Universiteit Utrecht

HydroLogic

Striving against saltwater intrusion

A model study on cost-effectiveness of alternative freshwater allocation strategies during freshwater shortages in the Hoogheemraadschap van Rijnland.

Master Thesis
Water Science and Management

M. Erkelens

September, 2016
Amersfoort, The Netherlands

Pictures of cover page (top to bottom):

- **Boskoop aerial photo (Boskoops.nl, n.d.);**
- **Hollandse IJssel at Gouda aerial photo (Izi.travel, n.d.);**
- **Freshwater spray installation on a tulip field. (Julianadorp, 2009);**
- **Princess Irene Locks with the Nederrijn and Lek Rivers in the background. (Siebe Swart, 2008);**
- **Pumping station Gouda. (HHRL, 2015);**

Striving against saltwater intrusion

A model study on cost-effectiveness of alternative freshwater allocation strategies during freshwater shortages in The Hoogheemraadschap of Rijnland.

M. Erkelens (Martijn)

Student number: 5525624
martijn.erkelens@hotmail.com

Universiteit Utrecht, The Netherlands
HydroLogic BV, The Netherlands

University Supervisor
Prof. dr. ir. Marc Bierkens
Department of Physical Geography
Universiteit Utrecht

Internship Supervisor
Meike Coonen MSc
Advisor Watermanagement
HydroLogic BV

Internship Organisation
HydroLogic BV
Stadsring 57
3800 CD Amersfoort

Final version

October, 2016

I. Preface

This Master's thesis is the end product of six years of study, which I started with a *bachelor Earth Science & Economics* at the *Vrije Universiteit* in Amsterdam and which I continued with a master *Water Science and Management* at *Utrecht University.* This thesis was performed in conjunction with an internship at HydroLogic in Amersfoort. HydroLogic is a consultancy company that aims to provide water stakeholders with reliable information, models and in-depth water knowledge. The thesis research largely involved the development of a new freshwater allocation model for which I had to apply a lot of what I have learned over my years of study and during which I had the opportunity to learn many new things as well.

I would like to express my gratitude towards the people without whom this thesis would not have been possible. First of all, I would like to thank, Meike Coonen, my supervisor at HydroLogic. Due to the experimental nature of the thesis research her regular feedback and guidance during the whole thesis period proved to be invaluable. Secondly, I would like to thank Marc Bierkens, my university supervisor, for his willingness to supervise the thesis and his detailed input and feedback. Furthermore, I would like to thank everyone at HydroLogic, for providing me with the opportunity to do my internship there and providing me with valuable advice, feedback, table tennis opponents and drinks. It has been a great pleasure doing my internship here.

Finally, I would like to thank my parents, Jeroen and Diana, my sisters, Roos and Nienke and the rest of my family and friends for their support during my studies in both Amsterdam and Utrecht.

Martijn Erkelens

Amersfoort, October 2016

II. Abstract

During low Rhine discharges, saltwater intrusion can occur on the tidal Hollandse IJssel River (HIJ), resulting in heightened chloride concentrations at the freshwater intake location of the Hoogheemraadschap van Rijnland at Gouda (HydroLogic, 2015a). Future climate change is expected to increase the occurrence and duration of dry periods in Rijnland, while simultaneously increasing saltwater intrusion at Gouda (Van Beek et al., 2008). When saltwater intrusion on the HIJ coincides with freshwater demands in the Rijnland areas, this can jeopardize the freshwater demanding high-value agriculture within its borders (Stuyt et al., 2013).

To secure Rijnland's future water demand an alternative freshwater supply has been realized: The "KWA" (small-scale water supply). To prevent intake of brackish water into Rijnland, this supply will commence when chloride concentrations on the HIJ exceed the threshold of 250mg/l. However, the quantity of this supply is insufficient for Rijnland's theoretical water demand during dry periods (HydroLogic, 2015a). Therefore, efforts are underway to expand its capacity: The "KWA+".

Current views on chloride acceptance levels of water systems in the Netherlands may be too pessimistic, and methods should be developed to increase shared understanding and commitment towards saltwater related policy (Stuyt, Kielen, & Ruijtenberg, 2015). This study aims to support this development by 1) developing a hydro-economic model to rationalize freshwater management cases, and 2) assessing the economic cost-effectiveness of implementing alternative water management investments and strategies.

An earlier study by Stuyt et al. (2013) to assess the effectiveness of water allocation strategies in Rijnland resulted in the €ureyeopener1.0 model. This rapid-assessment model uses single values for weather and chloride concentrations for a whole growing season and provides quick insights into the effects of changes to Rijnland's water system towards water requirements and agriculture damage. The main research gap in this model lies within its lack of temporal variability within the growing season for weather and chloride concentration data, resulting in an omission of infrequent weather events and its effects on the system.

Therefore, in this study the hydro-economic WAOR (Water Allocation and Optimization Rijnland) model was created. With this model the cost-effectiveness of multiple alternative water management strategies, such as the "KWA+" investment, can be assessed. The WAOR uses a dynamic boezem-polder schematization of Rijnland in which polders demand (fresh)water from the boezem based on their requirements. It combines weather and chloride concentration data, agriculture damage functions, temporal variability, climate scenarios, and system constraints, in order to optimize the water intake of Rijnland based on agriculture damage reduction. Furthermore, the WAOR can be used to determine the effects of a water allocation strategy on the agriculture crop yield losses in Rijnland for one or multiple growing seasons. The model was built 1) to be intuitive with regards to strategy and constraint selection and 2) to facilitate easy comparison of the different strategies.

It was found that the "KWA+" expansion results in noticeable agriculture damage reductions. However, for agriculture damage reduction alone the "KWA+" is not cost-effective with its investment costs, even for the most extreme climate scenarios. The results indicate that the consequences of delaying investments in freshwater infrastructure may not be as severe as anticipated. However, prevention of damage to nature and prevention of peat degradation, resulting from exposure to water with heightened chloride concentrations, are not modelled within this study and could provide additional (monetary) benefits. Additionally, sensitivity analysis with the WAOR has shown that lowering the chloride acceptance levels will reduce the agriculture damages, while requiring more frequent implementation of alternative freshwater allocation strategies.

The WAOR delivers a holistic approach to freshwater allocation questions and allows for the assessment of the cost-effectiveness of freshwater supply related investments within coastal areas. The inclusion of climate scenarios adds to understanding on how a changing climate may impact freshwater allocation strategies and investments in the future. Furthermore, the WAOR contributes to operational management by allowing for assessment of variations in strategies and chloride norms and helps to align hydro-economical concepts with contemporary water management practices.

Keywords: Rijnland, KWA+, WAOR, freshwater allocation, hydro-economics, saltwater intrusion, crop yield

III. Contents

List of Figures

List of Tables

Glossary

Boezem	Regional surface water system at a higher elevation than a polder
Cl	Chloride
Delfland	Hoogheemraadschap van Delfland
Discharge	Volumetric flow rate of water
EC	Electric conductivity
EEO1.0	€ureyeopener1.0
Flushing	Let in water to flush out undesired concentrations in surface waters
GHIJ	Gekanaliseerde Hollandse IJssel
HDSR	Hoogheemraadschap De Stichtse Rijnlanden
HIJ	Hollandse IJssel
KNMI	Royal Netherlands Meteorological Institute
KWA	Small scale water supply
KWA+	Small-scale water supply (expanded version)
NDB	Noordelijk Deltabekken Model
NKP	Nieuwkoopse plassen
NPV	Net Present Value
Polder	Artificially drained catchment in which surface water levels in a ditch network are regulated by pumping
Rijnland	Hoogheemraadschap van Rijnland
WAOR	Water Allocation and Optimization Rijnland

Chapter 1 - Introduction

Coastal areas are typical for their interface transition between salt- and freshwater dynamics (Figure 1.1). Availability of freshwater resources in such coastal areas is of utmost importance for nature agriculture and other economic and societal functions in those regions. Rising domestic, industrial and agricultural water use increases the pressure on coastal freshwater resources. Additionally, surface waters and aquifers in coastal areas are commonly under pressure from saltwater intrusion (Vincent Post & Abarca, 2010). The Netherlands uses a lot of its freshwater resources for agricultural purposes. About 37% of human water in the Netherlands consumption is used for agriculture, while industrial use and domestic use are 58% and 5% respectively (Hoekstra & Chapagain, 2004).

Figure 1.1. Simplified overview of fresh and salt water dynamics in the Netherlands (Rijnland, 2009).

The availability of freshwater is paramount for counteracting the negative impacts of water quality degradation. In the highly populated Dutch coastal region, freshwater resources are threatened by degradation in quality and quantity as a result of both natural and anthropogenic causes (Oude Essink, 2001; Post, Van der Plicht, & Meijer, 2003). Figure 1.2 presents a multitude of features affecting coastal aquifers, which illustrates the large amount of different factors that influence water management in coastal areas. Furthermore, during long dry periods with limited precipitation, the amount of water flowing down the Rhine and Meuse rivers often declines (RIZA, 2005), resulting in a reduction of freshwater supply. Consequently, the lack of precipitation increases the demand for freshwater. Especially when shortages occur during the growing season, the reduced water quality and water availability cause reductions of agricultural crop yields and damages to nature (De Louw, Van der Velde, & T. M. Van der Zee, 2011; Stuyt et al., 2013).

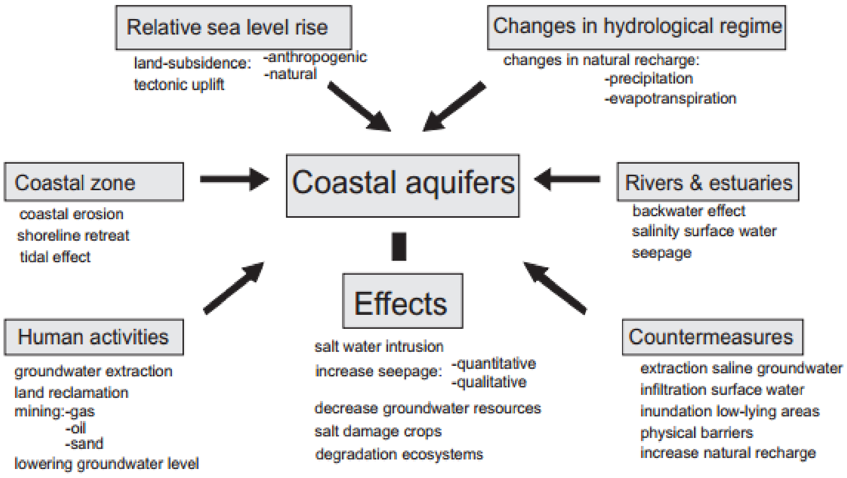


Figure 1.2. Features affecting coastal aquifers (Oude Essink, 2001).

The effects of climate change will increase the above patterns of precipitation and evapotranspiration (IPCC, 2014). In the future the occurrence of dry periods during the summer is expected to increase in the Netherlands, while low river discharges will occur more frequently (KNMI, 2015). This effect and the effect of expected (relative) sea level rise is likely to result in more frequent and more severe problems related to saltwater intrusion (Beersma, Buishand, de Goederen, & Jacobs, 2005; De Louw et al., 2011; RIZA, 2005). Important freshwater intake locations along the main rivers are therefore expected to experience more frequent salinization over longer periods of time (Arcadis, 2012).

To ensure the future availability of ample freshwater for essential purposes, such as agriculture, nature and drinking water, the Dutch Freshwater Delta Programme (Dutch: Deltaprogramma Zoetwater) has been set up to ensure the future availability of ample freshwater for essential purposes, such as agriculture, nature and drinking water. It describes how freshwater should be managed during dry periods, what measures should be taken to reduce the freshwater demand, and it aims to create a robust freshwater supply system (Deltacomissie, 2015).

One of the locations where the pressure on freshwater shortages is becoming increasingly evident is the Hoogheemraadschap van Rijnland (Figure 1.3). Rijnland is a water board in the western part of the Netherlands. It covers an area of 1070 km^2 and accommodates a population of 1.3 million (Rijnland, n.d.). Around two-thirds of Rijnland lies 3-4 m below sea level (Van Andel, Lobbrecht, & Price, 2008). Several of its areas are characterized by high-value agriculture: the “Greenports”, which are some of the most important agricultural areas of the Netherlands (Stuyt et al., 2013). Deep lying polders, such as the Haarlemmermeer Polder, experience upwards, often brackish, groundwater seepage. As a result the polders require regular flushing with freshwater to counteract the increased chloride concentrations that result from the saltwater seepage (De Louw et al., 2011). Furthermore, there are a lot of peat soils in Rijnland. These soils slowly subside when exposed to air. This process can be mitigated by keeping the water level high, which requires freshwater. While saltwater seems to enhance the subsidence (Stuyt et al., 2013). Additionally, water level retention is important to prevent irreversible damage to nature, and to facilitate the shipping industry (Arcadis, 2012).

Figure 1.3. The area of the Hoogheemraadschap van Rijnland and its surrounding area (Rijkswaterstaat, 2011).

1.1 Problem statement

Whenever Rijnland requires freshwater, water is let into the system from the Hollandse IJssel River (HIJ) at Gouda. The HIJ is a tidal river that drains its surrounding area and flows out into the Nieuwe Maas. When needed, it provides the surrounding water systems with freshwater. It is in open connection with the North Sea and therefore has tidal influence. Because of this, variations in chloride concentrations can occur as far as Gouda (~55km upstream). When the HIJ is not draining water from its surroundings and the discharge of the Rhine River is low (e.g. in the summer of 2011), these concentrations can become high, endangering the freshwater inlet at Gouda. The combination of upcoming brackish seepage in deep polders and increased chloride concentrations on the HIJ results in significant freshwater problems for Rijnland (Beersma et al., 2005; HydroLogic, 2014; Stuyt et al., 2013). To prevent salt damages to crops, inlet of water from the HIJ at Gouda is discontinued when the chloride concentration at the inlet location reaches the threshold of 250 mg/l. The inability to let in freshwater through the usual means can result in serious freshwater shortages in Rijnland. This is especially problematic for the high value agriculture in those areas of Rijnland that are particularly sensitive to increased chloride concentrations (that occur if the surface water system is not flushed by freshwater during periods without rain), such as tree nurseries and tulip fields (Stuyt et al., 2013). Up untill the present, water boards have been able to supply sufficient amounts of freshwater for the agriculture sector. However, due to increasing saltwater intrusion this could change (Brouwer & Huitema, 2007).

Future freshwater demand will increase due to the more frequent occurrence and longer duration of dry periods. Combined with the expected increase of chloride norm exceedances on the HIJ (Beersma et al., 2005; Van Beek et al., 2008), this will result in increasing difficulties in supplying the amount of freshwater necessary during the summer. In accordance with the Freshwater

Delta Programme, an alternative supply network has been developed to deliver freshwater to the boezem of Rijnland: The “Kleinschalige Wateraanvoer” (KWA; English: Small-scale water supply). Water from the KWA originates from sections of the Rhine where the water is not in danger of becoming brackish. The current KWA has been used effectively in the past, but its capacity is insufficient during severely dry periods. Efforts are underway to expand the capacity of the KWA to provide a higher freshwater service level: The “KWA+” (HydroLogic, 2015a). The KWA+ is an investment made to provide for more freshwater during future droughts. It is interesting to ascertain whether the benefits of reduced agriculture yield losses outweigh the costs of this investment. The cost-effectiveness of the investment can be assessed by comparing the costs of investment with the benefits of damage reduction.

Recent research identifies the (future) problems that the high value-agriculture in Rijnland will experience as a result of increased chloride concentrations at Gouda and recommend further investigation into this topic (De Louw et al., 2011; RIZA, 2005; Van Beek et al., 2008). Recently, Stuyt et al. (2013) created a model, the €ureyeopener1.0, to optimize the water intake in Rijnland based on the water demand of the polder systems and the chloride concentration on the HIJ. This model uses damage functions to calculate the agricultural damage by associating the resulting chloride content in the area.

Most of the literature investigates and describes how certain desired or optimal freshwater demands can be reached in Rijnland in terms of water quality and quantity. The aspect of monetary effects is often mentioned in association as an important aspect.

1.2 Research question

If a rational approach is made towards water management, should Rijnland go to extreme lengths to supply all necessary high quality-freshwater at all times? Or are certain amounts of damage to agriculture acceptable if the benefits of prevention do not outweigh costs of alternative water supply investments?

As opposed to optimal water intake reduction, this study develops and employs a Microsoft Excel-based deterministic model for optimal agriculture damage reduction. Its goal is 1) to gain insight in the water allocation practices of Rijnland, 2) to determine the optimal water inlet strategy based on cost-reduction and 3) determine the (future) effectiveness of proposed investments based on cost-effectiveness assessments.

Following this reasoning, the main research question has been formulated as:

How can a model to rationalize water management cases be developed that can support the assessment of the economic viability of implementing alternative freshwater management strategies within the western Netherlands during freshwater shortages in Rijnland and increased chloride concentrations on the Hollandse IJssel?

1.3 Objectives

To answer the research question, the following objectives will be addressed.

a) Conduct research on the current state of the fresh water supply system in Rijnland.
b) Formulate scenarios and different strategies for freshwater allocation in Rijnland.
c) Create a comprehensive and easy-to-use model in which different water allocation strategies can be compared in terms of monetary costs and benefits over multiple decades.
d) Analyze the sensitivity of the model to important input parameters by conducting a sensitivity analysis.
e) Analyze and discuss the model results and implications for theory and practice.

1.4 Relevance for society, science and the internship company

This section will discuss the relevance of the research topic with regards to Dutch society, the scientific literature and the internship company

During its history, Dutch **society** as a whole has been influenced strongly by the necessity to cope with water and the accompanying threats and benefits (chapter 2.4). Protection measures and water allocation agreements required collaboration of stakeholders, which was facilitated through the water boards. Traditional strategies often involved building water management infrastructure, such as dykes, windmills and sluices (Borger & Ligtendag, 1998). Nowadays, the increased availability and accessibility of accurate real-time (big-)data allows for water resources to be guided in a much more efficient manner. This efficiency will allow for more stretching of the available resources within waters systems and allows for delaying the necessity or frequency of large-scale infrastructure investments (HydroLogic, 2015b). The current views on the chloride acceptance levels may be too pessimistic as there are indications that many crops have a higher salt tolerance than assumed by water managers. A lot of areas have different chloride norms. There is no clear view on the best chloride norm level and there is ambiguity in its standardization. To allow for better freshwater solutions, instruments and methods are required to facilitate a shared understanding and commitment towards salt related water policy (Stuyt et al., 2015). This study will contribute to the above developments by providing a comparison between investment costs and the use of currently available resources and different water allocation strategies. Simultaneously it provides insights in the implications of heightened chloride concentrations for agriculture.

A topic that is currently researched by HydroLogic (the **internship company**) is Smart Watermanagement (SWM). SWM means using available water resources as effectively and efficiently as possible to optimize operational management. It involves using information services and looking across traditional management borders to make informed and deliberate decisions and to use the existing water system to its potential. SWM concept was introduced within the Delta Programme, causing it to receive explicit attention from water managers in the Netherlands. It can be used to manage areas during situations of extreme high water levels or freshwater shortages, but it can also facilitate catchment-wide cost reductions during regular situations. During freshwater shortages SWM means to prevent damages by using every available freshwater resource within the system as effectively as possible (HydroLogic, 2015b). This study will contribute by assessing the optimal economical usage of the available resources. The created model will have the ability to analyze historical data, while simultaneously having the ability to provide support for decision makers with advice on water allocation strategy when faced with freshwater problems in Rijnland.

Furthermore the research fits within the concept of hydro-economics (chapter 2.6), a field of **science** that incorporates both hydrology and (socio)-economic principles to facilitate decision making in water management. Hydro-economics encompasses the use of models that rationalize water management by determining optimal water allocation (Bierkens, 2015; Harou et al., 2009; Reca, Roldán, Alcaide, López, & Camacho, 2001). Reca et al. (2001) describe the relevance of models optimizing water management as an alternative to increasing the supply. There are increasing problems with unsustainable depletion of both surface and groundwater resources. This is most evident in drier regions in the world, such as the Mediterranean, where around 80% of the available freshwater is used for agriculture and freshwater resources are under heavy pressure. However, it is also interesting to explore this topic in a region where water quantity is often sufficient, but where the demand for freshwater of high quality is large. In the Rijnland case, both these elements are present: the use of the system as it is now, and the investigation of the costs and benefits of the proposed capacity investments. The study aims to contribute to hydro-economics by providing a new model and to gain new insights into the effects and possibilities of rationalizing water management.

1.5 Structure of the thesis

Chapter 2 will provide the theory and background of the thesis. The research area and its freshwater dynamics will be described and relevant (hydro-economical) concepts will be explained. Chapter 3 presents the development of the WAOR model, wherein all the functionalities of the WAOR will be explained. Chapter 4 covers the results of the WAOR model, including an analysis of the cost-effectiveness of the *KWA+* and a sensitivity analysis of the WAOR. In chapter 5, the findings of the WAOR will be discussed. The implications, relevance and limitations of the results will be discussed and recommendations for additions to the WAOR will be provided. Finally, chapter 6 will deliver the overall reflection on the used methodology, the conclusion and the overall recommendations based on the outcome of the research.

Chapter 2 - Theory and Background

Chapter 2 addresses the theoretical foundations and background for his thesis. It describes the used terms in this thesis and it sheds light on the research context and several possible alternative water management strategies for study will be introduced. Furthermore, the concept of hydro-economics will be explained, which then will be nuanced to further explain the theoretical reasoning underlying this thesis.

2.1 Description of used terms

This section provides short explanations of important terms used in this thesis.

Boezem: A "boezem" is a regional surface water system at a higher elevation than a polder. It is used for buffering polder water (De Louw et al., 2011). When polders have an excess of water, the excess is pumped into its surrounding boezem. During water shortages, water is let into the polder from the boezem (Figure 2.3).

Discharge: Discharge is the volumetric flow rate of water. In this thesis, the water in the boezem system has a certain discharge as it travels through the system. Pumping stations are limited in their capacity by a maximum discharge. Discharge is measured in cubic meters per second (m^3/s).

Dry period: In this thesis a dry period is defined as a situation which is drier than the long standing average during that period and caused by variability in precipitation and evaporation (Peters, 2004). Dry periods can often coincide with freshwater shortages; however, this is not necessarily always the case.

Flushing: During some situations, such as dry periods, undesirable concentrations can occur in water systems, such as heightened chloride concentrations. In order to lower these concentrations water is let into these systems to "flush out" these concentrations. This requires water of better quality than the water currently present in the system (De Louw et al., 2011). For polders this means that they let in water from the boezem with better quality.

Polder: A "polder" can be defined as an "artificially drained catchment in which surface water levels in a ditch network are regulated by pumping". Polders are enclosed by dykes to provide protection against flooding (De Louw et al., 2011), and usually obtain water from three main sources: Precipitation, water admission from the boezem and upcoming groundwater seepage. When necessary, polders can either receive water from the boezem or pump excessive water out into the boezem.

2.2 Area Description

The research area of this thesis is the Hoogheemraadschap van Rijnland. Rijnland has a population of around 1.3 million people in 33 municipalities, covers an area of 1070 km^2, of which 11.5% is surface water, and has around 11.000km worth of managed water channels. Rijnland contains 206 different polders. As a result of soil subsidence caused by land cultivation, the first polders came into existence around 1330 (Hoogheemraadschap van Rijnland, n.d.-b). Rijnland has several relatively deep polders, such as the Haarlemmermeer polder and the Noordplas polder. These deep polders came into being due to the history of peat extractions in Rijnland. Layers of peat were removed to be used as a fuel source. Due to the resulting elevation differences, lakes formed in these former peat areas. Simultaneously, these lakes were able to expand due to shore erosion. Later, a lot of these lakes were reclaimed by pumping out the water, resulting in (deep) polders (Hoogheemraadschap van Rijnland, n.d.-b).

There is a large variation of agricultural activity in Rijnland. There are vast amounts of grasslands for livestock, in the (deep) polders crops such as potatoes, corn and grain are being grown and there are three “greenports” which represent large economic value: “Aalsmeer”, the “Bollenstreek”, and “Boskoop”. In greenhouses around Aalsmeer a wide variety of flowers and vegetables is grown. West of this area, the Bollenstreek contains the famous Dutch tulip fields, while Boskoop harbors the world’s largest floriculture and arboriculture (tree nurseries) area (Stuyt et al., 2013).

Figure 2.1 and Figure 2.2 give an overview of Rijnland. The main freshwater intake location of Rijnland is at Gouda, where during dry situations water is let in under free fall from the Hollandse IJssel (HIJ). From here, freshwater is distributed through the boezem to the polders. Figure 2.3 shows a schematization of the Rijnland water system during times of water shortage and water surplus. When there is a shortage of water, the polder will demand water from the boezem system. This water is admitted from the boezem, which in turn receives water from the HIJ River. During water surplus, the polder discharge excess water onto the boezem system. Subsequently, the boezem discharges its excess water onto the sea at Katwijk, onto the Noordzeekanaal at Spaarndam and Halfweg, and (back) onto the HIJ at Gouda.

Figure 2.1. Schematization of the Rijnland boezem system during flushing and locations of polders with salt seepage. (Rijnland, 2009).

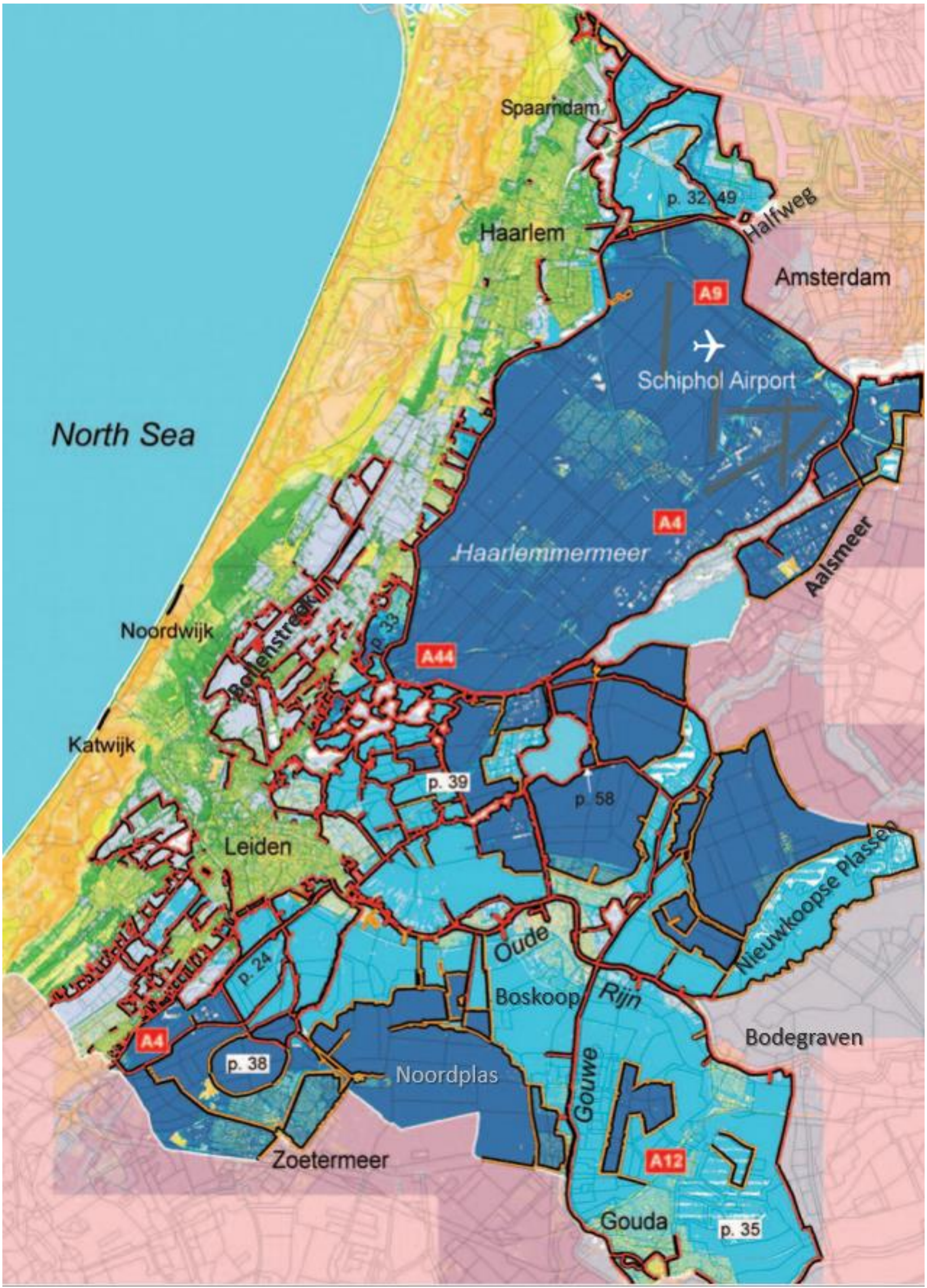


Figure 2.2. Overview of the Hoogheemraadschap van Rijnland. Legend: Red: Dykes of the Boezem system. Yellow: Smaller Polder levees. Dark Blue: Deep Polders. Light Blue: Peat meadow areas (Rijnland, 2013).

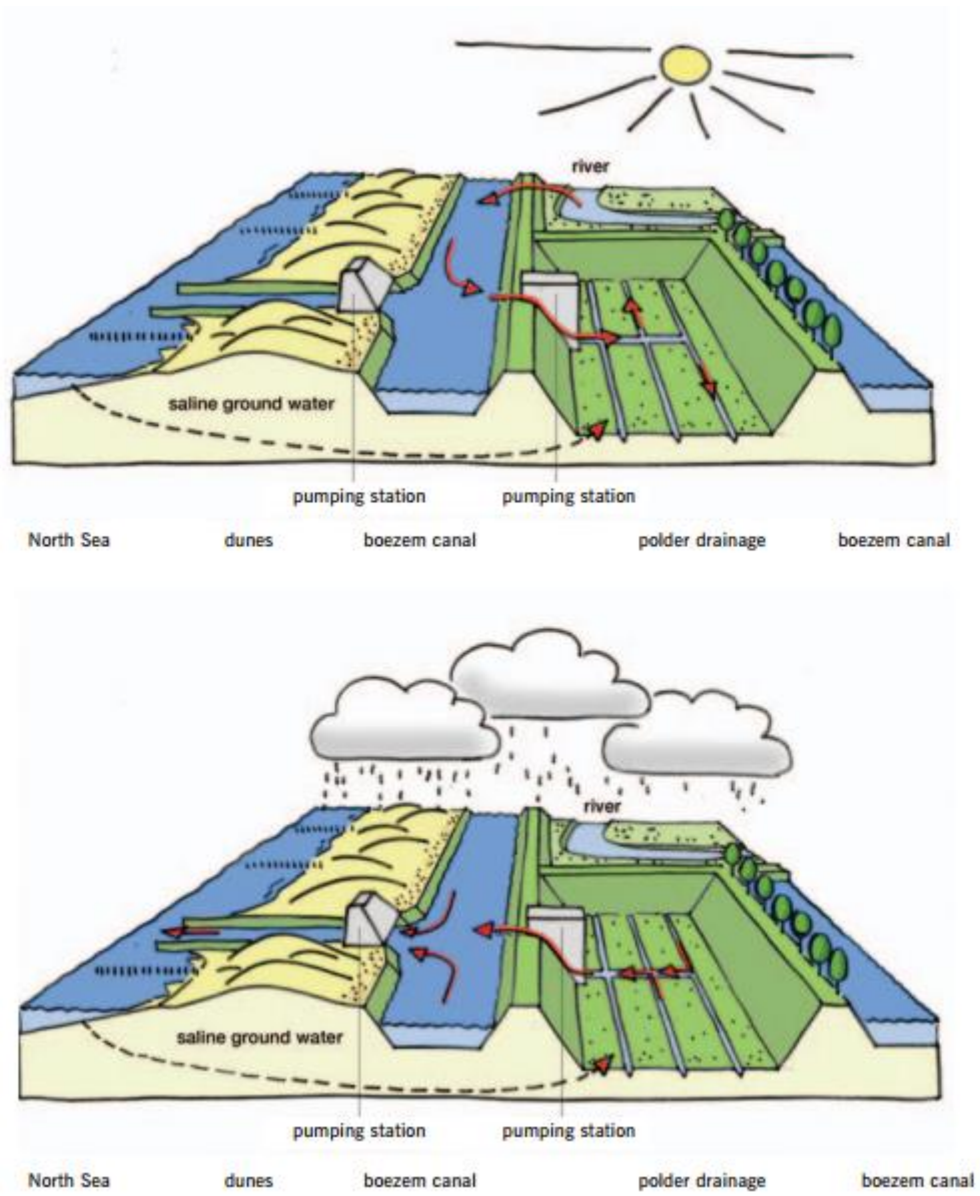


Figure 2.3. Schematisation of the Rijnland water system during water shortages (top) and water surplus (bottom) (Rijnland, 2013).

In this thesis Rijnland has been divided into 9 distinguishable polder systems (Figure 2.4):

The Greenports:

- Boskoop (BK): The world's largest floriculture area with famous tree nurseries (arboriculture).
- Bollenstreek (BS): Region with high-value flower-bulb fields
- Aalsmeer (AM): Contains large numbers of greenhouses horticulture and is home to the world's largest flower auction.

The deep polder systems:

- Noordplas/Middelburg-Tempelpolder (NPMTP): A large (combined) polder in the southern part of Rijnland.
- Haarlemmermeer (HMM): The largest polder in Rijnland (contains Schiphol International Airport).

Other systems:

- Zuidelijke Veenpolders (ZVP): The southern peat polders.
- Overige Polders (OV): All other polders not classified into one of the other systems
- Duingebied (DG): The coastal dune area.
- Nieuwkoopse Plassen (NKP): A large natura 2000 nature area in the eastern part of Rijnland.

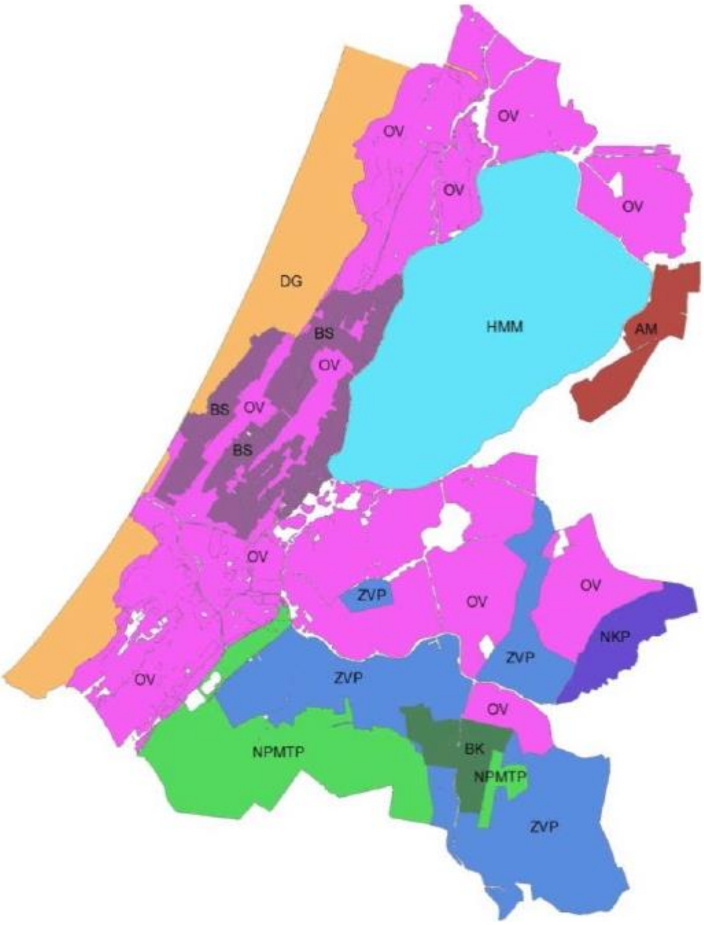


Figure 2.4. Combined polder systems in Rijnland (Deltares, 2015b).

2.3 Saltwater Intrusion

Rijnland is subject to two main sources of saltwater intrusion:

- External saltwater intrusion, originating from brackish water on the HIJ.
- Internal saltwater intrusion from the exfiltration of brackish of saline groundwater to the surface water system of the (deep)-polders.

2.3.1 External Salt Intrusion

External salt intrusion is caused by intrusion of salt water from outside surface water sources into the water system of Rijnland. For Rijnland this is relevant for the inlet location at Gouda. Due to the open connection with the sea, chloride concentration differences can occur as far as Gouda. Sea-water can enter the Rhine-Meuse estuary trough the Nieuwe Waterweg and the Nieuwe Maas (Figure 2.5). Salt water intrusion can occur at the mouth of the HIJ river at Krimpen aan de IJssel when the following situation(s) occur (HydroLogic, 2014):

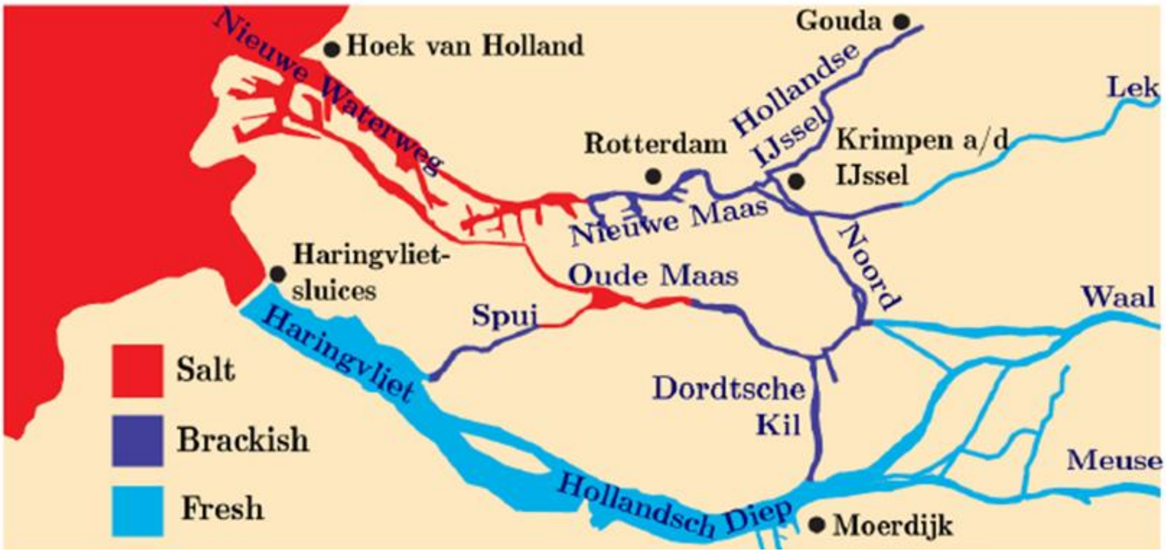


Figure 2.5. External salt water intrusion (Rijkswaterstaat, 2011).

- The discharge of the Rhine at is lower than 1200m^3/s at Lobith (where the Rhine enters the Netherlands)
- There are low amounts of precipitation, which causes a lack of drainage from the surrounding water systems onto the HIJ. In turn, this results in no water flowing down the HIJ to flush out the brackish water from the mouth of the river.
- Water is being let in at Gouda while there is salt influence at the mouth of the HIJ, pulling the "salinization front" upstream.

Figure 2.6 shows the route by which brackish water on the HIJ can flow upstream from Krimpen aan de IJssel. Due to tidal effects a "salinization front" can move upstream from the mouth of the HIJ. The influence of this tidal "advection" effect results in the front moving upstream by around six kilometers. The chloride concentration can increase further upstream due to the process of "dispersion". This process is a combined action of mixing of brackish water with freshwater and turbulence. The speed by which the salinization front can move upstream is enhanced when there is simultaneous abstraction of freshwater at Gouda, which causes an additional pulling effect in the upstream direction (HydroLogic, 2014). Climate change will affect the intensity of the external saltwater intrusion, due to rising sea levels and longer and more frequent low Rhine discharges (HydroLogic, 2015a).

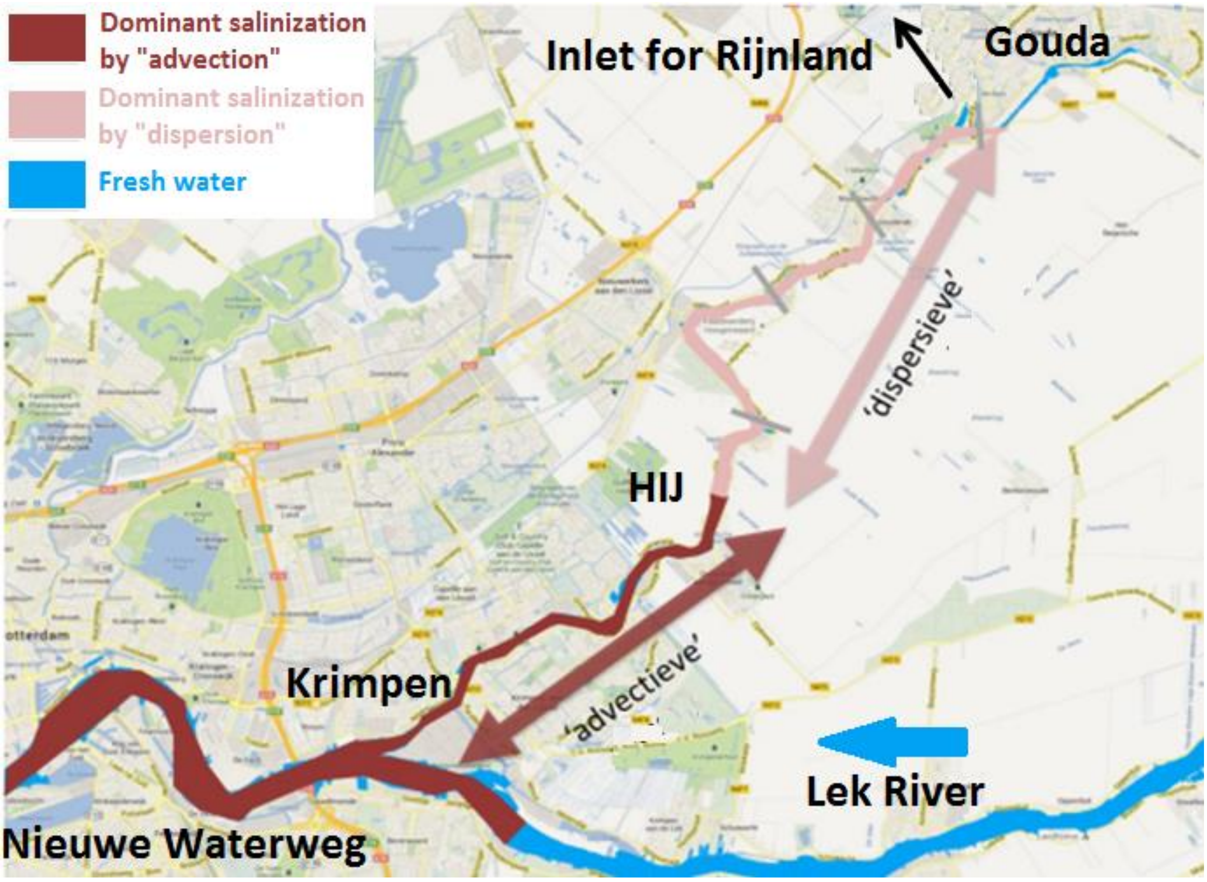


Figure 2.6. Salt intrusion on the Hollandse IJssel towards the Gouda inlet. The dark red route shows extent the tidal advection effect, while the light red route shows the part of the HIJ that gets influenced by dispersive salt intrusion (modified from HydroLogic, 2014).

2.3.2 Internal saltwater intrusion

Internal saltwater intrusion seepage derives from upward groundwater seepage within the polders in Rijnland. Deep polders are a significant source of internal salt intrusion. provides a schematization of the geohydrology of a low-lying polder system in the Netherlands. The upper layer of the polder is a confining layer of Holocene peat, loam and clay deposits. The underlying layers originate from the Pleistocene and contain brackish to saline groundwater. Due to the hydraulic head difference between the surface water in the deep polders and the surrounding areas there is a permanent upward groundwater seepage flux in the deep polders (diffuse seepage). Due to the confining layer, the rate of this seepage is low. However, at some locations parts of the confining layer have been eroded in the past due to streams and tidal channels, resulting in sandy belts (Berendsen & Stouthamer, 2000; de Louw, Oude Essink, Stuyfzand, & van der Zee, 2010). Because of differences in permeability, these belts result in upward preferential flow paths between the surface water and the Pleistocene aquifers beneath the Holocene confining layer (paleochannel seepage), which allow the groundwater to flow in the surface direction relatively quickly. Even more localized forms of this preferential flow of saline groundwater are seepage boils, which are commonly found in deep polders. These boils are small apertures that connect the underlying aquifer with the surface water, by which water discharges at relatively high rates. Furthermore the chloride content of this water is often higher than the other types of seepage, as it originates partly from deeper more saline groundwater. As a result of this seepage, brackish groundwater discharges into the surface water system of the polder. Preferential flow through the seepage boils is the largest source of salt intrusion into deep polders (de Louw et al., 2010). Since the deep polders were reclaimed, deeper more saline groundwater is gradually moving upward. Therefore, the chloride concentration of the internal groundwater seepage is expected to increase in the future (Deltares, 2015a).

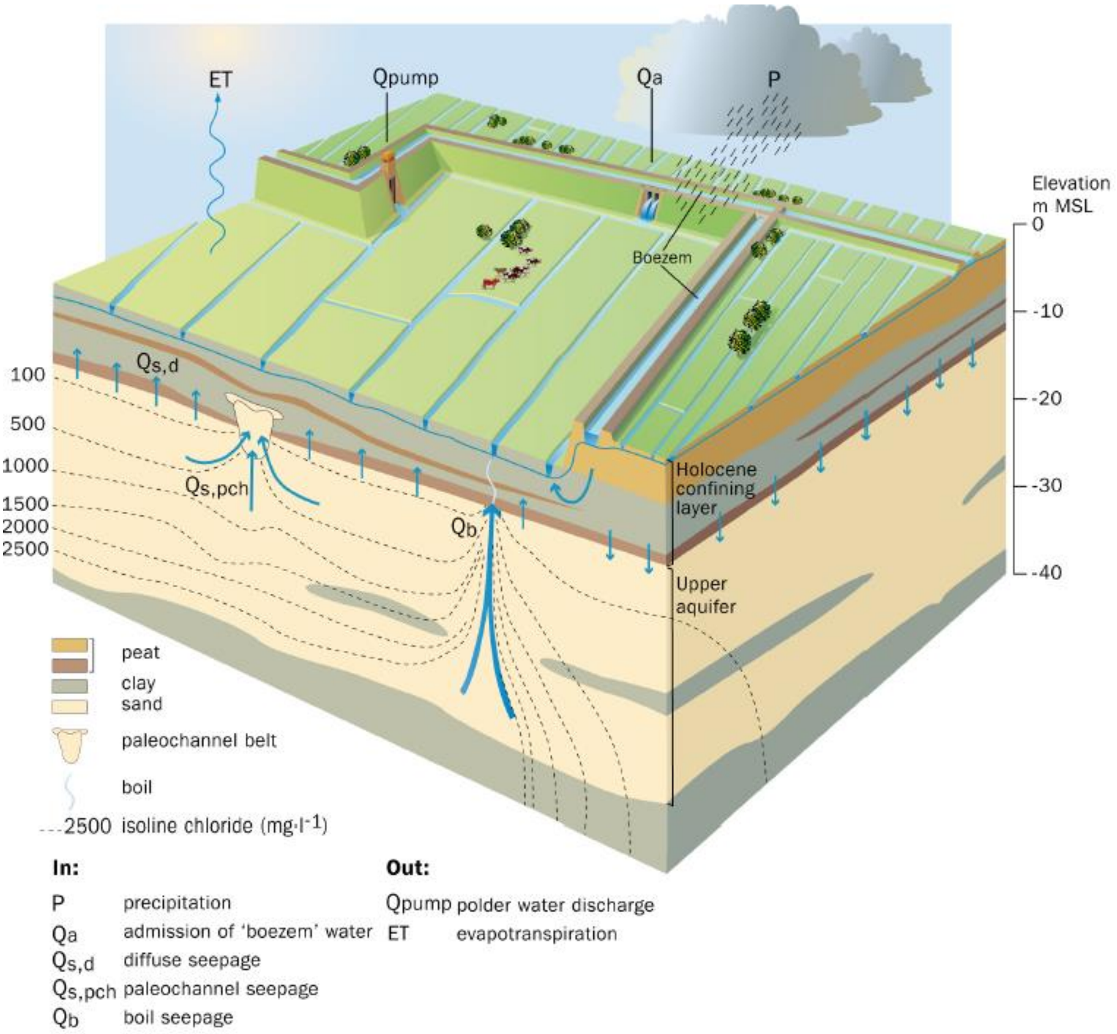


Figure 2.7. The geohydrology and (salt)-water fluxes in a polder catchment. Distinction is made between diffuse-, paleochannel- and boil seepage. Deeper layers contain higher chloride concentrations (De Louw et al., 2010).

2.4 Chloride vulnerability of crops

Salt damages occur when crops are irrigated with water with high chloride content or when brackish groundwater reaches the root zone of crops due to capillary action. Once the salt reaches the root zone of a crop, it increases the osmotic potential, resulting in a restriction of water intake of the roots, and leading to reductions in growth rate and therefore crop yield (Stuyt et al., 2006).

The saltwater intrusion has consequences for agriculture crops in Rijnland. As explained in section 2.2, Rijnland harbors a lot of different agriculture activities. Consequently, these crops have varying requirements for the quality of their irrigation water. Crops differ in their resistance to chloride. While some crops have low tolerance for heightened chloride concentrations, such as tulips and tomatoes, others are much more tolerant, such as potatoes (Stuyt et al., 2015). Maas & Hoffman (1977) investigated the effects of salt tolerance of crops and associated crop yield reduction with the electric conductivity (EC) of the water. It was found that crops can be classified into different categories based on their tolerance to salinity (Figure 2.8). Furthermore, they found that crops have a certain salinity tolerance threshold. When concentrations exceed this threshold, crops begin to suffer from yield losses (Figure 2.9). Additionally, crops have varying tolerance to chloride concentrations during their growth cycle, with some crops being especially intolerant to salt during early stages of development, such as tree seedlings (Stuyt et al., 2013).

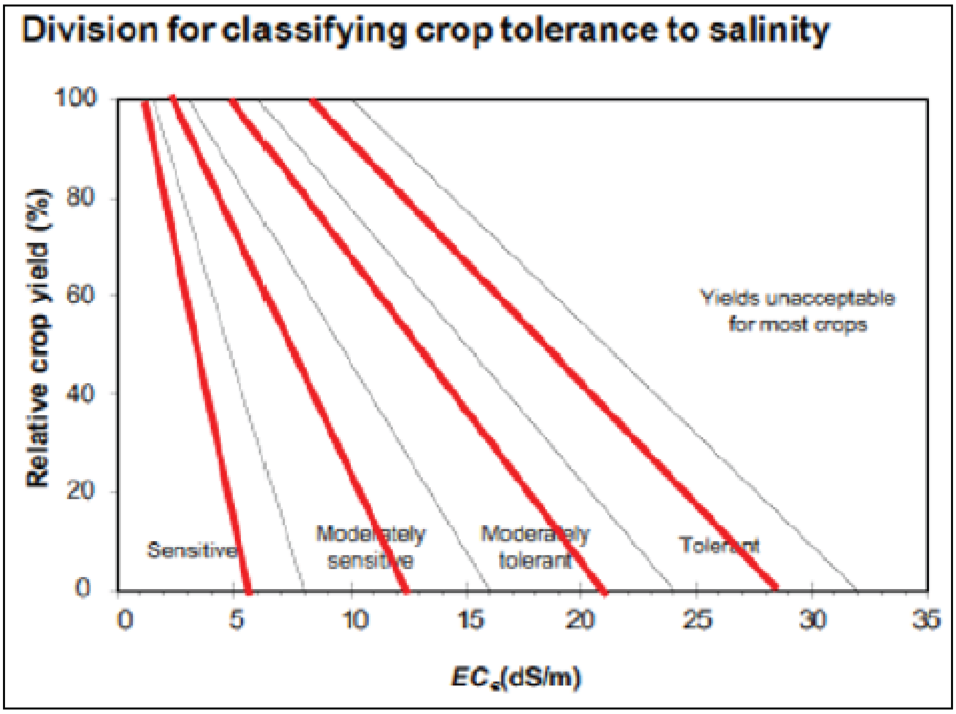


Figure 2.8. Relation between the relative crop yield and electric conductivity on crops with different gradations of salinity tolerance (Maas & Hoffman, 1977).

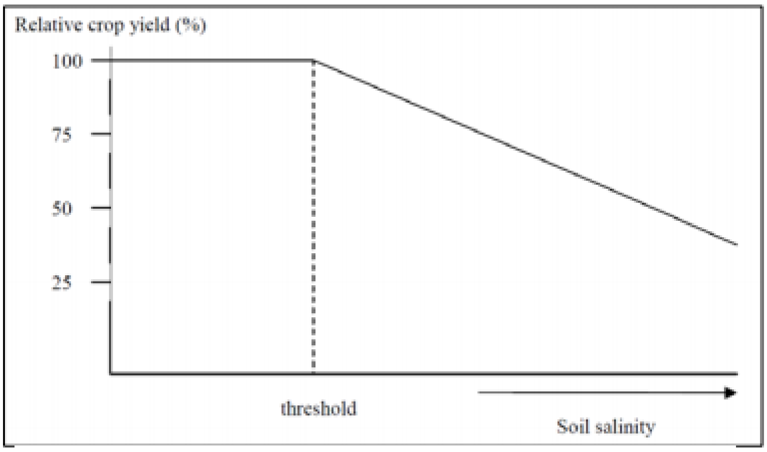


Figure 2.9. Soil salinity threshold. Whenever the chloride concentration exceeds this threshold (which is crop specific), the relative crop yield will begin to decline (Maas & Hoffman, 1977)

2.5 The kleinschalige wateraanvoer (KWA)

Due to the discussed salt intrusion issues, Rijnland has policy in place to prevent heightened chloride concentrations in the polders. Whenever chloride concentrations on the HIJ in the direction of Gouda exceed the chloride norm of Rijnland (250 mg/l), abstraction of water from the HIJ at Gouda is ceased. When this coincides with water demand from the polders (i.e. limited precipitation), an alternative water supply route is put into motion: The Kleinschalige Wateraanvoer (KWA). By this alternative supply route, water is supplied from (for Rijnland) alternative sources (Figure 2.10) than those used for Rijnland in customary situations. This water originates from the Amsterdam-Rijnkanaal and the Lek River, which are not endangered by saltwater intrusion. The transport of water from these locations to Rijnland is facilitated by the water system of Hoogheemraadschap De Stichtse Rijnlandsen (HDSR), the neighboring waterboard. It enters the Rijnland boezem system at Bodegraven, to provide freshwater to the water demanding polder systems (HydroLogic, 2015a).

Figure 2.10. Route of the KWA(+). The Red arrows indicate the routes by which freshwater is supplied to Rijnland when the KWA(+) is active. During regular situations freshwater is let in at Gouda (Modified from Hydrologic, 2015a).

The KWA will be implemented when the following conditions are met (Hydrologic, 2015a):

- Chloride concentrations at the mouth of the HIJ at Krimpen a/d Ijssel are higher than 200-250 mg/l.
- The discharge of the Rhine at Lobith (where it enters the Netherlands) is lower than 1100m^3/s.
- It can be expected that this situation will persist for some time, combined with water demand from Rijnland.

The year 2011 was the last time that the KWA was used. In 2011 the KWA was barely sufficient, and due to some positive mitigating circumstances, such as precipitation at the right moment, it managed to supply Rijnland with enough freshwater. In the agreements on the KWA, Rijnland is required to provide a portion of the freshwater from the KWA to the waterboards of Delfland and Schieland en de Krimpenerwaard. However, in 2011 these waterboards did not require this water and they could be supplied from the Brielse Meer (De Groot, 2012). In its current form the KWA cannot provide Rijnland with enough freshwater to satisfy the theoretical (maximum) water demand during dry periods (HydroLogic, 2015a).

The KWA+

Even though the current KWA has been used effectively in the past, there are concerns about the capacity that it provides. The current capacity is insufficient for the entirety of Rijnland's summer water demand (HydroLogic, 2015a). Furthermore, the future climate change is expected to increase the water demand, while simultaneously providing more frequent and severe salt intrusion problems on the HIJ. These facts have been acknowledged within the Delta Programme. Therefore expansion of the KWA is underway to increase the capacity from 6.9 m^3/s to 15 m^3/s: "the KWA+". The KWA+ consists of two expansion measures:

1) Creation of a freshwater buffer on the Hollandse IJssel to allow a (limited) amount of freshwater to be let in at Gouda. This buffer can be realized by letting in water from the Gekanaliseerde Hollandse IJssel (GHIJ) onto the HIJ through the Waaiersluis. By this route 4.5 m^3/s of freshwater can be supplied from Gouda (Figure 2.11). It is important to implement this measure on time, before the brackish water has travelled far upstream on the HIJ. If not, brackish water will need to be flushed out first, which will require more freshwater for implementation.

2) The regional water supply towards Bodegraven will be expanded from 6.9m^3/s to 10.5 m^3/s. This will be achieved by widening or deepening channels upstream and by replacing bridges by variants with larger through flow (HydroLogic, 2015a).

Figure 2.11. Freshwater buffer on the Hollandse IJssel for the KWA+. Water is supplied from HDSR through the Waaiersluis. By limiting the water abstraction at Gouda a "freshwater buffer" is created (modified from HydroLogic, 2014).

2.6 Climate Scenarios

In this thesis climate scenarios from the KNMI will be used (KNMI, 2015). Within these scenario's insights are provided in how the climate in the Netherlands will change in the future. There are four KNMI'14 climate scenarios for both 2050 and 2085. The difference of the four scenario's lies within expected global sea temperature rise and change in air circulation patterns. The four scenarios are:

- GL: Moderate global temperature increase and minimal changes in air circulation patterns
- GH Moderate global temperature increase and noticeable changes in air circulation patterns
- WL: strong global temperature increase and minimal changes in air circulation patterns
- WH: strong global temperature increase and minimal noticeable in air circulation patterns

The "H" scenarios have a relatively large change in temperature both in summer as in winter, and a (relatively) strong decrease in summer precipitation. The "L" scenarios have relatively low temperature changes and a moderate change in summer precipitation. The WH scenario is considered to be the most extreme as it results in the largest change in precipitation and evaporation patterns.

For future chloride concentrations on the HIJ the older KNMI'06 scenarios will be used, as modelled concentrations with the KNMI'14 scenarios were unavailable for this thesis. Further information on the application of the climate scenarios in this thesis is provided in section 3.4.3.

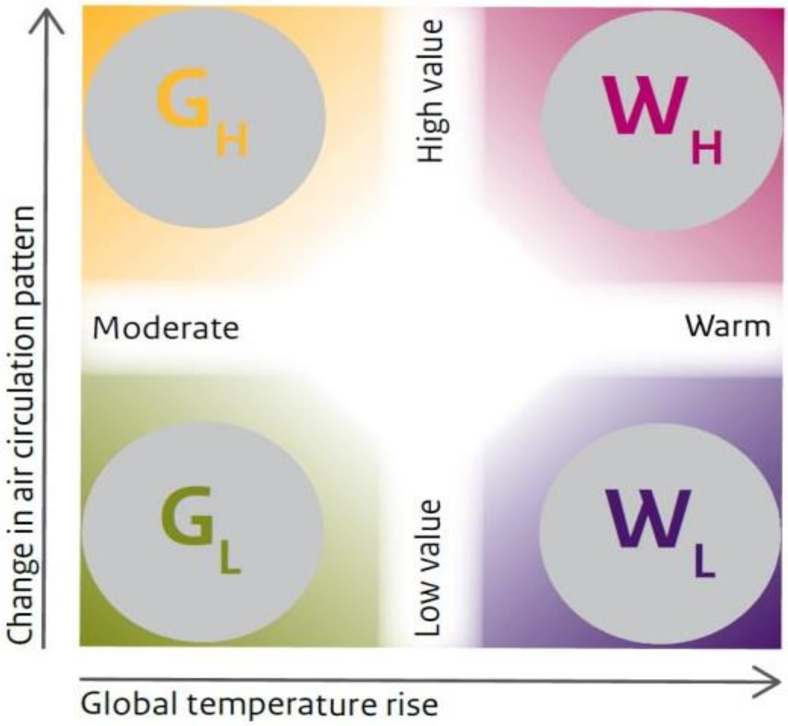


Figure 2.12. KNMI'14 Climate Scenarios (KNMI, 2015).

2.7 The Hydro-economics of freshwater management

Over the past 50 years, Hydro-economics has become an established field within water resources (Bierkens, 2015; Harou et al., 2009). It is a field of science that incorporates both hydrology and (socio)-economic principles to facilitate decision making in the field of water management. Economic principles assist in changing static views of water demand, defined through water rights and agricultural and industrial water demands, towards a view of water demand that leans more towards the economic concept of value (Harou et al., 2009). This value is often socio-economic in nature, as generated value is not limited to a single economic agent (e.g. cost reduction for a water board), but also encompasses costs and benefits for the wider society (e.g. lowered quality of nature).

Smart Water Management (SWM) fits within Hydro-economics. It contains hydrological practices, most notably allocation of (fresh)-water resources. It also includes socio-economic interests through effects on economic activity, productivity of agriculture, freshwater consumption and flood risk. Hydro-economics is potentially very useful for SWM as it allows analysis and support on how every available freshwater resource in a system can be utilized in the most (cost-)efficient way.

Hydro-economic models have been developed and used on subjects such as water prizing, water allocation and water infrastructure investments. These models are economic because they use economic valuation of water management options (Bierkens, 2015). Early examples of the usage of hydro-economic models consist of water allocation and optimization models in arid regions (Harou et al., 2009). There are also hydro-economic flood risk management models, where economic damages caused by inundations are calculated using tools such as depth-damage curves (de Moel & Aerts, 2011). Another example is the €ureyeopener1.0 model described by Stuyt et al. (2013), which assesses the effects of inlet water with different chloride concentration (mg/l) on damages to crops and nature. Models such as these use crop-water production functions to derive information of agricultural productivity of crops (Harou et al., 2009).

Hydro-economics is likely to become an increasingly important subject in the future, as climate change will cause extreme hydrological events to occur more frequently and a growing world population and the increase of economic activity will put an increasingly large burden on (fresh)-water resources. (Harou et al., 2009). These developments will likely result in all sorts of socio-economic consequences. Insight in the hydro-economics involved with the allocation of water resources will provide a contribution to the increasing amount of attention that hydro-economics receives within both governance and the scientific community.

Chapter 3 - Materials & Methods

Chapter 3 addresses the development of the **W**ater **A**llocation and **O**ptimization **R**ijnland model (WAOR). Developing the WAOR for water allocation strategy selection was a large part of the thesis research. First, the EEO1.0 model upon which the WAOR has been build will be described. Then, the modeling approach is discussed after which all components that were added into the WAOR will be discussed and the different water allocation strategies will be introduced. Finally, the assumptions underlying the WAOR model will be discussed.

3.1 The €ureyeopener 1.0

The €ureyeopener 1.0 (EEO1.0), developed by Stuyt et al. (2013), was used as a foundation upon which to build the WAOR model. The EEO1.0 is a spreadsheet-based analysis instrument that provides insight into the effects of chloride concentration of inlet water at Gouda and chloride norms of the polder systems on the water demand. It uses the water allocation strategy of Rijnland as a reference situation. Its purpose is to quickly evaluate measures, such as decreasing chloride norms of certain polder systems, changing land-use or disconnecting certain systems from the main water system.

The EEO1.0 uses a water distribution system (Figure 3.1) wherein water flows through the boezem. Individual polder systems demand certain quantities of water (section 3.1.1). It optimizes the water inlet to be as low as possible, while still letting in enough water to supply and flush the polder systems. By using damage functions, the EEO1.0 translates the amount of damage to crops based on the chloride concentrations within each polder. Every polder has separate damage functions based on the quantities and types of crops that are cultivated within that polder. As discussed in section 2.2, some areas in Rijnland are specialized in high value crops, which simultaneously being vulnerable to chloride concentrations. This causes some polders to be significantly more vulnerable to heightened chloride concentrations than others.

Tolerant crops can withstand higher levels of electric conductivity (EC) than sensitive crops before they begin to experience yield losses (Figure 2.8). In regional waters in the Netherlands chloride content is usually measured instead of EC. Stuyt et al. (2011) describes how chloride content can be used to replace EC for relative crop yield functions. After this, these functions were used to create the polder specific damage functions found in the EEO1.0. For a detailed explanation on how these damage functions were derived see Stuyt et al. (2013). Figure 3.2provides a simplified overview on the components of the EEO1.0.

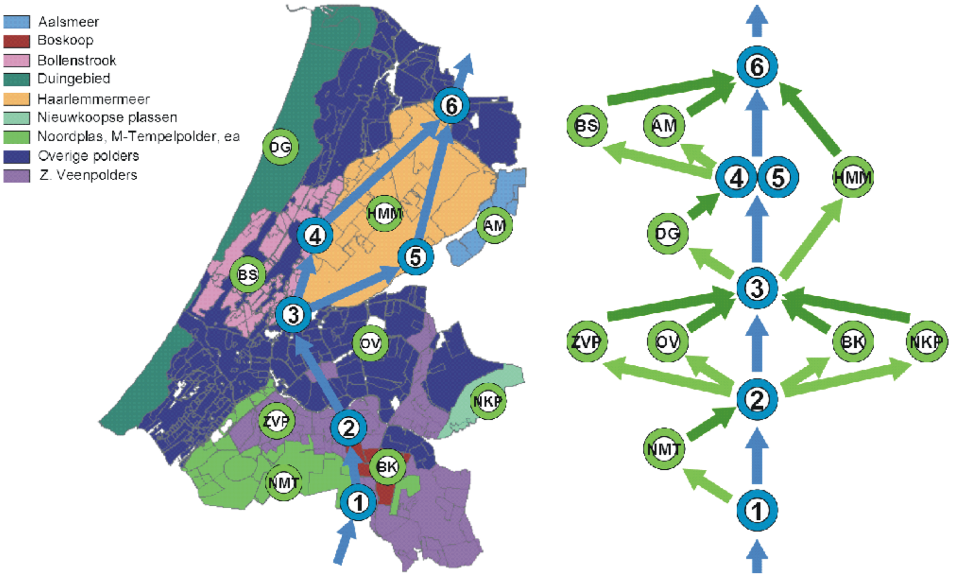


Figure 3.1. Polder-boezem system as used in the EEO1.0 (Stuyt et al., 2013)

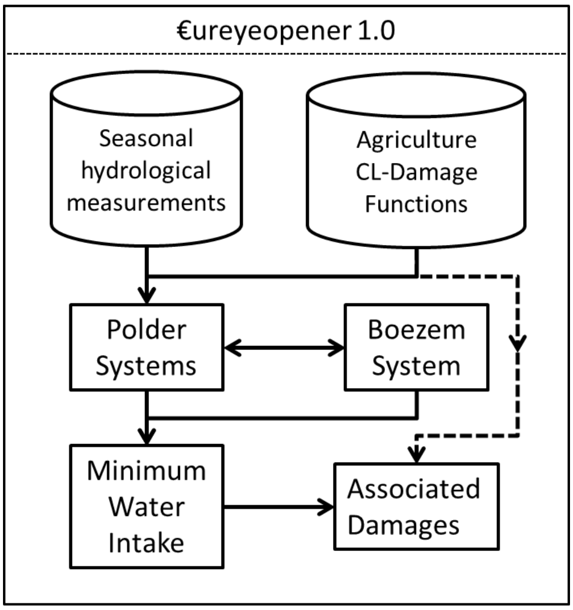


Figure 3.2. Model procedure of the €ureyopener1.0

3.1.1 Polder water- and chloride balance.

Stuyt et al. (2013) have divided Rijnland into separate polders systems. These systems have a certain water demand based on a unique water balance. They are designed so the water levels must remain equal at all times. If water demand and evaporation result in a negative balance, the polder system will demand water from the boezem system to fill the deficit.

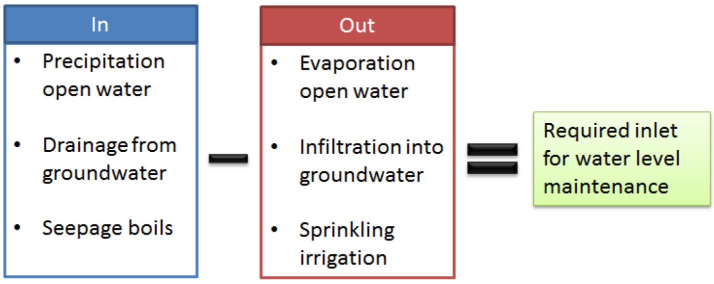


Figure 3.3. Polder water balance (Stuyt et al., 2013)

The EEO1.0 contains water balances for the surface water system within every polder system. These water balances calculate the amount of inlet water required for water level maintenance. The balance is calculated by using the water balance in Figure 3.3.

- **Precipitation open water** is the amount of precipitation that falls directly on the polder water.
- **Drainage from groundwater** is the amount of water that drains from the groundwater table into the ditches, after precipitation events this is usually high.
- **Seepage Boils** are caused by upward groundwater seepage. In deep polders seepage boils usually contain high chloride content (see section 2.3.2) and are a main reason why these polders require flushing (de Louw, van der Velde, & van der Zee, 2011)
- **Evaporation open water** is the amount of water that evaporates directly from the polder water.
- **Infiltration into groundwater** is the amount of water that infiltrates from the polder water into the groundwater. During dry periods this is usually high, because the groundwater table is often lower than the water level in the ditches.
- **Sprinkling irrigation** is the amount of polder water used for irrigation.

Evapotranspiration is abstracted within the other parts of the balance. If there is high evaporation there will be more infiltration and increased use of sprinkling irrigation, while during periods with high precipitation there will be more drainage. Figure 3.4 provides a schematization of this polder balance. Water level maintenance is always required. If the balance is negative, the polder system will let in water to fill the deficit. This water has the same chloride concentration as the water in the boezem at the inlet location, ignoring the chloride norm in place for the polder. Changes in storage are also neglected in the balances.

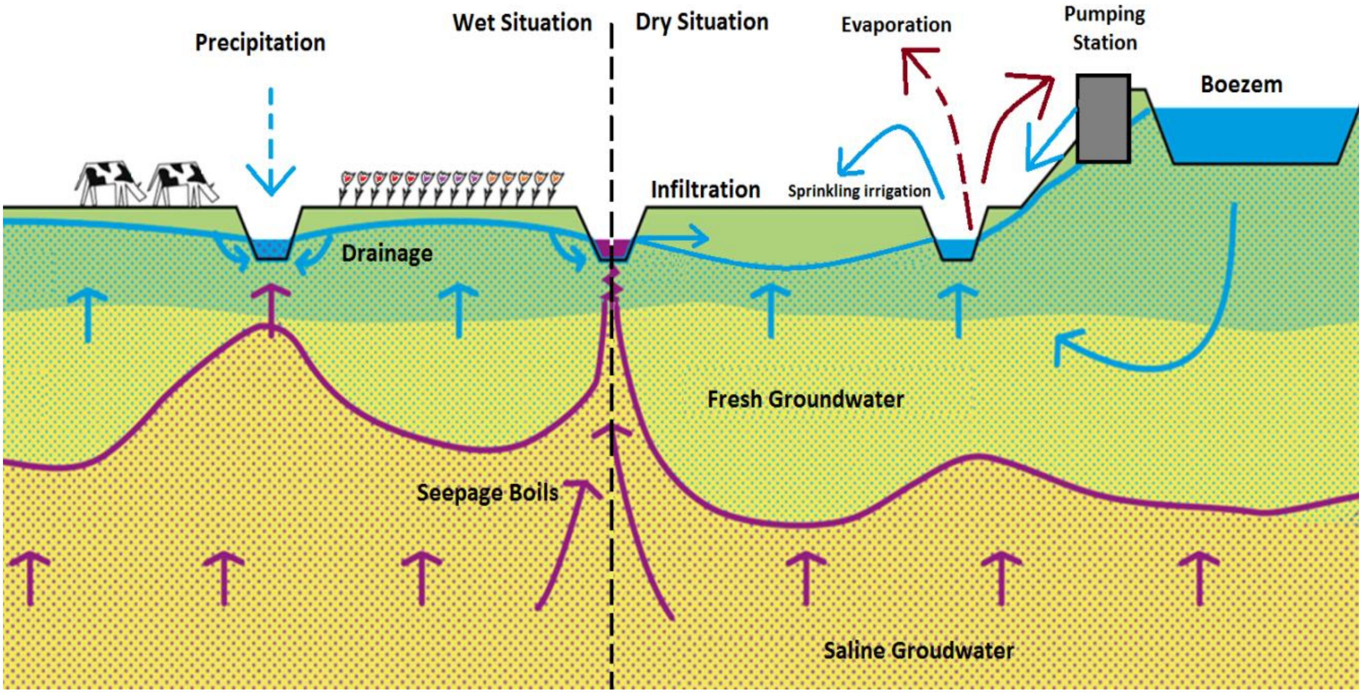


Figure 3.4. Schematisation of the polder water balance. The blue lines represent the movement of water and the groundwater table. The purple lines represent the deeper saline groundwater, which reaches the middle ditch. The left side shows the groundwater table during a wet period, while the right side shows it when it is dry (Modified from Stuyt et al., 2013).

As a secondary function the polder systems demand water from the boezem to ensure that the chloride content in the polders does not exceed the chloride norm specified for that polder system. The chloride balance in the system is coupled to the water balance, with each term in the water balance having a chloride value assigned. These are different for every polder system. For example, deep polders have seepage boils with high chloride content.

If the chloride content in a polder exceeds the chloride norm AND the chloride content in the boezem is lower than the norm, then water from the boezem is allocated to flush chloride content from that polder. A low chloride norm has the consequence that a polder system requires more water to flush the system to reach acceptable chloride levels. Therefore, a downside of a low chloride norm is the increased water demand of the polder system for flushing. If the water in the boezem has higher chloride concentration than the polder water, water will still be let in for maintaining the water level, even if the water exceeds the chloride norm, but there will be no boezem water allocated for flushing.

3.2 Modeling Approach

This part will go into detail on the different components that were added to create the WAOR model.

Model Development: The model development was approached by an evolutionary development strategy: constantly developing and implementing new functionalities in the model and subsequently reviewing them before continuing with the next component. With the €ureyeopener 1.0 as the foundation, this static rapid-assessment model has been developed into a dynamic and more comprehensive model.

A strong point of the EEO1.0 is its accessibility. The WAOR has been developed with this accessibility in mind. Stuyt et al. (2013) have built the EEO1.0 in the widely available Microsoft Excel spreadsheet software. Excel also allows for expanding the model. This can be done by using the Visual Basic for Applications (VBA) programming language.

Figure 3.5 provides an overview of the WAOR and its components and how these are related to each other. Developed and incorporated aspects are:

- Optimization based on cost reduction (Section 3.3.1).
- System constraints (Section 3.3.2).
- Temporal variability within the growing season: 15-day time steps for chloride content and weather data, dividing every growing season in 12 periods (Section 3.3.3).
- Changeable water allocation strategy options (Section 3.4.1).
- Climate scenario applicability (Section 3.4.3).
- Multi-year analysis options. Allows for a model run of up to 50 years.
- "Foreign water" disincentive (Section 3.4.4).

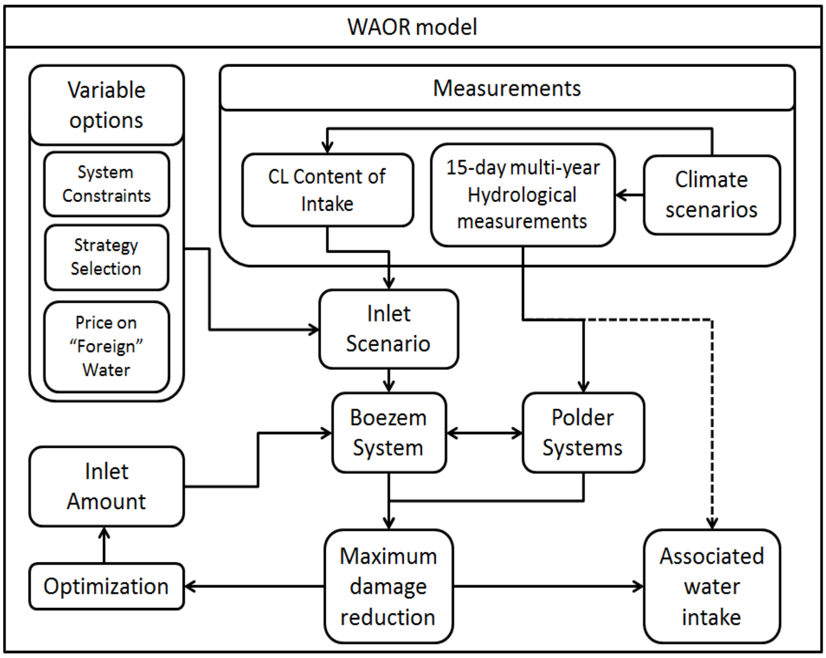
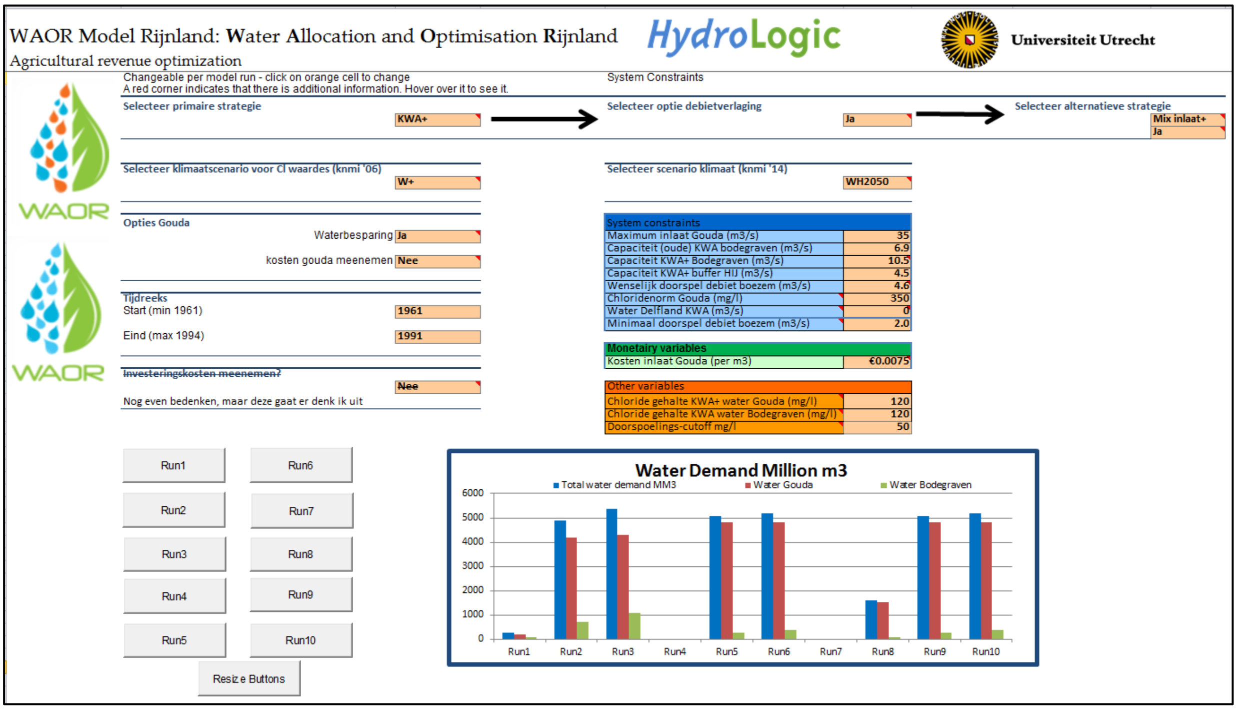


Figure 3.5. Overview of the WAOR model and its components.

Model Layout

As the following sections will show, there are a multitude of parameters and several possible strategies involved in the WAOR. The model has been divided into two parts, a front-end and a back-end. One of the aims is to use a front-end to allow for easy comparison of different strategies. This way, the user will not have to be confronted with the extensive cell references, formulas and VBA code.

From the **front-end** sheet (Figure 3.6) the user can manipulate the system constraints and select a desired strategy. Adjustable parameters include inlet constraints, pumping costs, required volumetric flow rate and climate scenarios. Parameters can be changed either by hand or using drop down menus. After setting up the desired parameters and strategies, an Excel macro can be called to run the model. This process can be started by pressing one of the "Run" buttons (e.g. "Run1"). The runtime of the calculation will depend on the amount of years selected. After completion, the results will be presented on the front-end sheet. After a run, the user can make changes to the run parameters and run the model again. By selecting a different "Run" button (e.g. "Run2"), the results will be presented in a different row of the result table, allowing for multiple strategies to be compared. The **back-end** is the extensive data access layer of the model where all calculations are performed. These contain all the data, such as chloride and weather measurements, polder balances and damage functions. If desired, this data can be easily viewed in separate worksheets. By using a link of mathematical formulas and IF-statements within the Excel worksheets and VBA macros, all possible strategies can be calculated. In Appendix B several screenshots of the worksheets are provided.



WAOR Model Rijnland: **W**ater **A**llocation and **O**ptimisation **R**ijnland

Agricultural revenue optimization

Changeable per model run - click on orange cell to change
A red corner indicates that there is additional information. Hover over it to see it.

Selecteer primaire strategie: KWA+

Selecteer klimaatscenario voor Cl waardes (knmi '06): W+

Opties Gouda
Waterbesparing: Ja
kosten gouda meenemen: Nee

Tijdreeks
Start (min 1961): 1961
Eind (max 1994): 1991

~~Investeringskosten meenemen?~~: ~~Nee~~
Nog even bedenken, maar deze gaat er denk ik uit

System Constraints

Selecteer optie debietverlaging: Ja

Selecteer alternatieve strategie: Mix inlaat+ / Ja

Selecteer scenario klimaat (knmi '14): WH2050

System constraints	
Maximum inlaat Gouda (m3/s)	35
Capaciteit (oude) KWA bodegraven (m3/s)	6.9
Capaciteit KWA+ Bodegraven (m3/s)	10.5
Capaciteit KWA+ buffer HIJ (m3/s)	4.5
Wenselijk doorspel debiet boezem (m3/s)	4.6
Chloridenorm Gouda (mg/l)	350
Water Delfland KWA (m3/s)	0
Minimaal doorspel debiet boezem (m3/s)	2.0

Monetairy variables	
Kosten inlaat Gouda (per m3)	€0.0075

Other variables	
Chloride gehalte KWA+ water Gouda (mg/l)	120
Chloride gehalte KWA water Bodegraven (mg/l)	120
Doorspoelings-cutoff mg/l	50

Figure 3.6. Screenshot of the WAOR initialization front-end slide.

3.3 Model Components

3.3.1 Optimization component

When the model runs, the inlet amount and distribution in the boezem and polder systems is optimized for every time step to achieve maximal cost reduction. Optimization in the WAOR model is conducted by using the basic Solver included Microsoft Excel. The solver can be used to find an optimal value, such as a minimum value for a formula in a cell (FrontlineSolvers, n.d.). This optimization can be subjected to constraints, such as maximum water inlet limit. In the EEO 1.0 the solver was used to optimize water intake at Gouda. In the WAOR the solving method has been changed to optimize based on agriculture damage reduction and pumping cost reduction instead.

Variables

The WAOR has dependent variables and independent variables. Dependent variables are the variables that are recalculated after making a change to the independent variables, while independent variables are deliberately manipulated to produce a change in the dependent variables. Independent variables are in this case the preferred water intake strategy, the chloride concentration of the intake water, the weather data and the climate scenario. Dependent variables are damage to agriculture and the pumping costs. In practice water managers cannot change the chloride concentration of the intake water or the weather. They can however, change the amount of water and the strategy by which source the water is let in the system and make investments to change the system constraints. Whenever a model run is initialized the model only has one remaining independent variable: the water intake distribution between Gouda and Bodegraven.

Optimization methods

The EEO1.0 optimizes water intake based on the GRG non-linear solving method for smooth non-linear functions, incorporated within the standard solver in Microsoft Excel. The solver selects a starting point and then follows the curve to search for an optimum. However in the WAOR model, optimization based on cost damage reduction led to problems with the EEO1.0's damage functions, as these were not developed for use in optimization methods. These polder-specific damage functions use linear regression between fixed points (), causing them to be non-smooth (i.e. having several derivatives at a single point). During testing with these functions the solver would provide a solution, but it was often a local optimum instead of the global optimum. This was made clear when subsequent model runs with identical parameters would provide varying results, some with costs being lower by a million euro's for a single year. While a local optimum may be an adequate solution, there may be a better one possible and when using local optima there will always be the uncertainty if the result is the most optimal one.

Methods exist for solving non-smooth functions, such as the Evolutionary Algorithms. However these may be more difficult to implement, have long run times and could prove unstable. If possible, converting the damage functions from non-smooth to smooth to accommodate the new optimization use would resolve these issues (Leine & Nijmeijer, 2004). By using the "Shape-preserving piecewise cubic Hermite interpolation" method (Fritsch & Carlson, 1980; Shiavi, 2007) to smoothly interpolate the measured values from the EEO1.0's damage function tables, a smooth function can be derived by using code in Matlab (Appendix A). This new smooth function is forced through the data points from the EEO1.0's damage functions. After implementing these new smooth non-linear damage functions, the results using the GRG non-linear method were always the same, greatly reducing the time required to run the model and increasing its reliability by always providing the same outcome for identical model runs.

An alternative interpolation technique would be to use splines. Splines can cause overshoots however (), which could cause the curve to have slightly lower damages at higher chloride content. In this case the damage at Boskoop would be higher at a chloride concentration of 900 mg/l than 1100 mg/l. This is undesirable when optimizing as the solver may counterintuitively choose to let in more water with high chloride content as that would lead to lower damages.

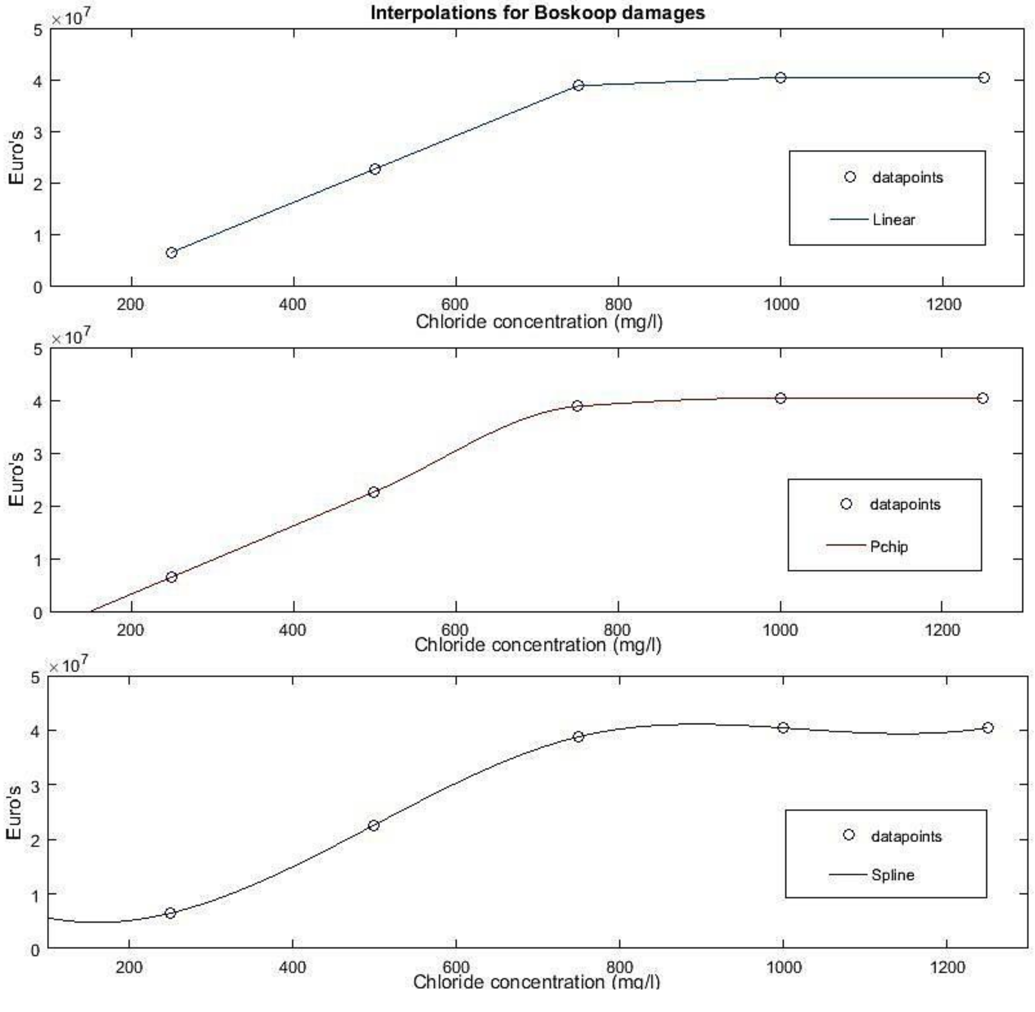


Figure 3.7. Comparison of original Linear interpolation (top), "Shape-preserving piecewise cubic Hermite interpolation" method (middle) and the spline function (bottom) for the data points derived from the EEO1.0 damage functions. The Y- axis shows agricultural damage in Euro's for an entire growing season. Based on agriculture damage functions by Stuyt et al. (2013).

3.3.2 System constraints

One of the first changes that were made to the model was the application of system constraints. As the new objective was cost reduction instead of water intake reduction, the water inlet would often reach unrealistically high levels, because there were no bounds in place. As there is a maximum capacity on the amount of water that goes through the system, constraints were imposed to prevent this capacity from being exceeded. The constraints must be satisfied, but can be changed manually from the front-end sheet if desired. The following constraints have been included in the model:

Maximum inlet: The water amount that can be let in for both Gouda and Bodegraven (Rijnland, 2011; Hydrologic, 2015a). These constraints vary based on the selected inlet strategy. For example, when the KWA+ is selected, a significantly lower amount of water can enter at Gouda (HydroLogic, 2015a).

Discharge in the boezem system: Rijnland desires a certain volumetric flow rate for flushing the boezem in order to keep certain concentrations, such as nutrients, at acceptable levels by diluting the water from the concentration discharge points with water in the boezem (WL | Delft Hydraulics et al., 2001). During the growing season, the desired minimal flow rate is 4.6 m^3/s in the boezem (Bulsink, 2010). This flow rate is not specified in explicit waterboard rules, but usually based on experience. It is an important requirement for the dilution of discharged polder water with boezem water. Without a minimal flow rate, concentrations remain at their discharge location and slowly spread out, pushing the surrounding cleaner waters away and only mixing slowly by diffusion (WL | Delft Hydraulics et al., 2001).

Polder water level retention: Minimum inlet into polder systems based on polder-specific water balance for maintaining water levels (required for dyke safety reasons). This is important, as lowered water tables can cause significant damages, especially in peat lands, as peat will irreversibly shrink when exposed to the air (Deltares, 2015b). This was already included within the EEO 1.0.

Maximum inlet chloride concentrations: Water will not be let into the polder that exceeds the specified maximum chloride concentrations for that polder. This term is subordinate to polder water level retention. The values originally defined by Stuyt et al. (2013) were used.

Freshwater delivery to Delfland and S&K: In the accords for the KWA, the waterboards of Delfland and Schieland en de Krimpenerwaard are entitled to the combined delivery of 2.9m^3/s of the KWA water when it is active (Rijkswaterstaat et al., 2005). In 2011 this was not necessary as these water boards did not require the water, so Rijnland had more freshwater at its disposal. However, this may not be the case every time the KWA is required. As this delivery goes through the boezem system of Rijnland it follows a portion of the water allocation route. The amount of water that should be delivered can be changed for every model.

Flushing cut-off: This constraint was already present in the EEO1.0. If the chloride content of the water on the boezem is lower than the water in the polder, but higher than the chloride norm, then water will be let in until the chloride content in the polder is the same as: inlet content + 50mg/l. This +50 cut-off ensures that no extreme amount of flushing is required. This way the chloride content in the polder is lowered and damage mitigated. For example, if the chloride norm of a polder is 300mg/l, the water in the polder is 500mg/l and the water in the boezem has 400mg/l, then the polder will let in water until it reaches a concentration of 450mg/l.

3.3.3 Modification of chloride and weather data

The EEO 1.0 uses a single value for chloride concentration at Gouda for the duration of an entire growing season. Because the WAOR model simulates a growing season in periods of 15 days, it is not realistic to always keep the chloride value at the same annual level as chloride concentration on the HIJ can vary a lot over the year (Figure 3.8). So a necessary implementation for modelling the water inlet strategy usage was the inclusion of chloride variability. When high chloride concentrations occur, they usually do so during a limited period of time, while during the remainder of the growing season the chloride concentrations are often much lower. The addition of this part of the model concept allows for a more detailed simulation of periods of droughts.

This chloride data was provided by Hydrologic and derived from the NDB model, which models the fluctuations of chloride concentrations in surface waters in the western Netherlands (Hydrologic, 2013). It contains hourly measured chloride levels from 1961 to 2011, as well as modelled KNMI '06 W+ climate scenario chloride measurements for 1961 to 1994. The WAOR extracts average 15-day average chloride levels for every year to use in the model runs. These two scenarios allow for the inclusion of both a normal scenario and a "worst case" scenario.

The 15-day period was selected as this allows for enough detail so drought periods can be simulated. If the number of days would be much lower it may not be realistic, as the water does not travel instantaneous throughout the system.

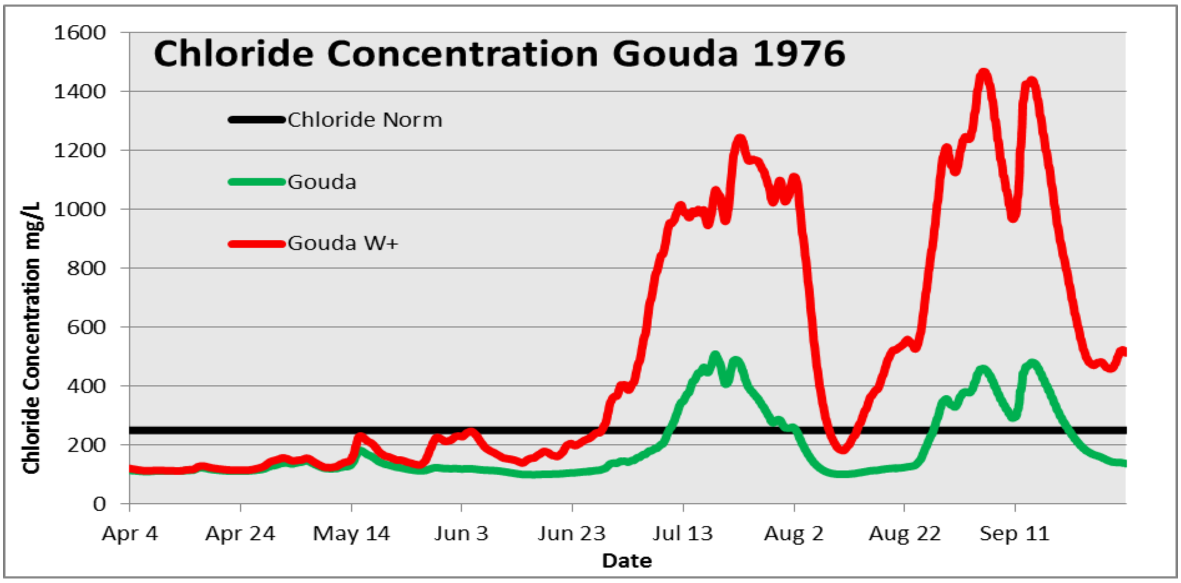
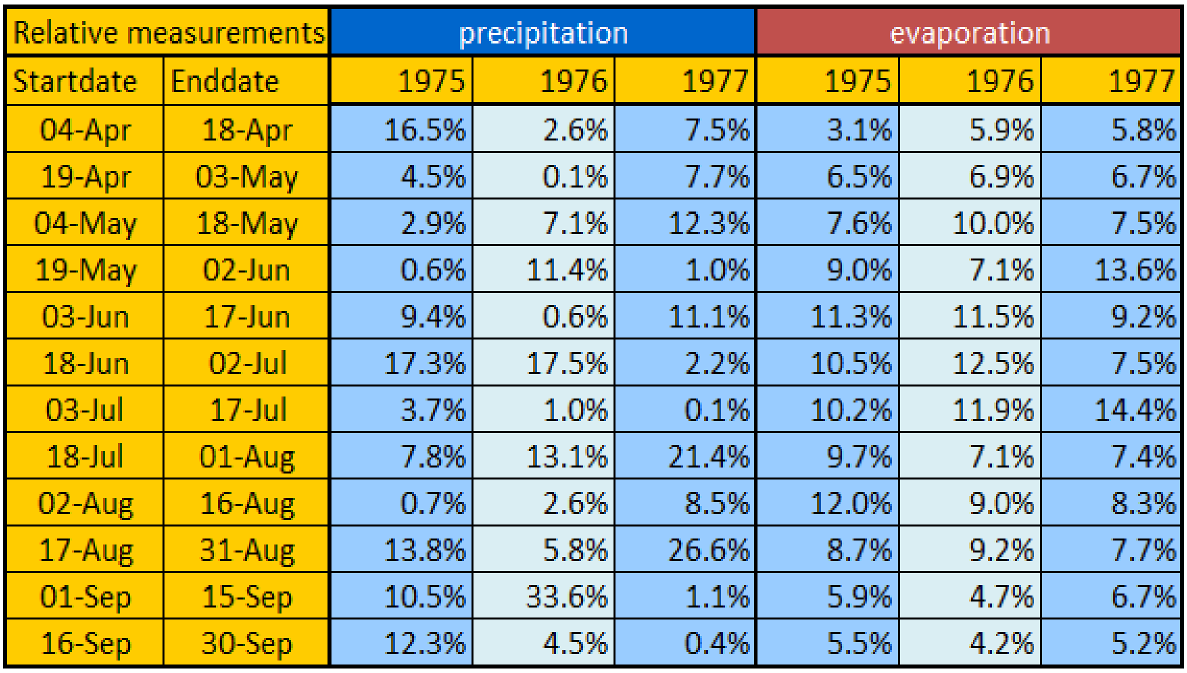


Figure 3.8. Chloride concentration for the normal situation and the KNMI'06 W+ scenario in the HIJ in 1976 derived from the DNB model.

The **weather data** used for the polder balances in the EEO1.0 had similar characteristics, as these were single values for the entire growing season as well. These values were available from 1961 to 1995. By using precipitation and evaporation measurements, derived from weather stations in and near Rijnland, the growing season values were distributed over the season based on the relative amount of rainfall and precipitation measured for the growing season in that year (Table 3.1). By multiplying the total rainfall and evaporation of that season with the relative amount measured of its respective 15-day window, the data used in the polder balances were adjusted for every year.

The adaptations to the growing season data for both chloride content and weather data allows for the simulation of periods when there is increased freshwater demand. During these periods the weather is often very dry and the chloride concentrations on the HIJ can be high. The KWA and its alternatives were developed for such periods.



Relative measurements		precipitation			evaporation		
Startdate	Enddate	1975	1976	1977	1975	1976	1977
04-Apr	18-Apr	16.5%	2.6%	7.5%	3.1%	5.9%	5.8%
19-Apr	03-May	4.5%	0.1%	7.7%	6.5%	6.9%	6.7%
04-May	18-May	2.9%	7.1%	12.3%	7.6%	10.0%	7.5%
19-May	02-Jun	0.6%	11.4%	1.0%	9.0%	7.1%	13.6%
03-Jun	17-Jun	9.4%	0.6%	11.1%	11.3%	11.5%	9.2%
18-Jun	02-Jul	17.3%	17.5%	2.2%	10.5%	12.5%	7.5%
03-Jul	17-Jul	3.7%	1.0%	0.1%	10.2%	11.9%	14.4%
18-Jul	01-Aug	7.8%	13.1%	21.4%	9.7%	7.1%	7.4%
02-Aug	16-Aug	0.7%	2.6%	8.5%	12.0%	9.0%	8.3%
17-Aug	31-Aug	13.8%	5.8%	26.6%	8.7%	9.2%	7.7%
01-Sep	15-Sep	10.5%	33.6%	1.1%	5.9%	4.7%	6.7%
16-Sep	30-Sep	12.3%	4.5%	0.4%	5.5%	4.2%	5.2%

Table 3.1. Relative precipitation (Alphen a/d Rijn) and evaporation (De Bilt) in the years 1975, 1976 and 1977. These relative amounts are multiplied with their respective data for that entire growing season.

3.4 Water allocation strategy options

This section contains a description of the various options available to the user of the model to compare different water allocation strategies. In normal situations the WAOR will always let water in at Gouda. However, when a chloride concentration higher than 250 mg/l is detected at Krimpen aan de IJssel, the water allocation strategy that is selected before the model run will be used instead.

3.4.1 Inlet strategy and routes

In this study, six strategies will be investigated for freshwater allocation in Rijnland during periods with high chloride concentrations on the HIJ (>250 mg/L). These strategies (Table 3.2) are:

Strategy	Description
Only Gouda	Let in all water from Gouda, even if Cl- values exceed the threshold
Old KWA	Only let water in through Bodegraven, with maximum flow rates of **6.9**m^3/s
Bodegraven+	Only let water in through Bodegraven, with an expanded maximum flow rate of **10.5**m^3/s
KWA+	Let in water from both Gouda and Bodegraven (KWA+), but create a freshwater buffer on the HIJ. Once in place, this buffer will keep the salt influence at bay and will allow for a relatively small freshwater flux on the HIJ from the Waaiersluis to the inlet of Rijnland with a maximum capacity of **4.5** m^3/s.
Mix Inlet	Let in water from both Gouda and Bodegraven (**6.9** m^3/s).
Mix Inlet+	Let in water from both Gouda and Bodegraven (**10.5** m^3/s).

Table 3.2. Water allocation strategies.

The EEO 1.0 uses a water system schematization with nodes and branches (Figure 3.1). It has one linear route (as it only used one entry point and one exit point). To be able to accommodate for an additional inlet location this schematization had to be changed for the WAOR (Figure 3.10). The consequence of two different water inlet locations is that the order in which newly entered water reaches a certain polder system changes. For example, if water is only let in at Gouda, the Nieuwkoopse plassen system receives water that has received extra chloride from the deep-lying NMT-polders. However, when the water is let in through Bodegraven, the inlet water will reach the Nieuwkoopse Plassen first, so the inlet is not "polluted" by the discharged chloride from the NMT-polders. This requires the ability for the model to change its water allocation route based on the chosen strategy (Figure 3.9). By addition of more nodes, an additional entry location and through use of If-statements in both the excel sheets and the VBA code, changing the strategies is facilitated. By selecting the desired strategy from the front-end sheet, the boezem system changes its water inlet and route. The arrows in the water system schematization change based on the selected strategy as well. The solver constraints were altered and depending on the strategy the solver will optimize based on either one or two inlet locations.

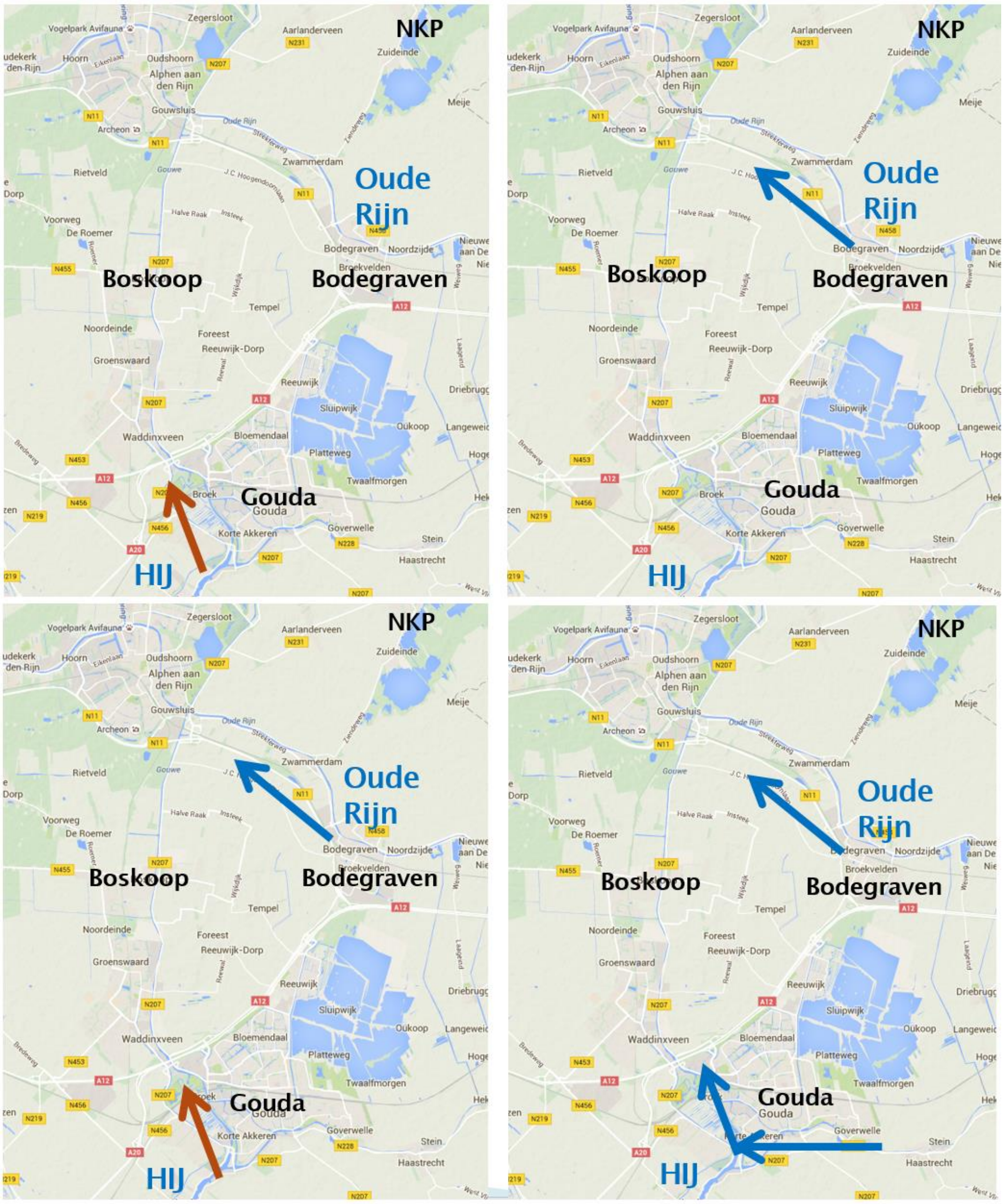


Figure 3.9. Overview of the four inlet routes during increased chloride concentrations on the HIJ. Top Left: *Only Gouda.* Bottom Left: *Mixed Inlet(+).* Top Right: Old KWA (and Bodegraven+). Bottom Right: KWA+. A blue arrow indicates freshwater, an orange arrow indicates the <u>possibility</u> of brackish water.

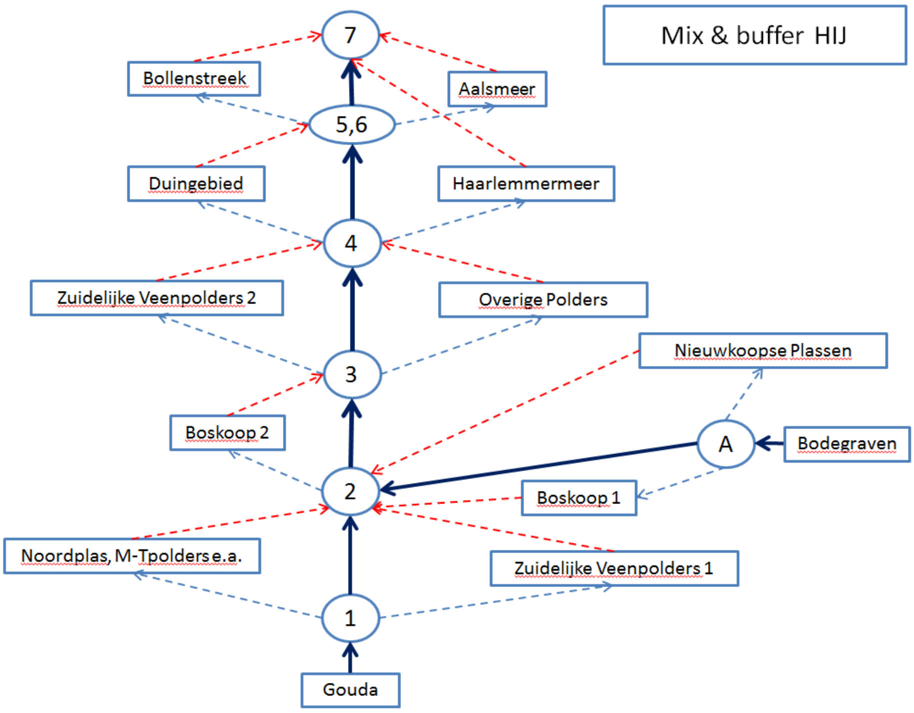


Figure 3.10. Schematization of the water allocation route in the WAOR during the mixed inlet or KWA+ strategies (these two strategies have the same routes, only different CL concentrations at Gouda). Blue arrows indicate inlet routed into polders, the red arrows indicate outlet routes onto the boezem. The solid dark blue arrows indicate the main flow path over the Boezem.

3.4.2 Alternative strategy.

It is possible that a selected strategy is insufficient for reaching the required water demand, especially during severely dry periods. To accommodate for this eventuality, a handling mechanism has been incorporated. Otherwise when there was insufficient water for water level maintenance, the model would return a no value error, resulting in lower total costs, while in reality the costs should be higher because of water shortages. When the selected strategy has insufficient water supply in a certain period, an alternative strategy can be used. There are two alternatives, which can be selected independently or combined as desirable:

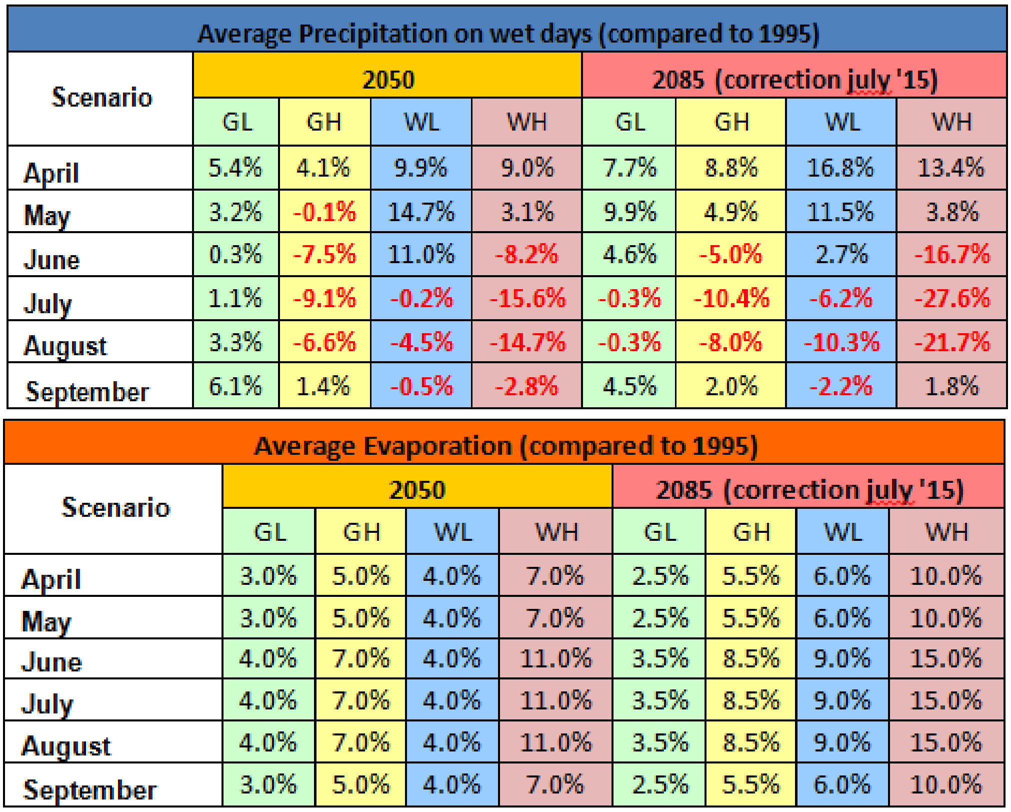
- The flushing discharge of the boezem gets lowered from the desirable amount to the minimal amount, reducing water demand.
- An alternative inlet strategy is selected, either the “Mix Inlaat” or the “Mix Inlaat+”. These are the only options, as only letting in by Gouda does not make sense when freshwater is already being delivered at Bodegraven. The remainder is capacity dependent and cannot be quickly implemented.

If the KWA+ is selected, the alternative strategy will consider this by mixing the freshwater buffer with the extra required inlet.

3.4.3 Climate scenarios application

Section 2.6 provides an overview of the KNMI'14 scenarios. The WAOR has been modified to allow for these climate scenario's to be applied. When a scenario is selected, the WAOR modifies the precipitation and evaporation accordingly. Over the course of a model run, the model derives the percentage changes (Table 3.3 and 3.4) for the selected scenario from the respective month, with months abstracted to 30-day periods.

Because the model transforms 15-day average historical data it is not possible to alter the occurrence of precipitation events, which may vary based on the scenario. Instead, the average precipitation values are transformed based on the percentage change in monthly values for average rainfall on wet days (KNMI, 2015). However, evaporation changes were unavailable per month and only available as summer averages and yearly averages. Therefore it was decided to change these based on the summer period for June, July and August, while April, May and September use the yearly averages (KNMI, 2015).



Average Precipitation on wet days (compared to 1995)								
Scenario	2050				2085 (correction july '15)			
	GL	GH	WL	WH	GL	GH	WL	WH
April	5.4%	4.1%	9.9%	9.0%	7.7%	8.8%	16.8%	13.4%
May	3.2%	-0.1%	14.7%	3.1%	9.9%	4.9%	11.5%	3.8%
June	0.3%	-7.5%	11.0%	-8.2%	4.6%	-5.0%	2.7%	-16.7%
July	1.1%	-9.1%	-0.2%	-15.6%	-0.3%	-10.4%	-6.2%	-27.6%
August	3.3%	-6.6%	-4.5%	-14.7%	-0.3%	-8.0%	-10.3%	-21.7%
September	6.1%	1.4%	-0.5%	-2.8%	4.5%	2.0%	-2.2%	1.8%

Average Evaporation (compared to 1995)								
Scenario	2050				2085 (correction july '15)			
	GL	GH	WL	WH	GL	GH	WL	WH
April	3.0%	5.0%	4.0%	7.0%	2.5%	5.5%	6.0%	10.0%
May	3.0%	5.0%	4.0%	7.0%	2.5%	5.5%	6.0%	10.0%
June	4.0%	7.0%	4.0%	11.0%	3.5%	8.5%	9.0%	15.0%
July	4.0%	7.0%	4.0%	11.0%	3.5%	8.5%	9.0%	15.0%
August	4.0%	7.0%	4.0%	11.0%	3.5%	8.5%	9.0%	15.0%
September	3.0%	5.0%	4.0%	7.0%	2.5%	5.5%	6.0%	10.0%

Table 3.3 and Table 3.4. Average monthly precipitation and evaporation changes per month based on the KNMI'14 climate scenarios.

3.4.4 Monetary value to inlet water

Apart from the increased damages caused by heightened chloride concentrations, the model had initially no further incentive to reduce the amount of inlet water below the constraints. This leads to a situation where often the model lets in large quantities of water at Gouda to achieve marginal cost reductions. To prevent the constant inlet of the maximum amount of water, the WAOR required an additional mechanism to reduce the amount of inlet water.

A (small) price per m^3/s inlet water was coupled to the inlet at Gouda as a disincentive to the introduction of "foreign" (Dutch: "gebiedsvreemd") water into the system and as a trigger to be frugal with water. Just as chloride concentrations can lead to agricultural and nature damages, other concentrations can cause water quality problems as well. "Foreign" surface water, originating from the Rhine, can have a composition with relatively high phosphorus, nitrogen (Fiselier et al., 1992), and sulphate concentrations (Roelofs, 1991), leading to eutrophication of the system (Runhaar, van Gool, & Groen, 1996). This price is coupled to the optimization process and it is possible to show this price as part of the total costs at the end of a run or leave it out of the results.

This price is only coupled to the inlet water at Gouda, because during a situation when the KWA is active, water managers would not try to reduce the inlet water at Bodegraven. This is because lots of efforts are made to transport the water to Bodegraven and this water generally always has lower chloride content than the water at Gouda. Being frugal with this water is therefore counterintuitive. Figure 3.11 shows the difference in water demand and total damage for different price levels per m^3/s inlet at Gouda. The results stabilize around a price level of €0.0075 per m^3/s for both damages and water usage. For the remainder of this thesis, this price level is used in all model runs, but it can be easily modified.

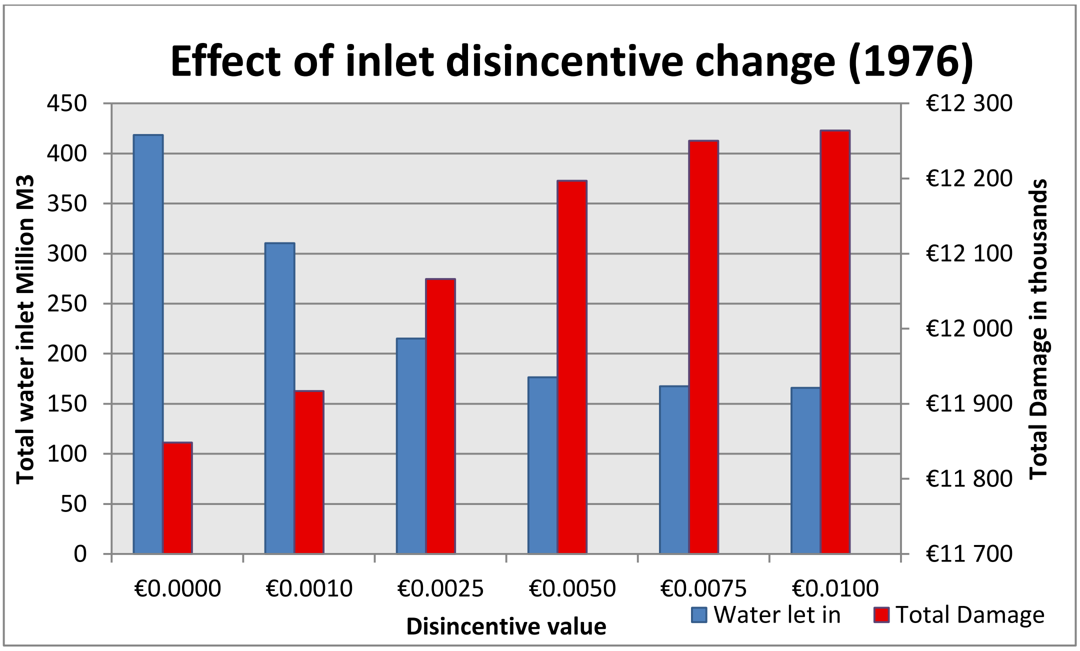


Figure 3.11. The effect of inlet disincentive change for five different values for the year 1976, using Mix inlaat+ and no climate scenario.

Adding a price per m^3/s on the running costs of the inlet, to abstract fuel and manpower costs, was considered, but not deemed realistic as the running cost difference for letting in different quantities of water at Gouda would be negligible.

3.5 Result analysis with NPV

As this study aims to assess the cost-effectiveness of investments for alternative water allocation over a long period, the principle of Net Present Value (NPV) needs to be applied. The value of money changes over time due to processes such as inflation and interest (one euro now is worth more than one euro in ten years). The values need to be expressed in NPV for the base year. This is done by applying a discount rate (Mouter, Annema & van Wee, 2013). The current Dutch guideline advises a discount rate at 3% (mkba-informatie.nl, 2016).

The NPV is calculated by the following formula (Bickel et al., 2006):

$$NPV = \sum_{n=0}^{N} \frac{(b_n - c_n)}{(1+r)^n} - \mathrm{I}$$

where: b = project benefits;
c = project costs;
n = the year(s) in which the benefits and costs occur
r = discount rate
I = Initial investment

3.6 Assumptions

This section will include assumptions in the WAOR model that are not (fully) described in the previous sections.

- As shown in Figure 2.4 a large portion of the polders in Rijnland were combined into larger polder systems for the EEO1.0. This method was preserved for the WAOR model. However, when water is supplied through Bodegraven as an alternative supply route the following assumptions have been made:

    - Inlet water over the boezem from Gouda goes through Boskoop over the Gouwe River. This causes a division of Boskoop between a western and an eastern part (Figure 3.12). Since 2013 it is possible for water to be supplied to the eastern part of Boskoop by use of a new pumping station near Bodegraven: the “Th. Aendekerk” pumping station (WUR, 2013). This pumping station has been realized with the argument that during dry periods, the chloride concentration on the Oude Rijn River is lower than on the Gouwe. Therefore, the assumption is made to divide the Boskoop water balance and damage functions in two equal parts. The only difference between the parts is in their intake location during an alternative strategy. Consequently, during water supply from Bodegraven this results in half of Boskoop receiving water with lower chloride content than the other half. In the model runs, the assumption is made that division of Boskoop between east and west is an equal 50%.

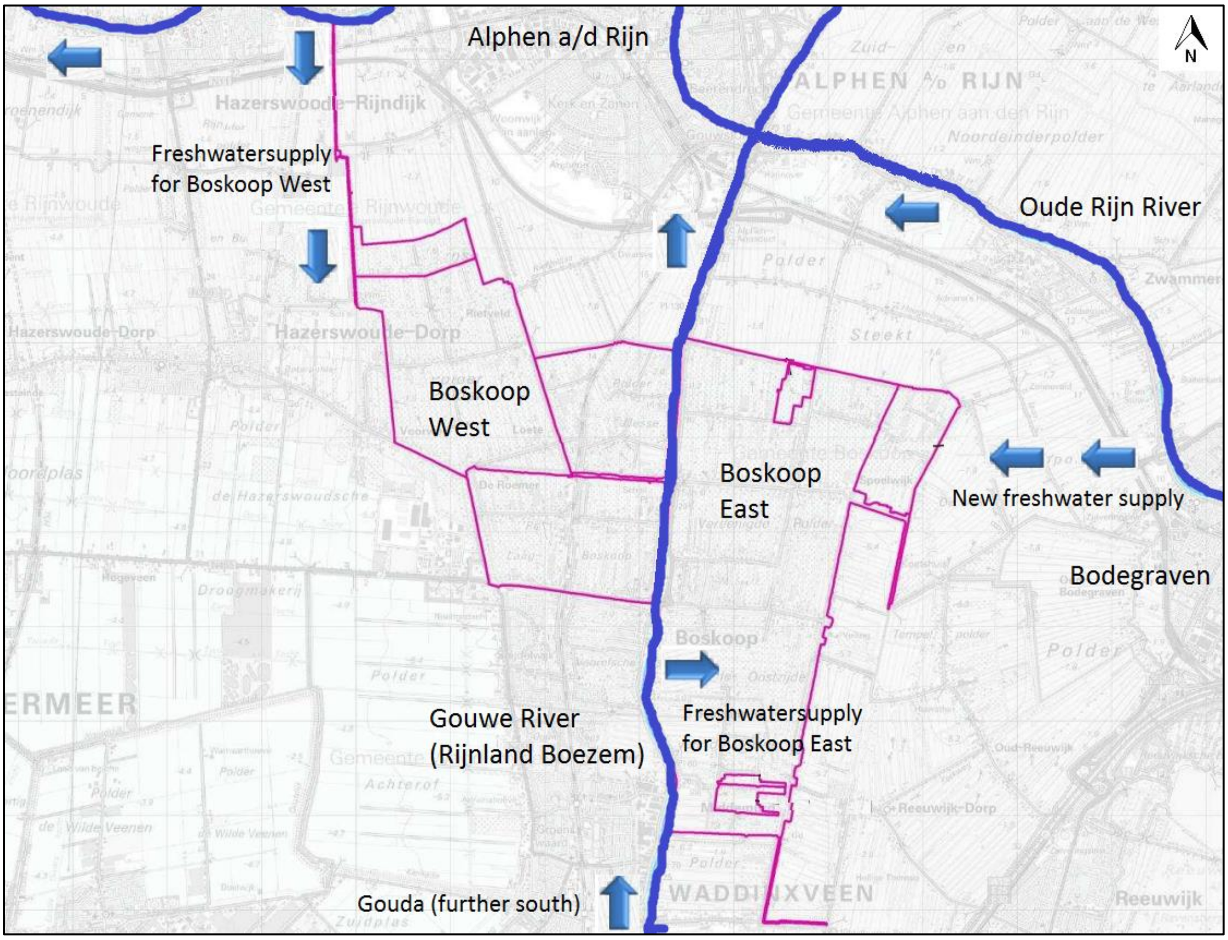


Figure 3.12. Overview of Boskoop and its water level areas (purple). The Gouwe River runs through the middle, dividing it in an Eastern and Western part. From Bodegraven an alternative freshwater supply is possible towards Boskoop East when the water on the Oude Rijn River has a lower chloride content than the water on the Gouwe River. (Rijnland, 2013 – modified).

  - Because of the proximity of the Nieuwkoopse Plassen nature area to Bodegraven, it is assumed that water that enters Rijnland through Bodengraven can immediately be let into the NKP, allowing this area to avoid taking in water with high chloride concentrations.

- In The WAOR model, a division of a growing season into periods of 15-days was chosen to allow for the inclusion of temporal variability of weather and chloride concentration data. When water enters the Rijnland system at Gouda, it takes some time before the water reaches the different polders and before heightened chloride concentrations have an effect on crop yield. The exact time this will require is unknown and it is assumed that within a 15-day period all water that is let in will reach its destination. An accompanying advantage of the 15-day period is that the amount of time that a multiple year model run takes (e.g. 30 years) remains manageable.

- The model combines the KNMI'14 WH2050 scenario and the KNMI'06 W+ scenario in one scenario for analysis. However, this is not completely correct. According to Deltares (2015a), there are differences between these scenarios. Mainly, the precipitation deficit is smaller for the WH2050 scenario than for the W+ scenario. However there was no updated version for the effects of the WH2050 scenario on the discharge of the Rhine. It is expected that low discharges will be less extreme than during the W+ scenario as well, which would lead to lower chloride concentration on the HIJ with the WH2050 scenario than with the W+ scenario.

- Because the WAOR uses 15-day periods instead of an entire growing season, the chloride damage functions had to be changed as well. As discussed in section 2.4, crops have varying levels of salt tolerance throughout the growing season. However, the WAOR does not make this distinction. For the purpose of this study the results of the damage functions were divided by the amount of measured 15-day periods (twelve).

- For reducing the wide range of possible scenarios that could be analyzed, some parameters were chosen to remain fixed during all model runs (Table 3.5). Some of these, such as the desired flushing discharge and the capacity of the freshwater buffer are assumptions based on discussions with experts (Dolf Kern, personal communication, July 14, 2016) and data found in reports (Bulsink, 2010). These parameters can be easily revised in future model runs.

System Parameters	
Maximum Inlet Gouda	**35 m^3/s**
Capacity *Old KWA* at Bodengraven	**6.9 m^3/s**
Capacity *Bodengraven+*	**10.5 m^3/s**
Capacity freshwater buffer *KWA+*	**4.5 m^3/s**
Desired flushing discharge in boezem	**4.6 m^3/s**
Minimum flushing discharge in boezem	**2 m^3/s**
Water reserved for Delfland	**0 m^3/s**
Chloride norm Gouda	**250 mg/l**
Inlet disincentive Gouda	**€0.0075**

Table 3.5. System parameters for all model runs used to generate the results in chapter 4.

- When insufficient to meet water quantity and quality standards, all of the strategies will first lower the desired flushing discharge of the boezem to 2m^3/s (assumption). If this is still insufficient the corresponding mixed strategy will be applied, as described in section 3.4.2. By doing so, water at Gouda with heightened chloride concentrations will be let in, and no situation will occur in the model runs where there was a quantitative shortage of water for water level maintenance.

Chapter 4 - Results

This chapter provides the results of the model runs with the WAOR model. First in section 4.1 the results of the model validation will be given. Then, in section 4.2 the main results between the different water allocation strategies will be provided. Section 4.3 will go into the cost-effectiveness of the KWA+ investment. Finally, section 4.4 will provide a sensitivity analysis of the model results.

There are two main variables that are modified while running the model runs to compare the results with each other: 1) The six different water allocation strategies, and 2) climate scenarios. The mild KNMI'14 GL2050 scenario was used for the weather data in conjunction with the chloride values as calculated with the NDB model (HydroLogic, 2013), while the WH2050 will be used with the modelled KNMI'06 W+ chloride concentrations.

4.1 Validation with EEO 1.0

It is interesting to ascertain what the differences are between the EEO1.0 and the WAOR model and validate the WAOR based on the results of the EEO1.0. The original EEO1.0 uses internal chloride concentration data that is different from what was provided during development of the WAOR. Therefore these newer values were put into the EEO1.0. The WAOR will run using the measured average 15-day chloride concentration values for 1989, while the EEO1.0 will use the average chloride concentration value of 95mg/l as the input for that entire year. As they use different solving methods, the EEO1.0's solving method had to be adjusted. Instead of reducing the intake as much as possible, the EEO 1.0 is set to solve on the exact intake amount that the WAOR gives as a result: 156 million M^3. The average 1989 CL-concentration value of 95mg/l was used as the input for the entire year.

Validation		
Model	Water Intake	Total Agriculture Damage
WAOR	156 Million m^3	€7 425 000
EEO1.0	156 Million m^3	€7 575 000

Table 4.1. Total agriculture damage difference between the models for 1989 for using the new meteo and hydrological data with an average cl concentration at the inlet of 95 mg/l.

The results of the validation are presented in Table 4.1. The model results are very similar. The differences can primarily be explained due to the difference in damage functions. In areas where a large increase in damages can occur by a relatively small increase in chloride concentration, such as in Boskoop, this will result in differences between the two types of damage functions. As was explained in section 3.3.1, the damage functions were changed for the WAOR. This resulted in a difference in damage functions as illustrated by Figure 4.1. For example, these differences can occur when chloride concentrations at Boskoop are between 150-250mg/l. As a result, small increases in chloride concentration can result in large differences in damage between the two types of damage functions.

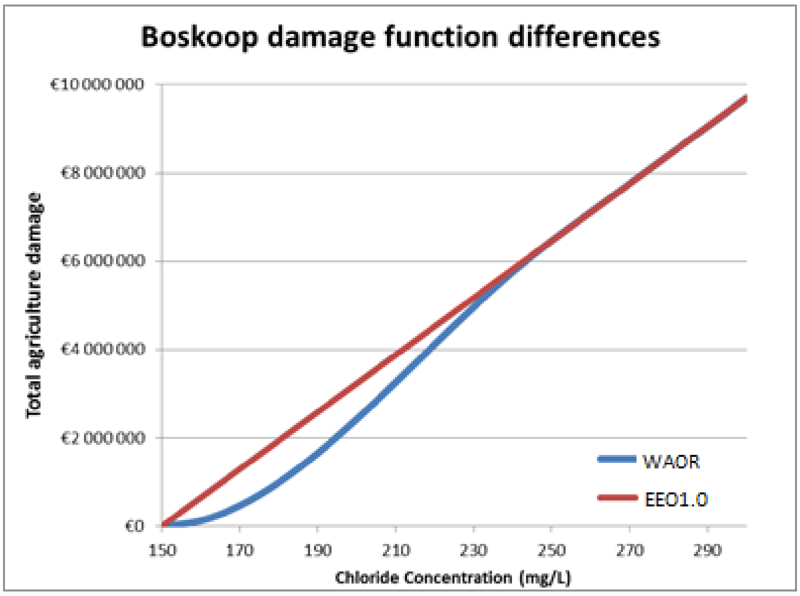


Figure 4.1. Damage functions differences at Boskoop for the WAOR model and the EEO1.0.

4.2 Comparison between water allocation strategies

This section will provide the results for the model runs for two single years and a longer range of years. This allows insights into the effects of strategies for both a single year and for their effects on a longer timescales

4.2.1 Difference in results for a single year (1976 and 1990)

This section will provide the results of model runs in the extremely dry year of 1976 and year 1990. These years were chosen because they are both years where external salt intrusion occurred on the HIJ.

1976

The record year of 1976 (Figure 4.2) is an interesting year: it is characterized by relatively high chloride concentrations on the HIJ, as well as low levels of precipitation and high evaporation. The characteristics of 1976 have a return period of 1:100 years (Deltares, 2015). As shown by Figure 4.3, the chloride concentration on the HIJ exceeded the chloride norm of 250 mg/l in the second half of July and in September. When the W+ scenario is applied, during a large portion of the growing season the chloride norm will be exceeded at Gouda. The results of the model runs for the year 1976 are provided in Figure 4.4.

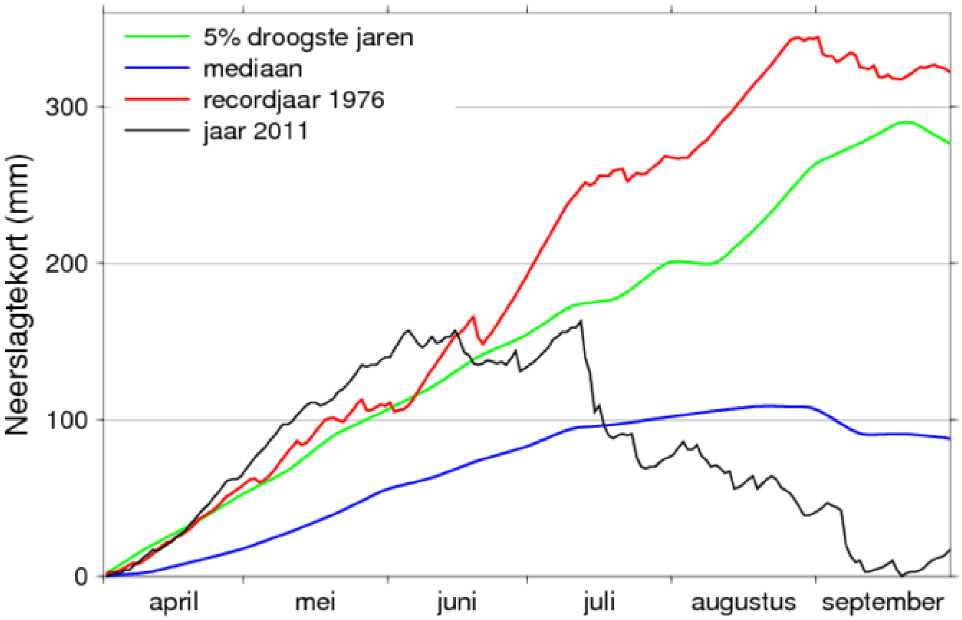


Figure 4.2. Cumulative precipitation deficit of 1976 (red) compared to the rainfall deficit of the 5% driest years (green, 5% of years are more dry), 2011 (black) and the median rainfall deficit (blue) for the period April-September (KNMI, 2016) (KNMI, n.d.).

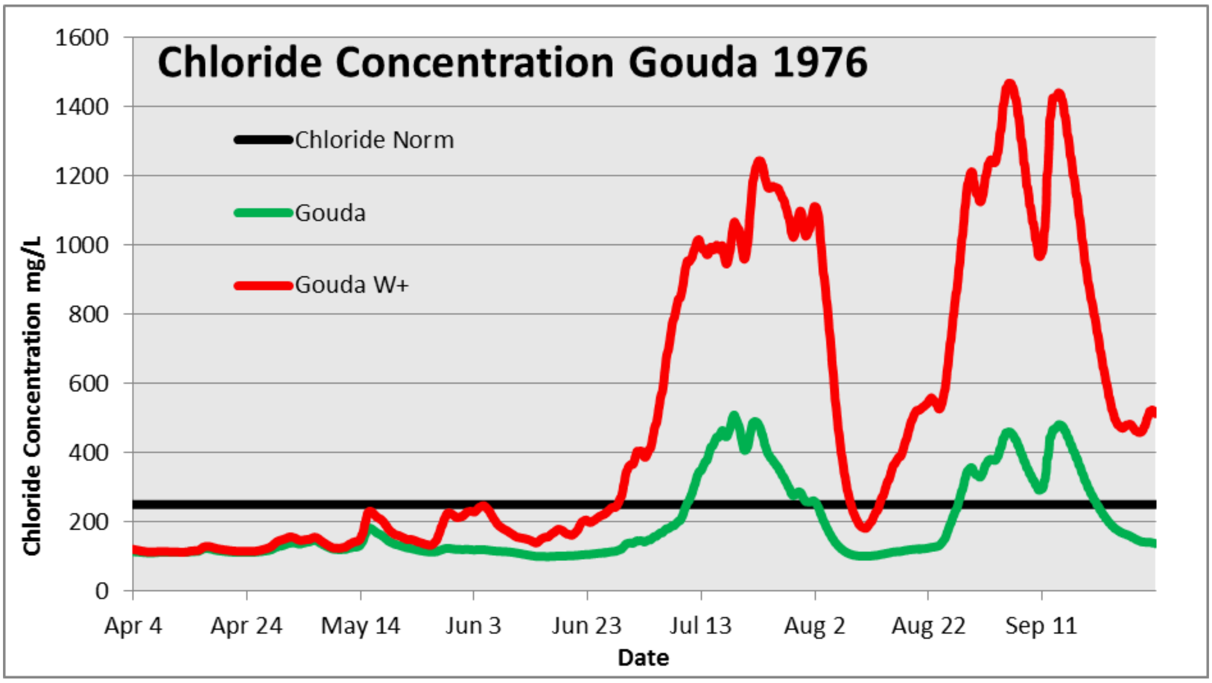


Figure 4.3. Overview of the chloride concentrations at Gouda during 1976 for both the measured amounts and the modelled KNMI'06 W+ amounts. Data retrieved from NDB model results (Hydrologic, 2013).

The success rates for the sufficiency of the strategies were determined as well and are provided in Table 4.2. Whenever a certain strategy is selected and the inlet does not meet the quantitative demands from the polder systems in Rijnland, then the strategy would fail. Upon failure a different (predefined) strategy would be selected (as specified in section 3.4.2), after which that 15-day period would be simulated again with the different strategy. The success rate is defined the percentage of times that a strategy was **quantitatively** successful out of every period that an alternative strategy was required (every period where the chloride concentration at Krimpen exceeds 250 mg/l). A success rate of 100% implies that the strategy always provides the required quantitative capacity in that year; however, this does not imply that it is a good strategy, as it only considers the **quantitative** demands (water level maintenance). In reality this would happen as well, because Rijnland would not let water levels drop too far, so inlet of water from Gouda with heightened chloride concentrations onto the boezem system would be commenced (Dolf Kern, personal communication, July 14, 2016).

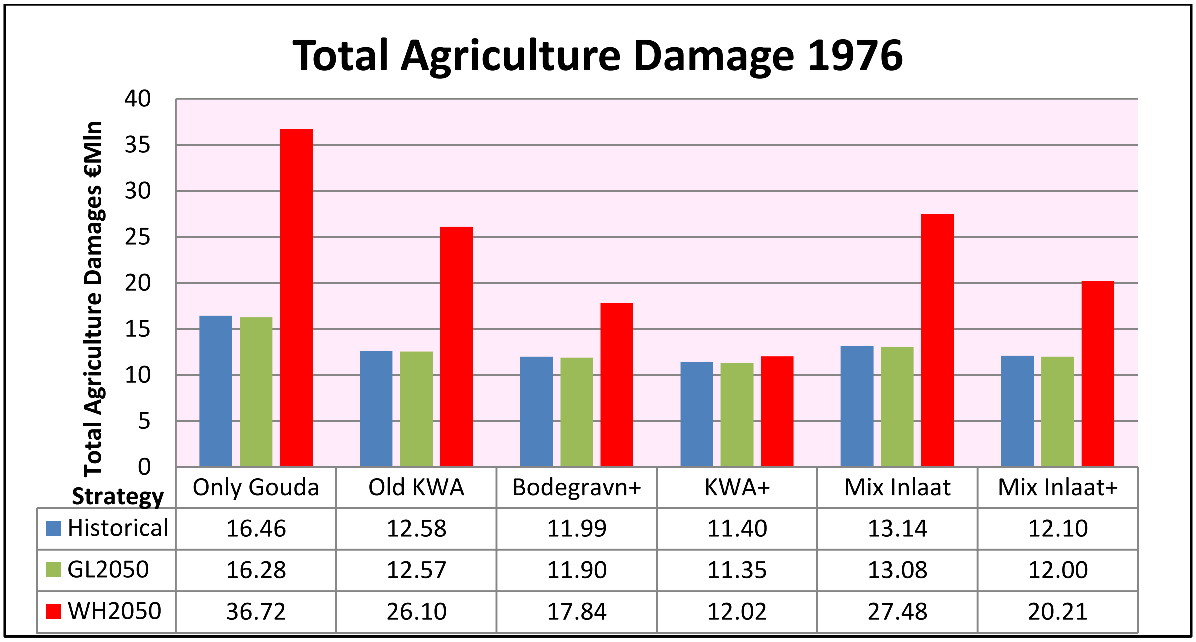
For the **historical runs** each subsequent "upgrade" to the freshwater system provides more damage mitigation. With the "*old KWA*" providing relatively the largest damage reduction when compared with the "*only Gouda*". The *KWA+* has the lowest agricultural damages. The Mixed strategies show higher damages than their respective KWA strategies (*Old KWA* and *Bodegraven+*). This is mainly caused by the fact that these strategies always let in some water at Gouda, resulting in higher damages. When the other strategies are insufficient they switch to the mixed strategies, when they are sufficient they use only freshwater, resulting in lower damages. The success rate with this scenario for the current strategy is 33%, while for the KWA+ this is 67%.

The **GL2050 scenario** is relatively similar to the historical scenario. There are only small differences, which causes this scenario to have slightly lower agriculture damages than the historical scenario. The success rates are the same.

When the **WH2050 scenario** is applied, the damages are much higher. This is primarily caused by higher chloride concentrations on the HIJ. Furthermore, an already extremely dry year is even more extreme when this scenario is applied. This results in high water demands, so a lot of inlet is required for water level maintenance.

During this scenario the *KWA+* has higher relative damage mitigation than in the GL2050 scenario. In that scenario the difference between the current system (*Old KWA*) and the *KWA+* is around ~€1.2Million, which is a damage reduction of ~10%. However in the WH2050 scenario this difference is around ~€14.1millions, which is a damage reduction of ~46%. Furthermore, in most strategies there is a noticeable difference between the historical and GL2050 result and WH2050 result, while with the KWA+ strategy these damage difference between the two scenarios are relatively small (i.e. small difference between the columns). Even though the success rate of the *KWA+* in 1976 is low (43%), mixing the water buffer with water of higher chloride content (section 3.4.2) gives an advantage over the other strategies, and results in lower damages.

It can be noted from Table 4.2 that there is one 15-day period where even the *Only Gouda* and *Mix Inlaat* strategies are insufficient and only the *Mix Inlaat+* strategy is sufficient. This is caused by the high polder water demand due to extremely low precipitation in those 15-days. In an already dry year, in that 15-day period only 0.9% of all the precipitation in 1976's growing season fell.



Strategy	Only Gouda	Old KWA	Bodegravn+	KWA+	Mix Inlaat	Mix Inlaat+
🟦 Historical	16.46	12.58	11.99	11.40	13.14	12.10
🟩 GL2050	16.28	12.57	11.90	11.35	13.08	12.00
🟥 WH2050	36.72	26.10	17.84	12.02	27.48	20.21

Figure 4.4. Results of 1976 model runs for the historical data and the GL2050 and WH2050 climate scenarios.

Success rate 1976	Historical	GL2050	WH2050
Only Gouda	100%	100%	86%
Old KWA	33%	33%	14%
Bodegraven+	33%	33%	14%
KWA+	67%	67%	43%
Mix Inlaat	100%	100%	86%
Mix Inlaat+	100%	100%	100%

Table 4.2. Success rate of the model runs in 1976 based on the selected strategy. The success rate is the percentage of times when the strategy was successful out of every time an alternative strategy was required. An unsuccessful strategy in the model results in an alternative strategy as described in section 3.4.2.

1990

1990 was not an exceptionally dry year. It had a larger amount of precipitation than 1989 (return time 1:10) and 1976 (return time 1:100). However, the chloride concentrations do exceed the chloride norm of 250mg/l in both the historical data and the modelled KNMI'06 W+ scenario (Figure 4.5). By comparison, in 1989, the chloride values did not exceed the chloride norm during the historical measurements.

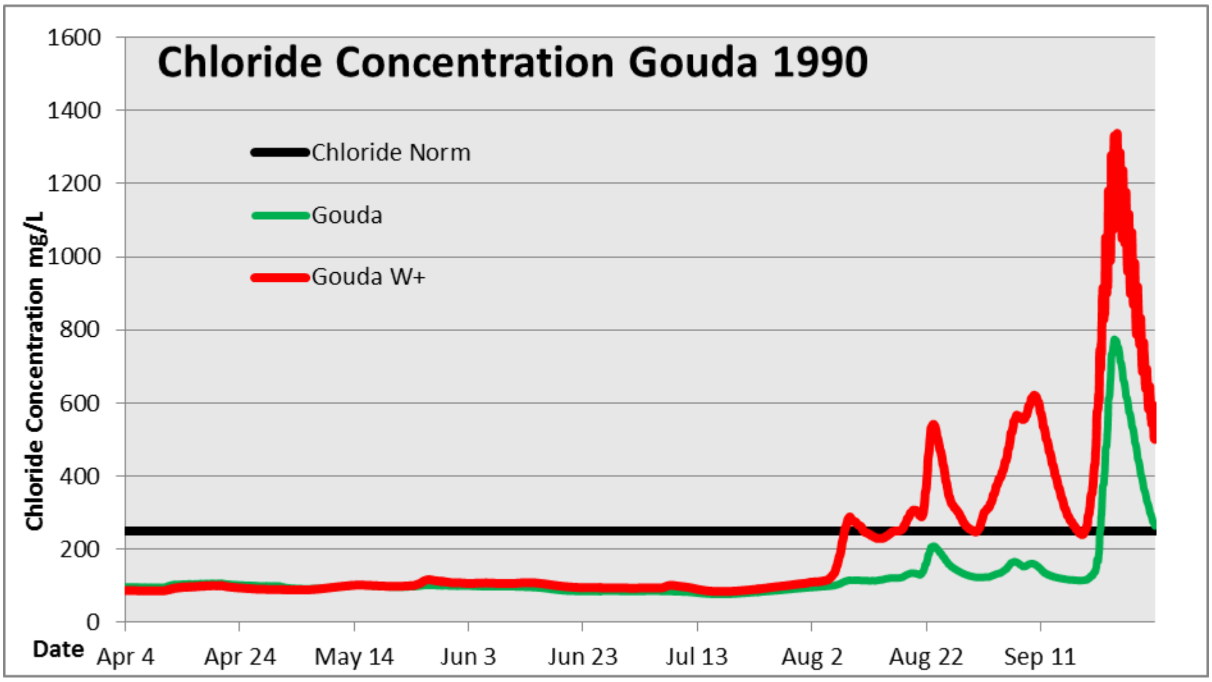
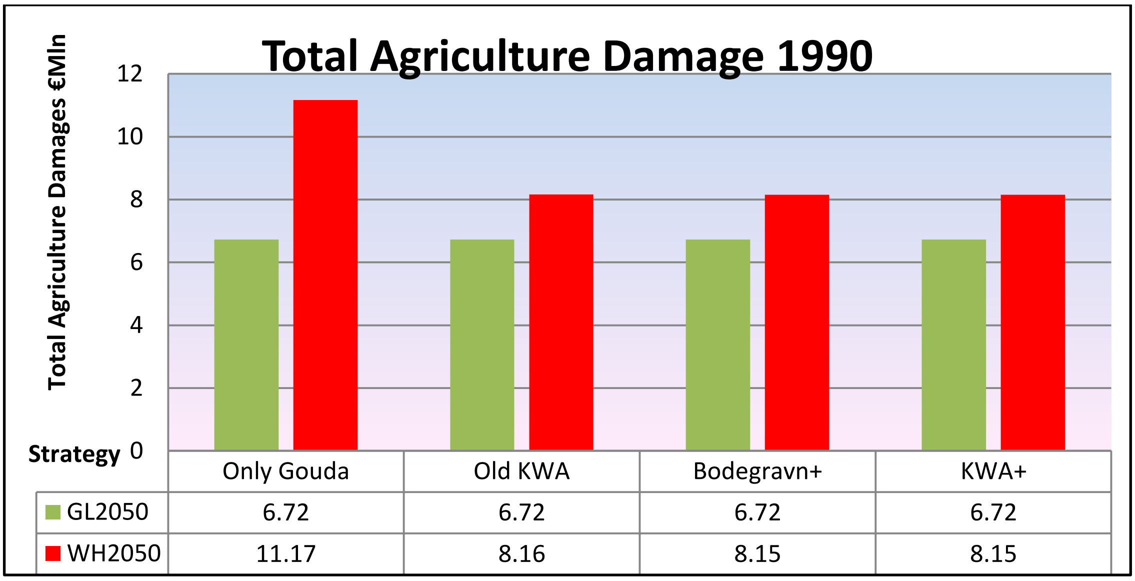


Figure 4.5. Overview of the chloride concentrations at Gouda during 1989 for both the measured amounts and the modelled KNMI'06 W+ amounts. Data retrieved from NDB model results (Hydrologic, 2013).



Strategy	Only Gouda	Old KWA	Bodegravn+	KWA+
🟩 GL2050	6.72	6.72	6.72	6.72
🟥 WH2050	11.17	8.16	8.15	8.15

Figure 4.6. Results of 1990 model runs for the GL2050 and WH2050 climate scenarios.

Figure 4.6 provides the results for 1990. When applying the GL2050 scenario, there is no agriculture yield reduction difference between each of the strategies. This is due to heightened chloride concentration occurring in a period where there is increased precipitation as well, so additional freshwater is unnecessary. For the WH2050 scenario there is a damage reduction of around €3 million between the Only Gouda and the Old KWA strategies. However, subsequent capacity improving strategies have negligible damage reduction. The historical model runs were left out of figure 4.6 as the difference in results was negligible.

4.2.2 Difference in results for 31 years

A period of 31 years between 1961 and 1991 was modelled to compare the different strategies over a longer time period.

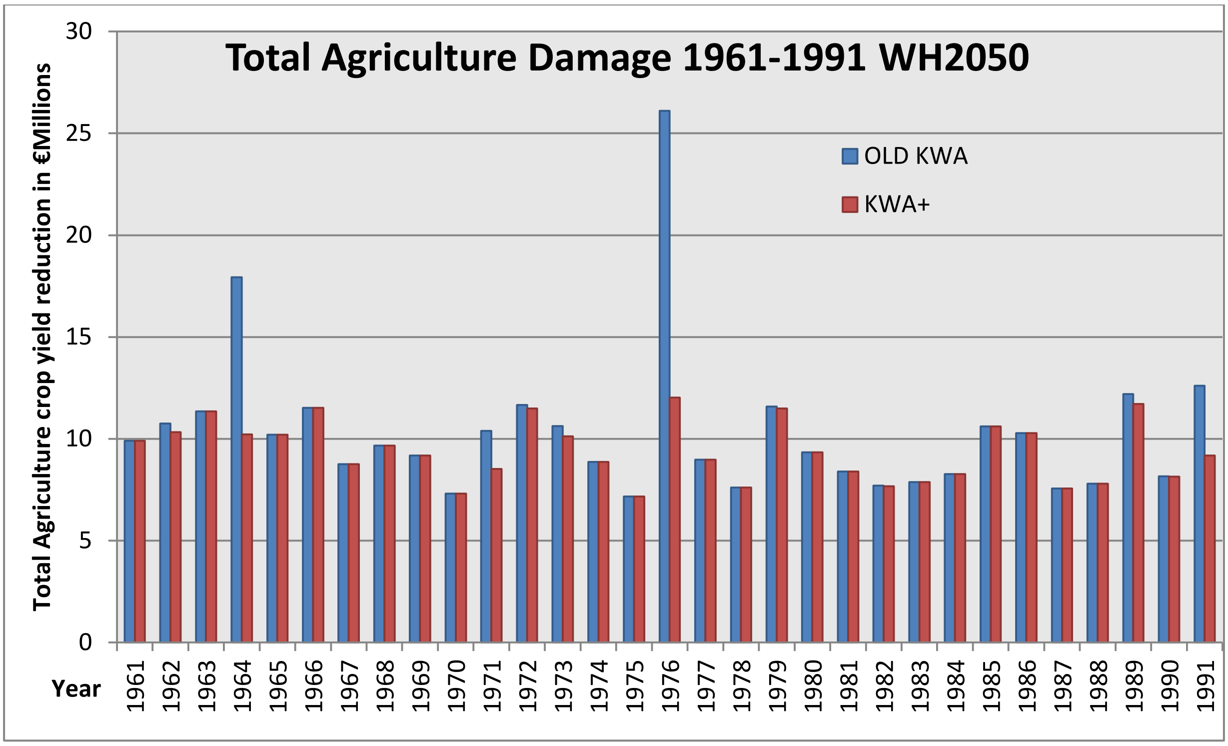
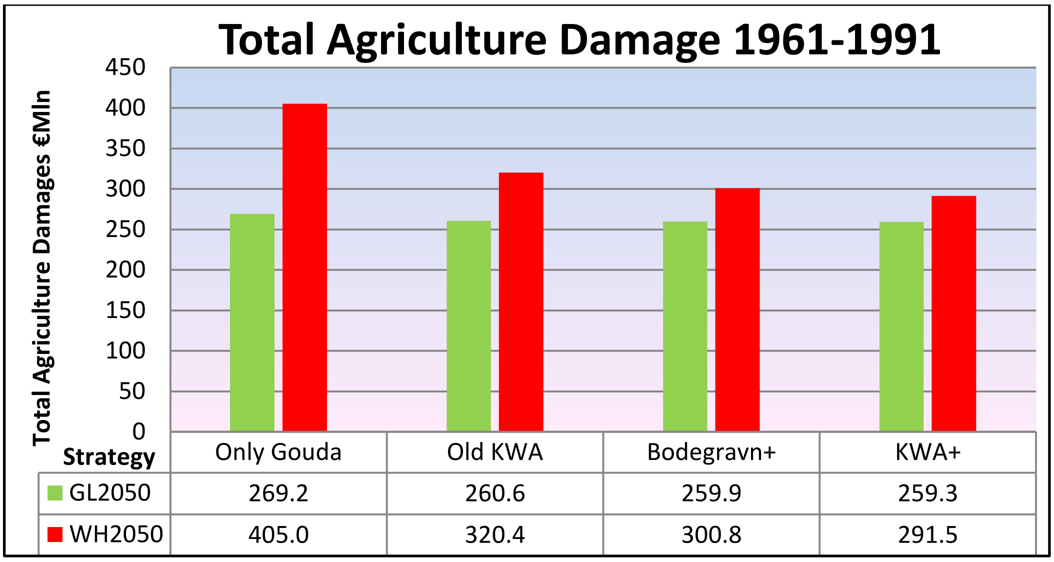


Figure 4.7. Agriculture crop yield for the Old KWA and KWA+ strategies with the KNMI'14 WH2050 climate scenario for weather data and the KNMI'06 W+ climate scenario for chloride concentrations.

Figure 4.7 shows the results between the old KWA and the KWA+ strategies for the WH2050 scenario. For every year the total agriculture damage is presented. For the extremely dry years (e.g. 1976) the difference between the two strategies is apparent. The extreme years are mitigated by the KWA+ strategy to be more in line with the other years. The reason for the high damages for the old KWA is due to the capacity problems, when the strategy is not sufficient, water with high chloride concentrations is let in at Gouda, primarily for water level maintenance, resulting in high agricultural damages. The main cost difference of the KWA+ is the mitigation of the damage from these extreme years.



Strategy	Only Gouda	Old KWA	Bodegravn+	KWA+
🟩 GL2050	269.2	260.6	259.9	259.3
🟥 WH2050	405.0	320.4	300.8	291.5

Figure 4.8. Results of 1961-1991 model runs for the GL2050 and WH2050 climate scenarios.

Figure 4.8 provides the results of the strategies for both climate scenarios. For the **GL2050 scenario**, Similar to the 1976 model runs, each subsequent upgrade to the freshwater system provides more damage mitigation. With the *Old KWA* strategy providing relatively the largest damage reduction when compared with the preceding strategy. The KWA+ has the lowest agriculture damages.

Again, the application of **the WH2050** scenario results in higher damages for the same reasons as during the 1976 and 1990 runs. During this scenario the KWA+ has a larger damage reduction. In the GL2050 scenario the difference between the current system (*Old KWA*) and the *KWA+* is around ~€1.3Million, which is an average annual damage reduction of ~0.5% over 31 years. However in the WH2050 scenario this difference is around ~€28.9millions, which is an average annual damage reduction of ~9% over 31 years. Furthermore the *KWA+* strategy results in a relatively low difference between both climate scenarios as well (in figure: column height closer to each other).

4.3 Cost-effectiveness of investments

This section will look into the cost-effectiveness of the investment and annual running costs of the KWA+, compared with the system how it is now (Old KWA strategy). The investment costs of the KWA+ are €39.5 million, paid for with funds coming from the Delta Fund. The running costs will be paid by the regional administrators, these are €400.000 annually, with an additional cost of €300.000 whenever the KWA+ is implemented (HDSR, 2014). For these calculations the assumption was made that the Old KWA costs around €100.000 annually and €50.000 whenever it is implemented. These costs are based on the De Groot (2012). These Old KWA running costs were subtracted from the KWA+ running costs. Note that these results only take agriculture damages caused by heightened chloride concentrations into account. Other damages, such as damages to nature, are not included. Furthermore, these results are based on the modelled period of 1961-1991.

As explained in section 3.5 the net present value (NPV) will be calculated to determine the cost-effectiveness of the investments. An annual discount rate of 3% will be used to calculate the NPV. Usually NPV calculations are done by using an initial investment, a discount rate and cash flow for each period. In this case the cash flow equals the damage reduction subtracted by the running costs. To see the effect of the discount rate on the result, the NPV with the old rate of 5.5% and a rate of 0% was calculated as well.

Table 4.3 shows the results for the NPV calculations. As shown in the previous sections, the difference between the Old KWA and the KWA+ is small for the **KNMI'14 GL2050** scenario. During this scenario the KWA+ is used 4 times within the 31 year period. Over these 31 years, the investment of the KWA+ results in a NPV of €-45.2 million. A large cause of the large negative NPV is that there is only one year (1976) where the cost reduction of the KWA+ is larger than the running costs. The recent change in the discount rate from 5.5% to 3% causes the NPV to be even more negative for this scenario.

When applying the **KNMI'14 WH2050** scenario, there are more years during which the cost reduction is larger than the running costs. The KWA+ is used in 18 years during the measured 31 years. For this scenario, the investment of the KWA+ results in a NPV of €-28.8Million. The recent Dutch guideline of changing the discount rate from 5.5% to 3% has some effect of the results which slightly mitigate the loss (otherwise it would be €-31.2Million). However, even with a discount rate of 0% the loss is still €24.5 million.

Discount rate	5.5% -old	3% - current	0%
GL2050 NPV (€)	**€-43.700.000**	**€-45.200.000**	**€-48.500.000**
WH2050 NPV (€)	**€-31.200.000**	**€-28.800.000**	**€-24.500.000**

Table 4.3. Results of the NPV calculations for the KWA+ for the period 1961-1991.

The reason for the GL2050 getting more expensive with a lower discount rate, while the WH2050 situation shows the opposite is due to the annual running costs for 31 years for the GL 2050 scenario being higher than the damage mitigation within those 31 years. For the WH2050 scenario the annual running costs are lower than the damage mitigation.

4.4 Sensitivity Analysis

In this section the sensitivity of a selection of parameters will be explored to see how they affect the model results. The explored sensitivities are:

- Averaged costs.
- Chloride norms of inlet water.
- Doubling the running period from 31 to 62 years
- The monetary disincentive at Gouda (section 3.4.4 and used for all results in this thesis).
- Climate scenarios (section 4.2).

4.4.1 Sensitivity to averaged costs

Due to cash flow differences occurring at specific moments in time there can be a large difference in results depending on at what moment in time a large damage reduction occurs. Due to the discount rate, when a damage reduction occurs in one of the early years it results in a higher NPV than if it were to occur during one of the later year. To see if this had a large effect on the calculation of the NPV's the damage reduction and the implementation costs of the KWA+ were averaged over the 1961-1991 period.

Discount rate	5.5% -old		3% - current		0%	
GL2050 NPV (€)	€-43.800.000	+0.23%	€-45.300.000	+0.22%	€-48.500.000	0%
WH2050 NPV (€)	€-32.400.000	-3.85%	€-29.800.000	-3.47%	€-24.500.000	0%

Table 4.4. Results of the NPV calculations with averaged cash flows. The percentages show the difference with the NPV calculated using the historical modelled cash flow reduction occurrences.

4.4.2 Sensitivity to a different chloride norm

The effects of different chloride norms during runs with the WH2050 scenario have been analyzed as well. The current chloride norm of inlet water at Gouda is 250mg/l. For the sensitivity analysis model runs were done with chloride norms of 150mg/l and 350mg/l to assess the sensitivity of the results to these changes. In effect a different chloride norm results in the model selecting the alternative strategy once that concentration is exceeded at Krimpen a/d IJssel. The results are provided in Table 4.5. A lower chloride norm results in lower agriculture damage, while a higher chloride norm results in more damage. For 1976 the differences are large, with the KWA+ strategy, the damage increase is almost 43% between a norm of 250mg/l and 350mg/l. For the entire period of 1961-1991 this is approximately 10 times lower, with 4% damage increase. When the chloride norm is lower, the alternative water allocation strategy needs to be used more often, almost twice the amount of usual during the 1961-1991 period. With a higher chloride norm the alternative strategy only needs to be used around 2/3's of the time.

The results for the NPV are provided in Table 4.6. These results follow a similar trend where a lower chloride norm results in a more positive NPV.

Circumstances		Old KWA		KWA+		Change
WH2050	Chloride norm	Agriculture damage	Percentage difference	Agriculture damage	Percentage difference	Periods (15days)
1976	150	**€24 940 000**	**-4.4%**	**€9 870 000**	**-17.9%**	**10**
	250	**€26 100 000**	**-**	**€12 020 000**	**-**	**7**
	350	**€29 190 000**	**+11.8%**	**€17 150 000**	**+42.7%**	**5**
1961-1991	150	**€308 900 000**	**-3.6%**	**€275 600 000**	**-5.5%**	**82**
	250	**€320 400 000**	**-**	**€291 500 000**	**-**	**45**
	350	**€329 200 000**	**+2.7%**	**€303 100 000**	**+4.0%**	**31**

Table 4.5. Sensitivity if the WH2050 model results to changes in chloride norm.

Circumstances KWA+		Discount rate 5.5%		Discount rate 3%		Discount rate 0%	
WH2050	Chloride norm	NPV	Percentage difference	NPV	Percentage difference	NPV	Percentage Difference
1961-1991	150	**€-30 390 000**	**-2.60%**	**€-27 450 000**	**-4.69%**	**€-21 700 000**	**-11.43%**
	250	**€-31 200 000**	**-**	**€-28 800 000**	**-**	**€-24 500 000**	**-**
	350	**€-32 000 000**	**+2.56%**	**€-29 900 000**	**+3.82%**	**€-25 900 000**	**+5.71%**

Table 4.6. Results of the NPV calculations with different chloride norms.

4.4.3 Sensitivity to doubling the running time.

The modelled period (1961-1991) is 31 years. This period was chosen due to data availability limitations in the modelled chloride concentration data on the HIJ with the KNMI'06 W+ scenario. However, to see the effect that a longer running time would have, a sensitivity analysis was conducted in which the modelled period was doubled. This was done by using the 31 years results, doubling it to 62 years and adjusting this in the NPV calculation. The results are provided in Table 4.7. For the current discount rate of 3%, the effect on the NPV of doubling the running time is an increase of almost 15%.

It remains to be seen if 31 years is a reasonable write-off period for the KWA+ investment. This is difficult to determine as a large part of the KWA+ involves increasing the discharge capacity of channels in HDSR. Once this capacity change has been realized the concept of a write-off period is difficult to implement, as these channels will have been lastingly altered. Maintaining this capacity (by dredging etc.) is already included within the annual running costs. However, 31 years does seem reasonable in this case, because due to the nature of the concept of NPV, a doubled write-off period would result in a limited change with the current discount rate. Furthermore, this doubling also resulted in the extremely dry year of 1976 (return time 1:100y) to be included twice (including the application of the climate scenario).

Discount rate	**5.5% -old**		**3% - current**		**0%**	
31 years (WH2050)	**€-31.200.000**	-5.13%	**€-28.800.000**	-14.93%	**€-24.500.000**	-61.63%
62 years (WH2050)	**€-29.600.000**		**€-24.500.000**		**€-9.400.000**	

Table 4.7. Results of the NPV calculations for 31 and 62 years. The percentages show the differences in negative NPV between 31 and 62 years.

Chapter 5 - Discussion

This study looked into how a model could be created to contribute to the advance of the rationalization of water management and to investigate the effects of different water allocation strategies under varying circumstances. The resulting WAOR model was used to assess the economic viability of alternative water management strategies within the western Netherlands during freshwater shortages in Rijnland and increased chloride concentrations on the Hollandse IJssel.

A similar investigation in Rijnland was done by Stuyt et al. (2013) with the EEO1.0 model. The EEO1.0 was designed as a rapid assessment model to provide quick insights in the effect of chloride concentration related changes to the Rijnland system. The WAOR was designed to provide functionality as a comprehensive analysis tool for strategic (investment) analysis and scenario analysis. The inclusion of temporal variability for weather data and chloride concentrations allows for simulation of different years and specific periods with freshwater supply problems. Multiple inlet strategies and system constraints allow for the assessment of the cost-effectiveness of these strategies for varying chloride situations, while the option for including multiple years and climate scenarios allows for the determining the cost-effectiveness of investments over longer timescales. Furthermore, an important difference is that the EEO1.0 optimizes based on inlet minimization, while the WAOR optimizes based on cost reduction.

Given the increasing saltwater intrusion, one might expect that investments for expansion of the freshwater supply in Rijnland would result a large socio-economic benefit for the region. However, the results of the model runs reveal that even though the alternative water management strategies reduce agriculture damages (especially during very dry years), the investment costs and annual running costs are not expected be overcome by agriculture damage reduction alone.

5.1 Discussion of the strategies

This section will discuss the results of the different strategies that were investigated with the WAOR and reflect on their effectiveness.

The **Only Gouda** strategy was included in the model runs to assess what would happen if no alternative freshwater supply were applied or available. Its advantage is that it is a cheap measure in terms of implementation; no process needs to be started for it to work as water is let in under free fall. However it has some highly negative downsides when confronted with heightened chloride concentrations on the HIJ. This strategy provides the highest amount of agriculture damages, while the increased chloride concentrations result in an inability to provide polders with the flushing required for reducing these concentrations. Furthermore, the high chloride concentrations may even provide irreversible damages to nature and cause land subsidence due to peat degradation (Deltares, 2015). However, as shown by Figure 4.6, in years such as 1990 (with the GL2050 scenario) when the chloride concentration at Gouda only slightly exceeds the chloride norm of 250 mg/l and the freshwater demand is low this strategy can occasionally prove to be sufficient (i.e. small or no difference with the other strategies), even during small exceedances of the chloride norm.

The current water allocation strategy in Rijnland is the **Old KWA**. Over the measured 1961-1991 period, the *Old KWA* often provides a sizable damage mitigation. When confronted with the WH2050 scenario this becomes most evident, with a total damage mitigation of around €85 million compared to the *Only Gouda* strategy. The *Old KWA* provides the largest relative damage mitigation of all the subsequent KWA upgrades. This results from the *Old KWA* being the first of the strategies to realize an alternative freshwater supply. This alternative supply allows for a different flow route through the boezem system and allows for some vulnerable areas to be supplied with good-quality freshwater, such as the Nieuwkoopse plassen and part of Boskoop. As this route is not surrounded by deep polders, it allows these areas to avoid taking in water that has heightened chloride concentration as a result of mixing with water originating from deep polders

Bodegraven+ is an interesting strategy to assess, as it is one part of the upgrades for the KWA+. The results (Figure 4.8) show that the *Bodengraven+* is part of a middle ground between the *Old KWA* and the *KWA+* strategies. When applying the WH2050 scenario for the 1961-1991 period it provides a damage mitigation of around €20 million compared to the *Old KWA*, which is roughly 2/3's of the mitigation of the *KWA+* strategy (compared to the *Old KWA*). However, the exact cost difference between the upgrade at Bodengraven and the creation of the freshwater buffer is uncertain as they are part of the same upgrade step. Depending on the costs difference between the *Bodegraven+* and the *KWA+* strategies, it could be possible that the *Bodegraven+* is considerably cheaper than the *KWA+*. In that case it may be worth a consideration as an alternative, so the full *KWA+* can be postponed until developments occur that make that investment more justifiable.

The **KWA+** provides the highest overall agriculture damage mitigation of all the strategies. For the years 1961-1991 and the WH2050 scenario, it provides an additional €9 million in damage reduction compared to the *Bodegraven+* strategy and a total reduction of €29 million compared to the *Old KWA*. Furthermore, the increased capacity allows it to have a higher success rate in delivering enough water with the desired quality than the *Old KWA* and the *Bodegraven+* strategies. Occasionally, when the *KWA+* is insufficient for the quantitative demand, it is often close to providing the required amount of water to Rijnland. When this situation occurs, additional water with higher chloride concentrations is let in at Gouda to accommodate for the remaining water demand. Due to the mixing of this water with water from the freshwater buffer, the negative effects of additional inlet of water are mitigated. The results have shown that in none of the scenarios the damage mitigation from the *KWA+* is cost-effective with the investment when only taking agriculture damages into account. However, other advantageous effects of the *KWA+* strategy, such as prevention of peat degradation, were not considered by the WAOR. If the climate will change in line with the WH2050 scenario and if other advantages make up for the NPV of -€28.8million over a 31 years period it could prove to be a cost-effective strategy, seeing as it can supply Rijnland with the most freshwater during dry period and as it can prevent undesirably high chloride concentrations from being let in.

As previously mentioned, there is often a conservative attitude towards chloride concentration related water allocation. Whenever inlet water surpasses the determined chloride norm, inlet is stopped. The **mixed** strategies were an interesting addition to see what the effects are of letting in water from both sources, even if water from one source (Gouda) has higher chloride concentrations than the chloride norm. The results show that the mixed strategies have higher damages than their corresponding KWA strategies. However, the advantage is that they are practically always successful in facilitating the water demand of Rijnland for polder water level maintenance and thus reliable for that purpose. The damages are often somewhat higher than their KWA counterparts, as these strategies will always let in some water at Gouda to ensure there is a certain level of discharge in the boezem. Often this leads to slightly increased but tolerable agriculture yield losses. However, in years such as 1976 these strategies can result in large damages. For now the mixed strategies provide a useful alternative for when a KWA strategy is insufficient in providing the required amount of water for water level maintenance.

5.2. Implications of the results.

According to the results, the investment for the KWA+ with regards to agricultural damage alone does not seem to be cost-effective. However, a distinction that is not made in the calculation of the cost-effectiveness is the distribution of the monetary effects. The KWA+ investment will be realized by funding from the delta fund, while the regional administrators are responsible for the running costs (section 4.4). However, the advantages of the damage reduction lie primarily with the agriculture sector. Consequently, if the investment would be put off, the resulting increase in agriculture damages would lie with the agriculture sector. If the KWA+ investment would be reconsidered, then it may be required to create a compensation mechanism to reimburse the agriculture sector for their losses in agriculture yield. This would require detailed modelling of individual polder systems to provide an overview on where exactly the damages would occur, so farmers that actually experience yield losses can be compensated.

The study was focused on the effects of chloride concentrations of inlet water on agricultural crop yields. There are other effects of increased chloride concentrations as well. As stated in section 3.3.2, higher chloride concentrations result in an increase in peat degradation, consequently resulting in land subsidence. These effects are not calculated in the WAOR, but they could have an additional long-term monetary consequence. Research by Deltares (2016) was conducted to investigate the economic effects of land subsidence of peat areas in Rijnland. It was found that land subsidence and its resulting damages occurred especially during dry years. Furthermore, the availability of an alternative water supply entering Rijnland at a different location allows for supplying vulnerable nature areas, such as the Natura2000 area of the Nieuwkoopse Plassen, with freshwater. Therefore, the negative result does not necessarily imply that the KWA+ is an unsound investment, as other effects of the increased freshwater availability were not investigated in this study.

The results of the WAOR model reveal that a rational approach to water management can be useful for assessments on the cost-effectiveness of water supply related investments. It provides a holistic approach to a field that otherwise often encompasses a conservative attitude towards chloride concentration related water allocation. Besides being valuable for the assessment of investments in the water allocation system, it is useful for the assessment of different operational decision when confronted with varying weather and chloride situations.

The WAOR model results in a more accurate and arguably more satisfying approach than the earlier approach made by Stuyt et al. (2013) with the EEO1.0. The results of the WAOR are based on more extensive and variable amounts of input arguments, strategies and system characteristics.

5.3 Relevance of the results

The results of the model supports the argument made by Stuyt et al. (2015) that current views of chloride acceptance levels for agriculture are pessimistic. As the results show, the amount of damage reduction that this conservative attitude prevents does not appear to be cost-effective with the investments made. Furthermore, Stuyt et al. (2015) identified the importance of the development of instruments and models to better understand the implications of different salt water allocation related policies. The WAOR facilitates this development by allowing comprehensive assessment of changes in the water system, such as changes in the chloride norms of polder systems and capacity changes. By doing so, it helps to create a shared understanding and agreement on the effects of water allocation changes.

The WAOR also complements the principle of Smart Water Management as it provides water managers with the option to assess their inlet strategy, information on how available water resources can be used effectively, and helps to determine the best approach during freshwater shortages, depending on the specific weather and chloride situation. Although real-time decision-making support has not been investigated in full detail in this study, the model is easily adaptable to allow for this functionality. This can be achieved by changing the historical data for measured data and predictions during a dry period moment and subsequently running the model with different strategies to compare the most effective allocation option.

Finally, the WAOR provides an addition to the existing collection of Hydro-economic models and provides insights into hydro-economics in general. It delivers a holistic approach to freshwater allocation questions and allows for the assessment of the cost-effectiveness of freshwater supply related investments within coastal areas. As an increasing number of people settle in coastal areas and some of these regions are coming under increasing pressure form salt-intrusion (Post & Abarca, 2009), it is interesting to identify the extent of the effects of freshwater supply shortages. The results of the study indicate that it is valuable to assess the investments made into freshwater supply systems, and that the negative aspects of not investing might not always be as severe as previously considered. Furthermore, optimization of existing systems can be considered before making large investments (Smart Water Management). The KWA+ investment likely has a limited environmental impact. But in other regions of the world, freshwater supply improvements may prove to be highly unsustainable. They could result in an increasing depletion of groundwater resources or result in significant landscape alterations (e.g. large dams) (Reca et al., 2001).

5.4 Limitations of the WAOR model

Limitations in model concept

- An alternative strategy requires some implementation time. Supplying freshwater to Bodegraven and Gouda and creating the freshwater buffer on the HIJ is not something that happens instantaneous. Especially the freshwater buffer needs to be implemented before the chloride concentrations at Gouda become too high, otherwise this water needs to be flushed out first, which will take time and freshwater that could otherwise be used by Rijnland.

- The model is limited in that it only considers damages for crops that are caused by the use of surface polder and its chloride concentration. Damages caused by peat degradation and damages to nature are not considered by the WAOR model. The effects of preventing these damages may result in a more positive assessment of the KWA+.

Limitations in input data:

- The use of the KNMI'06 W+ climate scenario for the chloride concentrations on the HIJ may result the use of too high concentration values and an overestimation of the agricultural damages. In the more recent KNMI'14 WH2050 scenario the chloride concentration values may be lower as low discharges on the Rhine River will be less extreme than during the W+ scenario. The effects of the KNMI'14 scenarios on the chloride concentrations on the HIJ were not available for this thesis.

- A limitation of the model is the division of the damage function for the entire growing season into twelve periods of fifteen days. The total growing season damage was calculated for every period and then divided by the amount of periods. This is not completely accurate, as the negative effect of heightened chloride concentrations on crops is not uniform in time during the growing season (Stuyt et al., 2013). This is likely to result in an underestimation of the agricultural damages, as heightened chloride concentration often occur later in the growing season and crops are more vulnerable to increased chloride concentrations during the earlier stages of their development. Furthermore, even though it is an improvement in accuracy compared to the EEO1.0, the 15-day periods for weather data may result in inaccuracies for precipitation as short intense events are spread out over 15 days as short intense events are spread out over 15 days.

5.5 Recommendations for additions to the WAOR

Currently, the WAOR allows for reasonably accurate estimates of the effects of different strategies on agriculture crop yield. However, efforts can be made to improve the model. Some additions to the model could prove valuable if the data required to realize this is made available. Distinction is made between recommendations for the model concept and recommendations for the input data.

Recommendations for the Model:

- In the WAOR, Rijnland has been divided into ten separate polder systems. As Rijnland has 206 different polders, it may prove valuable to divide these ten different polder systems into smaller units to better simulate the water allocation routes and the effects of chloride concentrations on specific smaller polder units. This would help to determine more accurately the location where the agriculture yield reductions may occur. Although this addition lies within the possibility of the WAOR, more precise water demand data will be necessary for each smaller polder system.

- When implementing real-time applicability to the model, the inclusion of weather and chloride concentration forecasts could prove a valuable addition as it allows for the model to provide the best option to use at that moment and for the predicted period. This will facilitate operational use of the WAOR model.

Recommendations for improved and more detailed input:

- The chloride data that was made available for the WAOR is based on modelled chloride concentration values based on historical discharge patters of rivers and seawater levels. Only one climate scenario application was available and included in the model: the KNMI'06 W+ scenario. An expansion of the model could be to include chloride data based on the newer KNMI'14 chloride concentrations for all four climate scenario's and see what its effects are on the results.

- Another valuable addition would be the ability to include more years in the model. This was not possible due to lack of data. The WAOR already contains a long period of years, However, It would be interesting to include the recent dry years of 2003 and 2011, which are the last two times the KWA was implemented, to assess the effects of these years on the results.

- Currently, the agriculture damage functions are based upon total damage functions for an entire growing season and divided by the amount of measured periods. However as presented by Stuyt et al. (2013), damage to agriculture is not uniform over the growing season. It would be possible to apply damage functions that consider the moment in time within the growing season. When available, these time-dependent damage functions would be easily implementable into the model. This could possibly lower the total damages, as near the end of the growing season some crops may experience lower yield reduction when exposed to heightened chloride concentrations (Stuyt et al., 2013). Furthermore, heightened chloride concentrations occur more often near the end of the growing season, while early in the growing season heightened chloride concentrations have a lower frequency of occurrence (Hydrologic, 2013). Finally, it can be considered to update the chloride damage functions in the WAOR model based on recent research by Stuyt et al. (July, 2016).

- Damages to nature are not included in the WAOR model. In the EEO1.0 a qualitative analysis was made to investigate the effects of heightened chloride concentrations on nature. No attempt was made to monetize any damages that may occur. It would be interesting to investigate how nature damages in Rijnland can be monetized and subsequently implemented into the WAOR model. A possibility would be to derive monetary values for certain chloride damage thresholds. Once damages exceed this threshold a certain amount of monetary damage will occur, therefore providing incentives to the model to try and keep chloride concentrations low in these areas. However, there is no clear answer among scientists on how to best monetize (loss of) nature. The value of nature is very subjective and techniques to accomplish nature monetization are found to often be uninformative (Stolwijk, 2004).

- A recommendation that would be valuable to enhance the information that the WAOR results provide be to include insight into the amount of additional water that would be required once a strategy is insufficient. This could be valuable for an analysis on the capacity requirements for a possible future expansion measure of the KWA+.

Chapter 6 - Conclusion and Recommendations

This chapter lists the main conclusion of this thesis. Section 6.1 provides a reflection on the used methodology. Section 6.2 summarizes the main conclusions. Section 6.3 summarizes the recommendations.

6.1 Reflection on Methodology

The first objective of this study was to develop a model which investigates the effects of and contributes to the advances of rationalization of water management. The earlier developed EEO1.0 has been used as a basis on which a more comprehensive deterministic model, the WAOR, is build. This new model combines input for weather and chloride concentration data, agriculture damage functions, temporal variability, climate scenarios, and system constraints, in order to determine the agriculture yield losses in one or multiple growing seasons. It provides results that showcase the effects of different water allocation strategies based on historical data measurements as well as on climate scenario predictions. By using these results, it is possible to investigate cost-effectiveness of investments into the freshwater supply system of Rijnland.

The WAOR is an expansion on the EEO1.0 in terms of comprehension and temporal variability within a growing season. However, it still suffers from several accuracy related issues, primarily due to issues with data availability. Firstly, Agriculture damage is calculated based on damage functions for an entire growing season and the result is divided by the amount of measured periods (in this case twelve). This is not completely accurate, as pointed out by Stuyt et al. (2013), crop tolerance can be time dependent. Therefore, it is difficult to determine how accurate the WAOR model is in this regard and whether it may overestimate or underestimate the amount of agricultural crop yield reduction, especially because there are no historical (monetary) agriculture damage amounts available to validate the results. Furthermore, it is difficult to determine the exact relationship between the length of the periods with heightened chloride concentrations and the actual agriculture crop yield reduction. As a safety margin, Periods of 15 days were chosen instead of daily values to allow the system time to “process” the water and chloride concentration distribution through the polder-boezem system. Secondly, the polder-boezem system used in the model was based on assumptions, as a lot of polders are combined in the systems of “Zuidelijke veenpolders” and “Overige polders”. Consequently they have a single inlet location for the entire system. Thirdly, the results are influenced by characteristics of the involved years. For example, as 1976 was a very dry year (occurrence of 1:100 years), it is largely responsible for the differences in results between the strategies. Inclusion of more (dry) years, such as 2003 and 2011, which are absent in the current version of the WAOR model, would allow for better understanding of the position of 1976 over longer timescales and it the effect of such extreme years on the overall assessment of the cost-effectiveness of the investment.

Improving the accuracy of the results can be achieved by:

1) Including damage functions that show variation according to the moment in time during the growing season. Adding monthly specific data will allow for better day-to-day insights and alignment of alternative water management strategies.

2) Expanding the polder-boezem system by dividing larger systems into smaller separate polder systems, which allows for increased accuracy on the spatial distribution of crop yield reductions. Additionally, it would provide improved insights into the exact locations where these damages occur.
3) Including chloride predictions based on all four KNMI'14 climate scenarios in order gain insight in the effects of applying the other climate scenarios.
4) Including more (recent) years so as to determine the effects of varying years.

6.2 Conclusion

The second objective of this study was to assess the economic viability of alternative water management strategies within the western Netherlands during periods of freshwater shortage in Rijnland and increased chloride concentrations on the Hollandse IJssel. As described in section 1.4, current views on chloride acceptance levels of water systems have been rather pessimistic (Stuyt et al. 2015). This calls for development of models and instruments to better understand implications of different salt water allocation related policies and to manage for alternative strategies

The model was built 1) to be intuitive with regards to strategy and constraint selection and 2) to facilitate easy comparison of the different strategies. Results are satisfactory in terms of expectations, as each of the subsequent investments to expand the freshwater supply system show increased agriculture damage reductions during dry periods. However, the degree of these damage reductions as calculated by the WAOR model was unexpected. The damage reduction by the *KWA+* strategy was lower than expected and not cost-effective with the investment costs based on agriculture damages. For mild climate scenarios damage reduction is low and even for the most extreme scenario, the achieved agriculture damage reduction is not cost-effective by itself for the investment involved. As a consequence of the used methodology, there are limitations to the assessment. The model does not consider all of the possible positive aspects of these investments. Prevention of damage to nature and prevention of peat degradation for example are not modelled within this study and could provide additional (monetary) benefits.

The WAOR model adds to the field of Hydro-economics by providing a holistic approach to water allocation problem, and allowing for the assessment of cost-effectiveness of freshwater supply related investments within coastal areas. In hydro-economics models are used for water prizing, optimal water allocation and guiding investments in water infrastructure (Bierkens, 2015). The results of the model indicate that assessment models for investments related to freshwater supply expansion and optimal water allocation can be very valuable. The inclusion of climate scenarios adds to understanding on how a changing climate may impact water allocation in the future. As such, the WAOR model adds upon the existing collection of hydro-economic models. The application of temporal variability for certain inputs is important for this analysis, as for salinization and freshwater shortages there is large variability within the growing season. Consequently, this makes this model interesting for operational management and helps with aligning hydro-economical concepts with contemporary and future water management.

The model complements the development of smart water management for operational water management by allowing for real-time assessment of variations in strategies and chloride norms. The results of the study support the idea of the pessimistic approach towards salt related water allocation in the Netherlands. The results show that the proposed KWA+ investment may not be as cost-effective (regarding agricultural damages) as previously anticipated. Furthermore, the results show that the consequences of delaying investments in water infrastructure may not be as severe as anticipated. By holistic assessment of water allocation strategies, the WAOR model is an important step in achieving a shared understanding on the effects of changes in the freshwater allocation system and supports development of shared commitment towards future salt related water policies.

6.3 Recommendations

Aside from the possible improvements to the WAOR model as provided in section 5.5, the following recommendations can be made:

- First, if possible it would be interesting to combine additional economic effects of freshwater shortages. This study focused on the effects of chloride concentrations of inlet water on agricultural crop yields. Other effects, such as land subsidence, effects on nature and effects on shipping, are not taken into account. Furthermore the flushing in the WAOR model only takes chloride concentrations into account. Other concentrations, such as toxins, could cause problems as well. Flushing may cease due to higher chloride concentrations of inlet water. This could result in the build-up of concentrations of other undesirable concentrations in the surface waters. These concentrations may also have monetary consequences, which could be an interesting addition to the model.

- Second, an important source of chloride in the boezem apart from inlet from the HIJ is water originating from deep polders with high chloride contents. When this water is discharged onto the boezem system and subsequently let into vulnerable areas, it could result in damage increases. A location where this is especially evident is the deep polder system Noordplas-Tempelpolder. Water let in at Gouda first reaches these polders and subsequently reaches the intake areas of Boskoop, making the Noordplas/Middelburg-Tempelpolder system in part responsible for agriculture yield losses at Boskoop. If possible, preventing the (brackish) water originating from the deep polders from entering Boskoop, would likely significantly reduce yield losses there.

- Third, since the KWA+ has not been built yet, the Bodengraven+ alternative should be seriously investigated. The investment and running cost difference between Bodegraven+ and the KWA+ should be made apparent. If these costs differ a lot, it may not only provide a notable investment cost reduction in, but may prevent the requirement of creating a freshwater buffer on the HIJ as well. This way the complete KWA+ can be postponed until its implementation is a more justifiable in terms of investment costs.

- Fourth, minimalizing the required water inlet of Rijnland, could help alleviate capacity problems. This can (partly) be accomplished by allowing variable water levels within (some of) the polder systems. Variable water levels act as a buffer during dry periods because they allow for the water level to fluctuate between two boundaries, instead of the requirement of always remaining the same. When evaporation is high it allows for the water levels to go down until a certain boundary is reached, and only then will the polder let in more water (Stowa, 2012). Rijnland already applies this principle in several areas (Rijnland, n.d-a.). If this principle can be incorporated into the WAOR it may result in a reduction of the required water. It may be especially valuable if this would prevent inlet of water with high chloride contents into a polder.

- Fifth, instead of disregarding the KWA+, it is interesting to determine what the extent is of using the KWA+ as effectively as possible. Sensitivity analysis of the WAOR has shown that lowering the chloride norm at Gouda results in lower agriculture damages. The KWA+ will become more cost-efficient when it gets used more often to positive effect. Such measures will entail a more effective usage of the KWA+ and complement the principle of smart water management.

Bibliography

Arcadis. (2012). *Regionale knelpuntenanalyse zoetwater 2.0 en verkennende maatregelen- en effectbepaling.* Retrieved from https://www.hhdelfland.nl/over-ons/vergaderoverzicht-bestuur-en-stukken/2012_6_11_college-van-dijkgraaf-en-hoogheemraden/

Beersma, J. J., Buishand, T. A., de Goederen, S., & Jacobs, P. (2005). *Zout, zouter, zoutst, statistiek van de externe verzilting in Midden-West Nederland.* De Bilt.

Berendsen, H. J. A., & Stouthamer, E. (2000). Late Weichselian and Holocene palaeogeography of the Rhine-Meuse delta, the Netherlands. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *161*(3-4), 311–335. http://doi.org/10.1016/S0031-0182(00)00073-0

Bickel, P., Friedrich, R., Burgess, A., Fagiani, P., Hunt, A., Jong, G. D., … Tavasszy, L. (2006). *Developing Harmonised European Approaches for Transport Costing and Project Assessment. Deliverable 5 Proposal for Harmonised Guidelines.* Stuttgard.

Bierkens, M. F. P. (2015). Global hydrology 2015: State, trends, and directions. *Water Resources Research*, *51*(7), 4923–4947. http://doi.org/10.1002/2015WR017173

Borger, G., & Ligtendag, W. (1998). The role of water in the development of The Netherlands— a historical perspective. *J Coast Conserv*, *4*(2), 109–114.

Brouwer, S., & Huitema, D. (2007). *We kunnen niet allemaal lamsoor eten; De uitkomsten van vijf focusgroep discussies over Leven met Zout Water*. Vrije Universiteit, Amsterdam.

Bulsink, F. (2010). *Zoetwaterverkenning Midden-West Nederland*. Universiteit Twente. Retrieved from http://essay.utwente.nl/59687/1/MA_thesis_F_Bulsink.pdf

De Groot, E. (2012). *Evaluatie inzet Kleinschalige Wateraanvoer Voorzieningen Midden-Holland*.

De Louw, P. G. B., Oude Essink, G. H. P., Stuyfzand, P. J., & van der Zee, S. E. A. T. M. (2010). Upward groundwater flow in boils as the dominant mechanism of salinization in deep polders, The Netherlands. *Journal of Hydrology*, *394*(3-4), 494–506. http://doi.org/10.1016/j.jhydrol.2010.10.009

De Louw, P. G. B., Van Der Velde, Y., & T. M. Van Der Zee, S. E. A. (2011). Quantifying water and salt fluxes in a lowland polder catchment dominated by boil seepage: A probabilistic end-member mixing approach. *Hydrology and Earth System Sciences*, *15*(7), 2101–2117. http://doi.org/10.5194/hess-15-2101-2011

De Moel, H., & Aerts, J. C. J. H. (2011). Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Natural Hazards*, *58*(1), 407–425. http://doi.org/10.1007/s11069-010-9675-6

Deltacomissie. (2015). *Deltaprogramma 2015 Werk aan de delta. De beslissingen om Nederland veilig en leefbaar te houden*. Retrieved from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/begrotingen/2014/09/16/deltaprogramma-2015/deltaprogramma-2015.pdf

Deltares. (2015a). *Cumulatieve effecten van externe ingrepen voor de zoetwatervoorziening in de 21e eeuw. 1220104-000.*

Deltares. (2015b). *Economische analyse van de zoetwatervoorziening in Nederland. 1220104-004.*

Faneca Sanchez, M., Gunnink, J. L., Van Baaren, E. S., Oude Essink, G. H. P., Siemon, B., Auken, E., … De Louw, P. G. B. (2012). Modelling climate change effects on a dutch coastal groundwater system using airborne electromagnetic measurements. *Hydrology and Earth System Sciences*, *16*(12), 4499–4516. http://doi.org/10.5194/hess-16-4499-2012

Fiselier, J., Klijn, F., Duel, H., & Kwakernaak, C. (1992). The choice between desiccation of wetlands or the spread of Rhine water over The Netherlands. *Wetlands Ecology and Management*, *2*(1-2), 85–93. http://doi.org/10.1007/BF00178138

Fritsch, F. N., & Carlson, R. E. (1980). Monotone Piecewise Cubic Interpolation. *SIAM Journal on Numerical Analysis*, *17*(2), 238–246. http://doi.org/10.1137/0717021

FrontlineSolvers. (n.d.). Excel Solver Help. Retrieved May 22, 2016, from http://www.solver.com/excel-solver-help

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., & Howitt, R. E. (2009). Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology*. http://doi.org/10.1016/j.jhydrol.2009.06.037

Hoekstra, A., & Chapagain, A. K. (2004). Water Footprints of Nations (Vol 2). *Water Research*, *2*(16), 240.

Hoekstra, A., & Chapagain, A. K. (2007). Water footprints of nations.Water use by people as a function of their consumption pattern. *Water Resource Management*, *21*(1), 35–48.

Hoogheemraadschap De Stichtse Rijnlanden. (2014). Uitvoeringsprogramma zoetwaterregio West-Nederland. Retrieved from http://www.hdsr.nl/beleid-plannen/deltaprogramma/deelprogramma-0/artikel/nieuwsbrief-nr-4/

Hoogheemraadschap van Rijnland. (n.d.-a). Flexibel Pijlbeheer. Retrieved July 5, 2016, from https://www.rijnland.net/over-rijnland/downloads-over-rijnland/

Hoogheemraadschap van Rijnland. (n.d.-b). Geschiedenis en canon. Retrieved July 12, 2016, from https://www.rijnland.net/over-rijnland/erfgoed/geschiedenis-en-canon-1

Hoogheemraadschap van Rijnland. (n.d.-c). Kentallen. Retrieved July 12, 2016, from https://www.rijnland.net/over-rijnland/organisatie/kentallen

Hoogheemraadschap van Rijnland. (2009). *Flood control in the Netherlands*. Leiden. Retrieved from https://www.rijnland.net/downloads/floodcontrolrijnland-1-1.pdf

Hoogheemraadschap van Rijnland. (2009). *Zoet & zout; Verzilting in Rijnland*. Leiden.

Hoogheemraadschap van Rijnland. (2011). Boezemgemalen. Retrieved from https://www.rijnland.net/over-rijnland/downloads-over-rijnland/boezemgemalen.pdf

Hoogheemraadschap van Rijnland. (2013). *Watergebiedsplan regio Greenport Boskoop-inventarisatie en knelpunten.* Leiden.

HydroLogic. (2013). *Waterverdelings- en verziltingsvraagstukken in het hoofdwatersysteem in West- en Midden-Nederland.* Amersfoort.

HydroLogic. (2014). *Verkenning zoetwaterbuffer Hollandsche IJssel. P557.* Amersfoort.

HydroLogic. (2015a). *Inventarisatie Slim Watermanagement Rijn-Maasmonding*. Amersfoort. Retrieved from http://slimwatermanagement.nl/file/download/41991672

HydroLogic. (2015b). *Optimalisatie Waterpeilbeheer regio Amsterdam-Rijnkanaal/ Noordzeekanaal.* Amersfoort.

IPCC. (2014). Summary for Policy Makers. *Climate Change 2014: Impacts, Adaptation and Vulnerability - Contributions of the Working Group II to the Fifth Assessment Report*, 1–32.

http://doi.org/10.1016/j.renene.2009.11.012

KNMI. (n.d.). Historisch verloop neerslagtekort. Retrieved July 1, 2016, from https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten/historisch-neerslagtekort

KNMI. (2015). *KNMI'14 climate scenarios fort he Netherlands. Revised edition 2015*. De Bilt.

Leine, R., & Nijmeijer, H. (2004). *Dynamics and bifurcations of non-smooth mechanical systems*. Berlin: Springer.

Maas, E. V., & Hoffman, G. J. (1977). Crop Salt Tolerance - Current Assessment. *Journal of the Irrigation and Drainage Division*, *103*(2), 115–134.

Mkbainformatie.nl. (n.d.). Disconteren / Discontovoet. Retrieved May 18, 2016, from http://www.mkba-informatie.nl/mkba-basics/abc-van-de-mkba/disconteren-discontovoet/

Mouter, N., Annema, J. A., & van Wee, B. (2013). Ranking the substantive problems in the Dutch Cost-Benefit Analysis practice. *Transportation Research Part A: Policy and Practice*, *49*, 241–255. http://doi.org/10.1016/j.tra.2013.01.020

Oude Essink, G. H. P. (2001). Saltwater intrusion in 3D large-scale aquifers: A Dutch case. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, *26*(4), 337–344. http://doi.org/10.1016/S1464-1909(01)00016-8

Peters, E. (2004). De droogte van 2003 in Nederland. *Stromingen*.

Post, V., & Abarca, E. (2010). Preface: Saltwater and freshwater interactions in coastal aquifers. *Hydrogeology Journal*, *18*(1), 1–4. http://doi.org/10.1007/s10040-009-0561-9

Post, V., Van der Plicht, H., & Meijer, H. A. J. (2003). The origin of brackish and saline groundwater in the coastal area of the Netherlands. *Geologie En Mijnbouw/Netherlands Journal of Geosciences*, *82*(2), 133–147.

Reca, J., Roldán, J., Alcaide, M., López, R., & Camacho, E. (2001). Optimisation model for water allocation in deficit irrigation systems. *Agricultural Water Management*, *48*(2), 117–132. http://doi.org/10.1016/S0378-3774(00)00127-X

Rijkswaterstaat, Hoogheemraadschap van Delfland, Hoogheemraadschap van Rijnland, Hoogheemraadschap De Stichtse Rijnlanden, Hoogheemraadschap van Schieland en de Krimpenerwaard, & Ministerie van Verkeer en Waterstaat. (2005). *Waterakkoord kleinschalige wateraanvoervoorzieningen Midden-Holland*. Nieuwegein.

Rijkswaterstaat. (2011). *Waterhuishouding en waterverdeling in Nederland*. Nieuwegein.

RIZA. (2005). *Water waar het wezen moet, effecten van beleidsstrategieën voor droogte in Midden-West Nederland. Eindrapport Modelspoor 2.* Lelystad.

Roelofs, J. G. M. (1991). Inlet of alkaline river water into peaty lowlands: effects on water quality and Stratiotes aloides L. stands. *Aquatic Botany*, *39*(3-4), 267–293. http://doi.org/10.1016/0304-3770(91)90004-O

Runhaar, J., van Gool, C. R., & Groen, C. L. G. (1996). Impact of hydrological changes on nature conservation areas in The Netherlands. *Biological Conservation*, *76*(3), 269–276. http://doi.org/10.1016/0006-3207(95)00119-0

Shiavi, R. (2007). *Introduction to applied statistical signal analysis*. Amsterdam: Elsevier Acedemic Press.

Stolwijk, H. (2004). *Kunnen natuur- en landschapswaarden zinvol in Euro's worden uitgedrukt? CPB memorandum;5/2004/04*. Retrieved from http://www.cpb.nl/nl/pub/cpbreeksen/memorandum/92/memo92.pdf

Stowa. (2012). *Flexibel peilbeheer, van denken naar doen*. Amersfoort.

Stuyt, L. C. P. M., Kielen, N., & Ruijtenberg, R. (2015). Is de landbouw echt zo gevoelig voor zout water? *Vakbladh2O*.

Stuyt, L. C. P. M., Kselik, R., Blom-Zandstra, M., & van Dam, J. (2016). *Nadere Analyse Zoutschade op basis van bestaande gegevens - Unpublished*. Wageningen.

Stuyt, L. C. P. M., Van Bakel, P. J. T. V., Kroes, J. G., Bos, E. J., Elst, M. V. d., Pronk, B., … Brandenburg, W. A. (2006). *Transitie en toekomst van de Deltalandbouw; indicatoren voor de ontwikkeling van de land- en tuinbouw in de Zuidwestelijke Delta van Nederland*. Wageningen.

Stuyt, L. C. P. M., Van Bakel, P., Delsman, J., Massop, H., Kselik, R., Paulissen, M., … Schipper, P. (2013). *Zoetwatervoorziening in het Hoogheemraadschap van Rijnland. Onderzoek met hulp van €ureyeopener 1.0*. Wageningen.

Van Andel, S., Lobbrecht, A., & Price, R. (2008). No Title. *Atmos. Sci. Lett.*, *9*(2), 57–60. Retrieved from http://dx.doi.org/10.1002/asl.178

Van Bakel, P. J. T., & Stuyt, L. C. P. M. (2011). *Actualisering van de kennis van de zouttolerantie van landbouwgewassen, op basis van literatuuronderzoek, expertkennis en praktische ervaringen.* Wageningen.

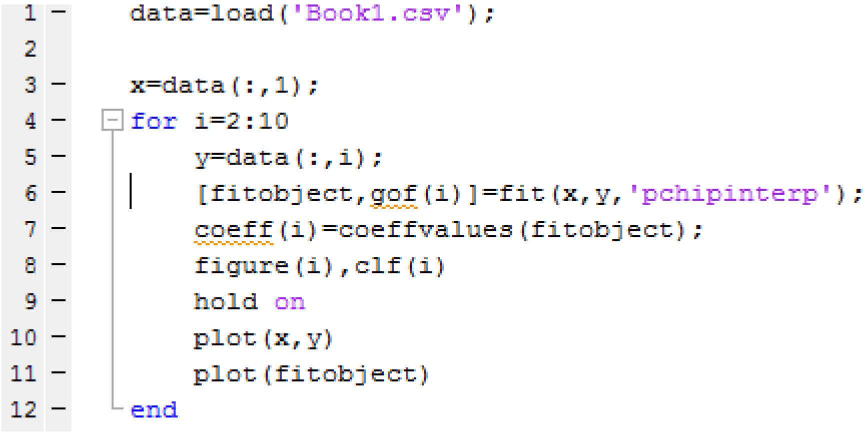
Van Beek, E., Haasnoot, M., Meijer, K. M., Delsman, J. R., Snepvangers, J. J. J. C., & Baarse, G. (2008). *Verkenning kosteneffectiviteit van grootschalige maatregelen tegen droogteschade als gevolg van de G+ en W+ klimaatscenario's*. Delft.

WL | Delft Hydraulics, Technische Universiteit Delft, & NS Consultants. (2001). *Operationeel waterkwaliteitsbeheer, sturing op waterkwaliteit haalbaarheidsonderzoek*. Delft.

WUR. (2013). *Theo Aendekerk naamgever nieuw gemaal Boskoop*. Retrieved from http://www.wur.nl/nl/show/Theo-Aendekerk-naamgever-nieuw-gemaal-Boskoop.htm

Appendices

Appendix A. Matlab code for piecwise cubic Hermite interpolation

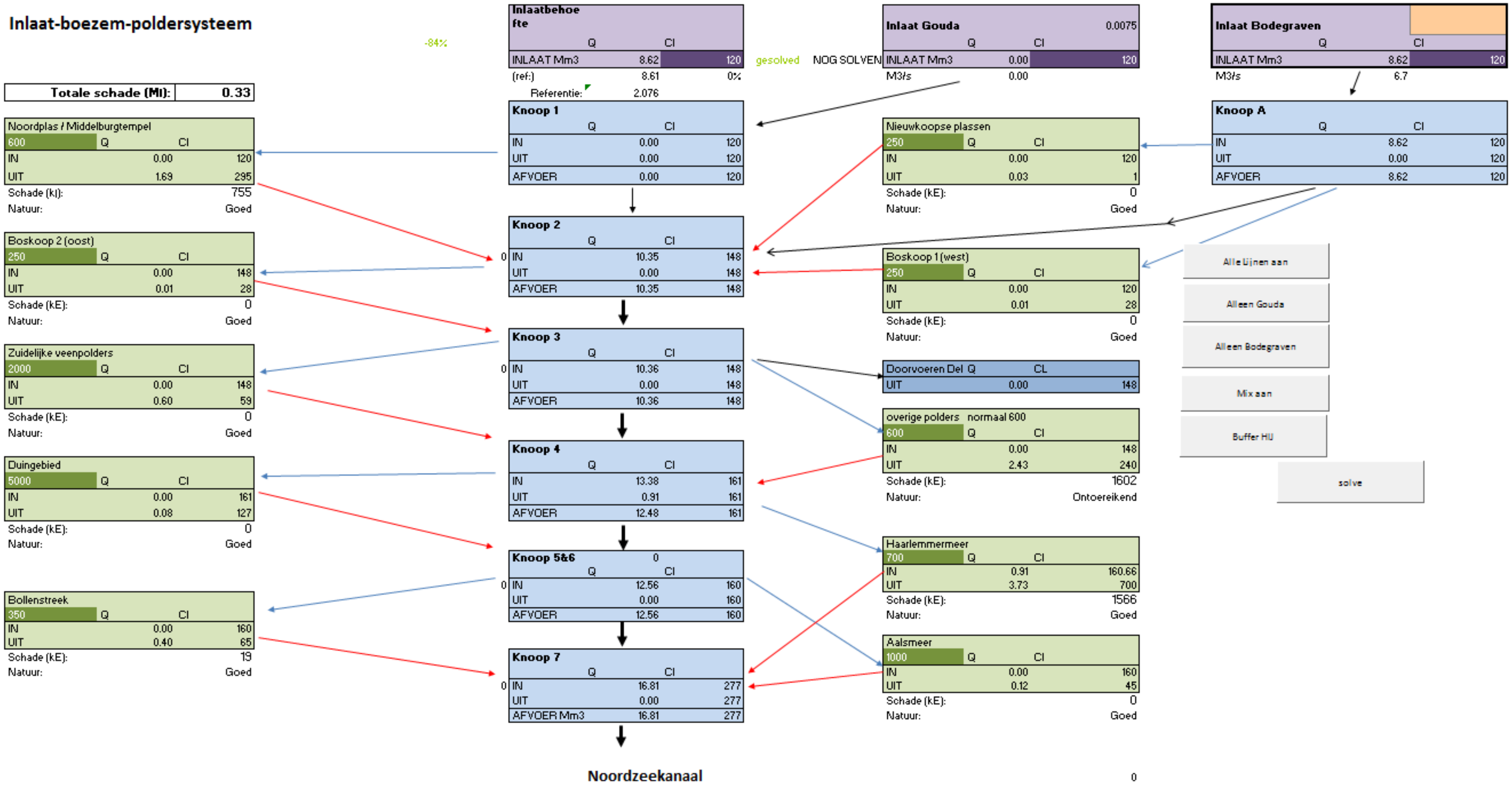


```
data=load('Book1.csv');

x=data(:,1);
for i=2:10
    y=data(:,i);
    [fitobject,gof(i)]=fit(x,y,'pchipinterp');
    coeff(i)=coeffvalues(fitobject);
    figure(i),clf(i)
    hold on
    plot(x,y)
    plot(fitobject)
end
```

Appendix B. Screenshots of the WAOR model

Polder-boezem calculation system:



Inlaat-boezem-poldersysteem

-84%

Totale schade (MI):	**0.33**

Noordplas / Middelburgtempel		
600	Q	CI
IN	0.00	120
UIT	1.69	295
Schade (kI):		755
Natuur:		Goed

Boskoop 2 (oost)		
250	Q	CI
IN	0.00	148
UIT	0.01	28
Schade (kE):		0
Natuur:		Goed

Zuidelijke veenpolders		
2000	Q	CI
IN	0.00	148
UIT	0.60	59
Schade (kE):		0
Natuur:		Goed

Duingebied		
5000	Q	CI
IN	0.00	161
UIT	0.08	127
Schade (kE):		0
Natuur:		Goed

Bollenstreek		
350	Q	CI
IN	0.00	160
UIT	0.40	65
Schade (kE):		19
Natuur:		Goed

Inlaatbehoefte	Q	CI
INLAAT Mm3	8.62	120
(ref:)	8.61	0%
Referentie:	2.076	

gesolved NOG SOLVEN

	Knoop 1	Q	CI
	IN	0.00	120
	UIT	0.00	120
	AFVOER	0.00	120

	Knoop 2	Q	CI
0	IN	10.35	148
	UIT	0.00	148
	AFVOER	10.35	148

	Knoop 3	Q	CI
0	IN	10.36	148
	UIT	0.00	148
	AFVOER	10.36	148

	Knoop 4	Q	CI
	IN	13.38	161
	UIT	0.91	161
	AFVOER	12.48	161

	Knoop 5&6	0	
		Q	CI
0	IN	12.56	160
	UIT	0.00	160
	AFVOER	12.56	160

	Knoop 7	Q	CI
0	IN	16.81	277
	UIT	0.00	277
	AFVOER Mm3	16.81	277

Noordzeekanaal

Inlaat Gouda		0.0075
	Q	CI
INLAAT Mm3	0.00	120
M3/s	0.00	

Nieuwkoopse plassen		
250	Q	CI
IN	0.00	120
UIT	0.03	1
Schade (kE):		0
Natuur:		Goed

Boskoop 1 (west)		
250	Q	CI
IN	0.00	120
UIT	0.01	28
Schade (kE):		0
Natuur:		Goed

Doorvoeren Del	Q	CL
UIT	0.00	148

overige polders	normaal 600	
600	Q	CI
IN	0.00	148
UIT	2.43	240
Schade (kE):		1602
Natuur:		Ontoereikend

Haarlemmermeer		
700	Q	CI
IN	0.91	160.66
UIT	3.73	700
Schade (kE):		1566
Natuur:		Goed

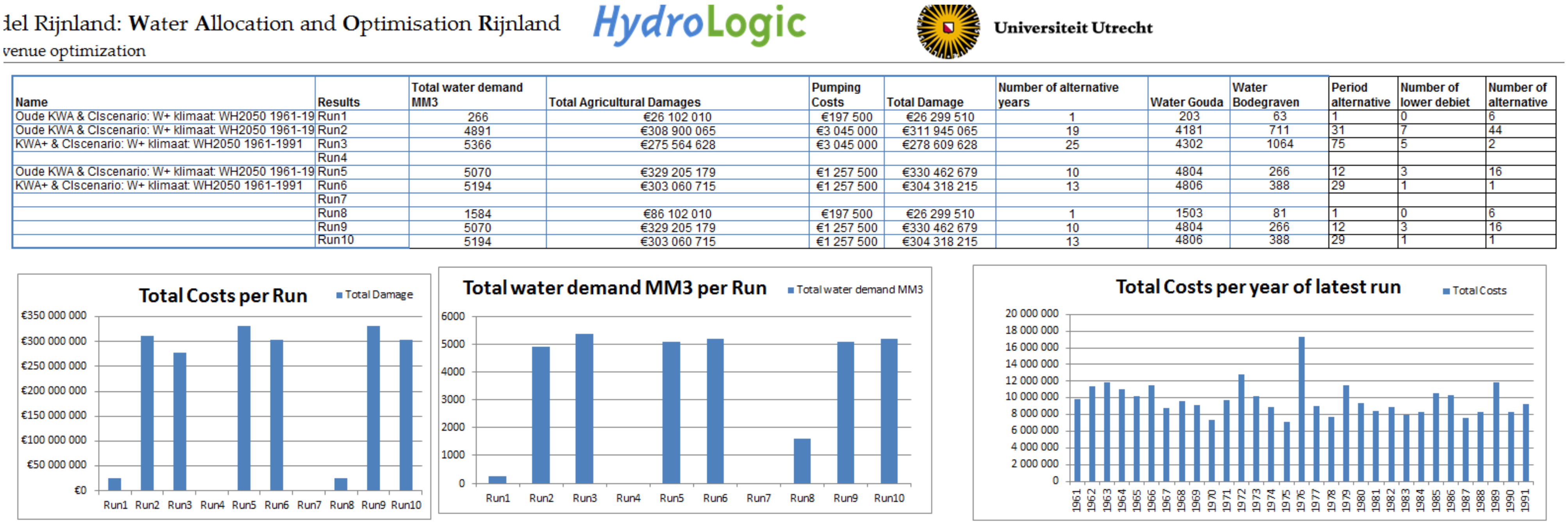
Aalsmeer		
1000	Q	CI
IN	0.00	160
UIT	0.12	45
Schade (kE):		0
Natuur:		Goed

0

Inlaat Bodegraven	Q	CI
INLAAT Mm3	8.62	120
M3/s	6.7	

Knoop A	Q	CI
IN	8.62	120
UIT	0.00	120
AFVOER	8.62	120

Table with model run results:



del Rijnland: **W**ater **A**llocation and **O**ptimisation **R**ijnland

venue optimization

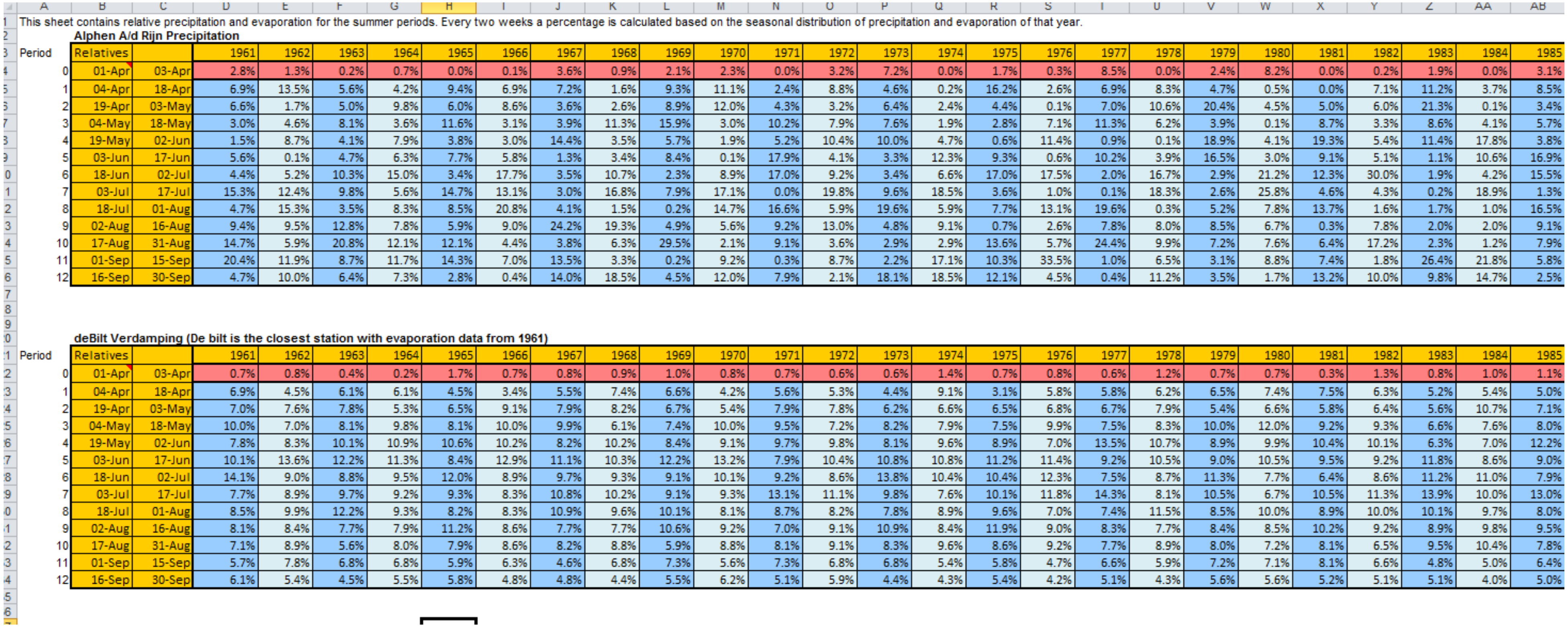
Name	Results	Total water demand MM3	Total Agricultural Damages	Pumping Costs	Total Damage	Number of alternative years	Water Gouda	Water Bodegraven	Period alternative	Number of lower debiet	Number of alternative
Oude KWA & Clscenario: W+ klimaat: WH2050 1961-19	Run1	266	€26 102 010	€197 500	€26 299 510	1	203	63	1	0	6
Oude KWA & Clscenario: W+ klimaat: WH2050 1961-19	Run2	4891	€308 900 065	€3 045 000	€311 945 065	19	4181	711	31	7	44
KWA+ & Clscenario: W+ klimaat: WH2050 1961-1991	Run3	5366	€275 564 628	€3 045 000	€278 609 628	25	4302	1064	75	5	2
	Run4										
Oude KWA & Clscenario: W+ klimaat: WH2050 1961-19	Run5	5070	€329 205 179	€1 257 500	€330 462 679	10	4804	266	12	3	16
KWA+ & Clscenario: W+ klimaat: WH2050 1961-1991	Run6	5194	€303 060 715	€1 257 500	€304 318 215	13	4806	388	29	1	1
	Run7										
	Run8	1584	€86 102 010	€197 500	€26 299 510	1	1503	81	1	0	6
	Run9	5070	€329 205 179	€1 257 500	€330 462 679	10	4804	266	12	3	16
	Run10	5194	€303 060 715	€1 257 500	€304 318 215	13	4806	388	29	1	1

Total Costs per Run

Total water demand MM3 per Run

Total Costs per year of latest run

Annual relative weather tables:



This sheet contains relative precipitation and evaporation for the summer periods. Every two weeks a percentage is calculated based on the seasonal distribution of precipitation and evaporation of that year.

Alphen A/d Rijn Precipitation

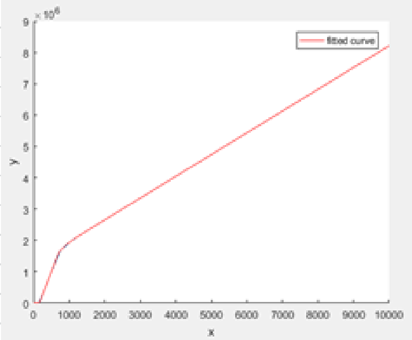
Period	Relatives		1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
0	01-Apr	03-Apr	2.8%	1.3%	0.2%	0.7%	0.0%	0.1%	3.6%	0.9%	2.1%	2.3%	0.0%	3.2%	7.2%	0.0%	1.7%	0.3%	8.5%	0.0%	2.4%	8.2%	0.0%	0.2%	1.9%	0.0%	3.1%
1	04-Apr	18-Apr	6.9%	13.5%	5.6%	4.2%	9.4%	6.9%	7.2%	1.6%	9.3%	11.1%	2.4%	8.8%	4.6%	0.2%	16.2%	2.6%	6.9%	8.3%	4.7%	0.5%	0.0%	7.1%	11.2%	3.7%	8.5%
2	19-Apr	03-May	6.6%	1.7%	5.0%	9.8%	6.0%	8.6%	3.6%	2.6%	8.9%	12.0%	4.3%	3.2%	6.4%	2.4%	4.4%	0.1%	7.0%	10.6%	20.4%	4.5%	5.0%	6.0%	21.3%	0.1%	3.4%
3	04-May	18-May	3.0%	4.6%	8.1%	3.6%	11.6%	3.1%	3.9%	11.3%	15.9%	3.0%	10.2%	7.9%	7.6%	1.9%	2.8%	7.1%	11.3%	6.2%	3.9%	0.1%	8.7%	3.3%	8.6%	4.1%	5.7%
4	19-May	02-Jun	1.5%	8.7%	4.1%	7.9%	3.8%	3.0%	14.4%	3.5%	5.7%	1.9%	5.2%	10.4%	10.0%	4.7%	0.6%	11.4%	0.9%	0.1%	18.9%	4.1%	19.3%	5.4%	11.4%	17.8%	3.8%
5	03-Jun	17-Jun	5.6%	0.1%	4.7%	6.3%	7.7%	5.8%	1.3%	3.4%	8.4%	0.1%	17.9%	4.1%	3.3%	12.3%	9.3%	0.6%	10.2%	3.9%	16.5%	3.0%	9.1%	5.1%	1.1%	10.6%	16.9%
6	18-Jun	02-Jul	4.4%	5.2%	10.3%	15.0%	3.4%	17.7%	3.5%	10.7%	2.3%	8.9%	17.0%	9.2%	3.4%	6.6%	17.0%	17.5%	2.0%	16.7%	2.9%	21.2%	12.3%	30.0%	1.9%	4.2%	15.5%
7	03-Jul	17-Jul	15.3%	12.4%	9.8%	5.6%	14.7%	13.1%	3.0%	16.8%	7.9%	17.1%	0.0%	19.8%	9.6%	18.5%	3.6%	1.0%	0.1%	18.3%	2.6%	25.8%	4.6%	4.3%	0.2%	18.9%	1.3%
8	18-Jul	01-Aug	4.7%	15.3%	3.5%	8.3%	8.5%	20.8%	4.1%	1.5%	0.2%	14.7%	16.6%	5.9%	19.6%	5.9%	7.7%	13.1%	19.6%	0.3%	5.2%	7.8%	13.7%	1.6%	1.7%	1.0%	16.5%
9	02-Aug	16-Aug	9.4%	9.5%	12.8%	7.8%	5.9%	9.0%	24.2%	19.3%	4.9%	5.6%	9.2%	13.0%	4.8%	9.1%	0.7%	2.6%	7.8%	8.0%	8.5%	6.7%	0.3%	7.8%	2.0%	2.0%	9.1%
10	17-Aug	31-Aug	14.7%	5.9%	20.8%	12.1%	12.1%	4.4%	3.8%	6.3%	29.5%	2.1%	9.1%	3.6%	2.9%	2.9%	13.6%	5.7%	24.4%	9.9%	7.2%	7.6%	6.4%	17.2%	2.3%	1.2%	7.9%
11	01-Sep	15-Sep	20.4%	11.9%	8.7%	11.7%	14.3%	7.0%	13.5%	3.3%	0.2%	9.2%	0.3%	8.7%	2.2%	17.1%	10.3%	33.5%	1.0%	6.5%	3.1%	8.8%	7.4%	1.8%	26.4%	21.8%	5.8%
12	16-Sep	30-Sep	4.7%	10.0%	6.4%	7.3%	2.8%	0.4%	14.0%	18.5%	4.5%	12.0%	7.9%	2.1%	18.1%	18.5%	12.1%	4.5%	0.4%	11.2%	3.5%	1.7%	13.2%	10.0%	9.8%	14.7%	2.5%

deBilt Verdamping (De bilt is the closest station with evaporation data from 1961)

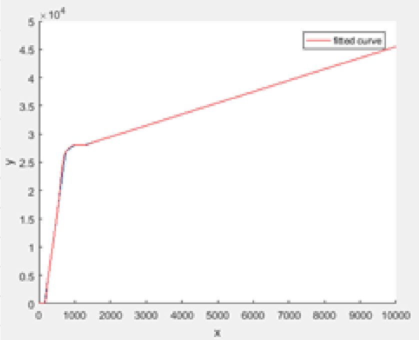
Period	Relatives		1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
0	01-Apr	03-Apr	0.7%	0.8%	0.4%	0.2%	1.7%	0.7%	0.8%	0.9%	1.0%	0.8%	0.7%	0.6%	0.6%	1.4%	0.7%	0.8%	0.6%	1.2%	0.7%	0.7%	0.3%	1.3%	0.8%	1.0%	1.1%
1	04-Apr	18-Apr	6.9%	4.5%	6.1%	6.1%	4.5%	3.4%	5.5%	7.4%	6.6%	4.2%	5.6%	5.3%	4.4%	9.1%	3.1%	5.8%	5.8%	6.2%	6.5%	7.4%	7.5%	6.3%	5.2%	5.4%	5.0%
2	19-Apr	03-May	7.0%	7.6%	7.8%	5.3%	6.5%	9.1%	7.9%	8.2%	6.7%	5.4%	7.9%	7.8%	6.2%	6.6%	6.5%	6.8%	6.7%	7.9%	5.4%	6.6%	5.8%	6.4%	5.6%	10.7%	7.1%
3	04-May	18-May	10.0%	7.0%	8.1%	9.8%	8.1%	10.0%	9.9%	6.1%	7.4%	10.0%	9.5%	7.2%	8.2%	7.9%	7.5%	9.9%	7.5%	8.3%	10.0%	12.0%	9.2%	9.3%	6.6%	7.6%	8.0%
4	19-May	02-Jun	7.8%	8.3%	10.1%	10.9%	10.6%	10.2%	8.2%	10.2%	8.4%	9.1%	9.7%	9.8%	8.1%	9.6%	8.9%	7.0%	13.5%	10.7%	8.9%	9.9%	10.4%	10.1%	6.3%	7.0%	12.2%
5	03-Jun	17-Jun	10.1%	13.6%	12.2%	11.3%	8.4%	12.9%	11.1%	10.3%	12.2%	13.2%	7.9%	10.4%	10.8%	10.8%	11.2%	11.4%	9.2%	10.5%	9.0%	10.5%	9.5%	9.2%	11.8%	8.6%	9.0%
6	18-Jun	02-Jul	14.1%	9.0%	8.8%	9.5%	12.0%	8.9%	9.7%	9.3%	9.1%	10.1%	9.2%	8.6%	13.8%	10.4%	10.4%	12.3%	7.5%	8.7%	11.3%	7.7%	6.4%	8.6%	11.2%	11.0%	7.9%
7	03-Jul	17-Jul	7.7%	8.9%	9.7%	9.2%	9.3%	8.3%	10.8%	10.2%	9.1%	9.3%	13.1%	11.1%	9.8%	7.6%	10.1%	11.8%	14.3%	8.1%	10.5%	6.7%	10.5%	11.3%	13.9%	10.0%	13.0%
8	18-Jul	01-Aug	8.5%	9.9%	12.2%	9.3%	8.2%	8.3%	10.9%	9.6%	10.1%	8.1%	8.7%	8.2%	7.8%	8.9%	9.6%	7.0%	7.4%	11.5%	8.5%	10.0%	8.9%	10.0%	10.1%	9.7%	8.0%
9	02-Aug	16-Aug	8.1%	8.4%	7.7%	7.9%	11.2%	8.6%	7.7%	7.7%	10.6%	9.2%	7.0%	9.1%	10.9%	8.4%	11.9%	9.0%	8.3%	7.7%	8.4%	8.5%	10.2%	9.2%	8.9%	9.8%	9.5%
10	17-Aug	31-Aug	7.1%	8.9%	5.6%	8.0%	7.9%	8.6%	8.2%	8.8%	5.9%	8.8%	8.1%	9.1%	8.3%	9.6%	8.6%	9.2%	7.7%	8.9%	8.0%	7.2%	8.1%	6.5%	9.5%	10.4%	7.8%
11	01-Sep	15-Sep	5.7%	7.8%	6.8%	6.8%	5.9%	6.3%	4.6%	6.8%	7.3%	5.6%	7.3%	6.8%	6.8%	5.4%	5.8%	4.7%	6.6%	5.9%	7.2%	7.1%	8.1%	6.6%	4.8%	5.0%	6.4%
12	16-Sep	30-Sep	6.1%	5.4%	4.5%	5.5%	5.8%	4.8%	4.8%	4.4%	5.5%	6.2%	5.1%	5.9%	4.4%	4.3%	5.4%	4.2%	5.1%	4.3%	5.6%	5.6%	5.2%	5.1%	5.1%	4.0%	5.0%

Damage functions:

					CL	700
0	Rij 6	Haarlemmermeer			R2	
50	0	0	0	0	1	1 565 984
150	-0.0029	2.29012	0	0		
250	-0.20717	42.63811	371.1305	20004.75		
500	-0.00437	1.810868	2683.721	276331.2		
750	-0.01705	3.91159	2769.196	992110.8		
1000	0.005077	-3.10748	1527.43	1662421		
1250	0.000685	-0.60637	925.677	1929393		
1500	0.000898	-0.44895	750.9105	2133616		
10000	0.00E+00	0	694.792	2307314		



					CL	1
0	Rij 7	Nieuwkoopse plassen			R2	
50	0	0	0	0	1	0
150	0	0	0	0		
250	-0.00448	0.896	0	0		
500	0	0	44.8	4480		
750	-0.00059	0.146618	44.8	15680		
1000	-1.30E-05	-0.0114	8.145455	26880		
1250	0	0	0	28000		
1500	-3.20E-05	0.01599	0	28000		
10000	0	0	1.99875	28499.69		



					CL	295
0	Rij 8	Noorplas Tempel			R2	
50	0	0	0	0	1	754 784
150	-5.73E-09	0.003863	0	0		
250	-0.51822	103.853	0.772443	38.625		
500	-0.00049	0.23409	5224.811	520427.3		
750	-0.06724	16.80176	5250.774	1833671		
1000	-0.00023	-1.79969	1043.743	3145815		
1250	0.000781	-0.37782	100.9084	3290688		
1500	-5.69E-05	0.028456	58.43698	3304504		
10000	0	0	61.994	3320003