The effects of salt water intrusion from the Dintel River, into the surrounding surface and groundwater system

Picture front page: Dintelsas southern direction, 2011

Status	Final version
Title	The effects of salt water intrusion from the Dintel River, into the surrounding surface and groundwater system
Date	7 March 2013
Graduation Thesis	Master Hydrology Track: Environmental Hydrogeology 40 ECTS
Executive organization	Deltares Department: Soil and Groundwater systems Princetonlaan 6, 3584 CB Utrecht
In cooperation with	Regional Water Authority Brabantse Delta Bouvignelaan 5, 4836 AA Breda N. Douben V. Witter
Author	I.W. Lugten (3144941) Graduation intern Deltares MSc student Environmental Hydrogeology University of Utrecht E: irenelugten@gmail.com T: 06-20977043
Supervisors	Dr. ir. G.H.P. Oude Essink (Deltares) Prof. dr. ir. M.F.P. Bierkens (University of Utrecht) Dr. P.P. Schot (University of Utrecht)

Acknowledgements

Before I started working on this project I was travelling in China. On a boat trip on the Yangtze our guide told us that we were sailing on a city which had purposively been flooded, because a new dam was built further downstream. All the citizens were moved to a new city that was built higher on the riverbank. I was quite shocked by the rigorousness of this migration.

In the Netherlands such a project would be out of question, although the Dutch water management has also had an impact on the residents throughout the centuries. For example, the building of dikes and impoldering. In my research project I studied the effects of reopening the connection between the Volkerak-Zoommeer and the North Sea. This connection was closed in 1987. However, the water currently contains blue algae in summer and autumn. In order to solve this problem the water in the lake has to be saline again. But since 1987 a lot of farms have established in the region of the Dintel, who are now dependent on local fresh surface and groundwater. In this project, the effects of salt water in the Volkerak-Zoommeer on the quality of the surface and groundwater in the area was studied.

This project is the master research project for my masters in Hydrology. The project has been assigned by Klaas-Jan Douben from the Regional Water Authority Brabantse Delta to my supervisor Gualbert Oude Essink from Deltares. My task was to develop a groundwater model for the region of the Dintel in West-Brabant, and analyze possible future salt water intrusion in the region.

The research has been carried out in roughly 9 months, wherein the model was built, the scenarios were run, and the final report was written. Most of this time I worked at Deltares at the Uithof in Utrecht. I really appreciated the company of all the workers at Deltares and the co-interns. In my opinion Deltares has a very motivating, welcome, down-to-earth, and open minded atmosphere.

During my project I have worked together with my supervisor Gualbert Oude-Essink and the other workers in the fresh-salt group at Deltares. The working spirit of this group has been an inspiration, and the fieldwork and dinners together were of great value for my enjoyment of working on the project. Moreover, the cooperation with the other interns of the fresh-salt group; Maitri, Kyra, Robin and Martijn, has been very pleasant and helpful.

I would like to thank my co-interns for the enjoyable period at Deltares. Furthermore, I would like to thank my friends Roderick, Annemarijn and Faline, and my parents, for correcting the report, and for their support. Furthermore, I would like to thank my supervisor Paul Schot (University Utrecht), especially for giving advises on the working-process of the project. Moreover, I would like to thank my supervisor Marc Bierkens (University of Utrecht), in particular for helping me immediately, when a deadline had to be met.

Finally, I would like to thank my supervisor Gualbert Oude Essink (Deltares) for all his help. Your working spirit and motivation have made a great impression on me. I have learned a lot from our meetings about fresh and salt water, and on the methods and decision making in groundwater research.

Summary

In the near future the water in the Volkerak-Zoommeer might be saline again to deal with the current blue-green algae problem in the lake. The watercourse Dintel is connected to the Volkerak, which means that in the future the salt water from the lake could flow into the Dintel via sluicing and could salinize the river. This salt water can intrude into the surface and groundwater of the regional system and thus possibly disturb the agricultural activities in the area. Therefore, this research is conducted on the effects of salt water intrusion from the Dintel into the surface and groundwater system in the region. The time-span and extent of the salt water intrusion have been investigated with a density dependent groundwater model in two dimensions. The model was built using MOCDENS3D, which is based on the MODFLOW code, though, adapted for density dependent groundwater flow. The average hydro(geo)logical conditions of the region were used as input for the model. Different scenarios were tested on the model. These scenarios contained various geological characteristics, different values for model parameters, and possible mitigation measures. With the largest part of these scenarios the autonomous process of salinization was calculated. Some of the scenarios contained possible mitigation measures. The results of the scenarios were analyzed with chloride concentration profiles, particle tracking, animations, and observation points. The results show that the salinization of the groundwater in the Dintel area is a slow process. However, the salinization of the surface water of the ditches, on the other hand, can start within 10 years. This means that the seepage ditches near the Dintel could salinize relatively quickly. Other ditches within 300 m from the Dintel also risk salinization. In addition, shallow fresh water lenses within a range of 300 m from the river can become thin. So it is recommended that the flow between the seepage ditches and the other ditches will be closed. Furthermore the chloride concentration in the ditches within 300 m from the Dintel should be monitored, as well as the thickness of the shallow fresh water lenses in this area, as they can become thin when the cone with salt groundwater under the river rises up to ground level.

Table of Contents

1. Introduction

The contact zone between fresh and salt groundwater has become an important and very much alive issue in groundwater research over the past decades. Fresh water is nowadays a scarce resource because of the predicted climate change and the ongoing population growth resulting in an increasing freshwater demand. Consequently, the concerns on the presence of water for drinking, agricultural and industrial purposes are increasing.

The summers in the Netherlands will become dryer and the sea level will rise due to climate change. Dryer summers will decrease the refill of the groundwater by rainwater. Furthermore, there will be less water available for flora and fauna.

A higher sea level increases the pressure on the fresh water resources in the rivers, and pushes the groundwater more inland, leading to an increase of saline to brackish groundwater in the coastal area. A large part of the worlds' population lives in these coastal zones, and thus it is very important to asses these changes in the contact zone between fresh and salt water (Oude Essink, 2001).

In the Dutch province of Zeeland there are several zones where fresh and salt groundwater meet each other in various ways. Predictions are made about the possible consequences of sea level rise on the availability of fresh groundwater in coastal areas (Oude Essink *et al,* 2010). Because of the relatively high population density in the Netherlands in comparison with the rest of the world, the high demand on fresh water and the large number farms in Zeeland; small changes in the condition of the groundwater quality status will be of great concern.

There is a great amount of hydrogeological data available in the Netherlands, and moreover, there is a lot of knowledge on groundwater systems. Therefore, the knowledge derived from the research on fresh and salt groundwater in the Netherlands can in the future be applied to cases in other parts of the world (Oude Essink *et al,* 2010).

This research will focus on the Dintel, a small watercourse in the western part of the province of Noord-Brabant. At this moment the bordering lake, the Volkerak Zoommeer, consists of fresh water. However, there are plans to change the Volkerak Zoommeer into a salt water lake in the nearby future (p.c. Douben, 2011). The salt water can enter the Dintel via the sluice complex at Dintelsas (fig. 1.1 and 1.2) and it could intrude into the surface and groundwater system of the region which has its consequences these systems (Oude Essink *et al,* 2008). This research project will be conducted to investigate the possible influences of salt water in the Dintel, on the regional surface and groundwater system. The project was assigned by the Regional Water Authority Brabantse Delta to Deltares.

Figure 1.1 The region of the Volkerak-Zoommeer (GoogleMaps, 2011, edited by I.W.Lugten)

Figure 1.2a. The sluice complex at Dintelsas **b.** The Volkerak seen from the sluice at Dintelsas

The main reason for the Regional Water Authority Brabantse Delta to further investigate this situation is the fact that over the past decades, lots of agricultural and horticultural industries have established in the area. For these farms the salinization of the water could have great consequences on crop production through salinized sprinkling water as local surface water is used for this. Hence it is important to research the possible salt water intrusion into the surface and groundwater system in this area (p.c. Douben, 2011)

The main goal of this research is to investigate the salt water intrusion from the Dintel in case its river water will become saline. The extent and speed of the salinization process of the surface and groundwater system will be studied. Furthermore, the effects of mitigation measures for salt water intrusion will be investigated so the following main and sub-questions will be answered.

Main research question

Will salt water intrusion through the bottom of the Dintel result into a significant salinization of the groundwater and surface water in the area?

Sub-questions

1. Which maximum chloride concentrations of surface and groundwater will be reached?

2. What is the size of the area that will be influenced by the salinization?

3. When does the salinization start? And what is the speed of the process after it has started? How long does it take until a dynamic equilibrium is reached?

4. What type of salt water intrusion is taking place; diffusive or convective? Which process dominates?

5. What is the influence of the geology on the salt water intrusion? Will the salt water intrusion be different at various locations in the region with different geological characteristics?

6. Which mitigation measures could be taken to make it possible for agriculturists and horticulturists to continue using the local ground and surface water?
   What is the influence of the increase of the local phreatic level on the salinization of the groundwater?

Hypothesis

Salt surface water from the Dintel River will intrude into the groundwater and will significantly salinize the surface and groundwater system.

This report contains the description of the research project wherein a groundwater model was built and with this model different scenarios were analyzed. In chapter 2 the background of the study will be given, and after this, the research methods will be explained. Then the results will be presented and discussed; and finally conclusions will be drawn and recommendations will be given.

2. Background of the study

2.1 Introduction

In this chapter the background information of this study will be discussed in more detail. First, information on the background of the location will be presented which includes the history, the hydrogeology, geology, seepage and data on chloride concentrations of the surface water. Second, the existing relevant research of the area will be summarized, and finally, the hydrogeological processes involved in the study will be described.

When talking about fresh, brackish and salt water the classification of Stuyfzand in table 2.1 is used.

Table 2.1 Classification of fresh, brackish of saline groundwater after Stuyfzand (1993). (Oude Essink, 2001)

Main type of groundwater	**Chloride concentration (mg Cl^-/l)**
Oligohaline	0 – 5
Oligohaline-fresh	5 – 30
Fresh	30 – 150
Fresh-brackish	150 – 300
Brackish	300 – 1,000
Brackish-saline	1,000 – 10,000
Saline	10,000 – 20,000
Hyperhaline or brine	≥ 20,000

2.2 History and current state of the Volkerak-Zoommeer

2.2.1 History of the Volkerak-Zoommeer

The Volkerak-Zoommeer is located on the borders of the provinces Noord-Brabant, Zeeland and Zuid-Holland. The lake consists of two separate lakes, Volkerak, and Zoommeer, which are connected by the canal Eendracht (fig. 1.1).

The region south of the Volkerak is called St. Philipsland, which is the northwestern part of the province of Noord-Brabant. To the north of the Volkerak you will find one of the islands of the province of Zeeland, called Goeree-Overflakkee. Currently, the Volkerak is a fresh water lake, with a fixed water level of around NAP. In figure 2.1 this closed lake is clearly visible. Until 1967, the lake was connected with the North Sea, and thus had a tidal regime. In 1987, the Volkerak sluices were closed and the Philipsdam and the Oesterdam were built, which closed the connection with the sea (Oude Essink *et al,* 2008). This was done because of several reasons. Firstly, this opened a connection for ships to sail from Rotterdam to the Antwerp without a tidal regime. Furthermore, it guaranteed a fresh water supply for agriculture in the area. And finally, this closing decreased the waterflow through the Oosterschelde which improved the conditions for the Oosterscheldekering (fig. 2.1) (BHIC, 2012).

Figure 2.1 The closed Volkerak-Zoommeer (Arcadis, 2009, edited by I.W. Lugten 2012)

But over the years a problem developed in the closed Volkerak-Zoommeer. Because of the decreased flow through the lake and the inflow of fertilizers from West-Brabant, Belgium (Flanders) and the lake sediments, blue-green algae (cyanobacteria) started to grow. In 1994 it became clear that it was a serious threat for the water quality. Blue green algae are a problem because they are toxic for animals and humans, and the water contaminated by blue algae cannot be used for agricultural purposes (Arcadis, 2008).

Research on this problem showed that the only sustainable and future proof solution is opening up the connection between the Volkerak-Zoommeer and the North Sea to make the water of the Volkerak-Zoommeer saline again. This way, the situation will be as before 1987, when there were no problems with the blue-green algae in the lake.
In the proposed method, named P300, there will be a in- and outflow of 300 m^3/s (max.) water through an opening in the Philipsdam. This opening in the Philipsdam will make a connection between the Volkerak-Zoommeer and the North Sea via de Oosterschelde. Furthermore, the Bathse lock complex will be reopened, through which water from the Zoommeer can exchange with water of the Westerschelde (fig. 1.1).

This open connection with the North Sea involves a tidal amplitude of 0.30 meter. The minimal tidal level will be -0.25 m NAP, and the maximal tidal level will be 0.05 m NAP, with a median of -0.10 m NAP.
The sluices of Dintelsas and Benedensas will be operated like before 1987, and two fresh-salt barriers will be built (a bubble curtain and a bar). Furthermore, there will be extra flushing to prevent the salt water from flowing into the watercourses.

The government did schedule taking the final decision on opening the Philipsdam for mid-2012. However, the prognosis is that the decision will be extended for a few more years (p.c. Douben, 2011).

Since 1987, a lot of farms have established in the region of the Dintel. These farms are dependent on the local fresh surface and groundwater. For that reason, the consequences of opening the Philipsdam on the groundwater in the region have been studied by Deltares.

Deltares investigated the influence of resalinization of the lake on the groundwater system in the area around it (Oude Essink *et al,* 2008). The study concluded that salt water might flow into the surface water through the sluice complexes of Dintelsas and Benedensas. This salt water could salinize the groundwater system upstream of the sluice complexes because of salt water intrusion into the bottom of the Dintel and the Vliet. The salt water which will flow into Dintel might reach as far upstream as Breda because that is what happened before 1987 (fig. 1.1) (p.c. Douben, 2011).

2.2.2 Hydrogeology

The Dintel is part of the Mark-Dintel-Vliet drainage basin, which is mainly supplied by water from higher elevated areas in West-Brabant and Flanders, and to a lesser extent by seepage from the 'Naad van Brabant'. The 'Naad van Brabant' is a strip of land that stretches from Ossendrecht in the southwest of the Noord-Brabant province to Maashees in the east. In the southern parts of the strip elevated sandy soils can be found and to the northern parts, low-lying clayey soils (fig. 2.2) (Roelofsma, 2004). At the northern edge of the strip, infiltrated rainwater from the 'Naad van Brabant' seeps towards the surface.

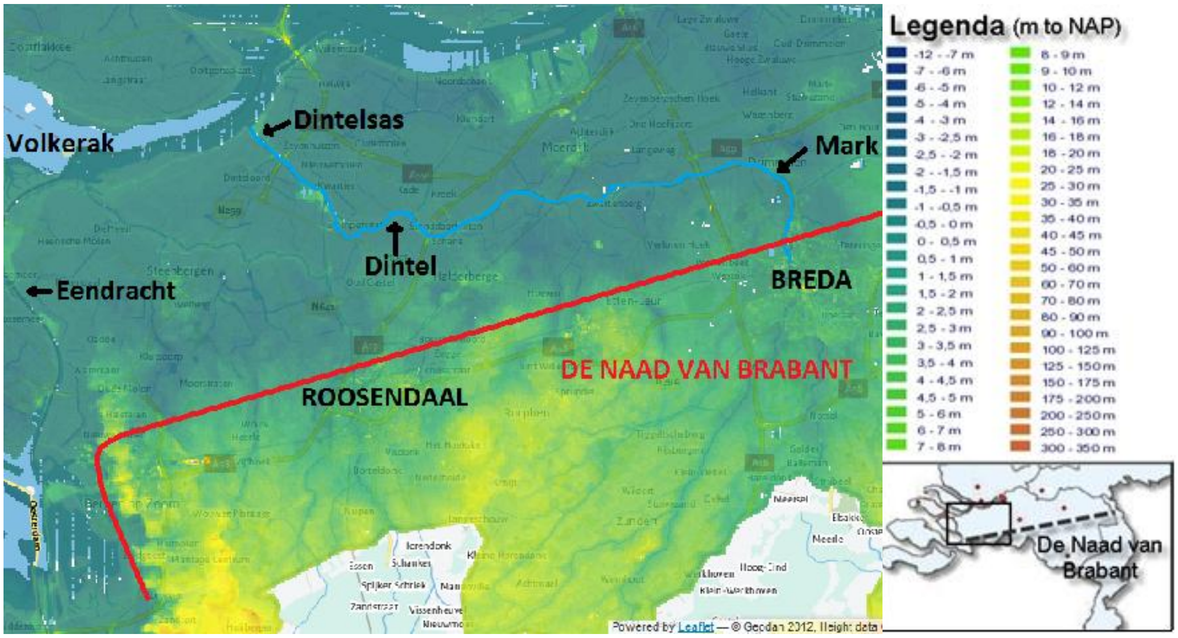


Figure 2.2 Elevation map of the area around the Volkerak-Zoommeer (AHN, 2012)

2.2.3 Geology

Throughout geological history, West-Brabant has alternatingly been land and sea. The sea has deposited silt and clayey layers, while since the Pleistocene, the rivers have deposited sand and clayey layers. Furthermore the last ice age brought a layer of loam.

The sea level rise after the last ice age increased the amount of fresh water seepage in the region. Seepage is groundwater flowing up to the surface, in this case because of a sloping watertable due to increased pressure from the salt sea water. Subsequently, the groundwater level was rising as well and in lower lying areas, peat was being formed.

This sea level rise increased the pressure on the embankments, ultimately resulting in breaking of these embankments. And thus the land was flooded again which led to a greater deposition of clay in the flooded areas (Witteveen & Bos, 1999).

These different layers and their spreading throughout the region are shown in the borehole data in figure 2.3 (also Appendix I). This overview of the geology shows a clayey or loamy layer near the ground level of the boreholes in the western part of the area, which is nearer to the sea, indicating that this layer was probably deposited by flooding by the sea. These flooding of the sea did apparently not reach the eastern part of the region as the top layer mostly consists of sand. Furthermore, there are layers of clay at different depths in the soil. These layers of clay are either residual to sea floodings or deposited by rivers. In some boreholes a peat layer can be found near ground level, which was developed by the previously discussed increase in fresh water seepage after the last ice age.

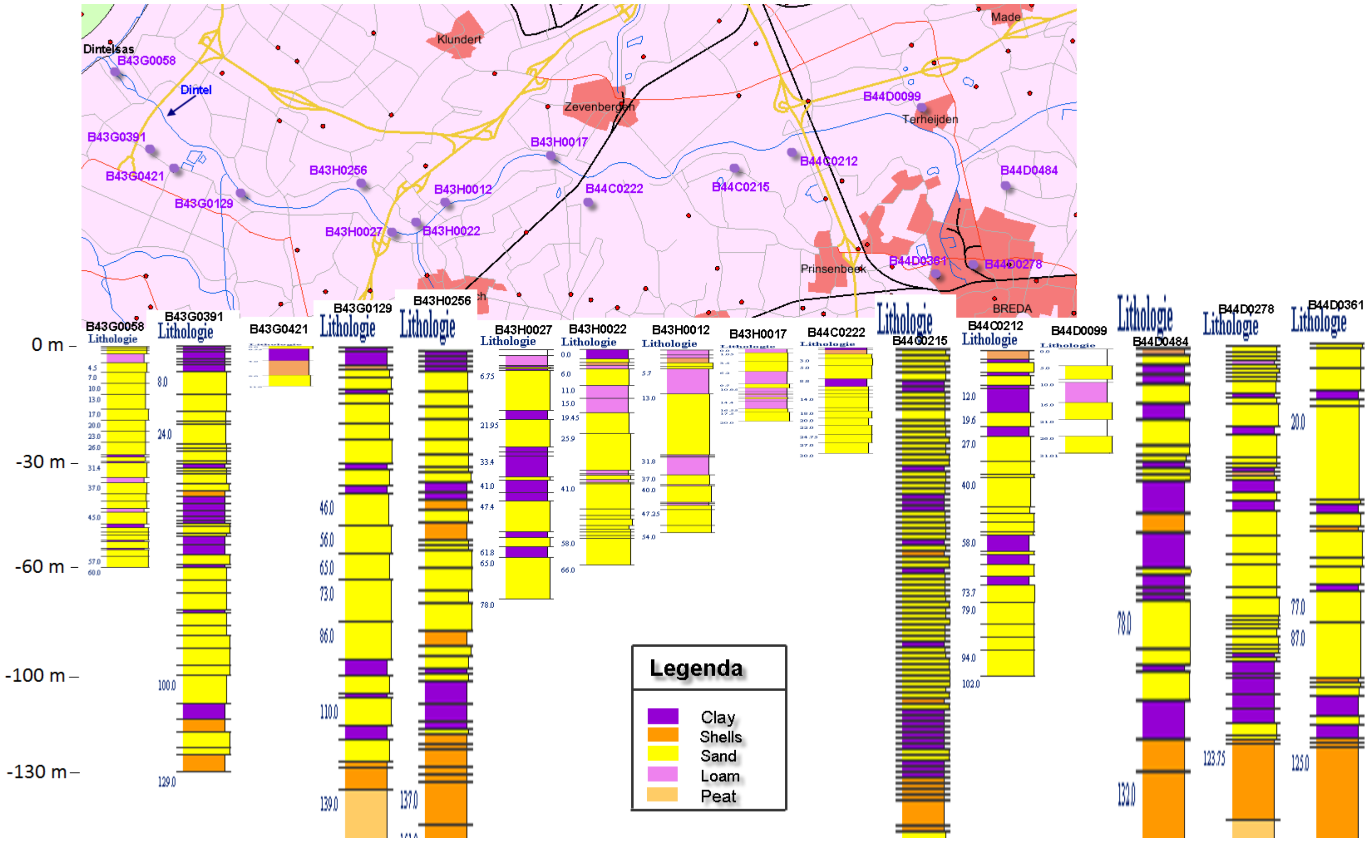


Figure 2.3 Geology of the Dintel region (Dino*loket*, 2011) (larger in Appendix I)

2.2.4 Seepage

At most locations in the West-Brabant area seepage takes place. In West-Brabant there is seepage because of various reasons, namely:

- There is seepage from the deep confining layers. This groundwater comes from the ‘Naad van Brabant’, wherein it has infiltrated. Then it has flowed to the lower lying northern parts of West-Brabant. There is an average seepage of 1-2 mm/day (Brabantse Delta, 2013).
- There is seepage of infiltrated water from the main rivers into the polders, as a result of water levels being lower in the polder. In the western part of West-Brabant this seepage is brackish to saline and on average has a flow rate of about 0,5–2,5 mm/day.
- There is local seepage of infiltrated water from the higher creek beds (Witteveen & Bos, 1999).

2.2.5 The current distribution of fresh and salt-water in the groundwater system

The subsurface of Zeeland was mainly formed in the Holocene. In this era, regions of land and sea alternated constantly and sea clay was deposited. Due to the interaction with the sea the present chloride concentrations in the groundwater in Zeeland are relatively high and have a high degree of variability (van Baaren *et al,* 2012). These varying chloride concentrations in the groundwater have an impact on the chloride concentrations in the surface water through saline seepage. For this research data on the distribution of the chloride concentration in the surface and groundwater was used from different sources, namely; an IMOD file with chloride concentrations of the groundwater from Oude Essink and Verkaik (2010) and measurements of the chloride concentrations of the surface and groundwater by the Regional Water Authority Brabantse Delta. This data is presented in Appendices and will be discussed in this section.

Groundwater

Appendix II shows cross-sections that give an overview of the chloride concentrations of the groundwater in this region (Oude Essink and Verkaik, 2010). It shows that near the Volkerak the chloride concentrations in the soil are very high; with levels up to approximately 8000 mg/l, which is approximately 50% of sea water (transsection 1-3). More inland the concentrations are in the range of 0-500 mg/l, with a few outliers in the top part of the soil of around 2000 mg/l (transsection 10 and 11).

Data on chloride concentrations in the groundwater from boreholes in the area upriver (Regional Water Authority Brabantse Delta, 2011) of Dintelsas were studied. These data show that chloride concentrations in Dintelsas vary between 10 and 3000 mg/l.

Surface water

The chloride concentration in the surface water was measured in the Dintel in Dintelsas and two locations further upriver (Regional Water Authority Brabantse Delta, 2011). According to these data, the chloride concentration in the Dintel has ranged between 3 and 100 mg/l from 2000 till 2011.

The electric conductivity in the various ditches near the sluice complex in Dintelsas was measured in October 2011. The measured values of the corresponding chloride concentrations can be found in Appendix III. According to these measurements, the three ditches on the eastern side of the sluice complex contain brackish-saline water (defined by table 2.1). The water in the other ditches in the area was brackish (see Appendix III).

2.3 Previous research in the area

Deltares has conducted research on the future groundwater situation in West-Brabant. The UNIT Subsurface and Groundwater Systems of Deltares carried out a research in 2008 on the influence of a possible salinization of the Volkerak-Zoommeer (VZM) on the surrounding groundwater system. This study describes the historical, current and future situation of the groundwater system around the Volkerak-Zoommeer. One of the conclusions of the study carried out by Deltares was to further research the possible salinization of the Dintel, which is the topic of this research (Oude Essink *et al,* 2008).

Witteveen & Bos carried out a study on the future state of the surface water in the area. The study of Witteveen & Bos (2006) on the future state of the surface water in West Brabant aimed to develop mitigation measures for salinization of this surface water. Both studies on the groundwater and the surface water will be shortly discussed in this section.

Groundwater

The groundwater system around the Volkerak-Zoommeer is changing autonomously because of the large differences in salt concentration, surface subsidence and the water management of the Netherlands. Apart from these autonomous changes, Deltares concluded that there will be changes in the system, as a result of the salinization of the Volkerak-Zoommeer. A couple of changes that are relevant for this research study will be discussed.

1. Before the Philipsdam and Oesterdam were built in 1987, the measured groundwater levels close to the Eendracht and the Volkerak were approximately 25 cm higher than after the building of the dams (fig. 2.4 and 2.5). The water level in the lake stayed the same during this period, therefore, the lower groundwater head is probably solely due to a decrease in pressure as a result of the lower chloride concentration in the lake.
   In the future, the water level in the Volkerak will most likely be -0.1 m N.A.P., which is 0.1 m lower than the level before 1987. Thus there will be a lower pressure of the saline lake on the surrounding groundwater than before 1987. So the groundwater levels will not reach the same levels as before 1987. The increase in groundwater level due to the increased pressure from the lake is expected to be within a range of 3 – 10 cm. However, this increase will only take place in the areas close to the Volkerak, and the scale of the area is predicted to be 0.5 – 1 km from the border of the lake.

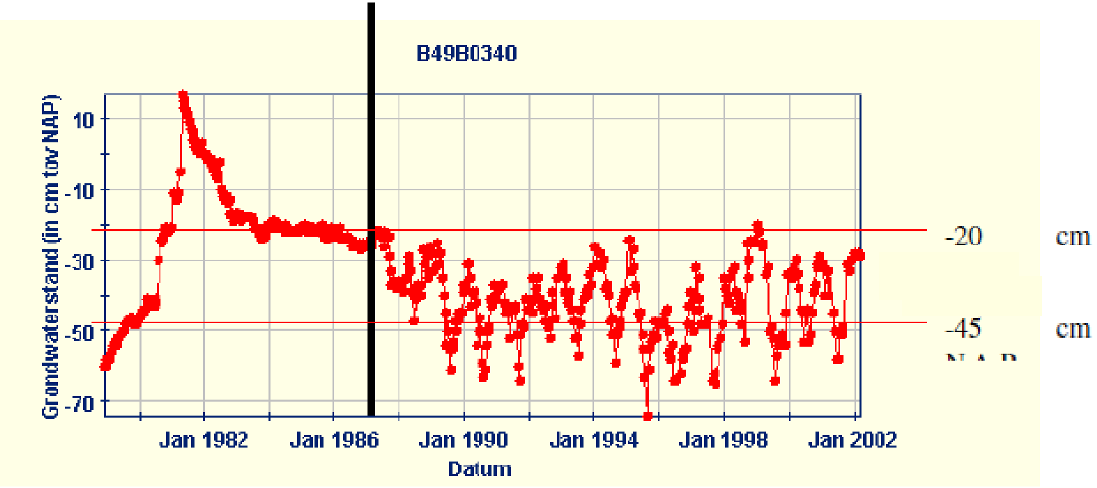


Figure 2.4 Groundwater head (cm to N.A.P.) 180 m from the edge of the Eendracht (location in figure 2.5) (Oude Essink *et al,* 2008)

Figure 2.5 Measurement location groundwater head figure 2.4 (Oude Essink *et al,* 2008).

2. The seepage will also increase in the areas where groundwater heads will increase (1.), as seepage and groundwater head are linearly related. Calculations on future seepage also proved that it will only increase within a couple of hundred meters from the Volkerak and the Eendracht. Along the northern part of the Eendracht, the chloride concentration increases substantially with depth. As such, the seepage will bring higher chloride concentrations from deeper layers upwards.
3. As was said before, the salt concentration of the groundwater in the area is changing spatially by nature. The influence of a saline Volkerak-Zoommeer on the chloride concentration of the groundwater in the future, is restricted to the areas wherein the groundwater heads and seepage will change.
4. The availability of fresh water in the fresh rain water lenses close to the borders of the Volkerak-Zoommeer can decrease significantly. In the other parts of the region, the fresh water lenses are expected to stay the same, and will not influence agricultural activities.
5. The chloride concentration in ditches nearby VZM will probably also increase due to increased seepage from underlying saline groundwater. The expectation is that the salt concentration in the seepage ditches will not become more than before 1987 (figure 2.6) (Oude Essink *et al*, 2008).

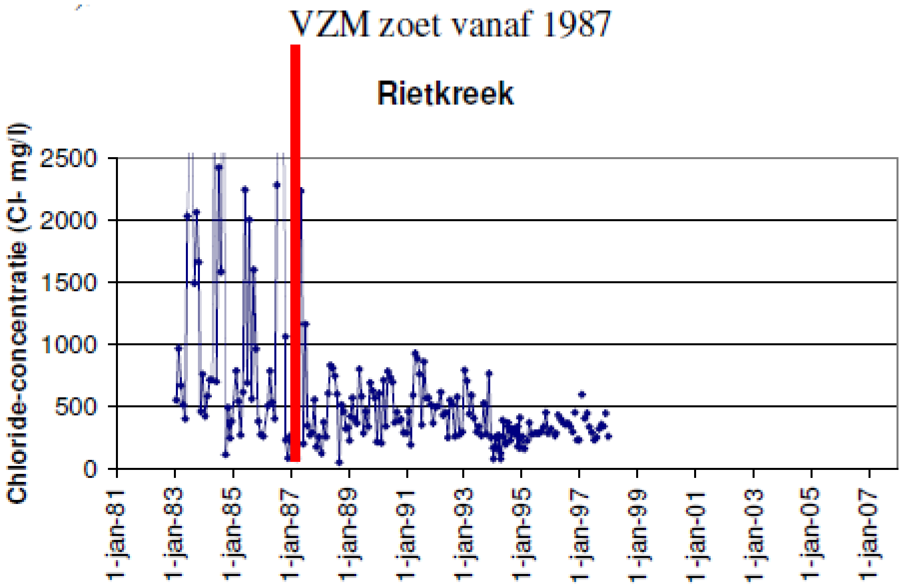


Figure 2.6 Chloride concentration (mg/l) in a ditch near the Eendracht (Oude Essink *et al*, 2008)

These are the main changes in the groundwater system according to Deltares if the Volkerak becomes saline in the future. In the following paragraph the changes in the surface water as found by Witteveen & Bos will be discussed.

Surface water

Witteveen & Bos studied the effects of a salt Volkerak-Zoommeer in the Mark-Dintel Vliet storage basin with a surface water model (Sobek). Witteveen & Bos concluded that the chloride concentrations in a large part of the system will exceed the tolerable limits for critical use of the soil (250 - 300 mg Cl/l) in the future. Therefore, they advised to flush the system continuously with ca. 10 m^3/s of fresh water.

Even with a high flow rate (30 m/s^2) without mitigation measures at the Dintel- and Benedensas sluices, water inlet points along the downstream stretch of the Dintel will occasionally exceed the chloride concentration limits from critical usage of the soil and probably have to be closed every now and then (W&B, 2008).

Furthermore, Witteveen & Bos advised to flush water from the Hollands Diep through de Roode Vaart and water from the Amer via Oosterhout into to the Mark-Dintel-Vliet drainage-basin (fig. 2.7) (W&B, 2008).

Figure 2.7 The Mark-Dintel-Vliet storage basin (GoogleMaps, edited by I.W. Lugten, 2012)

2.4 Hydrogeological processes

In this paragraph, the most important hydrogeological processes of salt water intrusion from a river into a groundwater system will be discussed. At first groundwater density will be shortly discussed, then the concept of fresh water head will be introduced and then Darcy's Law will be introduced and how it is rewritten with the term for density dependent groundwater flow.
In the second part of this paragraph the *advection-dispersion equation* is given and the processes of solute transport in groundwater flow that are relevant for this study will be discussed shortly.

2.4.1 The effect of density on groundwater flow

2.4.1.1 Groundwater density

The density of groundwater depends on pressure, temperature and Total Dissolved Solids (TDS), based on the *equation of state*:

$$\rho = f(p,T,S) \qquad (1)$$

Wherein;

ρ = density (kg/m^3),
p = pressure (kg/m/s^2),
T = temperature (°C),
S = salinity of total dissolved solids (TDS) (g/l).

The temperature influences the density only by a very small factor in comparison to the influence of TDS. Most of the time the temperature of groundwater is assumed to stay constant. Therefore, temperature is often neglected in its influence on groundwater density. Furthermore, groundwater is often considered incompressible, so pressure does not influence its density. And thus, TDS is assumed to be the only factor influencing the density of groundwater (Oude Essink, 2001).

The total dissolved solids consist of the total of positive and negative ions present in groundwater. In coastal groundwater, chloride represents more than half of the concentration of the total dissolved solids (table 2.2).

Table 2.2 Composition of ocean water. (Oude Essink, 2001).

Ions		**mg/l**	**Mass fraction of TDS (%)**
Negative ions	CL^{-}	19000	55,0
	$SO^{-}_{4}{}^{2}$	2700	7,8
	HCO^{-}_{3}	140	0,4
	Br^{-}	65	0,2
Total negative ions		21905	63,4
Positive ions	Na^{+}	10600	30,7
	Mg^{+2}	1270	3,7
	Ca^{+2}	400	1,2
	K^{+}	380	1,1
Total positive ions		12650	36,6
Total Dissolved Solids		34555	

So in fresh-salt groundwater research, the chloride concentration present is studied and represents the concentration of all the total dissolved solids in the groundwater.

There are various classifications for groundwater concentrations. The World Health Organization and the United States Environmental Protection Agency advise a maximum concentration of 250 mg/l of chloride for drinking water. This value is primarily based on the fact that when above this level, chloride starts influencing the taste of the water. However, there are no health risks known for drinking water with a chloride concentration slightly above 250 mg/l (EPA, 2009) (WHO, 2011).

The classification of groundwater used in this research is based on the classification by Stuyfzand (table 2.3).

Table 2.3 Classification of fresh, brackish of saline groundwater after Stuyfzand (1993). (Oude Essink, 2001)

Main type of groundwater	**Chloride concentration (mg Cl^{-} /l)**
Oligohaline	0 – 5
Oligohaline-fresh	5 – 30
Fresh	30 – 150
Fresh-brackish	150 – 300
Brackish	300 – 1.000
Brackish-saline	1.000 – 10.000
Saline	10.000 – 20.000
Hyperhaline or brine	≥ 20.000

2.4.1.2 Fresh water head

The hydraulic head is the level of the air-water interface in an observation well in an aquifer. Hydraulic head (h_i) is the sum of the elevation head (z_i) and the pressure head ($h_{p,i}$) (see fig. 2.8):

$$h_i = z_i + h_{p,i} = z_i + \frac{P_i}{\rho_i g} \qquad (2)$$

ρ_i = density in (kg/m^3),
g = gravitational acceleration (9.81 m/s^2),
P_i = pressure (kg/m/s^2).

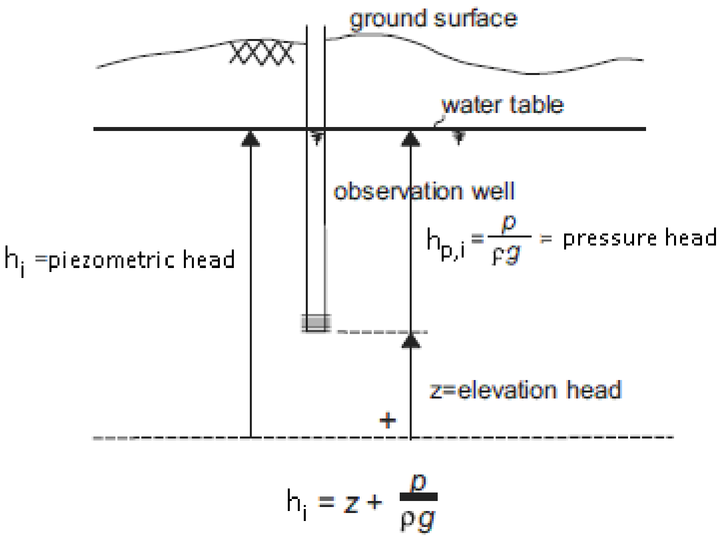


Figure 2.8 Definiton of the piezometric head (Oude Essink, 2001) (edited by I.W. Lugten, 2012)

The hydraulic head is used to determine the velocity and the direction of groundwater flow. Although pressure is the actual driving force of the flow, hydrologists are more used to using hydraulic head. When variations in density are influencing the groundwater flow, the hydraulic head can no longer be used to determine this flow because in definition 1, various densities ρ_i result in different pressure heads ($h_{p,i}$) for the same pressure (P_i). So pressure head ($h_{p,i}$) should be corrected for density differences by using a reference density. Most of the time fresh water density is used for this reference density. This method can be clarified by imaginarily implementing a piezometer with fresh water next to the piezometer with salt water. In these piezometers the same pressure applies. The point water head in the piezometer with fresh water will be higher than in the piezometer with salt water next to it (fig. 2.9).

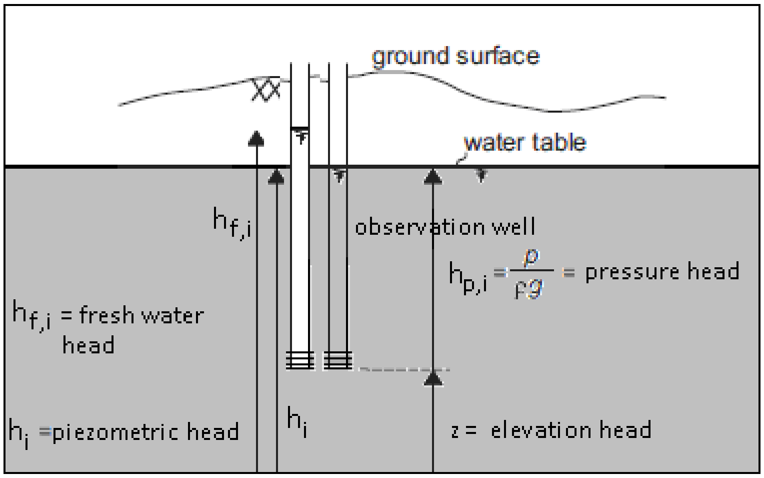


Figure 2.9 Concept of the fresh water head (Oude Essink, 2001) (edited by I.W. Lugten, 2012)

For the piezometer with fresh water, the head is calculated by this formula:

$$h_{f,i}=z_i+\frac{P_i}{\rho_f g} \qquad (3)$$

ρ_f= fresh water density (M/L^3)

This is called the fresh water head, which corrects for density differences. The fresh water head can be calculated from the point water head by the formula:

$$h_{f,i}=\frac{\rho_i}{\rho_f}h_i-\frac{\rho_i-\rho_f}{\rho_f}z_i \qquad (4)$$

This formula shows that if there is a point water head of 1 m, ρ_f = 1000 kg/m^3 and ρ_i= 1025 kg/m^3 (salt water), the fresh water head will be 1.025 m (Post, 2004) (Oude Essink, 2000).

2.4.1.3 Darcy's Law rewritten with the fresh water head

2.4.1.3.1 Darcy's Law

In 1856, the French engineer Henry Darcy discovered the equation for groundwater flow. The law was formulated after doing experiments with water flow in a sand-filled column. The equation is also known as Darcy's Law:

$$\vec{q}=-K\nabla h \qquad (5)$$

Wherein;

$\vec{q}$ = specific discharge (fluid per unit of cross-sectional area of the porous medium per unit of time, (L^3/L^2/T),

K = hydraulic conductivity, the ease with which the water can move through the porous medium (L/T),

∇h = driving force of groundwater flow per unit of weight (-).

The three flow components of Darcy's Law are;

$$q_x = -K\frac{\partial h}{\partial x} \tag{6a}$$

$$q_y = -K\frac{\partial h}{\partial y} \tag{6b}$$

$$q_z = -K\frac{\partial h}{\partial z} \tag{6c}$$

(Post *et al*, 2007)

2.4.1.3.2 Darcy's Law rewritten with the fresh water head

MOCDENS3D is based on the fresh water head, so Darcy's law has to be rewritten in terms of the fresh water head (3):

$$h_f = z + \frac{P}{\rho_f g} \tag{7}$$

(Post *et al,* 2007)

K_x = K_y so we use K_h for both and we use K_v for K_z. First we insert the fresh water head in x and y directions. There is solved for P and then differentiated.

$$q_x = -K_h\frac{\partial h}{\partial x} = -K_h\frac{\partial}{\partial x}\left(\frac{P}{\rho g} + z\right) = -\frac{K_h}{\rho g}\frac{\partial P}{\partial x} = -K_h\frac{\rho_f}{\rho}\frac{\partial h_f}{\partial x} = -K_{f,h}\frac{\partial h_f}{\partial x} \tag{8}$$

$$q_y = -K_h\frac{\partial h}{\partial y} = -K_h\frac{\partial}{\partial y}\left(\frac{P}{\rho g} + z\right) = -\frac{K_h}{\rho g}\frac{\partial P}{\partial y} = -K_h\frac{\rho_f}{\rho}\frac{\partial h_f}{\partial y} = -K_{f,h}\frac{\partial h_f}{\partial y} \tag{9}$$

From this can be seen that variable density does not influence the horizontal components of groundwater flow. Now we insert the fresh water head in the vertical component:

$$q_z = -K_v\frac{\partial h}{\partial z} = -K_v\frac{\partial}{\partial z}\left(\frac{P}{\rho g} + z\right) = -K_v\left(\frac{1}{\rho g}\frac{\partial P}{\partial z} + 1\right) = -K_{f,v}\left(\frac{\partial h_f}{\partial x} + \frac{\rho-\rho_f}{\rho_f}\right) \tag{10}$$

From the buoyancy term ($\frac{\rho-\rho_f}{\rho}$) we can see that the fresh water head does influence the vertical flow component.

2.4.2 Solute transport

The solute transport processes involved in density dependent groundwater flow are advection, diffusion and dispersion. These processes determine the chloride concentration distribution in the water, and thus the velocity and direction of the groundwater flow after each time-step of the model.

The three-dimensional equation for advection and hydrodynamic dispersion in homogeneous isotropic porous media is:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(CV_i) \tag{11}$$

Wherein:

C = concentration of the dissolved solids (M/L^3),

D_{ij} = coefficient of hydrodynamic dispersion (L^2/T),

$V_i = q_i/n_e$ = effective velocity of the groundwater in the direction of x_i (L/T).

This is the so-called *advection-dispersion equation* without the terms for decay and adsorption as these processes are not relevant for this study because chloride is a conservative solute which includes that it does not decay or adsorb (Oude Essink, 2000). In the following sections the processes of advection and hydrodynamic dispersion will be shortly discussed.

2.4.2.1 Advection

Advection is the movement of a solute along with its host fluid. In studying groundwater flow this host fluid is obviously groundwater. The amount of solute flowing is a function of its concentration and the volume of fluid flowing.

2.4.2.2 Hydrodynamic dispersion

Hydrodynamic dispersion (D_h) is the sum of molecular diffusion (D_m) and mechanical dispersion (D).

$$D_h = D + D_m \tag{12}$$

D = mechanical dispersion coefficient (L^2/T)

D_m = molecular diffusion coefficient (L^2/T)

(Oude Essink, 2000)

2.4.2.2.1 Mechanical (or convective) dispersion (D)

Mechanical dispersion is caused by small differences in flow velocities on pore-scale. These velocity differences in the porous medium are caused by (fig. 2.10):

1. variations in pore size; if the pore size is larger it allows the fluid to move faster.
2. variations in path length; due to different shapes of the grains some particles have to travel a longer path than other particles. This results in variations in travel time.
3. variations because of friction; friction with the grains slows the fluid down. Therefore, the fluid will travel faster in the center of the pore.

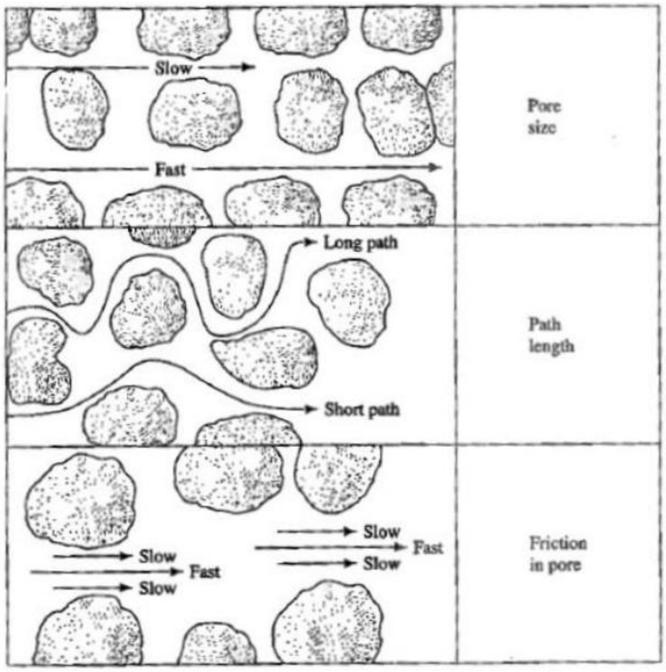


Figure 2.10 Mechanical dispersion (Fetter, 2008)

If the pore-scale flow velocities are different; the groundwater velocity also varies on the macro-scale. So particles of a tracer for example, which are injected at a certain point at the same time, will arrive at different times at the next point. This dispersivity increases when the length of the domain increases, due to more pore-scale deviations (Fetter, 2008). Also, dispersivity in the field is generally much larger than on laboratory scale, as the heterogeneity of the porous medium in the field is larger. Dispersion in the lateral direction is called longitudinal dispersion (α_L). The deviations in pore-scale groundwater velocity also cause spreading of the particles in the transverse direction, which is called transverse dispersivity (α_T). As a rule of thumb, most of the time the relation between longitudinal and transverse dispersivity used is:

$0.1\,\alpha_L = \alpha_T$ (Hassanizadeh, 2007)

2.4.2.2.2 Molecular diffusion (D_m)

Molecular diffusion is the spreading of solutes caused by the tendency of solutes to equally spread their concentration. The magnitude of this tendency is defined with the molecular diffusion coefficient D_m (L^2/T). This value depends on the properties of the solute, the fluid and the temperature (Fitts, 2002).

Molecular diffusion is only of significance in small groundwater velocities of 1×10^{-6} m/s (Bertsch 1978) (Oude Essink, 1996). The molecular diffusion of chloride is 10^{-9} m^2/s at a temperature of 25 degrees Celsius (Oude Essink, 2000).

2.5 Salt water intrusion

Saline and fresh groundwater mix when they make contact, which is mostly in coastal areas. There are different ways and directions in which the saline water mixes with the fresh water.
This paragraph first gives a general introduction on salt water intrusion and then gives a description of salt water fingering as this is a important process for this study.

2.5.1 General introduction on salt water intrusion

Salt water can flow on top of the fresh water due to a flooding for example, or salt-water can intrude into the fresh groundwater aquifer from underneath. The latter case is shown in figure 2.11. There is a salt water wedge from the direction of the sea under the fresh water aquifer. When fresh water levels drop, the salt water wedge flows more inland because the pressure of the fresh water from above decreases. So if a drinking water well has been placed close to the sea, it might pump up salt water when there is a low water table.

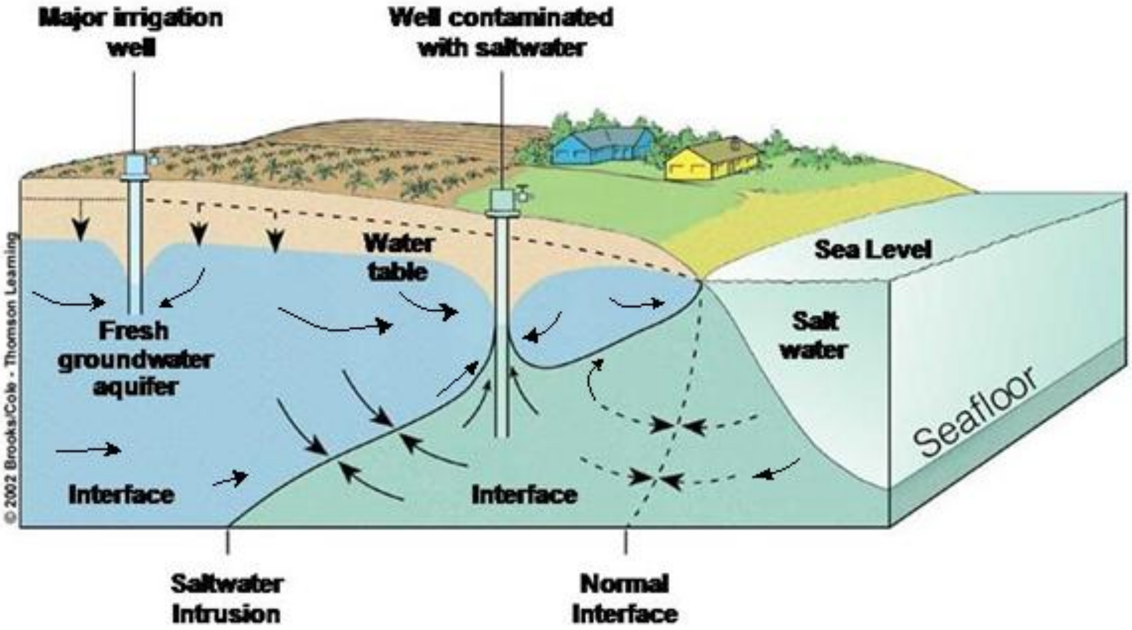


Figure 2.11 Salt water intrusion from under the aquifer (Butler, 2004)

On the other hand, there could be salt water on top of fresh water that can cause salt water intrusion from above. This intrusion starts due to unstable density stratification. If the layer underneath the salt water is of low permeability, the salt diffuses into the underlying fresh water. This is a very slow process, which can take centuries or even millennia. However, if the soil under the salt water is of high permeability, the convective flow of salt water downwards will develop because of the density differences. This is called salt fingering which is a much faster salinization process than diffusion (Post, 2000). The main topic of this research is salt-water intrusion from above, and especially the formation of salt fingers. This process will now be described shortly.

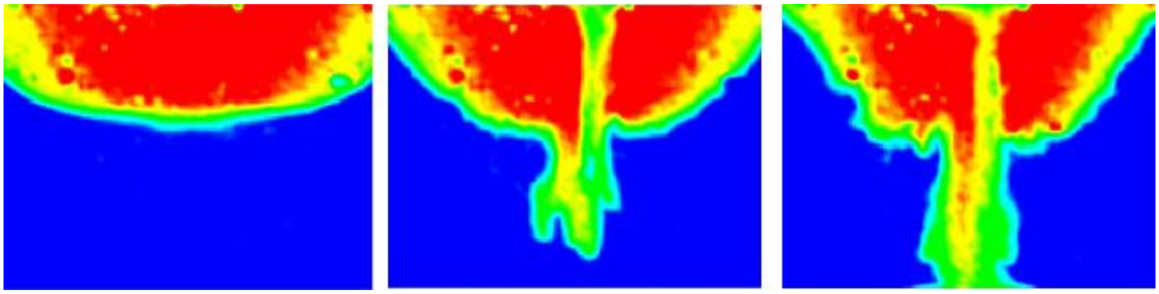
2.5.2 Salt water fingering

Literature on salt water fingering of Kooi and Groen (2000), Wooding *et al* (1997a) and Wooding *et al* (1997b), Elder (1967) and Post (2004) was consulted to study and understand the process of salt water fingering in this research. After looking at the results of the model, the literature of Post (2004) appeared to be the most applicable to this research and therefore it will be discussed in this paragraph.

Phases of salt water fingers

When salt water lies on top of fresh water, a boundary layer will develop by diffusion. The thickness of this boundary layer grows and at a certain moment this boundary layer becomes unstable and salt fingers flow down. This process can be divided into 4 different phases, which each have a different velocity (these phases can also be seen in figure 2.12):

1. growth of the diffusive boundary layer; slow velocity,
2. acceleration of the front when the boundary layer breaks up,
3. an almost linear descent of the front,
4. decreasing front velocity as the plumes reach the bottom of the model domain.



a: t= 241 s b:t = 241 + 4883 s c: t = 241 + 7126 s

Figure 2.12 Fingering processes in a saturated porous medium (red = salt; blue = fresh). (Johannsen *et al*, 2006)

Figure 2.12a shows the diffusive boundary from phase 1. Also, the breakthrough of the salt finger (phase 2) and its downward flow (phase 3) is clear in figure 2.12b and 2.12c. Figure 2.12c then shows phase 4, wherein the front of the plume reaches the bottom of the model domain (phase 4).

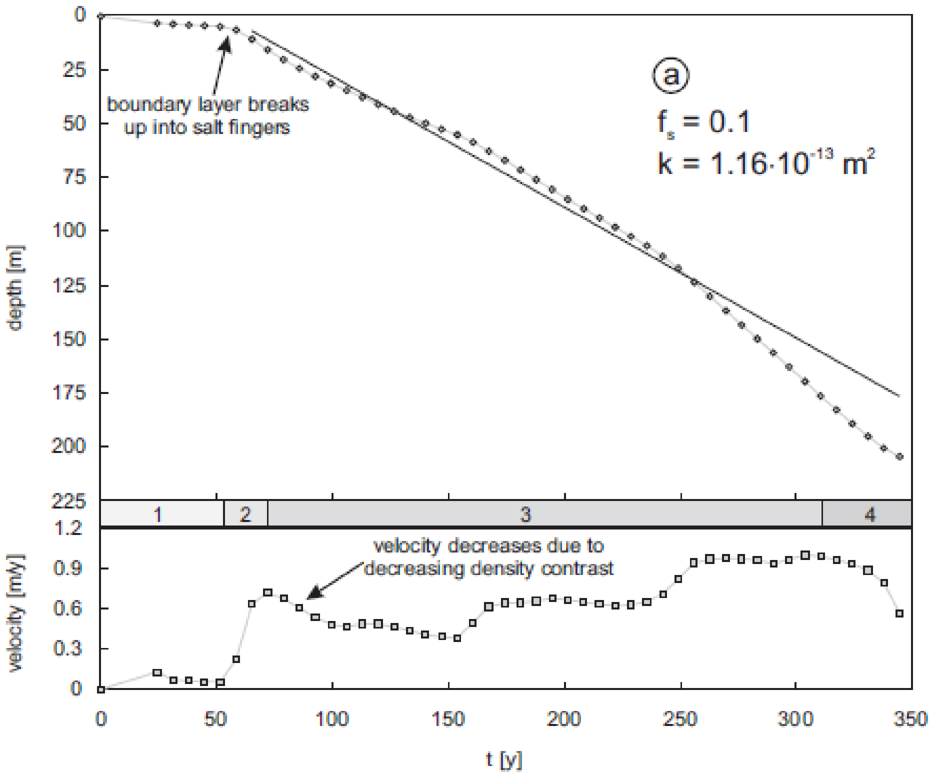


Figure 2.13 Graphs of depth (diamond symbols) and velocity (square symbols) of salinity front f_s (seawater fraction) = 0.1 vs. time for a simulation. The straight line is the average front velocity. The numbers in the bars refer to the different phases 1-4. (Post, 2004)

Figure 2.13 also shows a deceleration after breaking through the diffusive boundary layer (phase 2). This decrease in velocity is probably caused by lateral diffusion. Because of this lateral diffusion, the concentration of the salt water fingers decreases and thus the gravitational convection decreases. After this decrease, the velocity increases again, which might be due to of the superimposed pressure of salt water flowing out of the diffusive layer. Otherwise it might be because of finger coalescence to larger fingers (Post, 2004).

An empirical relationship describing the front velocity based on the intrinsic permeability and the salinity front (f_s) is:

$$v = \frac{\Delta\rho g\kappa}{\mu n_e}(0.20f_s^2 - 0.45f_s + 0.22) \qquad (13)$$

Wherein;

f_s = salinity front, a fraction of seawater,
κ = intrinsic permeability (L^2).
(Post, 2004)

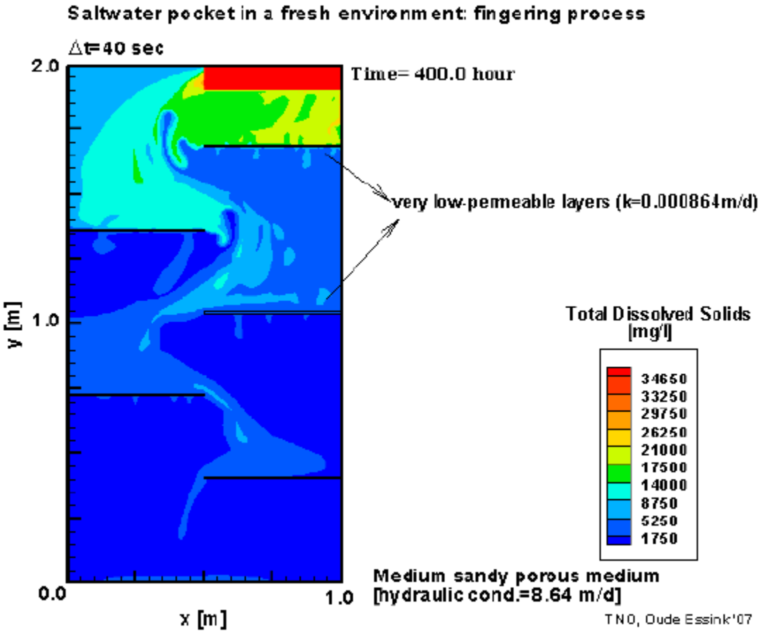


Figure 2.14 Salinization of a groundwater system with some low permeable layers (Oude Essink *et al,* 2008).

Figure 2.14 shows the importance of low permeable layers in the soil on the salt water flow. Low permeable layers spread out the salt water and only a small fraction flows though the layer. Thus, figure 2.14 clearly shows the importance of the geology of the region on the flow of salt water.

3. Methodology

3.1 Introduction

The groundwater flow model is built to predict the future state of the groundwater in the area of the Dintel if the water in Volkerak-Zoommeer will become saline as the mitigation measures for blue-green algae are being taken.
At first, a model was set up with the average conditions of the region. This model was discussed with the groundwater specialist of the region from the Regional Water Authority Brabantse Delta; Mr. K.J. Douben. When the model was finalized, the influence of different parameters, and region characteristics were tested in various scenarios. After this, the results of these different scenarios were evaluated, and conclusions on the future state of the groundwater were drawn.

This is a predictive design model, which is a model that tests the future effects of a non natural alteration in the system (Oude Essink, 2000).
The model domain is a 2D-transection wherein the watercourse Dintel lies in the middle. On both sides are the adjacent fields (fig. 3.1).

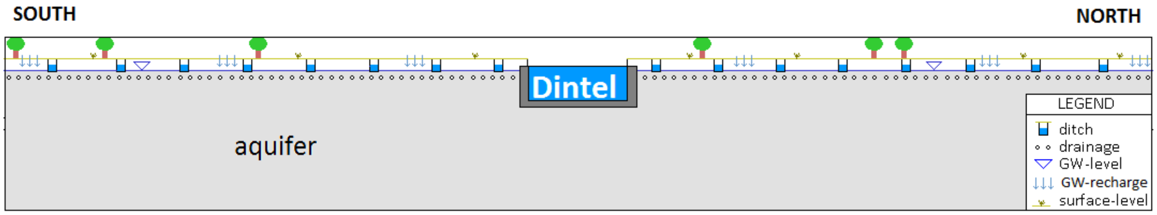


Figure 3.1 The model schematically (not to scale)

The model is called a conceptual model; which denotes that it was built according to average conditions of the area. So, for example, the hydraulic conductivity of the soil and the groundwater level are averaged for the whole region.
On the model some deviating characteristics of the region were tested, for example an extra low permeable layer in the ground. In this way one can tell something about the flow patterns on different locations in the region. So this method tests in each scenario the influence of one alteration in the model. This increases the understanding of the groundwaterflow in the model as the effects of each alteration are very clear.
In the scenarios different geological characteristics in the region were tested, and furthermore, various values for the model parameters. These parameters contain certain levels of uncertainty, so a sensitivity analysis was conducted.

In this chapter the set-up and input values of the model are discussed in paragraph 3.2. Then the different scenarios are described, and finally, the analysis of the model output is explained.

3.2 Description of the model

3.2.1 The model domain

The model transects the Dintel from Dinteloord to Breda (fig. 3.2). In figure 3.2 possible transections have been drawn. However, this is only in theory. As was said in the introduction, the model has average conditions for the region and in the different scenarios the characteristics for certain parts of the region are being tested. The north of the Dintel is the right side of the domain (fig. 3.1).

Figure 3.2 The Dintel region with possible transections (to scale) (Googlemaps, 2012)

3.2.2 Description of the programs and modeling package

The model was built and the results were analyzed with the computer programs Python and Tecplot 360 and the modeling package MOCDENS3D (Oude Essink *et al,* 2010a). Figure 3.3 shows a schematic overview of the order of usage.

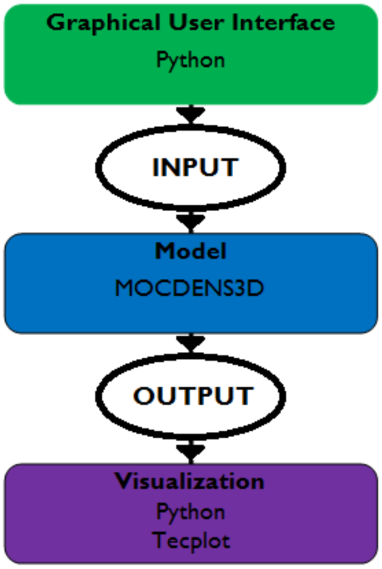


Figure 3.3 Computer programs and the modeling package in order of usage.

PYTHON

The graphical user interface used in this research is Python. Python is a programming language developed by Guido van Rossum in the late 1980s. Nowadays it is a very popular programming language, which is both powerful and accessible. Especially the use of indentation for block delimiters makes it unique and the syntax more clear (van Rossum, 2012). In this research the input for MOCDENS3D was written in Python.

Apart from generating model input files, Python was also used for the visualization of data in 2D with the plotting library called Matplotlib (Hunter *et al,* 2009).

MOCDENS3D

MOCDENS3D (Oude Essink *et al* 2010a) is a computer code for density dependent groundwater flow. A graphical user interface is made by Vanderbohede (2007) as pre- and postprocessor. The code is the solute transport module MOC3D (Konikow *et al.,* 1996), adapted for density differences. The module MODFLOW (USGS) solves the groundwater equation. The buoyancy term is integrated in the MODFLOW code used in MOCDENS3D. MOCDENS3D is especially used for modeling coastal aquifers to look the effect of salt water in the groundwater (Oude Essink, 2001).

TECPLOT 10

Tecplot 10 is part of the family of Tecplot visualization software. It has been developed by Tecplot, Inc from Bellevue in Washington. Tecplot 10 is a computational fluid dynamics and numerical simulation visualization software. It can, among other things, make 2D and 3D plots and animations (Tecplot, 2012).

3.2.3 Physiographic parameters of the model

The physiographic parameters of the model are divided in subsoil parameters, in- and outflows of the model and initial conditions (Oude Essink, 2001). These will be given and explained in this paragraph.

3.2.3.1 Subsoil parameters

Model and grid size

Table 3.1 Size of the model and the cells

	X	**Y**
Direction	Horizontal	Vertical
Size	2700 m	30 m
Number of cells	2700	120
Cell size	1 m	0.25 m

The length of the model is 2700 meters. This size captures a large zone next to the river and by using this length, no significant influence of the boundary conditions is to be expected.

The height of the model is 30 meters. This is the depth where in the largest part of the region the first low-permeable layer lies (Appendix I).

In the horizontal direction, the width of the cells is 1 meter. To model the process of salt water finger development, cells have to be relatively small as otherwise the salt finger development will not be modeled properly. Furthermore, if the width of the cell is too large, the salt finger will consist of only one cell in width (Kooi *et* al, 2000). Three different cell sizes for the x-direction have been tested and figure 3.4 shows the breakthrough curve of the salt water at 1 meter under the river bottom.

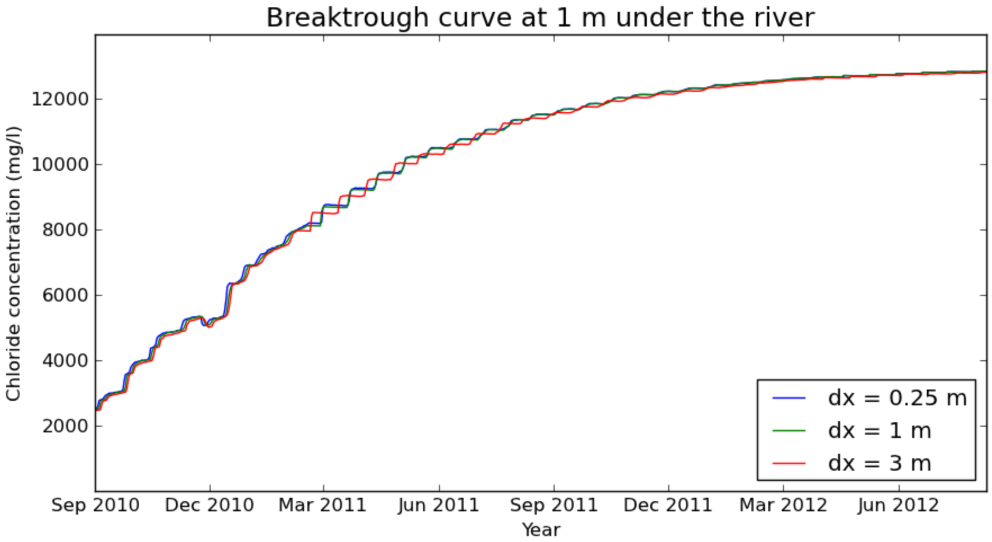


Figure 3.4 Average concentration 1 meter under the river bottom to time for three different cell width sizes.

The breakthrough curve for the model with a cell width of 1 meter has almost the same shape as the breakthrough curve of the model with a Δx of 0.25 m. The Δx of 3 meters shows some discrepancies with the breakthrough curves of the other cell widths that were tested. And thus a cell size of 1 m was chosen for the model, as a Δx of 0.25 m would make the computations of the model unnecessarily time-consuming.

In vertical direction, the cell size of the model is 0.25 meters. This is small but if the vertical discretization is too coarse; the fingering and salinization in the model will be incorrect (Kooi *et al*, 2000). The size of 0.25 m was chosen without testing it on the model. The very small Δy was chosen because grid refinement in the vertical direction is very important in salt fingering modeling. And thus, from previous experience in modeling salt water fingering, a cell size of 0.25 meter was chosen (p.c. Oude Essink, 2012).

Soil characteristics

Figure 3.5 shows hydraulic conductivities that are used in the model.

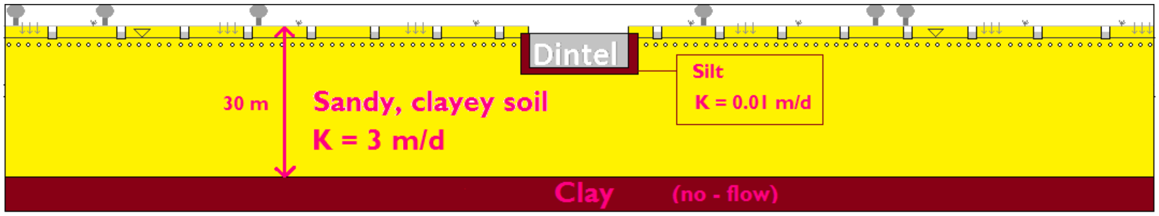


Figure 3.5 Geology of the model (not to scale)

This is based on the overview of the geology in the region in Appendix I. This drill core data shows a clay layer on an average depth of 30 meters. The depth of the model grid is 30 meters, and thus the no-flow boundary at the bottom of the model is an impermeable layer. Most soil in the first 30 meters of the drill cores is sandy, clayey soil. This is represented in the model with an hydraulic conductivity of 3 m/day. The bottom and sides of the Dintel consist of a silty substance. The hydraulic conductivity of this silt was set to 0.01 m/day (p.c. K-J Douben).

Steady-state model

The model is a steady-state model. When MODFLOW is set to steady-state, the time derivative for calculating heads in the groundwater flow equation is set to zero. The model develops an equilibrium which is adapted to its stresses. For a steady-state situation the input and output have to be constant over time (Fitts, 2002). This applies to this model as in time there is no change in the input like precipitation for example.

Porosity

Table 3.2 Porosity

Porosity (n_e)	0.3

The porosity in the entire grid has a value of 0.3. This is an average value used for various groundwater models of the Netherlands (e.g. Oude Essink, 2010b).

Ground level

Table 3.3 Ground level

Ground level	0.35 m NAP

The ground level for the whole grid was set to 0.35 m NAP. This level was set after studying the digital elevation map of the Regional Water Authority Brabantse Delta, and in agreement with K-J. Douben.

Dispersivity

Table 3.4 Longitudinal dispersivity

Longitudinal dispersivity (α_L)	0.1 m
Transversal dispersivity (α_T)	0.01 m

A longitudinal dispersivity of 0.1 m is an average value for the Netherlands (Oude Essink, 2010b). The ratio between transversal en longitudinal dispersivity is estimated to be 0.1 in Dutch coastal aquifers. And thus the transversal dispersivity of the model is 0.01 m (Oude Essink, 2001).

Time

Time-steps and stress period length

Table 3.5 Stress periods and time-steps length

Stress period length	365.25 days
Time-step length (Δt)	5 days

The length of the time-steps is of special importance in modeling density dependent groundwater flow. If the time-steps are too large, the velocity field of MODFLOW may not be in accordance with the buoyancy effects on the velocity field. The velocity field, as calculated with MODFLOW, makes the particles travel a certain distance in one time step. However, the influence of the density change on the velocity during this path is not included in the calculation, as this takes place after each time-step. So if Δt is too large, the location after the time-step might deviate a lot from the location it would have ended up after being under influence of density differences constantly (as in nature). And thus if time-steps are too large, the model results are probably inaccurate.
To test if the time-step is correct the CELDIS number in the MOCDENS3D output was considered. CELDIS uses the Courant Number to assess the distances that particles travel in one time-step.
The Courant number is the ratio between the advective distance in one time-step to the spatial discretization:

$$Co = \frac{V \Delta t}{\Delta x} \tag{14}$$

Wherein:

Co = Courant number (-),
V = velocity of the groundwater (L/T),
Δt = length of one time-step (T),
Δx = cell size in x-direction (L).

The Courant number is important in assessing the stability of the model. Especially in density dependent groundwater flow, where the chloride concentration defines the direction and the velocity of the flow, the particles should not travel too far within one time-step (Oude Essink, 2000).

After testing different time-step lengths such as 1,2 and 8 days, and evaluating the CELDIS number; the model was given a Δt of 5 days.

Total running time of the model

The model was run over 100 years and 1000 years. All model scenarios were run for 100 years. The focus was on the results of these runs as they were used to look at the possible effects of the salinization of the Dintel on the surface and groundwater in the region in the coming decades.

With some of the scenarios there were also runs of 1000 years made. This is not a realistic time period, but in this way the behavior of the model becomes more clear, as the effects are more pronounced after a longer time. By looking at these effects the influences of the boundary conditions and different input values can be analyzed. This is also useful for the interpretation of the results of the short term runs of the model.

Diffusion

Table 3.6 Molecular diffusion

Molecular diffusion (D_m)	0.0000864 m^2/day

For chloride the molecular diffusion at a temperature of 25 °C is 10^{-9} m^2/s. This is converted in to a daily value; 0.000864 m^2/day (Fetter, 2008).

Number of particles

Table 3.7 Number of particles per cell

Number of particles per cell	16

The number of particles in a cell is important for the distribution of the solute. In this model the distribution of the solute is also important the groundwater velocity and direction. Therefore, it is important that a sufficient number of particles is used. In this model 16 particles per cell were sufficient to obtain a reliable result (p.c. Oude Essink, 2012).

Layer type

LAYCON=0 was used. This type of layer in MODFLOW is used for a confined grid, wherein $T = kD$= constant which applies to this model as all the cells are confined.

3.2.3.2 In- and ouflows

Precipitation

Table 3.8 Precipitation

Precipitation rate ($r_{prec.}$)	0.7 mm/day
Chloride concentration	10 mg/l
Daily precipitation per cell ($Q_{prec/cell}$)	0.0007 (m^3/d)

In the model a precipitation rate of 0.7 mm/day was used because this is an average net precipitation rate for the Netherlands. The precipitation has a chloride concentration of 10 mg/l, which is also an average value for the Netherlands (p.c. Oude Essink, 2012). The precipitation per cell, per day, has been calculated with the following formula:

$$Q_{prec./cell} = r_{prec.}(m/d) * A_{cell}(m^2) \tag{15}$$

Wherein;

$Q_{prec/cell}$ = daily precipitation per cell (L^3/T),

$r_{prec.}$ = precipitation rate (L/T),

A_{cell} = surface of the cell (L^2).

With this formula an $Q_{prec/cell}$ = 0.0007 m^3/d was calculated for the model.

Drainage

Table 3.9 Features of the drainage included in the model

Depth	-1.05 m from ground level (-0.7 m NAP)
Conductance ($COND_{drn}$)	0.03 m^2/d
Distance in-between drainage pipes	9 m
Layer	3

The area around the Dintel is mostly used for agriculture. In the agricultural areas in the Netherlands there are drainage pipes in the soil. These pipes lie on average 1 m under ground level on a distance of 10 m from each other (p.c. Oude Essink, 2012).
The formula to calculate the conductance of the drainage the following:

$$COND_{drn} = \frac{2 * \pi * r_{drn} * L_{drn}}{C_{drn}} \tag{16}$$

Wherein;

$COND_{drn}$ = hydraulic conductance (L^2/T),
C_{drn} = hydraulic resistivity (T),
r_{drn} = radius of the drain (L),
L_{drn} = length of the drain in the cell (L).

For the hydraulic resistivity (C_{drn}) value between 5-10 days is usually used by the groundwater researchers at Deltares. For the model C_{drn}=10 days was chosen. Furthermore r_{drn} = 0.05 m and L_{drn} = 1 m. So for $COND_{drn}$ = 0.03 m^2/d was used in the model.

The level of the drainage pipes relative to the river and the ditches was drawn in figure 3.6.

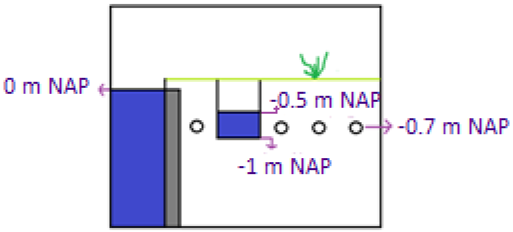


Figure 3.6 The river and the right seepage ditch schematically

Ditches

Table 3.10 Ditches

Conductance ($COND_{ditch}$)	0.33 m^2/d
Chloride concentration	812 mg/l
Stage	- 0.85 m from ground level (-0.5 m NAP)
Elevation bottom	- 1.35 m from ground level (-1 m NAP)

Table 3.10 shows the characteristics of the ditches. The conductance for the ditches has been calculated in the same way as the conductance for the river is calculated; which will be explained in subsection 3.2.3.3 '*River'.*

There are two seepage ditches on 9 meters from the sides of the river. The width of all the ditches is 3 meters.

In the rest of the transection the distance between the ditches is 200 m. This is an average distance based on studying the map of the region. Figure 3.7 shows the locations of the ditches with respect to the other ditches and the river. Figure 3.7 shows the waterlevel in the ditches relative to the drainage pipes and the water level in the river.

The waterlevels and the elevation of the bottom of the ditches have been set in accordance with K-J. Douben.

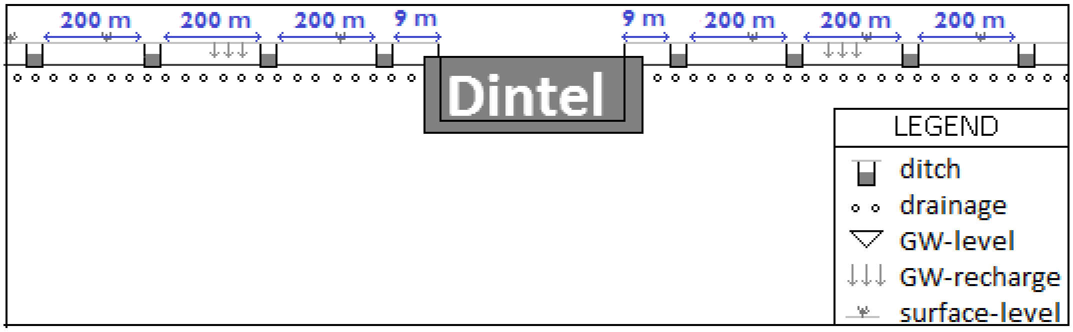


Figure 3.7 Part of the model domain (not to scale) (I.W. Lugten, 2012)

3.2.3.3 Initial conditions

Groundwater head

Table 3.11 Groundwater head for the boundaries

South	Av. -0.8 from GL (-0.45 m NAP)
North	Av. -1.25 from GL (-0.95 m NAP)

The groundwater levels are averaged for the region and are chosen after an investigation of a map on summer and winter groundwater levels (Regional Water Authority Brabantse Delta, 2011). In the southern direction of the river the elevated strip ‘The Naad van Brabant’ is located, and therefore the groundwater head is higher in this direction. The groundwater heads which were chosen for the model (table 3.11), have been approved by K.J. Douben.

Figure 3.8 shows the domain with the groundwater levels on both sides.

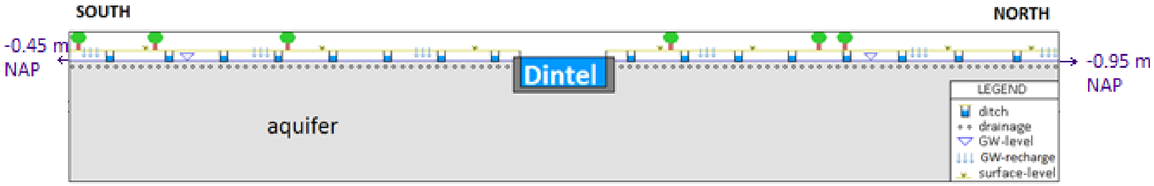


Figure 3.8 The domain with the groundwater levels schematically (not to scale) (I.W. Lugten, 2012)

Chloride concentration in the soil

Table 3.12 Chloride concentration in the ground

Chloride concentration	812 mg/l

The chloride concentration of 812 mg/l is an averaged value calculated from data from the area of Dintelsas. Furthermore, it seemed a reasonable concentration after studying the profiles in Appendix II. The representability of this value has been confirmed by K.J. Douben.

Model Boundaries

The lower boundary of the model is a no-flow boundary. This represents an impermeable layer which is being found in the largest part of the domain in -30 meters (Appendix I).

The side-boundaries are hydrostatic general head boundaries, which is a Cauchy boundary condition (Oude Essink, 2000). This boundary simulates the effect of an external resource with a fixed head connected to the boundary cells. In between the boundary cells and the external resource there is an artificial resistance. The strength of this resistance defines to what extent the fixed head boundary is influencing the groundwater flow in the model. When the resistance is low, the head in the boundary cells will influence the model more than when this resistance is high.

For $COND_{GHB}$ a value of 10 m^2/d was chosen. This value is not based on a calculation, as the general head boundary is difficult to set. And thus this value was chosen based on former experience (p.c. Oude Essink, 2012).

Table 3.13 General Head Boundary

Conductance ($COND_{GHB}$)	10 m^2/d
Chloride concentration	812 mg/l
Groundwater head south	- 0.45 m from ground level (- 0.8 m NAP)
Groundwater head north	- 0.95 m from ground level (-1.3 m NAP)

The general head boundary is hydrostatic to simulate the influence of density dependency in for these fixed head cells. The fresh water head for the cells at different levels of the hydrostatic general head boundary is calculated with the formula for the fresh water head (2) which was explained in paragraph 2.4.1.3.

River

Table 3.14 River

Conductance ($COND_{GHB}$)	0.33 m^2/d
Concentration water	13000 mg/l (REF)
Stage	0 m NAP
Depth	5 m
Width	66 m

The conductance of the riverbed can be calculated with the following formula:

$$COND_{riv} = \frac{KLW}{M} \tag{17}$$

Wherein:

$COND_{riv}$ = conductance of the reach of the riverbed (L^2/T),
K = hydraulic conductivity of the riverbed (L/T),
L = length of the reach (L),
W = width of the river (L),
M = thickness of the riverbed (L) (Oude Essink, 2000).

For this model the hydraulic conductivity of the river bottom was chosen to be 1 m/d. A value of this kind often used for rivers in groundwater modeling (p.c. Oude Essink, 2012). For the length of the reach 1 m was used as this is the length in z-direction of the cells. For the width of the river 1 m was used as this is the width of the cells. The thickness of the riverbed was chosen to be 3 meter.
Implementing these values in the formula one obtains a hydraulic conductance of 0.33 m^2/d.

In most scenarios without mitigation measures the water in the river has a chloride concentration of 13000 mg/l. This is the chloride concentration the connected Volkerak can become in the future, and therefore, the highest concentration the water in the Dintel will become in the future. So this is used in the scenarios to see what will happen in the worst-case situation.

The water level in the sluice of Dintelsas is around 0 meter NAP (Rijkswaterstaat). This value will also be used for the water level of the Dintel further upstream.

Both the depth and the width of the river are set according to borehole data of Dinoloket. The depth of the river is on average 5 m and the width of the river is on average 66 m (Dino*loket*, 2011) (fig. 3.9).

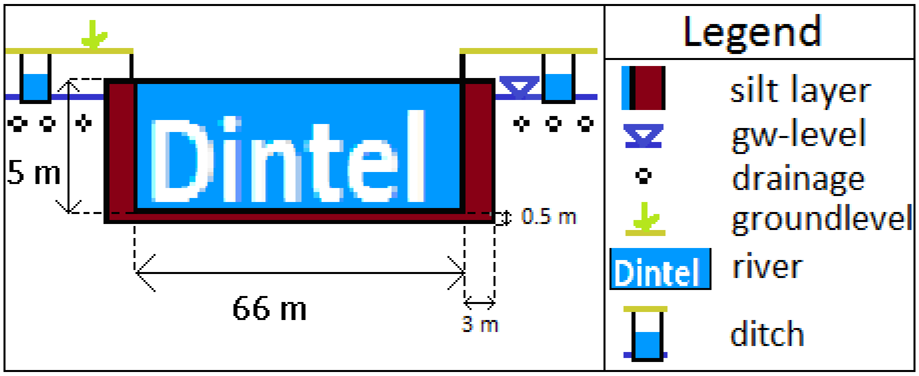


Figure 3.9 The lay-out of the Dintel as in the model (not to scale)

Around the river, there is a low-permeable layer in the soil which represents the silt on the bottom and the sides of the river. The hydraulic conductivity around the river is in the basic reference model 0.01 m/day (silt), though other values are tested. To the side the silt layer is 3 meters thick and on the bottom the layer is 0.5 m thick. This thickness is difficult to estimate, as there are no borings through the sides and river bottom of the Dintel. This value was set in agreement with K-J. Douben.

3.3 Scenarios

Table 3.15 shows an overview of the scenarios that were tested.

Table 3.15 Overview of all scenarios that were tested

Scenario	Name	Changed input	
Reference scenarios			
Model check	*Criv125*	Concentration in river to 125 mg/l	
Worst-case	*Criv13000*	Concentration in river to 13000 mg/l	
Different hydrogeological Characteristics			
Varying the water concentration in the river (Criv$_{REF}$= 13000)	*Criv2000*	Concentration in river to 2000 mg/l	
	Criv3000	Concentration in river to 3000 mg/l	
	Criv4000	Concentration in river to 4000 mg/l	
	Criv5000	Concentration in river to 5000 mg/l	
	Criv10000	Concentration in river to 10000 mg/l	
Varying the water concentration in the groundwater (Cgw$_{REF}$= 812)	*Cgw250*	Concentration in gw to 10000 mg/l	
	Cgw2000	Concentration in gw to 2000 mg/l	
	Cgw8000	Concentration in gw to 8000 mg/l	
Low permeable layer	*Lpl-4m_K=0.01*	Depth = -4 m	K=0.01
	Lpl-4m_K=0.01	Depth = -4 m	K=0.001
	Lpl-15m_K=0.01	Depth = -15 m	K=0.01
	Lpl-15m_K=0.01	Depth = -15 m	K=0.001
Sensitivity of the model parameters			
Varying the hydraulic resistivity of the drains	*Cdr=2d*	CONDdrn to 0.157 m^2/d	
Varying the hydraulic conductivity of the silt layer under the river (Kriv$_{REF}$=0.01m/d)	*Kriv=0.001m/d*	Kriv to 0.001 m/d	
	Kriv=0.1m/d	Kriv to 0.1 m/d	
Mitigation measures			
Varying the water level in the ditches (WLditch$_{REF}$=-0.5mNAP)	*WLditch=0mNAP*	An increase of the WL in the ditch to 0 m NAP	
	WLditch=-0.1mNAP	An increase of the WL in the ditch to -0.1 m NAP	
	WLditch=-0.2mNAP	An increase of the WL in the ditch to	

		-0.2 m NAP
	WLditch=-0.3mNAP	An increase of the WL in the ditch to -0.3 m NAP
	WLditch=-0.4mNAP	An increase of the WL in the ditch to -0.4 m NAP
Varying the water level in the river ($WLriv_{REF}$=0mNAP)	*WLriv=+0.1mNAP*	An increase of the WL in the river to +0.1 m NAP
	WLriv=-0.1mNAP	An decrease of the WL in the river to -0.1 m NAP

At first two reference scenarios were tested with the model. One reference case (the model check 'Criv=125') tests the present groundwater flow in the region, without any change of concentration in the river. And one reference case (the worst-case scenario 'Criv=13000'), wherein the water in the Dintel will totally salinize. After that, different scenarios were tested with various hydrogeological characteristics of the region, as for example the presents of a low-permeable layer in the soil. Additionally, the sensitivity of model parameters of which the value is difficult to set was tested. Finally, the effects of mitigation measures for salinization of the surface water were tested.

3.3.1 The reference scenarios

3.3.1.1 The model check 'Criv125'

In *Criv=125* the water in the river Dintel has a chloride concentration of 125 mg/l. This scenario was run to test the behavior of the present system. So with this scenario the groundwater flow in model can be studied without a strong influence of density differences.

3.3.1.2 The worst-case scenario 'Criv13000'

In the worst-case scenario, the river water has a chloride concentration of 13000 mg/l. This is the chloride concentration that the water in the connected Volkerak will reach in the future, if the mitigation measures for blue-green algae are being taken. As there are sluices in between the Volkerak and the Dintel, it is not likely that the water in the Dintel will reach this chloride concentration. However, it is the maximum concentration the river can possibly reach, and thus it is an useful concentration to model, because it shows what will happen in the worst-case scenario.

3.3.2 Different hydrogeological characteristics

3.3.2.1 Various concentrations of the river water

More chloride concentrations of the river were tested apart from the different chloride concentrations of the river water in the model check and the worst-case scenario (table 3.16).

Table 3.16 Different chloride concentrations of the river tested on the model

Criv (mg Cl/l)
2000
3000
4000
5000
6000
10000
13000 (REF)

The results of these runs could show what the influence of the concentration of the river water on the velocity of the salt water intrusion is.

3.3.1.1 Various concentrations of the groundwater

Different chloride concentrations of the groundwater were tested to see their influence on the salt water intrusion from the river (table 3.17). The chloride concentration of the groundwater in the region varies as can be seen in Appendix II. Therefore, the outcome of these scenarios can tell us something about the salt water intrusion in parts of the region where there is a higher or a lower groundwater chloride concentration than 812 mg/l.

Table 3.17 Different chloride concentrations of the groundwater tested on the model

Cgw (mg Cl/l)
250
812 (REF)
2000
8000

3.3.1.2 A low permeable layer at two different depths

In the region of the Dintel there are parts where there is a low permeable layer near the bottom of the river on approximately -4 m depth. There are also parts where there is a low permeable layer on a depth of approximately -15 m (Appendix I). The effect of such layer was simulated in the model in 4 different scenarios (table 3.18).

Table 3.18 Different chloride concentrations of the groundwater tested on the model

No.	**Depth the layer (2 m thick)**	**K of low permeable layer (m/d)**
1.	- 4 m	K = 0.01
2.	- 4 m	K = 0.001
3.	- 15 m	K = 0.01
4.	- 15 m	K = 0.001

First the layer on a depth of 4 meters was tested with two different values for the hydraulic conductivity. Then the layer on a depth of 15 m was tested for both of these K values.

3.3.2 The sensitivity of model parameters

3.3.2.1 Varying the hydraulic resistivity of the drains

For the hydraulc resistivity (C_{drn}) of the drainage pipes a value of 2 – 10 days is generally used among scientists in the groundwater department of Deltares. In the reference model Criv13000, a hydraulic resistivity of 10 m/d was used.
The conductance of the drainage pipes is calculated by the formula in section 3.2.2.2. Using this formula with an hydraulic resistivity of 2 m/d, the hydraulic conductance becomes 0.157 m^2/d.

Table 3.19 Varying the hydraulic conductance of the drains

$COND_{drn}$ (m^2/d)
0.157

3.3.2.2 Varying the hydraulic conductivity of the silt layer under the river

The hydraulic conductivity of the silt layer on the bottom of the river is an uncertain parameter and therefore, its influence on the salt water intrusion was tested using two other different values for K (table 3.20).

Table 3.20 Varying the hydraulic conductivity of the silt layer on the bottom of the river

K river bottom (m/d)
K = 0.001
K = 0.01 (REF)
K = 0.1

These runs will show the sensitivity of the model for the conductance of the layer of the river bottom.

3.3.3 Mitigation measures

3.3.4.1 Varying water level in the ditches

One of the mitigation measures to prevent the salt water from flowing into the surface water is increasing the water level in the ditches. The effect of this mitigation measure will be tested by running the model with the ditch levels as in table 3.21. A level of 0 m NAP was chosen as an extreme increase in water level in the ditches and next to this some less extreme increases were tested.

Table 3.21 Varying the water level in the ditches

Water level in the ditch (m from NAP)
0 m NAP (-0.35 m from GL)
-0.1 m NAP (-0.45 m from GL)
-0.2 m NAP (-0.55 m from GL)
-0.3 m NAP (-0.65 m from GL)
-0.4 m NAP (-0.75 m from GL)
-0.5 m NAP (-0.85 m from GL) (REF)

3.3.4.2 Varying water level in the river

Another mitigation measure that the Regional Water Authority Board Brabantse Delta has in mind is increasing the water level to +0.1 m NAP, as this will decrease the inflow of water from the Volkerak at the sluice complex into the Dintel. The effects of this measure will be investigated in this study.
Moreover, a decrease in the water level to -0.1 m NAP will be studied as this might decrease the salt water intrusion substantially.

Table 3.22 Varying the water level in the ditches

River level
+0.1 m NAP
0 m NAP (REF)
-0.1 m NAP

3.4 Analysis of model output

The output of the model was analyzed in various ways. These ways will be explained in this section.

The changes in the head and the chloride concentration of the whole domain are evaluated in video's and pictures. Both are made in Tecplot and show the development of the head and the concentration over time. Tecplot also shows velocity vectors; which can visualize the velocity and direction of particles in a particular stress-period.
Furthermore, observation points have been placed in the model to look more precisely at chloride concentrations over time at certain locations. The observation wells are placed under the river at three different depths in the domain. Namely, at - 6 m, -15 m and at - 30 meters. At each depth, 13 observation wells have been placed at equal distance from each other over the whole width of the river. By averaging the concentrations at these observation points, the salinization of the domain at in these areas can be seen. Moreover, there are observation points in all of the ditches and some of the drainage pipes (fig. 3.10). These observation points are important for the analysis

of the future situation of the surface water in the area. The observation points in the drainage pipes have been placed in the drainage pipes 3 meters of the riverbank and in drainage pipes every 270 meters (fig. 3.10).

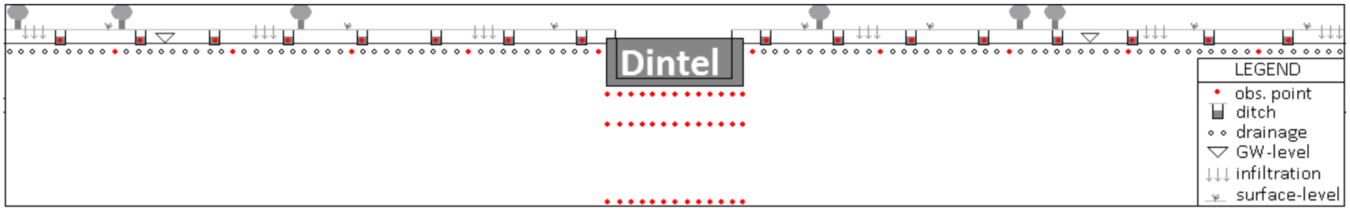


Figure 3.10 Locations of the observation points

The total volume of fresh, brackish and salt water in the domain can be calculated for every stress period. This method has been used to compare different scenarios on how much salt and fresh water is present in the domain. With this data one can asses if there is a lot of water flowing in from the rivers for example.

The inflow and outflow of the model are quantified in the output of MOCDENS3D. This shows where the water flows in and out of the model. For example, the inflow is most of the time from the rivers, the boundaries and from the precipitation. By looking at the ratio and the volume of this in and outflow, the groundwater flow in a certain scenario can be interpreted in a better way.

4. Results

4.1 Introduction

The results of the various scenarios runned by the model are described in this chapter. For most of the scenarios a summary of the results will be given in the beginning of the chapter. Then the short term results are described for every scenario. For some of the scenarios the long term results are also presented because it is interesting to see how the salt water intrusion takes places. In addition, the long term can tell us something about the model behaviour.

In the results the chloride distribution and the flow patterns in the various scenarios are described. This flow pattern is described by particle tracking and/or the distribution of the fresh water head. Furthermore, the chloride concentration in the seepage ditches and the rest of the ditches will be considered. Finally the chloride concentrations of the water in the drainage pipes close to and further away from the river are discussed.

4.2 Model check 'Criv125'

The behavior of the model was checked first in a run of a total period of 1000 years to look at the behavior of the model. The river water has a chloride concentration of 125 mg/l. The chloride concentration in the domain after 1000 years can be seen in figure 4.1. It is 3010, because 2010 is chosen as the starting point for the runs, as it is a convenient year to work with. The x and y axis are in meters and the chloride concentration is in mg/l.

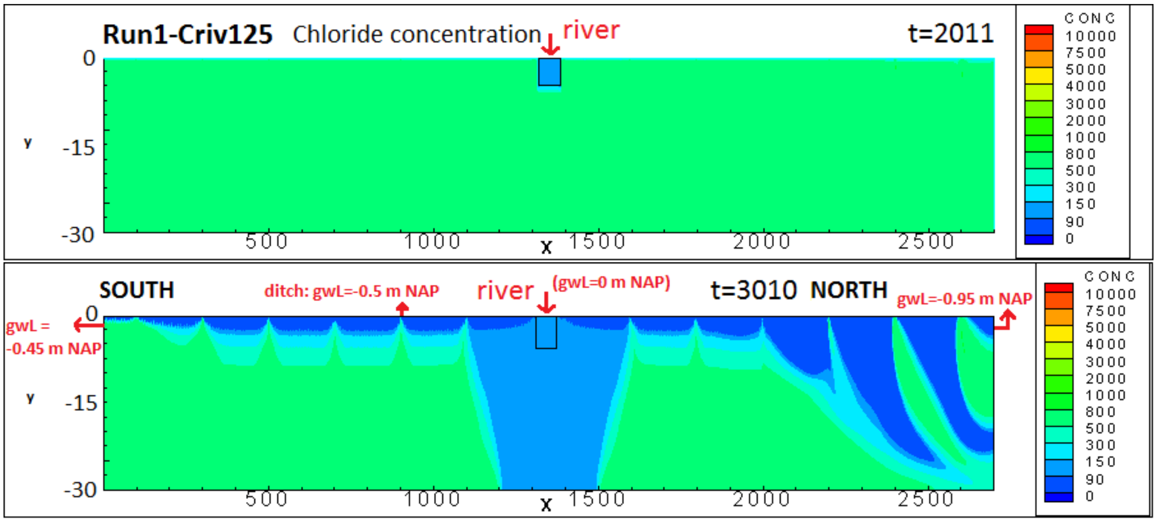


Figure 4.1 Chloride concentration for Run1-*Criv125* for t=2011 and t=3010

The fresh water flows out of the river because the waterlevel (0 m NAP) is higher than the groundwater heads at the boundaries of the domain (south and north: -0.45 m NAP and -0.95 m NAP respectively). Therefore it is called a recharging river.

The side boundaries seem to influence the groundwater flow in the model. On the north (right) side of the domain, the fresh water flows downwards into the direction of the right boundary of the domain. On the left side of the model, the fresh water layer is very thin in comparison with the layer in the rest of the domain (fig. 4.1).

The top boundary condition is set by the water level in the ditches, which is -0.5 m NAP. This is very close to the initial given value for the fresh water head of the groundwater, which is -0.45 m NAP. And thus because of this dominant boundary condition from the top; the fresh water head stays in most of the domain approximately -0.45 to -0.5 m NAP. This can be seen in figure 4.2, wherein the fresh water head in the domain in the year 3010 was given. Near the right boundary of the domain the fresh water head becomes the level which was given to this general head boundary condition; -0.95 m NAP.

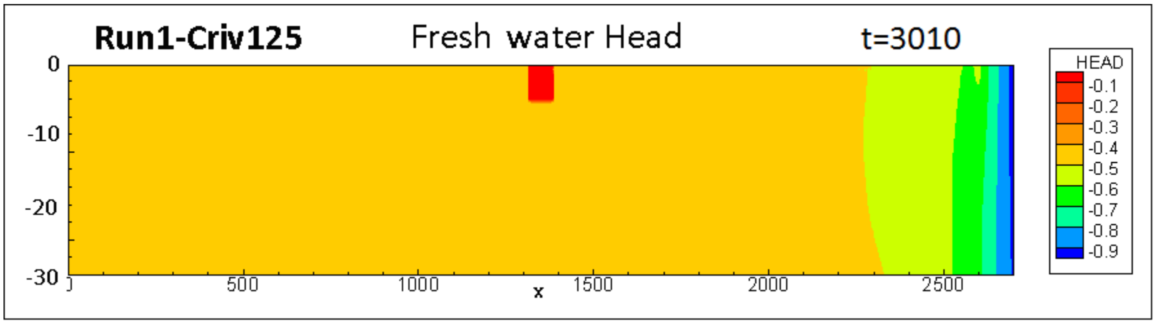


Figure 4.2 Freshwater head (in m NAP) Run1-*Criv125* in 3010

This relatively quick change in fresh water head causes a strong groundwater flow towards the right boundary. This strong flow pulls the fresh water layer from between the ditches downwards (fig. 4.1).

The left boundary condition (-0.45 m) also influences the groundwaterflow on the left side of the domain. There is an inflow from the left boundary because of a head difference of 0.05 m between the boundary and the ditches. This flow pushes the fresh water layer upwards. Both effects boundary effect on the concentration distribution, and will not be translated into the real world situation. So for the results of this study, we will only look at the part of the domain from 700 – 2000 meters, because in this part of the domain the boundary conditions do not influence the groundwater flow (fig. 4.3).

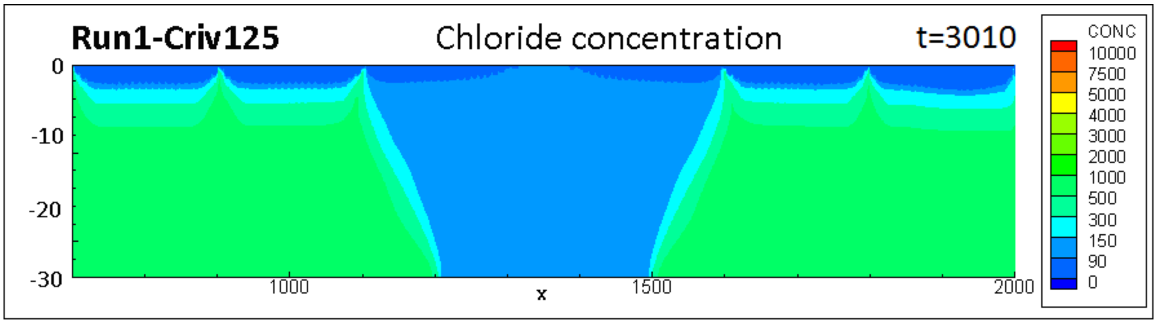


Figure 4.3 Chloride concentration (mg/l) Run1-*Criv125* in 3010

4.3 Various river water concentrations (Criv)

4.3.1 Criv 13000 mg/l

Summary

In this scenario the river water has a chloride concentration of 13000 mg/l, the salt water will flow from the river into the light brackish groundwater. This flow is caused by the density as well as head difference between the water in the river and the groundwater in the rest of the domain. The chloride concentration in the two seepage ditches will only significantly increase after a period of approximately 250 years.

Short term

Figure 4.4 shows the chloride concentration in the groundwater for 1, 11, 21, 41 and 61 years of running the model for scenario *Criv13000*: so the years 2011, 2021, 2031, 2051 and 2081 respectively. The process of salt water intrusion from the river can be seen in this figure. After 1 year, there is only diffusion of chloride through the sides of the river. This is visible in figure 4.4 in the yellow and green edges of the river. In 2031, one can clearly see salt water fingers flowing down from the river into the brackish groundwater. By this time, a fresh water layer has formed on top of the domain due to fresh precipitation coming into the top of the domain. This fresh water layer is 1.5 – 2 m thick. In 2051 and in 2071, the widening of the salt water cone is visible, and there is clearly still salt water flowing out of the river in finger like shapes.

A video of *Criv13000* for the first 50 years can be found online on the following link: http://www.youtube.com/watch?v=10tIKblFIEk&feature=youtu.be

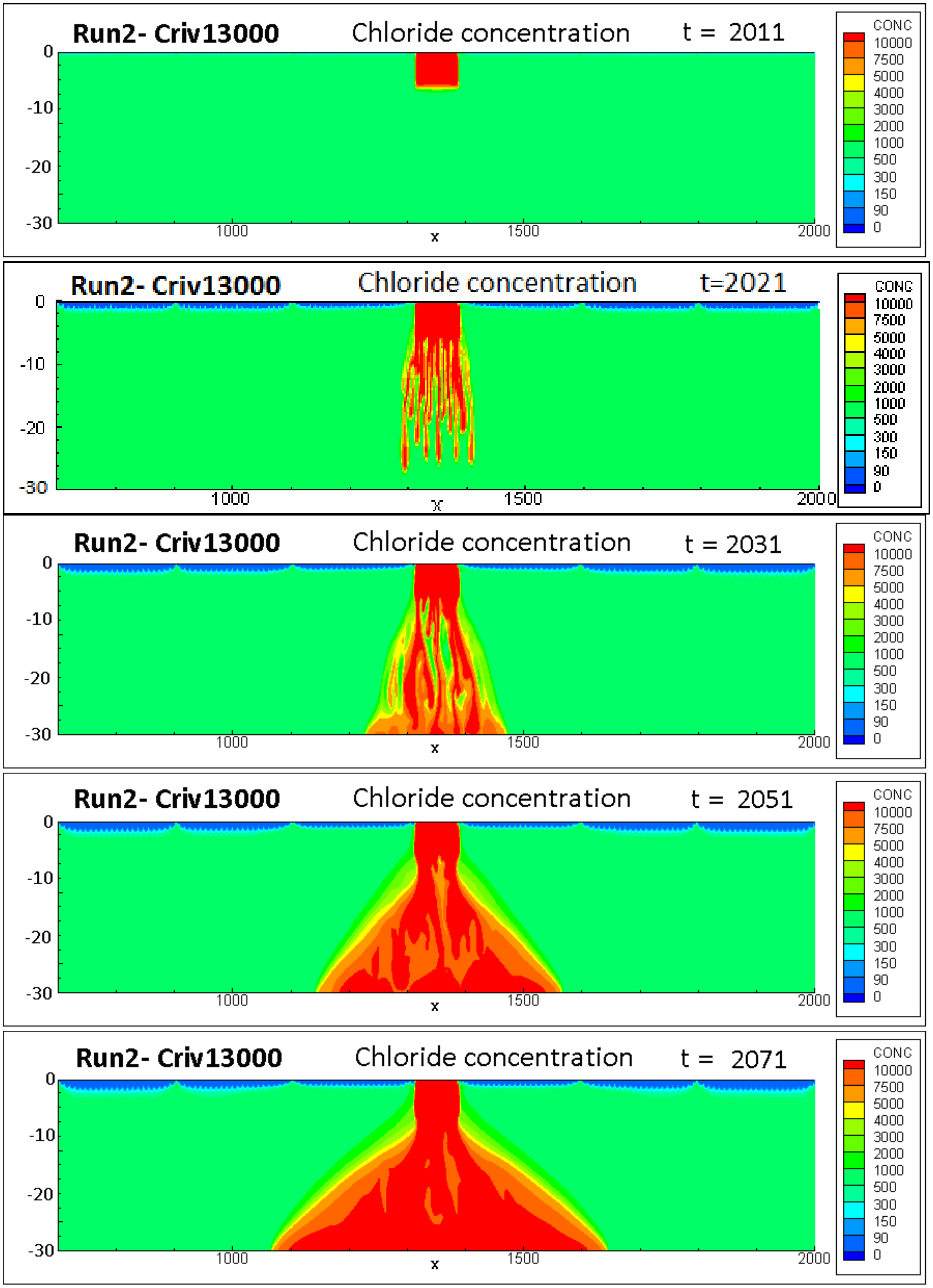


Figure 4.4 Chloride concentration in the groundwater Run2-*Criv13000* in 2011, 2021, 2031, 2051 and 2071.

Figure 4.5 shows the chloride concentration over the years in the seepage ditches at 3 m from the riverbank for scenario *Criv13000*. The seepage ditches next to the river do not salinize in the nearby future. Only around 2200, the chloride concentration of the water in the right seepage ditch will be more than 1000 mg/l.

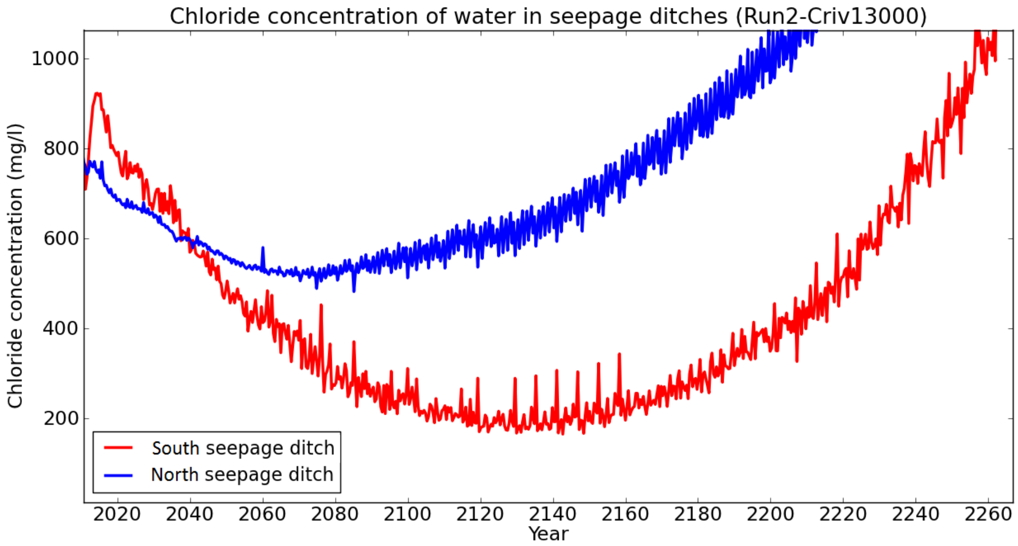


Figure 4.5 Chloride concentration in the seepage ditches in scenario *Criv13000*.

The graph in figure 4.5 shows that in the first year(s) the concentration in the ditches increases a little. The oscillations are due to particles used in the model and it is therefore a numerical artifact which should not be interpreted to the real world situation. One should only look at the general behaviour of the graph over time.
The small increase in the southern seepage ditch in the beginning is caused by salt molecules diffusing through the sides of the river. Figure 4.6 shows this process. This salt flows into the seepage ditches (fig. 4.6). This process causes the increase in concentration in these ditches in the first few years which is seen in the graph in figure 4.5.

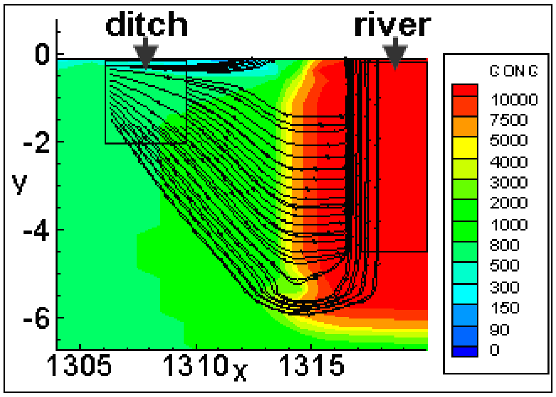


Figure 4.6 Chloride concentration in Run2-*Criv13000* the southern seepage ditch at t=2011 with forward velocity vectors for particles

In the northern seepage ditch the solute transport is somewhat different. A suttle different flow system causes different inflows of groundwater sources: more precipitation apparently infiltrates there than river water does.

After this increase in the first years of running the model at the southern seepage ditch, there is a decrease in the chloride concentration that continues for a some decades. The flow of the first years towards the ditches most likely stops when the flow of salt water from the bottom of the river starts. This causes a preferential flow of water from the river downward, which has been visualised by particle tracking in figure 4.7. The particles from the sides of the river flow a little to the side and then bend in the vertical direction.

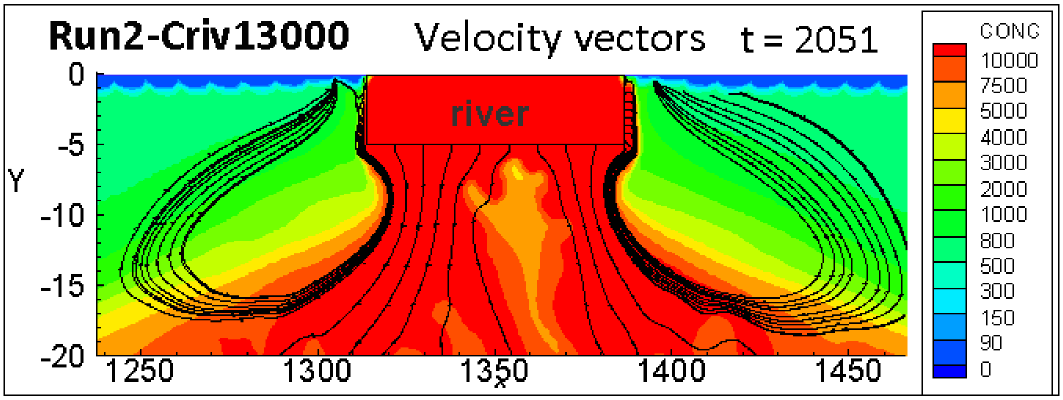


Figure 4.7 Chloride concentration in Run2-*Criv13000* at t=2051 with the forward velocity vectors for particles flowing from the river edges.

At a depth of approximately 16 meter, the flow bends upwards and flows to the seepage ditches. This flow is apparantly not salinizing the seepage ditches because in 2051 the chloride concentration in both seepage ditches is still decreasing. This is most likely caused by the fresh water flow from above and from the sides into these seepage ditches, which can be seen in figure 4.8. The chloride concentration of the ditch decreases and thus we can state that the fresh water flow from above into the ditches is dominating the brackish-saline water flowing in from below.

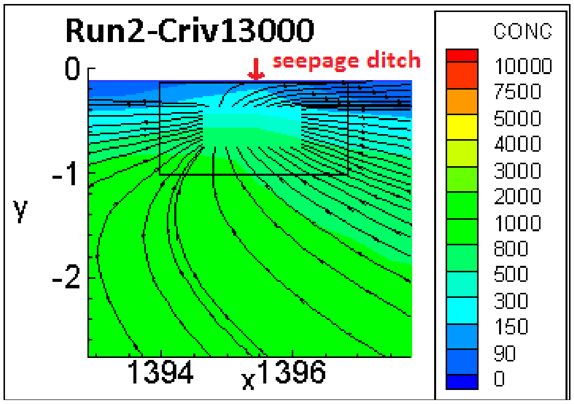


Figure 4.8 Chloride concentration at t=2051 with backward velocity vectors for particles flowing into the northern seepage ditch.

The graph in figure 4.6 shows that in 2060 and 2140 the chloride concentration in the ditches of the northern and southern seepage ditch respectively, starts increasing again. This increase can be explained by looking at the chloride concentration in the domain in 2071 in figure 4.5. At this moment a salt water cone has formed under the river. The presence of this salt water increases the fresh water head under the river. So the gravitational convection of the salt water from the river downward has decreased. And thus more salt water from the river starts to flow to the sides again.

Long term

After 1000 years of running scenario *Criv13000*, a large part of the groundwater in the domain has become saline (fig. 4.9), and salt water still seeps from the river into the groundwater enlarging the salt water cone.

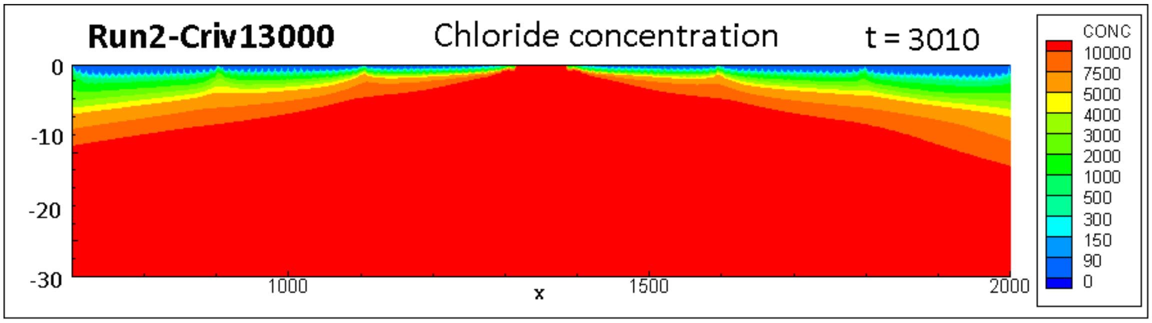


Figure 4.9 Chloride concentration in the groundwater after 1000 years

Especially near the riverbanks, the fresh-saline groundwater boundary is very close to ground level in 3010. This is caused by the upward pressure of the salt cone which is the highest under the river, where salt water is flowing into the domain.

In figure 4.10 the chloride concentration in the seepage ditches on the long term was plotted. It shows that both seepage ditches next to the river salinize on the long term and their chloride concentration reaches approximately 6.500 mg/l in 1000 years (fig. 4.10). The chloride concentration in the other ditches in the domain does not increase much, only from 800 mg/l up to approximately 900 mg/l in 1000 years.

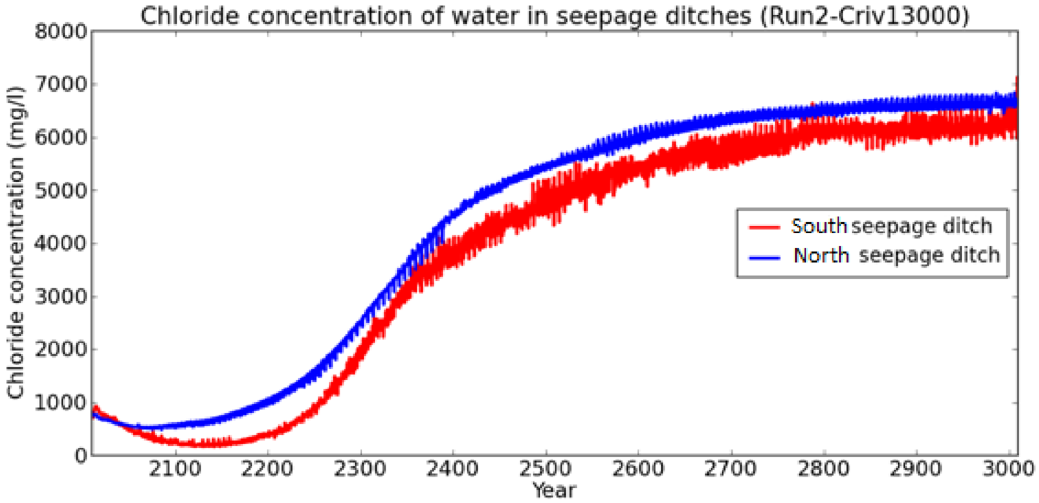


Figure 4.10 Chloride concentration in seepage ditches

This salinization of the seepage ditches is caused by salt water flowing out of the river sides, upwards, into the seepage ditches next to river. This can be seen in figure 4.11, wherein particle tracking shows the flow from the sides and bottom of the river. From the sides of the river the particles flow upward towards the seepage ditch or into the drainage system. From the bottom of the river particles flow downwards.
The water flows from the river sides into the seepage ditches because the level of the ditches is 0.05 m lower than the groundwater head. The groundwater head in the river is 0 m NAP, so the salt water flows through the sides of the river towards the seepage ditches.

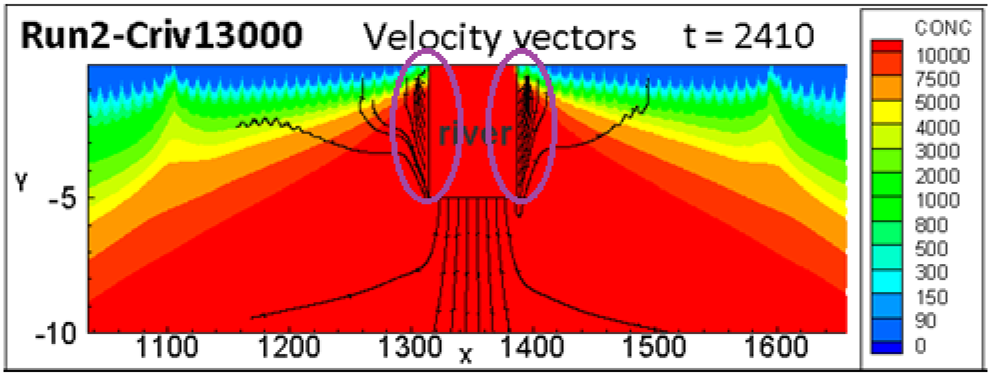


Figure 4.11 Chloride concentration in Run2-*Criv13000* at t=2412 with the forward velocity vectors.

Figure 4.11 also shows that particles from the sides of the river bottom, flow with a slope upward into the drainage system, of which the head is -0.7 m NAP. Some particles from the edges of the downward stream derived from the bottom of the river first flow down, and then deflect towards the boundaries of the model, as the fresh water head is lower there. This can be seen in figure 4.12, which shows the fresh water head after 990 years. The fresh water head shows a cone like shape under the river, in which there is an increase towards the centre. This is caused by the comparatively high density in the salt water cone, which has the same shape (fig. 4.9). The relatively heavy salt water causes the increasing pressure with depth.

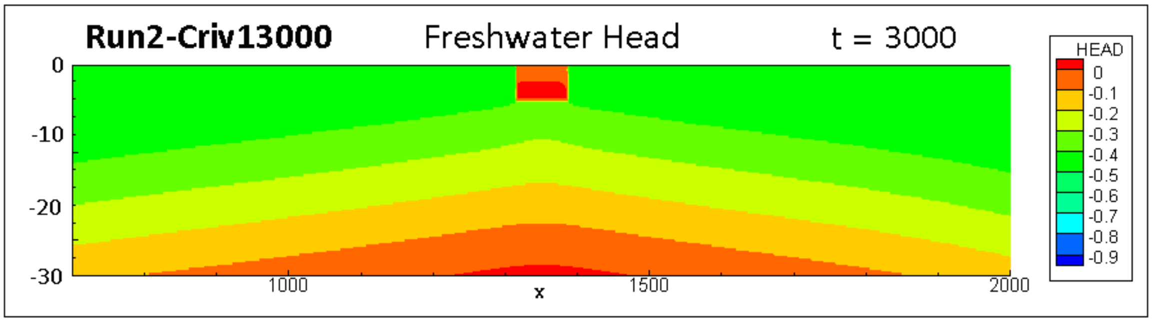


Figure 4.12 The freshwater of scenario Run2-*Criv13000* in 3000

The more salt water there is on top of a certain place, the higher the pressure, and thus the higher the fresh water head at that location. The fresh water head in the middle of the bottom of the domain is approximately the same head as in the river, namely 0 m NAP (fig. 4.12).

The chloride concentration in the drainage closests to the river has a maximum concentration of 9000 mg/l over time (table 4.1). The drainage further away from the river have a maximum chloride concentration of 800 mg/l.

Table 4.1 Maximum chloride concentration in the drainage system in 1000 years (summary from the graph)

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	<9000 mg/l	<800 mg/l

4.3.2 Different chloride concentrations of the river water

Summary

The velocity of the downward water flow from the river depends on the chloride concentration of the river water. If the river has a low chloride concentration, the downward flow velocity is small and water from the river is constantly flowing into the seepage ditches. If the river has a high chloride concentration, there is a strong vertical preferential flow which pulls all the water from the sides of the river downward. So in these scenarios there is less water flowing towards the seepage ditches in the beginning, disabling the salinization of the seepage ditches. The higher the chloride concentration in the river, the longer the preferential downward flow.

Short term

The scenarios with river water of different chloride concentrations show that over the years the chloride concentration of the groundwater under the river becomes the same concentration as the river water of the relating scenario (fig. 4.13).

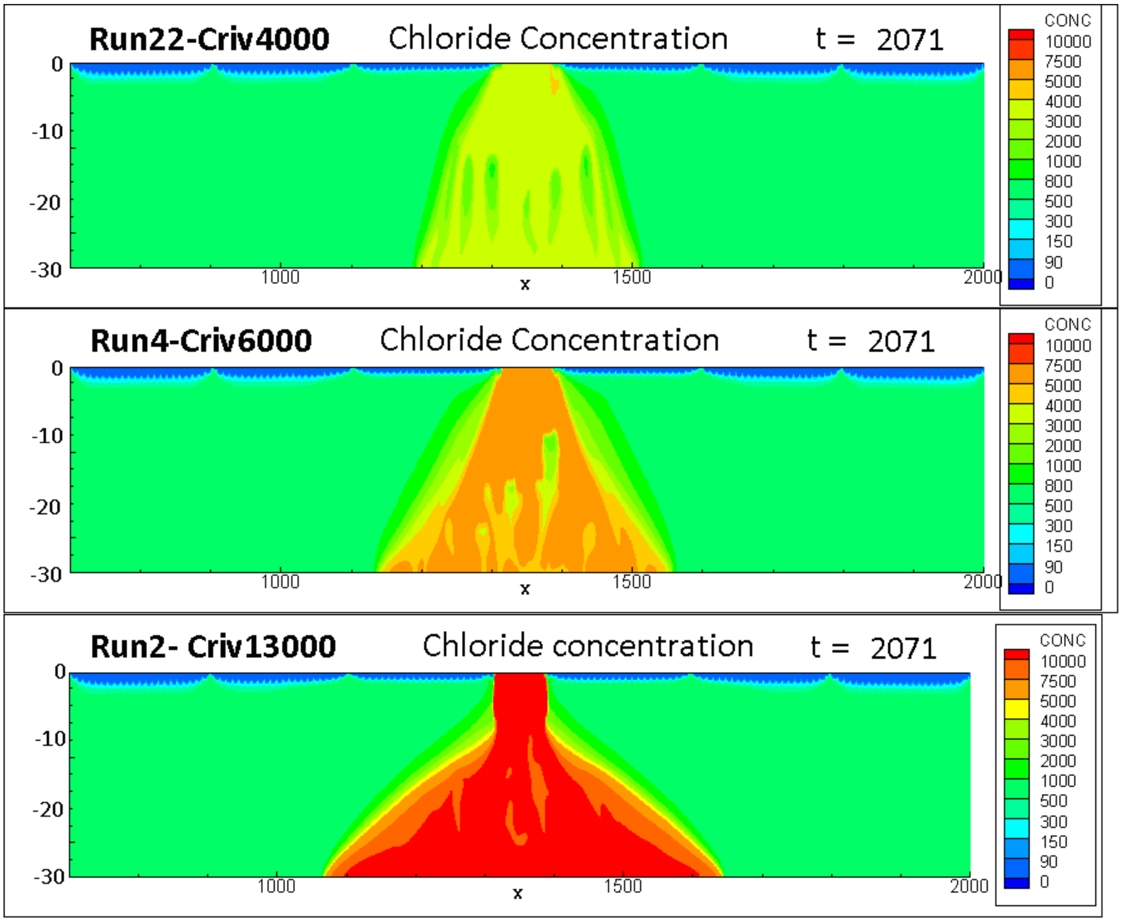


Figure 4.13 Chloride concentration in the groundwater in Run2-*Criv13000* 2071 for different scenarios

Furthermore, the shape of the cone depends on the chloride concentration of the river water; the higher the chloride concentration, the wider the cone at the bottom of the domain for the coming 200 years. This is visible in figure 4.14, wherein the width of the salt plume at the bottom of the domain was plotted for different chloride concentrations of the river water. This shows a pattern wherein the increase of the width of the plume is decreasing as the chloride concentration of the river water increases.

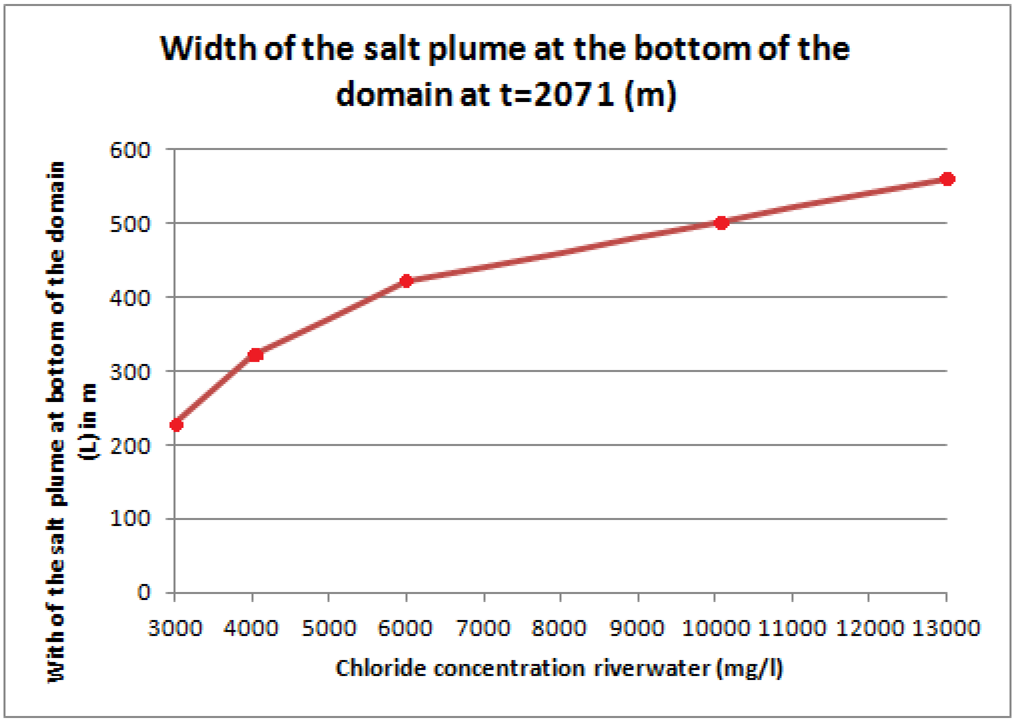


Figure 4.14 With of the salt plume at the bottom of the domain in 2071 for different chloride concentrations of the river water.

Figure 4.15 shows the chloride concentration in the seepage ditch. The first 100 years of the various scenarios show different developments. In the scenarios *Criv4000* up to *Criv6000*, the chloride concentration in the ditch increases in the first 10 years, after which it temporarily decreases, and then increases again. In scenario *Criv2000* and *Criv3000*, the chloride concentration increases and after approximately 15 years the concentration stays roughly the same with a slight increase.

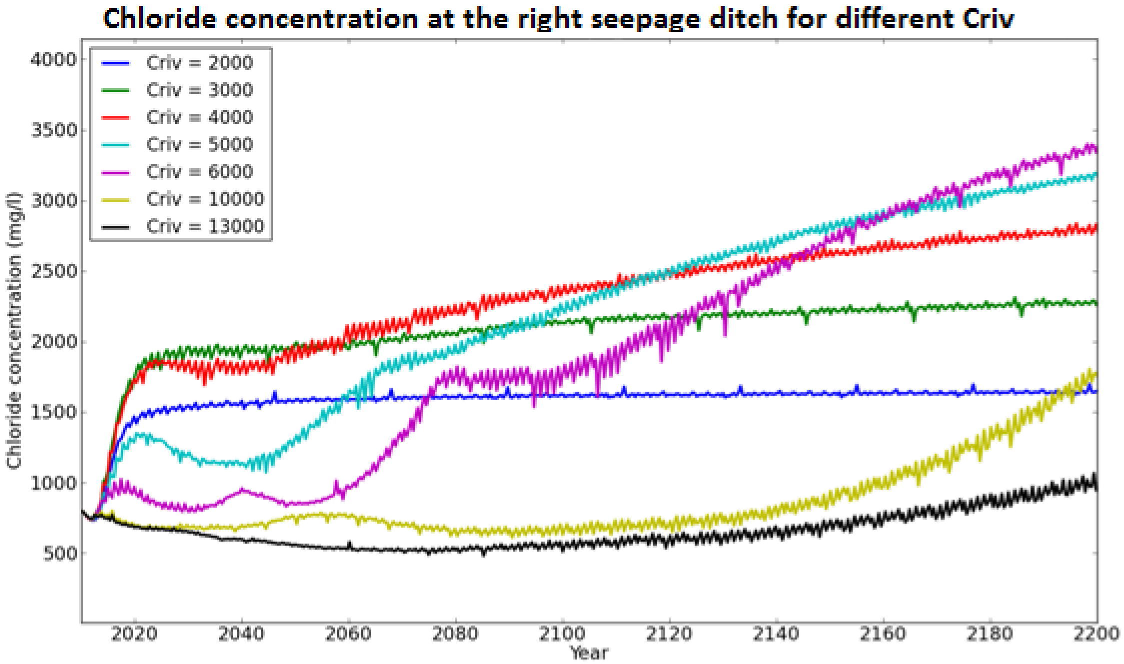
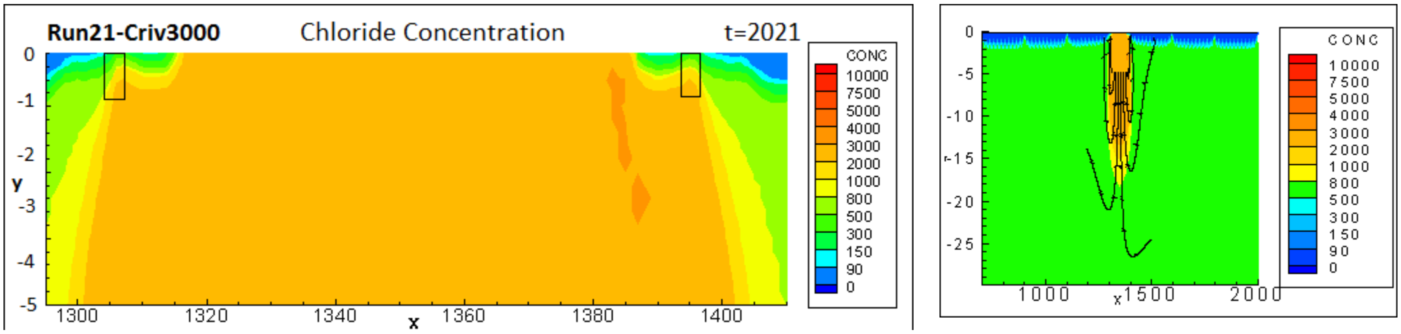


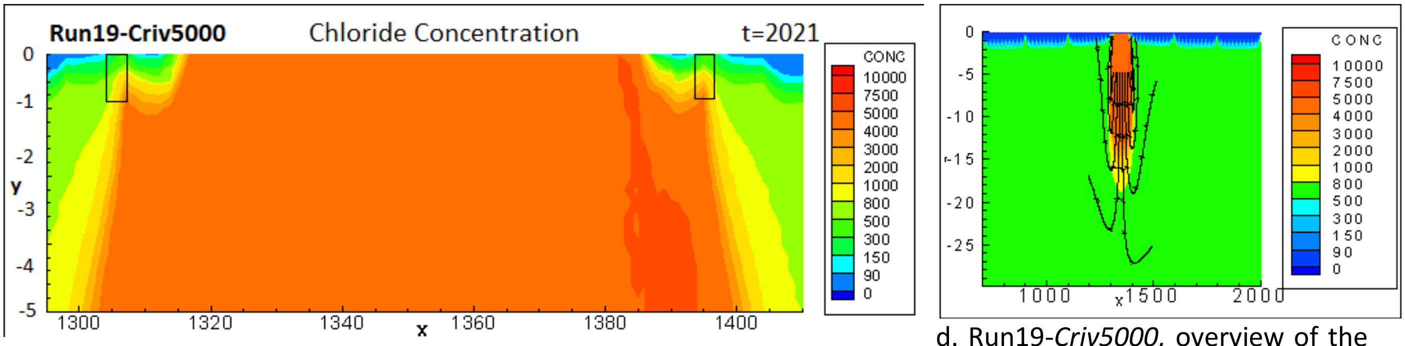
Figure 4.15 Chloride concentration in right seepage ditch.

These different developments in the first 100 years of the graph in figure 4.16 are caused by variations in water outflow from the river for the different scenarios.
Figure 4.16 shows the concentration in the seepage ditches in more detail in a 2D profile.



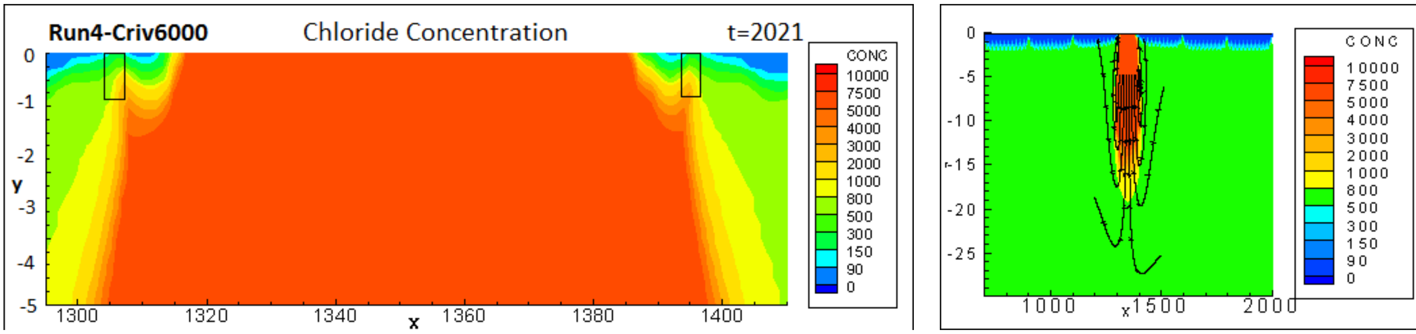
a. Run21-*Criv3000*, overview of the river and the seepage ditches for t=2021

b. Run21-*Criv3000*, overview of the whole doman for t=2021



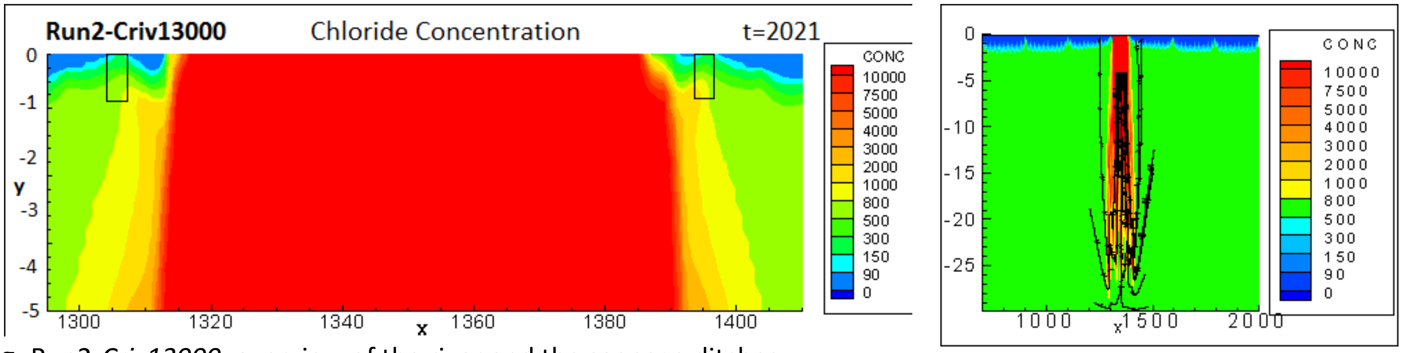
c. Run19-*Criv5000*, overview of the river and the seepage ditches

d. Run19-*Criv5000,* overview of the whole domain t=2021



e. Run4-*Criv6000*, overview of the river and the seepage ditches for t=2021

f. f. Run4-*Criv6000*, overview of the
w whole doman for t=2021



g. Run2-*Criv13000*, overview of the river and the seepage ditches for t=2021

h. Run2-*Criv13000*, overview of the whole doman for t=2021

Figure 4.16 Chloride concentration in seepage ditches in 2021 for various scenarios.

In the scenarios with low chloride concentration, the chloride from the river has spread more towards the sides. In the scenarios with high chloride concentration in the river, the salt water has spread to a lesser extent to the sides (fig. 4.16 a,c,e,g).

The overview of the whole domain to the right side of figure 4.16 shows the particles flowing out of the river. These overviews show that the higher the chloride concentration in the river; the more pronounced the flow downwards is. This is caused by the density difference between the river water and the groundwater. The larger this difference, the larger the difference in fresh water head and the larger the gravitational pull; which results in a higher vertical velocity. If there is preferential flow downwards, there is less flow to the sides, and thus a lower chloride concentration in the seepage ditches in the first 100 years.

The scenarios in the graph of figure 4.16 can be divided into 3 different cases with approximately the same behavior of water flow:

A. Scenario *Criv2000* and *Criv3000*; the concentration in the seepage ditches increases towards an approximately stable level. And thus the downward flow apparantly does not dominate the sideward flow.
B. Scenario *Criv5000* and *Criv6000*; the preferential flow downwards starts after 10 years and lasts a few decades. Then the flow to the sides of the river starts to increase again. At first the downward flow is fast as the difference in concentration is large between the water in the river and the groundwater, and thus a large difference in fresh water head. As the chloride concentration of the groundwater increases the fresh water head under the river increases too, and thus the downward flow decreases.
C. Scenario *Criv10000* and *Criv13000*; the preferential flow downwards takes approximately 100 years. In this period the difference between the fresh water head in the river and the fresh water head in the groundwater are very different due to the difference in chloride concentration between the river water and the groundwater. After this period a wide salt cone has formed under the river (fig. 4.4), and thus the the difference in fresh water head is smaller so more water flows to the sides of the river.

The behaviour of the waterflow in scenario *Criv4000* lies in between case A and case B, because after the first increase of the chloride concentration graph there is a slight decrease, whereafter the concentration increases again towards a stable level.

The behavior of the water flow from the river is thus dependent on the chloride concentration of the river water. The higher the chloride concentration of the river water, the longer the downward preferential flow. This downward flow will be explained more extensively in the next section.

Downward flow

The downward flow velocity changes over time as was seen in the former section. 13 observation points in location 1 (fig. 4.17) are used to study the downward flow. The average concentration of these observation points at 10 m under the river was taken. This average chloride concentration over time was plotted in figure 4.18.

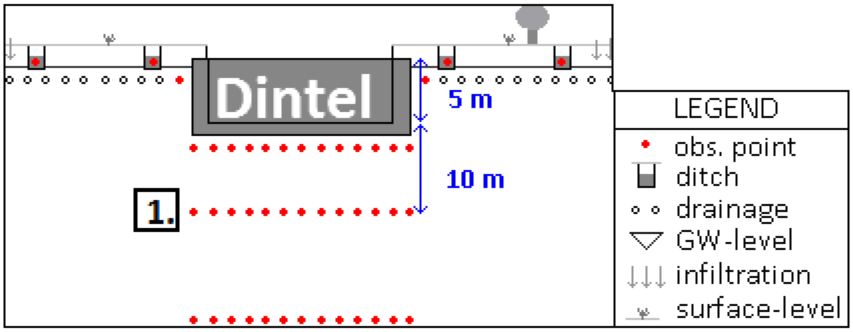


Figure 4.17 Location of the observation points

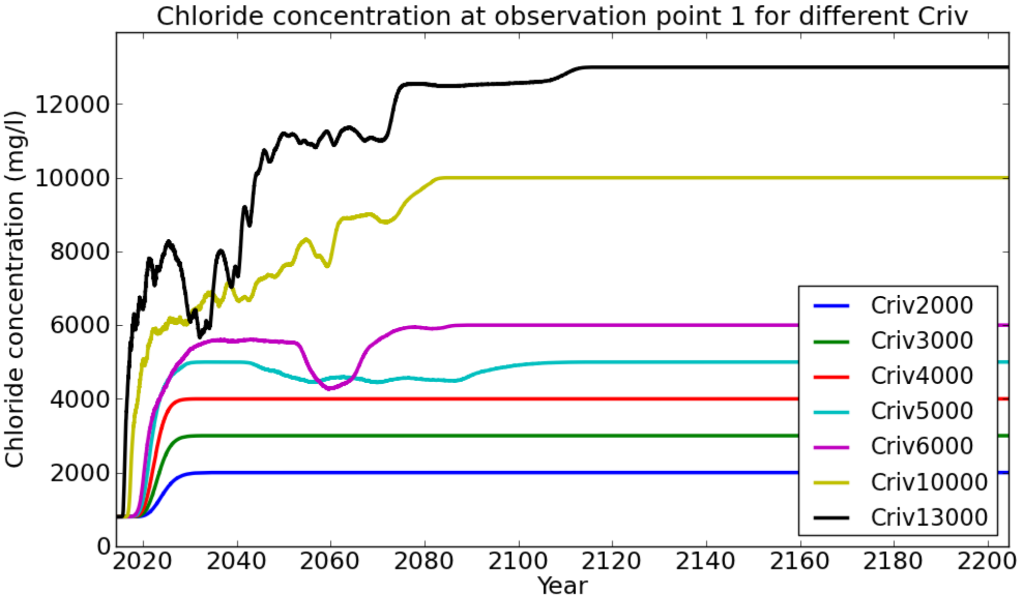


Figure 4.18 Chloride concentration at observation point 1 (fig. 4.17)

The graph shows smooth and less smooth breakthrough curves. For the scenarios *Criv2000* up to *Criv4000* the breakthrough curve is smooth. The reason for this can be seen in figure 4.19a, which shows the salt water cone in scenario *Criv2000* flowing past the observation points at location 1. The salt water flows as a cone of an approximately equal chloride concentration, and thus the breakthrough curve of the chloride concentration is smooth.

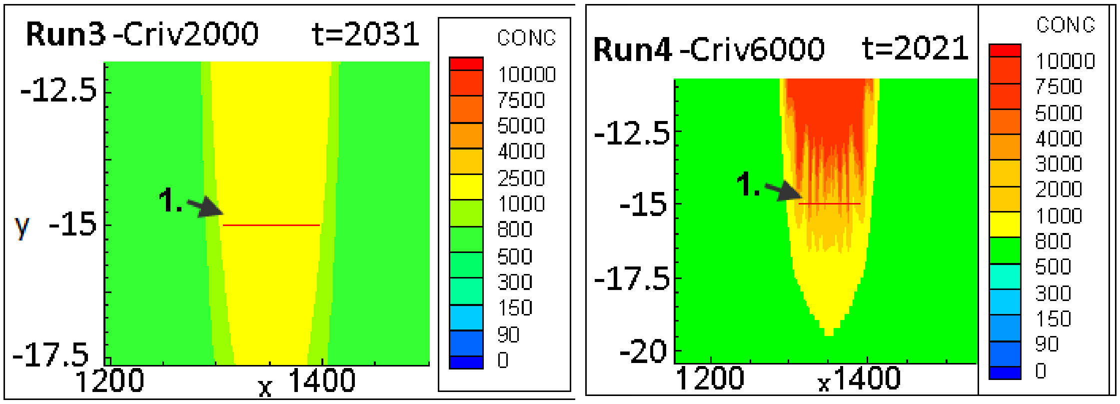


Figure 4.19a. Run3-*Criv2000* **b.** Run4-*Criv6000*

The breakthrough curves of *Criv5000* and *Criv6000* are initially more or less smooth. The salt water cones of these scenarios start having an equally spread chloride concentration in the front. Thereafter it starts to become unevenly spread as can be seen in location 1 in figure 4.19b. This causes the wobly parts in the graphs in the first decades of the model run. In 2061 there is a decrease in average concentration on location 1, as the salt water cone has broken up into salt water fingers (fig. 4.19c). These salt water fingers are rays of salt water flowing down, which means that the chloride concentration is not the same in all observation points. Therefore, the average concentration can decrease.

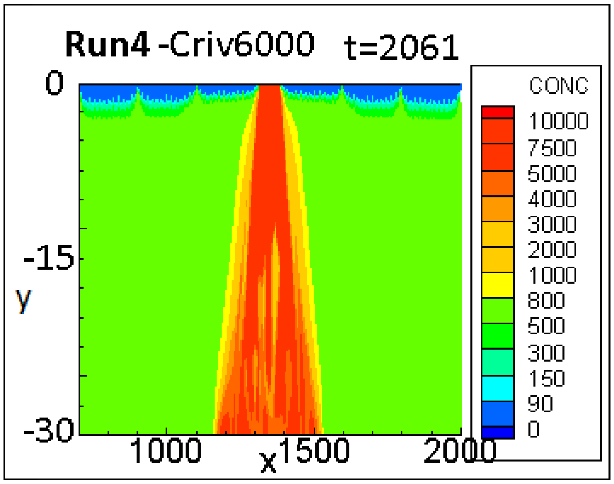


Figure 4.19c. Chloride concentration

The breaktrough curves of scenario *Criv1000* and scenario *Criv13000* fluctuate up to 2080 and 2110 respectively, which means that up to those years the water passes location 1 in finger like shapes. These salt water fingers can be seen in figure 4.20.

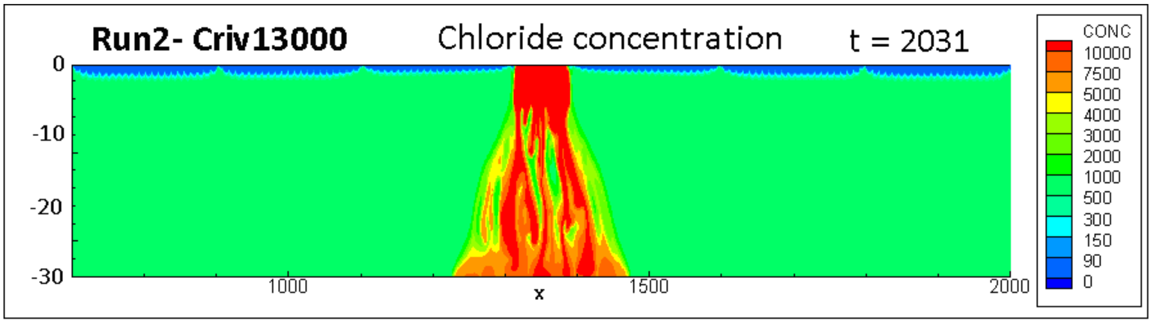


Figure 4.20 Chloride concentration for scenario *Criv13000* in 2031

The animations show that in both scenarios the salt water cone already breaks up into salt water fingers in the first couple of years of the model run.
(*Criv13000:* http://www.youtube.com/watch?v=10tIKblFIEk&feature=youtu.be)

The three cases which were discussed in the former section can be explained according to the way in which the water flows down from the river bottom:

1. In scenario *Criv2000* and *Criv3000* the water flows down in a cone and the flow towards the ditches is steady.
2. In scenario *Criv5000* and *Criv6000* the water flows down in a cone, and after approximately 12 years the cone breaks up into salt water fingers. This increases the velocity of the downward flow. The salt water from the river is pulled into the preferential downward flow, and thus the flow towards the ditches decreases. This preferential downward flow stops when the salt water reaches the bottom of the domain.
3. In scenario *Criv10000* and *Criv13000,* salt water fingers are formed in the first couple of years of the run, and thus there is preferential flow downwards and the chloride concentration in the ditches stays approximately the same. The chloride concentration in the ditches only starts increasing after approximately 150 years. And from the animation can be seen that at this moment almost all the salt water fingers flowing down have disappeared. A salt water cone was formed under the river so from the river downward there are no density differences anymore. Therefore, the preferential gravity driven vertical flow has stopped, and more water from the river is flowing sideways.

The chloride concentration of the water in the drainage pipes is given in table 4.2. The maximum chloride concentration in the drainage pipes near the river is lower when the chloride concentration of the river water is lower.

Table 4.2 Chloride concentration in the drainage pipes in the coming 200 years

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	<9000 mg/l	<800 mg/l
Run18-*Criv10000*	<6800 mg/l	<800 mg/l
Run4-*Criv6000*	<4000 mg/l	<800 mg/l
Run29-*Criv5000*	<3500 mg/l	<800 mg/l
Run12-*Criv4000*	<3000 mg/l	<800 mg/l
Run20-*Criv3000*	<2300 mg/l	<800 mg/l
Run3-*Criv2000*	<1500 mg/l	<800 mg/l

4.4 Low permeable layer under the river

4.4.1 Low permeable layer on -15 meters 'Lpl-15m_K=0.01' and 'Lpl-15m_K=0.001'

Summary

In scenario *Lpl-15m_K=0.001* and *Lpl-15m_K=0.01* the water stays on the low permeable layer in the short term. This causes a fast salinization of the seepage ditches. In the very long term the water eventually flows through the low permeable layer of K=0.01 m/day.

Short term

In the scenario *Lpl-15m_K=0.001*, the low permeable layer entirely blocks the salt water intrusion at 15 meter below ground level (fig. 4.21). The salt water cone flows down and settles on the low-permeable layer. And as the salt water does not flow down through the layer, there is a lot of flow to the sides and then upwards (fig. 4.21). The salt water cone becomes wider over time and more salt water flows upward towards the drainage pipes and the ditches.

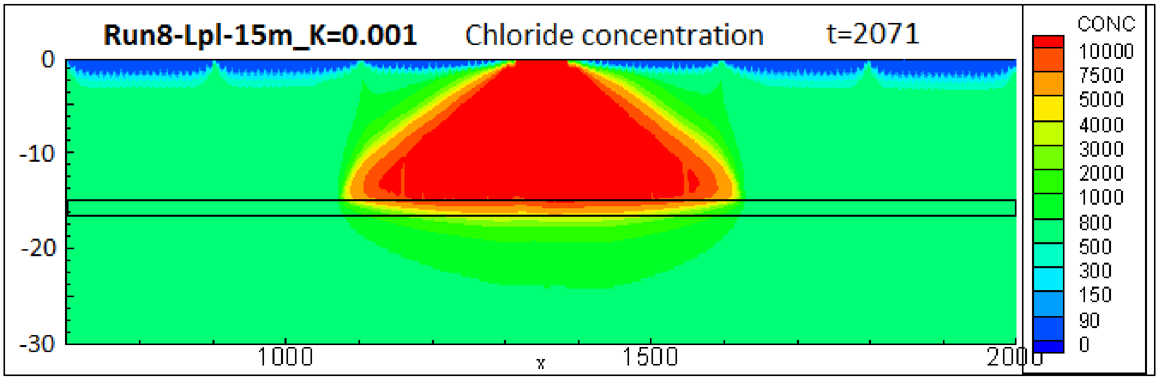


Figure 4.21 Run8- *Lpl-15m_K=0.001* in 2071, x and y-axes in meter

In scenario *Lpl-15m_K=0.01* the salt water cone also settles on the low permeable layer, however, there is salt water seeping through this layer (fig. 4.22).

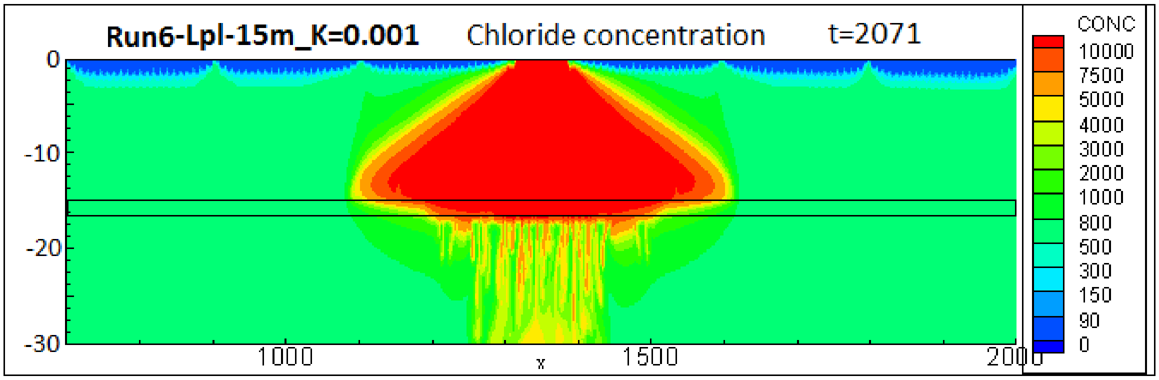


Figure 4.22 Run6- *Lpl-15m_K=0.01* in 2071

In figure 4.23 the salinization of the seepage ditches in the different scenarios was plotted. In both scenarios with a low permeable layer at -15 m, the seepage ditch salinizes faster than in scenario *Criv13000*. This is a result of less downward flow in the scenarios including a low permeable layer, as the groundwater flows quicker towards the sides and thus into the seepage ditches. The graph in figure 4.23 also shows that in scenario *Lpl-15m_K=0.001* the seepage ditch salinizes faster than the seepage ditch in scenario *Lpl-15m_K=0.01*. This is caused by the fact that in scenario *Lpl-15m_K=0.01* there is still groundwater flowing down through the layer at -15 m. In scenario *Lpl-15m_K=0.001* there is hardly any groundwater flow through the layer at -15 m. Comparing figure 4.21 and figure 4.22, you can see that there is more downward flow in scenario *Lpl-15m_K=0.01*. So in scenario *Lpl-15m_K=0.001* there is more water flowing towards the seepage ditches.

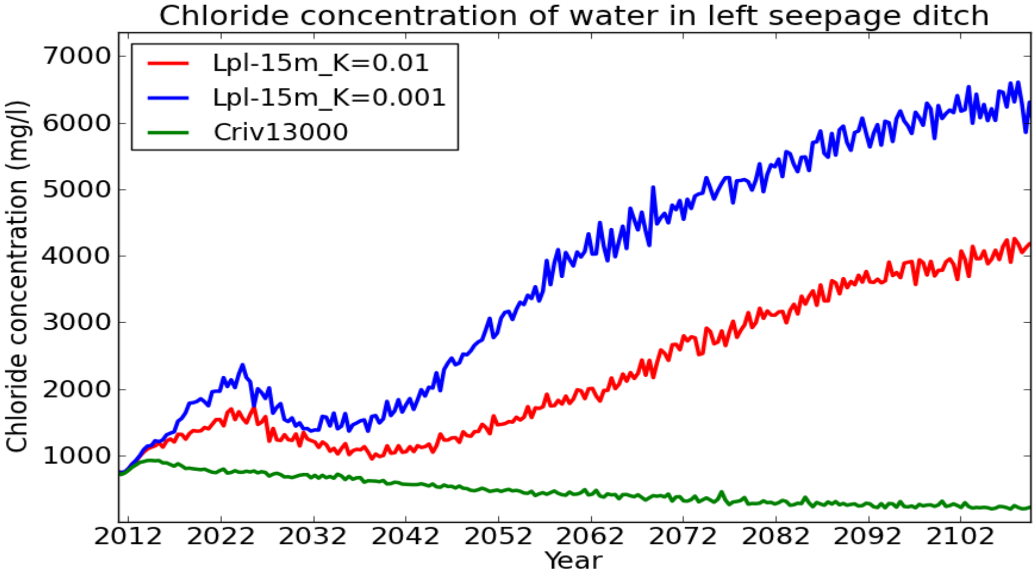


Figure 4.23 Chloride concentration in the left seepage ditch

The ditches next to the seepage ditches (at 209 m from the river) in scenario *Lpl-15m_K=0.01* and scenario *Lpl-15m_K=0.001* also salinize more than in scenario

Criv13000. In the first 200 years of the model run their maximum concentration becomes 1200 mg Cl/l.

Long term

On the long term the salt water seeps through the layer with K=0.01 m/day. This is shown in figure 4.24. Figure 4.25 shows that the layer with a hydraulic conductivity 0.001 m/day blocks the salt water from seeping through. Only very little salt water flows through the low permeable layer in 900 years.

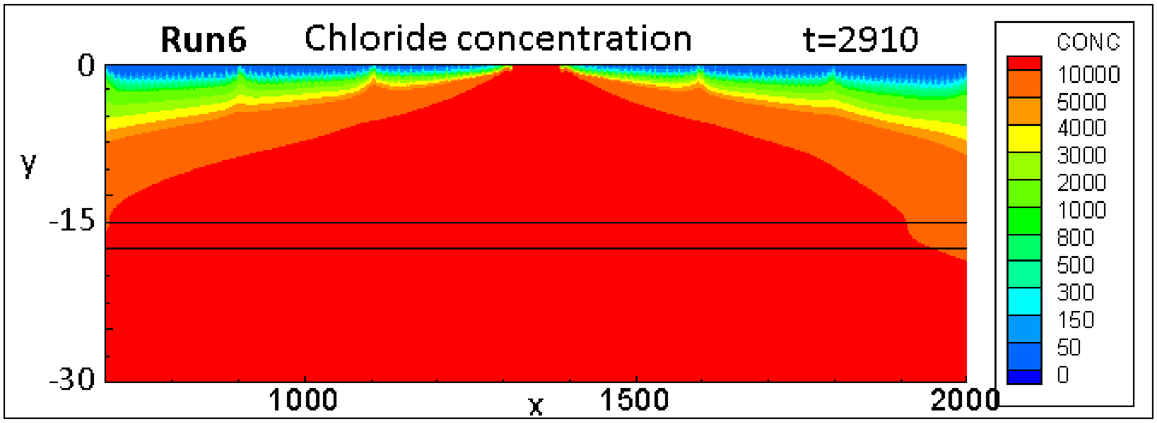


Figure 4.24 Chloride concentration in scenario Run6-*Lpl-15m_K=0.01* in 2910

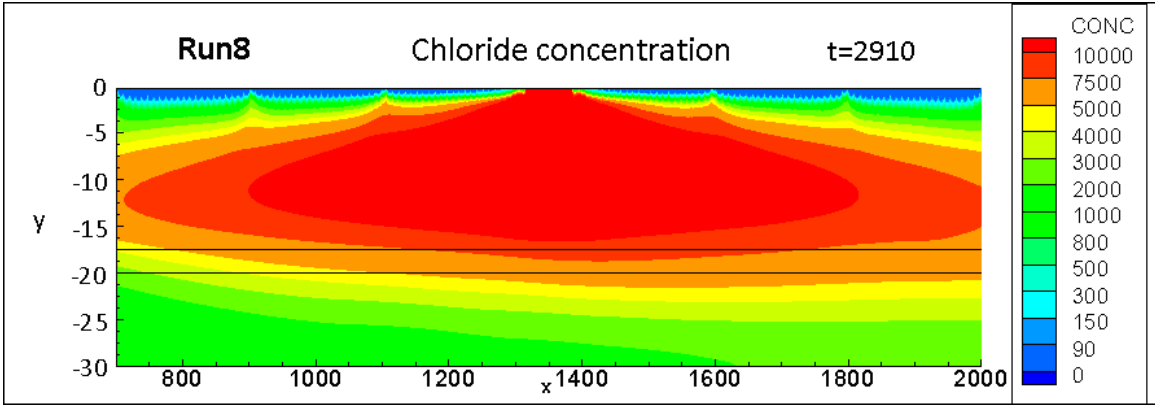


Figure 4.25 Chloride concentration in scenario Run8-*Lpl-15m_K=0.001* in 2910

The water in the drainage pipes in scenario *Lpl-15m_K=0.001* and scenario *Lpl-15m_K=0.01* has approximately the same chloride concentration as in scenario *Criv13000* over the very long term (table 4.3).

Table 4.3 Chloride concentration in the drainage pipes in 1000 years

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	<9000 mg/l	<800 mg/l
Run6- *Lpl-15m_K=0.01*	<9000 mg/l	<800 mg/l
Run8- *Lpl-15m_K=0.001*	<9200 mg/l	<800 mg/l

4.4.2 Low permeable layer on -4 meters ‘Lpl-4m_K=0.01’ and ‘Lpl-4m_K=0.001’

Summary

In scenario *Lpl-4m_K=0.01* part of the salt water is flowing through the low permeable layer. The low permeable layer in scenario *Lpl-4m_K=0.001* blocks a large part of the salt water from flowing out of the river. The seepage ditch of scenario *Lpl-4m_K=0.01* thus salinizes faster than in scenario *Lpl-4m_K=0.001,* but eventually the concentrations are approximately equal.

On the long term the whole domain of scenario *Lpl-4m_K=0.01* salinizes, while in scenario *Lpl-4m_K=0.001* only a small fraction of the salt water flows through the low permeable layer.

Short term

Similar to the scenarios in the previous section; the layer in scenario *Lpl-4m_K=0.001* blocks more water than the layer in scenario *Lpl-4m_K=0.01*. In scenario *Lpl-4m_K=0.001*, a small amount of salt water seeps through the low permeable layer (fig. 4.26). The salt water flows through the sides of the river and a salt water cone settles on the low permeable layer under the river. This salt water cone widenes over the years.

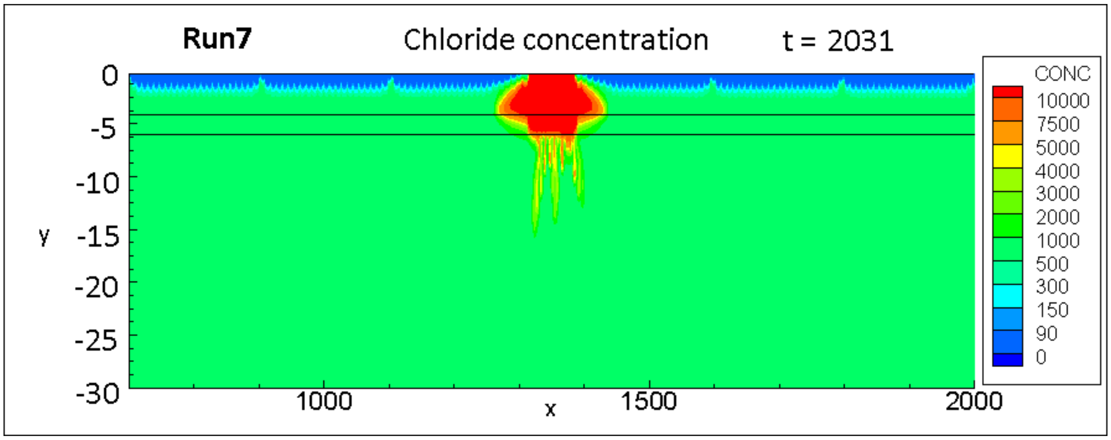


Figure 4.26a. Chloride concentration in scenario *Lpl-4m_K=0.001* in 2031

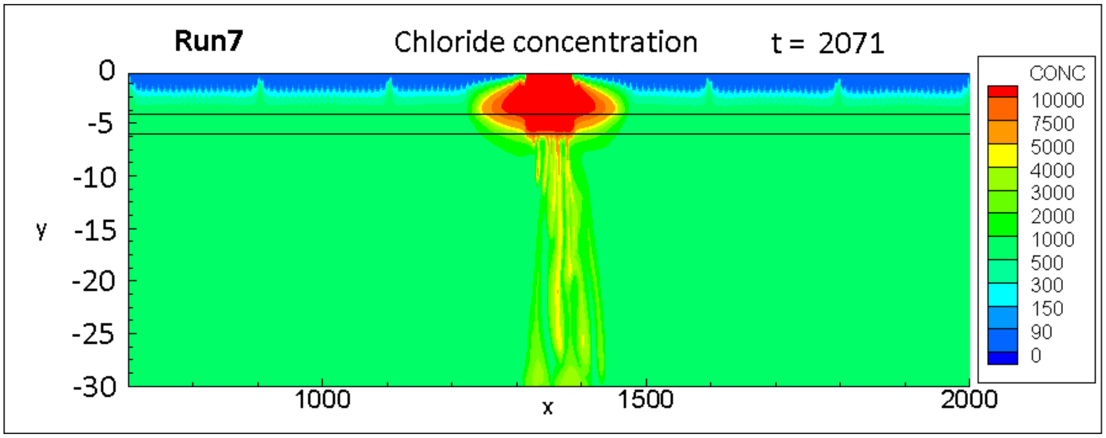


Figure 4.26b. Chloride concentration in scenario *Lpl-4m_K=0.001* in 2071

In scenario *Lpl-4m_K=0.01*, there is more groundwater seeping through the low permeable layer at -4 m below ground level (fig. 4.27) than in *Lpl-4m_K=0.001 (*fig. 4.26). The salt water cone which has settled on the low permeable layer has approximately the same shape for both scenarios in 2071.

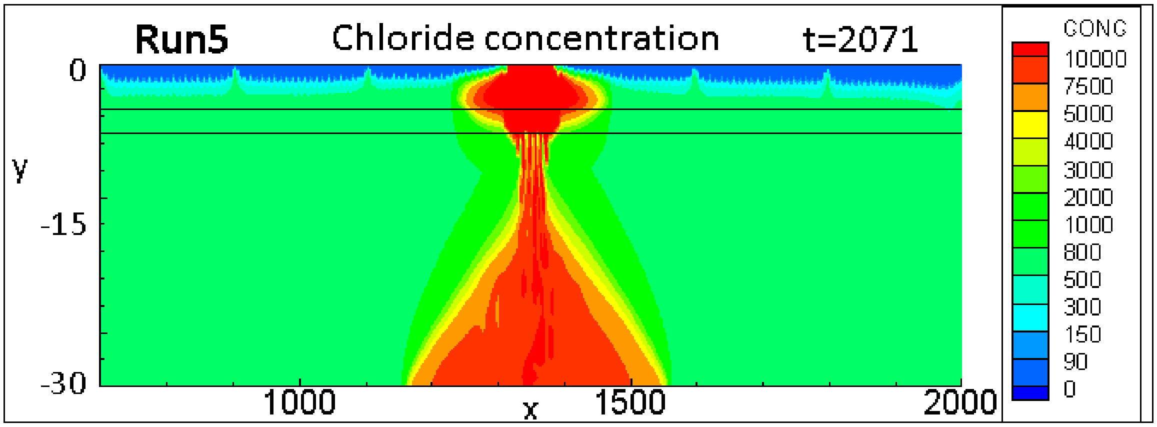


Figure 4.27 Chloride concentration in scenario *Lpl-4m_K=0.01* in 2071

The seepage ditch salinizes faster in scenario *Lpl-4m_K=0.01* than in scenario *Lpl-4m_K=0.001* (fig. 4.28). Particle tracking shows that around 2020 there is more flow towards the sides parralel to the low permeable layer in scenario *Lpl-4m_K=0.01* than in scenario *Lpl-4m_K=0.001*. This is because the low permeable layer of K=0.001 m/day is at the same level as the bottom of the river, and blocks the salt water from flowing out of the river. And thus in scenario *Lpl-4m_K=0.01* more water is flowing out of the river into the seepage ditches.

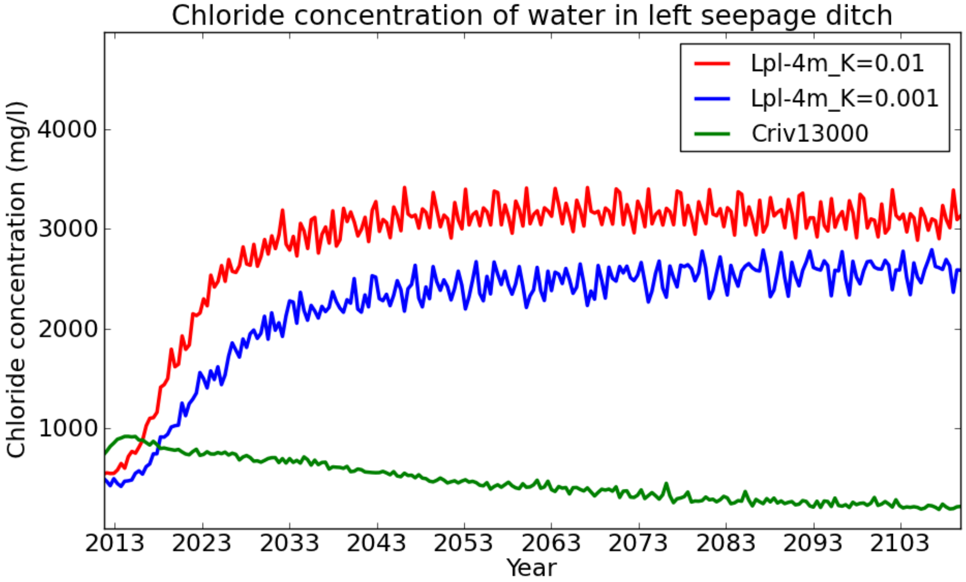


Figure 4.28 Concentration in the left seepage ditch for scenario *Lpl-4m_K=0.01* and *Lpl-4m_K=0.001*

Long term

On the long term, salt groundwater seeps through the low permeable layer with an hydraulic conductivity of 0.01 m/d (fig. 4.29), like in scenario *Lpl-15m_K=0.01*.

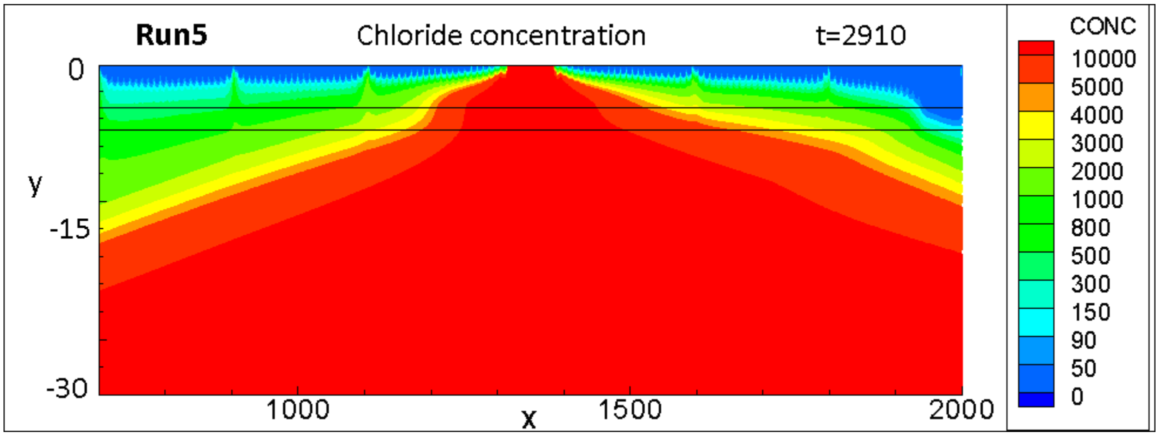


Figure 4.29 Chloride concentration in scenario *Lpl-4m_K=0.01* in 2910

In scenario *Lpl-4m_K=0.001* there is also some salt water seeping through the low permeable layer (fig. 4.30).

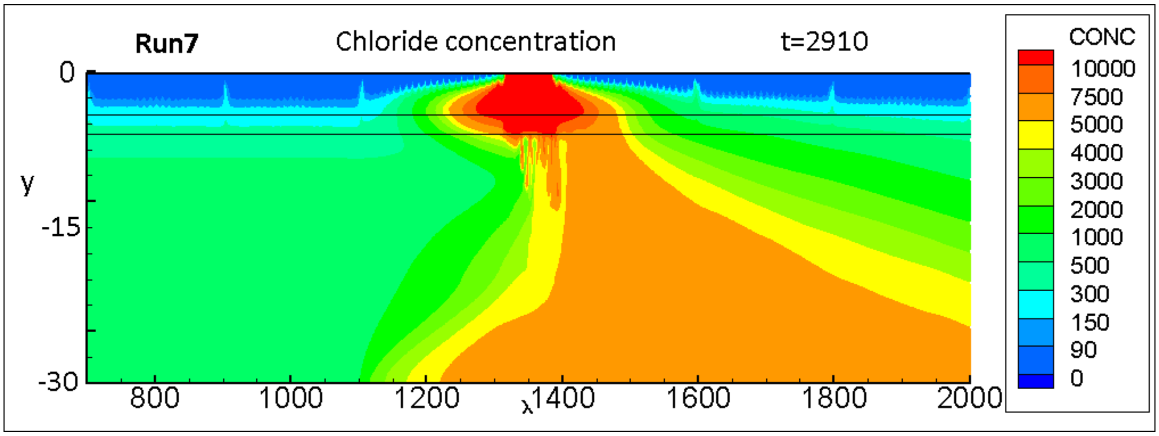


Figure 4.30 Chloride concentration in scenario *Lpl-4m_K=0.001* in 2910

The water that is seeping through the low permeable layer flows to the right side of the domain. This is caused by the presence of the low permeable layer at -4 m, which makes the top boundary less important for the groundwater head under the layer. And thus, the water under the low permeable layer flows towards the boundary with the lowest groundwater head. This can be seen in figure 4.31, wherein the fresh water head is visualized.

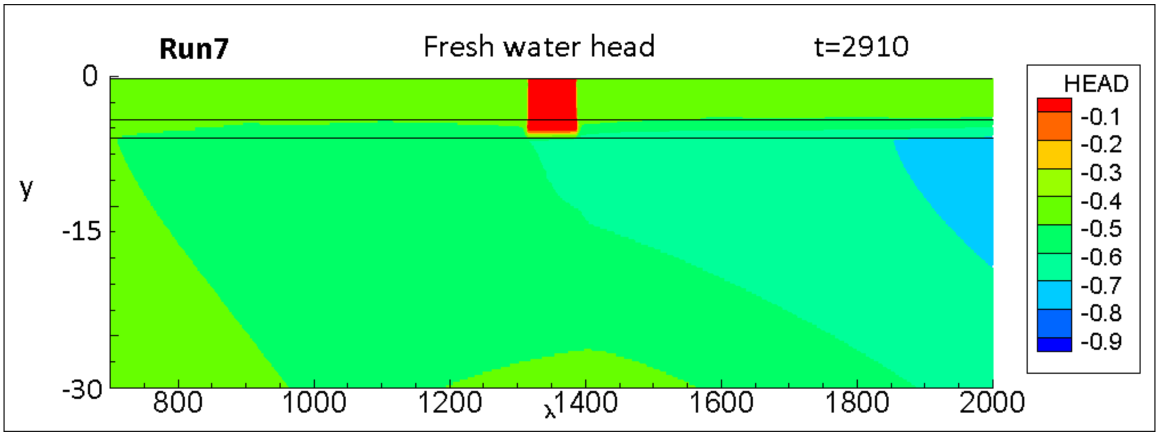


Figure 4.31 Fresh water head (m) in scenario *Lpl-4m_K=0.001* in 2910

The chloride concentrations in the drainage pipes in scenario *Lpl-4m_K=0.001* and in scenario *Lpl-4m_K=0.01* show on the long run the same values as the chloride concentration in the drainage pipes in scenario *Criv13000.*

Table 4.4. Chloride concentration in the drainage pipes in 1000 years

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	<9000 mg/l	<800 mg/l
Run6- *Lpl-4m_K=0.01*	<9000 mg/l	<800 mg/l
Run8- *Lpl-4m_K=0.001*	<9000 mg/l	<800 mg/l

4.5 Varying the hydraulic resistivity of the drains 'Cdr=2d'

Summary

When the hydraulic resistivity of the drains decreases, more water flows into the drainage system. Furthermore, the difference in the head between the river and the groundwater increases, and thus more water flows out of the river and the ditches. The chloride concentration in the drainage pipes near the river will reach a maximum of 9000 mg/l, further away from the river the concentration stays 800 mg/l in the drainage pipes.

Short term

In this scenario the hydrualic resistivity of the drains is 2 days whereas in *Criv13000* the hydraulic resistivity of the drainage system is 10 days; which means that the drains are more active in scenario *Cdr=3d*. Figure 4.32 shows the spreading of the chloride concentration in 2031 for scenario *Cdr=2d*. In figure 4.32 it can be seen that the thickness of the shallow fresh water lens near ground level has decreased significantly when comparing scenario *Cdrn=2d* with scenario *Criv13000* (fig. 4.33). In scenario *Cdrn=2d* this layer is smaller than 1 meter on average, and in scenario *Criv13000* this layer is 1.5 m thick on average. This is caused by the decrease in hydraulic resistivity in scenario *Cdrn=2d.* This decreased hydraulic resistivity pulls more of the groundwater into the drainage pipes, so the division between fresh and salt water lies at the same level as the drainage pipes.

In scenario *Cdrn=2d* the water from the middle of the domain flows upwards into the drainage pipes (fig. 4.32). In *Criv13000*, the water from the middle of the domain flows into the ditches, which can be seen in figure 4.33. This difference in flow pattern is a result of the change in fresh water head in scenario *Cdr=2d.*

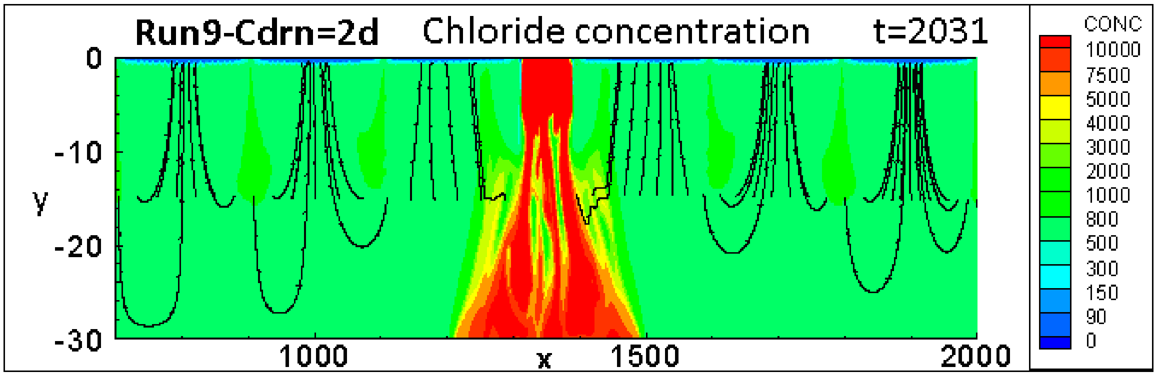


Figure 4.32 Chloride concentration for scenario *Cdrn=2d* in 2031

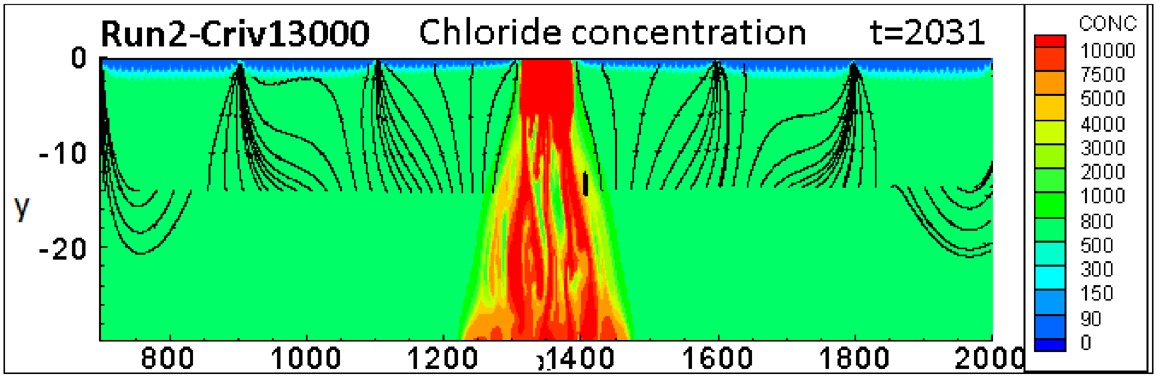


Figure 4.33 Chloride concentration for scenario *Criv13000* in 2031

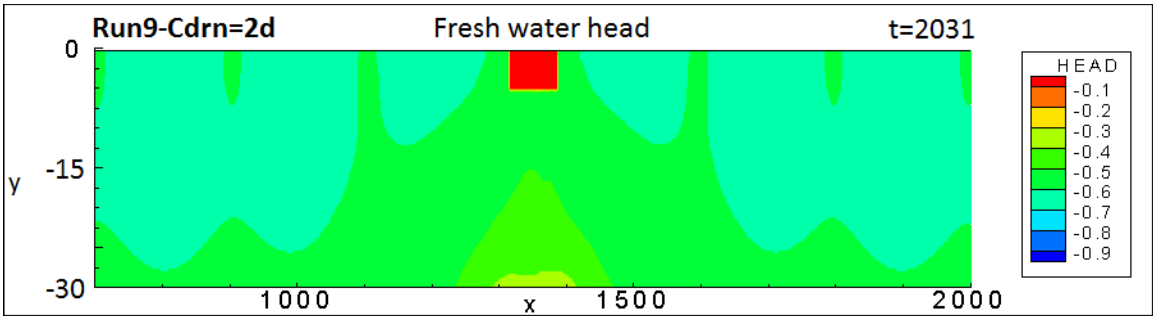


Figure 4.34 Fresh water head for scenario *Cdrn=2d* in 2031

Figure 4.34 shows the distribution of the fresh water head in scenario *Cdr=2d.* In this figure it is clearly visible that the drainage pipes influence the fresh water head from the top downward as the drain level is -0.7 m NAP. The average fresh water head in the domain is lower than in scenario *Criv13000.* And therefore, the head difference between the rivers and the domain increased, and thus there is more water flowing out of the river and the ditches into the groundwater. Table 4.5 quantitatively shows these differences in water flow between scenarios *Criv13000* and *Cdrn=2d*. The cumulative inflow and outflow volumes for stress period 21 are given, and their corresponding percentages of the total.

Table 4.5 Cumulative volumes of the inflow and outflow in stress-period 21 (2031)

INFLOW				
	Criv13000		*Cdr=2d*	
	Volume (m^3/m)	Percentage	Volume (m^3/m)	Percentage
Recharge	139 x 10^2	75.92%	139 x 10^2	44.85%
River leakage	41 x 10^2	22.56%	154 x 10^2	49.70%
Head dep bounds	3 x 10^2	1.5%	17 x 10^2	5.45%
TOTAL	183 x 10^2	100%	310 x 10^2	100%
OUTFLOW				
Drains	131 x 10^2	71.72%	269 x 10^2	86.90%
Rivers	30 x 10^2	16.06%	21 x 10^2	6.7%
Head dep bounds	22 x 10^2	12.21%	20 x 10^2	6.4%
TOTAL	183 x 10^2	100%	310 x 10^2	100%

This table shows that in scenario *Cdrn=2d*; there is two times more groundwater flowing into the drainage system in scenario *Criv13000* than in scenario *Cdr=2d*, whereas this is also a larger percentage of the total outflow.

Furthermore, there is four times more water flowing into the domain from the rivers in scenario *Cdr=2d*. This is half of the total volume of water flowing into the domain, while in scenario *Criv13000*, only a quarter of the water flowing in comes from the rivers. This increase in inflow from the rivers is caused by the increase in difference in head between the river and the groundwater system as was explained earlier in this section.

Overall there is in total a larger volume of inflow and outflow in scenario *Cdrn=2d*. As there is salt water flowing from the ditches and the river into the domain, and more groundwater flowing through the drainage pipes out of the domain; the groundwater salinizes faster in scenario *Cdr=2d* than in scenario *Criv13000*. Table 4.6 shows this quantitatively as it gives the total volume of water after 21 years of running the model.

Table 4.6 Fresh, brackish and salt water in the domain in 2031

	Fresh water (m^3/m) (<=300 mg/l)	**Brackish water (m^3/m) (<=3000 mg/l)**	**Salt water (m^3/m) (<=13000 mg/l)**
Run2-*Criv13000*	1665	21478	1157
Run9-*Cdr=2d*	678	22348	1274

There is more fresh water in the domain in scenario *Criv13000.* Moreover, there is less brackish and salt water in *Criv13000* than in scenario *Cdr=2d.*

The chloride concentration of the water in the drainage pipes is maximum 800 mg/l over the whole domain. Except for the drainage pipes close to the river; in these drainage pipes the water has a chloride concentration of maximum 9000 mg/l.

In all ditches the chloride concentration of the water stays 800 mg/l over time.

4.6 Varying hydraulic conductivity of the river bottom 'Kriv=0.1m/d' and 'Kriv=0.001m/d' (in ref. case *Criv13000* Kriv=0.01m/d)

Summary

The hydraulic conductivity of the silt layer around the river bottom is of large influence on the velocity of the salt water intrusion from the river into the groundwater. When the hydraulic conductivity is 0.1 m/d, there is a lot of salt water flowing out of the river which salinizes the water in the drainage pipes and the seepage ditches quickly. When the hydraulic conductivity is 0.001 m/d, there is hardly any salt water seeping out of the river, and thus the water in the seepage ditches and drainage pipes does not salinize.

Short term

In scenario *Kriv=0.001m/d* there is hardly any salt water seeping into the groundwater (fig. 4.35). Thus the low permeable silt layer around the river stops most of the salt water from seeping through the river bottom and the sides of the river. This was also seen earlier in scenario *Lpl-4m_K=0.001;* wherein hardly any salt water seeps through the low permeable layer.

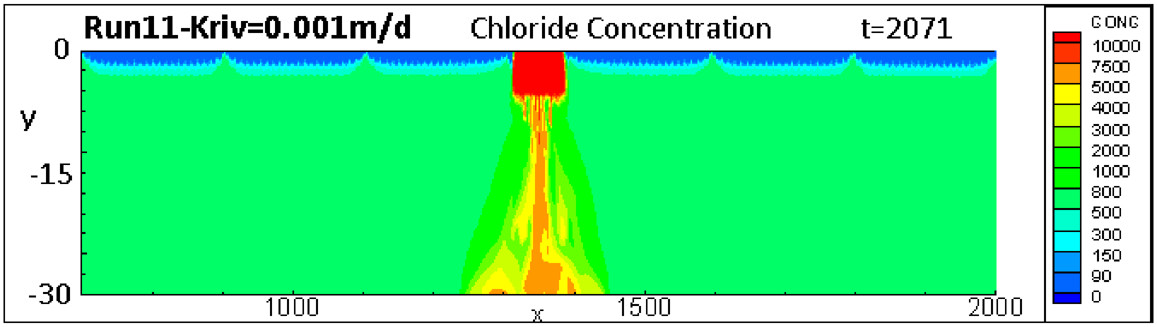


Figure 4.35 Chloride concentration (mg/l) in scenario *Kriv=0.001m/d* in 2071, x and y axes in m

In scenario *Kriv=0.1m/d* there is more salt water flowing out of the river than in scenario *Criv13000* with Kriv=0.01m/d (fig. 4.36). The salt plume under the river is very wide from the top. In the animation can be seen that water from the river flows both through the side of the river sideways, and through the bottom of the river downward. In 2071 the salt water cone under the river is clearly much larger than in scenario *Criv13000* (fig. 4.36 and 4.37).

The animation of *Run12-Kriv=0.1m/d* can be found online on the following link:

http://www.youtube.com/watch?v=10aXDXh4U4w&feature=youtu.be

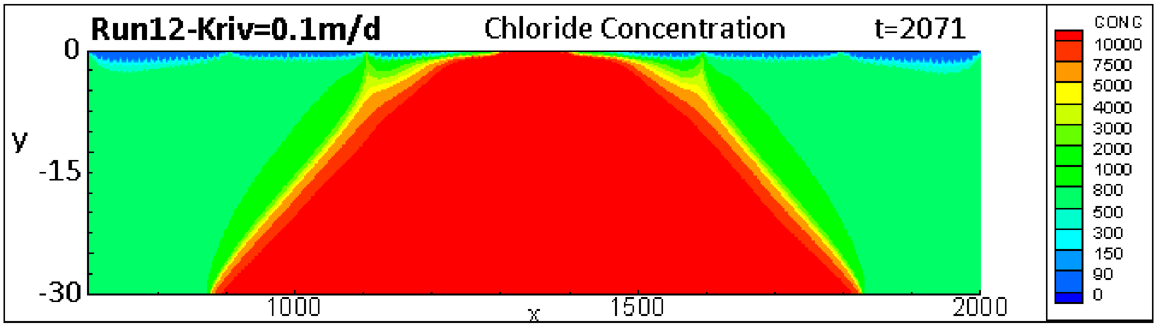


Figure 4.36 Chloride concentration in scenario *Kriv=0.1m/d* in 2071

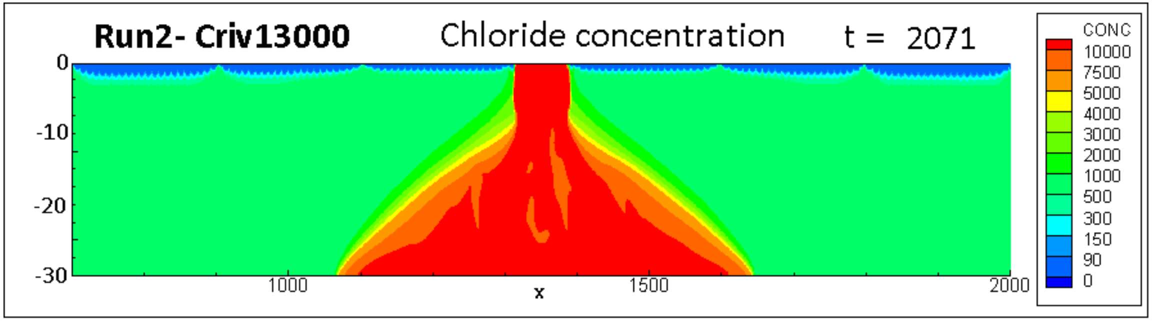


Figure 4.37 Chloride concentration in scenario *Criv=13000* (Kriv=0.01m/d) in 2071

In scenario *Kriv=0.1m/d,* the seepage ditch next to the river salinizes very quick; in the first couple of years the chloride concentration in the ditch increases to approximately 12000 mg/l (fig. 4.38). However, when the hydraulic conductivity of the river bottom is small, like in scenario *Kriv=0.001m/d,* there is no salinization of the seepage ditches in the first 100 years of the model run.

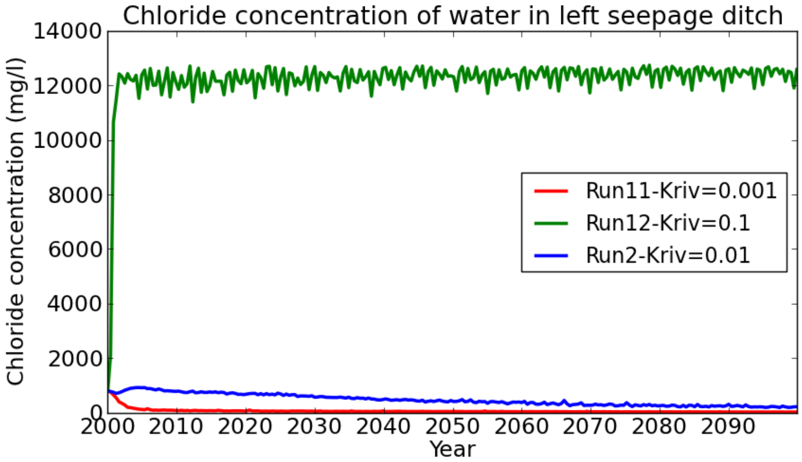


Figure 4.38 The chloride concentration in the left seepage ditch

The chloride concentration for all the ditches in the domain of *Kriv=0.1m/d* is plotted in figure 4.39. This graph shows an increase for the ditches next to the seepage ditches after 2050 (1105 m and 1596 m). The maximum concentration in the ditch at 1596 m is just over 2000 mg/l. After 2070, the chloride concentration in this ditch starts decreasing again. This is possibly caused by the downward pulling effect of the right boundary of the domain. This pulling effect is possibly the reason that the water at the right side of the domain flows down after approximately 2070, and thus that the concentration in the ditch at 1596 m, at the right side of the river, decreases after 2070.

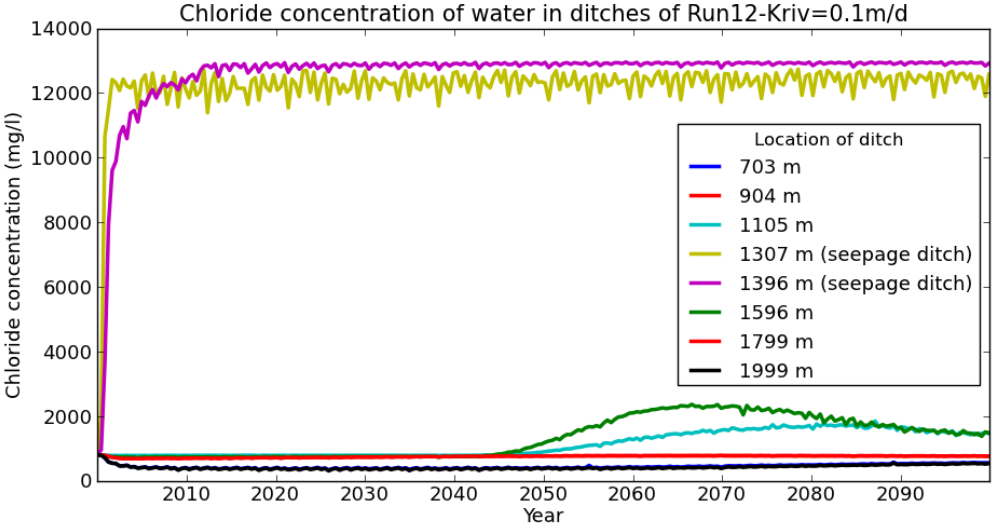


Figure 4.39 Chloride concentration in the ditches *Kriv=0.1m/d*

The chloride concentration of the water in drainage pipes near the river in scenario *Kriv=0.1m/d* reaches a level of 13000 mg/l. This can be seen in figure 4.36, as the salt water next to the river is very close to ground level.

4.7 Increase of the waterlevel in the ditches

4.7.1 Scenario 'WLditch=0mNAP'

Summary

An increase of the water level in the ditches from -0.5 m NAP to 0 m NAP increases the fresh water head in the domain. And thus there is less water from the river flowing into the groundwater and therefore there is a smaller salt water volume in the domain.

Short term

The increase in waterlevel of the ditches has a large influence on the shape of the salt water cone in the groundwater (fig. 4.40).

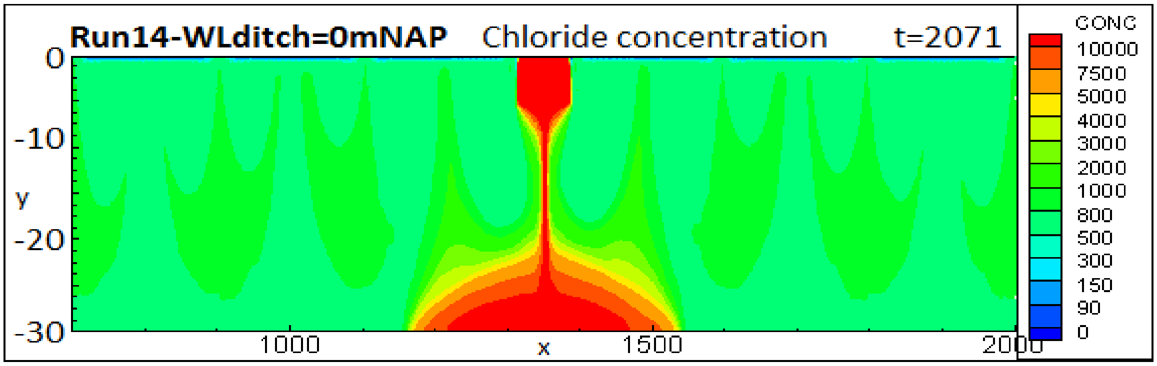


Figure 4.40 Chloride concentration in scenario *WLditch=0mNAP* in 2071

This is caused by the increase in waterlevel in the ditches to 0 m NAP, which is the same water level as the river. This causes a change in the fresh water head in the domain (fig. 4.41). The head in the largest part of the domain is between -0.1 and -0.2 m NAP, wheras in the reference case *Criv13000* the fresh water head in the largest part of the domain is between -0.4 and -0.5 m NAP in 2071 (fig. 4.43). This proves the dominance of the waterlevel in the ditches on the fresh water head in the domain which was also seen before in scenario *Criv13000*. In figure 4.41 can also be seen that drainage pipes in between the ditches influence the fresh water head.

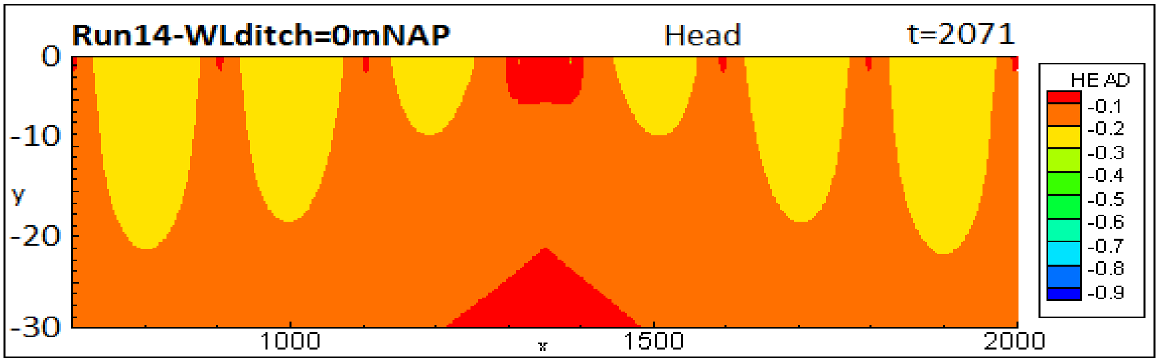


Figure 4.41 Fresh water head (m) in scenario *WLditch=0mNAP in* 2071

The salt water cone in figure 4.40 is smaller than the salt water cone in scenario *Criv13000* in 2071 (fig. 4.42), and thus there is less salt water present in the domain

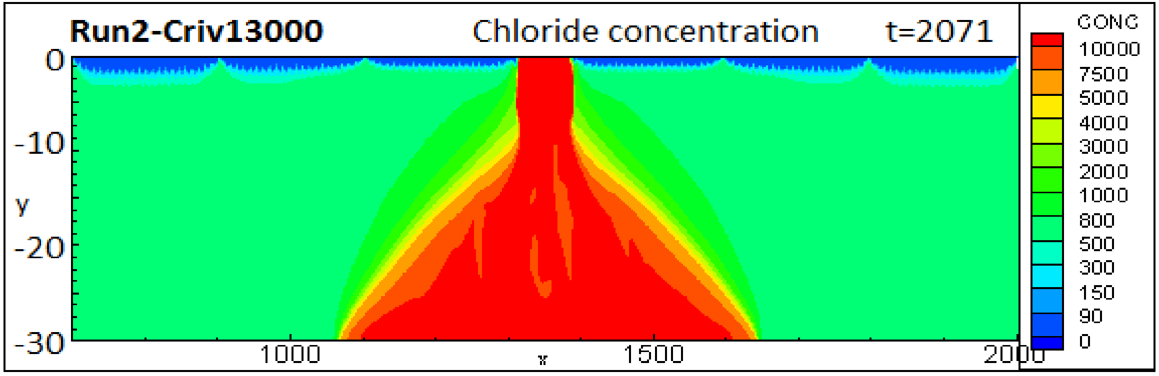


Figure 4.42 Chloride concentration in scenario *Criv13000* in 2071

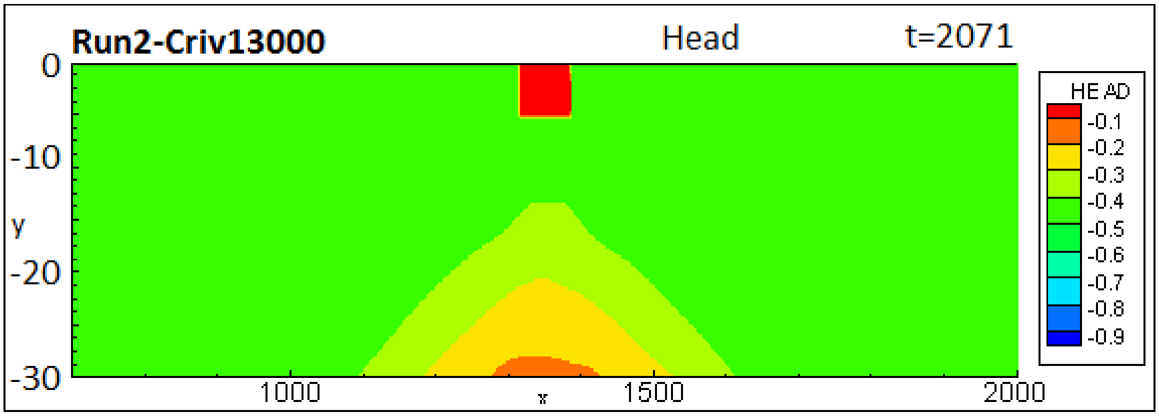


Figure 4.43 Chloride concentration in scenario *Criv13000* in 2071

which also shows in table 4.7. In this table the total salt water volume in the domain for scenario *Criv13000* and scenario *WLditch=0mNAP* is presented. There is also a smaller volume of fresh water in the domain in scenario *WLditch=0mNAP,* than in scenario *Criv13000.* This is due to the fact that there is more salt water leaking out of the river in scenario *Criv13000* than in scenario *WLditch=0mNAP.* This can be seen in table 4.8, which shows the inflow and outflow of river water in both scenarios.

Table 4.7 Volumes of fresh, brackish and salt water in 2071

	Fresh water (m^3/m) (<=300 mg/l)	**Brackish water (m^3/m) (<=3000 mg/l)**	**Salt water (m^3/m) (<=13000 mg/l)**
Run2-*Criv13000*	2480	19189	2631
Run14- *WLditch=0mNAP*	404	22876	1020

Table 4.8 Volume (m^3/m) in and out by river leakage in stress period 1

	Run2-*Criv13000* (m^3/m)	**Run14- *WLditch=0mNAP* (m^3/m)**
River leakage – IN	1153	196
River leakage – OUT	123	144

The larger volume of river water leaking into the domain in scenario *WLditch=0mNAP* is coming from the ditches; as their waterlevel has increased. Consequently, in scenario *WLditch=0mNAP,* there is a larger volume of brackish water in the domain, which is the water from the ditches with a chloride concentration of 800 mg/l.

The total volume of salt water is larger in scenario *Criv13000* than in scenario *WLditch=0mNAP* (table 4.7). This is visible as there is a larger salt water cone under the river in scenario *Criv13000* (see figure 4.41 and 4.43). The fresh water head of the domain in scenario *Criv13000* is lower than in scenario *WLditch=0mNAP,* because the fresh water head of the latter is increased by the waterlevel in the ditches. Therefore, there is more water flowing out of the river in scenario *Criv13000* than in scenario *WLditch=0mNAP.*

In scenario *WLditch=0mNAP* the chloride concentration in the ditches of the domain stays 800 mg/l over time, as the ditch water is flowing out of the ditches into the domain. And thus even the seepage ditches do not salinize as the chloride concentration stays 800 mg/l.

The chloride concentration in the drainage pipes near the river increases in 200 years to approximately 6000 mg/l. In *Criv13000* this is higher as in this scenario there is more salt water from the river flowing to the sides (see figure 4.40 and 4.42). In the drainage pipes in the rest of the domain the chloride concentration stays around 800 mg/l over time, as this is the concentration of the groundwater in the domain that is flowing into the drainage pipes.

4.7.2 Scenario ‘WLditch=-0.3mNAP’ (Ref. case ditch level= -0.5 m NAP)

The salt water cone in scenario *WLditch=-0.3mNAP* in the year 2071 (fig. 4.44) has an intermediate shape in between the shape of the cone in *Criv13000* (fig. 4.42) and *WLditch=0mNAP* (fig. 4.40). In figure 4.44 can be seen that there is salt water flowing out of the ditches into the groundwater system because of the higher fresh water head in the ditches, than the fresh water head of -0.45 m in the rest of domain. And thus all the ditches including the seepage ditches do also not salinize until 2110 in this scenario as was seen from a the graph showing the chloride concentration in the seepage ditches until 2010.

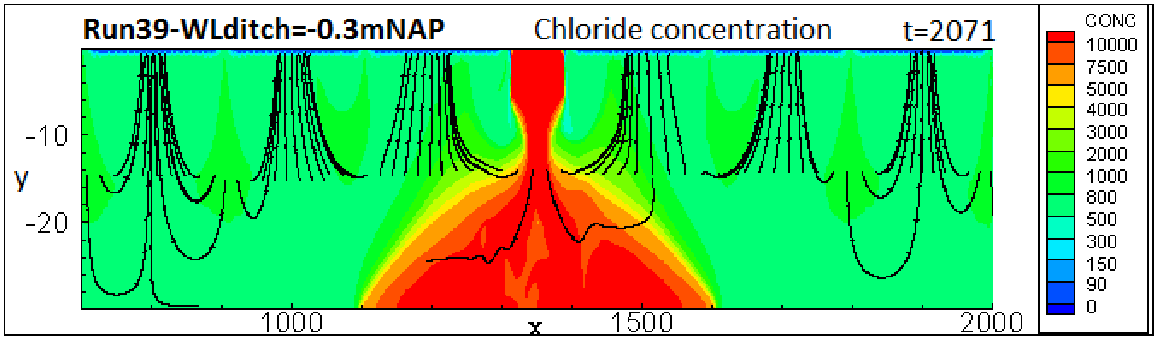


Figure 4.44 Chloride concentration in scenario *WLditch=-0.3mNAP* in 2071

4.7.3 Scenario ‘WLditch=-0.4mNAP’

In scenario *WLditch=-0.4mNAP,* the waterlevel in the ditches is 0.1 m higher than in *Criv130000*. Figure 4.45 shows the chloride concentration in the domain in scenario *WLditch=-0.4mNAP* in 2071. There is still brackish water flowing out of the ditches as their waterlevel is 0.05 m higher than the groundwater head.

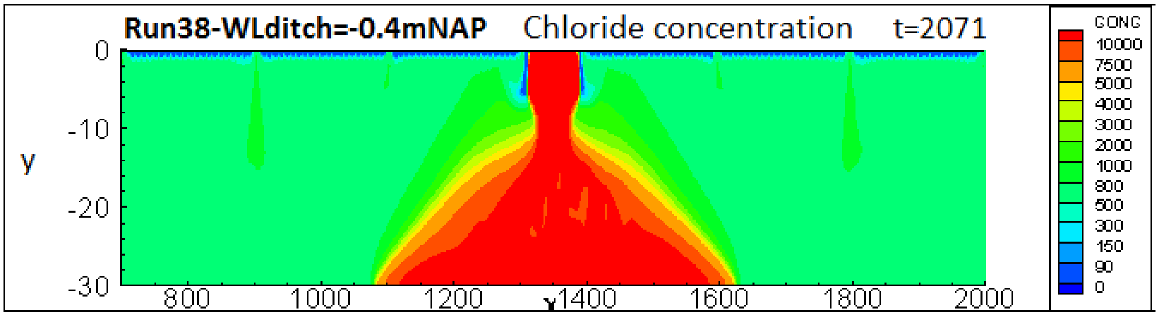


Figure 4.45 Chloride concentration in scenario *WLditch=-0.4mNAP* in 2071

In figure 4.45 there is a fresh water cone on both sides of the river. This cone develops as brackish water is flowing out of the seepage ditches. This water flows directly to the drainage pipes as their level is -0.7 m NAP (fig. 4.46). This waterflow pulls the fresh infiltration water from in between the river and the seepage ditch downward.

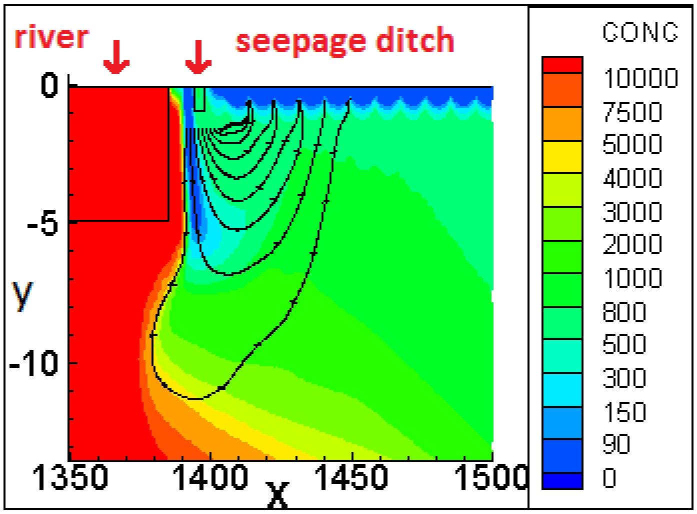


Figure 4.46 zoom on seepage ditch in scenario *WLditch=-0.4mNAP in* 2071

The chloride concentration in the ditches stays 800 mg/l, as water is flowing out into the domain. Only the seepage ditches first decreases in chloride concentration and then increase towards a level of 800 mg/l again (fig. 4.47). This scenario was only run for 100 years, however, one can predict that the concentration in the seepage ditches will stay around 800 mg/l after 2110, as they are outflow ditches in this scenario.

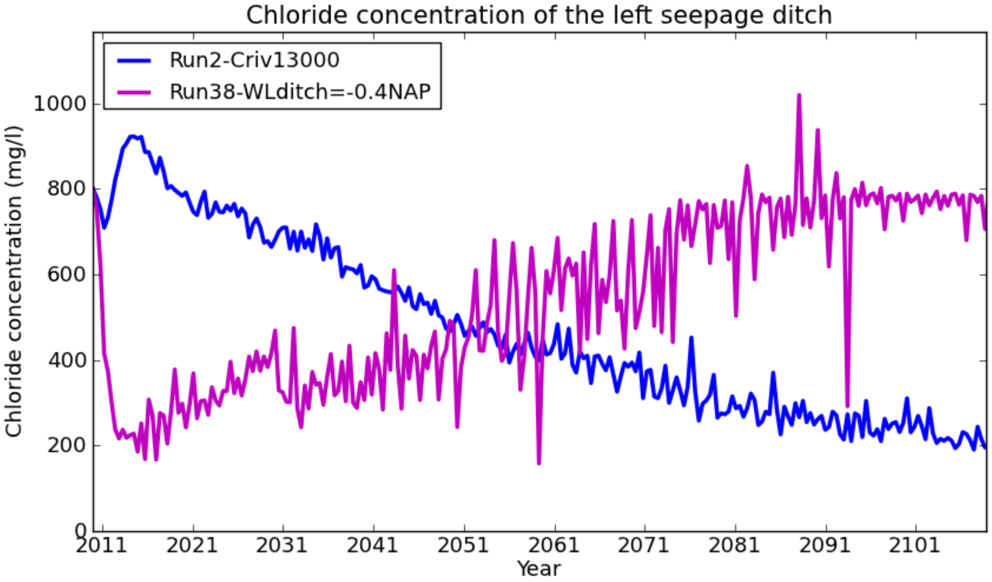


Figure 4.47 The chloride concentration in the left seepage ditch

4.8 Varying the water level in the river

4.8.1 Heigher waterlevel in the river 'WLriv=0.1mNAP'

In this scenario the waterlevel of the river is 0.1 m higher than in *Criv13000*. So the difference between the head in the river and the head in the groundwater is larger and thus the water from the river flows faster into the groundwater. Figure 4.48 shows the salt water cone in 2071. Table 4.9 shows that indeed the volume of salt water in scenario *WLriv=0.1mNAP* is larger than in scenario *Criv13000* in 2071, but the difference is not so large.

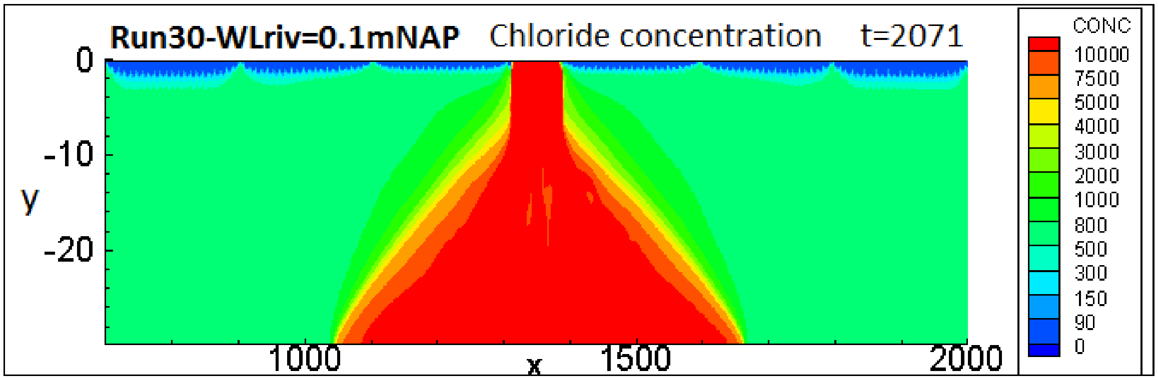


Figure 4.48 Chloride concentration in scenario *WLriv=0.1mNAP* in 2071

Table 4.9 Volumes of fresh, brackish and salt water in 2071

	Fresh water (m^3/m) (<=300 mg/l)	**Brackish water (m^3/m) (<=3000 mg/l)**	**Salt water (m^3/m) (<=13000 mg/l)**
Run2-*Criv13000*	2480	19189	2631
Run14- *WLriv=0.1mNAP*	2452	18898	2950

Figure 4.49 shows a graph of the total volume of salt water in the domain over time.

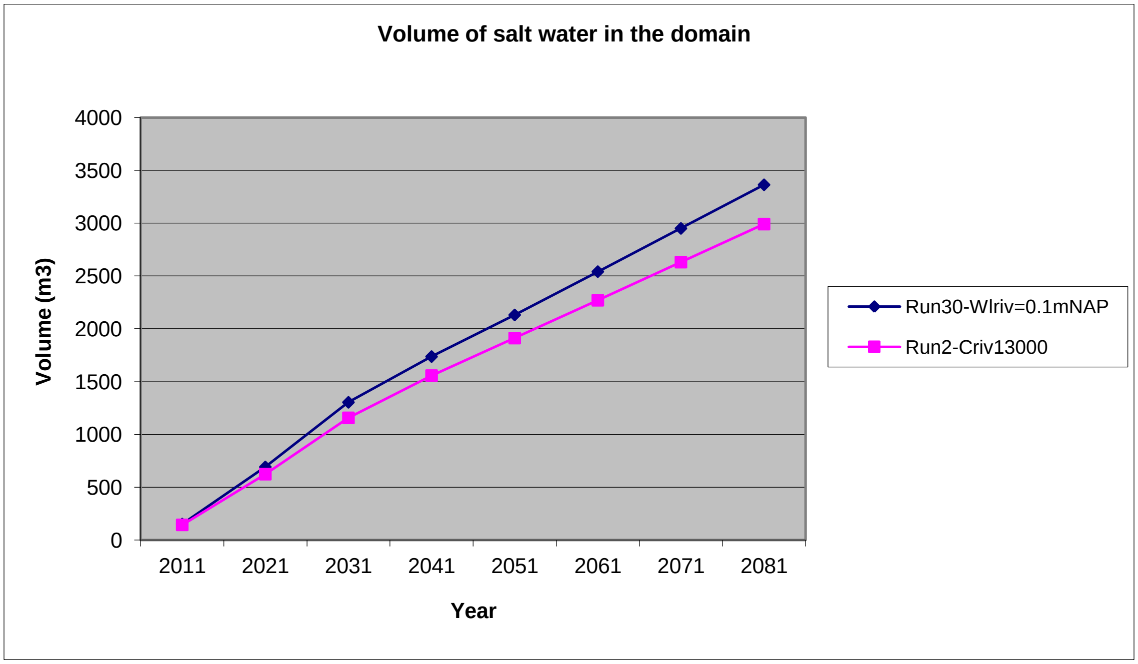


Figure 4.49 Salt water volume in the domain over time

The volume of salt water in the domain in *WLriv=0.1mNAP* is increasing faster than the total volume of salt water in the domain in scenario *Criv13000.* This faster salinization of the domain also makes the chloride concentration in the left seepage ditch starting to increase earlier, namely around 2120 (fig. 4.50). In the right seepage ditch the concentration also starts to increase earlier than in scenario *Criv13000.* In the other ditches the chloride concentrations of scenario *WLriv=0.1mNAP* show also higher values than in *Criv13000* over time, however, they never reach levels over 1150 mg/l in the first 200 years (compared to ≤1000 mg/l in *Criv13000*).

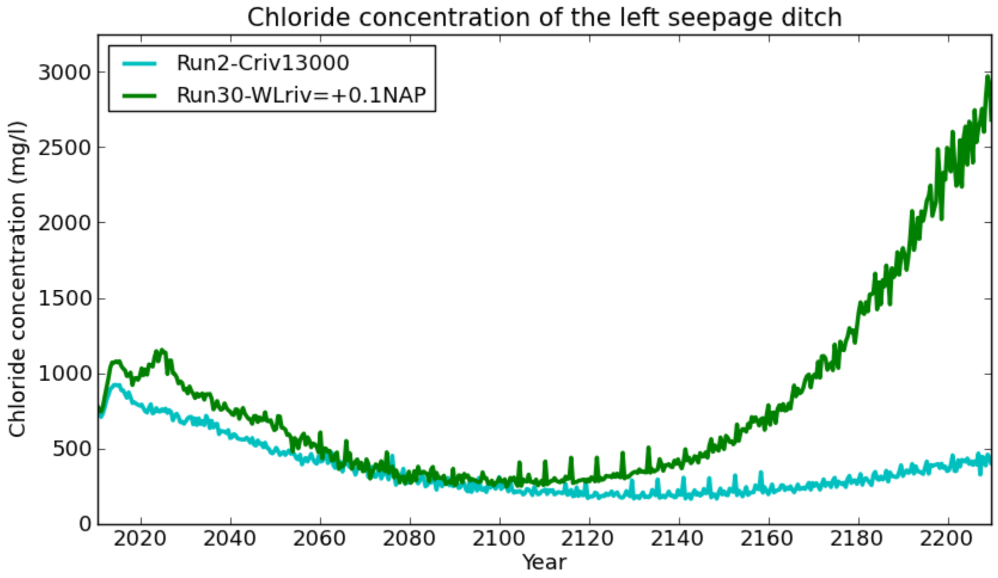


Figure 4.50 Chloride concentration in the left seepage ditch over time

In the drainage pipes next to the river the maximum chloride concentration is 9500 mg/l (table 4.10). Further away from the river the chloride concentration will not be more than 800 mg/l.

Table 4.10 Maximum chloride concentration in the drainage pipes in 1000 years

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	<9000 mg/l	<800 mg/l
Run30- *WLriv=0.1mNAP*	<9500 mg/l	<800 mg/l

4.8.2 Lowering the water level in the river 'WLriv=-0.1mNAP'

In *WLriv=-0.1mNAP* the head in the river is -0.1 m lower than in scenario *Criv13000*. Therefore, the difference in head in the river and in the groundwater is smaller, and thus less water is seeping out of the river. In figure 4.51 the salt water cone in 2071 is shown. The difference between the salt water cone in *Criv13000* and *WLriv=-0.1mNAP* in 2071 (figure 4.42 and 4.51 respectively) is difficult to see from these figures. However, table 4.11 shows that the volume of salt water in 2071 in scenario *Criv13000* is clearly larger than in scenario *WLriv=-0.1mNAP*.

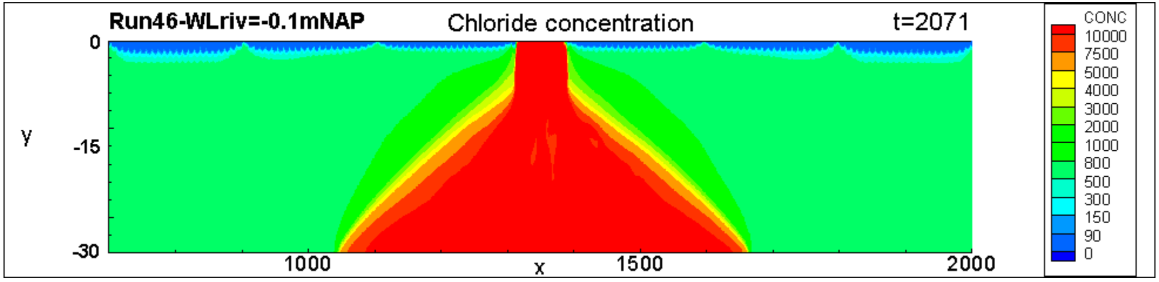


Figure 4.51 Chloride concentration in scenario *WLriv=-0.1mNAP* in 2071

Table 4.11 Volumes of fresh, brackish and salt water in 2071

	Fresh water (m^3) (<=300 mg/l)	**Brackish water (m^3) (<=3000 mg/l)**	**Salt water (m^3) (<=13000 mg/l)**
Run2-*Criv13000*	2480	19189	2631
Run46-*WLriv=-0.1mNAP*	2509	19544	2247

The water in the left seepage ditch salinizes at a slower rate in scenario *WLriv=-0.1mNAP* than in *Criv13000.* This can be seen in figure 4.52 which shows the chloride concentration in the left seepage ditch over time. The concentration in the seepage ditch in *WLriv=-0.1mNAP* stays until 2200 lower than in scenario *Criv13000* which is reasonable as the difference in head between the river and the groundwater, and the difference in head between river and the seepage ditches is smaller. And thus the velocity wherein the water is flowing out of the river is smaller. This is also shown in table 4.12, which compares the volume of water flowing out of the rivers in scenario *WLriv=-0.1mNAP* and *Criv13000*, although the difference is very small.

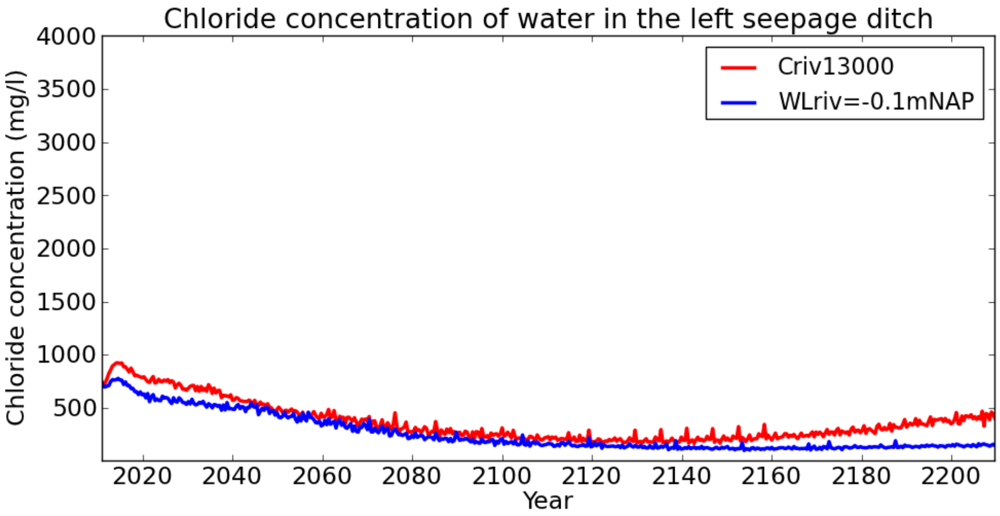


Figure 4.52 Chloride concentration in the left seepage ditch *WLriv=-0.1mNAP* over time

This decrease in river outflow in *WLriv=-0.1mNAP* is caused by the decrease in outflow of the river and not from the ditches, because the head in the ditches has not changed in this scenario, so the water flow in and out of the ditches will not have changed much.

Table 4.12 River leakage in 2031

	Run2-*Criv13000*	**Run46- *WLriv=-0.1mNAP***
River leakage (m^3/m) - IN	4129	4099

Table 4.13 shows the chloride concentration of the water in the drainage pipes in scenario *WLriv=-0.1mNAP* and *Criv13000*. The chloride concentration of the water near the river has a maximum of 8000 mg/l in the first 100 years of the model run. This is

because of the same reasons that the water in the seepage ditches salinizes slower, namely, the salt water is flowing out of the river at a slower rate.

Table 4.13 Chloride concentration in the drainage pipes until 2110

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	<9000 mg/l	<800 mg/l
Run46- *WLriv=-0.1mNAP*	<8000 mg/l	<800 mg/l

4.9 Low permeable layer at 4 m to 6 m and water level in the ditches 0 m NAP ‘LPL-4m&WLditch=0mNAP’

In this scenario there is hardly any water seeping from the river into the groundwater (fig. 4.53). On top of the low permeable layer at -4 m to -6 m the groundwater flows out of the ditches as their level is higher than the groundwater head. So the water flows into the drainage pipes. Underneath the low permeable layer the water flows towards the right boundary, as the head under the low permeable layer is mainly determined by the heads of the boundaries. The same process was also seen in scenario *Lpl-4m_K=0.001.*

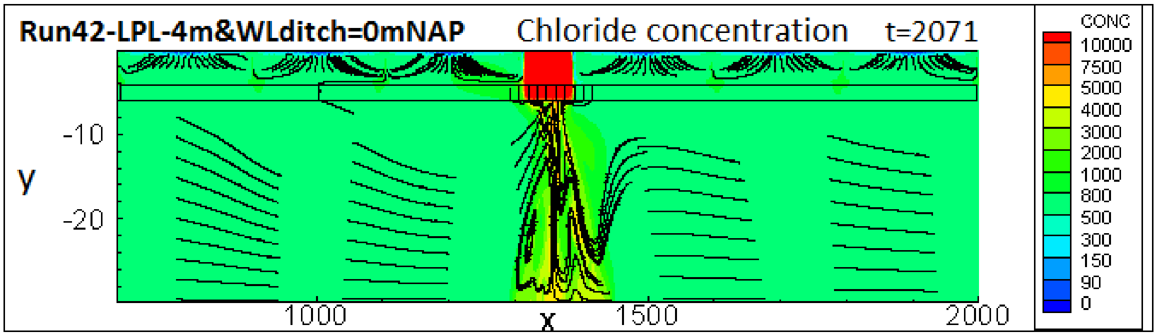


Figure 4.53 Chloride concentration in scenario *LPL-4m&WLditch=0mNAP* in 2071

The chloride concentration in all the ditches stays 800 mg/l uptil 2110.
The water in the drainage pipes close to the river reaches a maximum concentration of 9500 mg/l (table 4.14). Further away from the river the concentration of the water in the seepage ditches will not be over 800 mg/l.

Table 4.14 Chloride concentration in the drainage pipes until 2110

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	<9000 mg/l	<800 mg/l
Run42- *LPL-4m&WLditch=0mNAP’*	<9500 mg/l	<800 mg/l

4.10 Varying the concentration of the groundwater 'Cgw=250, 2000 and 8000'

If the chloride concentration in the groundwater is higher, the salt water cone under the river will be smaller. This can be seen in figure 4.54.

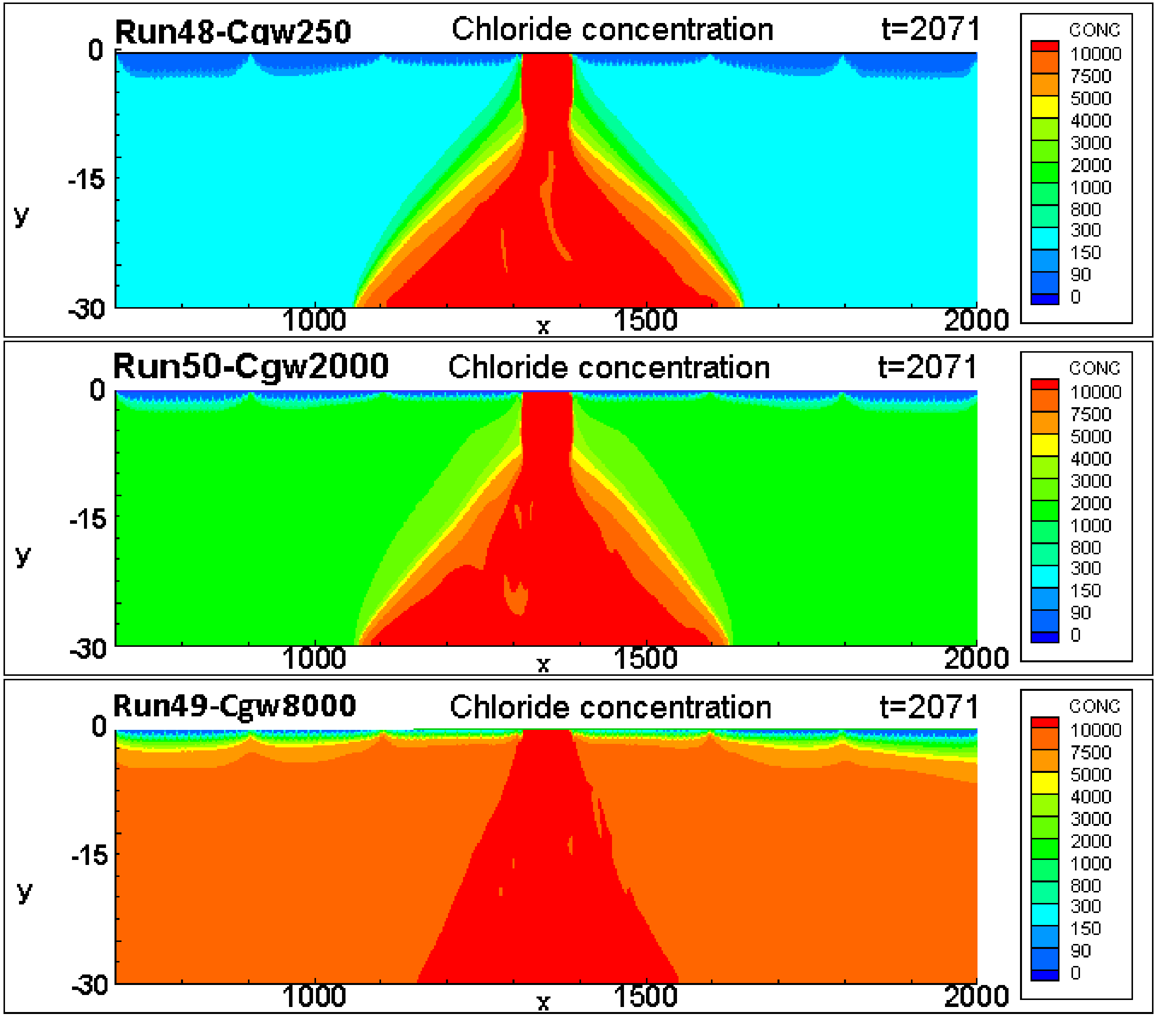


Figure 4.54 Chloride concentration in scenario *Criv250-2000-8000* in 2071

This is due to smaller density differences between the groundwater and the river if the concentration in the groundwater is higher. In this case the river water will flow with a slower velocity into the groundwater. However, by looking at the graph of the chloride concentration in the domain (fig. 4.55), the total salinization of the domain seems to take approximately the same amount of time, because in all scenarios the chloride concentration in observation point 1 reaches 13000 mg/l around 2080. Except for *Cgw812* (Ref.-case) wherein the chloride concentration is approximately 12500 mg/l in 2080.

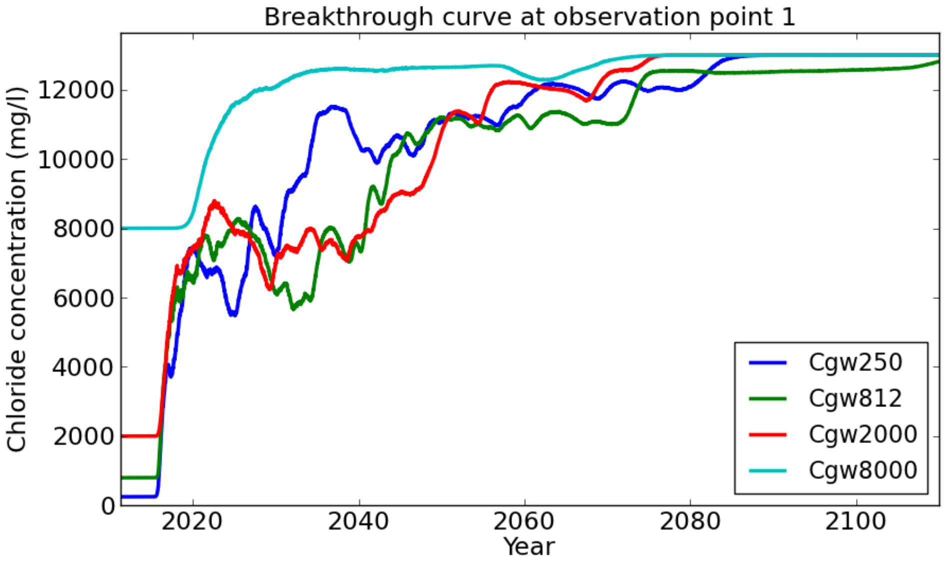


Figure 4.55 Chloride concentration at observation point 1 for *Criv250, 2000 and 8000*

5. Discussion

This research project contains a large number of model scenarios. The purpose of this large number of scenarios was to cover as much as possible the characteristics of the region. This method can be linked to the famous saying of Copernicus:

“To know what we know what we know, and to know that we do not know what we do not know, that is true knowledge”

Copernicus (Polish Astronomer, 1473 – 1543)

So in this research the large number of model scenarios was used to increase our knowledge on the system and on how and if the salt water intrusion will take place in the future.

Salt water in the Dintel will salinize the groundwater under the watercourse and the water in the seepage ditches. The extent and timing of this salinization is dependent on the hydrogeological factors as the chloride concentration in the river, the geology of the region, and the chloride concentration in the groundwater. The extent and timing of the salinization is also influenced by the possible mitigation measures as varying the water level in the river and the ditches. The influence of each of these factors will be explained and discussed in this chapter. Then the research questions will be discussed and answered when possible and finally the robustness of the research project will be discussed.

Hydrogeological factors

Chloride concentration in the river

The future chloride concentration in the watercourse Dintel is difficult to predict. Bubble screens will possibly be placed in the sluices and innovation has made water bubble screens nowadays a very effective way to keep the salt water out (p.c. Douben, 2011). However, small volumes of salt water will flow into the Dintel via the sluice complex at Dintelsas, and they eventually could add up to large volumes in the watercourse. Moreover, salt water can settle at the bottom of the watercourse, which might have the same effects as a completely saline river.

Consequently all kinds of chloride concentrations of the river water have to be considered. The tests on *Criv* show that if the chloride concentration in the river is high; the seepage ditches salinize on the long term. And if the chloride concentration in the river is low; the seepage ditches salinize on the short term, which conflicts with one’s basic knowledge on hydrogeological flow processes. This is caused by the development of the downward flow velocity of the salt water as this varies a lot because in some cases salt fingers are being formed. In Chapter 2 of this report the phases and velocity of these salt water fingers which have been described by Vincent Post are summarized. For all clarity a summary is given below:

1. growth of the diffusive boundary layer; slow velocity,
2. acceleration of the front when the boundary layer breaks up,
3. an almost linear descent of the front,
4. decreasing front velocity as the plumes reach the bottom of the model domain.

(Post, 2004)

These different phases were recognized in the three different cases in which the model scenarios on *Criv* were divided. The downward flow in these cases will now be repeated shortly, after which the corresponding phases of Post will be discussed.

Case A: In scenario Criv2000 and Criv3000 the water flows down in a cone and the flow towards the ditches is steady.

In this case the downward spreading of chloride is both convective and diffusive. Due to the small density contrast there is no development of salt water fingers. And thus this case cannot be linked exactly to the phases described by Post. However, phase 1 describes diffusion which is also taking place in this case.

Case B: In scenario Criv5000 and Criv6000 the water flows down in a cone, and after approximately 12 years the cone breaks up into salt water fingers. This increases the velocity of the downward flow. The salt water from the river is pulled into the preferential downward flow. This preferential downward flow stops when the salt water reaches the bottom of the domain.

In case B phase 2 of Post is taking place, namely: “..after approximately 12 years the cone breaks up into salt water fingers.” The increase in downward flow was also recognised in: “increases the velocity”.
Furthermore, phase 4 of Post was recognised in: “..stops when the salt water reaches the bottom of the domain.”

Case C: In scenario Criv10000 and Criv13000, salt water fingers are formed in the first couple of years of the run, and thus there is preferential flow downwards. After 150 years almost all the salt water fingers flowing down have disappeared. A salt water cone was formed under the river and thus from the river downward there are no density differences anymore. Therefore, the preferential gravity driven vertical flow has stopped.

In case C the salt fingers are being formed in the first years of the run. And thus before this moment the downward flow from the river has been a combination of convective flow and the building of a diffusive boundary layer, which is phase 1 of Post. This can be seen in figure 5.1 (same as figure 4.4); as a diffusive layer under the river can be seen in this figure.
The salt water fingers flowing down causing the increase in downward flow are phase 2 of Post. And the settlement of the salt water cone after 150 years is phase 4 of Post.

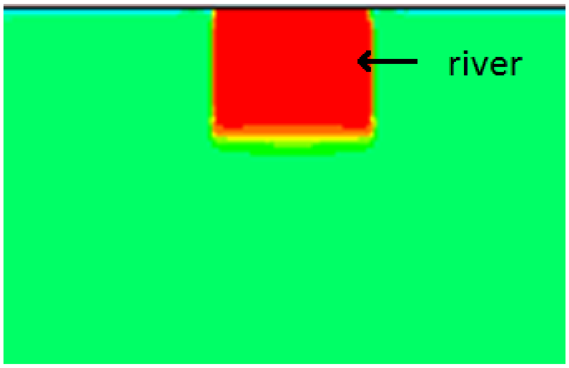


Figure 5.-*Criv13000* in 2011 chloride concentration, zoomed in on the river

When the downward flow velocity is high, there is not much water flowing to the sides of the river, and into the seepage ditches. And thus as said before; the lower the chloride concentration in the river, the faster the salinization of the seepage ditches takes place. However, the final chloride concentration will be higher as the chloride concentration in the river is higher.

Until 2050 an increase in chloride concentration in the seepage ditches to 2000 mg/l is expected. This value is too high for the usage for agricultural purposes (max. 250 mg/l for the critical soil usage in this area). And thus, the salinization of the seepage ditches on the middle-long term should be taken into account by the Regional Water Authority Brabantse Delta.

Furthermore, the groundwater under the river acquires the same chloride concentration as the river on the long term. For high concentrations this salt water cone could push the shallow fresh water lens up near the river. But it happens only in a couple of hundred years.

Geology of the region

The depth of low permeable layers in the region varies (Appendix I). However, the results show that the presence of a low permeable layer at -4 m and -15 m both accelerate the salinization of the seepage ditches to roughly the same extent. Appendix I shows that in all locations in the region a low permeable layer of various substances, for example loam, clay or peat is present. And therefore, again, a salinization of the seepage ditches on the short term has to be expected.

In *LPL-4mK=0.001m/d* the fresh water layer near the river becomes very thin relatively quick. The same thing happens in *LPL-15mK=0.001m/d,* however, then for a wider zone, as the salt water cone is wider than in *LPL-4mK=0.001m/d.* This means the shallower the low permeable layer, the more local, but stronger the decrease of the thickness of the shallow fresh water lens will be.

Concentration of the background groundwater

The concentrations of the background groundwater (Cgw250, Cgw2000 and Cgw8000) does not influence the speed of the total salinization of the groundwater under the river.

The hydraulic resistivity of the drainage pipes

A variation in the hydraulic resistivity of the drains can make the drains a more important factor in determining the fresh water head in the aquifer domain. As the level of the drains is lower than the average groundwater level in the region, a lower resistivity of the drains lowers the fresh water head in the aquifer domain. If there is a lower fresh water head; the salt water flows faster out of the river and all ditches become outflow ditches. So the ditches do not salinize from water that is flowing in. However, there is water flowing in from the drainage pipes, which is saline near the river. This means that a salinization of the seepage ditches should in this case also be expected.

The hydraulic conductivity of the silt layer of the river

The hydraulic conductivity of the silt layer of the river has a large influence on the salt water intrusion into the groundwater. If the silt layer has K=0.1 m/d the salt water intrusion in the domain takes place very quickly, as well as the salinization of the seepage ditches. Furthermore, even the chloride concentration in the ditches 200 m from the seepage ditches increases slightly after 50 years.

A hydraulic conductivity of K=0.001 m/d causes very little salt water intrusion in the first 100 years, wherein the seepage ditches also do not salinize.

The exact hydraulic conductivity of the silt layer around the river is difficult to determine, however, these results show the importance of the presence of this layer. If the hydraulic conductivity increases; there is immediately much more salt water flowing into the groundwater system. So hypothetically, if there are holes in this silt layer; the salt water will flow quickly out of the river and salinize the groundwater system, and the seepage ditches and possibly other ditches in the surroundings.

The hydraulic conductivity of the soil

The hydraulic conductivity of the soil was not tested in the model. However, the formula of Post for the front velocity of the salt water finger shows that this velocity is dependent on the permeability of the soil:

$$v = \frac{\Delta\rho g \kappa}{\mu n}(0.20f_s^2 - 0.45f_s + 0.22) \qquad (18)$$

(Post, 2004)

The intrinsic permeability of the soil is related to the hydraulic conductivity (κ) of the soil by this formula:

$$k = \frac{\kappa \rho g}{\mu} \qquad (19)$$

(Hubbert, 1940)

Therefore, an increase in permeability of the soil is thus an increase in hydraulic conductivity, as the other parameters of this formula will stay the same in the model. So an increase in hydraulic conductivity of the soil will lead to an increase in velocity of the salt water fingers.

If the hydraulic conductivity of the soil is higher than 3 m/d (scenario *Criv13000)*, the downward velocity of the salt water increases. In case of a low chloride concentration in the river, this could lead to a slower salinization of the seepage ditches than in *Criv13000,* as first a preferential downward flow will develop. But in case of a high chloride concentration in the river water, the salinization can take place earlier, as the salt water cone at the bottom of the river will develop faster, where after water starts flowing to the seepage ditches.

On the other hand; if the hydraulic conductivity of the soil is lower than in 3 m/d, the downward velocity will decrease. This might cause a faster salinization of the seepage ditches; the same effect that was seen for lower chloride concentrations of the river water i.e. case B that was explained earlier in this chapter.

Mitigation measures

Increasing the water level in the ditches

If the water level in the ditches increases, the fresh water head in the domain increases too. Therefore, less salt water will flow out of the river into the groundwater. Furthermore, the ditches become outflow ditches, so there is hardly any water flowing in. However, as was said earlier in this chapter, salt water from drainage pipes near the river can salinize the seepage ditches.

Varying the water level in the river

If the water level in the river increases, the velocity of the salinization of the groundwater and the seepage ditches will also increase. If the water level in the river decreases; the salinization of the groundwater and seepage ditches will take place in a slower rate.

On answering the research questions

The results show that if the river water in the Dintel becomes saline, it will intrude into the groundwater and the seepage ditches. The process in the deeper parts of the groundwater system is slow, however, the chloride concentration in the seepage ditches can, under certain circumstances, which are described earlier in this chapter, already increase after 10 years. The final chloride concentration in the seepage ditches depends on the chloride concentration of the water in the river.

The range of influence of the salt water intrusion from the river on the surface water is roughly 300 m. In this region the seepage ditch salinizes and in some cases the chloride concentration in the ditch 200 m next to the seepage ditch could also increase. Furthermore, the presence of a low-permeable layer can decrease the thickness of the shallow fresh water lens in a range of 300 m from the river. The range wherein the groundwater system salinizes is much larger, up to 1000 m on the long term. The size of the salt water cone under the river is dependent on factors as the geology and the chloride concentration of the water in the river.

As was said before; the salinization of the seepage ditches could already take place after 10 years. The salt water intrusion into the groundwater system is not a very fast process; even after 1000 years the salt water cone under the river is still increasing. And this means that no equilibrium has been developed in this millennium.

There are two kinds of intrusion processes that are taking place; diffusion and convection. It is dependent on the scenario which intrusion process is dominant. The convection is mostly more dominant in the scenarios with high chloride concentrations of the river water as in these cases the density differences are larger. The convective process takes place in vertical direction through the river bottom and ditch bottom. The diffusive process is mostly more dominant in the scenarios with low chloride concentrations in the river. The diffusive process takes place vertically and horizontally through the sides and bottom of the river.

The geology of the domain is very important for the distribution of the salt water. If there is a low permeable layer the salt water will settle on this layer. When the layer lies close to the ground level, the salt water will flow into the ditches.

Two kinds of mitigation measures could be taken; changing the water level in the river and changing the water level in the ditches. Increasing the water level of the river will not help as this is only accelerating the salinization process. Lowering the water level of the river would be a better mitigation measure. However, with this decrease in water level the seepage ditches will probably still salinize on the short term. So this will only decelerate the process, but it will certainly not stop it. Lowering the water level more than 0.1 m could possibly decrease the salinization of the seepage ditches more as the difference in fresh water head between the river and the seepage ditches and groundwater system decreases.

A higher water level of the ditches in the model seems to work well, as the seepage ditches do not salinize because the water only flows out of them. However, this does not guarantee that there will be no salt water in the surface water, as salt water from the drainage pipes near the river will flow into the ditches. The impact of this is not sure, however, as the salt water will mix with fresher water; it is expected to salinize the seepage ditches not to a very large extent.

Research method

This research contained a lot of scenarios to cover the hydrogeology of the region and its uncertainties and furthermore to test possible mitigation measures. If a 3D-model would have been used, a lot of the scenarios on different geologies, as for example the low permeable layer, could have been left out. In a 3D-model the regional spreading of the salt water can be predicted in a better way as 3D-data on the geology from Geotop (voxels) could have been included. Furthermore, in this way the groundwater does not have to flow always perpendicular to the river.

The hydraulic conductivity of the silt layer around the river is very uncertain. More investigations on the characteristics of this silt layer will have to be done in order to make better predictions on the extent and speed of the outflow of salt water from the river. Furthermore, runs should be done on scenarios wherein there are holes in this silt layer around the river. This could be a case wherein salinization would take place very quickly.

In most of the scenarios, the effects of various mitigation measures have been tested as for example lowering the ditch level to different levels. This gave a reasonable good insight on these effects. In some cases the results of more scenarios would have been interesting to see, as for example lowering the water level in the river more, because the decreased difference between the fresh water head in the river and the fresh water head in the groundwater system decreases the salinization of the groundwater system.

A better uncertainty analysis could have been done for more characteristics of the model. For example the resistance of the river and the drains as these values are always unsure in groundwater modeling. And by thus by getting to know more about their influence, we will get to know the groundwater system better.

6. Conclusions

The salinization of the groundwater in the Dintel area is a slow process. The salinization of the surface water of the ditches, on the other hand, can take place within 10 years. This accounts for the seepage ditches, but also other ditches within a range of 300 m from the river can salinize in the near future. The salinity of the ditches further than 300 m from the river does not change in any of the modeled scenarios. The final chloride concentration in the ditches within a range of 300 m depends on the future chloride concentration of the river water of the Dintel. Density effects have a severe impact on the salinization of the ditches and furthermore, the speed of this salinization depends strongly on the presence of a low permeable layer in the soil, and the hydraulic conductivity of the silt layer around the river. When a low permeable layer is present in the soil, the groundwater settles on this layer and makes quicker contact with the surface water. When the hydraulic conductivity of the silt layer around the river is increased with a factor 10, relative to the reference case (*Criv13000*), the outflow of salt water from the river increases significantly and a relatively large salt groundwater cone develops much more rapidly.

In this study various chloride concentrations of the river water in the Dintel have been tested as it is very difficult to predict the future chloride concentration of the river water. This will have to be done with a surface water model. However, an average vertical chloride concentration of the river water might still not help in predicting the extent of the salt water intrusion into the groundwater, as salt water which has settled on the river bottom could have the same intrusion effects as a totally saline river. And thus it is important to take the scenarios with various chloride concentrations of river water into account.

Another effect of the salt water intrusion from the Dintel is that the current shallow fresh water lens could become thin in a range of 300 m from the river. The decrease of the shallow fresh water lens only takes place in a couple of hundred years. This happens when the salt water cone in the groundwater system comes close to the field level and thus pushes the shallow fresh water lens towards the ground level. For example, when the salt water cone becomes very big, if the silt layer around the river has a relatively high hydraulic conductivity, and thus the salt water seeps at a fast rate through this layer.

The flows in the groundwater system are complex and they vary in the different scenarios as the fresh water head changes due to the changing conditions. Most of the time these changing flows do not change the chloride concentrations in the surface water much, as the increase of the chloride concentrations in the ditches is limited to the ditches near the river.

The seepage ditches on both sides of the river salinize on the long term. Their chloride concentration reaches approximately 6500 mg/l in 1000 years. The chloride concentrations of the other ditches in the domain do not increase much, only up to a maximum of 900 mg/l in a millennium.

The effects and main conclusions from different scenarios will now shortly be discussed.

The effects of different chloride concentrations in the river

Over the years the chloride concentration of the groundwater system equals the concentration of the river water in the relating scenario.

The higher the chloride concentration in the river; the more pronounced the flow downward. This is caused by the density difference between the river and the groundwater system. The larger this difference, the larger the difference in fresh water head and the larger the gravitational pull; which results in a higher vertical velocity. If there is preferential flow downwards, there is less flow sideways, and thus a lower chloride concentration in the seepage ditches in the first 100 years.

The downward flow of the different chloride concentrations in the river shows similarities with the salt water finger development findings described by Post in 2004. This has been elaborated thoroughly in paragraph 4.3.1. and in the discussion in Chapter 5. Table 6.1 gives a summary of this.

Table 6.1 Summary of the salt water finger phases (Post,2004) linked to the results of the model for different chloride concentrations of the study

Different cases	**Salt water finger development phases** 1. growth of the diffusive boundary layer; slow velocity, 2. acceleration of the front when the boundary layer breaks up, 3. an almost linear descent of the front, 4. decreasing front velocity as the plumes reach the bottom of the model domain. (Post, 2004) **Phases recognized**
***Case A**: In scenario Criv2000 and Criv3000 the water flows down in a cone and the flow towards the ditches is steady.*	1
***Case B**: In scenario Criv5000 and Criv6000 the water flows down in a cone, and after approximately 12 years the cone breaks up into salt water fingers. This increases the velocity of the downward flow. The salt water from the river is pulled into the preferential downward flow. This preferential downward flow stops when the salt water reaches the bottom of the domain.*	2,4

***Case C**: In scenario Criv10000 and Criv13000, salt water fingers are formed in the first couple of years of the run, and thus there is preferential flow downwards. After 150 years almost all the salt water fingers flowing down have disappeared. A salt water cone was formed under the river and thus from the river downward there are no density differences anymore. Therefore, the preferential gravity driven vertical flow has stopped.*	1,2,4

The drainage pipes near the river also salinize in the coming 200 years. The final (equilibrium) chloride concentration depends on the chloride concentration of the water in the river (table 6.2). The chloride concentration of the water in the drainage system further away from the river will not change.

Table 6.2 Chloride concentration in the drainage pipes in the coming 200 years

	Chloride concentration 50 m from the river (mg/l)	**Chloride concentration >50 m from the river (mg/l)**
Run2-*Criv13000*	< 9000 mg/l	< 800 mg/l
Run18-*Criv10000*	< 6800 mg/l	< 800 mg/l
Run4-*Criv6000*	< 4000 mg/l	< 800 mg/l
Run29-*Criv5000*	< 3500 mg/l	< 800 mg/l
Run12-*Criv4000*	< 3000 mg/l	< 800 mg/l
Run20-*Criv3000*	< 2000 mg/l	< 800 mg/l
Run3-*Criv2000*	< 1500 mg/l	< 800 mg/l

The effect of a low permeable layer

If there is a low permeable layer on -15 m or -4 m in the domain, the salt groundwater settles on this layer in short term. This causes an accelerated salinization of the seepage ditches within the first 100 years, as the salt groundwater stays close to the ground level.

On the long term the salt groundwater flows through the low permeable layer of K=0.01 m/d. A layer of K=0.001 m/d blocks the salt groundwater from seeping through. Only very little salt groundwater flows through the low permeable layer in 900 years.

For the chloride concentration of the water in the drainage pipes it makes no difference on the very long term whether a low permeable layer is on -15 m or -4 m present or not. The chloride concentration of the drainage pipes near the river reaches a maximum 9000 mg/l, and the chloride concentration of the water in the drainage pipes more than 50 m from the river stays 800 mg/l.

The effect of a decrease in hydraulic resistivity of the drains

When the hydraulic resistivity of the drains decreases, more water will flow into the drainage system. Furthermore, the difference between the fresh water head of the river and the fresh water head of the groundwater system increases, and thus more water flows out of the river and the ditches. This does not affect chloride concentration of the water in the drainage system: the chloride concentration in the drainage pipes near the river reaches a maximum of 9000 mg/l and further away from the river it stays 800 mg/l.

The effect of a change in water level of the ditches

When the water level in the ditches increases from -0.5 m NAP to 0 m NAP, the fresh water head in the domain changes, as the water level in the ditches has a large influence on the fresh water head in the groundwater system. When the water level in the ditches is 0 m NAP, the difference between the fresh water head in the river and in the groundwater system decreases, and thus less water flows out of the river resulting in a smaller salt water volume in the domain.

7. Recommendations

In order to prevent the salt water from disturbing the agricultural activities in the region, and to decrease the salt water intrusion as much as possible, some recommendations for the Regional Water Authority Brabantse Delta are listed. The recommendations are formulated according to the results of this study and thus they are based salt water intrusion into the soil. Then some extra recommendations are given which can reduce the salt water intrusion into the surface water of the Dintel river and the ditches. Finally, some recommendations for additional research on this topic are given.

The recommendations according to the outcomes of this study are:

1. The connection of the seepage ditches of the Dintel with the rest of the surface water system in the area should be closed. The water from the seepage ditches cannot be used for agricultural purposes anymore.
2. The chloride concentration in the ditches within 300 m from the river, apart from the seepage ditches, should be monitored because they also risk salinization.
3. The water level in the ditches should be increased, as this decelerates the salt intrusion from the river. Another effect of this measure is that the chloride concentration in the ditches near the river will not become high.
   This recommendation should always come together with recommendation 1 as this mitigation measure (recommendation 3) only decreases the problem.
4. The thickness of the shallow fresh water lens near the Dintel should be monitored, as the lens can become thin and thus might harm the crops of the farmers.

To reduce the salt water intrusion from the Volkerak into the surface water it is recommended to place a bubble curtain and a bar in the sluice complex. Furthermore, flushing of the Dintel and the ditches next to the Dintel with fresh surface water from other rivers and canals. The periods that the sluice will be opened should be as short as possible to minimize the water flow from the Volkerak into the Dintel. Another mitigation measure is to collect the heavy salt water upstream from the sluice complex, and pump it back into the Volkerak to prevent it from intruding into the groundwater.

The recommendations for additional research on this topic are:

1. Creating a 3D-model of the region as it gives a better spatial overview of the salt water intrusion effects. In this 3D-model the geology can be implemented, and thus for example the effects of the presents of low permeable layers in the area can be simulated better, which would be helpful as the effects of a low permeable layer on the spreading of the salt water are severe (which could be

concluded from the results of this research). Therefore, the distribution of the salt water could be predicted more precisely.

2. The characteristics of the silt layer on the bottom of the Dintel should be researched. This could give more information on the rate of salinization, as the salt water intrusion changes a lot when the hydraulic conductivity of this layer changes. Furthermore, if this will be done at more locations in the Dintel; the rate of salinization could more specified per location. Also, the possible effect of holes in this silt layer should be tested.
3. More uncertainty analyses on the resistance of the drains and the river should be done, as these are uncertain values in the study.
4. The geology of the region was taken from borings from Dino*loket,* as using a very exact geology was not necessary because a 2D-model was used. However, for further investigations on this topic of the databases with 3D information of the geology of West-Brabant should be used. These will give a more precise overview of the geology (Geotop).
5. The future concentration of the water in the Dintel is very difficult to predict. And therefore, a large range of different concentrations were tested in this study. With a surface water model better predictions on the development of a salt water wedge and thus the future chloride concentration of the river water could be made. With these outcomes better predictions of the salt water intrusion into the groundwater could be made.

   Also, the influence of the mitigation measures for salt water intrusion through the sluice complex, as named earlier in this chapter, could be tested with this surface water model.

References

AHN, 2011, General Ground level database of the Netherlands, www.ahn.nl (accessed November 2011).

Arcadis, 2009, Milieueffectrapportage waterkwaliteit Volkerak-Zoommeer –ontwerp MER, 284 p.

Baaren, E.S. van, Oude Essink, G.H.P., Janssen, G.M.C.M., Heerdink, R., Goes, B. 2012. Freshening and salinization of the groundwater in the province of Zeeland, Concept report 3D regional fresh-salt groundwater model.

Bear, J., 1972, Hydraulics of Groundwater, McGraw-Hill Book Company, New York

Beijk, V., 2009, Effect van een zout Volkerak-Zoommeer op de chloride concentratie in het Benedenrivierengebied, Rijkswaterstaat Waterdienst- rapport, 25 p.

BHIC, 2012, Rivers > Het Volkerak, http://www.bhic.nl/site/pagina.php?id=12261

Butler, M.J., 2004, The Ecology and Conservation of Natural Resources, RWFM 2302, Section 004.

Deltares*,* 2009, Over Deltares, http://www.deltares.nl/nl/over-deltares (accessed Juni 2012).

Dino*loket,* 2011, TNO, www.dinoloket.nl (accessed November 2011).

Douben, N., 2011, personal communication, meeting, Regional Water Authority Brabantse Delta, d.d. 21 -09- 2011.

EPA, 2009, National Primary Drinking Water Regulations, United States, EPA 816-F-09-004, 6 p.

Fetter, C.W., 2008, Contaminant Hydrogeology – second edition, Waveland Press, Inc, Illenois, 500 p.

Fitts, C.R., 2002, Groundwater Science, Academic Press, London, 450 p.

Hassanizadeh, S.M., 2007, Summary Lecture Notes Hydrogeological Transport Phenomena, Department of Earth Sciences, Utrecht University, Utrecht, 40 p.

Heide, P.K.M., van der & Boswinkel, J.A., 1982, The fresh-saline distribution of the groundwater in the Netherlands. Part 2A, Theoretical Background, (in Dutch), TNO Institute of Applied Geoscience

Hubbert, M.K., 1940, The theory of groundwater motion, Geology, 48, p. 785-944

Hunter, J., Darren, D., Droettboom, M., (2009), Matplotlib, http://matplotlib.sourceforge.net (accessed April 2012).

Johannsen, K., Oswald, S., Held, R., Kinzelbach, W., 2006, Numerical simulation of three-dimensional saltwater-freshwater fingering instabilities observed in a porous medium, Advances in Water resources 29, p.1690-1704.

Konikow, L.F., Goode, D.J., Hornberger, G.Z., 1996, A Three-Dimensional Method-Of-Characteristics Solute-Transport Model (*MOC3D)*, U.S. Geological Survey, Water-Resources Investigations Report 96-4267, 87 p.

Kooi, H., J. Groen, Leijnse, A., 2000, Modes of seawater intrusion during transgressions, Water Resources Research, Vol. 36, No. 12, p. 3581 – 3589.

McDonald, M.G., Harbaugh, A.W., 1988, Techniques of Water-Resources Investigations of the United States Geological Survey – Chapter A1 A MODULAR THREE-DIMENSIONAL FINITE-DIFFERENCE GROUND-WATER FLOW MODEL – Book 6 MODELING TECHNIQUES, United States Government Printing Office, Washington.

Oude Essink, G. H. P., 1996, Impact of Sea Level Rise on Groundwater Flow Regimes – A Sensitivity Analysis for the Netherlands, [PhD Thesis]: Delft, Delft University of Technology, 411 p.

Oude Essink, G.H.P., 2000, Groundwater Modelling I, Lecture Notes, LN0302/04/1, 194 p.

Oude Essink, G.H.P., 2001, Density Dependent Groundwater Flow, Lecture Notes, L4018/GWM1, 136 p.

Oude Essink, G.H.P., Baaren, E. van, Lange, W. de, Wit, A. de, 2008, Beschouwing van de effecten van een zout Volkerak-Zoommeer op het grondwatersysteem, Deltares-rapport 2008-U-R0774/A, 120 p.

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

Oude Essink, G.H.P., Baaren, E. van, Louw, P.G.B. de, 2010b, Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands, Water resources research Vol. 46, 16 p.

Oude Essink, G.H.P. en Verkaik, J., 2010, NHI zoet-zout: grondwater in het Nederlandse kustgebied, memo, 9 p.

Post, V.E.A., 2004, Groundwater salinization processes in the coastal area of the Netherlands due to transgressions during the Holocene, [PhD Thesis]: Amsterdam, Free University of Amsterdam, 138 p.

Post, V.E.A., Kooi, H., Simmons, C., 2007, Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses, GROUND WATER, Vol.45, No. 6, p. 664 – 671.

Regional Water Authority Brabantse Delta, 2011, Provincie Noord Brabant; Bureau ISP, http://atlas.brabant.nl/wateratlas/ (a: accessed in March 2013, b: accessed in February 2012)

Rossum, R. van, 2012, Python Tutorial *Release 2.7.2*, Python Software foundation, 122 p.

Roelofsma, K.P., 2004, Vastgesteld Waterplan Roosendaal, Royal Haskoning-rapport 9M6677/R00013/KR/DenB, 56 p.

Tecplot, 2012, www.tecplot.com (accessed July 2012).

Vandenbohede, A., 2007. Visual MOCDENS3D: visualisation and processing software for MOCDENS3D, a 3D density dependent groundwater flow and solute transport model. User Manual. Research Unit Groundwater Modelling, Ghent University.

WHO , 2011, Guidelines for drinking water quality – 4th edition, WHO Press, Switzerland, 564 p.

Witteveen & Bos, 1999, WaterRaam Land van Nassau – Ontwikkelingsvisie naar duurzame watersystemen kaders voor ruimetelijke ontwikkelingen (1e deelrapport: lange termijn visie), no. 624.8256.00, p. 112.

Witteveen & Bos, 2006, Effecten van een zout Volkerak-Zoommeer op de West-Brabantse rivieren – vaststellen zoutindringing Mark-Vliet en mitigerende maatregelen, BR585-1/winb/013, p. 157.

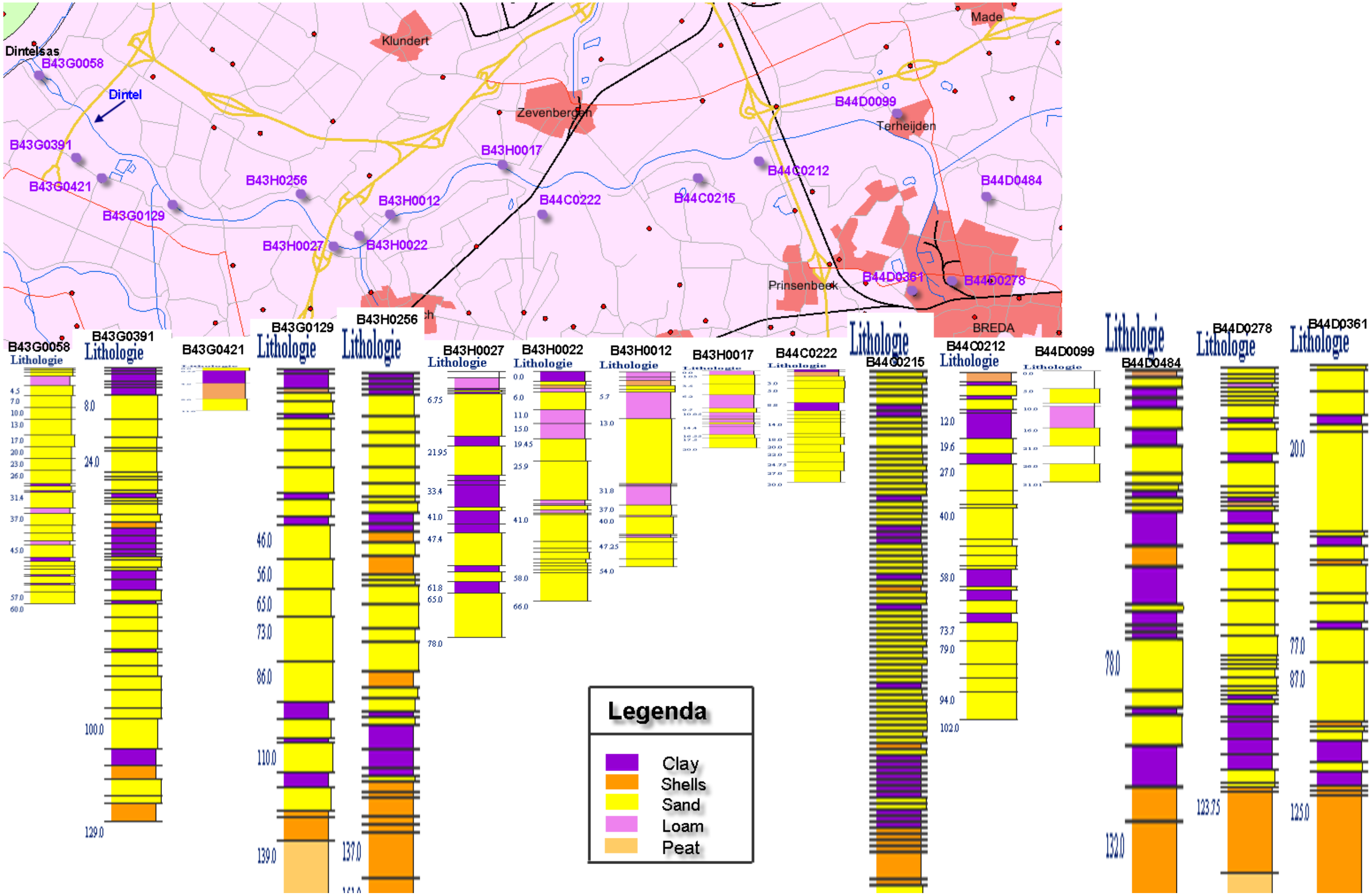
Witteveen & Bos, 2012, http://www.witteveenbos.nl/nl/missie-en-visie (accessed March 2012).

Wooding, R.A., Tyler, S.W., *et al*, 1997a, Convection in groundwater below an evaporating salt lake: 2. Evolution of fingers of plumes, Water Resources Research 33(6), p. 1219-1228

Wooding, R.A., Tyler, S.W., *et al*, 1997b, Convection in groundwater below and evaporating salt lake: 1. Onset of instability. Water Resources Research 33(6): 1199-1217

Zandvoort, M., 2006, Verandering van kans op wateroverlast in het Mark-Vlietsysteem, Essay University of Twente, p. 216.

Appendice I (Dino*loket*)



Appendice II

IMOD transactions chloride concentration (Deltares, 2011)

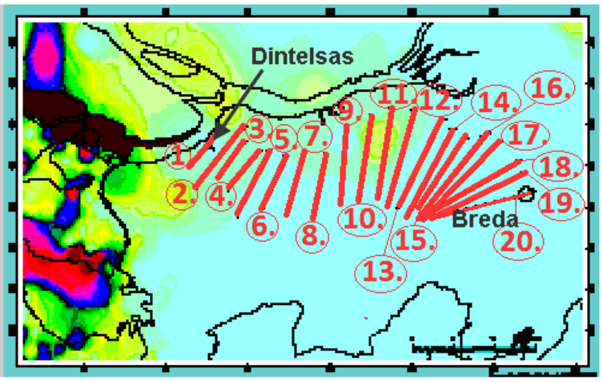
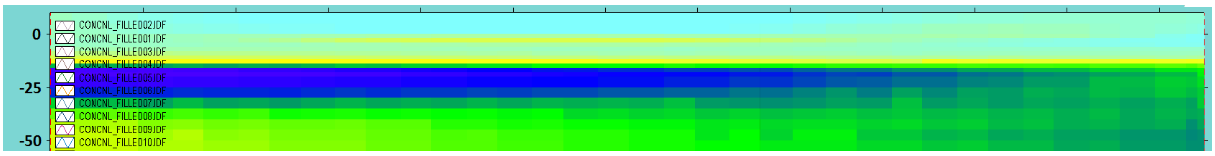


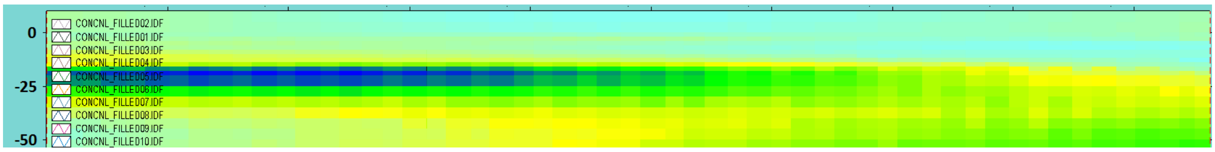
Figure V.1. Locations transections

Legenda Chl. Conc. (mg/l)

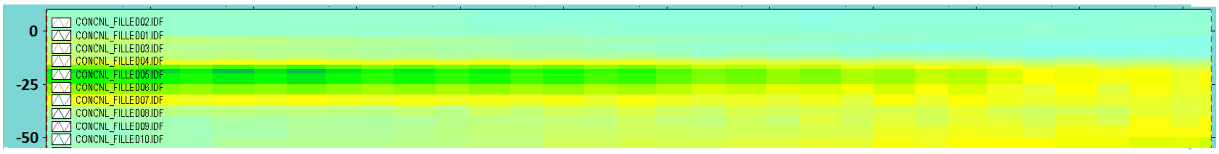
🟦	0 - 500
🟩	500 - 1000
🟩	1000 - 1500
🟨	1500 - 2000
🟨	2000 - 2500
🟨	2500 - 3000
🟨	3000 - 3500
🟩	3500 - 4000
🟩	4000 - 4500
🟩	4500 - 5000
🟩	5000 - 5500
🟩	5500 - 6000
🟩	6000 - 6500
🟩	6500 - 7000
🟦	7000 - 7500
🟦	7500 - 8000
🟦	8000 - 8500
🟦	8500 - 9000



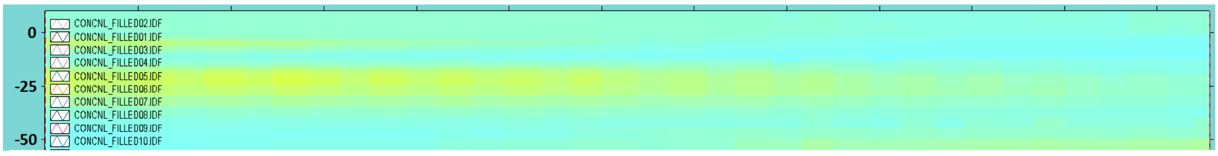
Transection 1.



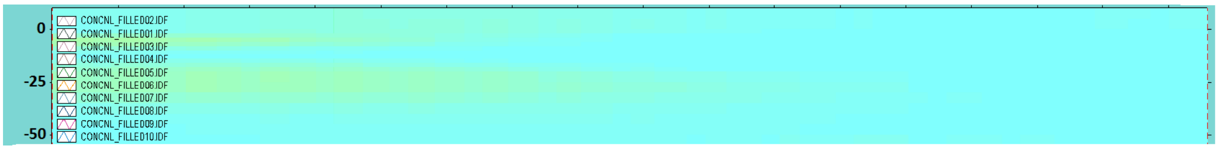
Transection 2.



Transection 3.



Transection 4.



Transection 5.

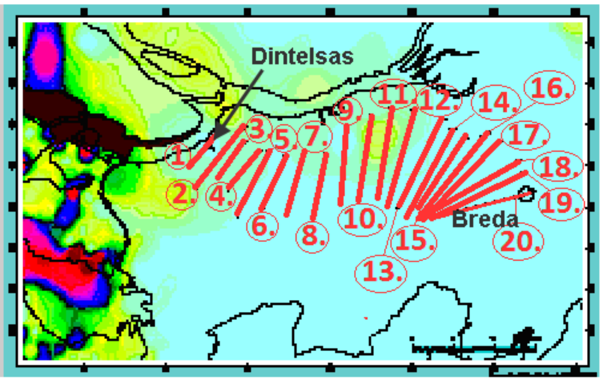
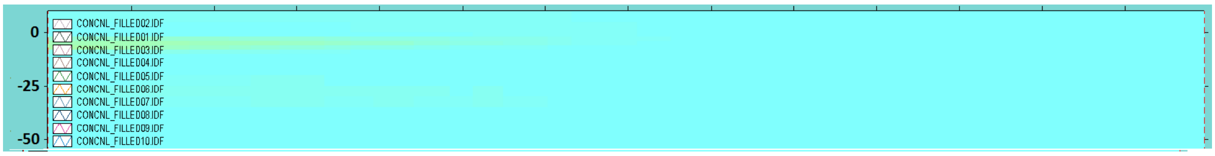


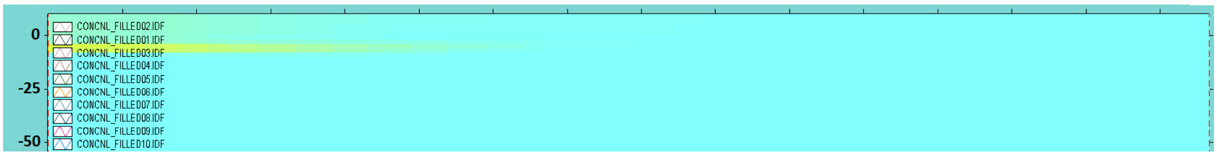
Figure V.1. Locations transections

Legenda Chl. Conc. (mg/l)

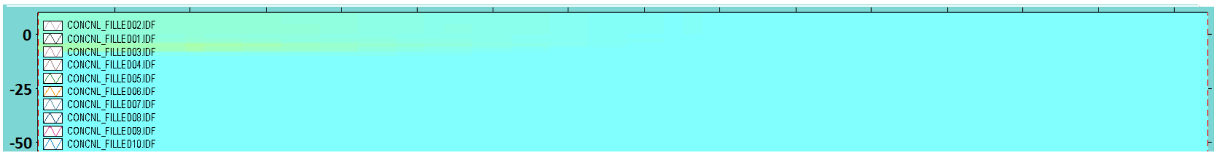
🟦	0 - 500
🟩	500 - 1000
🟩	1000 - 1500
🟨	1500 - 2000
🟨	2000 - 2500
🟨	2500 - 3000
🟨	3000 - 3500
🟩	3500 - 4000
🟩	4000 - 4500
🟩	4500 - 5000
🟩	5000 - 5500
🟩	5500 - 6000
🟩	6000 - 6500
🟩	6500 - 7000
🟦	7000 - 7500
🟦	7500 - 8000
🟦	8000 - 8500
🟦	8500 - 9000



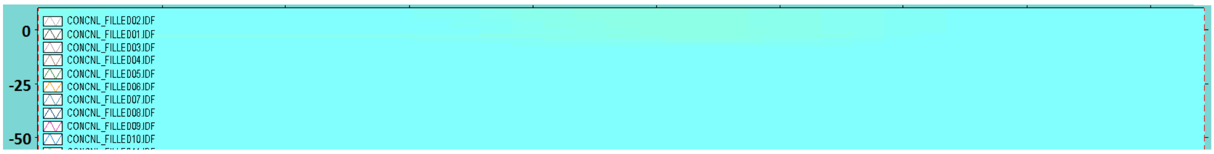
Transection 6.



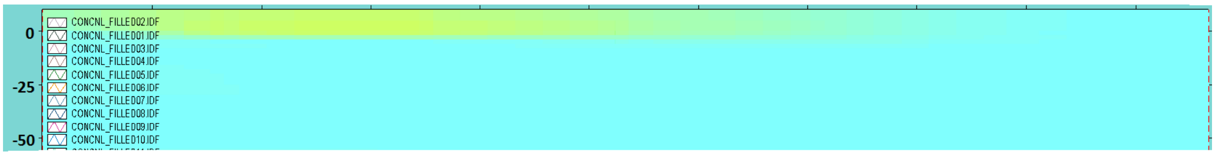
Transection 7.



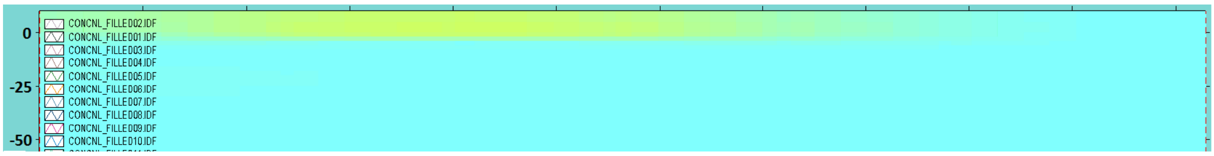
Transection 8.



Transection 9.



Transection 10.



Transection 11.

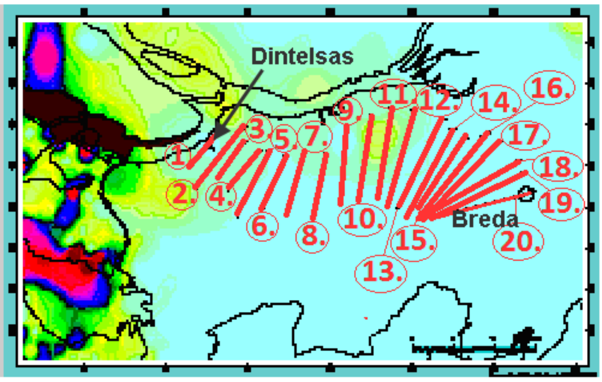
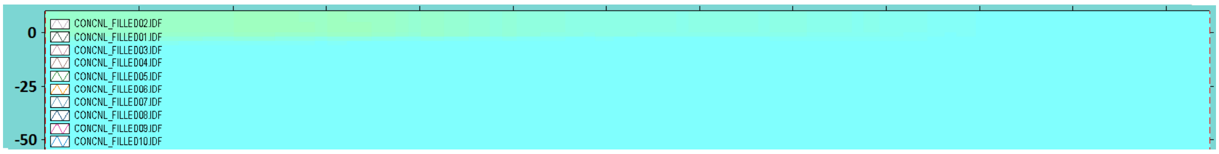


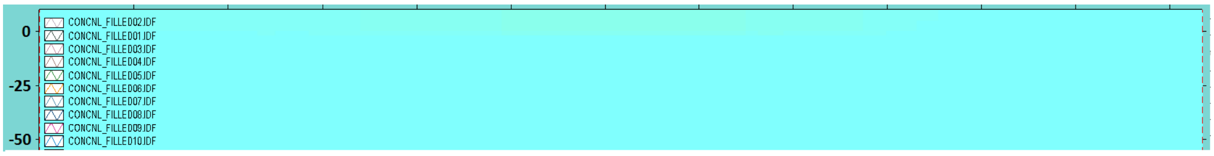
Figure V.1. Locations transections

Legenda Chl. Conc. (mg/l)

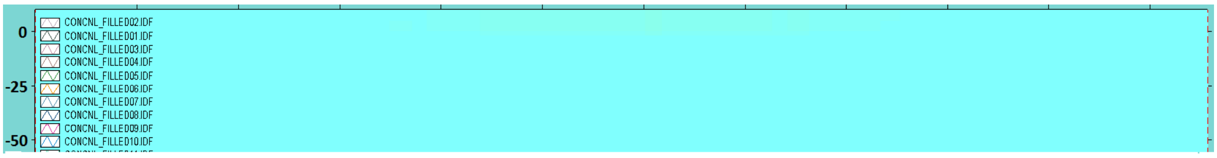
🟦 0 - 500
🟩 500 - 1000
🟩 1000 - 1500
🟩 1500 - 2000
🟨 2000 - 2500
🟨 2500 - 3000
🟨 3000 - 3500
🟩 3500 - 4000
🟩 4000 - 4500
🟩 4500 - 5000
🟩 5000 - 5500
🟩 5500 - 6000
🟩 6000 - 6500
🟩 6500 - 7000
🟦 7000 - 7500
🟦 7500 - 8000
🟦 8000 - 8500
🟦 8500 - 9000



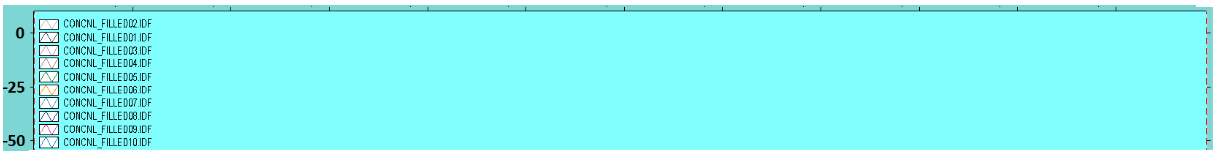
Transection 12.



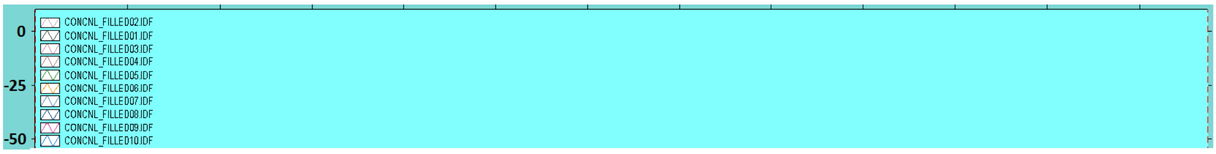
Transection 13.



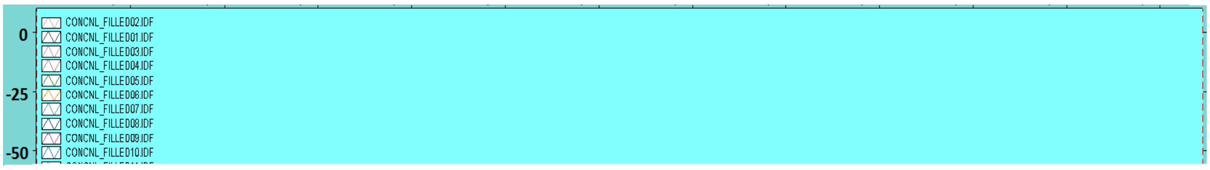
Transection 14.



Transection 15.



Transection 16.



Transection 17.

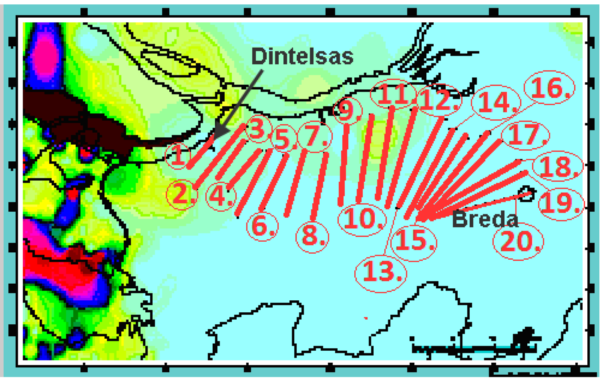
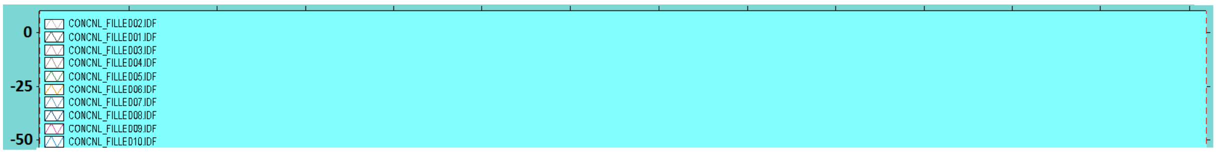


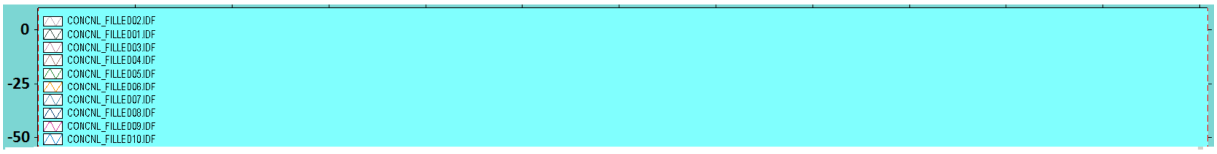
Figure V.1. Locations transections

Legenda Chl. Conc. (mg/l)

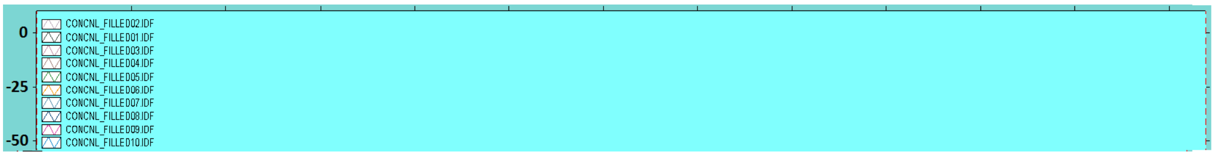
🟦	0 - 500
🟩	500 - 1000
🟩	1000 - 1500
🟨	1500 - 2000
🟨	2000 - 2500
🟨	2500 - 3000
🟨	3000 - 3500
🟩	3500 - 4000
🟩	4000 - 4500
🟩	4500 - 5000
🟩	5000 - 5500
🟩	5500 - 6000
🟩	6000 - 6500
🟩	6500 - 7000
🟦	7000 - 7500
🟦	7500 - 8000
🟦	8000 - 8500
🟦	8500 - 9000



Transection 18.



Transection 19.



Transection 20.

Appendice III

Table VI.1: Electric Conductivity measurements in the surface water in Dintelsas (19-10-2011)

Location	EC	Temperature	NITG (800 mg HCO3) mg/l	NITG (100 mg HCO3) mg/l	van Wirdum (2004) mg/l	(definition according to Stuyfzand (1993) p. 22)
1	3,94 mS/cm	13,3 C	989,1	1286	1048	brackish-saline
2	8,6 mS/cm	13,1 C	2657,5	3003	2295	brackish-saline
3	3,56 mS/cm	11,6 C	851	1184	950	brackish
4	1,365 mS/cm	10,8 C	112,5	392	363	brackish
5	1,565 mS/cm	9,9 C	177	460	417	brackish
6	1,630 mS/cm	12,6 C	198	483	435	brackish
7	1,290 mS/cm	11,2 C	91	367	343	brackish
8	4,46 mS/cm	11,0 C	1236,5	1475	1189	brackish-saline
9	1,840 mS/cm	9,4 C	268	552	489	brackish

Note: ‘NITG (800 mg HCO3)’, ‘NITG (100 mg HCO3)’ and ‘van Wirdum (2004)’ are different methods to convert the EC (in mS/cm) to the chloride concentration.