MSc thesis research

Understanding Holocene coastal development and the resulting evolution of groundwater chloride distribution in the North-West coastal region of the Netherlands.

A historical modelling approach

K.R.M. Hu-a-ng (3221563)
University of Utrecht
Department of Physical geography
Programme: Hydrology
Period: January 2012 – October 2012
Supervisors: Prof. Dr. Marc Bierkens (University of Utrecht)
Drs. Joost Delsman (Deltares)

Abstract

The origin and evolution of chloride distribution in the Dutch coastal area has been the subject of many studies. Most of these studies formulated their conclusions concerning the evolution of groundwater chloride distribution by reconstructing and interpolating present day data to earlier times. This research analyzes the evolution of the current groundwater chloride distribution using forward modelling integrated with hypothesis on palaeogeographical development and groundwater salinization. The analysis is conducted using a 2D-profile from Zandvoort till Hilversum, modelled with a density dependent groundwater flow model, MODFLOW and SEAWAT. Results show that the hypotheses represented the dune area correctly and that the extensive salinization of the subsurface in the west was indeed caused by Holocene transgression. However, amelioration of boundaries, such as surface level,s and taking account of inflow from northern and eastern regions is needed to get a better understanding of differences between simulated results and measured or interpolated data. We conclud that Holocene transgression, lithology and landscape change were important controls on the evolution of the chloride distribution during de Holocene coastal development. Holocene transgression proved to be the main source of salinization, while lithology caused retardation of salinization in areas with low permeable sediments and landscape change caused hydraulic gradients which resulted in repositioning of the fresh-brackish groundwater interface.

Table of contents

List of Figures

List of Tables

1. Introduction

Groundwater of the Dutch coastal region is a complex system of fresh, brackish and saline water. Knowledge of the spatial distribution and evolution of fresh, brackish and saline groundwater is vital for several reasons: First, many practical coastal hydrological problems (e.g. crop damage, surface water quality deterioration and well field salinization) are connected to contamination of freshwater resources by seawater (Post, 2004). Second, salinization of the coast is expected to increase due to climate change (Bonte and Zwolsman, 2010; Oude Essink, 2001 and Oude Essink et al., 2010). Third, fresh-saline groundwater modelling results are affected by chosen boundary conditions and initial chloride concentration distribution input (Oude Essink, 2001; Minnema et al., 2004).

The complexity of the Dutch groundwater chloride system is a result of transgressions, geology and the resulting hydrogeology that occurred over the past 10,000 years (Post, 2004). The origin of chloride distribution in the Dutch coastal area has been the topic of many studies (Post and Kooi, 2003; TNO rapport, 2004; Oude Essink, 2001; Gieske, 1991; Meinardi, 1991 and Stuyfzand, 1993). The current hypothesis is that during transgressions in the Holocene seawater infiltrated into the fresh groundwater causing brackish and saline groundwater at different depths of the Dutch coast (Post, 2004; Gieske, 1991; Meinardi, 1991 and Stuyfzand, 1993). This current understanding of the chloride evolution and distribution is based on previous studies which formulate their conclusions by reconstructing and interpolating present day data to earlier times. Up to now the combination of landscape development and solute transport models, in order to simulate chloride distribution evolution throughout the Holocene, has not been tested. Also the use of forward modelling to predict current chloride distribution has not been tried. This gap in our knowledge is remarkable because previous studies (Oude Essink, 2001; Minnema et al., 2004) have shown the existence of saline groundwater to be heavily dependent on past initial conditions and current upper boundary conditions.

However, recently gained insights in the palaeogeographical development of the Netherlands during the Holocene (Bazelmans et al., 2011) and the recent availability of new 3D-stratigraphic models of the upper geological formation (GeoTOP 30) present the opportunity to simulate landscape evolution and the resulting spatio-temporal chloride distribution in detail. This is the subject of this thesis.

1.1 Background

Several studies focussed on the spatial distribution (see Figure 1.1) and origin of saline water in the Dutch coastal region (Gieske, 1991; Meinardi, 1991; Appelo and Geirnaert,1991; Stuyfzand, 1993; Oude Essink, 1996). There are conflicting hypotheses regarding the possible origin of this complex system of fresh, brackish and saline groundwater in the Dutch coast: (1) vertical intrusion during past transgressions (Post, 2004; Appelo and Geirnaert, 1991; Stuyfzand, 1993;) and (2) connate seawater from Pliocene to early Pleistocene (Meinardi,1991). Connate seawater refers to salinization of a layer by saline marine sediments (Post, 2004).

Although still much is unclear about the origin of saline groundwater, we can make a robust estimate of current chloride distribution based on observations (Figure 1.1) and we do know the processes that enhance salinization. Salinization is the process where fresh groundwater is replaced by saline groundwater. Salinazation is enhanced by a rising sea level, land subsidence, groundwater extraction and men-made water management systems. All these factors enhance the difference in potentiometric head causing more seepage to low potentiometric head areas. Since dissolved solutes move in the same flow direction as groundwater, salinization is bound to occur in areas with a low potentiometric head, though solutes can experience a time lag (Oude Essink, 1996). Clay layers or less permeable layers prohibit or retard salinization of underlying layers, although the discontinuity of the clay layer may still cause vertical saline water intrusion to the underlying layers. The appearance of high salinity groundwater below clay layers is therefore thought to be caused by additional horizontal migration of intruding seawater. Salinazation is a threat for agriculture and nature, because most crops and vegetation cannot cope with saline groundwater. Also our drinking water resources decrease due to shrinkage of freshwater lenses by salinazation. Future problems with salinization were studied by Stuyfzand (1993). He proposed that because of the never ending chemical exchange at the fresh-brackish interface, there will be a further salinization of the deep polders, especially to the south of the North Sea Canal, where Holocene groundwater is currently less saline than to the North. Conclusions concerning further salinization of groundwater were also drawn by Oude Essink et al. (2010). They used a three-dimensional numerical model for density dependent groundwater flow and solute transport, to describe future chloride distribution in the Dutch coastal region under climate change and anthropogenic activities. Also in Oude Essink (2001) a three-dimensional model (MOCDENS3D) showed that sea level variations have a significant influence on the salinization process. His results showed that severe salt water intrusion is taking place in the groundwater system due to low phreatic water levels in the entire polder area in North Holland.

For the origin of saline groundwater Stuyfzand (1993) concluded that the growth of local salt and brackish water bodies occurred since 6000 B.C. Post and Kooi (2003) studied the interface of fresh-brackish water. They used numerical modelling to simulate and describe the salinization of a highly permeable aquifer by free convection from a salt source overlaying the aquifer. The relationship derived from this numerical modelling described the development of the horizontally averaged salinity with depth and time as a function of permeability and initial-density. The relationship suggested that the salinization of the Pleistocene aquifer of the Netherlands occurred in the order of decades to centuries (Post and Kooi 2003). Their derived relationship was based on theory suggested by Gieske (1991) in which he used a simple expression to demonstate the occurrence of brackish and saline water at depths of 450 meters over a period of 60 years. Post (2004) studied the processes that caused salinization of groundwater in the coastal area of the Netherlands during Holocene epoch under natural conditions. His area of interest was the entire Dutch coastal region. Conclusions from his research were that former transgressions are the source of the extensive salinization of the subsurface. One of the main processes behind this salinization is free convection, a density driven process, that resulted from experiments of Post (2004). Other processes named by Post are modern seawater intrusion, aerosols, evaporates, anthropogenic pollution, ultrafiltration and freezing. However, Post (2004) concluded that these processes are minor inputs that can be neglected.

Post (2004) also made a general palaeohydrological reconstruction of the Dutch coast, based on the findings of four earth-scientific disciplines i.d. hydrochemistry, numerical transport modelling, quaternary geology isotope hydrology and pore water research. He showed that the Pleistocene aquifers had fresh groundwater after the Weichselian glacial stage, which also caused the freshening of marine strata to depths of hunders of meters. Sea level rise in the Holocene caused marine incursion in the Pleistocene surface therefore causing salinization by free convection to the sub-layers.

After the closure of tidal channels and coastal areas the influence of direct free convention ceased. Salinization occurred then by diffusion in areas that were flooded. Since the Middle Ages the hydrology changed to the pattern we know mainly due to human intervention. Another historical landscape modelling study by Van Loon (2010), was exerted in the Gooi and Vechtstreek area to study hydrological mechanisms behind fen deterioration.Van Loon (2010) made a palaeo-groundwater model from 0 until 2000 AD incorporating natural and human impacts. Vandenbohede and Lebbe (2002) used a numerical model (MOCDENS3D) to simulate the effect of landscape change (mainly land reclamation) on the chloride distribution along the Belgian coast. Their findings showed that aquifer heterogeneity and human interference are the main factors that influence chloride distribution.

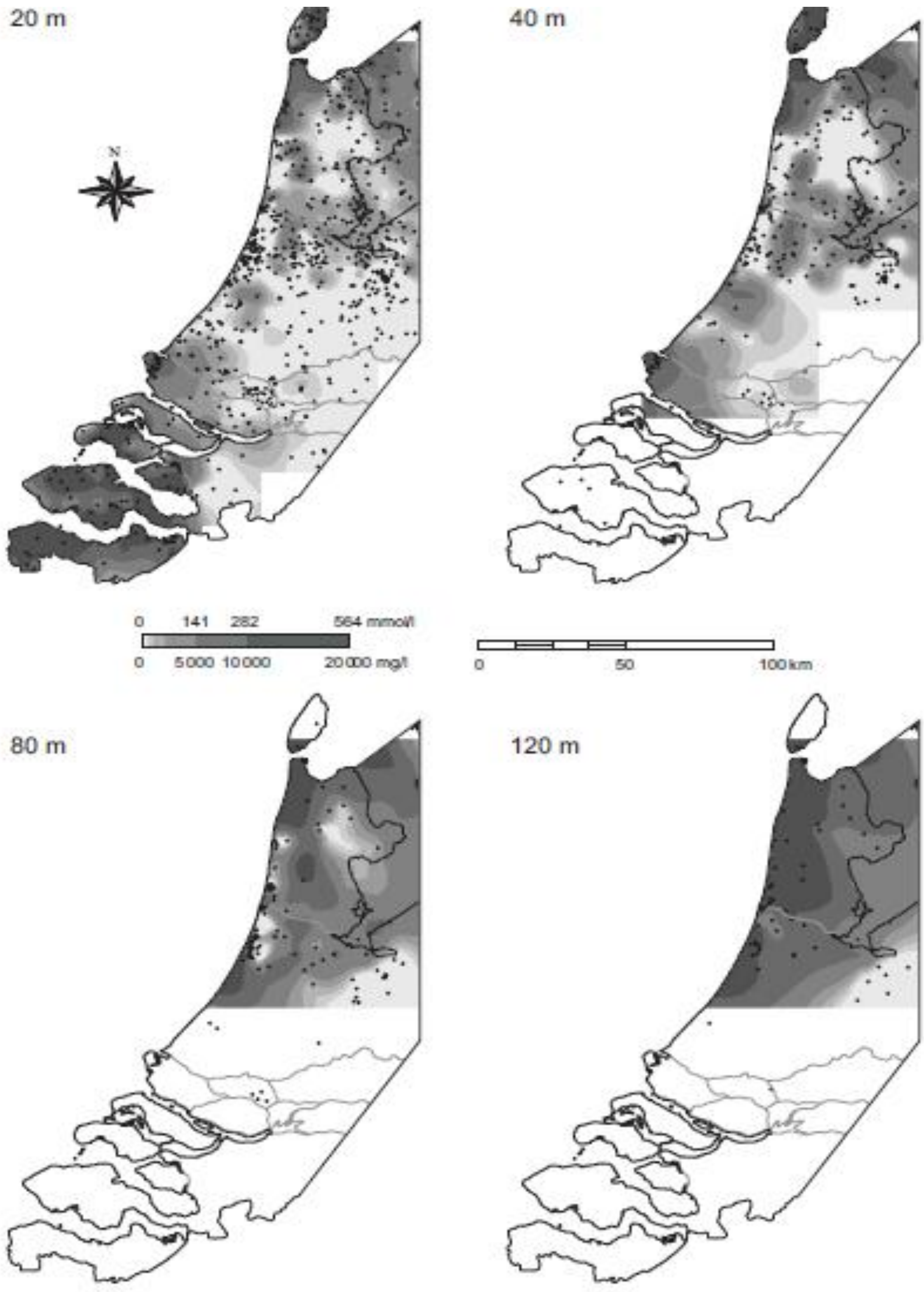


Figure 1.1: “Maps showing the spatial distribution of Cl concentrations at 20, 40, 80 and 120 below mean sea level. Dots indicate the location of observation wells within 5 m above or below the shown depth interval. No contours are shown in areas with too little observations. Based on data from the province of Noord-Holland, Netherlands Institute of Applied Geoscience TNO – National Geological Survey and Ouwerkerk (1993)” (Post, 2004, p.20).

1.2 Problem definition and research questions

Our current knowledge of the origin of saline groundwater is based on interpolation and interpretation of present day data to earlier times. Current hypotheses fail in incorporating landscape changes and human interference together with chloride distribution evolution. No study was done in the Netherlands on the evolution of chloride distribution together with landscape changes. Also, no forward modelling study was done to test our current understanding of the saline groundwater origin hypothesis. This gap in understanding the chloride distribution is important since chloride evolution and distribution is highly dependent on landscape changes. The main objective of this research was therefore to get better insight into the processes that occurred during the Holocene coastal development and resulted in the present day chloride distribution of the Dutch coast. The processes are changes in sea level and natural and anthropogenic change. From the above mentioned the following main research question was formulated:

What are the main processes that affected the chloride distribution in the North-West coastal region of the Netherlands during the Holocene coastal development?

To answer the main research question the following sub-questions were formulated:

- *What processes affect and/ or cause the chloride distribution?*

  Understanding the basic processes like diffusion, advection and free convection, that cause movement of solutes is the first step in understanding the whole problem.

- *How does the geological setting affect the chloride distribution?*

  Geological layering and resulting lithostratigraphy has an impact on how water and solutes move through the subsoil. So changes in soil profile or sedimentation can cause retardation on solute movements.

- *How did landscape changes/developments influence the salt/fresh water distribution?*

  Morphology has an impact on recharge and surface waterlevels. Changes in these boundary conditions influence groundwater flow and thus the chloride distribution.

- *What are the causes of differences between the model output with the observed chloride distribution?*

  Explaining these differences will give a better insight into the whole development of the chloride distribution.

The research questions were answered by making a palaeo-reconstruction of the chloride distribution using models which incorporate landscape changes based on hypotheses of the landscape evolution. Subsequently, a two-dimensional groundwater model was used to simulate density-dependent flow and solute transport following landscape evolution and sea level change. Nine important landscape changes were simulated in nine time frames and than incorporated in the model.

1.3 Research outline

In this thesis, ages are in calender years, unless indicated differently (e.g. 14C yr for uncalibrated radiocarbon dates). Salinity of groundwater is given in Cl^- mg/l and catagorized according to Table 1.

Chapter 2 gives an overview of the physical geographical setting of the model area as well as its historical development. This is followed by a description of the stratigraphy and hydrogeology. The methodology together with explanation of the chosen time frames is explained in chapter 3. Chapter 4 will show the results followed by a discussion in chapter 5. Conclusions and recommendations will be formulated in chapter 6.

2. Research area and its palaeogeographical and historical development

2.1 Research area

The research area is situated in the Netherlands in the province North-Holland. A profile was modelled running from west to east, which extends from 12 kilometres off the coast of Zandvoort to Hilversum situated on the Utrechtse Heuvelrug to the east (see Figure 2.1). The research profile has a length of approximated 64 kilometres. Along the profile, one finds from west to east the cities Zandvoort, Haarlemmermeer, Amstelveen, Abcoude, Horstermeer and Hilversum. Zandvoort is a city situated in the coastal dune area. Haarlemmermeer and Horstermeer are deep polders and former lakes now used for agriculture whereas Amstelveen is a polder area that developed into a city (Schultz, 1992).

On the northeastern side the area is bordered by the IJsselmeer, a freshwater lake that resulted from the closing of an inland sea called Zuiderzee in 1932 (IJsselmeer www.wikipedia.org, 2011). On the western side, the area is bordered by the North Sea and to the south-east the Utrechtse Heuvelrug forms a barrier of ice-pushed ridges. The profile is positioned perpendicular to the Dutch coast, this because of the assumption that the main groundwater flow occurs perpendicular to the coast. Based on this assumption also a 2D-profile, which simulated one main groundwater flow direction, was chosen as modelling method. We chose to extent the profile into the North Sea to be able to account for the shifting position of the Dutch coastline during the Holocene. The maximum expansion of the coast was chosen as the minimum length into the sea. To the south -east the profile runs until the highest point near Hilversum at the Utrechtse Heuvelrug. This area was chosen since the Pleistocene aquifers here are extensively researched and enough data is available due to a dense network of wells and geo-electrical surveys (Post, 2001). Also it being a representative area for the Dutch coast, with dunes and deep polders, was one of the reasons for chosing this area. Understanding the chloride distribution in this well-documented area can be of use for the explanation of chloride distribution in areas where there is less or no data.

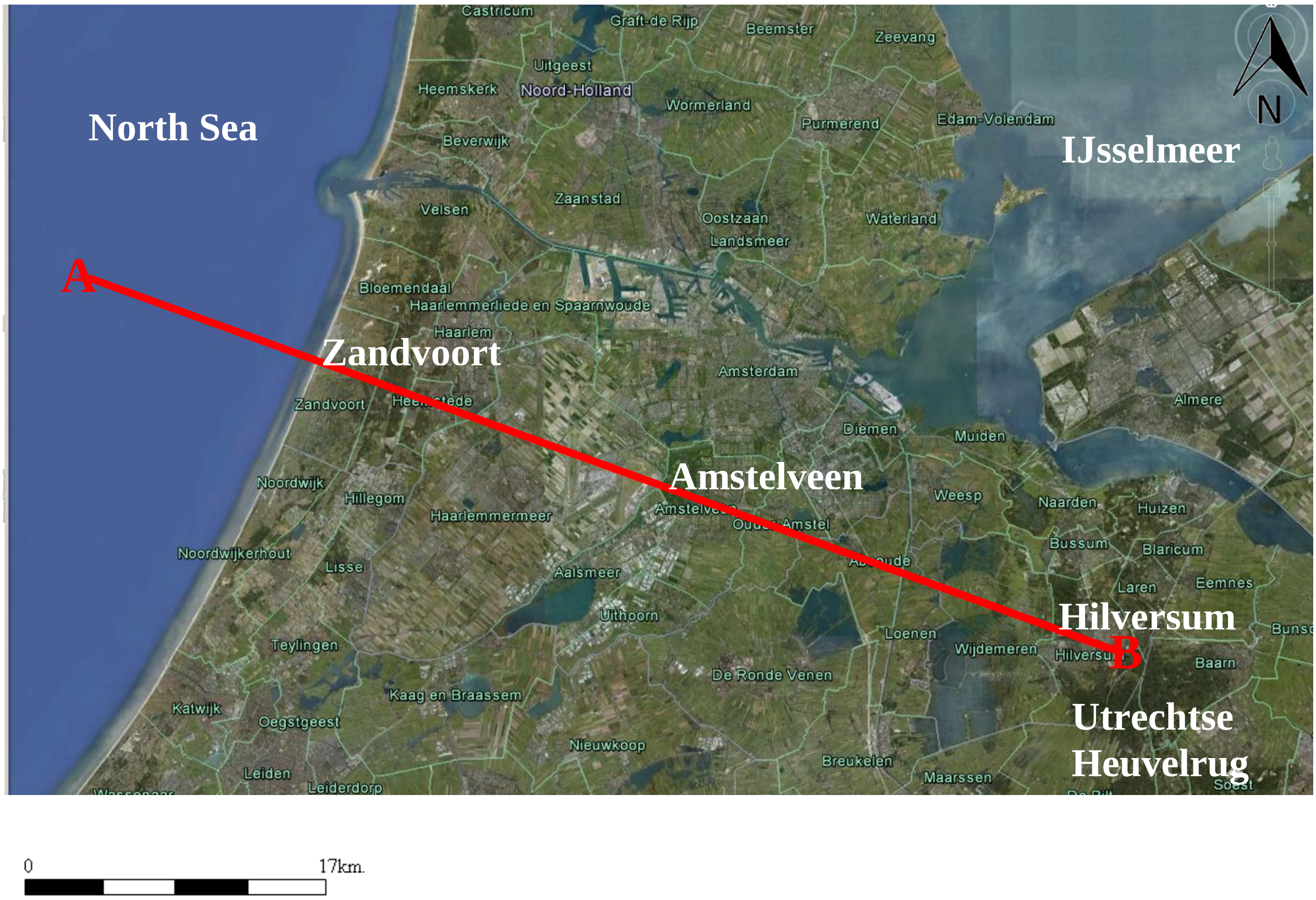


Figure 2.1: The research profile from the coast of Zandvoort to Hilversum (A-B). Profile is 64 kilometers.

2.2 Geological history

After the Weichselien ice age which lasted from 115.000 to 10.000 C^{14}years BP, a new interglacial period (Berendsen, 2008), called the Holocene, started. The boundary between Pleistocene and Holocene is based on the change of a glacial to an interglacial climate, concluded from the disappearance of open vegetation to a closed birch forest (Berendsen, 2008). Climate during most of the Holocene period in the Netherlands was comparable to current climate with a yearly average temperature of 10 °C and precipitation of 700-800 mm per year (Valk, 1994). No significant changes were observed except for a few exceptions, the recent one of which is the little ice age from 1600 to 1800 AD (Lamb, 1969). The Dutch climate is classified as a moderate oceanic climate (Berendsen, 2008). The Holocene is divided into several stages according to vegetation analysis (Table 2.1). These periods are described in more detail in the following sections, with special attention to the landscape evolution in the Netherlands and around our profile. Main factors that caused the development of the coast were the Pleistocene subsurface, relative sea level changes and the position of river discharge from eastern uplands.

Table 2.1: Holocene division based on vegetation (Mulder et al., 2003; Berendsen, 2008).

Chronostratigraphy	**Age in C^{14} years BP**	**Age in Calendar years B.C.**	**Vegetation characteristics**
Present	0	0	Oak, beech, as and pine forest and tall grass
Subatlanticum	2900	1100 B.C.	Beech more than 5%, many crop
Subboreal	5000	3850 B.C.	Beech more than 1%, elm less than 5% and agriculture
Atlanticum	8000	7000 B.C.	Alder and oak are dominant trees
Boreal	9000	8000 B.C.	oak, elm and hazel dominant
Preboreal	10000	9000 B.C.	Birch and pine trees are dominant

Preboreal and boreal (9000- 7000 B.C.)

At the end of the Weichselien sea level was 50 meters below O.D. (O.D.: Ordnance Datum, approximately mean sea level of current time) and most of the North Sea was dry. The North Sea shoreline was located North West of the Netherlands near Doggersbank, a 300 kilometers long sandbank, (Mulder et al. 2003). The Netherlands were part of a vast plain in north-western Europe with a land climate and braided rivers as predecessors of the Rhine and Meuse. The Pleistocene relief (see Figure 2.2) formed the basis for the creation of the Dutch subsurface. It controlled the geometry and size of the tidal back-barrier basins (Cleveringa, 2000).

Between 9000 to 7000 B.C. sea level rose till approximately 20 meters below O.D. caused by melting of northern ice-sheets. During this period, Pleistocene rivers and aeolian cover sands formed the surface of the Netherlands. Rivers changed from a braiding to a meandering pattern causing deep incisions and river valleys along the Dutch coast. The groundwater system was influenced by surface morphology and rivers had a freshwater environment (Post, 2004). Dutch landscape morphology was smooth in our research area during this period so the main groundwater flow was from east to west, with the exception of small local groundwater flow systems caused by low lying areas (Post, 2004).

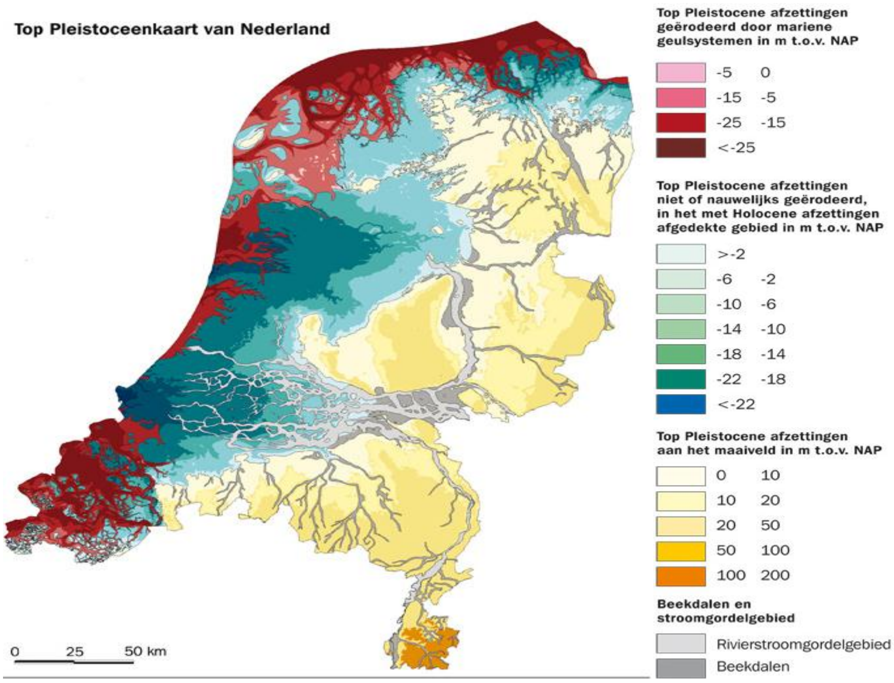


Figure 2.2: Top of Pleistocene surface with pleistocene formations eroded by marine tidal systems and less eroded sites (Bazelmans et al., 2011).

Atlanticum (7000-3850 B.C.)

Sea level was 23 meters below O.D. at the beginning of the Atlanticum. During the Atlanticum the Dutch coast shifted eastward. Sea level rise and the eastward relocation of the Dutch coastline caused salinazation of the groundwater system along the coast. The Dutch coast was characterized as an open barrier beach system situated only a couple of meters west from the current Dutch coastline and 15 meters below O.D. (Dufour, 1998). Between the barriers, marine influence created tidal basins which were surrounded by tidal flats (see Figure 2.3). These tidal flats turned landward into marsh areas and further inland peat developed under the rising groundwater table. Barriers and peat growth caused elevation differences in the Dutch landscape resulting in the development of more local groundwater flow systems and freshwater lenses under elevated areas. The fast sea level rise caused a decrease in slope, which meant that rivers flooded easier over their banks creating a greater chance for avulsion and crevasse formation. Crevasse formation is a breach through the banks of a river (Berendsen, 2008). River patterns changed from meandering to straight anastomosing river patterns with many crevasses. In addition, the Rhine changed its course from the Benschop-system to the Oude Rhine, creating a delta near the city of Leiden. In the west the river area was now characterized as an accumulation area. Northern parts of the Netherlands including the eastern Wadden Sea were still dry (Berendsen, 2008).

Subboreal (3850-1100 B.C.)

The Subboreal was a period with less sea level rise (Figure 2.3) and an average sea level of 5 meters below O.D. at the beginning of the period. A closed barrier beach system developed along the Dutch coast causing freshening of the groundwater system, since the influence of sea water was haltered. The coast changed from a retrograding to a prograding coast extending to the west until 2500 year B.C. The sand deficiency that existed before the Subboreal ceased to exist because enough sand could be transported from the North Sea to the barrier beach system to keep up with the sea level rise. After the barrier beach closure five inlets were left: at Bergen, at Castricum and the outlet of Old Rhine, Meuse and Schelde. Only the coast at the Wadden Sea was still open and continued to develop during this period till 3500 year B.C. Rivers in the west changed from straight anastomosing to more meandering patterns or to straight rivers with crevasse complexes. The river area was still a big accumulation area (Berendsen, 2008).

Since sea water intrusion and marine incursions were almost non-existent during this period, lakes became fresh, which stimulated peat development. Hence, peat areas occurred on a large scale except behind the tidal inlets, were tidal flats existed as long as there was a sediment deficiency. An important change was that the Rhine had as main discharge location the Old Rhine. These changes in sedimentation and peat growth resulted in four remaining outlets the Oer-IJ, Old Rhine, Maas and Schelde. Also the groundwater system changed considerably with the growth of the coast, barriers and peat areas, which caused high groundwater levels, complex local groundwater systems and freshwater lenses at elevated sites.

Subatlanticum (1100 B.C.- present)

The rate of sea level rise decreased even more in the Subatlanticum. However high storm frequencies promoted a degradation of the Dutch coast between 500 - 100 year B.C. Coast degradation in Zeeland and North-Holland resulted in marine incursions. These incursions caused soil compaction in peat areas because of dewatering. The coast changed again to a prograding system after silting up of the back-barrier basins (800 A.D.). Sediment previously designated to these back-barrier basins became available for coastal formation, creating the so-called Young dunes around 1000 A.D. which increased the volume of freshwater under the dunes. The coastal profile became much steeper and natural freshwater lakes developed behind the dunes. Lakes developed because of erosion of peat and peat extraction. In the Wadden Sea, the beginnings of the Zuiderzee started to appear due to peat erosion caused by the expansion of the Vlie dewatering channel.

In the south-western river area a high frequency of river avulsions resulted in important new river courses such as the Lek, Waal, Hollandse IJssel and Gelderse IJssel. Increased avulsion rates were due to a higher river discharge that was caused by the change in vegetation from forest land to crops. After the Roman times the Rhine shifted towards the Maas – estuary following the steeper slope. This caused the Old Rhine system to silt up.

Anthropogenic changes

Since the late –middle ages more anthropogenic influences were seen across the Netherlands in the form of land cultivation and dike building. The first polders appeared in the 15th century and were dewatered by sluices during low tide on low river stages (Bazelmans et al., 2011). In 1850, windmills that were used to dewater the polders were replaced by steam powered mills. The Haarlemmermeer polder was the first polder to be drained with steam powered mills in 1852. From the 15th century until now approximately 445 polders were constructed in the Netherlands (Schultz, 1992). Changes also occurred in the river area. Discharge and sediment load of rivers increased during this period probably caused by deforestation of upstream areas. Most of the sediment load never reached the sea since most of it was deposited on the floodplains creating a clay layer on top of the peat. High discharge rates caused high avulsion frequencies, which were devastating for the surrounding villages. Therefore, man embanked the whole river area between 1100 and 1300 A.D. as prevention measure for floods. Landscape changes such as soil pavements needed for urban development and infrastructure were now constructed by man. Groundwater systems were starting to be managed such that target groundwater levels can be maintained. Land reclamation and protection projects as the Deltaplan, Afsluitdijk and IJsselmeer polders now define the appearance of the Netherlands (see Figure 2.3).

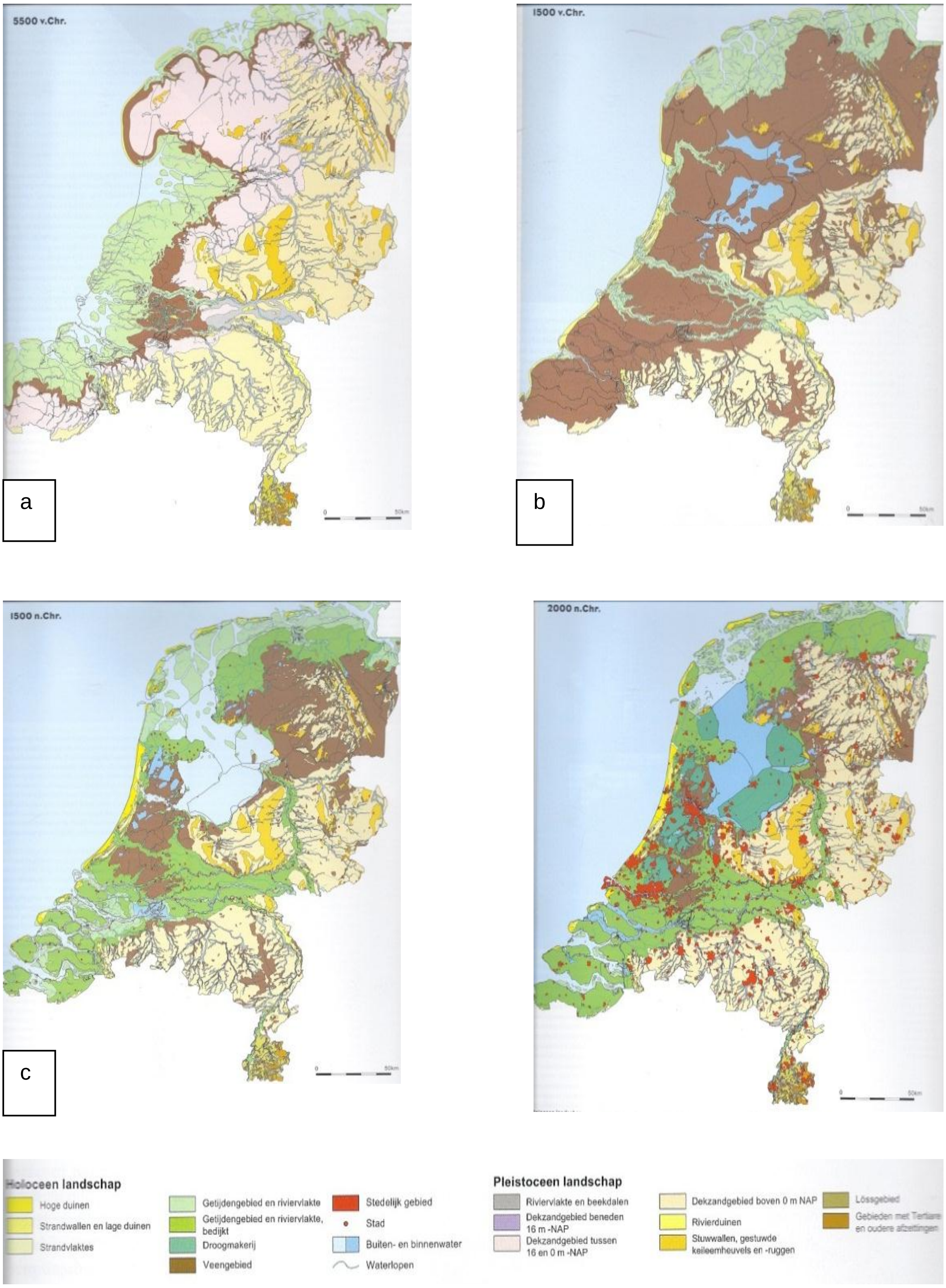


Figure 2.3: Palaeogeographic maps of the Netherlands. a) 5500 B.C., b) 1500 B.C., c) 1500 A.D. and d) 2000 A.D. (Bazelmans et al., 2011)

2.3 Sea level rise during the Holocene

The Holocene epoch is a period of substantial sea level rise (see Figure 2.4). Relative sea level rise differs for each part of the world since it consists of absolute sea level rise and land subsidence (Bazelmans et al., 2011). The curve for sea level rise in the Netherlands is based on ^{14}C dating of basal peat. Basal peat is used as an indicator for the position of the sea level because of the following assumptions:

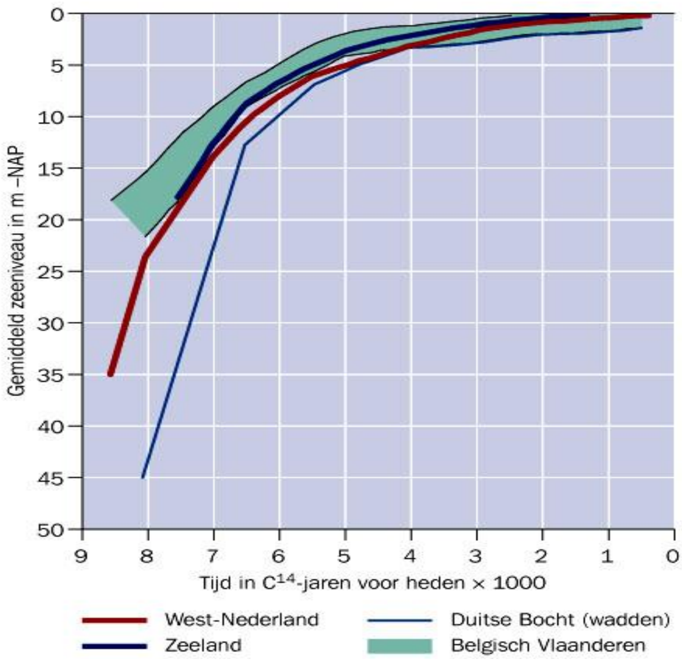


Figure 2.4: Relative sea level rise during the Holocene along different regions of the North Sea coast. From Mulder et al. 2003 cit. Jelgersma, 1979; Ludwig et al., 1981; Plassche, 1982; Denys en Baeteman, 1995; Kiden, 1995.

1. The groundwater level rises with the sea level
2. Peat formation took place under the influence of a rising groundwater table.
3. The relation between groundwater table and peat type is known.
4. Datable ^{14}C of basal peat

It is assumed that the rising sea level pushed the groundwater table up to a point where it caused seepage, which stimulated peat growth (Berendsen, 2008).

Around 6000 B.C. the ice-sheets stopped melting meaning that there was no net loss of ice. The relative sea level rise was from then onwards mainly due to land subsidence.

2.4 Stratigraphy and hydrogeology

A description of the geology and associated formation is briefly explained here in chronological sequence (see Figure 2.6 and 2.7). The formations are named according to the classification of Weerts et al. (2000) and Mulder et al. (2003). Aquifers and aquitards defining the hydrogeology are defined from geology and lithology. A simple subdivision in aquifer and aquitard for the entire profile was not possible here, since there are substantial small-scale differences in lithology. All aquitards and aquifers are heterogeneous both in their hydraulic properties and spatial distribution. Based on data from REGIS II and GeoTOP in the DINO system we can identify approximately three aquifers in this region (see Figure 2.7) assuming that the bottom of Maassluis, a formation that consists of mainly thick impermeable clay layers (Berendsen, 2008), is the hydrogeological base. All geoscientific data on the shallow and deep Dutch subsurface are stored in the DINO (Data and Information of the Subsurface of The Netherlands) system. In DINO the hydrogeological information for the profile is found in REGIS II (Regional hydrogeological information system) and GeoTOP. GeoTOP visualizes the upper 50 meters op the Dutch subsurface in detail with grid cells of 100 by 100 meters horizontally and 50 centimeters vertically (TNO-NITG, 2012). Groundwater levels in the research area are artificially controlled with a dense network of ditches and canals. Excess rain in polder areas is pumped into canals and rivers, so desireable water levels can be maintained. Groundwater flow patterns are therefore mainly controlled by surface water level differences between polders, lakes, canals and rivers (Post, 2004). As for our knowledge of the chloride distribution, Figure 2.5 shows interpolated current chloride concentration distribution based on point measurements (Minnema et al.,2004).

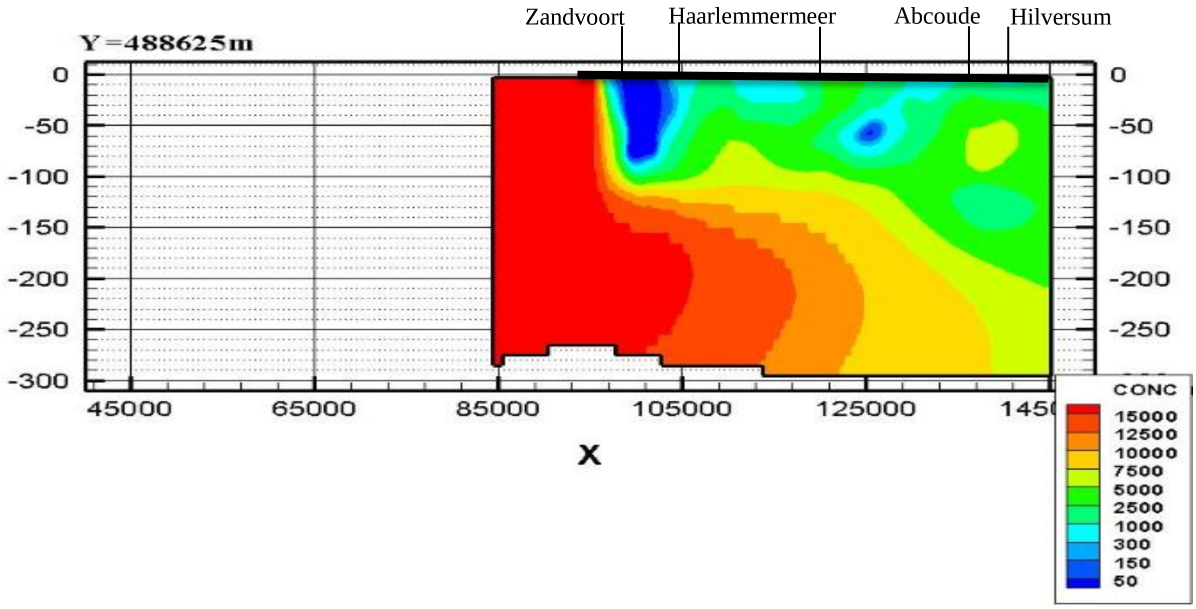


Figure 2.5: Chloride distribution from Zuid-Holland model by Minnema et al., (2004). Chloride concentrations are in mg/l.

Above the Maassluis formation, sediments of the Eridanos river system are found, as part of the Peize and Appelscha formations. Eridanos river system consisted of rivers from Scandinavia together with rivers from North Germany which drained in the nortern part of the North Sea basin of which a part was to become North-Netherlands. These formations were formed before the mid-pleistocene and consist of coarse white sands with gravel. The Rhine and Meuse were also active rivers from this period. Sediments of Rhine were given the following three names from old to young: Waalre, Sterksel and Urk formation. These formations contain coarse to fine sands with gravel, while the last two formations have substantial amounts of augiet, a volcanic mineral. The Beegden formation consist of Meuse deposits and was formed by river terraces with a fining upwards composition of coarse to fine sand mixed with gravel.

Moving up in the chronology of Figure 2.7 we see signs of Saalien Ice age, by the presence of the Drente formation, which consists of glacio-fluvial sediments and boulder clay. The Utrechtse Heuvelrug is also a morphological unit that was formed during Saalien but is defined as a complex unit on the geological map. The Saalien ended with the interglacial Eemien, which resulted in the growth of peat forming the Woudenberg formation and marine sedimentation along the Eem sea composed of fine sand and clay in the Eem formation. The cold Late-Pleistocene period is represented by sediments of the braided predecessores of the Rhine and Meuse rivers forming the Kreftenheye formation. Coarse sands and gravel mainly characterize this formation. The Boxtel formation was also formed in this period, consisting of aeolian and local creek deposits made up of fine sands. Sea level rise enhanced the influence of marine sedimentation in the Dutch coast, which resulted in the Naaldwijk formation. The Naaldwijk formation encompasses all clastic marine sediments of the Holocene including dunes. It consists of medium to fine sand and clay layers with shell fragments. This formation is mostly bordered by peat belonging to the Nieuwkoop formation. After the closure of the coast, peat growth was at a maximum in the back-barrier basins. This gave rise to a vast area of peat belonging to the Nieuwkoop formation, which also includes basal peat and all other peat development in the Holocene. Holocene river deposits belonging to the Echteld formation are made up of channel fills i.e. coarse sand and gravel, and overbank deposits i.e. fine sand, silty clay and clay (Berendsen, 2008).

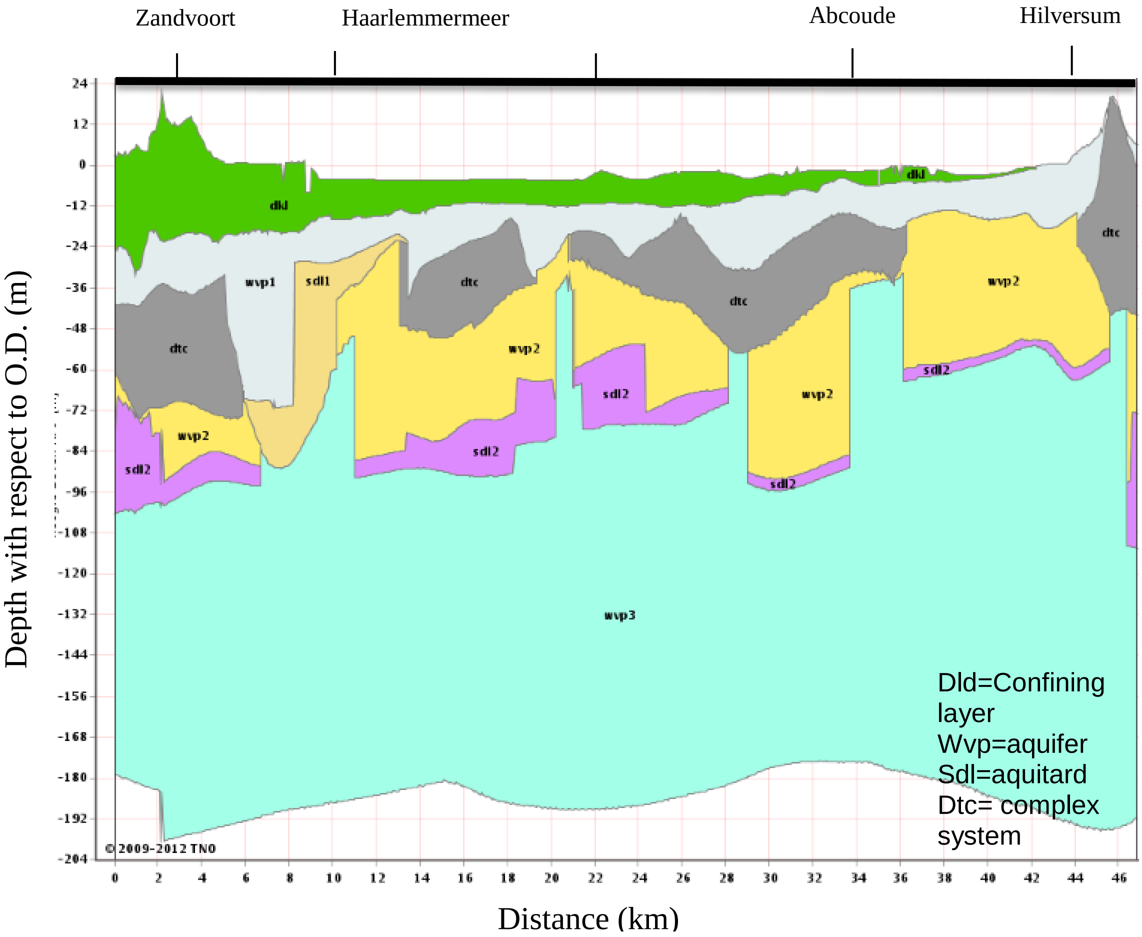


Figure 2.6: Schematization of hydrogeology with aquitards and aquifers. Numbers behind the aquifer or aquitard refer to the first second ect. (TNO, Geohydrologisch model, provincie Noord-Holland).

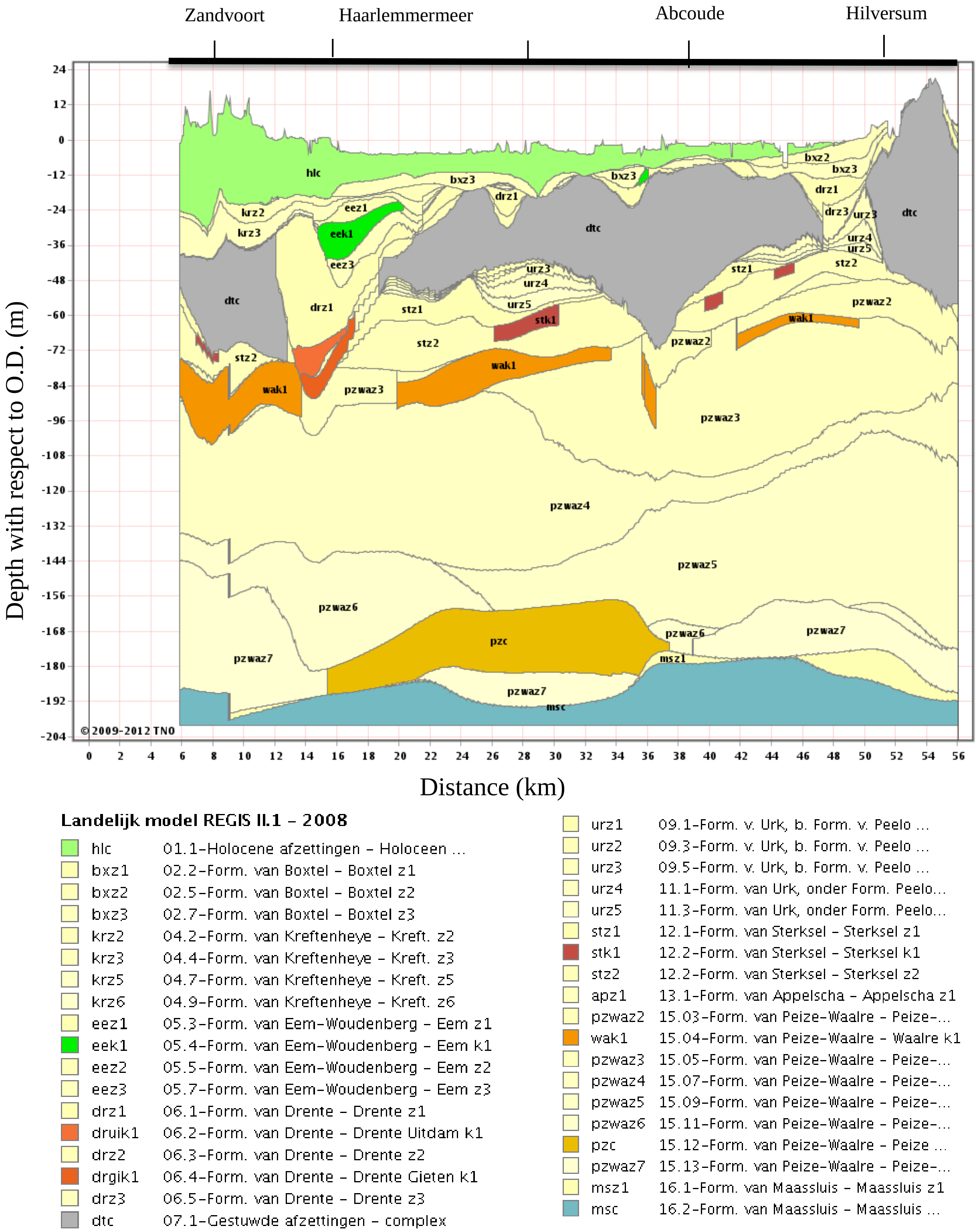


Figure 2.7: Overview of the formations in the profile (TNO-NITG Landelijk model REGIS II, 2005)

3. Modelling methodology

3.1 Method

The objective of this thesis was to understand the processes behind the chloride concentration distribution that developed during the Holocene. Three hypotheses were tested to understand these processes. Incorporation of landscape development was the same for all three hypotheses. Variation between the hypotheses existed in the assumptions about the initial chloride concentration distribution and chloride boundary condition. For hypothesis 1 we assumed freshwater concentrations (Table 1) as initial chloride distribution for the entire subsoil and chloride boundary conditions ranged from 16000 mg/l for the sea to 150 mg/l at the coast which is noted with an arrow labelled as North Sea. This boundary condition was set for time frames 5000 B.C. and 3850 B.C. Hypothesis 2 had also freshwater as initial chloride distribution for the entire subsoil but chloride boundary conditions for time frames 5000 B.C. and 3850 B.C. ranged from 16000 mg/l for the sea area to 5000 mg/l near the coast area. This chloride boundary condition was chosen because of its possiblility to be the source for high concentration levels of chloride measured near Abcoude. Hypothesis 3 was based on the theory that the Maassluis formation (depth of 190 to 260 meters below O.D.) in time frame 5000 B.C. had a brackish initial chloride concentration (Meinardi, 1991), while upper layers had freshwater concentrations. This theory was rejected by Post (2004) in which he used well measurements that showed an age of 24000 C^{14}BP for brackish water in Maassluis (see Figure 3.4). Maassluis is much older than 24000 C^{14}BP hence proving that connate seawater from Maassluis was not the cause of salinization for the upper layers. The chloride boundary conditions here were similar to hypothesis 1. It should also be mentioned that an extra fourth hypothesis was simulated with a longitudinal dispersitivy of 0.001 and same conditions as hypothesis one. This however did not show substantial differences in the results compared to hypothesis 1 and was therefore disregarded here for further evaluation.

The tool chosen to answer our research question and test our hypotheses was numerical modelling. Here we used a two-dimensional groundwater model (MODFLOW), coupled with a density dependent module (SEAWAT) to simulate the chloride distribution evolution. Because this was a first attempt to use forward modelling for simulation of landscape changes together with chloride distribution evolution and because of the assumption that there was one main groundwater flow direction perpendicular to the coast, a two-dimensional model was deemed appropriate. Over-/under estimations of chloride concentrations can arise because of the choice for a two-dimensional profile, but we considered this during the analysis of the results. The SEAWAT module was used since groundwater flows are affected by density differences. Overall, coastal groundwater modelling studies take water density differences into account since water density differences, arising from differences in temperature and solute composition affect groundwater flow. Temperature differences are not large along the Dutch coast and thus can be neglected. However, solute composition has a large effect as differences in dissolved sodium chloride, between seawater and fresh groundwater are large (Table 1).

Table 3.1: Classification of types of groundwater based on chloride concentration (Stuyfzand, 1993).

Main type of groundwater	Chloride concentration(mg Cl^-/l)
fresh	**< 150**
fresh-brackish	**150-300**
brackish	**300-1000**
brackish-saline	**1000-10.000**
saline	**10.000-20.000**

To model the evolution of chloride distribution during the Holocene several subsequent models needed to be made to capture the different landscape changes over time, starting with the oldest landscape and ending with the present situation. The base of the model was the Maassluis formation which is the base of the quaternary epoch. The method used here was to construct a two-dimensional model which we called a time frame and subsequently simulate the hydraulic heads and chloride distribution for that time frame. Nine time frames were modelled for each hypothesis. A time frame represents one period in time for which natural and/or anthropogenic changes contributed to a significant change in the groundwater system. The time frames were chosen such that they represented the approximated average time that the landscape that was analyzed existed. The general set up of a time frame was to reconstruct the surface level based on literature or calculated elevations. A rolling averaged mean was applied to the reconstructed surface values to obtain a smooth surface line in accordance with the regional scale of the analysis. Figure 3.1 shows the reconstructed nine surface elevations where we see an increase in surface level from 5500 B.C. with the appearance of the dunes in 3850 B.C. From 1500 A.D. there is no further increase of landscape in the vertical direction. After 1500 A.D. till 2000 A.D a total decrease of approximately 4 meters in the Haarlemmermeer is seen. For the remainder lands between Haarlemmermeer and Hilversum a decrease of the surface level is visible with a maximum of 2 meters near Abcoude and Horstermeer. Values for the model parameters were collected from literature or REGIS II and GeoTOP. Boundary conditions, e.g. sea levels, coast position and recharge, were defined based on assumptions or hypotheses from literature (Mulder et al. 2003; Van Loon, 2010; Bazelmans et al.,2011) . After simulation, results for the chloride distribution from the first time frame (hence oldest period) were used as initial chloride distribution for the second time frame and results from the second time frame for the third time frame and so on. Modelled for hydraulic heads were calibrated based on hydraulic head measurements from NHI. Below follows a detailed description of all the time frames explaining the model building procedure. All groundwater flow calculations used were steady-state while solute transport models were transient.

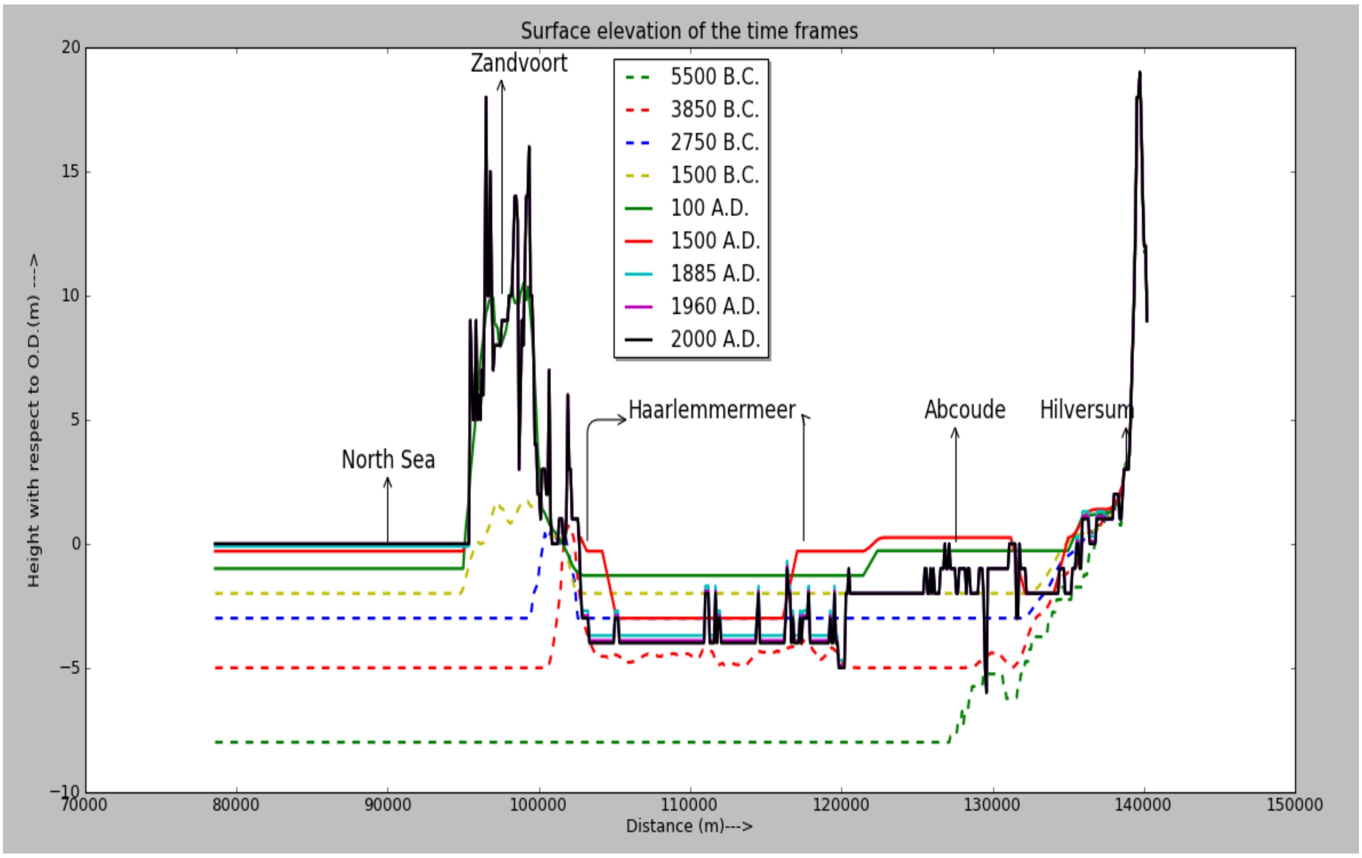


Figure 3.1: Calculated surface elevations of the nine time frames.

3.2 MODFLOW

MODFLOW is a three-dimensional finite-difference groundwater model, which solves the groundwater flow-equation (equation 1).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

K_{xx}, K_{yy}, and K_{zz}: values of hydraulic conductivity along the x, y, and z coordinate axes, which areas sumed parallel to the major axes of hydraulic conductivity (L/T);

h: potentiometric head (L);

W = volumetric flux per unit volume representing sources and/or sinks of water, with W <0.0 for flow out of the ground-water system, and W>0.0 for flow in (T^{-1});

S_s = specific storage of the porous material (L^{-1});

t = time (T).

MODFLOW was published by United States Geological Survey (USGS) by McDonald and Harbaugh (1988), and was designed to simulate saturated three-dimensional groundwater flow through a porous medium. Since 1988 many computer codes have been developed adding new capabilities to MODFLOW (Simcore software, 2011; Harbaugh et al., 2000).The version used here is MODFLOW-2005. Complete documentation of MODFLOW can be found in McDonalds and Harbaugh (1988) and Harbaugh et al. (2000). Here only the used packages are explained.

Packages used

Modflow packages used for these time frames were General Head Boundary (GHB), Recharge(RCH), River (RIV) and Drain(DRN) package. For a detailed description on the packages we refer to Haraugh (2005).

a) General head boundary package

The general head boundary package was used to simulate flow into or out of a cell from an external source. This is done based on the difference between the calculated head in the cell and the external head defined by the user. The linear relation between the flow into the cell and head in the cell is given by equation 2 (Harbaugh, 2005):

$$QB_n = CB_n\left(HB_n - h_{i,j,k}\right) \qquad (2)$$

n = boundary number,

QB_n= flow into cell i,j,k from the boundary (L^3T^{-1})

CB_n= boundary conductance (L^2T^{-1})

HB_n = head assigned to the external source (L)

$h_{i,j,k}$ = head in cell i,j,k (L).

b) Recharge package

Recharge package was used to simulate groundwater recharge based on an user defined flux assigned to the upper cell (Harbaugh, 2005).

c) River package

The river package was used to simulate interaction of surface water and groundwater by calculating the fluxes between these two systems. The flux between surface and groundwater are calculated based on the head difference of the user defined surface water level and calculated potentiometric head of the aquifer (Harbaugh, 2005). There can be flow into or out of the river dependent on the value of the two heads. (see equations 3 and 4)

$$QRIV_n = CRIV_n(HRIV_n - h_{i,j,k}) \qquad h_{i,j,k} > RBOT_n \qquad (3)$$

$$QRIV_n = CRIV_n(HRIV_n - RBOT_n) \qquad h_{i,j,k} \leq RBOT_n \qquad (4)$$

$QRIV_n$ = river discharge (m^3/d)

$CRIV_n$ = streambed conductance (m^2/d)

$HRIV_n$ = user defined potentiometric head of river stage (m)

$h_{i,j,k}$= calculated potentiometric head (m)

$RBOT_n$ = elevation of river bottom (m)

d) Drain package

The drainage package was used to simulate removal of a surplus of water out of the system. If the potentiometric head is higher than that the user defined elevation of water level in the drain, water is removed from the system, otherwise the drains will have no effect on the system (Harbaugh, 2005).

3.3 SEAWAT

For the simulation of density dependent flow the U.S.G.S. developed SEAWAT code was used. SEAWAT is the combination of MODFLOW and MT3DMS into one program that can solve the coupled flow and solute-transport equation. Calculations of SEAWAT are based on the conservation of fluid mass rather than fluid volume. SEAWAT uses freshwater head as the dependent variable instead of the normal potentiometric head. Freshwater head is used as an alternative to potentiometric head, in areas where there is difference in water density. From Post et al. (2007) it follows that in areas with the same pressure, different potentiometric heads will follow, depending on the water density. To cope with this problem a reference density is chosen, so that we can compare head levels with each other. Any density can be chosen as reference density but the most often used is freshwater density of 1000 kg/m^3. The conversion from measured head is calculated according to equation 5 (Post, Kooi and Simmons, 2007):

$$\phi_{f,i} = \frac{\rho_i}{\rho_f} h_i - \frac{\rho_i - \rho_f}{\rho_f} z_i \qquad (5)$$

$\phi_{f,i}$ = freshwater head at point i (L)

ρ_i = density of water in column at i (kg/m^3)

ρ_f = density of freshwater (1000 kg/m^3)

h_i = point water head (measured head in terms of native aquifer water) (L)

z_i = elevation of point i from a reference level (L)

So the flow from cell to cell is now calculated from freshwater head gradients. Output of SEAWAT are expressed in terms of the head of the native aquifer water, called point water head (Guo and Langevin, 2002). Complete documentation of SEAWAT can be found in Guo and Langevin (2002).

3.4 Model description

The model consists of 67053 cells with the size of 100 meters in the horizontal direction and different sizes in the vertical direction, resulting in a model domain of 103 layers and 651 columns. All model parameters are given in Table 3.2. Since interest is directed towards processes that influence the distribution of chloride concentration during landscape development in the Holocene, we used a detailed discretization for the upper layers. We chose a vertical discretization as a trade –off between computational time and measured accuracy. The vertical discretization, going from the top layer to the bottom layer, was:

61 layers with a 1-meter thickness
20 layers with a 2-meter thickness
8 layers with a 5-meter thickness
13 layers with a 10-meter thickness
1 layer with a 28-meter thickness

Based on the calculated mean hydraulic conductivities of a layer, distinction was made between permeable and semi-permeable layers. The hydraulic conductivities were taken from REGIS II (TNO-NITG, 2005) of which the values for the Holocene confining layer were replaced by values from GeoTOP (TNO-NITG, 2012) (see Figure 3.2 and 3.3). Mean values for the horizontal and vertical hydraulic conductivities were calculated using equation 6 (arithmic mean) for the horizontal hydraulic conductivity and 7 (harmonic mean) for the vertical hydraulic conductivity. Averaging of the hydraulic conductivities was needed since the grid size of the conductivity values are smaller than the grid used in this model, so an upscaling was in order.

$$Kh_{mean} = \frac{kh_1 D_1 + kh_2 D_2}{D_1 + D_2} \qquad (6)$$

$$Kv_{mean} = \frac{D_1 + D_2}{\frac{D_1}{kv_1} + \frac{D_2}{kv_2}} \qquad (7)$$

Kh_{mean}/Kv_{mean} = mean hydraulic conductivity (m/d)
kh_1= horizontal hydraulic conductivity of layer 1
kh_2= horizontal hydraulic conductivity of layer 2
kv_1= vertical hydraulic conductivity of layer 1
kv_2= vertical hydraulic conductivity of layer 2
D_1 = thickness of layer 1
D_2 = thickness of layer 2

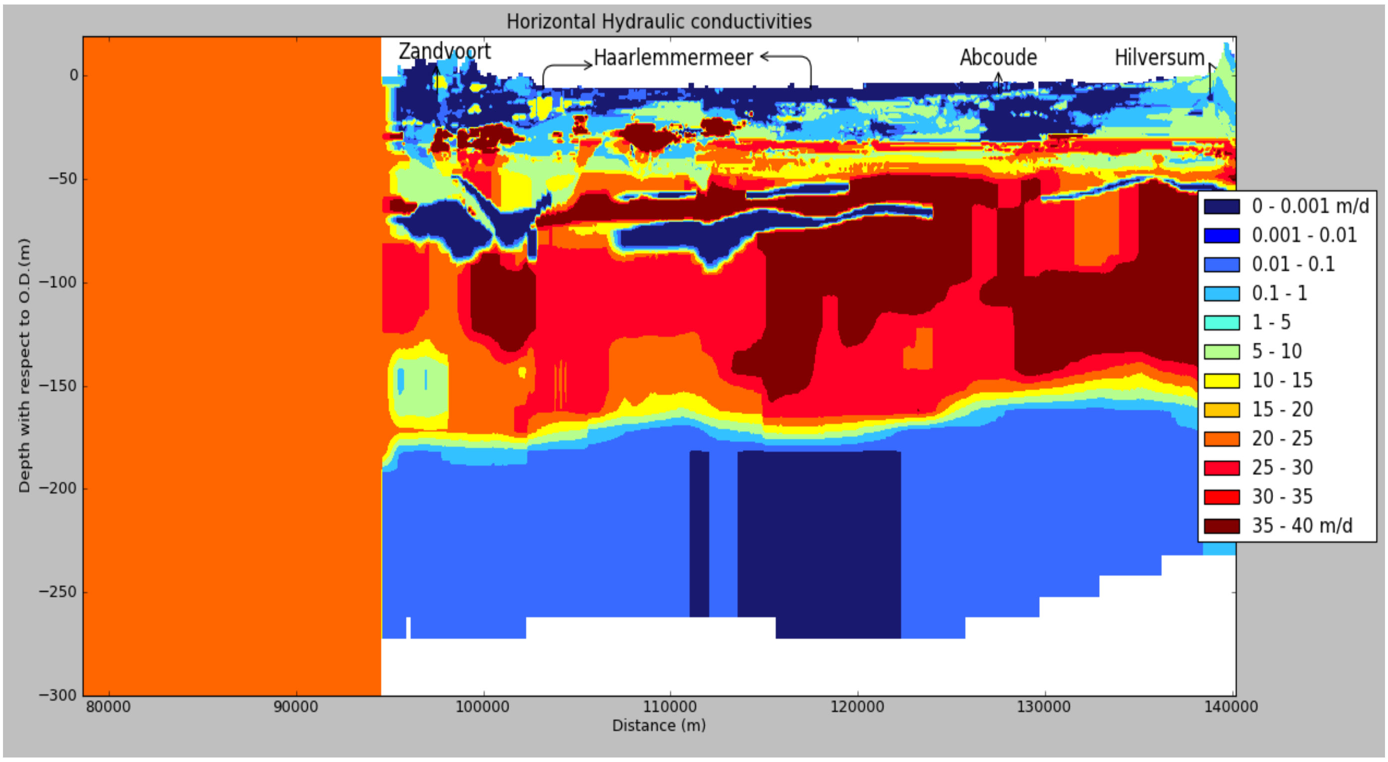


Figure 3.2: Horizontal hydraulic conductivities for the profile.

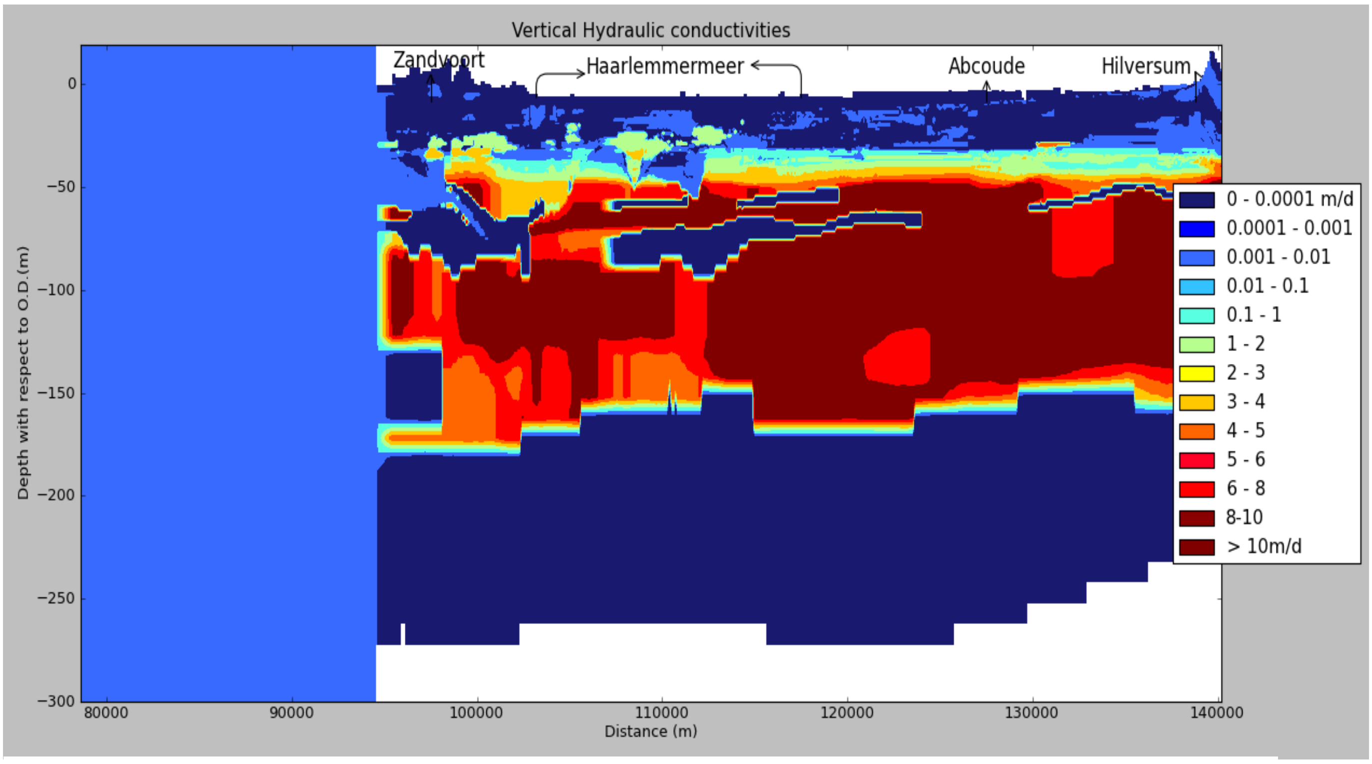


Figure 3.3: Vertical hydraulic conductivities for the profile.

Boundary conditions

For the east side of the model a no flow boundary was chosen based on the water divide in the Utrechtse Heuvelrug. Each time frame had the same boundary for the east side, assuming this to be constant throughout the Holocene. Also the following parameters were kept constant for all the time frames: anisotropy, general head boundary conductance, river conductance, porosity, longitudinal and horizontal dispersivities (see Table 3.2). For the west side of the model the boundary varied for each time frame depending on the sea level. The GHB was used in the time frames to account for the sea level such that a constant hydraulic head is maintained at the sea boundary and to remove the surplus of water and solutes out of the system. The GHB values were set for the top cells, head value was chosen as the sea level for that time frame (see Table 3.3). The value used for the recharge was taken from Van Loon (2010) based on his palaeo-groundwater model study of the Gooi and Vechtstreek area, which intersects our study area. Van Loon (2010) used equation 8 to calculate recharge for his palaeo-hydrological modelling.

$$R = (1 - f_i)P - f_m E_m \qquad (8)$$

R = precipitation surplus(m/d)

f_i= interception factor(-)

P= precipitation (m/d)

f_m= crop factor(-)

E_m= reference potential evapotranspiration(m/d) according to Makkink reference

This equation only changes the recharge based on a change in vegetation type, assuming that precipitation has not changed during the Holocene (Pauling et al., 2006) and evapotranspiration stayed constant, because solar radiation which is the source of energy for evapotranspiration, varied less than 0.5% since 800 AD (Cubasch et al.,1997; Pongratz et al., 2009) was made. Since different vegetation types existed accros the profile, different recharge values would have to be implemented accros the transect according to the vegetation type. However, to simplify things we decided to use a single value for recharge for the whole profile and all times. This will not affect the results too much because the recharge values for the possible different vegetation types i.e. deciduous forest, heather land, grass and crops, that existed in the research do not change much. We used the averaged value of 0.000745 m/d. (Van Loon, 2010) for all locations and times.

Solute transport model boundaries

For the solute transport model SEAWAT, the same discretization and boundaries as for the groundwater flow model were used. The initial concentrations varied for each time frame. For solving the advection component of the equation the MOC method (Guo and Langevin, 2002) was chosen after comparison with the Finite difference method and TVD. The MOC resulted in a better solution for the problem especially at the sharp boundaries between fresh and saline water. For the dispersion package a longitudinal dispersivity of 0.05 was used after comparison of a trial with a dispersivities of 0.5 and 0.005, since dispersivity is scale dependent (Oude Essink, 1996) and transverse dispersivity of 0.005 was applied. For the variable density flow package the densities for fresh and saline water (saline water here has a concentration of 16000 mgCl^-/l) were set to 1000 kg/m^3 and 1025 kg/m^3 .

Table 3.2: Table with model properties and constant parameters

Model parameter	Value
Length of profile	64 km
Heigth of profile	20 m above O.D.
Depth of profile	≈ 300 m, bottom of Maassluis formation
Horizontal cell size	100 m
Vertical cell size	Start with 1m and increases after 61 layers
Total layers	103
Total columns	651
Recharge	0.00074 (m/d)
Porosity	0.35
Longitudinal dispersivity	0.05
Transvere dispersivity	0.005
GHB conductance	100 d
River conductance	10 d

3.5 Time frames

The Pleistocene surface (9000 B.C.) was used as starting surface for the model. Surface levels for the Pleistocene were extracted from REGIS II (TNO-NITG, 2005) based on the underlying stratigraphy and after comparing there with maps from the reconstructed Pleistocene surface from Bazelmans et al.(2011). Elevation levels were more or less similar to the border based on REGIS II. Based on this surface level hydraulic conductivities were extracted from the merged hydraulic conductivity maps. REGIS II has no values for the sea, hence the horizontal hydraulic conductivity (Kh) was set to 30 m/d and the vertical hydraulic conductivity (Kv) to 3.0 m/d assuming a sandy sea subsurface. The above mentioned procedure for extracting hydraulic conductivity values was used for all the time frames unless mentioned otherwise. Peat area fills had values of uncompacted peat, namely Kh value of 2.2 m/d and Kv of 1.2 m/d (Kechavarz et al., 2010), unless mention otherwise. For peat area growth an accumulation rate of 0.06 cm/y was used to calculate the peat area elevation (Ovenden,1988 and Asselen,2010).

Cells above the surface level were set to inactive, parts where values were missing were filled with the corresponding value based on lithology (Bazelmans et al., 2011; Berendsen, 2008). According to literature description, the Pleistocene surface was characterized by bare soils that consisted of sands, varying from coarse sand in the river sites (western area of the profile) and fine aeolian cover sands in the eastern area of the profile bordered by the ice pushed ridges of the Utrechtse Heuvelrug. So hydraulic conductivity values of clays at the surface, deposited by rivers after the Pleistocene, were replace by values of fine sand given by GeoTOP. Each time frame had a different surface with the exception of the Utrechtse Heuvelrug which was constant for all the time frames.

Table 3.3: Table with description of time frames

Time frame	Event	Sea level (m. O.D.)	Surface elevation of peat (m.)	Water level of the Vecht (m. O.D.)	Extraction rate per well	Run time (y)
5500 B.C.	Maximum transgression	-8.0	Basal peat	-	-	3500
3850 B.C.	Open system with small barriers	-5.0	+0.9	-	-	1650
2750 B.C.	Closed system Freshwater environment behind dunes	-3.0	+0.7	-	-	1100
1500 B.C.	Coast protruded to maximum position	-2.0	+0.6	-	-	1250
100 A.D.	Young dunes Coast at its current position	-1.0	+0.72	-0.68	-	1600
1500 A.D.	Appearance of freshwater lakes Haarlemmermeer Horstermeer	-0.3	-0.2	0.05	-	500
1885 A.D.	Land reclamation Haarlemmermeerpolder Amstelveen Horstermeer	-0.1	Current surface level+0.3	Current situation NHI data	-	385
1960 A.D.	Groundwater extraction in dunes at Zandvoort	-0.1	Current surface level+0.1	Current situation NHI data	0.85 m^3/d Total 4 wells	75
2000 A.D.	Current water management	0.0	Current surface level	Current situation NHI data	0.18 m^3/d at Zandvoort 4.55 m^3/d at Hilversum. Total 3 wells	40

5500B.C.

In this time frame the marine transgression was at its maximum (Bazelmans et al., 2011). Reconstruction of the peat surface was based on the assumption that basal peat grew at sites where groundwater levels were higher than the surface level. A time frame with the Pleistocene surface was run as steady –state to simulate the heads that followed from a sea level of 8.0 meters below O.D. These heads were visually compared to the top of the basal peat maps from REGIS II and Bazelmans et al.(2011). The calculated heads were in agreement with the maps so these were used as the top of the surface in peat areas. Apart from the peat areas the landscape did not change much and was the same as the Pleistocene surface.

From this time frame onwards drains were placed at the surface unless mentioned otherwise, because all surface drainage was through overland flow (Bos, 2010; Van Loon et al., 2009). The initial chloride concentration of all Pleistocene deposits was assumed to be all freshwater (Post, 2004) so to create a chloride source the top cells representing the sea had a starting concentration of freshwater at the coast and increases to 16000 mg/l with a rate of 90 mg/l /100m towards the sea.

3850 B.C.

At the end of the Atlanticum the profile had developed into an open system with small barriers at the coast. The change from a totally open system to a half open system consisting of a tidal area with barriers was the reason to simulate this time frame.

Reconstruction of surface level was based on the top of the formations of Naaldwijk, Wormer and Zandvoort. This followed from the assumption that the top of the formations coincided with the end of Atlanticum. Hence the top values were used as surface levels in areas of sand and clay with the assumption that compaction of sand and clay is negligable. The boundary between the dunes and the sea was estimated at the cross-section of the sea level and Zandvoort formation because the dunes continued to grow until the Subboreal. The chloride concentration at the top cells was set at 16000 mg/l. At the sea side behind the barriers concentrations were set with a declining rate of 90 mg/l /100m towards the coast.

2750 B.C.

After closure of the barrier beach system, the profile behind the dunes changed into a freshwater environment. Areas behind the dunes were filled with peat up to the calculated peat surface growth or up to sea level, where the calculated surface of peat was below sea level. Dune heights were extracted from the Zandvoort member, included in the formation of Naaldwijk. For the Kh and Kv values of the dunes fine sand and medium sand values were used, since these were not in the merged hydraulic conductivity maps. From this time frame onwards the chloride source of the top cells at the sea side were fixed at 16000 mg/l, while the area behind the dunes were fixed at the chloride concentration of freshwater.

1500 B.C.

By 1500 B.C. the coast protruded to its maximum position (Bazelmans et al., 2011). Values for dune heights and extension were gathered from REGIS II maps of the Naaldwijk formation and Schoorl member. Values of the base of the member were chosen as the top of the dune surface since the dunes were still growing in the Subboreal (Berendsen, 2008). For the growth of the rest of the profile see Table 3.3.

100 A.D.

No human influence was yet visible and the dune system had developed to its current position with the growth of the Young dunes. Therefore the top of the Young dunes was used as the surface level of the dunes. A sea level of 1.0 m below O.D. based on a sea level rise of 0.05 m/century (Beets et al.2003) was used. The Vecht system which drained most of the Vecht area (Bos, 2010) had a water level of 0.68 meters below O.D. This level was calculated based on an assumed hydraulic head gradient of 0.004 m/km towards former inland sea Zuiderzee. The floodplain area was assumed 0,4 m higher than the river level (Van Loon et al.,2009).

1500 A.D.

Around 1500 A.D. many lakes appeared throughout the Dutch landscape. Haarlemmermeer and Horstermeer changed into lakes because of erosion of peat bulks by wind and peat extraction by men. The depth of the Haarlemmermeer was based on the deepest point of the polder that exist now, because

Haarlemmermeerpolder was drained until the bottom of the Haarlemmermeer lake, and then corrected for compaction. Water levels of the Haarlemmermeer were taken as the sea level since no real record exist of its position. Since the influence of men, peat areas compacted with a rate of 2 mm/y (Van Loon, 2010; Asselen, 2010), when there was overburden or dewatering of the area. A water level of 0.05 meters below O.D. for the Vecht, was assumed/calculated with the same approach as for 100 A.D.. The same level was assumed. The floodplain area of the Vecht was set at 0.25 meter above the Vecht surface water level after compensation for compaction of the peat under the clay and silt layers that are currently present.

1885 A.D.

The main changes in the following time frames were caused by human intervention. Haarlemmermeer, Amstelveen and Horstermeer were all reclaimed. These areas became polders with intensely controlled groundwater levels. The surface level for this time frame and the remaining frames was constructed based on the topography of our current landscape compensated for compaction. Here we did not use the rolling average method to smooth the surface level. Drainage and river levels here were taken from the current situation based on data from Netherlands Hydrological Model(NHI), version 2.1.

1960 A.D.

The time frame 1960 A.D. differs from that of 1885 A.D. by the existence of extraction wells in the dune area of Zandvoort. Herein the rivers and drains had the same settings as the current situation. Four wells were placed in the dunes each with an extraction rate of 0.85 m^3/d. This extraction rate was calculated based on the maximum total extracted water of 18 million m^3/y before 1960 A.D. in the dune area, covering an area of 36 million m^2. Hence 0.5 m/y per square meter is extracted in the area. Giving a total of 1250 m^3/y of extracted deep groundwater at a depth of 23 meters.

2000 A.D.

Time frame 2000 A.D incorporates all current drainage, river, infiltration and extraction well systems. Data for rivers and drains were gathered from NHI. Wells in the dunes have an extraction rate of 0.18 m^3/d (Oude Essink, 1996) and three wells near Hilversum have each an extraction rate of 4.55 m^3/d (Van Loon, 2010).

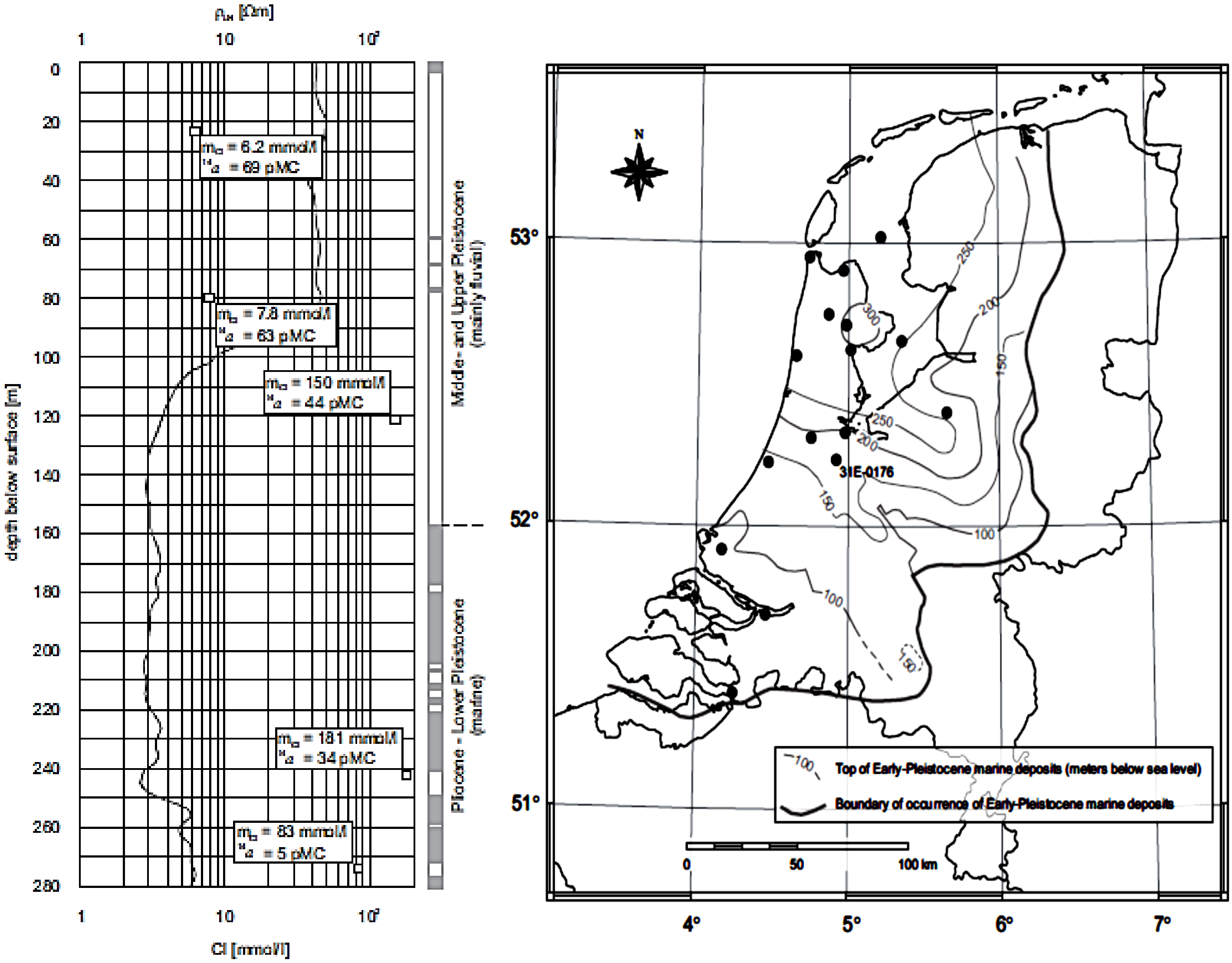


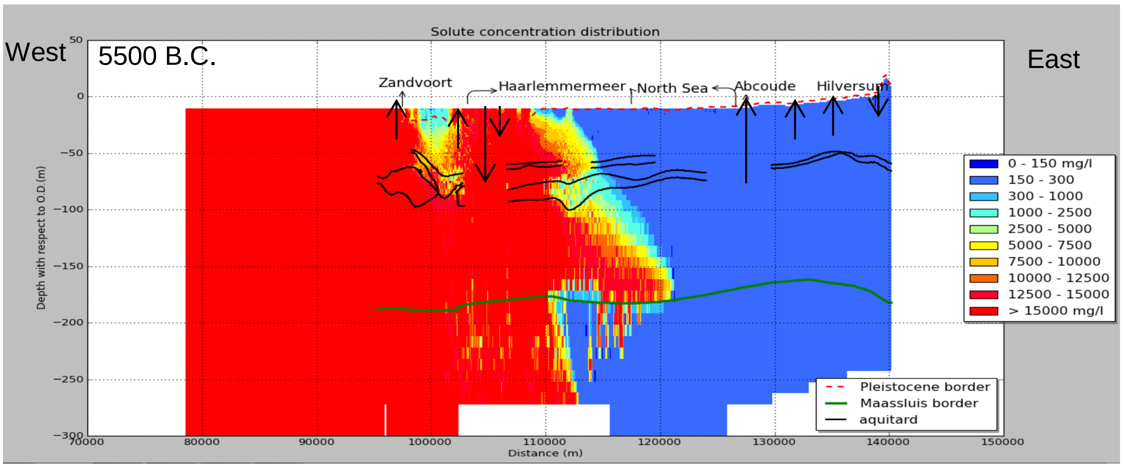
Figure 3.4: Graph of Cl concentration and long-normal resistivity (ρLn,solid line) vs. depth in well 31E-0-176 location shown in right figure (point denoted by 31E-0-176). Column on righthand side indicates sand (white) and clay layers(shaded). The top of the Early-Pleistocene marine strata is found here at a depth of approximately 160 meters addepeted from Post(2004, p.20). Values of the measured points have been converted from mmol to mg/l and the age of mpC converted to C^{14}BP years. From top to bottom converted measured values are:
219 mg/l age 2900 C^{14}BP
276 mg/l age 3700 C^{14}BP
5317 mg/l age 6600 C^{14}BP
6416 mg/l age 8600 C^{14}BP
2942 mg/l age 24000 C^{14}BP

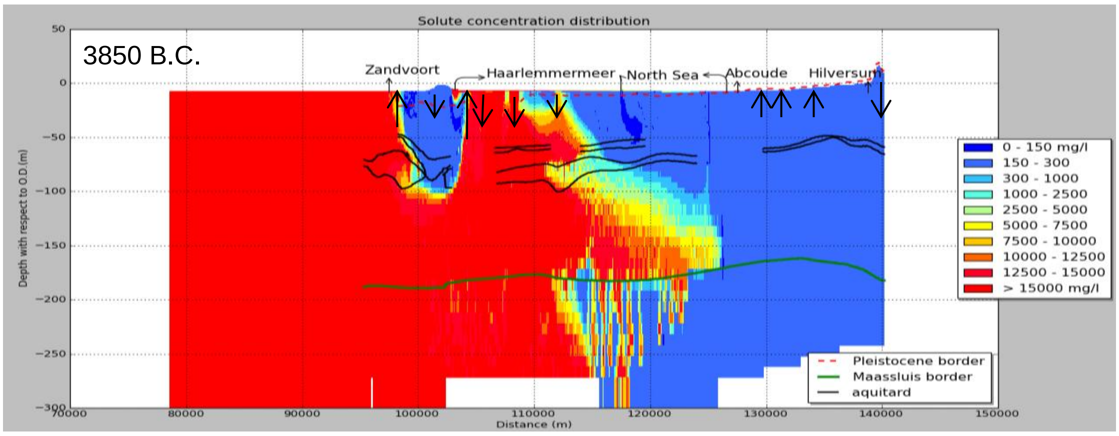
4. Results

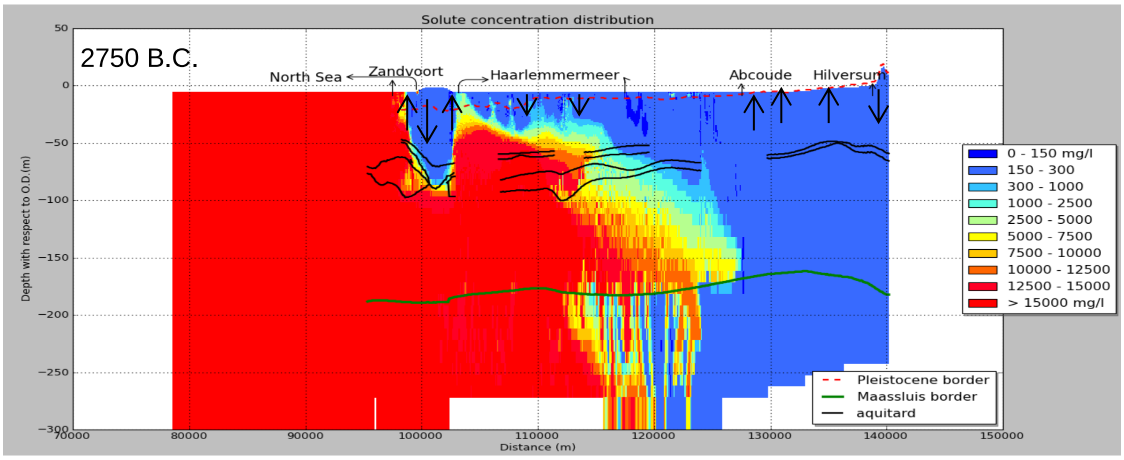
Figure 4.1 gives an overview of the development of the chloride concentration distribution throughout the time frames for hypothesis 1. The east side of the profile has a fresh-brackish groundwater compostition and an increasing amount of seepage between Abcoude and Utrechtse Heuvelrug throughout the periods. Sites which we expected to be fresh fall in the 150-300 mg/l category because we gave the recharge an concentration of 150 mg/l. When this accumulates due to poor drainage and removal of solutes it can reach higher concentration than 150 mg/l therefore falling in the category of 150-300 mg/l. Examples are seen at the Utrechtse Heuvelrug and dunes for all time frames but we consider them fresh rather than brackish. Potentiometric heads of the profile for all the time frames are near surface level, except for the dunes with heads of 20 centimeter lower than the dune elevation, and the Heuvelrug, where heads are around 3 meters above O.D. where they should be 10 meters above O.D. (DINOLoket). Freshwater and saline water distribution changes take place mainly between Zandvoort and half way between Abcoude and Haarlemmermeer. There is infiltration of saline water at the west side of Haarlemmermeer for the first two time frames. This saline water infiltration coincides with the infiltration arrows and the occurrence of highly permeable sediments. Noticeable is that the larger part of the surface below North Sea for time frames 5500 B.C. and 3850 B.C. has no salt water infiltration and stays fresh. There is also little or no infiltration or seepage in the midsection of the profile below sediments of low permeability (see Figure 3.2 and 3.3). The absence of saline infiltration and its coincidence with low permeable sediments is also visible at the fresh-brackish water lens near Zandvoort for time frame 5500 B.C. At the top of some aquitards and Maassluis formation there is a horizontal spread of chloride across the boundaries towards the east which also shows a retardation of infiltrating saline water. Whereas in other areas with high permeable sediments, e.g. west side of the Maassluis formation, parts below the boundaries are already saline. In some areas, e.g. east side of Maassluis formation and at the aquitard at a depth of 75 meter below O.D. below Haarlemmermeer, where retardation of infiltration is visible, we see the occurrence of fingered flow throughout the time frames. Fingered flow is a process that takes place at the instable interface of two fluids when one invades the other (Rezanezhad et al., 2006).

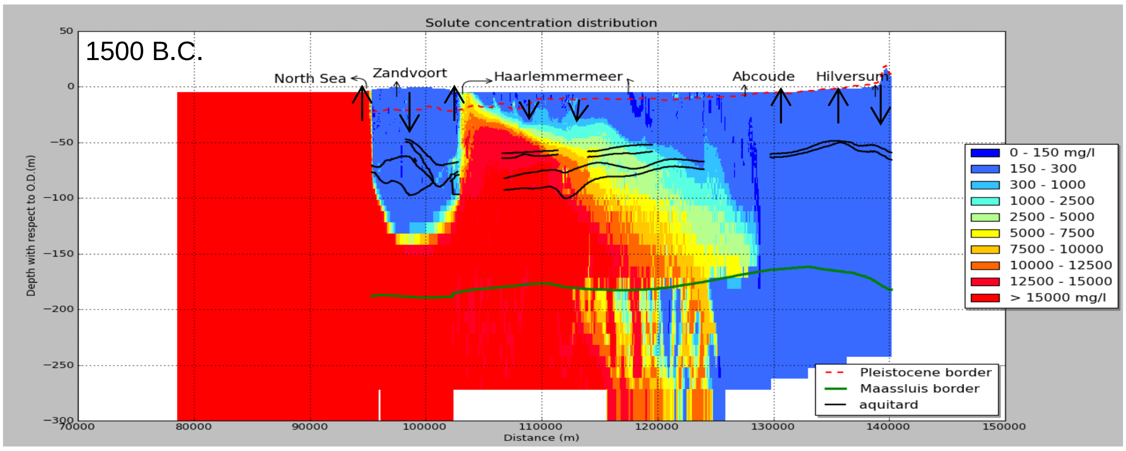
From 3850 B.C. onwards a fresh-brackish water lens developes underneath the barriers which become the dunes after 2750 B.C.. This fresh-brackish water lens has a larger width than the width of the barriers in time frames 3850 B.C. and 2750 B.C. which is explained by merges of this lens with the already existing fresh-brackish water lens near Zandvoort. Another remarkable feature in time frame 3850 B.C. is the development of a small saline water lens at the east boundary of the barriers and the appearance of small freshwater blobs. These blobs are most likely to appear from the discretization of the boundary conditions in which values of 150.000 are assigned to the freshwater class, and 150.001 to the next class of fresh-brackish, but they are still fresh. It can be seen that the fresh-brackish interface near the dunes coincides with upward flow at or near the dune boundaries. From 2750 B.C. on, so after the closure of the barriers, first a freshening of the midsection of the profile can be seen until 1500 A.D. During the freshening of the midsection we see a rising chloride concentration at the west boundary of the Haarlemmermeer from 2750 B.C. until current time frame. A similar increase in chloride concentration also takes place at the east boundary of the Haarlemmermeer but starts from 1500 A.D. until 2000 A.D. The appearance of high chloride concentrations at the east side of the Haarlemmermeer coincide with elevation change of the landscape (see Figure 3.1). These changes resulted in more seepage and higher flow rates there. Also the upward movement of the fresh-brackish interface is visibly related to man made water management systems that appeared in 1885 A.D. at the Haarlemmermeer. The drainage made by men also shows a remarkable removal of solutes near the Utrechtse Heuvelrug and Zandvoort, which develop a freshwater concentration from 1885 A.D. onwards. From 1885 A.D. the fresh-brackish interface below the dunes moves upwards until current situation in 2000 A.D. i.e. due to land subsidence by drainage and due to the formation of deep ploders. Also a horizontal movement of the west side of the freshwater lens below the dunes is visible in time frame 1885 A.D. The west boundary of the freshwater lens underneath the dunes coincides well with the chloride data points from DINO. Also the majority of the data points from DINO are in agreement with the simulated chloride concentrations at the east side of the profile, except for the chloride concentration below Haarlemmermeer, were simulated concentration are higher than those of the data points, while simulated concentrations are lower than observed values near Abcoude. The position of the main fresh-brackish interface, i.e. the interface between the east boundary of the Haarlemmermeer till Abcoude, stops moving to the east from 1500 A.D., hereafter the interface even moves back to the west.

For hypothesis 2, we increased the starting chloride concentration for time frames 5000 B.C. and 3850 B.C. at the then existing coast up to 5000 mg/l compared to hypothesis 1. Changes are visible in the aforementioned time frames, particulary near Abcoude where there is saline water infiltration (see Figure 4.2). Also for this hypothesis we see that there is no infiltration of saline water below the North Sea at places with low permeable sediments in the midsection, therefore a fresh-brackish water lens stays in existence up to a depth of 100 meters below O.D. and saline water infiltrates at the boundaries of this fresh-brackish water lens. The infiltrating saline water near Abcoude expands to the east and west to eventually merge with saline water from the west at a depth of 70 m below O.D. The area near and below Abcoude stays more saline, around 1000 mg/l, than hypothesis 1 until 100 A.D., whereafter there is a freshening of brackish water in the remaining time frames. The west side of the profile has the same patterns and development of chloride distribution as hypothesis one for all the time frames with the exception of the east side of the Haarlemmermeer. We see the same increase in chloride concentration at the east Haarlemmermeer boundary but for hypothesis 2 this increase starts in time frame 1500 B.C. and has a larger width with a position more to the east. The final frame of 2000 A.D. shows a more eastward and upward position of the main fresh-brackish interface, than hypothesis 1 (see Figure 4.2). Also the values for freshwater sites below the Utrechtse Heuvelrug and dunes are higher than hypothesis 1. The resemblance of the simulated chloride concentration for hypothesis 2 deviates more from the observed values than hypothesis 1. Although they are closer to the measurements near Abcoude.


Solute concentration distribution
West
5500 B.C.
East
Zandvoort
Haarlemmermeer
North Sea
Abcoude
Hilversum
Depth with respect to O.D (m)
Distance (m)
0 - 150 mg/l
150 - 300
300 - 1000
1000 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
> 15000 mg/l
Pleistocene border
Maassluis border
aquitard


Solute concentration distribution
3850 B.C.
Zandvoort
Haarlemmermeer
North Sea
Abcoude
Hilversum
Depth with respect to O.D (m)
Distance (m)
0 - 150 mg/l
150 - 300
300 - 1000
1000 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
> 15000 mg/l
Pleistocene border
Maassluis border
aquitard


Solute concentration distribution
2750 B.C.
North Sea
Zandvoort
Haarlemmermeer
Abcoude
Hilversum
Depth with respect to O.D (m)
Distance (m)
0 - 150 mg/l
150 - 300
300 - 1000
1000 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
> 15000 mg/l
Pleistocene border
Maassluis border
aquitard


Solute concentration distribution
1500 B.C.
North Sea
Zandvoort
Haarlemmermeer
Abcoude
Hilversum
Depth with respect to O.D (m)
Distance (m)
0 - 150 mg/l
150 - 300
300 - 1000
1000 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
> 15000 mg/l
Pleistocene border
Maassluis border
aquitard

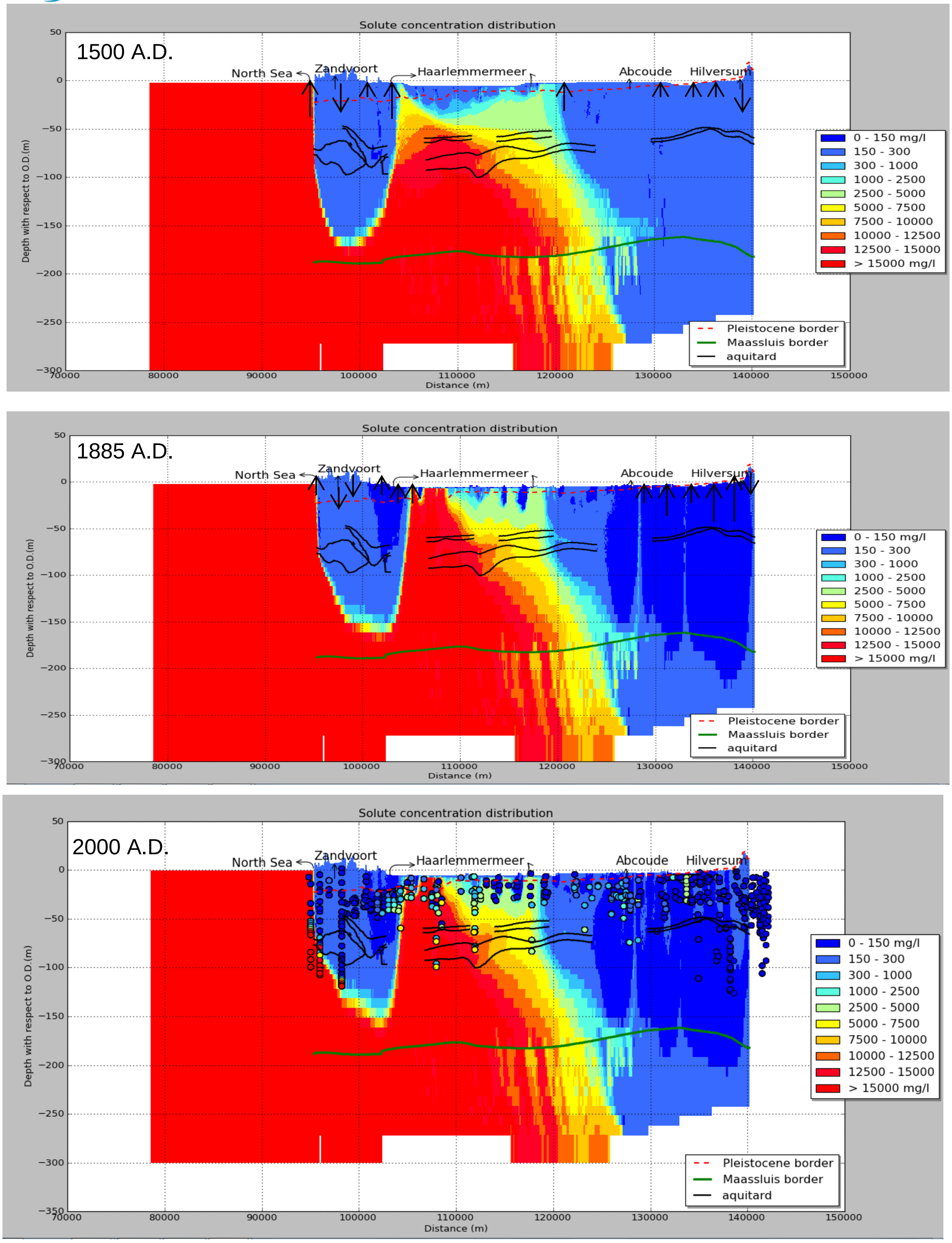
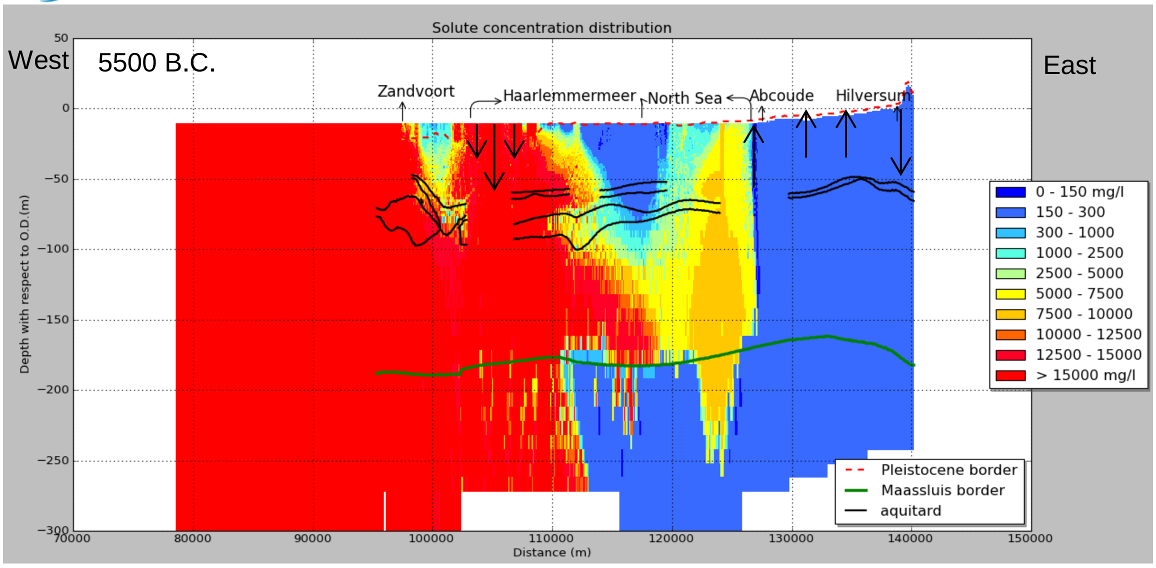
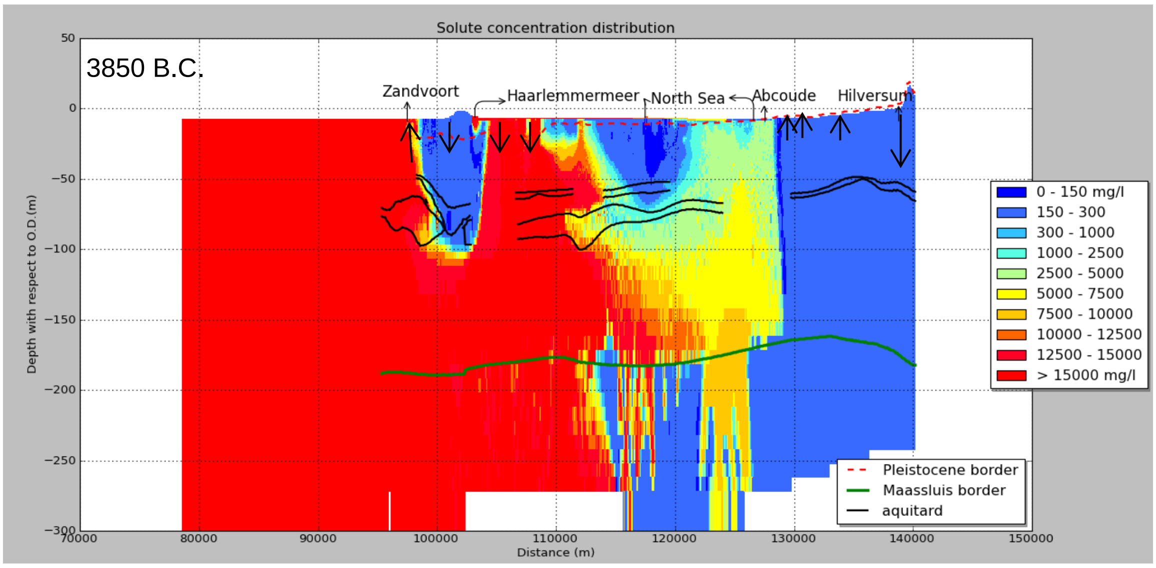
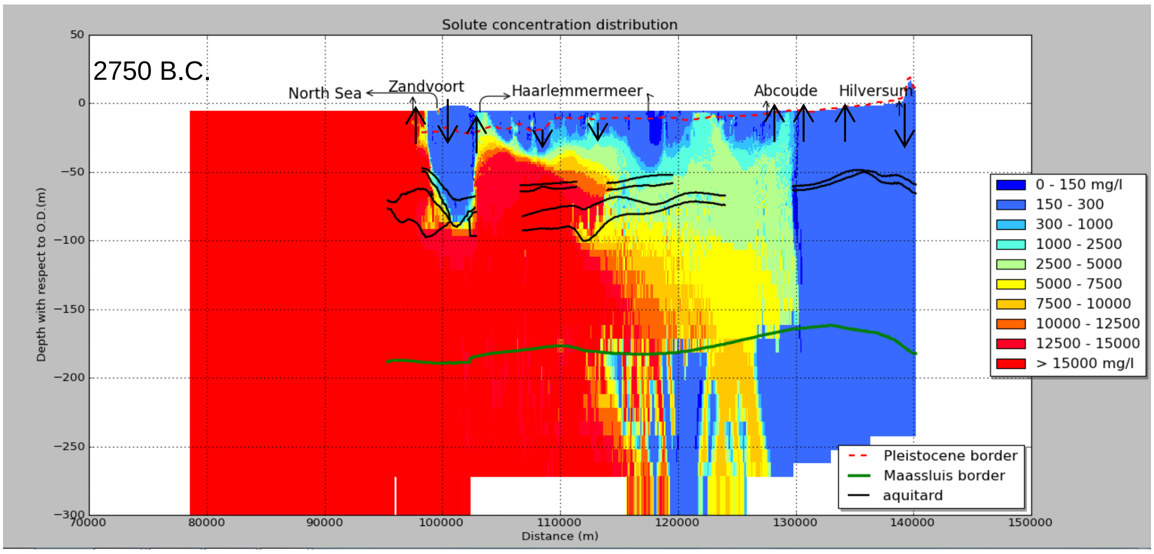


Figure 4.1: Results for chloride distribution evolution throughout the time frames for hypothesis 1. Arrows in the figures indicate seepage (arrow upward) or infiltration (arrow downward). Size of the arrows indicate a large or small rate of seepage or infiltration compared to one another. Arrows of time frame 2000 A.D. have the same orientation as time frame 1885 A.D. with more seepage between Abcoude and Utrechtse Heuvelrug. Circles in time frame 2000 A.D. give measured chloride data points from DINO database.


Solute concentration distribution
West
5500 B.C.
East
Zandvoort
Haarlemmermeer
North Sea
Abcoude
Hilversum
0 - 150 mg/l
150 - 300
300 - 1000
1000 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
> 15000 mg/l
Pleistocene border
Maassluis border
aquitard
Depth with respect to O.D.(m)
Distance (m)


Solute concentration distribution
3850 B.C.
Zandvoort
Haarlemmermeer
North Sea
Abcoude
Hilversum
0 - 150 mg/l
150 - 300
300 - 1000
1000 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
> 15000 mg/l
Pleistocene border
Maassluis border
aquitard
Depth with respect to O.D.(m)
Distance (m)


Solute concentration distribution
2750 B.C.
North Sea
Zandvoort
Haarlemmermeer
Abcoude
Hilversum
0 - 150 mg/l
150 - 300
300 - 1000
1000 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
> 15000 mg/l
Pleistocene border
Maassluis border
aquitard
Depth with respect to O.D.(m)
Distance (m)

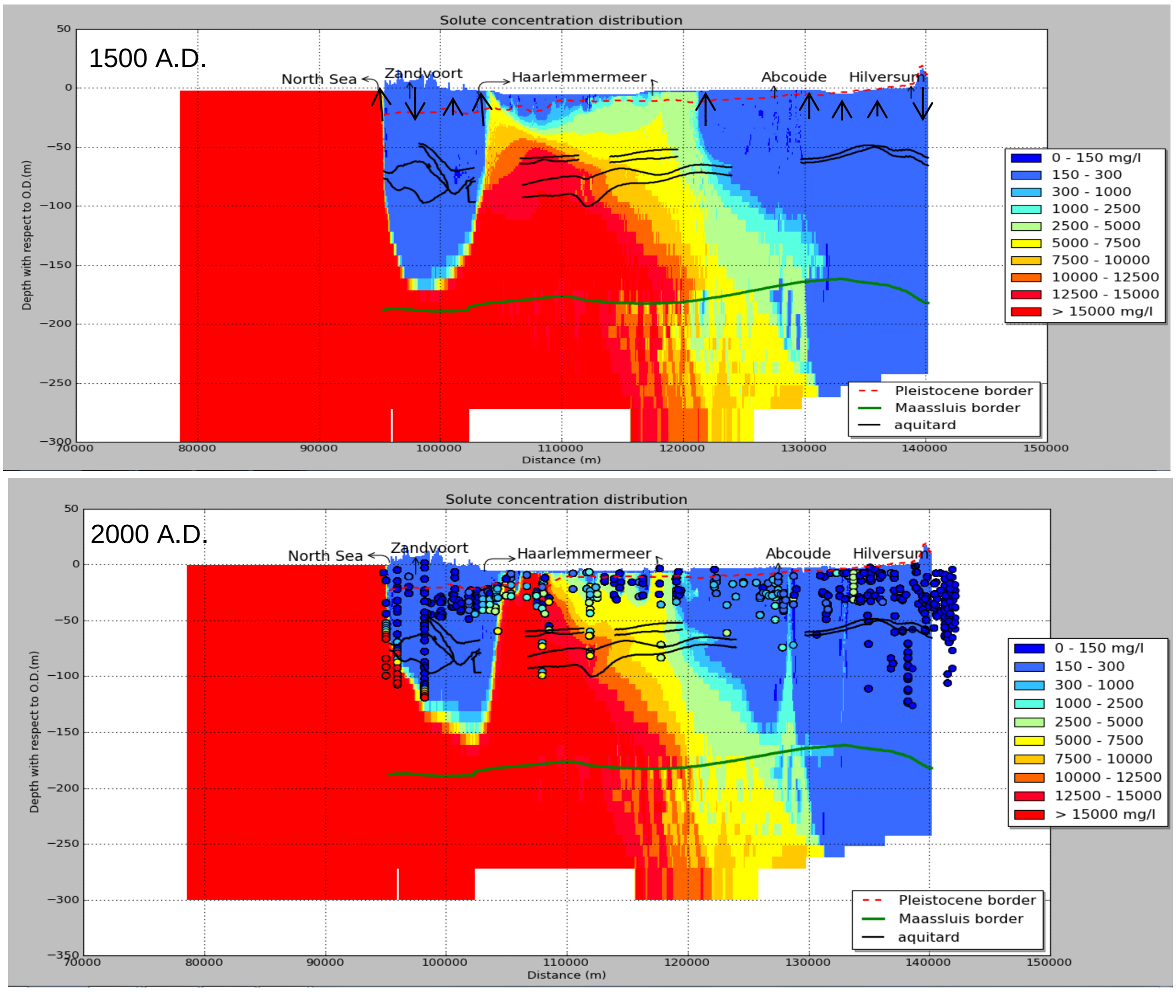
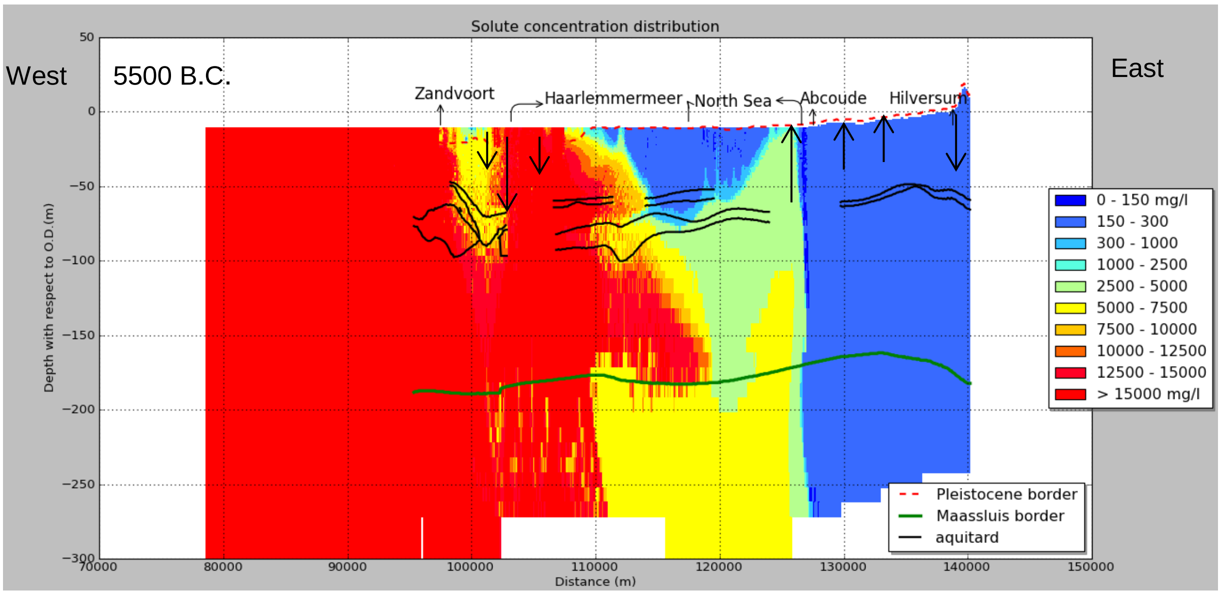
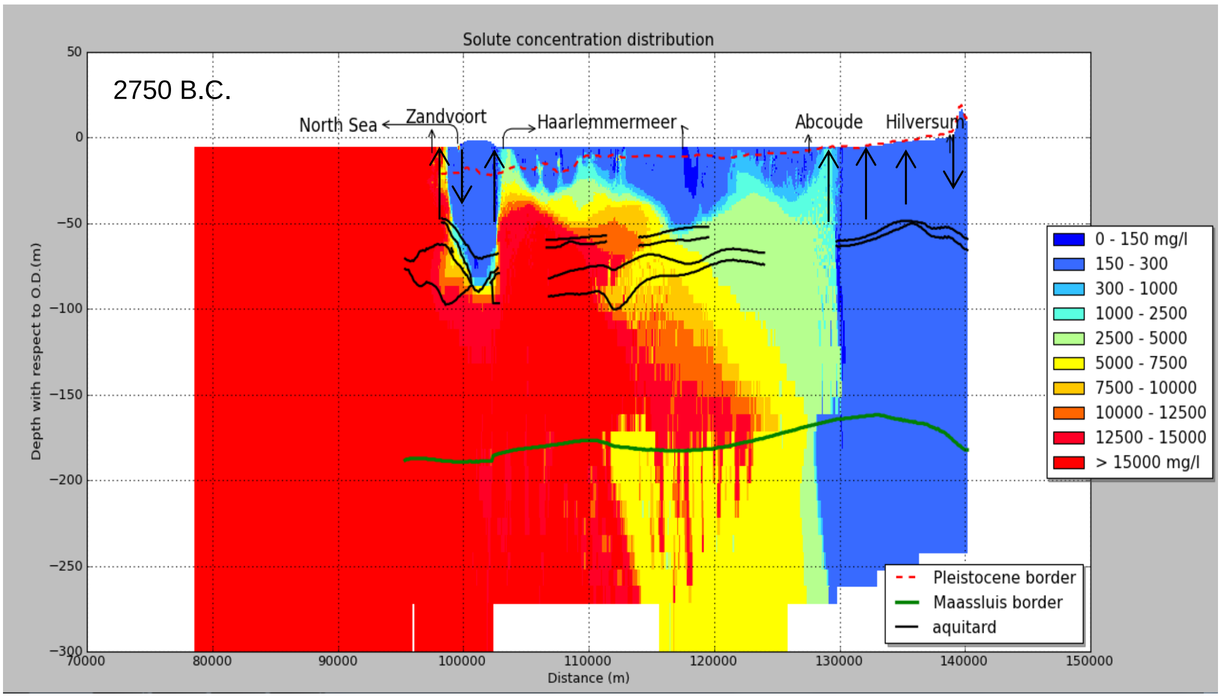


Figure 4.2: Results for chloride distribution evolution throughout the time frames for hypothesis 2. Arrows in the figures indicate seepage (arrow upward) or infiltration (arrow downward). Size of the arrows indicate a large or small rate of seepage or infiltration compared to one another. Arrows of time frame 2000 A.D. have the same orientation as time frame 2000 A.D. of hypothesis 1. Circles in time frame 2000 A.D. give measured chloride data points from DINO database**.**

For hypothesis 3 in which the starting concentration of Maassluis formation had a value of 5000 mg/l, we see a fresh-brackish water lens up to a depth of 75 meters below O.D. between Abcoude and Haarlemmermeer in the first two time frames. This freshwater lens is surrounded by brackish water at the east side near Abcoude and saline water at the west side. The western pattern evolution of the chloride distribution is the same as hypothesis 1 and 2, with the exception of the brackish lens below Zandvoort which was a freshwater lens in the previous two hypotheses. The area below Abcoude is more saline than in hopothesis 1 with values of 1000 mg/l more for the periods until 100 A.D. After 100 A.D. this area becomes fully fresh-brackish except for the high concentrations to the east of Haarlemmermeer in 1500 A.D. and unwards. The final postion of the main fresh-brackish interface in time frame 2000 A.D. is at the same position as hypothesis 2 with the same concentrations but with a larger width (see Figure 4.3). Noticeable is that for this hypothesis the concentrations for the Haarlemmermeer are higher than hypothesis 1, therefore deviating even more from observed data points. But the freshwater pattern near Utrechtse Heuvelrug resemble that of hypothesis 1. For all hypotheses the simulated concentrations are higher than observations at Haarlemmermeer and lower than those of Abcoude at a depth of 50 meters below O.D.





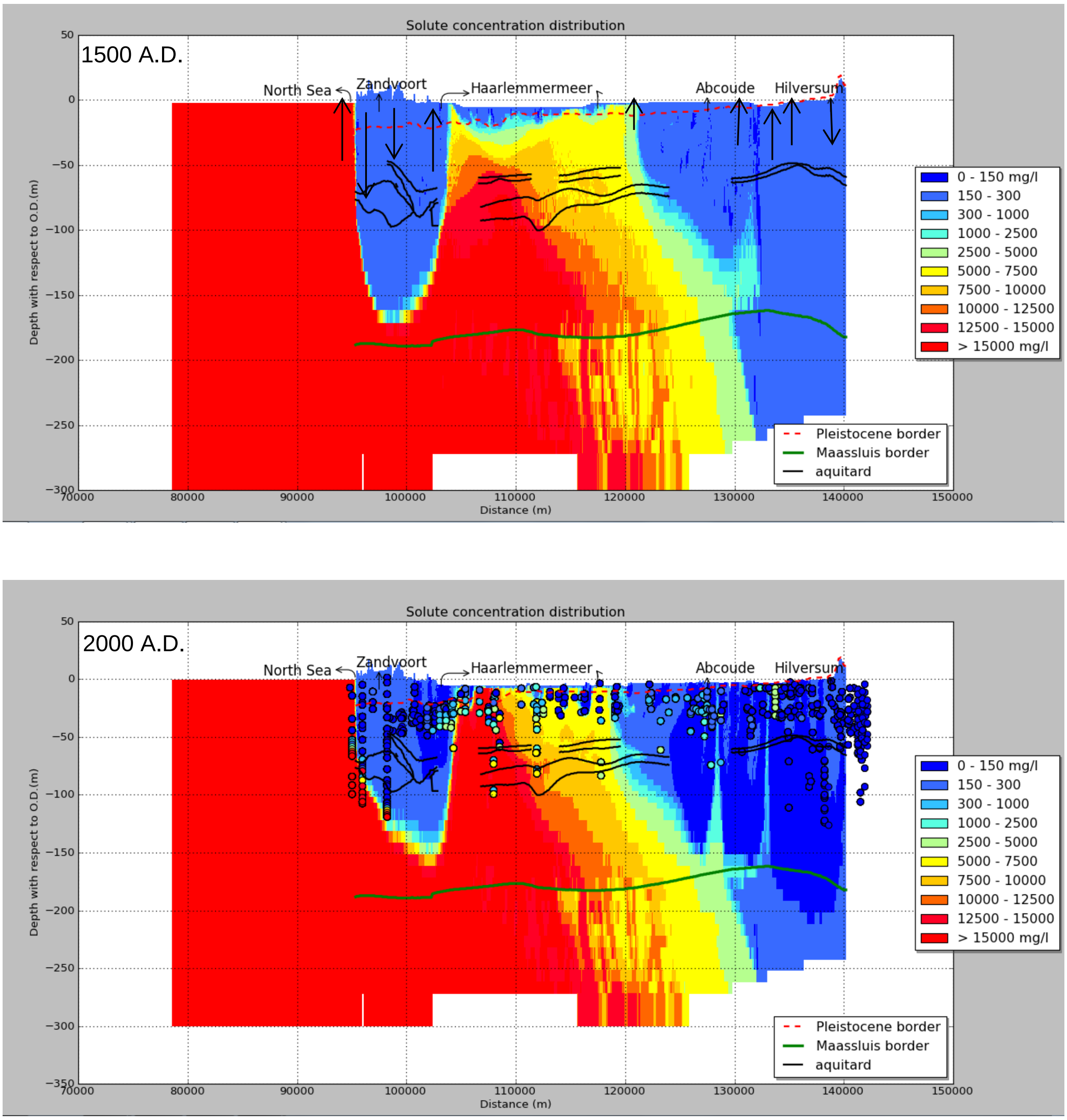


Figure 4.3: Results for chloride distribution evolution throughout the time frames for hypothesis 3. Arrows in the figures indicate seepage (arrow upward) or infiltration (arrow downward). Size of the arrows indicate a large or small rate of seepage or infiltration compared to one another. Arrows of time frame 2000 A.D. have the same orientation as time frame 2000 A.D. of hypothesis 1. Circles in time frame 2000 A.D. give measured chloride data points from DINO database.

5. Discussion

The aim of this thesis was to understand the influence of landscape changes and antropogenic changes on the chloride distribution evolution during the Holocene coastal development in the North-West coastal region of the Netherlands. This because there is a gap in our knowledge concerning the evolution of chloride distribution toghether with landscape changes and antropogenic changes. Therefore we tested three hypotheses based on our interpretation of the landscape evolution during the Holocene, with forward modelling using SEAWAT and MODFLOW. Results from the hypotheses were in line with conclusions from previous studies (Post, 2004; Appelo and Geirnaert, 1991 and Stuyfzand, 1993.), supporting the origin of saline groundwater in the Dutch groundwater coming from Holocene transgression. Our results showed that the majority of the salinization of the Dutch coastal groundwater took place during the first two time frames, which was during the Holocene transgression (see Figure 4.1). During these time frames the surface was inundated by the North Sea and seawater infiltration occurred through free convection in areas with high permeable sediments (see Figure 4.1). Because free convection was the main transporting mechanism, saline water reached the Pleistocene layer within 100 years. If diffusion were to be the transporting mechanism it would have taken a much longer time (Post et al., 2003). In areas below low permeable sediments results showed a retardation of salinization during transgression and these also caused fingered flow. Salinization in these layers occurred most possibly through a combination of convection and diffusion where before vertical transport first a horizontal movement occurred on top of the low-permeable layer (see Figure 4.1 time frame 5500 B.C.). The theory that salinization of the upper layers was from connate seawater from Maassluis was shown not to be a necessary condition, but could also not fully be disregarded as being partly true as seen from simulations of hypothesis 3. Connate seawater from Maassluis formation did cause higher chloride concentrations throughout the simulations in the midsection of the profile and did reach the Holocene confining layer, but did not have an extreme influence on the chloride evolution pattern, since the results showed the same chloride concentration patterns as the other hypotheses (see Figure 4.3). It is not fully understood how connate seawater could have reached the Holocene confining layer except that the topography (see figure 3.1 surface of 5500 B.C.) seems to have played a significant part in causing high seepage rates, related to advection, near Abcoude. Nevertheless it is indeed visible that Maassluis did have an influence on the salinization of layers above the Maassluirs formation. Although all the hypotheses sustain the theory of Holocene transgression none of the hypotheses could explain the high chloride concentration below Abcoude and surroundings.

From the results it was also clear that changes in landscape affected the groundwater flow patterns and therefore also the chloride distribution. This was visible in the development of a fresh-brackish water lens under the dunes, which is well represented and agrees with measured data points in that area (see Figure 4.1). Changes in hydraulic gradient due to elevation differences in surface level caused higher seepage rates. Human changes through drainage, land reclamation and groundwater extraction caused shrinkage of freshwater lenses making the fresh-brackish interface to move upwards. From this it followes that apart from sea level change, lithology and landscape changes are the main drivers of the chloride distribution. The hypotheses presented the evolution of the chloride distribution well for the west side of the profile in contrast to the east side of the profile. Also the comparison of our results for the east side of the profile with interpolation maps of Post (2004) and Minnema et al.(2004) (see Figure 1.1 and 2.5), showed considerable differences. However, it should be pointed out that interpolated maps have errors to due to outdated measured points or estimation errors of the interpolated map. The higher chloride concentration in the subsurface of Abcoude and surroundings was not explained by any of the three hypotheses, and therefore raises the hypothesis of another source of chloride. Since other processes for possible sources were already disregarded by Post (2004), such as aerosols, evaporates, anthropogenic pollution etcetera, the source had to be from another saline water body. A possible explanation for the higher chloride concentration below Abcoude is that there was saline water inflow from the north side, the former Zuiderzee, either caused by reclamation of land, which caused a head gradient and subsurface salinization by seawater intrusion during the past.

The over-estimation of chloride concentration below Haarlemmermeer can be caused by a number of reasons. First, sediment conductivities still form a big uncertainty in groundwater modelling. Interpolated data from GeoTOP and REGIS II for the hydraulic conductivities give a good representation but might still fail in smaller scale variations of the subsoil. The second reason may be related to the assumption that the boundaries stayed the same throughout the model run per time frame. A third reason is that there might have been a bigger freshwater lens there caused by a higher peat dome or localized higher potentiometric heads or more recharge which was not well captured because of the assumption of uniform recharge. The fourth reason, as was already mentioned in chapter 3.1, is the choice of a two-dimensional model, that could not capture a different direction of groundwater flow that might have been important for the outflow of saline water. Nevertheless, the two-dimensional model was good enough to provide an idea about the main processes that affected the evolution of coastal chloride distribution and to demonstrate its evolution by forward modelling. Our results gave a good representation of the chloride distribution in the west side of the profile and can therefore be used in coastal models to represent the position of the brackish-salt interface and its evolution. The method used here needs to be improved for more inland studies with the incorporation of a third dimension and can then be used in other models to predict future and or past chloride concentration evolutions.

6. Conclusions

The overall conclusion of this research is that the main controls on the chloride distribution evolution were the Holocene transgression, lithology and landscape changes. The Holocene transgression had an extensive impact on Dutch coastal groundwater causing salinization in the west region of the profile for sediments with a high permeability. Localized differences in lithology caused the most important source of differences in chloride concentration distribution, showing retardation of salinization below aquitards or fast salinization in highly permeable sediments. Landscape changes formed an important component in the chloride distribution through the development of a freshwater lens below the dunes, freshening of the subsoil after the closure of the barriers, and the creation of hydraulic gradients by surface elevation changes through managed groundwater levels and peat excavations. The latter caused strong seepage rates that pulled the fesh-brackish interface upwards. The main conclusion was formulated based on the conclusions of the sub-questions.

- What processes affect and/ or cause the chloride distribution?

  The main causes for the development of the chloride concentration are transgression, lithology and landscape change. Free convection a density driven proces, advection a hydraulic head gradient driven process and diffusion, a solute driven process were the driving mechanisms for the solute transport. Free convection took place in high permeable sediments and diffusion in sediments with low permeability. Also horizontal migration of intruding seawater in areas of less permeable layers, contributed to the chloride distribution.

- How does the geological setting affect the chloride concentration distribution?

  Low permeable sediments caused a retardation for the movement of chloride, protecting underlying sediments from salinization for a longer period. Though this effect was sometimes counteracted by the discontinuity of the low permeable layer causing partly salinization in the underlying layer which migrated horizontally below the low permeable layer.

- How did landscape changes/developments influence the chloride distribution?

  Landscape changes provided elevation differences on the surface which led to hydraulic head gradients that caused strong seepage or infiltration in various parts of the profile. These strong gradients moved solutes through advection therefore also moving the fresh-brackish interface.

- What are the causes of differences between the model output with the observed chloride distribution?

  It is difficult to pinpoint one cause for this. Canidates for these differences are wrong assumptions about boundaries, neglect of inflow from the northern and eastern regions and the uncertainty of model parameters.

The results provide a good representation of the chloride concentration distribution below the dunes but needs to be revised with regard to the east side of the profile. High chloride concentrations from measurements and interpolated maps for the east side of the profile were not visible in the results of the hypotheses. This might be due to the neglect of northern inflow or because of the use of a two-dimensional model. Also the choice for boundary conditions, e.g. surface elevation, drainage position around the Haarlemmermeer, in prior times needs to be studied further.

References

Asselen, S.van, Stouthamer, E.and Smith, N.D. (2010) *Factors controlling peat compaction in alluvial floodplains: a case study in the cold-temperate Cumberland Marshes, Canada.* Journal of Sedimentary Research 80, 155-166.

Bazelmans, J., Meulen, M.van der, Weerts, H. and Vos, P. (2011) *Atlas van Nederland in het Holoceen. Landschap en bewoning vanaf de laatste ijstijd tot nu.*Uitgeverij Bert Bakker.

Berendsen, H.J.A. (2008) *De vorming van het land. Inleiding in de geologie en de geomorfologie.*Uitgeverij, Koninklijke van Gorcum, Assen.

Beets, D.J., Fischer, M.M., de Gans, W. (1996) *Coastal studies on the Holocene of the Netherlands,* Mededelingen Rijks Geologische Dienst, Nr 57, Haarlem.

Beets, D.J., De Groot, T.A.M. & Davies, H.A., (2003) *Holocene tidal back-barrier development at decelerating sea-level rise: a 5 millennia record, exposed in the western Netherlands*. Sedimentary Geology, 158(1-2), 117–144.

Bonte, M. and Zwolsman, J. J. G. (2010) *Climate change induced salinization of artificial lakes in the Netherlands and consequences for drinking water production.* Water research 44, 4411-4424.

Bos, I. J. (2010) *Distal delta-plain successions. Architecture and lithofacies of organics and lake fills in the Holocene Rhine Meuse delta plain, the Netherlands.* Doctoral dissertation, University of Utrecht.

Cleveringa, J. (2000) *Reconstruction and modelling of the Holocene coastal evolution of the western Netherlands.* Doctoral dissertation, University of Utrecht.

Cohen, K.M. (2003) *Differential subsidence within a coastal prism: Late-Glacia-Holocene tectonics in the Rhine-Meuse delta, the Netherlands.*
Doctoral dissertation, University of Utrecht.

Denys, L., Baeteman, C. (1995) *Holocene evolution of relative sea level and local mean high water spring tides in Belgium*—a first assessment. Mar. Geol. 124, 1–19.

Dufour, F.C. (1998) *Grondwater in Nederland, Onzichtbaar water waarop wij lopen.* Uitgeverij, Van de Rhee, Rotterdam.

Fitts, C.R., (2002) *Groundwater science.* Academic Press, an imprint of Elsevier, London.

Gieske, J. M. J. (1991) *De oorsprong van het brakke grondwater in het IJsselmeergebied: diffusie, dispersie, of dichtheidsstroming? (Origin of brackish groundwater in the IJsselmeer area: diffusion, dispersion or density-driven flow?)* H2O 24 (7), 189–193.

Guo, W. and Langevin, C. D. (2002) *User's Guide to SEAWAT: A Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow.* U.S. Geological Survey, Techniques of Water-Resources Investigations 6-A7, Tallahassee, Florida

Harbaugh, A. W., Banta, E. R., Hill, M. C. and McDonald, M. G. (2000) *MODFLOW-2000, the U.S. Geological survey modular groundwater model – User guide to modularization concepts and the groundwater flow process.* U.S. Geological survey , Open-file report 00-92, Reston, Virgina.

Harbaugh, A.W. (2005) *MODFLOW-2005, The U.S. Geological Survey modular ground-water model. The Ground-Water Flow Process*. U.S. Geological Survey Techniques and Methods 6- A16, Reston, Virgina.

Hill, M. C. (2003) *Preconditioned conjugate-gradient 2(PCG2), a computer program for solving groundwater flow equations.* U.S. Geological Survey, water resources investigation report 904048.

Jelgersma, S. (1979) *Sea-level changes in the North Sea basin.* In: Oele, E., Schuttenhelm, R.T.E., Wiggers, A.J. (Eds.) , The Quaternary History of the North Sea, Acta Universitatis Upsaliensis, Uppsala, Sweden. pp. 233–248.

Kechavarzi,C., Dawson,Q., Leeds-Harrison, P.B. (2010) *Physical properties of low-lying agricultural peat soils in England.* Geoderma 154, 196–202.

Ludwig, G., Muller, H., Streif, H. (1981) *New dates on Holocene sealevel changes in the German Bight.* Spec. Publ. Int. Assoc. Sedimentol. 5, 211–219.

McDonald, M.G. and Harbaugh, A.W. (1988) *A modular three-dimensional finite-difference ground-water flow model.* U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586.

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J. (1992) *A method of converting no-flow cells to variable head cells for the U.S. Geological Survey modular finite-difference ground-water flow model*. U.S. Geological SurveyOpen-File Report 91-536, 99 p.

Meinardi, C. R. (1991) *The origin of brackish groundwater in the lower parts of The Netherlands. In: Breuck, W. d. (Ed.)*, Hydrogeology of salt water intrusion: A selection of SWIM papers. International contributions to hydrogeology. 11, 271–290.

Minnema, B., Kuijper, M.J.M, Oude Essink,G.H.P., Maas,C. (2004) *Bepaling toekomstige verzilting van het grondwater in Zuid-Holland.* TNO-rapport, NITG04-189-B.

Mulder, E.F.J. de, Geluk, M.C., Ritsema, I.L., Westerhoff W.E., and Wong, T.E. (2003) *De ondergrond van Nederland.* Uitgeverij Wolters-Noordhoff, Groningen/Hounine.

H.H. Lamb, "Climatic Fluctuations", in H. Flohn (ed), *World Survey of Climatology. Vol.2. General Climatology* (New York: Elsevier, 1969), p. 236

Kiden, P. (1995) *Holocene sealevel change and crustal movement in the southwestern Netherlands.* Mar. Geol. 124, 21–41.

Olsthoorn, T.N., Kamps, P.T.W.J., and Droesen,W.J. (1993) *Groundwater modelling using GIS at the Amsterdam water supply*. HydroGIS 93: Application of geographic systems in hydrology and water resources.

Oude Essink, G.H.P. (1996) *Impact of sea level rise on groundwater flow regime. A sensitivity analyses for the Netherlands.* Doctoral dissertation, Delft University.

Oude Essink, G. H. P. (2001) *Salt water intrusion in a three-dimensional groundwater system in the Netherlands: A Numerical study.* Transport in Porous Media 43, 137–158.

Oude Essink, G. H. P., Baaren, E. S. van, and Louw, P. G. B. de, (2010) *Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands.* Water Resour. Res., 46, W00F04, doi:10.1029/2009WR008719

Plassche, O. van de, (1982). *Sea level change and water-level movements in the Netherlands during the Holocene.* Mededelingen Rijks Geologische Dienst 36, 1–93.

Post, V.E.A, Kooi, H. and Simmons, C. (2007) *Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses*. Ground water 45 no. 6, 664-671.

Post, V.E.A., Plicht, H. van der, Meijer, H.A.J. (2003) *The origin of brackish and saline groundwater in the coastal area of the Netherlands.* Netherlands journal of Geosciences/ Geologie en Mijnbouw 82, 133-147.

Post, V. E. A. (2004) *Groundwater salinization processes in the coastal area of the Netherlands due to transgressions during the Holocene.* Ph.D. thesis, Vrije Universiteit Amsterdam, 2004.

Rezanezhad, F., Vogel, H.J., Roth, K. (2006) *Experimental study of fingered flow through initially dry sand.* Hydrology and Earth System Sciences Discussions 3, 2595–2620.

TNO-rapport (2004) *Bepaling toekomstige verzilting van het grondwater in Zuid-Holland.* Nederlandse instituut voor toegepaste Geo wetenschappen projectnummer 00553054.

TNO-NITG (2005) REGIS II, Regionaal Geohydrologisch Informatie Systeem, database TNO-NITG, Delft.

TNO-NITG (2012) GeoTOP, database TNO-NITG, Delft.

Schultz, E. (1992) *Waterbeheersing van de Nederlandse droogmakerijen.* Ministerie van Verkeeren Waterstaat, Rijkswaterstaat, Directie Flevoland. Doctoral dissertation Delft University.

Simcore software (2011) Processing MODFLOW, *An integrated modelling environment for the simulation of groundwater flow, transport and reactive processes.*

Styfzand, P. J. (1993) *Hydrochemistry and hydrology of the coastal dune area of the western Netherlands.* Ph.D. thesis, Vrije Universiteit Amsterdam.

Van Loon, A.H. van, (2010) *Unraveling hydrological mechanisms behind fen deterioration in order to design restoration strategies.* Doctoral dissertation, University of Utrecht.

Van Loon, A.H. van, Schot,P.P., Griffioen, J., Bierkens, M.F.P. and Wassen, M.J., (2009) *Palaeo-hydrological reconstruction of a managed fen area in The Netherlands*, Journal of Hydrology, 378, 205-217.

Vandenbohede, A., Lebbe, L. (2002) *Numerical modelling and hydrochemical characterisation of a fresh-water lens in the Belgian coastal plain.* Hydrogeology journaal 10, 576–586.

Valk, L. van der, (1994), *Coastal barrier deposits in the central Dutch coastal plain.* Mededelingen Rijks Geologische Dienst Nr.57, 1994.

Vos, P., Berg, M., van de, Buma, J., Cohen, K., Kruze, H., Meernine, H. van, de Vries, S. (2010*), Geologisch bureau-onderzoek met betrekking tot het gasleidingtracé Beverwijk-Wijngaarden A-803*.(report 1203000-000 Deltares).

Weerts, H.J.T., Cleveringa, P., Ebbing, J.H.J, Lang, F.D.van & Westerhoff, W.E. (2000) *De lithostratigrafische indeling van Nederland. Formaties uit het Tertiair en Kwartair.* TNO-Rapport 00-95-A. Utrecht: Nederlands Instituut voor Toegepaste Geowetenschappen TNO.

Zagwijn, W.H. (1986) *Nederland in het holoceen.* ’s-Gravenhage: Staatsdrukkerij

Zheng, C. and Wang, P.,P. (1999) *MT3DMS, A modular three-dimensional multispecies transport model.* Hydrogeology group, university of Alabama.

IJsselmeer (2011) http://nl.wikipedia.org/wiki/IJsselmeer, consulted on November 22nd 2011.
Dinoloket (2012) http://www.dinoloket.nl, consulted on November 30th 2012