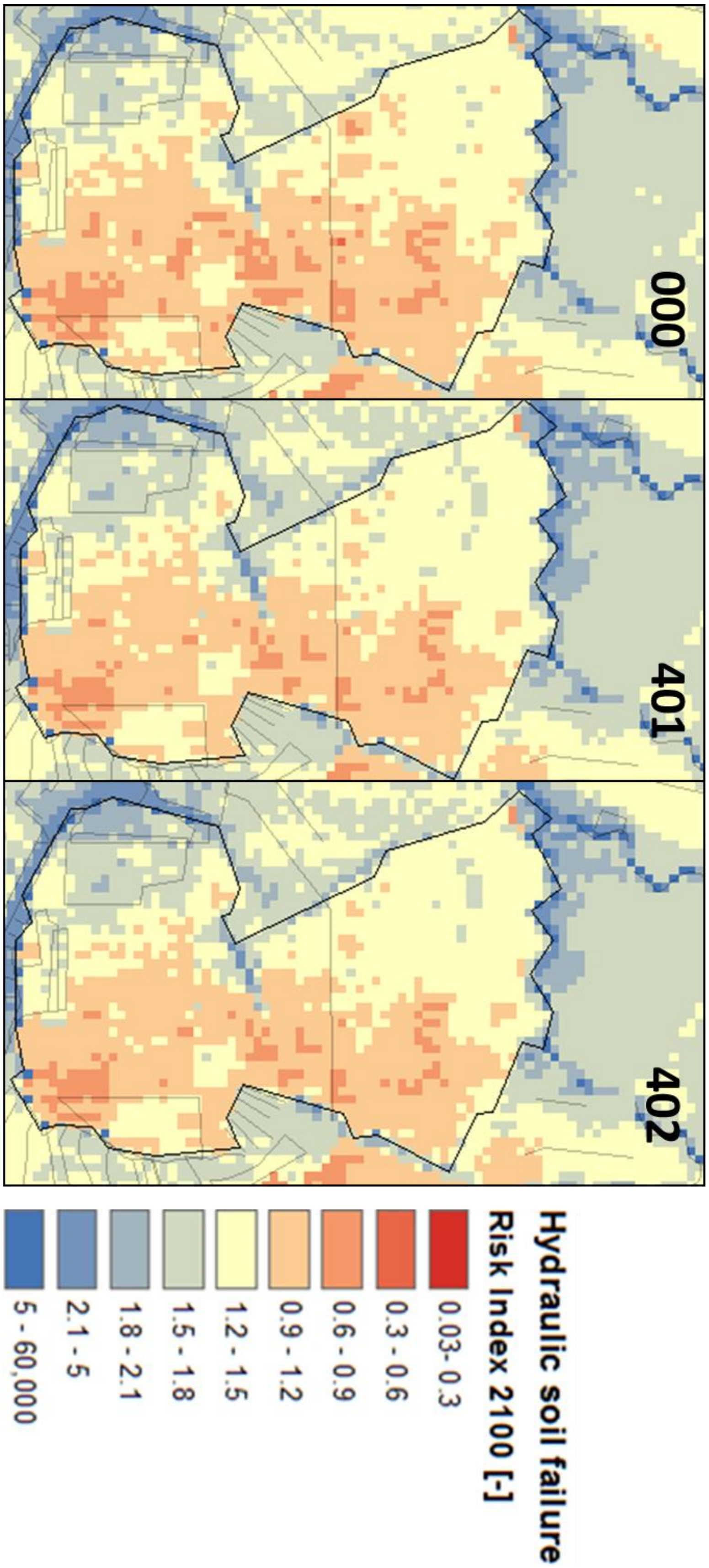

Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
000
Dunes
Den Haag
460000
455000
450000
445000
440000
65000
70000
75000
80000
85000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100


Province of South-Holland, salinization of the subsoil
layer=1, -2.5 m N.A.P.
Time=2100 AD
501
Dunes
Den Haag
460000
455000
450000
445000
440000
65000
70000
75000
80000
85000
Saltload in [kg/ha/y]
Salt.
60000
30000
10000
5000
2500
1000
500
250
100

Appendix VI: The hydraulic soil failure risk

Noordplas polder scenarios.

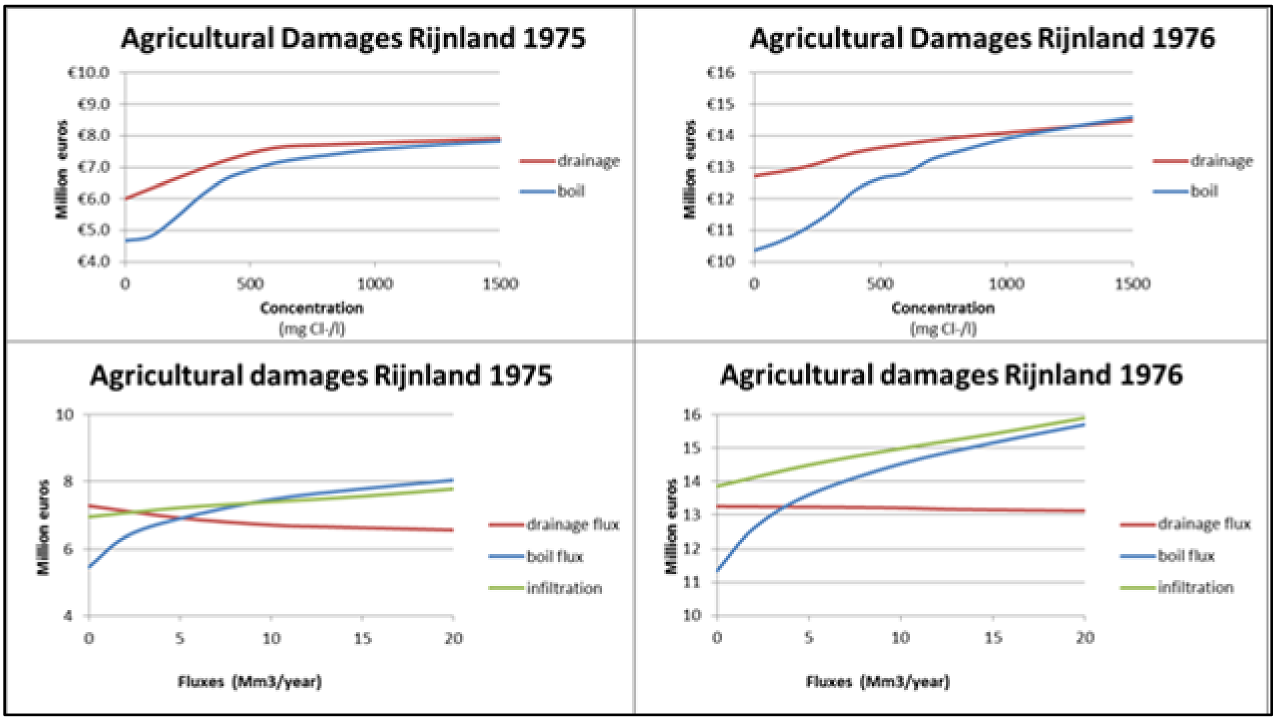



000
401
402
Hydraulic soil failure
Risk Index 2100 [-]
0.03- 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 1.8
1.8 - 2.1
2.1 - 5
5 - 60,000

Appendix VII Fresh-salt data per scenario

Scenario 2100	Qout (Mm3/yr)	Qin (Mm3/yr)	drainage Seepage (m3 /day)	boil seepage (m3/day)	Infiltration (m3 /day)	Drainage Salt load (ton Cl-/yr)	Boils Salt load (ton Cl-/yr)	Volume fresh water (Mm3)	Volume brackish water (Mm3)	Head upper aquifer (m NAP)	Concentration drainage (mgl-1 Cl-)	Concentration boils (mgl-1 Cl-)
Noordplas												
0	0	0	-16,500	-16,000	750	-4,100	-6,000	40	365	-5	650	1,020
1	8	4	-11,400	-6,500	950	-1,800	-1,900	55	425	-5	450	810
2	8	0	-9,000	-3,600	1,450	-1,100	-900	70	505	-5	380	700
3	16	8	-7,800	-2,600	2,650	-900	-600	75	515	-5	350	620
MT-polder												
0	0	0	-9,800	-39,800	650	-900	-9,800	10	60	-4	30	670
101	5	2.5	-7,650	-24,900	800	-300	-1,500	50	50	-4	20	160
102	5	0	-7,350	-22,200	800	-300	-1,100	60	50	-4	20	140
Zuidplas												
0	0	0	28,700	-8,000	2,050	-3,050	-1,700	110	670	-5	100	570
201	8	4	23,300	-5,700	2,700	-1,750	-1,000	140	680	-6	40	460
202	8	0	20,900	-4,700	4,100	-1,300	-700	170	780	-6	30	390
Meerpolder												
0	0	0	-850	-	10	-500	-	0	0	-4	1,230	-
301	3	1.75	-200	-	60	-100	-	5	25	-4	190	-
302	3	0	-100	-	210	-50	-	10	30	-5	150	-
Groot-Mijdrecht												
0	0	0	-33,900	-81,100	2,250	11,900	-44,400	0	145	-5	70	1,500
401	6.6	0	-26,950	-59,500	2,420	7,300	-33,900	0	185	-5	60	1,560
402	6.6	0	27,700	-62,950	2,410	7,900	-36,800	0	210	-5	60	1,600
Dunes												
0	0	0	-9,365	0	219,080	-2,995	-	2,630	1,100	1	-	1,080
501	1.5	0	-9,360	0	219,470	-2,990	-	2,630	1,105	1	-	1,075

Appendix VIII: WAOR parameter sensitivity analysis.



This appendix shows the influence of a parameter on the agricultural damages of Rijnland. For the sensitivity analysis one parameter was changed for both a dry (1976) and a wet year (1975), while the other parameters were kept constant (figure below). It is visible that all parameters are relevant for the calculation of agricultural damages. Drainage flux has the smallest effect on agricultural damages, while the agricultural damages stabilize when the drainage and boil concentrations reach a concentration of 1000 mg mgl^{-1} Cl^{-} or higher in a wet year.

	1975	1976
infiltration:	-1.8	-2.7
boilflux	8.0	3.1
drainage flux	4.3	3.9
Conc drainage	242.8	272.5
Conc boil	701.3	704.2

The reference parameter values (above) were kept constant and only one parameter was changed for the sensitivity analysis.