Risk-based control of salt water intrusion for the Rhine-Meuse Estuary

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RISK-BASED CONTROL OF SALT WATER INTRUSION FOR THE RHINE-MEUSE ESTUARY

by

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Abstract

The fresh water supply will be more under pressure, due to the predicted effects of climate change in the Netherlands. More frequent salt water intrusion during the summer semester is caused by the joint occurrence of low river discharges and the expected sea level rise. The control of external salinity is necessary to guarantee a sufficient water quality of the main water system and so protect the fresh water inlets from the intruding saline water. Consequently, regional water systems are able to take in fresh water of the main water system to control internal salinity, through counteracting salt seepage by means of salt flushing.

The control of external salinity can be realized by the implementation of measures that interfere in the main water system; e.g. by optimizing the fresh water distribution. Whether a measure will be implemented depends on the decision-making process. This study is initiated, because of the arisen discussions about the pursued fresh water policy for the drought in 2003. Salinity risk management aims to assess the cost-effectiveness of measures that focus on the fresh water supply, by means of evaluating the costs and the benefits of a measure. This study investigates the possibilities of the implementation of a risk-based approach within the present Dutch fresh water policy, which is nowadays based on a deterministic approach.

A salinity risk management model is developed that basically is composed of three phases that research the following questions; i.e. 1.) How does the system of external salt water intrusion in the Rhine-Meuse Estuary function for given scenarios? 2.) What is the frequency of occurrence of external salinity? Given that external salinity occurs, what are the consequences? What is the resulting salinity risk? 3.) Is the established risk acceptable? If not, which alternative measures are able to reduce the present risk level? The developed research model is examined in a case study for the risk evaluation of external salt water intrusion in the Hollandse IJssel, in particular the fresh water inlet of Gouda that provides fresh water to the control area of Rijnland.

This study concludes that a risk-based approach is implementable in the Dutch fresh water policy, but extended research is necessary to obtain more reliable exceedance frequencies of a Chloride concentration. This study developed two probabilistic models; i.e. for tide-dominated locations and for river-dominated locations. A third type probabilistic model should be developed for locations that are not tide- or river-dominated. Secondly, more precise statistical analysis should be conducted after the discharge variation in course of time for low river discharges. Besides, statistical research is recommended after the variation of the probability distributions thorough the summer semester of low river discharges, high sea water level set-ups and a precipitation deficit.

Executive summary

Introduction

The 'Fresh water Delta program' states that the effects of climate change result for the Netherlands in a warmer and drier climate. This causes a more frequent salt water intrusion during the summer semester, due to occurrence of low river discharges in combination with the expected sea level rise. An increasing demand of the external fresh water supply (quantity and quality) is imposed. The control of salinity is necessary to guarantee a sufficient water quality and protect the fresh water inlets from intruding saline water (external salinity). Regional water systems take in fresh water from the main water system to the counteract salt seepage (internal salinity) by salt flushing.

Salinity can be controlled by measures that focus on the fresh water supply. The current fresh water policy is based on a deterministic approach, that does not incorporate uncertainties. This master thesis aims to develop a risk-based approach, which includes uncertainties. In such a way an optimum safety level against salinity can be derived, which is based on an assessment of the costs and benefits of a measure. A salinity risk management model is developed that identifies, qualifies and evaluates the risk associated with salt water intrusion in the Rhine-Meuse Estuary and analyses the risk reducing effects of alternative measures. This risk-based approach is examined by means of a case study for the fresh water inlet of Gouda, which provides fresh water to the control area of Rijnland.

Salinity risk management model

The developed salinity risk management model is composed of all phases of a risk analysis (figure 1), based on the principle:

'Risk = probability x consequence'

The risk assessment analyses the risks associated with salt water intrusion in the Rhine-Meuse Estuary in the Netherlands. An analysis after the risk reduction alternatives is included in the risk management framework.



Figure 1: Research model salinity risk management

Overall, the research model can be divided in three submodels that aim to answer the following questions:

» How does the system of external salt water intrusion in the Rhine-Meuse Estuary function for given scenarios?

» What is the frequency of occurrence of external salinity? Given that external salinity occurs, what are the consequences? What is the resulting salinity risk?

 $\ensuremath{\scriptscriptstyle >}$ Is the established risk acceptable? If not, which alternative measures are able to reduce the present risk level?

Scenario analysis

The risks associated with external salt water intrusion are derived for a set of scenarios, concerning the salinity safety, hydrologic conditions and the socio-economic conditions.

A salinity safety scenario defines the critical event, for which the risk level will be established. Failure of the fresh water supply is the effect of an insufficient water quality and water quantity, which leads to the following defined critical event:

Exceedance of a Chloride concentration standard cl due to external salt water intrusion between 01. April and 30. September (crop growth season).

Failure of this critical event will be investigated for a Chloride concentration standard cl of 250 [mg/l] for two design time scales: short-term situation of 2015 for calamity measures and the long-term situation of 2050 for preventive measures. This research presumes that in the context of this study it is most appropriate to define a 'worst case' set of scenarios; W+ KNMI'06 climate change scenario and present land use and no agricultural crop price developments in course of time are incorporated in this research¹.

System analysis

The system analysis distinguishes two research areas of the Rhine-Meuse Estuary, since it is assumed that the physical processes that describe external salt water intrusion are subarea specific (figure 2):

» Main water system: Rhine-Meuse Estuary (Case-study Krimpen aan den IJssel);

Locations in this area are located along river branches that are in open connection with the downstream landward flowing salt sea water and the upstream seaward flowing fresh river water. Salt water intrusion is described by both dispersive and advective transport.

¹Socio-economic scenarios predict a decreasing agricultural area for Mid-West Netherlands.

» Regional water system: Hollandse IJssel-Rijnland (Case-study Gouda);

Locations along the Hollandse IJssel are not described by the upstream seaward flowing fresh river water. Since the Hollandse IJssel is an upper closed-off river branche that functions as a storage basin, with a slow variation of the physical processes in course of time. Salt water intrusion is affected by the discharged and abstracted water volumes of Rijnland onto the Hollandse IJssel, related to Rijnland's water shortage.



Figure 2: Overview spatial division two research areas; main water system and regional water system

The Chloride concentration cl of the Hollandse IJssel will increase \uparrow in case of a:

- river discharge Q_f decrease \downarrow ;
- sea water level h_0 increase \uparrow ;
- Rijnland's abstraction ΔQ_{Gouda} increase \uparrow .

Physical salinity model

A physical simulation model is able to verify the above stated relations between the Chloride concentration and the descriptive parameters Q_f , h_0 and ΔQ_{Gouda} for different locations in the Rhine-Meuse Estuary. This research investigates the relations for Krimpen aan den IJssel and Gouda by the one-dimensional fysical Sobek model. The extent of external salt water intrusion is related to the tide- or river dominance of each location, based on the simulation results: Krimpen aan den IJssel is assumed to be tide-dominated and Gouda is assumed to be river-dominated.

Salinity probability

The derivation of the exceedance probability of salinity is based on the development of two probabilistic models:

1. Tide-dominated salinity probability model for locations that are joint influenced by the river discharge q and the water level set-up Δh , under the restriction the the tidal influence dominates $\Delta h > 0$:

 $Cl_{q_i,\Delta h_j} = f(q_i,\Delta h_j)$

suitable for locations subject to short exceedance periods for Cl > cl; i.e. shorter then 36 [hours].

2. River-dominated salinity probability model for locations that are only influenced by the river discharge q and the astronomical tide $\Delta h = 0$: $Cl_{q_i} = f(q_i)$

suitable for locations subject to long continguous exceedance periods for Cl > cl; i.e. longer then 36 [hours].

The dominance of the tide or river is location specific and determines the frequency [1/year] and the duration [days or 36-hours period] of an exceedance period Cl > cl.

An exceedance frequency F(Cl > 250) of about once per 17 [year] is derived for the short-term situation of 2015. The exceedance frequency F(Cl > 250) for the long-term situation strongly increases, since a once per year exceedance frequency is predicted.

Salinity consequences

This research aims to develop a probabilistic agricultural damage model that establishes the relation between the external salinity of the Hollandse IJssel and the Rijnland's agricultural drought damage.

A direct relation between the exceedance duration D_{Cl} in the Hollandse IJssel and Rijnland's agricultural damage AD_{dr} is complex to derive, due to the combined influence of:

- 1. Human intervention into the system (control of fresh water distribution);
- 2. Time variation of the external salt water intrusion;
- 3. Balance of water demand of the regional water system and the water supply of the main water system.

Therefore a quick scan model for Rijnland's agricultural drought damage is developed that relates the exceedance duration D_{Cl} of Cl > 250 as a function of the annual maximum precipitation deficit ΔP and the discharge deficit ΔQ .

An exceedance of a Chloride concentration $Cl > 250 \ [mg/l]$ lasts for about 15 [days] and causes an agricultural damage for Rijnland AD_{dr} of about 85 $[10^6 \in]$. The derived exceedance frequencies F(Cl > cl) for the short- and the long-term situation establishes that Rijnland is about respectively once every 17 and 1,2 [year] subject to an agricultural damage AD_{dr} of about 85 $[10^6 \in]$.

Risk evaluation

This study evaluates salinity risk in terms of economical risk. Risk can be expressed as an yearly expected value of:

- 1. Exceedance duration D_{Cl} for Cl > 250 [mg/l]; i.e. YED_{Cl} in [days/year].
- 2. Agricultural drought damage AD_{dr} ; i.e. $YEAD_{dr}$ in $[\in/\text{year}]$.

Economic salinity risk is expressed as a yearly expected value [€/year] that can be discounted with discount rate r over the lifecycle time n of a measure to establish the present value of the economic salinity risk in [€]. This research analyses the sensitivity of the discount rate r for 2,5 and 4,0 [%] and the lifecycle time n for 50 [year] and an infinity long period. A present value of salinity risk which is discounted over a time horizon of 50 [year] with a discount rate r of 4 [%], results in the lowest risk level.

If decision-maker establish the present salinity risk level as unacceptable, the risk level of alternative measures can be investigated. Salinity risk can be reduced by means of reducing the probability of external salinity or by reducing the consequence of external salinity:

- 1. Reduce the probability of external salinity;
 - $F(Cl > cl)_{(n)} > F(Cl > cl)_{(n+1)} \rightarrow$ intervention into the water system; e.g. redistribution of river water, reduces the exceedance frequency of external salinity of the Hollandse IJssel.

- 2. Reduce the consequence of external salinity;
 - $AD_{dr(n)} > AD_{dr(n+1)} \rightarrow$ adjustments of Rijnland's agricultural area; e.g. relocation of cultivations to salinity prone areas, reduces the agricultural damage AD_{dr} in times of salinity.

This research investigates the risk reducing effects of measures that aim to reduce the probability of external salinity; e.g. redistribution of the fresh water supply.

This study evaluates the economic acceptable risk level by means of two investment criteria; cost-benefit evaluation and the economic risk optimization. A measure should be implemented if benefits (avoided damage) exceed the costs of a measure; i.e. the risk reduction should exceed the sum of the investment costs, the management and maintenance costs. The most cost-effective measure is the project for which the largest salinity safety level is found; i.e. largest risk reduction at lowest investment costs.

Risk reduction and control

This research performed a risk analysis for three measures (figure 3):

1. Krimpenerwaard route (calamity measure);

Goal is to abstract fresh river water of the Lek that will be transported via the regional control area of the Krimpenerwaard polder towards the Hollandse IJssel were it will be discharged.

- 2. Optimization discharge distribution (preventive measure); Goal is to optimize the Rhine discharge distribution over the rivers Waal and Pannerdens Kanaal to gain a larger seaward flowing Nederrijn/Lek discharge.
- 3. Spui closure (preventive measure);

Goal is to optimize the seaward flowing fresh water volume of the Beneden Merwede via the Noord, Nieuwe Maas and Nieuwe Waterweg towards the North Sea, by means of the closure of the river Spui.



Figure 3: Overview location of the three measures

The risk-reduction ΔR_i is assessed against the investment costs for each measure, where the risk level R is discounted over t is 50 [year] with a discount rate r of 4 [%] leading to the 'worst-case' risk reduction. All measures are cost-effective since for all measures counts, that the sum of the investment costs I and the new risk costs R_i are lower than the original risk costs of the reference situation R_{ref} .

The Krimpenerwaard route is the economical optimum measure, with the largest risk reduction ΔR of 2.316 [10⁶ \in] against to lowest investment costs I of 17 [10⁶ \in]. The investment criteria $\frac{d(I_i)}{d(\Delta R_i)}$ yields 0,0073 [-].

Only in the context of economical risk-reduction all measures are cost-effective; i.e. the benefits exceed the costs. Next to that, side-effects of measures should also be considered:

» Krimpenerwaard route (calamity measure)

The Krimpenerwaard route is very attractive for both short-term and long-term, but it is questionable if the capacity of the Krimpenerwaard polder will be sufficient to transport the required water volumes for the long-term².

» Optimization discharge distribution (preventive measure)

The redistribution of the Rhine discharge is still cost-effective, but the least economic optimum of all three measures. This side-effects of this measure are of great relevance for the navigational sector, since the river Waal is the most important navigable waterway between the Rhine and the North Sea. An optimal navigation is not feasible for lower Rhine discharges, due to the reduced vessel transport load and so an required increase of the number of movements. Discussions arise which sector is prioritized in fresh water policies in times of drought, since drought damage is larger for the navigational sector compared to the agricultural sector.

» Spui closure (preventive measure)

The temporarily closure of the Spui is cost-effective, but the risk-reductional effects of this measure the lowest of the three measures. It is assumed that the salinity reduction of this measure is larger for locations along the Nieuwe Maas and Nieuwe Waterweg.

Evaluation

This study was a first investigation after the possibilities of the implementation of a risk-based approach within the present national fresh-water policy. It can be concluded that salinity risk management is implementable, if further statistical research will be conducted to derive reliable exceedance frequencies of a Chloride concentration standard cl.

 $^{^{2}}$ The long-term (2050) water demand of the Krimpenerwaard polder is not analysed in this study.

Samenvatting

Introductie

In het 'Deltaprogramma Zoet Water' staat dat de effecten van klimaatsverandering voor een warmer en droger klimaat in Nederland zullen zorgen. Door lage rivierafvoeren en de verwachte zeespiegelstijging zal tijdens het zomerhalfjaar zout water vaker het hoofdwatersysteem indringen. De druk op de externe aanvoer van zoet water (kwantiteit en kwaliteit) zal toenemen. De bestrijding van verzilting is noodzakelijk om een voldoende waterkwaliteit te garanderen en bescherming te bieden aan de zoetwaterinnamepunten tegen het indringende zoute water (externe verzilting). De regionale watersystemen laten zoet water uit het hoofdwatersysteem in om het systeem door te spoelen en zo de nadelige effecten van zoute kwel (interne verzilting) tegen te gaan.

Verzilting is beheersbaar door maatregelen te implementeren die focussen op de aanvoer van zoet water. Het huidige zoet water beleid is gebaseerd op een deterministische benadering, waarbij geen rekening wordt gehouden met onzekerheden. Deze Master Thesis onderzoekt de mogelijkheden voor de implementatie van een risicobenadering binnen het zoet water beleid. Hierbij worden onzekerheden meegenomen die het optimale veiligheidsniveau tegen verzilting bepalen, door de kosten en baten van een risico reducerende maatregel te beoordelen. Een verzilting risico management model is ontwikkeld, dat de risico's van zout water indringing in de Rijn-Maasmonding vaststelt, kwantificeert en evalueert en tevens de risico reducerende effecten van verschillende alternatieve maatregelen analyseert. Deze risicobenadering is getoetst via een case studie voor het zoetwater inlaat van Gouda, die zoet water aanlevert voor het beheergebied van het Hoogheemraadschap van Rijnland.

Verzilting risico management model

Het ontwikkelde verzilting risico management model is opgebouwd uit alle fases van een risicoanalyse (figuur 4), gebaseerd op het principe:

'Risico = kans
$$x$$
 gevolg'

De risicobeoordeling analyseert de risico's van zout water indringing in de Rijn-Maasmonding in Nederland. Een analyse naar de risico reducerende alternatieven is opgenomen in het totale risico management model.



Figure 4: Onderzoeksmodel verzilting risico management

Globaal kan het onderzoeksmodel worden opgesplitst in drie deelmodellen die antwoord trachten te geven op de volgende vragen:

» Hoe werkt het systeem van externe zout water indringing in de Rijn-Maasmonding voor gegeven scenario's?

» Hoe vaak zal verzilting plaatsvinden? Gegeven dat verzilting plaatsvindt, wat zijn dan de gevolgen? Welk risico resulteert hieruit?

» Is het vastgestelde risico acceptabel? Zo nee, welke alternatieve maatregelen kunnen worden onderzocht die het risico reduceren?

Scenarioanalyse

De risico's van externe zout indringing worden bepaald voor een combinatie van scenario's, die het veiligheidsniveau tegen verzilting beschrijven voor gegeven hydrologische en socio-economische condities.

Een verzilting veiligheidsniveau definieert de kritieke gebeurtenis, waarvoor het risico zal worden berekend. Ten gevolge van onvoldoende waterkwaliteit en waterkwantiteit zal de zoetwatervoorziening niet gegarandeerd kunnen worden, hetgeen gedefinieerd kan worden door de volgende kritieke gebeurtenis:

Overschrijding van de Chloride concentratie norm cl veroorzaakt door externe zout water indringing tussen 01 april and 30 september (gewas groeiseizoen)

Falen van de kritieke gebeurtenis zal worden onderzocht voor een Chloride concentratie norm cl=250 [mg/l] voor twee tijdschalen: calamiteiten maatregelen voor de situatie op korte termijn (2015) en preventieve maatregelen voor de situatie op lange termijn (2050). In de context van deze studie wordt een combinatie van scenario's veronderstelt die de 'worst-case' situatie voor de lange termijn beschrijven; W+ KNMI'06 klimaatsverandering scenario en het huidige landgebruik. De ontwikkelingen van de prijzen van de gewassen binnen de landbouwsector zijn niet meegenomen.

Systeemanalyse

De systeemanalyse verdeelt de Rijn-Maasmonding onder in twee deelgebieden, waaraan de onderscheidende fysische processen die externe zout water indringing beschrijven ten grondslag liggen (figuur 5):

» Hoofdwatersysteem: Rijn-Maasmonding (Case-studie Krimpen aan den IJssel);

Locaties in dit gebied staan in open verbinding met de benedenstrooms landwaarts stromende zoute zeewater en het bovenstrooms zeewaarts stromende zoete rivierwater. Zout water indringing wordt beschreven door zowel het dispersief en affectief transport. » Regionaal watersysteem: Hollandse IJssel-Rijnland (Case-studie Gouda);

Locaties langs de Hollandse IJssel worden niet beschreven door het bovenstrooms zeewaarts stromende zoete rivierwater, doordat de Hollandse IJssel een bovenstrooms afgesloten riviertak. De Hollandse IJssel fungeert als een bekken, waarbij de fysische processen langzaam in de tijd variëren. De mate van zout water indringing in de Hollandse IJssel wordt beïnvloedt door de lozingen en onttrekkingen van Rijnland op de Hollandse IJssel, die gerelateerd zijn aan Rijnland's watertekort.



Figure 5: Overzicht ruimtelijke verdeling deelonderzoeksgebieden; hoofdwatersysteem en regionaal watersysteem

De Chloride concentratie clzal stijgen \uparrow als de:

- rivierativer Q_f daalt \downarrow ;
- zeewaterstand h_0 stijgt \uparrow ;
- onttrekkingen van Rijnland ΔQ_{Gouda} stijgen \uparrow .

Fysisch model verzilting

Een fysisch simulatie model kan de bovenstaande relaties tussen de Chloride concentratie cl en de beschrijvende variabelen Q_f , h_0 en ΔQ_{Gouda} verifiëren voor verschillende locaties in de Rijn-Maasmonding. Deze studie onderzoekt de relaties voor de locaties Krimpen aan den IJssel en Gouda via het 1-dimensionale fysische Sobek model. De mate van externe zout water indringing is gerelateerd aan de getij- of rivier dominantie voor elke locatie, gebaseerd op de simulatieresultaten: Krimpen aan den IJssel en Gouda worden verondersteld als respectievelijk getij dominant en rivier dominant.

Probabilistisch model verzilting

De afleiding van de overschrijdingskans van verzilting volgt uit de ontwikkeling van twee probabilistische modellen:

1. Getij dominant verzilting probabilistisch model voor locaties onder het gezamenlijke invloed van de rivierafvoer q en de opzet van de zeewaterstand Δh , onder de voorwaarde dat de invloed van het getij overheerst $\Delta h > 0$: $Cl_{a_i,\Delta h_i} = f(q_i,\Delta h_i)$

Geschikt voor locaties onderhevig aan korte overschrijdingsperiodes waarbij
$$Cl > cl$$
; dat wil zeggen korter dan 36 [uur].

2. Rivier dominant verzilting probabilistisch model voor locaties onder invloed van alleen de rivierafvoer q en het middenstand van het getij $\Delta h = 0$:

 $Cl_{q_i} = f(q_i)$ Geschikt voor locaties onderhevig aan lange aaneengesloten overschrijdingsperiodes waarbij Cl > cl; dat wil zeggen langer dan 36 [uur].

De dominantie van het getij of de rivier is locatie specifiek en bepaalt de frequentie [1/jaar] en de duur [dagen of 36-uurs perioden] van een overschrijdingsperiode Cl > cl.

Voor de situatie op korte termijn (2015) is een overschrijdingsfrequentie F(Cl > 250) van eens per 17 [jaar] afgeleid. De overschrijdingsfrequentie F(Cl > 250) voor de situatie op lange termijn neemt sterk toe, aangezien een overschrijding eens per jaar is afgeleid.

Gevolgen van verzilting

Dit onderzoek heeft tot doel een probabilistisch landbouwschade model te ontwikkelen dat de relatie vaststelt tussen de mate van externe verzilting van de Hollandse IJssel en de droogteschade van Rijnland's landbouwsector .

Het is complex om een directe relatie tussen de overschrijdingsduur D_{Cl} en de droogteschade van Rijnland's landbouwsector AD_{dr} af te leiden, ten gevolge van de gecombineerde invloed van:

- Menselijk ingrijpen in het watersysteem (beheer van de zoetwaterverdeling);
- Tijdsvariatie van externe zout water indringing;
- Balans van de watervraag van het regionale watersysteem en het wateraanbod van het hoofdwatersysteem.

Zodoende is een quick-scan model ontwikkelt voor de droogteschade van Rijnland's landbouwsector, dat de overschrijdingsduur D_{Cl} in geval Cl > 250 beschrijft als een functie van het jaarlijks maximum neerslagtekort ΔP en het afvoertekort ΔQ .

Een overschrijding van de Chloride concentratie $Cl > 250 \ [mg/l]$ heeft een voorspelde duur van ongeveer 15 [dagen] en zal een schade aan Rijnland's landbouwsector van 85 [$10^6 \in$] toebrengen. De overschrijdingsfrequenties F(Cl > 250) voor de situatie op korte- en lange termijn stellen vast dat Rijnland respectievelijk eens per 17 en 1,2 [jaar] te kampen heeft met een landbouwschade AD_{dr} van ongeveer 85 [$10^6 \in$].

Risico evaluatie

Het risico dat in deze studie geëvalueerd wordt is het economische risico van verzilting. Het risico kan worden uitgedrukt als een jaarlijks verwachte waarde van:

- 1. Overschrijdingsduur D_{Cl} voor Cl > 250 [mg/l]; dus YED_{Cl} in [dagen/jaar];
- 2. Landbouw droogteschade AD_{dr} ; dus $YEAD_{dr}$ in $[\notin/jaar]$.

Het economisch risico van verzilting is uitgedrukt als een jaarlijks verwachte waarde [\notin /jaar] dat kan worden verdisconteerd via de discontovoet r over de levensduur n van een maatregel om de contante waarde van het economische risico van verzilting in [\notin] vast te stellen. Dit onderzoek analyseert de gevoeligheid van de discontovoet r voor 2,5 en 4,0 [%] voor een levensduur n van 50 [jaar] en een oneindige levensduur. De laagste risico reductie wordt gevonden voor een verdiscontering over een tijdshorizon van 50 [jaar] met een discontovoet r van 4,0 [%].

Als beleidsmakers het huidige risico niveau van verzilting als onacceptabel markeren, kan het risico niveau van alternatieve maatregelen worden onderzocht. Het risico van verzilting kan worden gereduceerd door de kans van externe verzilting te reduceren of door de gevolgen van externe verzilting te reduceren:

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1. Reduceer de kans van externe verzilting;

 $F(Cl > cl)_{(n)} > F(Cl > cl)_{(n+1)} \rightarrow$ interventie in het watersysteem; bijv. herverdeling van het rivierwater, reduceert de overschrijdingsfrequentie van externe verzilting van de Hollandse IJssel;

2. Reduceer de gevolgen van externe verzilting;

 $AD_{dr(n)} > AD_{dr(n+1)} \rightarrow$ adaptatie van Rijnland's landbouwareaal; bijv. verplaatsen van gewassen naar gebieden die bestand zijn tegen verzilting, reduceert de landbouwschade AD_{dr} ten tijden van verzilting.

Deze studie onderzoekt de risico reducerende effecten van maatregelen die tot doel hebben om de kans van externe verzilting te reduceren; bijvoorbeeld door een herverdeling van de aanvoer van zoet water.

Deze studie evalueert het acceptabele economisch risico niveau, door middel van twee investeringscriteria; kosten-batenanalyse en een economische risico optimalisatie. Een maatregel zal worden geïmplementeerd als de baten (vermeden schade) de kosten van een maatregelen overschrijden; dat wil zeggen de risico reductie zal het totaal van de investeringskosten en kosten voor beheeren onderhoud moeten overschrijden. De meest kosteneffectieve maatregel is het project die het grootste veiligheidsniveau tegen verzilting biedt tegen de laagste investeringskosten.

Risico reductie en beheersing

Deze studie heeft een risicoanalyse uitgevoerd voor drie maatregelen (figuur 6):

- 1. Krimpenerwaard route (calameiten maatregel); Doel is om zoet rivierwater van de Lek te onttrekken en via het regionale beheersgebied van de Krimpenerwaard polder in de richting van de Hollandse IJssel te transporteren al waar het zal geloosd.
- 2. Optimalisatie afvoerverdeling (preventieve maatregel);

Doel is om de afvoerverdeling van de Rijn over de Waal en het Pannerdens Kanaal te optimaliseren, hetgeen zal resulteren in een groter zeewaarts stromende Nederrijn/Lek afvoer.

3. Afsluiting Spui (preventieve maatregel);

Doel is om het zeewaarts stromende zoet water volume van de Beneden Merwede via de Noord, Nieuwe Maas en de Nieuwe Waterweg richting de Noordzee, door middel van de tijdelijke afsluiting van het Spui.



Figure 6: Overzicht situering van de drie maatregelen

De 'worst-case' risico reducti
e ΔR_i is afgewogen tegen de investeringskosten van elke maatregel, waarbij het risico niveau
 Ris verdisconteerd over een tijdshorizon
 nis 50 [jaar] met een discontovoet
r van 4,0 [%]. Alle maatregelen zijn kosten
effectief, sinds voor alle maatregelen geldt dat de som van de investeringskosten Ien de risico kosten van een maatregel
 R_i lager zijn dan de originele risico kosten voor de referentie situatie R_{ref} .

De Krimpenerwaard route is de economisch meest optimale maatregel, met de grootste risico reductie ΔR van 2.316 $[10^6 \in]$ tegen de laagste investeringskosten I van 17 $[10^6 \in]$. Voor het investeringscriteria $\frac{d(I_i)}{d(\Delta R_i)}$ wordt een waarde van 0,0073 [-] gevonden.

In de context van de economische risico reductie zijn alle maatregelen kosteneffectief; dat wil zeggen dat de baten groter zijn dan de kosten. In het totale besluitvormingsproces zullen de neveneffecten ook moeten worden meegenomen:

» Krimpenerwaard route

De Krimpenerwaard route is een erg aantrekkelijke maatregel voor zowel de situatie op korte als op lange termijn, maar het is onzeker of de capaciteit van de Krimpenerwaardpolder toereikend is voor het transport van de vereiste watervolumes die benodigd zijn de situatie op lange termijn³.

» Optimalisatie afvoerverdeling

De herverdeling van de Rijnafvoer is kosteneffectief, maar wel de minst economische aantrekkelijke maatregelen van de drie maatregelen. De neveneffecten van deze maatregel zijn heel belangrijk voor de scheepvaartsector, omdat de rivier de Waal de belangrijkste scheepvaart route is tussen de Rijn en de Noordzee. Een optimale scheepvaart is niet haalbaar bij lage Rijnafvoeren, vanwege verminderde beladingscapaciteit per schip en hetgeen resulteert in een toenemend aantal scheepvaartbewegingen. In tijden van droogte ontstaan er discussies binnen het zoetwaterbeleid welke sector een hogere prioriteit krijgt toegewezen; de scheepvaart- of de landbouwsector.

» Afsluiting Spui

De tijdelijke afsluiting van het Spui is kosteneffectief, maar de risico reducerende effecten van deze maatregel zijn relatief het laagst. Er wordt verwacht dat het reducerende effect van verzilting voor deze maatregel groter is voor andere locaties langs de Nieuwe Maas en Nieuwe Waterweg.

Evaluatie

Deze studie was een eerste verkenning naar mogelijkheden van de implementatie van een risicobenadering binnen het huidige Nederlandse zoetwaterbeleid. De conclusie is dat een risico-benadering binnen het zoetwaterbeleid implementeerbaar is, onder de voorwaarde dat extra statistisch onderzoek moet worden uitgevoerd om betrouwbare frequenties en duren van de overschrijding van de Chloride concentratie norm cl af te leiden.

 $^{^{3}\}mathrm{De}$ watervraag van de Krimpenerwaardpolder op de korte- en lange termijn (2015 en 2050) is niet onderzocht in dit onderzoek.

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Preface

This Master thesis concludes my Master of Science Civil Engineering at the faculty of Civil Engineering and Geosciences of Delft University of Technology. The graduation project was carried out at HKV Lijn in water.

This thesis reflects the present discussion regarding the Dutch fresh water policy. At this moment, the Netherlands is subject to an exceptional drought for the months April and May. The present drought conditions do not yet endanger the guarantee of the fresh water supply. But for how long can the fresh water demand be fulfilled? When should alternative fresh water supply routes be set in operation, as was the case of the drought of 2003. These uncertainties cause the unpredictability of the evolvement of the drought of 2011, which topic addresses to this Master thesis.

This Master thesis is supervised by the graduation committee, prof.dr.ir M.J.F. (Marcel) Stive (TU Delft, hydraulic engineering section), dr.ir. S.N. (Bas) Jonkman (TU Delft, hydraulic engineering section), dr.ir. P.J.A.T.M. (Peter-Jules) van Overloop (TU Delft, water management section), dr. ir. B.G. (Saskia) van Vuren (HKV Lijn in Water), prof. ir. E. (Eelco) van Beek (Deltares) and drs. V.A.W. (Vincent) Beijk (Rijkswaterstaat, Dienst Zuid-Holland). I would like to thank my graduation committee for their support and interesting discussions during the committee meetings.

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Marit Zethof,

Delft, May 2011

Chapter 1

Introduction

1-1 Study context

Drought is an arising problem in the Netherlands. It is a comprehensive concept, without an international applicable distinct definition [34]. Peters [34] defined drought as a temporary period indicated as drier than the long-term averaged situation, which is caused through the variance of the precipitation and the evaporation.

In the context of this definition, dry years have passed the Netherlands the last century, where the year 2003 is a recent example¹. The severity of drought can be established by an estimation of the return periods for several dry years. The year 2003 is indicated as an once per 10 year drought, based on the current meteorologic and hydrologic conditions. Drought's frequency of occurrence is expected to increase in the near future due to the effects of climate change. The return period of the drought of 2003 is estimated onto once per 2 year for the worst-case climate change scenario for 2050^2 .

The 'Fresh water Delta program'³ states that the effects of climate change will result for the Netherlands in a warmer and drier climate with a more frequent salt water intrusion during the summer and contrary wet and mild winters with an increased flooding probability. A result of this is an increased demand on the external fresh water supply to compensate for the decreased precipitation during the summer semester. Figure 1-1 assigns the salinity prone areas (purple hatch) and the areas with an increased independence of the fresh water supply (yellow hatch), which are the areas with a future expected increasing water demand.

 $^{^1\}mathrm{The}$ year 2003 is stated as a record year sunshine, warmness and drought [35]

²i.e. W+ KNMI'06 scenario [35]; see further section 3-3

 $^{^{3}}$ Subprogram of the National Waterplan [1] that sets up the guidelines for the fresh water policy



Figure 1-1: Combined water assignment Randstad area of the Netherlands [1]

The expected increase of the frequency of occurrence of drought asks for a new drought policy. Recent studies investigated the expected impacts of drought for the present and future [12, 36, 37, 38, 25, 39, 32], in particular the effects onto the fresh water quality. The Droogtestudie proposed three types of policy perceptions; i.e. preventance, react and acceptance [32]. An acceptable safety level against drought should be established to determine which consequences should be accepted and which ones should be prevented. The damage of an extreme dry year can be imposed as acceptable, since its occurrence is so rare. Measures can be implemented to reduce either the probability of drought or the consequences of less extreme droughts. The cost-effectiveness of a measure can be assessed by its costs and benefits.

Drought affects the fresh water quality. The main sectors that are subject to the effects of drought are agriculture, navigation, drinking water, industry and nature. Each sector has specific requirements towards water quality and water quantity. Droughts enable the external salt water intrusion from the sea into an estuary, in case of low-lying deltaic countries. The Rhine-Meuse Estuary is the transitional area, where intruding salt sea water mixes with outflowing fresh river water which results in 'salinated water'. The frequency of occurrence and the resulting consequences of external salt water intrusion in the Rhine-Meuse Estuary will be investigated in the first part of this research. The second part of this research analyses the possibilities to reduce external salt water intrusion's frequency of occurrence or even prevent it.

Section 1-2 exposes the shortcomings of the current fresh water policy that should be solved by the implementation of a new probabilistic policy. This imperfections are translated to research objectives, which are defined in section 1-5. Section 1-3 indicates salinated water by its Chloride concentration and explains the two types of salt water intrusion. The past and the present fresh water policy to control each of these types of salinity are discussed in section 1-4.

1-2 Problem statement

The current national fresh water policy elaborates possible measures to control salinity, which are discussed in section 1-4. The control of salinity is necessary to guarantee a sufficient water quality and protect the fresh water inlets from intruding saline water (*external salinity*)[5]. Regional water

2

systems take in fresh river water from the main water system to counteract salt seepage (*internal salinity*) by salt flushing.

There are two types of salt water intrusion that are defined as external salinity and internal salinity, which affect the water quality of respectively the main water system and the regional water system (discussed in section 1-3). Measures can be taken to reduce either the effects of external salinity onto the main national water system or internal salinity onto the regional water system [1]. External salinity can be reduced by an improved control of the fresh water distribution onto the main water system. Internal salinity can be reduced by obtaining a self-relying regional system.

Whether a measure will be implemented depends on the decision-making process. Decision-makers should gain insight whether a measure is cost-effective, or in other words, are the total implementation costs lower than the avoided damage in case of doing nothing? Discussions arise about the pursued fresh water policy during the year 2003. Optimum policy making is based on the following type of questions; What was the severity of the drought year 2003 (probability)? If no measures were taken, what would have been the total damage (consequences)? Does the whole discussion focus on economical loss or emotional damage?

The current fresh water policy is based on a deterministic approach. The fresh water supply to a regional water system is restricted by the water quality conditions of the main water system, which are defined as the Chloride concentration that a water volume contains. This inlet requirement is a deterministic value, that does not incorporate uncertainties⁴. A probabilistic approach includes uncertainties to derive an optimum safety level, based on an assessment of the costs and benefits of a measure. A probabilistic approach is allready accepted in flood related decision-making; i.e. known as flood risk management.

Deterministic vs. probabilistic decision-making

A deterministic approach analyses a single design scenario, without the implication of uncertainties. A deterministic approach results in a conservative at too high costs design, in this case a very severe but highly unlikely design scenario is chosen [40].

A probabilistic approach makes an inventory of the probabilities and consequences for all possible scenarios. A probabilistic approach results in an effective design, based on the evaluation of an optimal risk level. If the risk reduction balances the investment cost, an optimal effective design is obtained [40].

A probabilistic decision making processes can be conducted by a risk analysis, which tries to answer the questions [22]:

- 1. What can happen?
- 2. How likely is it to happen?
- 3. Given that it occurs, what are the consequences?

Risk analysis

Risk assessment is a framework that identifies, qualifies and evaluates the risks associated for a given system, i.e. salt water intrusion in the Rhine-Meuse Estuary in the Netherlands. Governmental decision makers want to evaluate the acceptability of the associated risks. The question whether the current frequency of salt water intrusion and its accompanying consequences is acceptable or not, can be answered. *Risk management* is the total framework of a risk assessment including risk reduction and control. A risk assessment supports the decision regarding the acceptability of the safety against salinity and the need for measures in the current system to reduce

 $^{^{4}}$ Uncertainty concerns something that it is not known definitely [40]

the risk. The design process of future implementable measures is based on the outcomes of a risk assessment.



Figure 1-2: Schematic conceptual overview phases of risk assessment and risk management

This research aims to develop a risk-based approach for the fresh water supply in the Rhine-Meuse Estuary. There are two important fresh-water inlets that are located in the Rhine-Meuse Estuary; i.e. Bernisse along the river Spui for the supply of industrial and drinking water and Gouda along the Hollandse IJssel for the supply of agricultural water. A salinity risk management model is developed that will be examined in a case-study for the location Gouda.

Section 1-5 defines the research objective and scope, which will be subdivided in subresearch questions for all chapter. Each subresearch question summarizes the research goal of each chapter. The salinity risk management model is outlined in chapter 2.

1-3 Typology of salinity

External salt sea water intrusion is one of the processes that low-lying coastal and deltaic areas should encounter⁵. Salinity is the comprehending processes where the soil, ground- or surfacewater becomes more saline⁶. The extent of salinity can be quantified by the concentration Chloride in [mg/l] in the salinated surface (see table 1-1).

Typology water quality	Chloride concentration
	$\lfloor mg/l floor$
Fresh water	< 200
Saline water	200 - 1.000
Brackish water	1.000 - 10.000
Salt water	10.000 - 18000
Sea water	> 18.000

Table 1-1: Typology of water quality expressed in Chloride concentration in [mg/l]; after [6]

Both natural processes and human interventions are the underlying causes of salt water intrusion.

 $^{^{5}}$ At the moment, half of the world's population (about 2.5 billion people) lives within 60 kilometres of the shoreline. Problems as coastal erosion, loss of environmental habitat and natural disasters due to extreme weathers, tsunamis and algal blooms are encountered in coastal areas [2].

 $^{^{6}}$ Velstra et al. [41] define salinity as 'water with an excessive Chloride concentration through which an optimal land use cannot be guaranteed'
Nowadays saline water originates from various area-specific salt loads [4].⁷

The Netherlands and specific the Rhine-Meuse Estuary with its adjacent control areas are subject to the following salt loads, addressed to:

- 1. Internal salinity; seepage of brackish or saline ground water originating from old marine deposits;
- 2. External salinity: salt sea water intrusion into open estuaries;
- 3. Salinity through human intervention;
 - a. leakage of saline water through sluices and locks;

b. salt load of a river, existing of brackish effluents from agricultural drainage and industrial wastes.

These three processes are discussed in the following subsections 1-3-1 till 1-3-3.

1-3-1 Internal salinity

Internal salinity is the upward flow of salt water (seepage). A continuous ground water flow between the North Sea and the low-lying polders is caused by the lower water levels of the polders. Besides that, an upward flow of salt water exists from old marine deposits in deep-lying polders⁸.

The Dutch coastal evolution

Two processes in the Dutch history are today's sources of internal salinity: the evolution of the coastline since the last Ice Age (Holocene) and the reclamation of land since the Middle Ages [42].

The Holocene coastal evolution since the last Ice Age

The last Ice Age prevailed in the Netherlands over 10.000 years ago. The sea penetrated into the coastal provinces of the Netherlands about 7.500 years ago, because of the rising sea level due to an increasing temperature. Large zones of the fresh, brackish and saline ground water in the upper parts of the groundwater system are the historical remains of the coastal regression and transgression of the sea in the Northern and Western Netherlands (see figure 1-3).

⁷Savenije [4] states that saline ground water comes to the surface in case of the irrigation without proper drainage (e.g. Iraqi) or in case in forest harvesting (e.g. Australia). ⁸E.g. Mijdrecht polder in Rijnland



Figure 1-3: Depth transition fresh to brackish groundwater in the Netherlands [2]

Figure 1-4: Ground surface in the Netherlands in [m M.S.L.] [2, 3]

The reclamation of land

The development of the Dutch man-made polder environment has found its origins in the third centuary BC, when the inhabitants primitively drained land and constructed dwelling mounds (*terpen*). A region of small impoldered areas surrounded by dikes (*polder*) was formed around 1100 AD, through the building of embankments along main rivers and the construction of sluices at the smaller stream outlet. Afterwards land subsidence resulted, since the draining process occurred more efficiently with the use of windmills and the paddle wheel (16th century). The reclamation of large lakes resulted in deep-lying polders (*droogmakerijen*) in the 'Golden Age' (figure 1-5). Nowadays 25 [%] of the Netherlands is situated below mean sea level (M.S.L.) (figure 1-4).



Figure 1-5: Development of the Dutch polder region [2, 3]



Figure 1-6: Processes groundwater system in the Dutch coastal areas [2]

This man-made environment in the provinces Noord-Holland and Zuid-Holland causes a pattern of smaller and larger polders. Each polder controls it own phreatic water level, which differs from the adjacent areas. Consequently, a groundwater flow is set into motion that causes seepage in the polders (figure 1-6).

1-3-2 External salinity

External salinity is the intrusion of salt water from sea into a fresh water system. The level of the salt water intrusion is related to the degree of mixing between the salt sea water and the fresh river water. Without tidal influences the salt sea water is flowing under the less dense fresh river water and a salt water wedge is formed as a result of the density difference of about 2,8 [%] (figure 1-7). Contrary, the tide induces mixing processes at the interface near the water surface and near the bottom (figure 1-8). The latter type of external salt water intrusion dominates the Rhine-Meuse Estuary.



Figure 1-7: Stratified estuary; after [4]

Figure 1-8: Partly mixed estuary; after [4]

In case of the Rhine-Meuse Estuary, sea water is able to penetrate into the main water system via the Nieuwe Waterweg at Hoek van Holland onto the Nieuwe Maas and Oude Maas. The fresh water discharge of the rivers Rhine and Meuse should act as a counter pressure to prevent the penetration of the salt sea water during high tide. Backward external salinity is a special terminology used for the salt water intrusion via the Nieuwe Waterweg, Oude Maas into the Spui and its adjacent hinterland [5]. Backward external salinity is mainly the effect of a strongly increased sea water level set-up due to storm conditions (figure 1-9).



Figure 1-9: External salt water intrusion into the Rhine-Meuse Estuary, in particular the process of backward external salinity in the river Spui during the drought of 2003 [5]

The main objective of external salinity control is the protection of the fresh water inlets against saline water [5]. Regional water systems take in fresh river water from the main water system to counteract internal salinity by salt flushing. This positively affects the consequences of external and internal salt water intrusion.

1-3-3 Salinity by human intervention

Next to natural salt water intrusion, human intervention also contributes to the extent of salinity. Specified onto the Rhine-Meuse Estuary, salt water intrudes via the Haringvliet sluices during a flood period, in case of a sufficient Rhine discharge at Lobith larger then 1.500 $[m^3/s]$. The Haringvliet sluices control the distribution of the total seaward flowing fresh water discharge via the Nieuwe Waterweg and the Haringvliet sluices. Besides the intended restoration of the estuarine dynamics into the Volkerak-Zoommeer to improve the water quality affects the fresh water supply for the Rhine-Meuse Estuary⁹.

Salt water intrudes as well via navigational locks; i.e. into the main water system via the Noordzee sluices at the entrance of the North Sea canal and into the regional water system of Rijnland via the sluice of Spaarndam.

The water quality in the Rhine-Meuse Estuary is as well related to the Rhine's background Chloride concentration, which is the Chloride concentration that the water contains while flowing into the Dutch part of the Rhine's catchment area. Industrial discharges of the French Kali mines cause an increased background Chloride concentration. The Rhine Salt Convention obliged France to store the maximum salt load, if the background Chloride concentration at Lobith exceeds 200 [mg/l].

1-4 Fresh water policy

The current pursued drought policy focuses on optimization of the external water supply side; i.e. main fresh water distribution (subsection 1-4-1). The future policy adapts as well onto the water demand side; regional self-reliance (subsection 1-4-2). The present and future fresh water policies are discussed on a national level and on the regional level of Mid-West Netherlands.

1-4-1 Present policy

Dutch national fresh water policy

A specific drought policy concerning the fresh water distribution, to control the fresh water supply from the main water system towards the regional water systems should be pursued. The government can optimize the fresh water distribution by three measures [5]:

- 1. Operation of Driel's weir; Controller of the fresh water distribution between the IJssel and the Neder-Rijn/Lek, and minor for the Waal.
- 2. Closure of the Haringvliet; Controlling the outflowing river discharge via the Nieuwe Waterweg, instead of via the Haringvliet sluices.

 $^{^{9}}$ Multiple studies feasibility studies are recently executed. The governmental decision process concerning the improvement of the water quality of the Volkerak-Zoommeer is planned for the year 2012.

3. Closure of the Afsluitdijk sluices;

Increasing the water level of the IJsselmeer, such that the fresh water reserves stored in the IJsselmeer is enlarged.



Figure 1-10: Overview fresh river water flow and salt sea water flow [6]

Katwijk Content Con

Figure 1-11: Overview water distribution of Rijnland to guarantee water level management, salt flushing and irrigation [6]

Mid-West Netherlands fresh water policy

Two regional drought strategies were implemented during the drought of 2003 to cope with the increased pressure on the fresh water demand of Mid-West Netherlands; i.e. The Kleinschalige Water Aanvoer route and the Tolhuissluis route. Appendix A includes detailed geographical maps of both routes.

Kleinschalige Water Aanvoer¹⁰

The Hollandse IJssel could not be protected of external salt water intrusion in 2003. The Water boards of Rijnland, Delfland, Schieland and De Stichtse Rijnlanden agreed on the shared commitment for an increased fresh water supply capacity. The Kleinschalige Water Aanvoer measure is a network routing system that supplies fresh water originating from the Amsterdam-Rijnkanaal and the Lek via three flow routes to the mentioned control areas. The Water board of Rijnland transports and distributes the fresh water discharge to the control areas of Delfland and Schieland.

$To lhuiss luis\ route$

The operation of the Tolhuissluis route is addressed as a calamity measure, in case of insufficient external fresh water supply capacity towards Mid-West Netherlands. The Tolhuissluis route is a fresh water supply route between the IJmeer and the control area of Rijnland via opposite directed flow over the river Amstel towards the Tolhuis sluice.

Discussions arise whether the implementation of these two measures was cost-effective.

¹⁰i.e. in English: Small-scale water supply measure

1-4-2 Future policy

Dutch national fresh water policy

The National Waterplan sets up the guidelines for the current policy for the period between 2009 and 2015. This guideline is a governmental state plan for the water policy [1]. The fresh water supply programme is one of subprogrammes of the National Waterplan. The government has guided two visions for the future:¹¹

- 1. Optimization of the fresh water distribution;
- 2. Larger self-reliance of the regions.

The optimization of the fresh water distribution affects the fresh water supply for the Netherlands as a whole. Figure 1-12 gives an optimal discharge distribution for a Rhine discharge of 1.200 $[m^3/s]$ at Lobith. An improvement of the self-reliance of the agricultural sector is a measure that focuses on the fresh water demand side of the regional water balance. The latter measure is discussed below under the future policy of the Mid-West Netherlands.



Figure 1-12: Fresh water distribution main water system for a Rhine discharge at Lobith of 1.200 $[m^3/s]$ [1]

The National Waterplan [1] elaborates the fresh water policy advice of the Delta committee Veerman.¹² This committee has given two recommendations concerning the fresh water supply, based on the two concepts of safety and sustainability:

¹¹The central question calls: 'What are the options to handle the increasing fresh water demand of the different regions and users?' A large range of solutions exists; e.g. fresh water storage basins, valuate fresh water, stimulate reuse, international agreements for the cross-border fresh water use. The total plan should be a mixture of multiple solutions, since different sectors have to deal with different problems [1].

 $^{^{12}}$ The Delta committee Veerman is an inquiry committee of the government in 2008. Their research goal was to investigate the effects of climate change regarding water safety and give a policy advice for a climate-proof Netherlands in the years 2050 and 2100 [39].

- 1. The IJsselmeer should function as a fresh water reservoir, that supplies fresh water to the western Netherlands in times of drought; increasing the IJsselmeer water level should enlarge the total storage volume of the IJsselmeer.
- 2. The construction of four closable flood defences in the Spui, Oude Maas, Dordtse Kil and Merwede;

the salt water intrusion via the Nieuwe Waterweg does not have to be compensated with a large fresh water river discharge for these river branches.

Mid-West Netherlands fresh water policy

The recent study Droogtebestendigheid West-Nederland¹³ [7] is conducted in the context of the Subprogram Fresh Water of the Delta program. This study labels four measures as auspicious:

- 1. Flexible water level management; storage of the precipitation volume during the winter semester.
- 2. Dynamical water level management; active control of the water level in times water shortage; e.g. extra storage through dynamical weirs, inlet of fresh water, increase of the water level.
- 3. Salt flushing;

flushing of the regional water system to aime controlling salinity, reducing eutrophication¹⁴ and the control of the flow direction;

4. Self-reliance cultivations.

increasing collect of rainwater, optimal usage of condensation water and effluent and the realisation of a closed water loop for each business unit.

Figure 1-13 gives an overview of the efficient of the four described measures for varying areas of Mid-West Netherlands.



Figure 1-13: Fresh water reducing measures Mid-Western Netherlands [7]

¹³i.e. in English Drought sustainability West-Netherlands

 $^{^{14}}$ Eutrophication are caused by discharged industrial process and drinking water; defined as effluent, of wastewater treatment works (abbreviated as WWTW)

1-5 Research objective

This research investigates the implementation of a probabilistic approach within the current fresh water policy of the Netherlands, which does not presume risk-based decision-making.

RESEARCH OBJECTIVES, SCOPE AND SUBQUESTIONS

The main research goal of this thesis can be defined by two research objectives:

- 1. Develop a framework to assess the risks associated with external salt water intrusion into the Rhine-Meuse Estuary for the short term (2015) and the long-term (2050);
- 2. Evaluate measures to reduce the risk of external salinity for the long-term (2050), focussing on the optimization of the fresh water supply to the control area of Rijnland;

The scope of this thesis can be characterized by the following focus constraints: External salinity of the Rhine-Meuse Estuary, in particular the associated effects onto the fresh water distribution to the control area of Rijnland supplied by the *inlet of Gouda*.

The elaboration of the following sub research questions should guide this thesis towards the achievement of the stated research goal:

- 1. Develop a framework to assess the risks associated with external salt water intrusion into the Rhine-Meuse Estuary for the short term (2015) and the long-term (2050);
 - How can a general risk analysis model be adapted for the implementation into salinity risk-based decision making? (*chapter* 2)

• Which scenarios establish the stochastic input parameters for the salinity probability and consequences model and determine the constraints of the salinity risk management framework? (*chapter 3*)

• Which critical events determine the failure mechanisms of external salinity, that induce the consequences of external salinity in case of exceedance? Can external salt water intrusion in the Rhine-Meuse Estuary be described by a system-wide definition? Or should each subcatchment area be described by area-specific external salt water intrusion processes? (*chapter 4*)

• Which boundary conditions that describe the physical processes of external salinity are defined as the independent probabilistic stochastic parameters and should be analysed by a hydraulic model? (chapter 5)

• What is the general definition of the salinity probability? How can a general salinity probability model that is applicable for the Rhine-Meuse Estuary be adjusted for derivation of the failure mechanism of the Hollandse IJssel? (*chapter 6*)

• What are the consequences of salinity of the Hollandse IJssel for the control area of Rijnland? Which drought conditions determine the severity of the economical effects onto Rijnland's agricultural sector? (*chapter 7*)

• How is salinity risk defined? What are the decision-making instruments that evaluate risk? (chapter 8)

- 2. Evaluate measures to reduce the risk of external salinity for the long-term (2050), focussing on the optimization of the fresh water supply to the control area of Rijnland
 - What are possible risk-reducing measures for the long-term situation (2050)? What is the technical and economic feasibility of each measure? (*chapter 9*)

A conceptual salinity risk management model is developed that describes all phases of a risk analysis. The developed model outlines the thesis methodology (*chapter 2*).

Chapter 2

Salinity risk management model

2-1 Salinity risk management

The current fresh water decision-making process is based on a deterministic approach. This research aims to develop a risk-based decision making model for fresh water supply in tidal areas. The developed salinity risk management model includes of all phases of a risk analysis. A risk assessment investigates the risks associated with salt water intrusion in the Rhine-Meuse Estuary in the Netherlands. An analysis after the risk reduction alternatives is included in the risk management framework (figure 1-2).

This chapter outlines the salinity risk management model, from which an overview is given in figure 2-1. The research goal of each phase of the model will be clarified by means of the stated subresearch questions in section 1-5.



Figure 2-1: Research model salinity risk management

2-1-1 Scenario analysis (chapter 3)

A scenario analysis investigates the following subresearch question in chapter 3: Which scenarios establish the stochastic input parameters for the salinity probability and consequences model and determine the constraints of the salinity risk management framework?

A scenario analysis establishes the constraints of the research framework. The defined scenarios are the input for the definition of the salinity probability and consequences model.

Scenario

Figure 2-2: Phase I: Scenario analysis

A scenario should be defined that identifies the critical event for which the salinity risk should be established; i.e. a salinity safety scenario. The critical event is defined as the exceedance of a Chloride concentration standard due to external salinity of the Hollandse IJssel. A given salinity safety scenario depends on the defined time scales for which the probability and consequences of the failure mechanisms of the critical event will be investigated. Hydrologic and socio-economic conditions define the climate change scenario and the land-use change scenario for each time scenario.

2-1-2 System analysis (chapter 4)

A system analysis investigates the following subresearch questions in chapter 4: Which critical events determine the failure mechanisms of external salinity, that induce the consequences of external salinity in case of exceedance? Can external salt water intrusion in the Rhine-Meuse Estuary be described by a system-wide definition? Or should each subcatchment area be described by area-specific external salt water intrusion processes?

A system definition analyses the system with its mechanisms that cause an exceedance of the critical event; i.e. failure mechanisms of the critical event. A system is described by the location and object characteristics of the study area.



Figure 2-3: Phase II: System analysis

This research analyses the system of external salt water intrusion into the Rhine-Meuse Estuary, in particular the Hollandse IJssel with Rijnland's fresh water inlet Gouda. A spatial analysis investigates the location and object characteristics of the research areas that are subject to salinity; i.e. Rhine-Meuse Estuary and Rijnland.

A literature study is conducted after the physical conditions that cause drought. A physical model study will simulate external salt water intrusion in the Rhine-Meuse Estuary in chapter 5.

2-1-3 Physical salinity model (chapter 5)

A physical simulation model simulation aims to investigate the following subresearch question: Which boundary conditions that describe the physical processes of external salinity are defined as the independent probabilistic stochastic parameters and should be analysed by a hydraulic model?

Physics	of	salinity
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Figure 2-4: Phase III: Physical salinity model

Hydraulic simulations of the 1-dimensional Sobek flow model are performed, in order to establish the relation between the level of salt water intrusion and the descriptive stochastic parameters. The sensitivity of the individual parameters onto the variation of the Chloride concentration follows as well from the Sobek simulation results.

The results of the Sobek simulations are the basis for the probabilistic model set-up that should derive the exceedance frequency of the Chloride concentration for a given location in chapter 6.

2-1-4 Probabilistic salinity model (chapter 6)

A probabilistic model definition is based on the insight into the following subresearch questions: What is the general definition of the salinity probability? How can a general salinity probability model that is applicable for the Rhine-Meuse Estuary be adjusted for derivation of the failure mechanism of the Hollandse IJssel?

A probabilistic model derives the exceedance frequency and the exceedanc duration of a Chloride concentration.



Figure 2-5: Phase IV: Probabilistic salinity model

The exceedance probability of a Chloride concentration will be derived for the defined time horizon, based on the hydrologic conditions. The probabilistic model is composed of the submodels that will be examined for two locations in the Rhine-Meuse Estuary in a case study. A tide-dominated salinity probability model derives the exceedance probability for the location Krimpen aan den IJssel. A river-dominated probability model derives the exceedance probability for the location Gouda.

2-1-5 Salinity damage model (chapter 7)

An estimation of the consequences of salinity is based on the insight into the following subresearch questions:

What are the consequences of salinity of the Hollandse IJssel for the control area of Rijnland? Which drought conditions determine the severity of the economical effects onto Rijnland's agricultural sector?

A developed probabilistic quick scan agricultural damage model estimates the consequences of external salinity, in case of exceedance of the critical event. This model aims to compute Rijnland's agricultural damage in times of drought.



Figure 2-6: Phase V: Salinity damage model

The consequences of salinity can be defined as a loss of economical, environmental and social values. This research aims to determine the economical consequences that result of the exceedance of a Chloride concentration for Rijnland's agricultural sector for each defined set of scenarios.

2-1-6 Risk calculation and risk evaluation (chapter 8)

A risk calculation and evaluation can be conducted after the following subresearch question: How is salinity risk defined? What are the decision-making instruments that evaluate risk?

A salinity risk level R_i is defined as the salinity probability p_i times the consequences of salinity x_i for each scenario s_i .



Figure 2-7: Phase VI/VII: Risk calculation and risk evaluation

A risk evaluation determines whether a certain salinity risk level R is acceptable or not. Decisionmaking models support the risk evaluation phase and determine if a given salinity risk level is acceptable. This research evaluates the economic risk by a cost-benefit analysis and the economic optimum risk level.

2-1-7 Risk reduction and control (chapter 9)

A total framework of risk management evaluates the reduction of the salinity risk level by answering the following two subresearch questions:

What are possible risk-reducing measures for the long-term situation (2050)? What is the technical and economic feasibility of each measure?

If the present risk level will not be accepted by decision-makers, risk reducing measures will be analysed to find the optimal risk level.



Figure 2-8: Phase VIII: Risk reduction and control

The economical risk reducing effects of three measures will be analysed. The most cost-effective measure is the project for which the largest salinity safety level is found; i.e. largest risk reduction at the lowest investment costs. An economical optimal risk level is the optimum between the risk costs (avoided yearly damage) and the investment costs of a possible measure.

PART I: SALINITY RISK ASSESSMENT

Chapter 3

Scenario analysis

3-1 Introduction

A scenario analysis establishes the constraints of the research framework. A set of scenarios is directive for the risk analysis. The risk analysis should be conducted for each set of scenarios, in case of multiple defined sets of scenarios.



Figure 3-1: Research outline: phase I scenario analysis

This research distinguishes three types of scenarios:

- 1. Salinity safety scenario; defines the safety level against salt water intrusion.
- 2. Hydrologic scenarios; defines the effects of climate change.
- 3. Socio-economic scenario; defines the land use and price development in course of time.

This chapter discusses these three scenarios.

Master of Science Thesis

Design time scale

Drought has negative effects on the guarantee of the fresh water supply in the Netherlands. This research investigates the impacts of drought for two time horizons; short-term situation and long-term situation.

It is desirable to implement measures that focus on the optimization of the fresh water supply, in case the reference situation can not fulfill the fresh water requirements; regarding water quality and water quantity. Rijkswaterstaat [43] investigates the possibilities for two types of measures:

- Calamity measure¹ for the short-term situation;
 - » short operation periods, with an expected frequency of once per 5 to 10 year;
 - » relatively easily implementable with a minimal effect on the present land use;
 - \gg feasible in operation for the year 2015.
- Preventive measures for the long-term situation;
 - » expected operation frequency, once a year;
 - » sustainable measure, with accepted effects on the present land use;
 - » feasible in operation for the year 2050.

Measures will be designed for a design period of 50 [year], based on the governmental infrastructural investment-planning horizon.

3-2 Salinity safety scenario

A salinity safety scenario defines the critical event, for which the risk level will be established. Failure of the fresh water supply is the effect of an insufficient water quality and water quantity. Salt water intrusion leads to reduced water quality and water quantity.

Critical event

The defined failure mechanism can be described by the following critical event: exceedance of a Chloride concentration standard cl due to external salt water intrusion between 01. April and 30. September.

Each fresh water inlet has its own requirements to the water quality of the external water that will be taken in. The water quality requirements are of relevance during the crop growth season, which lasts from April until September. The remaining water-demanding function of Rijnland; water level management, does not impose requirements, regarding the water quality. The present fresh water policy applies a deterministic Chloride concentration standard cl that is location-specific and depends on the fresh water requiring functions of the control area. This research aims to develop a risk-based approach for the fresh water supply in the Rhine-Meuse Estuary. The applicability of this approach will be investigated by a case study that focuses on the fresh water supply of the control area of Rijnland. The Water Board of Rijnland imposes a deterministic Chloride concentration standard of 250 [mg/l] to the water quality of the Hollandse IJssel.

This studie's overall goal is to implement a risk-based approach for fresh water supply. A future risk-based fresh water policy should apply a probabilistic critical event, instead of a deterministic critical event. A risk analysis is able to investigate the optimal salinity safety level.

¹Also stated as 'no-regret measures' in the Delta programm $\left[44\right]$

An optimal safety level can be a function of a(n):

- Chloride concentration standard cl in [mg/l] that will exceed once per n year.
- Exceedance duration of the Chloride concentration cl in [mg/l] that will exceed once per n year.
- Damage level AD_{dr} in $[\in]$ for a specific fresh water requiring function² that will exceed once per n year.

3-3 Hydrologic scenario

A hydrologic scenario defines a climate change scenario. The expected severity and frequency of external salinity and drought events depends on the effects of the defined climate change scenario. The occurrence of external salinity is related to the occurrence of high sea water levels and low river discharges. Climate change scenarios predict the non-seasonal rising sea water levels and falling river discharges in the summer semester. The occurrence of drought is related to the increasing evaporation and the decreasing precipitation.

The present insights into the change of temperature, precipitation, wind and sea level are defined in the KNMI'06 climate change scenarios³ [8]. The KNMI'06 climate change scenarios together describe the most likely climate changes for 2050 and 2100. The KNMI predicts the climate change by four scenarios (see figure 3-2). The scenarios differ in their extent of global temperature rise and air circulation pattern variation (see figure 3-2).

The W/W+ scenarios characterize a strong global temperature rise (2 °C), which is contrary to the G/G+ scenarios that characterize a moderate rise (1 °C). The air circulation patterns variations above the Atlantic Ocean and western-Europe cause extra warm and wet winters and extra warm and dry summers in case of the G+/W+ scenarios. These effects will be minimal for the G/W scenarios.



Figure 3-2: Climate change scenarios KNMI'06 [8]

The current insights indicate each climate change scenario as probable, but not equally likely.^{4,5}

²e.g. an agricultural crop yield loss of 50 [%] of potatoes

³The KNMI'06 climate change scenarios replace the previous WB-21 (abbreviation for Waterbeheer 21e eeuw) scenarios

⁴The current climate change insights differ regarding the likeliness of each of the four KNMI-06 climate change scenarios; expert judgment (Deltares, HKV Consultants)

 $^{{}^{5}}$ Climate change models are based on a range of uncertainties. Uncertainties of temperature, precipitation, wind and sea level are included. This uncertainties are caused by [8]:

[•] uncertainties of social-economical developments, regarding land use and emissions of greenhouse gases and particles;

Climate change scenario advices can be specific addressed to different policy sectors. It should be stated that not every scenario is equally likely for each sector. Klijn et al. [38] gives a qualitative assessment of the relevance of each scenario for three main policy themes, including sub themes. The W+ scenario is the guideline for water supply and economical water use policies, with the subtheme 'agricultural water supply'.

This research presumes the W+ climate change scenario, based on the advice of Klijn et al. [38]. This research prefers to presume a 'worst case' scenario that at least includes the effects of the 'less worse case' scenarios. Besides that, each climate change scenario is labelled as probable and the 'worst case' scenario includes the uncertainties of a 'less worse case' scenario.

3-4 Socio-economic scenario

Socio-economic scenarios represent the change of land use. Van Beek et al. [36] states that the drought impacts of a shifting land use have a larger effect than the climate change scenarios, therefore socio-economic scenarios are incorporated in drought studies. This research derives an agricultural damage model that uses the derived agricultural drought damage figures of Van Beek et al. [36], which includes a shifting land use and financial crop values. This will be discussed.

A most extreme case is the scenario with the largest dependency of available fresh water; in case of the largest agricultural area. WLO⁶ defined 4 land use scenarios⁷; Global Economy, Strong Europe, Transatlantic Market and Regional Communities. All four scenarios predict a decreasing total agricultural area⁸. The type of agricultural cultivation does shift, with an intensification and extensification for several types of agriculture to effect. This possibly results in a variation of the agricultural yield value per hectare.

Since the present agricultural land use contains the largest agricultural area and so requires the largest fresh water volume, no land use scenarios will be incorporated by Van Beek et al. [36]. Besides that, the shift of crop-type specific market value is as well neglected.

3-5 Conclusions

A scenario analysis gives the following insights:

- Scenarios are the constraints of the research framework. The defined scenarios are the basis for the derivation of the probability and consequences of failure of the critical event.
- The critical event is defined as the exceedance of a Chloride concentration standard *cl* due to external salt water intrusion between 01. April and 30. September.
- Failure of the critical event will be investigated for two design time scales, based on the time horizon of possible implementable measures: calamity measures for the short-term situation of 2015 and preventive measures for the long-term situation of 2050.

[•] uncertainties of external factors of solar activity and volcanic eruptions;

[•] uncertainties through limited climate knowledge.

⁶Abbreviation of Milieu- en Natuurplanbureau, de Welvaart en Leefomgeving

⁷characterized by national/international developments and private/public developments

 $^{^{8}}$ The Global Economy scenario predicts an increasing glasshouse cultivation, where this sector decreases for all remaining three scenarios.

- This research defines three types of scenarios for each design time scale, with the presumption that in the context of this study it is most appropriate to define a 'worst case' set of scenarios: For the short-term 2015:
 - 1. Salinity safety scenario: maximum Chloride concentration of 250 [mg/l];
 - 2. Hydrologic scenario: present climate conditions;
 - 3. Socio-economic scenario: present land use and agricultural crop price.

For the long-term 2050:

- 1. Salinity safety scenario: maximum Chloride concentration of 250 [mg/l];
- 2. Hydrologic scenario: W+ KNMI'06 climate change scenario;
- 3. Socio-economic scenario: present land use and no agricultural crop price developments in course of time.

Chapter 4

System analysis

4-1 Study context

A system definition describes the processes of a given system. In this research a system analysis is executed for the understanding of the physical processes in the Rhine-Meuse Estuary. In particular, the conditions of external salt water intrusion are analysed for different locations. The extent of salt water intrusion is location-specific and is determined by the location and object characteristics. The results of the system analysis are the input assumptions for the physical model simulations in chapter 5.



Figure 4-1: Research outline: phase II system analysis

This investigation aims to develop a salinity risk management model, which is examined in a case study for the location Gouda. Gouda is located at the river upstream end of the Hollandse IJssel (figure 4-2). The system analysis will be discussed for two subareas of the Rhine-Meuse Estuary, since it is assumed that the level of external salt water intrusion is location-specific (figure 4-2). The type of water system assigns the two subareas. The main water system is in this research reported for the Rhine's and Meuse's catchment areas that flow into the Rhine-Meuse Estuary, which is bounded at the North by the Hollandse IJssel in situ Krimpen aan den IJssel and at the South by the Volkerak sluices in situ the entrance of the Volkerak-Zoommeer. The regional water system is in this research reported for the transitional water system of the Hollandse IJssel that interacts at the South in situ Krimpen aan den IJssel with the main water system and at the North in situ the fresh water inlet of Gouda with the regional control area of Rijnland. It should be stated that theoretical the regional water system belongs to the main water system, but the physical processes at the Hollandse IJssel are of different kind than for main water system. Concluding, this research studies the following two water systems:

1. Main water system: Rhine-Meuse Estuary;

case study location Krimpen aan den IJssel situated at the junction of the Nieuwe Maas and Hollandse IJssel;

2. Regional water system: Hollandse IJssel-Rijnland;

case study location Gouda situated at the upstream end of the Hollandse IJssel.



Figure 4-2: Overview spatial division two research areas; main water system and regional water system

In section 4-2 are the results of the spatial analysis for both sub areas reported. The external salt water intrusion into the main water system is investigated in section 4-3, by means of the salinity theory of Savenije [28, 4]. This section clarifies as well the made distinction between the two subareas, based on the tidal- or riverine dominance of the water system. The influence of the regional abstraction and discharges of Rijnland of the extent of salt water intrusion on the Hollandse IJssel is explained in section 4-4. The results of a data analysis for the drought indicating parameters for Krimpen aan den IJssel are included in section 4-5 and an evaluation of the hydrologic conditions of 1976 and 2003 is discussed in section 4-6.

4-2 Spatial analysis

The Rhine-Meuse Estuary is a tidal area where the rivers Rhine and Meuse meet the North Sea [28]. The Rhine-Meuse Estuary is affected by the marine influences of the North Sea and the riverine influences of the rivers Rhine and Meuse. Characteristics of an estuary caused by the river influence are the banks, directional flow of water, sediment transport, occasional floods and

the presence of fresh water in the upper layers. The marine characteristics of an estuary find its expression in the presence of tides and saline water in the lower layers. Savenije [28] has given an overview of the interaction between characteristics of sea, estuaries and rivers (table B-1) in Appendix B.



Figure 4-3: Overview three Dutch connected water bodies: North Sea, Rhine-Meuse Estuary and the rivers Rhine and Meuse; after [1]

4-2-1 Main water system: Rhine-Meuse Estuary

The Rhine-Meuse Estuary is the confluence of the catchment areas of the rivers Rhine and Meuse. The Rhine and the Meuse flow respectively at Lobith and Borgharen into the Netherlands. The seasonal discharge variation of the Dutch river branches is determined by the cross-boarder water sources of the Rhine and Meuse. The Rhine is a melt river and the Meuse is a rain-off river. Therefore, low discharges dominate the discharge variation between August and October. Appendix C gives a more extensive description of the Rhine and Meuse catchment areas.

The Meuse and the Nederrijn are both controlled by multiple weirs (see figure 4-4) in order to control the discharge distribution and to guarantee a navigable flow depth [9]. The three weirs of Driel, Amerongen and Hagestein are located along the Nederrijn. Driel's weir controls a sufficient fresh water discharge flowing towards the IJssel in times of drought and minor influences the Waal discharge. The Waal is the largest navigable river branch that is not controlled by weirs, since it is the most important river branch for the navigational sector. The weirs of Amerongen and Hagestein should control the water level of the Nederrijn for navigation.



Figure 4-4: Overview of the Dutch Rhine's and Meuse's catchment areas [9]

Figure 4-5: Water balance Netherlands 1971-2000 [10]

A water balance reports all the inflowing and outflowing water volumes. The water balance for the Dutch catchment area is averaged for the period between 1971 and 2000 by the $\rm NHV^1[10]$ in figure 4-5. River water of the Rhine and precipitation run-offs are the two main sources of the Dutch catchment area. In times of drought, the water balance is characterized by both low extents of the river discharge and the precipitation. The relative contribution in [%] of these two sources to the total water balance remains about constant, contrary to the evaporation and the use which extent increase about respectivily 1,5 and 2,5 times due to the warm weather.

4-2-2 Regional water system: Hollandse IJssel-Rijnland

Rijnland is the main control areas of the Mid-West Netherlands. The total surface of the control area of Rijnland is 1.113 $[km^2]$. Rijnland is enclosed by the adjacent control areas of Delfland, Schieland & Krimpenerwaard, De Stichtse Rijnlanden and Amster, Gooi & Vecht. Rijnland's main fresh water inlet is located at Gouda just downstream of the sluice² that upstream closes-off the Hollandse IJssel³. Consequently, the Hollandse IJssel is only influenced by the landward-directed sea water transport and not by the seaward directed river water transport. Therefore the Hollandse IJssel functions as a storage basin.

Fresh water of the Hollandse IJssel is supplied to the river Gouwe via the pump house at Gouda and the Oude Rijn supplies fresh water via the sluice of Bodegraven (respectively upper green and orange arrows in figure 4-6). Rijnland further transports water to the northern part of the control area of Delfland via the pump house Dolk⁴. Rijnland's internal water surplus is discharged via the three pump houses of Katwijk, Spaarndam and Halfweg (figure 4-7).

¹i.e. Nederlandse Hydrologische Vereniging

 $^{^2\}mathrm{i.e.}$ located at Waaiersluis

 $^{^{3}}$ The Hollandse IJssel and the Gekanaliseerde Hollandse IJssel originally had a open connection between the river Lek and the Nieuwe Maas. The upper branch (Gekanaliseerde Hollandse IJssel) was dammed from the lower branch (Hollandse IJssel) in 1285 (since 1856 Waaierssluis Gouda), to protect the hinterland against flooding.

⁴Delfland is provided as well by fresh water from the south via the Brielse Meer pipeline (lower green arrow in figure 4-6)



Figure 4-6: Overview of the control area of the Water board of Rijnland, located with the adjacent Waterboards of Delfland (South-West), Schieland & Krimpenerwaard (South-East), De Stichtse Rijnlanden (East) and Amstel, Gooi & Vecht (North-East) [5]

Figure 4-7: Overview control area of Rijnland with the pump house locations

The total area of surface water amounts 12.326 [ha], specified to 6.760 [ha] boezem water (main watercourses), 5.555 [ha] polder water (remaining watercourses) and 2.300 [ha] dune water. This subsection discusses Rijnland's internal water distribution system by means of the annual abstraction and discharge variation in course of time.

Figure 4-8 schematises Rijnland's water system (figure 4-7) as an internal water distribution network. The two main sources that flow into Rijnland's water system are the fresh water flows of the Hollandse IJssel via Gouda and the Oude Rijn via Bodegraven. The total inflowing and outflowing fresh water volume is averaged for the period 2003 - 2009 and amounts about 770 $[10^6 m^3]^5$. Figure 4-8 gives an indication of the individual components contributing to Rijnland's water balance.



⁵Individual water balances of Rijnland are provided by the Water board of Rijnland [11]

4-3 External salinity main water system

The physical processes that describe external salt water intrusion are reviewed in this section according to the salinity theorem of Savenije [28, 4]. The intensity of salt water intrusion can be measured by the Salinity in $[\mu S/cm]^6$ or the Chloride concentration in [mg/l] that a water volume contains.

4-3-1 Mixing driving forces

External salt water intrudes into an estuary by mixing processes. A seaward flowing fresh water river discharge desalinates the intruding sea water. If inflowing sea water does not mix with outflowing river water, the whole intruded sea water volume will leave the estuary on the ebb tide without further intrusion [28].

There are three main mixing driving forces [28]:

1. Tide

Kinetic tidal energy generated by the tidal movement of water, dissipates through mixing processes. Kinetic tidal energy exceeds the potential energy deficit of river water and induces tidal mixing.

2. River

A potential energy deficit of river water exists through a river discharge deficit. The discharge is too low to compensate for the counter pressure of the intruding sea water by gravitational circulation.

3. Wind

Wind driving horizontal and vertical circulation is of minor influence (see for further details [28]).

The tidal and river influence are the main forces that determine the mixing process. The sea water level h_0 is a measure for the tidal influence and the river discharge Q_f is a measure for the riverine influences. The paragraphs below introduce the relation between Chloride concentration and respectively the sea water level and the river discharge.

Tidal influence: sea water level Hoek van Holland

The sea water level h_0 at the estuary mouth is a measure for the intruding salt sea water volume that enters the Nieuwe Waterweg. An evaluation of the drought period of 2003 [46] remarks that the Chloride concentration increases, with an increasing water level gradient in the Rhine-Meuse Estuary (stated as the HL-parameter). A water level gradient is the gradient between the low water at Moerdijk and the high water water at Hoek van Holland (located at the river branch Hollands Diep; see figure 1-9). The water level gradient increases due to above average wind conditions at sea, which raise the water level at Hoek van Holland by a height Δh that is known as the water level set-up.

The water level set-up Δh is the difference between the observed water level h_{obs} and the standard astronomical tide h_{ast} (see figure 5-5). Western winds are responsible for water level set-ups into the Rhine-Meuse Estuary. Eastern winds are not of great relevance, since they result in a water

⁶Dissolved salts can be measured by the Electric Conductivity EC in $[\mu S/cm]$. Rijnland obtains the salinity of its surface water by the EC, which varies between 400 for extreme fresh water and 4.000 for extreme salt water. Distilled water is indicated by an EC of 0 $[\mu S/cm][45]$.

level set-down.

Figure 4-9 represents the standard astronomical and the spring tidal cycle for three locations ahead of Hoek van Holland and the Haringvliet sluices, which are the boundary conditions of the water level for this research and correspond with the Hydraulische Randvoorwaarden study (HR 2006) [47].



Figure 4-9: Upper figure: standard astronomical tidal cycle of 24 hours and 50 minutes for three locations at Hoek van Holland (blue line) and the Haringvliet sluices (green en red line); lower figure: spring tidal cycle of 24 hours and 50 minutes for the similar locations

It is assumed that the level of salt water intrusion increases with an increasing sea water level at Hoek Holland, due to storm-conditions:⁷

- Chloride concentration $Cl\uparrow$, if the sea water level $h_0\uparrow$
- Chloride concentration $Cl\downarrow$, if the sea water level $h_0\downarrow$

Riverine influence: Rhine discharge Lobith

A lower Rhine discharge enables the sea water further to intrude into the Nieuwe Waterweg during high water. The level of salt water intrusion is assumed to increase inversely with the river discharge:

- Chloride concentration $Cl\uparrow$, if Rhine discharge $Q_f\downarrow$
- Chloride concentration $Cl \downarrow$, if Rhine discharge $Q_f \uparrow$

Therefore this salinity research focuses on the discharge distribution of low Rhine discharges; i.e. $Q_f \leq 2.000 \ [m^3/s].^8$

The Rhine divides at two main junctions in the Rhine network after it enters the Netherlands at Lobith⁹. The first river junction is the Pannerdense Kop, where the Rhine discharge divides into 2/3 to the Waal and 1/3 to the Pannerdens Kanaal. The Pannerdens Kanaal branches by

⁷The tidal averaged Chloride concentration is totally addressed to the river discharge variation Q_f in case of a zero water level set-up Δh

⁸Contrary to flood control studies where high discharges are of decisive influence; i.e. $Q_f \ge 6.000 \ [m^3/s]$

 $^{^{9}}$ The current discharge distribution has been recorded since 1771 by a conferences between the Pruise and the Rebuplic and is nowadays still a stable discharge distribution.

Arnhem into 2/3 to the Nederrijn and 1/3 to the IJssel [48]. The described Rhine discharge distribution is only applied for moderate to large Rhine discharges; i.e. $Q_f \ge 2.000 \ [m^3/s]$.

The conducted discharge distribution is presented in table 4-1. The discharge distribution has a lower boundary of 600 $[m^3/s]$. The Meuse discharge is related to the Rhine discharge via the assumption that the Rhine-Meuse Estuary is influenced by a Rhine-dominated discharge in this research.

	Rhine	Lek	Waal	Maas
	Lobith	Hagestein	Tiel	Lith
	$[m^3/s]$	$[m^3/s]$	$[m^3/s]$	$[m^3/s]$
	600	25	550	55
Leewarden Gotinger	2.000	308	1.401	217
Crietern Asum	4.000	750	2.697	687
Akmar Brownsord Meptingerson 27/2/1/3	6.000	1.158	3.997	1.156
Markenson Nage Contract Rena	8.000	1.572	5.296	1.626
Total and the second	10.000	2.077	6.473	2.095
weakly weakly blue they to be they wall 2/3 Lobith				
Rhine				
Masside				

Table 4-1: Detail overview discharge distribution at the junction Pannerdense Kop [5] as a function of the Rhine discharge at Lobith and a Rhine-dominated Meuse discharge at Lith [47]

4-3-2 Characterization tidal-dominated or river-dominated estuary

Two characteristic estuary numbers indicate the dominance of the tide or the river and so the dominance of tidal mixing or gravitational circulation¹⁰ (see table 4-2):

- \bullet Canter Cremers Number N
- Estuarine Richardson Number N_R

The Rhine-Meuse Estuary can be characterized by an Estuarine Richardson Number N_R between 0,4 and 2 [-]; i.e. indicating that the estuary is a stratified system and is partly mixed [12]. A large estuarine Richardson number indicates the presence of enough potential energy in the river to maintain a sharp interface, resulting in stratification. A low estuarine Richardson number indicates the presence of enough kinetic energy in the tidal currents¹¹ to mix the river water with saline water, resulting in a well-mixed estuary.

The intrusion of salt water varies over the longitudinal distance and over the depth, since the Rhine-Meuse Estuary is a stratified and partly mixed system. This variation will be clarified in subsection 4-3-3.

 $^{^{10}}$ Savenije states that gravitational circulation is dominant in the Rhine-Meuse Estuary, since it is a near prismatic estuary [49] with a long convergence length. Dyer [49] established the Nieuwe Waterweg as a channel with a constant cross-section and parallel estuary bank, maintained through regularly dredging and protecting stabilizing banks. Therefore this survey assumes gravitational circulation as the main driving force causing salt water intrusion in the Rhine-Meuse Estuary.

¹¹The tidal kinetic energy varies over the tidal cycle, since spring tide increases the influence of tidal mixing over gravitational circulation and contrary at neap tide decreases the influence of tidal mixing over gravitational circulation [37]

INTERMEZZO: THE CANTER CREMERS NUMBER N & THE ESTUARINE RICHARDSON NUMBER N_R

The Canter Cremers Number N is the ratio between the seaward flowing river volume during a tidal period $Q_f T$ and the landward entering flood volume P_t :

$$N = \frac{Q_f T}{P_t} = \frac{Q_f T}{E_0 A_0} \tag{4-1}$$

where E_0 is the tidal excursion and A_0 is the cross-sectional area at the estuary mouth.

The Estuarine Richardson number N_R is another indicator to determine the degree of stratification, which is the ratio of the Canter Cremers Number N and the densimetric Froude number F_d :

$$N_R = \frac{N}{F_d} \tag{4-2}$$

The densimetric Froude number is defined as $F_d = \left(\frac{\rho}{\Delta\rho}\right) \frac{v_0^2}{gh}$, where v_0 is the amplitude of the tidal flow velocity at the estuary mouth.

Fischer et al. (1979) stated that if N_R is very large ($N_R > 0, 8$), the estuary is expected as strongly stratified and the flow will be dominated by density currents. If N_R is very small ($N_R < 0, 08$), it is expected to have a well-mixed estuary and density effects might be neglected.

Table 4-2: Intermezzo: The Canter Cremers Number N & the Estuarine Richardson Number N_R

4-3-3 Salt balance Rhine-Meuse Estuary

The movement of dissolved salts can be described by the interaction between the advective transport and the dispersive transport. The advective transport describes the seaward directed flow of river water with its background salinity S_f . The dispersive transport describes the landward directed flow of sea water with a tidal averaged salinity S_{TA} .

The salt balance equation can be distinguished in a steady state and unsteady state equation. In a tidal averaged steady state situation exists an equilibrium between the advective transport and the dispersive transport¹²; i.e. the long term variation of salinity $\frac{\Delta s}{\Delta t} = 0$. If no mixing processes take place, the tidal averaged salinity would be zero.

The steady state salt balance equation for a tidal averaged situation yields [28]:

$$Q_f(S_{TA} - S_f) - A_{TA}D_{TA}\frac{\Delta S_{TA}}{\Delta x} = 0$$
(4-4)

Where Q_f is the river discharge $[m^3/s]$, A_{TA} is the tidal averaged cross-section $[m^2]$, D_{TA} is the tidal averaged dispersive coefficient $[m^2/s]$ and S is the salinity of respectively the river discharge (f) and the tidal averaged situation (T_A) .

Salt water intrusion into the Rhine-Meuse Estuary reaches its maximum at High Water Slack

$$\frac{\Delta D(x)}{\Delta x} = -K \frac{Q_f}{A(x)} \tag{4-3}$$

Where K is the Van den Burgh constant [-].

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 $^{^{12}}$ The dispersive coefficient varies over the longitudinal distance, according to the Van den Burgh equation [28]:

(HWS). The maximum salt intrusion length in the Rhine-Meuse Estuary can be derived after [12]:

$$L_{max} = \frac{D_0^{HWS} A_0}{KQ_f} \tag{4-5}$$

Where L_{max} is the maximum salt intrusion length [m], D^{HWS} is the dispersion coefficient at High Water Slack $[m^2/s]$, A_0 is the cross-sectional flow area at the estuary mouth (x = 0) $[m^2]$ and K is the Van der Burgh coefficient [-].

Figure 4-10 describes the variation of the Chloride concentration along the Nieuwe Waterweg and Nieuwe Maas over the longitudinal distance from the North Sea (kmr. 1033) for the depth averaged, surface and bottom layer Chloride concentration. Observations of the Chloride concentration were accomplished on the 28. September 1999 [12], during prevailing conditions of a Rhine discharge Q_f of 1.200 $[m^3/s]$ and a zero water level set-up $\Delta h = 0$ at Hoek van Holland.



Figure 4-10: Longitudinal and depth variation of the Chloride concentration along the Nieuwe Waterweg and the Nieuwe Maas [12]

Historical observed Chloride concentration at Beerenplaat and Krimpen aan den IJssel

Van der Kaaij et al. [13] studies the variation of the Chloride concentration between 1983 and 2008 for the locations Krimpen aan den IJssel (in situ entrance Hollandse IJssel) and Beerenplaat (in situ entrance Spui). According to figure 4-11 shows that the annual average Chloride concentration is larger at Beerenplaat, compared to Krimpen aan den IJssel. The number of exceedance days that the Chloride concentration $cl > 250 \ [mg/l]$ is as well larger for Beerenplaat (figure 4-12). The tidal influences on the Chloride concentration are more observable at Beerenplaat, since the longitudinal distance to the North Sea is shorter. Beerenplaat is subject to more frequent exceedances of the Chloride concentration and a larger averaged Chloride concentration.

It can be noticed that both the Chloride concentration and the amount of exceedance days decreases, since the year 1997. This is the effect of the construction of the Hartel Barrier¹³ and the simultaneous reopening of the Beerdam in 1997. The demolition of the Beerdam had a decreasing effect of the salt water intrusion into the Oude Maas and an increasing effect of the salt water intrusion into the Nieuwe Maas.

¹³i.e. in Dutch Hartelkering



Figure 4-11: Overview annual averaged Chloride concentration $cl \ [mg/l]$ for two locations in the Rhine-Meuse Estuary between 1983-2005; Beerenplaat and Krimpen aan den IJssel [13]



Figure 4-12: Overview number of exceedance days that Chloride concentration $cl > 250 \ [mg/l]$ for two locations in the Rhine-Meuse Estuary between 1983-2005; Beerenplaat and Krimpen aan den IJssel [13]

4-4 External salinity regional water system

4-4-1 Salt balance Hollandse IJssel

The movement of dissolved salts in and out the Hollandse IJssel differs from the Nieuwe Waterweg and Nieuwe Maas, since the Hollandse IJssel is not described by the advective transport. The Hollandse IJssel has no upstream river discharge that desalinates the salt water by the ebb flow. The retention time of intruded salt water into the Hollandse IJssel slowly varies in course of time, since the Hollandse IJssel functions as a storage basin.

The variation of the abstracted water volumes of the Hollandse IJssel into Rijnland and the discharged water volumes of Rijnland onto the Hollandse IJssel influences the degree of salt water intrusion into the Hollandse IJssel:

- The Chloride concentration of the Hollandse IJssel increases $(Cl \uparrow)$, if Rijnland abstracts at the Hollandse IJssel at the pump house of Gouda $(\Delta Q_{Gouda} > 0)$
- The Chloride concentration of the Hollandse IJssel decreases $(Cl \downarrow)$, if Rijnland discharges at the Hollandse IJssel at the pump house of Gouda $(\Delta Q_{Gouda} < 0)$

If Rijnland's water surplus is discharged onto the Hollandse IJssel with Gouda's pump capacity ΔQ_{Gouda}^{14} and with Rijnland's background salinity S_{Gouda} , this can be interpreted as the temporarily advective transport of the Hollandse IJssel. In case Rijnland discharges water onto the Hollandse IJssel, the salt balance equation of the Hollandse IJssel can be described by:

$$\Delta Q_{Gouda}(S_{TA} - S_{Gouda}) - A_{TA}D_{TA}\frac{\Delta S_{TA}}{\Delta x}$$
(4-6)

Where A_{TA} is the tidal averaged cross-section varying along the Hollandse IJssel $[m^2]$, D_{TA} is the tidal averaged dispersive coefficient varying along the Hollandse IJssel $[m^2/s]$ and S_{TA} is the tidal averaged salinity varying along the Hollandse IJssel. ΔQ_{Gouda} $[m^3/s]$ is Rijnland's discharge at the pump house of Gouda and S_{Gouda} is the background salinity of the discharged water.

Severe conditions of a low river discharge Q_f and the large flood volume P_t (equation 4-1) induce the salt water intrusion into the Hollandse IJssel. Figure 4-13 gives the long-term variation

 $^{^{14}}$ The daily abstracted or discharged water volume $\Delta V_{Gouda;in/out}$ is equal to Gouda's pump capacity ΔQ_{Gouda} integrated over its operation time t

of the Chloride concentration at Gouda between 1971 and 2008 related to the periods with a low Rhine discharge; i.e. $Q_f \leq 1.000 \ [m^3/s]$. The slightly decreasing trend of the Chloride concentration is caused by the Rhine Salt Agreement that oblige France to minimize their instrustrial discharges onto the Rhine. The improvement of the 'trapjeslijn' in the Nieuwe Waterweg has a more effective mixing of salt and fresh water to effect, which results in a long-term decrease of the Chloride concentration for locations along the Nieuwe Waterweg, Nieuwe Maas and Hollandse IJssel.



Figure 4-13: Long-term decreasing variation of the Chloride concentration at Gouda [12]

Subsection 4-4-2 discusses the seasonal variation of the abstracted water volumes at Gouda and Bodegraven and discharged water volumes at Gouda, Katwijk, Spaarndam and Halfweg.

4-4-2 Seasonal variation abstractions and discharges Rijnland

Fresh water will be admitted to Rijnland to guarantee three functions:

- 1. water level management;
- 2. salt flushing;
- 3. irrigation.

Water level management is the first priority of providing water to Rijnland in times of drought, according to the National Verdringingsreeks [5]. The total water requirements of a system can be specified for each function. Figure 1-12 gives an overview estimated water requirements for water level management (about 55 [%]), salt flushing (about 30 [%]) and irrigation (about 9 [%]) and the remaining usage (about 6 [%])¹⁵[1].

The hydrologic conditions of the precipitation $P \ [mm]$ and the potential evaporation $E \ [mm]$ determine the water requirements:

- If a precipitation deficit (P E < 0) causes Rijnland's water shortage, Rijnland abstracts water of the Hollanse IJssel via the pump house of Gouda $(\Delta Q_{Gouda} > 0)$;¹⁶
- If a precipitation surplus (P E > 0) causes Rijnland's water surplus, Rijnland discharges water at the Hollanse IJssel via the pump house of Gouda $(\Delta Q_{Gouda} > 0)$;¹⁷

 $^{^{15}}$ The total water requirements differ from the inlet water requirements, since the water quality determines its applicability for each function. Onto the boezem discharged effluent of drinking water and industrial process water is only applicable for water level management, since its water quality is insufficient for the application of salt flushing and irrigation.

 $^{^{16}\}mathrm{Rijnland}$ abstracts fresh water as well via the pump house of Bodegraven

 $^{^{17}}$ Rijnland discharges fresh water as well via the pump houses of Katwijk, Spaarndam and Halfweg

An extra restriction is imposed via the Chloride concentration of the external Hollandse IJssel water. The Water board of Rijnland applies a maximum Chloride concentration standard cl of 250 [mg/l] for the Hollandse IJssel. Rijnland does not abstract water of the Hollandse IJssel, Rijnland's water demand can be met by the abstraction of Oude Rijn water at Bodegraven with a maximum capacity of 7 $[m^3/s]$, supplied via the Kleinschalige Water Aanvoer supply route (see subsection 1-4-1). If the capacity of the Kleinschalige Water Aanvoer supply route is insufficient to guarantee water level management, Hollandse IJssel water has to be admitted to Rijnland or alternative fresh water supply routes should be investigated¹⁸[14].

Figure 4-14 presents the seasonal variation of the abstracted water volumes at Gouda (black) and Bodegraven (blue) and the discharged water volumes at Katwijk, Spaarndam, Halfweg and Gouda (red) between 1991 and 2000. The largest contribution of Rijnland discharged water volume occurs during the winter semester, from October till February. Rijnland abstracts water at Gouda mainly during the summer semester, between March and September. External water of the boezem of Woerden is discharged onto the Oude Rijn and supplied to Rijnland via the sluice of Bodegraven. The water surplus of Woerden's boezem occurs mainly during the winter semester at Bodegraven during this period [14].



Figure 4-14: Overview seasonal variation of the abstracted water volumes at Gouda (black) and Bodegraven (blue) and the discharged water volumes at Katwijk, Spaarndam, Halfweg and Gouda (red) between 1991 and 2000 [14]

Groot et al. [14] analysed Rijnland's abstraction and discharge variation in course of time, amongst others for the dry year 1996 (figures 4-15 and 4-16). The abstraction and discharge variation during 1996 correspond to the described seasonal variation pattern.¹⁹

 $^{^{18}}$ i.e. the operation of the Tolhuissluis route during the drought of 2003;

¹⁹i.e. meaning that relatively a large water volume was abstracted at Gouda and a low water volume was discharged via Rijnland outlets, compared to the other years between 1991 and 2000;



Figure 4-15: Abstractions of Gouda and Bodegraven varying in course of time for the dry year 1996 [14]

Figure 4-16: Discharges of Gouda, Katwijk and the Noordzeekanaal (pump houses Spaarndam and Halfweg) varying in course of time for the dry year 1996 [14]

4-5 Data analysis Chloride concentration Krimpen aan den IJssel for 2003

A data analysis of the Chloride concentration variation in course of time during the year 2003 can verify the previous described salinity theory of Savenije in section 4-3. The year 2003 is characterized by two drought periods which are indicated by the periods #1 and #2 in figures 4-17 and 4-18.

Sea water level and Rhine discharge variation

The Chloride concentration is related to the sea water level at Hoek van Holland in figure 4-17. An average maximum high water level during standard tide and spring tide are respectively about 110 and 150 [+cm NAP]. In relation to the water level variation in course of time during 2003, it can be noted that the water level conditions were average during the first period and above average during the second period. The tidal effects do only contribute to the extent of salt water intrusion during the second period. The Chloride concentration variation during the first period is only caused by the riverine influences of the river Rhine.



Figure 4-17: Relation of the observed Chloride concentration at Krimpen aan den IJssel and the water level at Hoek van Holland for the year 2003 [15]; A sea water level $h_0 > 150$ [+cm NAP] is indicated as an increased water level due to storm conditions.

The annual maximum water level does as well not correspond with the annual maximum Chloride

concentration at Krimpen aan den IJssel (figure 4-17). This implies as well the joint contribution of the tidal influences and the riverine influences on the Chloride concentration.



Figure 4-18: Relation of the observed Chloride concentration at Krimpen aan den IJssel and the Rhine discharge at Lobith for the year 2003 [15]; a Rhine discharge $Q_f < 1.000 \ [m^3/s]$ prevailed during the two drought period with increased Chloride concentrations in 2003 (# 1 and #2)

This statement can be as well clarified by the Rhine discharge variation in course of time for 2003 in figure 4-18. The discharge graph shows that the Rhine discharge increases since the beginning of October, i.e. when the annual maximum water level occurs.

Rijnland's abstraction and discharge variation

Excessive water of Rijnland's water system was only discharged between January and mid of February due to a precipitation surplus and between 26. August and 12. September due to the operation of the Tolhuissluis route²⁰ (figure 4-19).



Figure 4-19: Discharges and abstractions at Gouda for 2003 (Data: Rijnland)



Figure 4-20: Chloride concentration at the Rhine (Lobith), Hollandse IJssel (Gouda) and the Gouwe (Gouda) 2003 (Data: Rijnland & RWS via www.aqualarm.nl)

Figure 4-20 gives the variation of the Chloride concentration in course of time for the Rhine (Lobith), Hollandse IJssel (Gouda) and the Gouwe (Gouda)²¹. Three periods are discussed:

 $^{^{20}}$ The large discharged water volume between 26. August and 03. September is the result of the reversed salt flushing of the deep-lying Mijdrecht polder, in order to provide Rijnland by fresh water of the IJmeer.

 $^{^{21}}$ A phase-lag of 48 [hour] between Lobith and Gouda has been included, which corresponds with the travelling time of a water particle between Lobith and Rhine-Meuse Estuary [50]. Only weekly measurements of the Chloride concentration at the Hollandse IJssel are available, resulting in a distorted graph compared to the daily respectively 10 minutes observations at the Rhine and Gouwe.

- A. 01. Januar 15. Februar: $(Cl_{Rhine} \downarrow; Cl_{Holl,IJssel} \downarrow; Cl_{Gouwe} \downarrow)$ High precipitation $(P \uparrow)$ and high Rhine discharges at Lobith $(Q_f \uparrow)$ have to effect low Chloride concentrations of the Rhine, Hollandse IJssel and Gouwe between 50 and 100 [mg/l].
- **B.** 15. August 01. Septembers: $(Cl_{Rhine} \uparrow; Cl_{Holl,IJssel} \uparrow; Cl_{Gouwe} \uparrow)$ A long period of low Rhine discharges at Lobith $(Q_f \downarrow)$ and moderate water levels; i.e. no water level set-up $(\Delta h \approx 0)$; at Hoek van Holland $(h \leftrightarrow)$ has salt water intrusion into the Hollandse IJssel to effect. The Chloride concentration of the Gouwe is bounded at 250 [mg/l] contrary to the Chloride concentration of the Hollandse IJssel, due to the inlet restriction of the maximum Chloride concentration.
- C. 07. October 10. October: $(Cl_{Rhine}\uparrow; Cl_{Holl,IJssel}\downarrow; Cl_{Gouwe}\downarrow)$ Low Rhine discharges at Lobith $(Q_f\downarrow)$ and high water levels at Hoek van Holland $(h\uparrow)$ has salt water intrusion in the Rhine-Meuse Estuary to effect. The closure of the Hollandse IJssel storm flood defense prevents the Hollandse IJssel of salt water intrusion.

4-6 Data analysis historical drought conditions of 1976 and 2003

A data analysis of the hydrological conditions of two historical drought years gives insight into the determining conditions for a dry year and the relating effects onto the Chloride concentration. This subsection analysis the two historical drought years 1976 and 2003.

A historical year can be indicated as a dry year. The severity of the drought can be assessed by the derived frequency of occurrence of a historical dry year. A drought with a low exceedance frequency indicates a very extreme event. Beersma et al. [21] executed a frequency analysis, based on historical data of the precipitation deficit and the discharge deficit. The year 1976 is characterized as an once per 110 [year] event and 2003 as an once per 12 [year] event by Beersma et al. [20]. Therefore 1976 is indicated as an extreme dry year and 2003 as an average dry year. The variation in course of time of the following variables is discussed:

- 1. Rhine discharge Q_f and discharge deficit ΔQ ;
- 2. Precipitation deficit ΔP .

4-6-1 Rhine discharge Q_f and discharge deficit ΔQ in 1976 and 2003

The year 1976 and 2003 are both characterized by river discharges of the Rhine and the Lek. The lowest river discharge occurs during August and October. The discharge graph of both years differs for the period of January and February were the Rhine discharge is extremely large with a maximum observed value $Q_f = 9.372 \ [m^3/s]$.
Statistics Rhine discharge (Lobith) and Lek discharge (Hagestein) 01. Januari - 31. December 1976 & 2003



Figure 4-21: Overview historical observed Rhine discharge and Lek discharge for 1976 and 2003

The annual averaged discharge of the Rhine was 1.336 $[m^3/s]$ in 1976 and 1.822 $[m^3/s]$ in 2003, which causes the difference in return period.

4-6-2 Precipitation *P* and the precipitation deficit ΔP in 1976 and 2003

The precipitation deficit ΔP in [mm] is the difference between the reference crop evaporation E_{ref} and precipitation P between 01. April and 30. September²² [35].



Figure 4-22: Precipitation deficit for period 01. April till 30. September 1976 and 2003

The precipitation deficit was more extreme in the 1976, compared to 2003. The precipitation deficit had a total value of $361 \ [mm]$ in 1976 and $217 \ [mm]$ in 2003 (see figure 4-22).

 $^{^{22}}$ The continuous precipitation deficit will be determined from the 01. April for the first decade, where the evaporation exceeds the precipitation till a precipitation surplus exists. The maximum precipitation deficit is the largest value of the continuous precipitation deficit between 01. April and 30. September [21].

4-6-3 Conclusions

Table 4-3 summarizes the statistical drought indicators of the year 1976 and 2003.

		1976	2003	Average 1900-2009
Minimum Rhine discharge Q_f	$[m^{3}/s]$	793	784	713
Average Rhine discharge $\overline{Q_f}$	$[m^{3}/s]$	1.048	1.108	2.100
Discharge deficit ΔQ	$[10^9 m^3]$	10,7	7,3	0,3
Precipitation deficit ΔP	[mm]	361	217	100

Table 4-3: Statistics of the drought year 1976 and 2003 between 01. April and 30. September

- Low river discharges Q_f have the largest probability density between August and October;
- The precipitation deficit ΔP has the largest probability density between June and August;

4-7 Conclusions

The system analysis has given the following insights:

- The extent of salt water intrusion depends on the mixing of salt sea water and fresh river water, which can be indicated by the tidal influences and the riverine influences. The tidal influences describe the dispersive transport and the riverine influences describe the advective transport of dissolved salts.
- The presence of the dispersive and advective transport are the basic assumption for the division of the total research area into subareas, since the physical processes that describe salt water intrusion are distinct for both areas:
 - 1. Main water system: Rhine-Meuse Estuary (Case-study Krimpen aan den IJssel);

Locations in this area are in open connection with the downstream landward flowing salt sea water and the upstream seaward flowing fresh river water.

Salt water intrusion is described by both dispersive and advective transport.

2. Regional water system: Hollandse IJssel-Rijnland (Case-study Gouda); Locations along the Hollandse IJssel are not described by the upstream seaward flowing fresh river water, since the Hollandse IJssel is an upper closed-off river branch. The Hollandse IJssel functions as a storage basin, with a slow variation of the physical processes in course of time.

Salt water intrusion is affected by the discharged and abstracted water volumes onto the Hollandse IJssel, which variation in course of time is related to the occurrence of a water shortage.

- The long-term variation of the Chloride concentration in course of time shows a slightly decreasing trend, which is caused by three processes: a diminished industrial salt water discharge of the French Kali mines (Rhine-Salt Agreement), a more effective construction of the trapjeslijn in the Nieuwe Waterweg and the reopening of the Beerdam due to construction of the Hartel Barrier (Hartelkering)
- The annual maximum precipitation deficit and the discharge deficit are the two drought indicators, whose severity is a measure for the characterization of the drought. The maximum contribution of both indicators differs over the summer semester. The annual maximum precipitation deficit has its largest probability density between June and August and the discharge deficit has its largest probability density between August and October.

• The variation of the Rhine discharge in course of time for the drought years 1976 and 2003 demonstrates that the joint occurrence of a precipitation deficit and a discharge deficit establishes drought's severity. The Rhine discharges outside the summer semester are of relevance for a study after the consequences of a drought.

The following table summarizes the relation between the river discharge Q_f , sea water level h_0 and the abstractions and discharges of Rijnland ΔQ_{Gouda} to the Chloride concentration Cl:

Rhine discharge Q_f	$Q_{f}\uparrow$	$Cl\downarrow$
u u u u u u u u u u u u u u u u u u u	$Q_{f}\downarrow$	$Cl\uparrow$
Sea water level h_0	$h_0\uparrow$	$Cl\uparrow$
	$h_0\downarrow$	$Cl\downarrow$
Abstractions (+)/ discharge (-) Rijnland ΔQ_{Gouda}	$\Delta Q_{Gouda} > 0$	$Cl\uparrow$
	$\Delta Q_{Gouda} < 0$	$Cl\downarrow$

Table 4-4: Summary relations river discharge Q_f , sea water level h_0 and the abstractions and discharges of Rijnland ΔQ_{Gouda} to the Chloride concentration Cl

Chapter 5

Physical salinity model

5-1 Study context

Hydraulic simulations are performed that should expose the sensitivity of salt water intrusion and the descriptive stochastic parameters. The system analysis assumed that the Chloride concentration depends on the Rhine discharge and the sea water level for the main water system. Salt water intrusion onto the Hollandse IJssel is assumed to be described by an extra descriptive parameter; i.e. the abstractions and discharges of Rijnland onto the Hollandse IJssel. These stated assumptions will be verified with a model study that makes use of the 1-dimensional Sobek flow model.



Figure 5-1: Research outline: phase III physical salinity model

5-2 Hydraulic model

Salt water intrusion in the Rhine-Meuse Estuary is simulated with an 1-dimensional flow SOBEK model¹. The model is able to compute river discharges Q_f , water levels h and Chloride concentrations Cl for multiple locations in the Rhine-Meuse Estuary. This study is interested in the Chloride concentrations at the two gauging stations at the boundaries of the Hollandse IJssel (figure 5-2) that correspond with the indicated area of the main water system and regional water system (chapter 4):

¹Provided by V.A.W. Beijk; Rijkswaterstaat Zuid-Holland

1. Main water system: Rhine-Meuse Estuary;

case study location Krimpen aan den IJssel situated at the junction of the Nieuwe Maas and Hollandse IJssel;

2. Regional water system: Hollandse IJssel-Rijnland;

case study location Gouda situated at the upstream end of the Hollandse IJssel.



Figure 5-2: Rhine-Meuse Estuary with the gauging points along the Hollandse IJssel

Since the system analysis discussed the longitudinal and depth-variation of the Chloride concentration, it should be remarked that an 1-dimensional flow model does not suit salinity simulations. This research assumes the depth-average Chloride concentration, which is appropriate with figure 4-10 and justifies the negligible of the depth variation of the Chloride concentration.

5-2-1 Boundary conditions

The SOBEK model simulates the Chloride concentration for each location in the Rhine-Meuse Estuary based on a large set of input conditions². The simulations are modelled to establish the extent of salt water intrusion for the short-term and the long-term boundary conditions of river discharge q_i and water level set-up Δh_j . The long-term boundary conditions include the predicted sea level rise h of +35 [cm] for the W+ KNMI'06 climate change scenario.

Each simulation is distinguished by a combination of boundary conditions of the Rhine discharge Q_f^3 and the water level set-up at Hoek van Holland Δh^4 for a simulation period that lasts 106 days:

- Simulations of the Rhine discharge Lobith $Q_f [m^3/s]$: 600, 700, 800, 900, 1.000, 1.200, 1.400, 1.600, 1.800, 2.000, 2.250, 2.500 and 4.000;
- Simulations of the water level set-up Hoek van Holland Δh [cm]: 0, 60, 75, 100, 125, 150 and 175

The Rhine-Meuse Estuary is schematisated in the SOBEK model as a network of branches and nodes (figure 5-3).

 $^{^2 \}mathrm{i.e.}\,$ flow area profiles, river discharge, water level, tidal period, lateral discharges, background salinity, flood defenses

 $^{^{3}}$ The boundary conditions of the river discharge are imposed as a continuous data serie at the Lek (Hagestein), Waal (Tiel) and Meuse (Lith).

 $^{^{4}}$ The boundary conditions of the water level set-up are imposed as a continuous data set of the water level at the mouth of the Nieuwe Waterweg and at two locations in situ the Haringvliet sluices.



Figure 5-3: Sobek schematisation of the Rhine-Meuse Estuary

Some background details of the constraint boundary conditions of the river discharge, water level, background Chloride concentrations and flood defenses will be discussed.

River discharge

Boundary conditions of the river discharge are imposed at the Lek (Hagestein), Waal (Tiel) and the Meuse (Lith). The river discharges of the Lek, Waal and Meuse are related to the Rhine discharge via the discharge statistics of the Lek and the Waal since 1989 and the Meuse between 1996 - 2007. Each discharge wave has an equal base duration B of 65 [days] and a varying peak duration b_k [days].

A real flood wave is described by a peak discharge $q_k > 6.000 \ [m^3/s]$, which lasts for about 2 to 3 [days]. The three simulated flood waves should not be interpreted as a real flood wave and therefore their variation in course of time is distinct. A simulated flood wave with a peak discharge $q_k = 4.000 \ [m^3/s]$ has a peak duration b_k of about 8 [days].

Trough waves can be interpreted as reversed flood discharge wave. A trough wave with a peak discharge of $q_k = 600 \ [m^3/s]$ has a peak duration b_k of 5 [days].

The variation in course of time of the 13 discharge wave simulations is represented for the Lek discharge in figure 5-4. The Waal discharge and the Meuse discharge have an equal variation in course of time and a varying peak value.



Figure 5-4: Schematisation discharge wave scenarios for the boundary location Hagestein at the river Lek for the fictituous simulation time

Water level

The water level h at Hoek van Holland is composed of the standard astronomical tide h_{ast} and the water level set-up Δh . The water level set-up due to stormconditions is added onto a standard tidal cycle, where the occurrence of spring tide is neglected. An average storm lasts for 30 [hours]. The sea water level is correlated to the wind conditions. Storm conditions at sea raise the water level at the estuary boundary, i.e. Hoek van Holland.



Figure 5-5: Schematisation water level set-up scenarios for the boundary location Hoek van Holland for the fictituous simulation time

Three continuous water level data serie are imposed on the mouth of the Nieuwe Waterweg and at two locations at the Haringvliet sluices. Figure 5-6 represents the 7 simulated scenarios of the water level set-up variations in course of time.



Figure 5-6: Water level set-up scenarios simulated with the flow model Sobek

Lateral discharges

The inflow and outflow volumes from and towards the control area of Rijnland are not taken into account, meaning that all lateral discharges along the Hollandse IJssel are imposed as a zero flow.

Background salinity

An initial salinity level is implosed on each branch in the Rhine-Meuse Estuary. The rivers Lek, Waal, Meuse and Hollandse IJssel have an imposed background salinity of 0,2 $[kg/m^3]$ and the river mouths of the Nieuwe Waterweg and Haringvliet have a background salinity of 34 $[kg/m^3]$.

Flood defense

The flood barriers Maeslantkering, Hartelkering and the Hollandse IJssel kering in the Rhine-Meuse Estuary will not close between 01. April and the 30. September, if the water level exceeds the closure water level.

5-3 Hydraulic results

5-3-1 Salinity: Chloride concentration Krimpen aan den IJssel

The maximum Chloride concentration at Krimpen aan den IJssel is computed for each simulation combination of river discharge and water level set-up. A contourplot gives insight into the contribution of the river discharge q_i and the water level set-up Δh_j onto Chloride concentration $c_{i,j}$. The contourplot shows vertical Chlority lines for the classes c_j with $\Delta h_j < 0$, with a maximum Chloride concentration $c_{i,j} = cl$; e.g. $c_{i,j} = 250 [mg/l]$.



Figure 5-7: Chlority lines for the Chloride concentrations at Krimpen aan den IJssel for the reference situation in 2015

Figure 5-8: Chlority lines for the Chloride concentrations at Krimpen aan den IJssel for the reference situation in 2050

Figures 5-7 and 5-8 show curved Chlority lines⁵ at 45° for a water level set-up $\Delta h > 0$, which approves the asumption that the water level set-up is of influence onto the Chloride concentration at Krimpen aan den IJssel. This is contrary to Gouda, where the water level set-up does not significant contribute 5-9 and 5-10.

⁵The Chlority lines are derived for maximum Chloride concentrations $c_{i,j}$ varying between 200 and 4.000 [mg/l].

5-3-2 Salinity: Chloride concentration Gouda

The Chlority lines for the short-term (2015) and the long-term (2050) situation for Gouda are presented in figures 5-9 and 5-10.



Figure 5-9: Chloride concentrations at Gouda for the reference situation in 2015



The Chlority lines are allmost vertical for all combinations of Rhine discharge q_i and water level set-up $h_j \leq 75 \ [cm]$. This indicates that the water level set-up does only contribute to the variation of the Chloride concentration for a water level set-up $h_j \geq 75 \ [cm]$. This conclusions is of importance for the definition of a probability model, which will derive the exceedance frequency of Chloride concentration $c_{i,j} = cl$ in chapter 6.

5-4 Sensitivity analysis: Rhine discharge

A sensitivity analysis gives insight into the sensitivity of the dependent variable to variations of the independent variables. In the context of this research, the sensitivity of the Chloride concentration to variations of the water level set-up and the river discharge is investigated. Here are the effects of a variation in the discharge distribution analysed.

The observations of the Rhine discharge distribution at the Pannerdense Kop do not correspond with the pursued discharge distribution (tabel 4-1 and figures 5-11 till 5-13 [15, 16]).

Multiple weirs are located along the river branches Nederrijn/Lek and Meuse controlling the discharge distribution [9]. The observations of the Lek discharge give the largest deviations for Rhine discharges below 1.600 $[m^3/s]$, which can be clarified by the Driel's weir policy. The Lek discharge strongly decreases for Rhine discharges below 1.600 $[m^3/s]$, due to the closure of the weir. The discharge distribution describes the observations for discharges larger then 2.000 $[m^3/s]$, since the weirs are partly opened for Rhine discharges between 1.600 and 4.000 $[m^3/s]$. The Waal riverprofile is not normalized by weirs, resulting in an agreement of the Waal discharge observations and the pursued policy discharge distribution. The Meuse discharge can be related to the Rhine discharge by a Rhine- or a Meuse discharge distribution, which explains the deviations of the Meuse discharge observations.



Figure 5-11: Correlation Lek discharge Hagestein to Rhine discharge Lobith for 1989 - 2009 [15]
Discharge division Rhine - Waul
Discharge division Rhine - Meuse



Figure 5-12: Correlation Waal discharge Tiel to Rhine discharge Lobith for 1989 - 2009 [15]

Figure 5-13: Correlation Meuse discharge Lith to Rhine discharge Lobith for 1996 - 2007 [15]

The maximum Chloride concentration for the reference situation (2015) is computed with the discharge boundary conditions according to the policy discharge distribution (table 4-1). Figure 5-14 gives an overview of the Chlority lines according to the simulations discharge distribution (blue fit lines in figures 5-11 till 5-13). The exceedance frequency of the Chloride concentration standard of 250 [mg/l] is 0,3 storms per summer semester, which is a factor 3 [-] lower.



Figure 5-14: Chlority lines for the Chloride concentrations at Gouda for the reference situation in 2015; simulated for the policy discharge distribution (blue lines in figures 5-11 till 5-13)

5-5 Conclusions

The hydraulic simulations has given the following insights:

- The extent of external salt water intrusion is affected by the tide-dominance for the location Krimpen aan den IJssel. The extent of external salt water intrusion is affected by the river-dominance for the location Gouda.
- The curvuture of the Chlority lines Cl = cl that are a function of the river discharge and the water level set-up indicates the dominant variable:

» Horizontal Chlority lines indicate that the Chloride concentration is only described by the water level set-up.

» Vertical Chlority lines indicate that the Chloride concentration is only described by the river discharge.

» A curved chlority line (towards 45°) means an equal contribution of the variations of the river discharge and water level set-up.

The Chloride concentration at Krimpen aan den IJssel is equally joint contributed by the water level set-up and the river discharge. The Chloride concentration at Gouda can be mainly assigned to the river discharge; i.e. the water level set-up contributes only for yields Δh larger then 75 [cm].

• The longitudinal variation of the Chloride concentration between Krimpen aan den IJssel and Gouda can not be described by a simple relation, based on the historical observed Chloride concentrations. Rijkswaterstaat executes Chloride concentration observations per 10 minutes at Krimpen aan den IJssel. The Waterboard of Rijnland executes Chloride concentation observation per week at Gouda. This inequality of observation method and frequency, causes difficulties concerning the derivation of the longitudinal variation of the Chloride concentration along the Hollandse IJssel.

Chapter 6

Probabilistic salinity model

6-1 Study context

This research aims to investigate the probability of external salt water intrusion into the Rhine-Meuse Estuary, in particular focussing onto the variation of the Chloride concentration along the Hollandse IJssel.



Figure 6-1: Research outline: phase IV probabilistic salinity model

6-2 Probabilistic research outline

The system analysis evinces that the contribution of the tidal and riverine influences is distinctive along the Hollandse IJssel. The water level set-up is only of some influence for Krimpen aan den IJssel. Therefore two conceptual probabilistic models are derived:

- 1. Tide-dominated model suitable for locations jointly influenced by the river discharge q and water level set-up Δh , with the restriction that the tidal influence $\Delta h > 0$ prevails; $Cl = f(q, \Delta h)$
- 2. River-dominated model suitable for locations only influenced by the river discharge q and the average tidal cycle $\Delta h = 0$; Cl = f(q)

The applicability of these two probability model will be verified for this case study for two locations in the Rhine-Meuse Estuary.

The tidal-dominated probability model is examined for the location Krimpen aan den IJssel (section 6-3). It should be noted that the tidal-dominated model is actually not suitable for the location Krimpen aan den IJssel, since the river discharge q dominates the tidal influence Δh . Further extended research should be conducted to verify the applicability of this model for a location along the Nieuwe Waterweg or Nieuwe Maas; i.e. at least closer located to the North Sea.

The river-dominated probability model is examined for the location Gouda (section 6-4). The simulation results of the 1-dimensional Sobek model approve that the tidal influence for the location Gouda is neglible (subsection 5-3-2). Therefore, this case study assumes a zero water level set-up $\Delta h = 0$ for the location Gouda.

6-2-1 Definition critical event

A salinity probability model should derive the exceedance frequency of a Chloride concentration in a given period, i.e. $Cl_{i,j} > cl$. In terms of this study, the exceedance frequency of a Chloride concentration is only of importance during the period that Rijnland abstracts external water of the Hollandse IJssel; i.e. in times of a precipitation deficit. Rijnland applies a Chloride concentration standard cl of 250 [mg/l], above which Rijnland will not abstract water of the Hollandse IJssel at Gouda.

The exceedance frequency of Chloride concentration standard $Cl > 250 \ [mg/l]$ is derived for the summer semester from 1. April - 30. September.

6-3 Framework tide-dominated probability model: Rhine-Meuse Estuary

6-3-1 Background

The Chloride concentration at Krimpen aan den IJssel is defined in this research as a function of the river discharge and water level set-up:

$$Cl_{q_i,hj} = f(q_i, \Delta h_j) \tag{6-1}$$

here $q_i \ [m^3/s]$ is the Rhine discharge at Lobith and $\Delta h_j \ [cm]$ is the water level set-up at Hoek van Holland. Each combination of the boundary conditions q_i and Δh_j results in an unique Chloride concentration $Cl_{q_i,\Delta h_j}$ for a specific location. The Rhine discharge q_i can be discretized in n classes with a discretization interval Δi . The water level set-up Δh_j can be discretized in mclasses with a discretization interval Δj .

The individual Chloride concentration $Cl_{q_i,\Delta hj}$, further indicated as $Cl_{i,j}$, for each class i, j can be represented by a mathematical graph (see figure 6-2). A Chlority line indicates all classes i, jfor which the Chloride concentration Cl has an identical value cl. Figure 6-2 displays a fictitious Chlority line for $cl = 250 \ [mg/l]$.



Figure 6-2: Representation of the Chloride concentration $Cl_{i,j}$ as a function of the Rhine discharge q_i and the water level set-up at Hoek van Holland Δh_j , for which a Chlority line can be derived through all classes i, j obtaining an identical Chloride concentration cl.

All classes above the Chlority line $Cl_{i,j} = cl$ obtain a Chloride concentration Cl larger than cl. The marked area in figure 6-2 indicates all classes $c_{i,j}$ with $Cl_{i,j} > cl$.

6-3-2 Model assumption

This subsection treats the tidal salinity probability model that is only applicable for locations where external salt water intrusion is caused mainly by the sea water level set-up Δh . The duration of the exceedance in this case is limited by the duration of a storm. Since during this exceedance the discharge does not vary much (a practically constant discharge during the exceedance). Since storms normally occur separate in time, the exceedances generally will not be consecutive in time, as illustrated in the figure.



Figure 6-3: Illustration of (normally separately occurring) exceedances with Cl>cl during storms; in this study 36 [hour] is taken as the duration of a storm.

The aim of the model is to calculate the salinity exceedance frequency F(Cl > cl), i.e. the average number of exceedances in times per year, of a Chloride concentration cl.

In the model statistical information is used of the water level set-up and discharge. For the water level set-up the exceedance probabilities during a single storm duration are needed, whereas for the discharge so-called momentaneous non-exceedance probabilities are needed. A momentaneous non-exceedance probability that a measurement at an arbitrary instant of time yields a value smaller then q.

The extent of salinity should be derived as a function of q and Δh . This salinity is derived from the Sobek simulation results (chapter 5), where a maximum Chloride concentration is simulated for each combination of q_i and Δh_j . It is presumed that during a (short) storm the time evolvement preceding this storm does not strongly influence the Chloride concentration during the storm. Available Sobek results are used for schematised discharge waves with a base duration B of 65 [days], where the storm with peak value Δh_k is assumed to occur at the peak of the discharge wave, these Sobek results are used. The peak durations of the discharges last at least 5 [days].



Figure 6-4: Model assumption: simultaneously occurence of the discharge peak value of a discharge wave q_k and the peak value of the water level set-up Δh_k

TIDE-DOMINATED PROBABILISTIC MODEL: EXCEEDANCE FREQUENCY F(Cl > cl)

The Chloride concentration Cl is a function of the Rhine discharge Q_f and the water level set-up ΔH at Hoek van Holland (equation 6-1). The derivation of the exceedance frequency F(Cl > cl)is based on the *independency principle*:

The Rhine discharge Q_f and the water level set-up ΔH at Hoek van Holland are assumed to be statistically independent for all possible combinations of $q_i, \Delta h_j$:

$$P(Q_f \le q, \Delta H > \Delta h) = P(Q_f \le q)P(\Delta H > \Delta h)$$
(6-2)

The individual momentaneous probability density $p(cl_{i,j})$ for each class $c_{i,j}$ is derived by the joint probability densities of q_i and Δh_j :

$$p(cl_{i,j}) = p(q_i)p(\Delta h_j) \tag{6-3}$$

The exceedance probability of cl for a random 36-hours period $P_{36}(Cl > cl)$ is the sum of all individual probabilities $p_{i,j}(cl_{i,j})$ of classes $c_{i,j}$ with $Cl_{i,j} > cl$:

$$P_{36}(Cl > cl) = \sum_{(i,j) \text{ for } Cl_{i,j} > cl} p(q_i) p(\Delta h_j)$$

$$(6-4)$$

The exceedance frequency of cl for a summer semester F(Cl > cl) is defined as the exceedance probability of cl for a random 36-hours period $P_{36}(Cl > cl)$ multiplied with the total number of 36-hours period within a summer semester N:

$$F(Cl > cl) = N * P_{36}(Cl > cl)$$
(6-5)

To apply the tide-dominated probabilistic model, the following statistical probabilities are required:

- The momentaneous non-exceedance probability of the Rhine discharge q at Lobith: $P(Q_f \leq q)^1$
- The exceedance probability of the water level set-up Δh at Hoek van Holland: $P(\Delta H > \Delta h)^2$

6-4 Framework river-dominated probability model: Gouda

6-4-1 Background

The Sobek simulations show that the water level set-up Δh does not influence the Chloride concentration at Gouda³. The Chloride concentration at Gouda is defined in this research as a function of only the river discharge:

$$Cl_{q_i} = f(q_i)$$

(6-6)

¹The momentaneous probability density of Rhine discharge q at Lobith is derived by: $p(q_i) = P(Q < q_i + 0.5\Delta(q)) - P(Q < q_i - 0.5\Delta(q))$ ²The momentaneously probability density of the water level set-up is derived by:

 $p(\Delta h_j) = P_{36}(\Delta H \le \Delta h_j + 0.5\Delta(\Delta h)) - P_{36}(\Delta H \le \Delta h_j + 0.5\Delta(\Delta h))$ ³The water level set-up only influences the Chloride concentration at Gouda for $\Delta h > 75$ [cm]. See figures 5-9 and 5-10 for the contourplots of the Chloride concentration.

Where $q_i \ [m^3/s]$ is the Rhine discharge at Lobith. The Rhine discharge q_i can be discretized in n classes with a discretization interval Δi . The water level set-up is of no account; indicating as a zero water level set-up $\Delta h = 0 \ [cm]$. Each imposed boundary condition q_i results in a unique Chloride concentration Cl_{q_i} for the location Gouda.

The Chloride concentration Cl_{q_i} , further indicated as Cl_i , can be represented in a mathematical graph as a function of the Rhine discharge for each class *i* (see figure 6-5). A Chlority exceedance line indicates all classes q_i for which the Chloride concentration exceeds at least $cl \ [mg/l]$. Figure 6-5 presents a random allocated Chlority exceedance line for $cl = 250 \ [mg/l]$.



Figure 6-5: Representation of the Chloride concentration $Cl_{i,j}$ as a function of the Rhine discharge q_i , for which an exceedance Chlority line Cl = cl can be derived through all discharge classes *i* resulting in a minima Chloride concentration cl.

6-4-2 Model assumption

The river-dominated salinity probability model that is only suitable for locations in the Rhine-Meuse Estuary subject to Chloride concentration exceedances that are not influenced by the tide. In case tidal influences can be neglected, long exceedance durations of $Cl_i > cl$ are caused by the slow variation of the river discharge q in course of time.

This model derives the exceedance frequency of a Chloride concentration standard F(Cl > cl), based on the assumption that the exceedance of the Chloride concentration is caused by a single discharge wave with peak discharge value q_k and peak discharge duration b_k :



Figure 6-6: Overview random distribution of one contiguous exceedance periods Cl > cl with a varying exceedance duration D_{Cl_i} [days]

The river discharge variation in course of time differs annually with a random number of discharge waves of basis duration $B_{k_1}...B_{k_n}$ with varying peak values $q_{k_1}...q_{k_n}$ and peak duration $b_{k_1}...b_{k_n}$.

This model assumes a discharge wave with a basis duration B of 65 [days] and peak discharge value q_k , between which the river discharge varies in course of time for q_i .

RIVER-DOMINATED PROBABILISTIC MODEL: EXCEEDANCE FREQUENCY F(Cl > cl)

The Chloridse concentration Cl is a function of the Rhine discharge Q_f (see equation 6-6). The exceedance of the Chloride concentration standard cl is assumed to be caused by one single discharge wave with peak value q_k during the summer semester.

The exceedance frequency of the Chloride concentration standard cl in [1/year] F(Cl > cl) is defined as the non-exceedance frequency of peak value q_k in [1/year] $F(Q_k \leq q_k)$, with $Cl = cl(q_k)$ (figure 6-5):

$$F(Cl > cl) = F(Q_k \le q_k) \tag{6-7}$$

The exceedance duration D_{Cl_i} can be derived by the ratio of the momentaneous non-exceedance frequency of discharge level q in [1/year] $F(Q_f \leq q)$ and the non-exceedance frequency of the annual minima summer peak discharge q_k in [1/year] $F(Q_k \leq q_k)$:

$$D_{Cl(i)} = \frac{F(Q_f \le q)}{F(Q_k \le q_k)} \tag{6-8}$$

Where the momentaneous non-exceedance frequency of discharge $F(Q_f \leq q)$ is defined as momentaneous non-exceedance probability of discharge level q for a random day $P(Q_f \leq q)$ multiplied with the total number of days within a summer semester M:

$$F(Q_f \le q) = M * P(Q_f \le q) \tag{6-9}$$

The non-exceedance frequency of annual summer peak discharge $F(Q_k \leq q_k)$ can be obtained from the annual minima summer discharge Q_{Summer} :^{*i*}

$$F(Q_k \le q_k) = -ln[1 - P(Q_{Summer} \le q_k)] \tag{6-10}$$

[i] The non-exceedance frequency $F(Q_k \leq q_k)$ is interchangeable with the non-exceedance probability $P(Q_{summer} \leq q_k) \leq \frac{1}{10}$. In case of non-exceedance probability $P(Q_{summer} \leq q_k) \leq \frac{1}{10}$. In case of non-exceedance probability $P(Q_{summer} \leq q_k) \leq \frac{1}{10}$ it is highly probable that multiple discharge peak value q_k occur during a summer semester. Therefore the non-exceedance frequency is derived by a Poisson distribution, which describes the occurrence of random points in time or space. The Poisson process is based on two basic assumptions; i.e. the rate λ at which the peak discharges q_k is constant over time and the number of peak discharges q_k in disjoint time intervals are independent random variables [51]. The non-exceedance frequency can be derived by $F(Q_k \leq q_k) = -ln[1 - P(Q_{summer} \leq q_k)]$

To apply the river-dominated probabilistic model, the following statistical probabilities are required:

- \bullet The momentaneous non-exceedance probability of the Rhine discharge q at Lobith: $P(Q_f \leq q)$
- The non-exceedance probability of the a summer minimum Q_{Summer} with peak value of the Rhine discharge q_k at Lobith: $P(Q_{Summer} \leq q_k)$

6-5 Statistical analysis

6 - 5 - 1River discharge Q_f

This research derives the momentaneous non-exceedance probability of the Rhine discharge q at Lobith $P(Q_f \leq q)$ and the non-exceedance probability of the annual summer minima Q_{Summer} with peak value of the Rhine discharge q_k at Lobith $P(Q_{Summer} \leq q_k)$, based on the statistics of the historical daily observed river discharges between 1901 and 2009.

A summer semester lasts 183 days, in the course of which multiple discharge waves with varying peak values q_k occur. The average summer discharge \overline{Q}_{Summer} is 2.100 $[m^3/s]$ and the annual summer median is $Q_{50\%}$ is 1.960 $[m^3/s]$ [15]⁴. The lowest observed peak summer discharge is 713 $[m^3/s]^5$. Figure 6-7 shows the discharge variation over time, with the marked annual minimum summer discharge (o) and maximum summer discharge (x). The lowest discharges generally have their occurrence in September and October (see figure 6-8).



Figure 6-7: Annual minima and maxima Rhine discharge at Lobith from 01. April -30. September 1901 - 2009 [15]

Figure 6-8: Histogram of the 10 lowest annual discharges at Lobith from 01. April - 30. September 1901-2009 [15]

This research assumes an uniform probability density of the river discharge over the summer semester. This is incompatible with the historical observed lowest river discharges, which have especially their occurrence in August and September. Further statistical research should be conducted to improve the probability density distribution of the river discharge for all moments of the summer semester.

A discharge wave is defined as a variation of the river discharge between its equilibrium value Q_{Summer} and a peak value q_k . The equilibrium discharge is assumed as the average summer discharge \overline{Q}_{Summer} of 2.100 $[m^3/s]$. The peak discharge q_k varies for a peak value k between 0 and a maximum observed discharge (theoretically infinity). As a simplified probability model, two types of discharge waves are considered (see figure 6-9):

- trough discharge waves with a peak discharge $q_k \leq 2.100 \ [m^3/s];$
- flood discharge waves with a peak value $q_k > 2.100 \ [m^3/s]^{.6}$

⁴The average annual discharge \overline{Q} is 2.220 $[m^3/s]$ and the annual median is $Q_{50\%}$ is 1.960 $[m^3/s]$ for 1901 - 2009 [15] ⁵Observation at 28. September 1947

 $^{^{6}}$ A real flood wave is defined as a discharge wave with peak discharge value q_{k} larger then 6.000 - 8.000 $[m^{3}/s]$; Here are flood waves defined with a maximum peak discharge q_k of 4.000 $[m^3/s]$, meaning that this are moderate flood waves.



Figure 6-9: Overview of a trough wave and a flood wave with the descriptive parameters [16]

 L_{q,q_k} is the duration in [days] that a discharge q lasts during a discharge wave with peak value ${q_k}.^7$

The probability of occurrence of either a trough discharge wave (p) or a flood discharge wave (1-p) is determined by the statistics of the daily summer discharges between 1901 and 2009:

- 58,4 [%] of the observations have a river discharge smaller then 2.100 $[m^3/s]$;
- 41,6 [%] of the observations have a river discharges larger than 2.100 $[m^3/s]$.

The non-exceedance probability $P(Q_{Summer} \leq q_k)$

An extreme value analysis of the annual minima summer discharges between 1901 and 2009 will be provided by the distribution of the annual minima summer discharges Q_{Summer} . The annual minima summer discharges are fitted on three extreme value distributions: Weibul distribution, Generalized Extreme Value distribution and a Gumbel distribution.

The momentaneous non-exceedance probability $P(Q_f \leq q)$

The momentaneous non-exceedance probability $P(Q_f \leq q)$ indicates the probability that for a random day, e.g. today, the observed river discharge non-exceeds a discharge level q. The non-exceedance probability $P(Q_f \leq q)$ derivation distinguishes two discharge ranges:

- 1. $P(Q_f \leq q)$ for peak discharges $q_k \leq 1.100 \ [m^3/s]$; The non-exceedance probability will be determined by a derivation of the non-exceedance probability for the duration of a discharge wave with peak value q_k .
- 2. $P(Q_f \leq q)$ for peak discharges $q_k > 1.100 \ [m^3/s]$; The non-exceedance probability will be established by the occurence frequency of historical observed daily discharges with peak value q_k .

The derivation of the non-exceedance probability based on the occurence frequency of historical observed daily discharges with peak value q_k , requires a sufficient percentage of discharge observations with peak value q_k . In case of a limited amount of discharge observations with peak value q_k , this method is unreliable. The reliability threshold discharge q_k is set at a discharge with at least 5 [%] of the total number of observations, resulting in a threshold discharge q_k of 1.100 $[m^3/s]$.

The two derivation methods for the momentaneous non-exceedance probability $P(Q_f \leq q)$ will now be explained.

$${}^{7}L_{q,q_{k}} = b_{k} + (B - b_{k})\frac{q - q_{k}}{2100 - q_{k}}$$

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1. $P(Q_f \leq q)$ for discharge peak values $q_k \leq 1.100 \ [m^3/s]$

The momentaneous non-exceedance probability of discharge level q is defined as:

$$P(Q_f \le q) = \frac{1}{B} \int_0^q f(q_k) L_d(q, q_k) dk$$
(6-11)

where $f(q_k)$ is the probability density of a discharge wave minima Q_{65}^8 with peak value q_k :

$$f_{q_k} = \frac{dP(Q_{65} \le q_k)}{dk} \quad \text{with} \quad P(Q_{65} \le q_k) = 1 - \left[1 - exp\left(-\frac{3000 - q_k}{A}\right)^B\right]^d \tag{6-12}$$

2. $P(Q_f \leq q)$ for discharge peak values $q_k > 1.100 \ [m^3/s]$

The momentaneous non-exceedance probability of discharge level q is defined as:

$$P(Q_f \le q) = \frac{D(Q \le q)}{M} \tag{6-13}$$

Where $D(Q \leq q_i)$ is the total number of historical observed discharges smaller then q and M is the total number of days of a summer semester; i.e. M = 183 [days].

A smooth transition between the two discharge ranges is accomplished.

River discharge Q_f for 2015

An extreme value analysis of the annual minima summer discharges between 1901 and 2009 provides the distribution of the annual minima summer discharges Q_{Summer} . The annual minima summer discharges are fitted on three extreme value distributions: Weibul distribution, Generalized Extreme Value distribution and a Gumbel distribution. A graphical analysis and the Kolgomorov Smirnov test [51] both indicate the Weibul distribution as the best fit (figure 6-10).

The Rhine discharge is assumed to be Weibul distributed with a location parameter A of 1863,9 $[m^3/s]$ and a shape parameter B of 7,3 $[m^3/s]$:

$$P(Q_{Summer} \le q_k) = exp\left(-\frac{3000 - q_k}{A}\right)^B \tag{6-14}$$

An annual minima summer Rhine discharge q_k of 700 $[m^3/s]$ has a non-exceedance probability of $P(Q_{Summer} \leq q_k) = 0,0098 ~(\approx 1/100 \text{ year})$, which approaches the lowest observed summer discharge for 110 year (1900 - 2009).

 $^{{}^{8}}Q_{65}$ denotes the peak value of a single through wave. The non-exceedance probability for Q_{65} is derived from the one for the summer minima by a standard rescaling procedure: in this rescaling one puts $P(Q_{65} > q_k) = P(Q_{summer} > q_k)^d$, where d equals the average number of trough waves in the summer semester. In this study, Chris Geerse adviced to take d = 0,36, but later he concluded that the value 0,584 should have been used. The conclusions of this study would not change significantly if the proper value 0,584 had been used, so that the calculations were not carried out again.



Figure 6-10: Extreme value analysis for the annual summer minima Rhine discharges 01. April - 30. September 1901-2009 [15]

The momentaneous non-exceedance probability $P(Q_f \leq q)$ is presented in figures 6-11 and 6-12. A Rhine discharge q of 1.960 $[m^3/s]$ has a momentaneous non-exceedance probability $P(Q_f \leq 1.960)$ of 0,50 [-], which is in accordance with the derived median $q_{50\%}$ of the daily discharge statistics between 1901 and 2009.



The momentaneous probability density $p(q_i)$ can be derived for all classes *i* of river discharge q_i , where the river discharge q_i is discretized in *n* classes with class width *i* of 5 $[m^3/s]$.



Figure 6-13: Momentaneous probability density $p(q_i)$ of the Rhine discharge for 2015

The momentaneous probability plot indicates the largest probability density $p(q_i)$ for a Rhine discharge between 1.600 and 2.000 $[m^3/s]$ (figure 6-13).

River discharge Q_f for 2050

The non-exceedance probabilities of the momentaneous discharge $P(Q_f \leq q)$ and of the summer annual minima discharge $P(Q_{Summer} \leq q_k)$ will alter for the long-term situation of 2050, due to the predicted effects of climate change onto the river discharge.

The KNMI'06 climate change scenarios [8] predict decreasing river discharges during the summer semester and increasing river discharges for the winter semester. The predicted temperature rise will cause a shift of the snow intensity towards a larger rain intensity and more over, the snow-fall will melt earlier. A strong decrease of the precipitation and an increase of the evaporation is predicted for the summer semesters, which all together will result in larger river discharges in the winter semester and lower river discharges in the summer semester.

Van Deursen et al. [17] investigated the effects of climate change for each scenario (G/G+/W/W+) per decade [days], concerning the decade averaged temperature T, precipitation P and evaporation E. Van Deursen et al. established the decade averaged procentual variation (+/-) of T, P and E, which are simulated with the RHINEFLOW model to derive the decade averaged procentual variation of the Rhine discharge Q_f (see figure 6-14). This research presumes the decade averaged procentual variation of the Rhine discharge predicted for the W+ climate change scenario (see chapter 3).



Figure 6-14: Predicted discharge variations for the climate change KNMI-06 W+ scenario [17]

The daily historical discharge observations between 1901 and 2009 are adjusted onto the predicted decade averaged procentual variation for 2050. The derivation of the non-exceedance probability of a momentaneous Rhine discharge q; $P(Q_f \leq q)$ and the non-exceedance probability of the annual minima summer Rhine discharge q_k ; $P(Q_{summer} \leq q_k)$ are established below for the long-term situation in 2050.

An extreme value analysis of the adjusted annual minima summer Rhine discharge for 2050 is derived. The annual minima summer Rhine discharge for 2050 is Weibul distributed with a location parameter A of 2236,7 $[m^3/s]$ and a shape parameter B of 12,6 $[m^3/s]$ (see equation 6-14). An annual minima summer Rhine discharge with a non-exceedance probability $P(Q_{Summer} \leq q_k)$ of 0,01 ($\approx 1/100$ year) amounts 475 $[m^3/s]$ for the long-term situation of 2050.

The momentaneous non-exceedance probability $P(Q_f \leq q)$ for the long-term situation is presented in figures 6-15 and 6-16. A momentaneous Rhine discharge q of 1.500 $[m^3/s]$ has now a non-exceedance probability $P(Q_f \leq q)$ of 0.50 [-]. This indicates that 50 [%] of the Rhine discharges Q_f are lower than q is 1.500 $[m^3/s]^9$.



The momentaneous probability density has its largest contribution $p(q_i)$ for a Rhine discharge of 1.250 $[m^3/s]$ (figure 6-17).



Figure 6-17: Momentaneous probability density $p(q_i)$ of the Rhine discharge for 2050

 $^{^{9}\}mathrm{In}$ relation: the derived median $q_{50\%}$ of the historical daily observation between 1901 and 2009 amounts 1.960 $[m^3/s]$

6-5-2 Water level set-up Δh

In this research the momentaneous exceedance probability of the water level set-up Δh is determined for a 36-hours period (see subsection 6-3-2), denoted as $P_{36}(\Delta H > \Delta h)$. This derivation is based on a statistical analysis of the historical water level set-ups.

Historical observations does only exist of water levels h. An extreme value analysis gives insight into the distribution of the annual maximum water levels H_{Summer} between 1888 and 2010. The observed water levels can be transformed to a water level set-up via a quadratic relation (see figure 6-18). This relation is used in the Hydraulische Randvoorwaarden (abbreviated as HR2006) [47] between the water level h and the water level set-up Δh (figure 5-5).



Figure 6-18: Correlation observed water level h to water level set-up Δh Hoek van Holland

Water level set-up Δh for 2015

The annual maxima summer water levels are observed since 1888 [15, 18]. A good fit of an extreme value distribution that describes the annual summer maxima water levels can not be obtained. Figure 6-19 shows the plotting positions of the annual summer maxima water level h between 1888 and 2010. All water levels larger than 250 [cm] are observed befor 1971.



Figure 6-19: Extreme value analysis for the annual maxima summer water levels at Hoek van Holland for 01. April - 30. September 1888-2009; [15, 18]

The derivation of the exceedance probability $P_{36}(\Delta H > \Delta h)$ is based on the historical frequency of occurrence of each water level set-up Δh_j for all classes j, where the transformed historical observed

water level set-up is the maximum water level set-up for each 36-hours period¹⁰. A frequency line shows the total number of observations of a water level set-up $\Delta H \leq \Delta h_j$ in [36-hours periods / summer semester] (see figure 6-20).



Figure 6-20: Frequency line of the water level set-up in Hoek van Holland in [36-hours periods/-summer semester]

A water level set-up of 0 [cm] has a exceedance probability $P_{36}(\Delta H > \Delta h)$ of 0,71 [-], meaning that 71 [%] of the observed maximum water level set-ups per 36-hours period between 1971 - 2010 has a water level set-up larger than zero (figures 6-21 and 6-22).



Figure 6-21: Exceendance probability water level set-up Hoek van Holland $p(\Delta H > \Delta h)$ for 2015 and 2050 (linear)



Figure 6-22: Exceendance probability water level set-up Hoek van Holland $p(\Delta H > \Delta h)$ for 2015 and 2050 (logaritmic)

 $^{^{10}\}mbox{Hourly}$ observations of the water level are available since 1971 and 10-minutes observations of the water level are available since 1987.

The momentaneous probability density $p(\Delta h_j)$ can be derived for all classes j of water level set-up Δh_j , where the water level set-up Δh_j is discretized in m classes with a class width j of 5 [cm]:



Figure 6-23: Momentaneous probability density water level set-up $p(\Delta h_i)$ for 2015 and 2050

The momentaneous probability density plot shows the largest probability densities for a water level set-up between 0 and 20 [cm]. This indicates a mild wind climate of the Netherlands resulting in on average a minimal water level set-up.

Water level set-up Δh for 2050

The momentaneous probability density of the water level set-up in 2050 will be taken the same as the momentaneous probability density of the water level set-up in 2015, since the KNMI'06 climate change scenarios predicts a minimal negligible variation of the wind conditions.

The KNMI'06 scenarios predict a sea level rise in the near future. The predicted extent of the sea level rise depends on the climate change scenario. The W+ scenario assumes a sea level rise of 35 [cm]. KNMI investigated that the frequency and the intensity of the storm conditions will only be subject to minimal negligible variations, resulting in a similar water level set-up pattern.

6-6 Exceedance frequency salt water intrusion

The exceedance frequency F(Cl > cl) in [1/year] can now be determined for each of the two derived probability models:

- 1. Tide-dominated probability model provides the number of individual 36-hours periods per summer semester, that the Chloride concentration cl will be exceeded (subsection 6-6-1).
- 2. River-dominated probability model provides the contiguous duration in days per summer semester, that the Chloride concentration cl will be exceeded (subsection 6-6-2).

The simulations results of the 1-dimensional SOBEK flow model establish the boundary conditions of q_i that should be non-exceeded and Δh_j that should be exceeded to result in an exceedance of a Chloride concentration $cl_{i,j}$ (subsection 5-3-1 and 5-3-2).

6-6-1 Results tide-dominated probability model: Krimpen aan den IJssel

The exceedance frequency F(Cl > cl) is derived by the momentaneous exceedance probability of a random 36-hours period $P_{36}(Cl > cl)$ multiplied with the number of 36-hours periods per summer semester N (see equation 6-5).

The sum of the individual momentaneous probability densities $p(cl_{i,j})$ for all classes $c_{i,j}$ with Cl > cl determine momentaneous exceedance probability of a random 36-hours period $P_{36}(Cl > cl)$. The individual momentaneous probability densities $p(cl_{i,j})$ for all classes $c_{i,j}$ is derived by the joint probability densities of q_i and Δh_j .

$$p(cl_{i,j}) = p(q_i)p(\Delta h_j) \tag{6-15}$$

The joint probability density $p(cl_{i,j})$ for the short-term situation (2015) and for the long-term situation are presented respectively in figures 6-24 and 6-25. The largest contribution of the joint probability density for 2050 is shifted towards lower Rhine discharges for equal water level set-up conditions. The momentaneous probability density function of the Rhine discharge has its peak value at 1.775 $[m^3/s]$ in 2015 and 1.250 $[m^3/s]$ in 2050, which supports the shift of the joint probability density function.



Figure 6-24: Joint momentaneous probability density Chloride concentration $p(Cl_{i,j})$ for 2015

Figure 6-25: Joint momentaneous probability density Chloride concentration $p(Cl_{i,j})$ for 2050

The exceedance frequency of the Chloride concentration standard cl of 250 [mg/l] is expressed in number of 36-hours periods per summer semester for the short-term situation 2015 and the long-term situation in 2050 in table 6-1:

Location	Exceedance frequency				
	F(Cl > 250)				
	[# 36-hours periods/summer semester				
	2015	2050			
Krimpen aan den Ussel	6.2	27.8			
Kimpen aan den 15sser	0,2	21,0			

Table 6-1: Exceedancy frequency Chloride concentration standard $F(Cl > 250) \ [mg/l]$ Krimpen aan den IJssel for the reference situation in 2015 and 2050

The exceedance frequency of varying Chloride concentration standards cl_i for the short-term situation 2015 and the long-term situation in 2050 is presented in figure 6-26 and 6-27:



Figure 6-26: Exceedancy frequency Chloride concentration standard F(Cl > cl) [mg/l]Krimpen aan den IJssel for the reference situation in 2015



Figure 6-27: Exceedancy frequency Chloride concentration standard $F(Cl > cl) \ [mg/l]$ Krimpen aan den IJssel for the reference situation in 2050

The time distribution of the exceedance days over the summer semester is an uncertainty. An exceedance frequency F(Cl > cl) of for instance 10 periods of 36-hours per summer semester should be interpreted as 10 individual periods of 36-hours. The individual exceedance periods can have their occurrence as a contiguous period with each 36-hours the occurrence of an exceedance or as two contiguous periods of 5 exceedings of 36-hours and so on. The probability model of this research did not include the time variation of the Chloride concentration exceedings over the summer semester.

The established exceedance frequencies F(Cl > 250) are not very reliable for Krimpen aan den IJssel, since the tidal influence is not so significant dominant that the tide-dominated probability model is applicable for Krimpen aan den IJssel.

6-6-2 Results river-dominated probability model: Gouda

The exceedance frequency of a Chloride concentration standard F(Cl > cl) is equal to the nonexceedance frequency of summer annual minima peak discharge $F(Q_k \leq q_k)$, with $q_{k(i)}$ is the river discharge that should be non-exceeded to result in the exceedance of the Chloride concentration standard Cl > cl(i).

The exceedance duration $D_{cl(i)}$ can be derived for varying Chloride concentration standards $cl(i)^{11}$. The exceedance duration $D_{cl(i)}$ of Chloride concentration cl_i can be estimated by the ratio of the non-exceedance probability of a momentaneous river discharge level q_i and the non-exceedance probability that this momentaneous river discharge level is the annual summer minima river discharge $q_i = q_{k(i)}$.¹²

The exceedance duration $D_{Cl(250;q_k)}$ is the duration that the Chloride concentration cl exceeds 250 [mg/l] during a discharge wave with peak value $q_k \ [m^3/s]$. The derivation of the exceedance duration $D_{Cl(250;q_k)}$ is based on the relation between the observed length (duration) of the discharge

¹¹Simulations are only executed for boundary conditions of the Rhine discharge larger then or equal to 600 $[m^3/s]$. The predicted climate change scenarios indicate a significant non-exceedance probability $P(Q_f \leq 600)$ of once per 2 [year]. Further research should investigate the exceedance duration $D_{Cl(i)}$ for boundary conditions of the Rhine discharge $q_i < 600 [m^3/s]$

¹²If for instance a Rhine discharge q_i of 1.000 $[m^3/s]$ has a momentaneous non-exceedance frequency $F(Q_f \leq q)$ of 5 times a year and an annual summer minima peak Rhine discharge $q_i = q_k$ of 1.000 $[m^3/s]$ has a once per 2 year non-exceedance frequency $F(Q_k \leq q_k)$, then once per 2 year a Rhine discharge of 1.000 $[m^3/s]$ results in an exceedance duration $D_{Cl(i)}$ of $\frac{5}{0,5} = 10$ [days].

wave on level $q(D_{Cl(i)})$ and the length of the discharge wave on level $q(D_{Cl(250)})$:

$$D_{Cl(250)} = D_{Cl(i)} + 2 * \frac{q(D_{Cl(250)}) - q(D_{Cl(i)})}{28,7}$$
(6-16)

The discharge decreases during a trough discharge wave in course of time with the gradient $\frac{\Delta q}{\Delta t}$ of 28,7 [m^3/s /day], based on a graphical analysis for multiple discharge variations in course of time. Specifically 13-04-1976 till 20-04-1976 $\frac{\Delta q}{\Delta t} = \frac{1.266-1.065}{7}$ (figure 6-28).



0 01-Jan 01-Feb 01-Mar 01-Apr 01-May 01-Jun 01-Jul 01-Aug 01-Sep 01-Oct 01-Nov 01-Dec Time I-I

Figure 6-28: Overview graphical analysis: discharge graph Rhine discharge Lobith for 1976 and 2003

Table 6-2 and 6-3 give an overview of the derived exceedance duration $D_{Cl(250;q_k)}$ for the short-term situation (2015) and the long-term situation (2050) (see as well figures 6-29 and 6-30).

Chloride	Discharge	Non-exceedance	Non-exceedance	Exceedance	Exceedance	
concentration		Irequency	nequency	uuration	duration	
cl(i)	q	$F'(Q_f \leq q)$	$F(Q_k \le q_k)$	$D_{Cl(i)}$	$D_{Cl(250;q_k)}$	
[mg/l]	$[m^3/s]$	[1/year]	[1/year]	[days]	[days]	
250	845	0,8691	0,05774	15,1	15,1	
300	790	0,4134	0,03190	13,0	16,8	
350	755	0,2423	0,02082	11,6	17,9	
400	715	0,1231	0,01217	10,1	19,2	
450	670	0,05254	0,006219	8,4	20,6	
500	625	0,02057	0,002904	7,1	22,4	

Table 6-2: Exceedancy duration D_{Cl_i} and $D_{Cl_{250;q_k}}$ with the exceedance frequency F(Cl > cl) [mg/l] for the reference situation of Gouda in 2015

Chloride	Discharge	Non-exceedance	Non-exceedance	Exceedance	Exceedance	
concentration		frequency	frequency	duration	duration	
cl(i)	q	$F(Q_f \le q)$	$F(Q_k \le q_k)$	$D_{Cl(i)}$	$D_{Cl(250;q_k)}$	
[mg/l]	$[m^3/s]$	[1/year]	[1/year]	[days]	[days]	
250	890	13,82	0,9639	14,3	14,3	
300	845	10,17	0,7649	13,3	16,4	
350	800	7,124	0,5868	12,1	18,4	
400	765	5,192	0,4644	11,2	19,9	
450	735	3,830	0,3711	10,3	21,1	
500	700	2,573	0,2767	9,3	22,5	
550	660	1,535	0,1880	8,2	24,2	
600	620	0,8592	0,1196	7,2	26,0	

Table 6-3: Exceedancy duration D_{Cl_i} and $D_{Cl_{250;q_k}}$ with the exceedance frequency F(Cl > d) [mg/l] for the reference situation of Gouda in 2050



Figure 6-29: Exceedancy frequency Chloride concentration standard F(Cl > cl) [mg/l] Gouda for the reference situation in 2015



Figure 6-30: Exceedancy frequency Chloride concentration standard $F(Cl > cl) \ [mg/l]$ Gouda for the reference situation in 2050

6-7 Conclusion probability models

The derivation of the exceedance probability of salinity is based on the development of two probabilistic models:

- 1. Tide-dominated salinity probability model for tide dominated locations: suitable for locations subject to short exceedance periods for Cl > cl; i.e. shorter then 36 [hours].
- 2. River-dominated salinity probability model for river dominated locations: suitable for locations subject to long continguous exceedance periods for Cl > cl; i.e. longer then 36 [hours].

A third probability model should be developed for locations with an equal contribution of the tide and the river, meaning that they are not tide- or river dominated.

The design process of a salinity probability model provides the following insights:

- The dominance of the tide or river is location specific and determines the frequency [1/year] and the duration [days or 36-hours period] of an exceedance period Cl > cl;
- The tide-dominated salinity probability model is applied for the location Krimpen aan den IJssel in this research. The results of the Sobek simulations show that tidal influences only prevail for Rhine discharges q_i larger then 1.000 $[m^3/s]$ at Krimpen aan den IJssel, meaning that short exceedance duration $D_{Cl_{i,j}} \leq 1,5$ [days]¹³ only occur at this discharge range (see red labels in table 6-4).

Exceedance duration Sobek		Rhine discharge $q_{k(i)}$ $[m^3/s]$									
$D_{Cl_{i,j}}$ [days]		600	700	800	900	1000	1200	1400	1600	1800	2000
	0	13,2	13,3	11,0	1,5	0,0	0,0	0,0	0,0	0,0	0,0
	60	13,3	13,2	11,2	3,4	0,9	0,1	0,0	0,0	0,0	0,0
Water level set-up	75	13,3	13,5	11,9	3,1	1,3	0,6	$_{0,1}$	0,0	0,0	0,0
$\Delta h_j \ [cm]$	100	13,4	$13,\!6$	12,2	6,4	2,2	1,0	0,7	0,3	0,0	0,0
	125	13,6	13,7	12,5	7,6	3,2	1,6	0,9	0,8	$_{0,1}$	0,0
	150	13,9	14,0	12,8	8,6	4,1	2,3	1,6	0,9	0,5	$_{0,1}$
	175	14,2	14,3	13,2	9,8	5,3	3,0	2,2	1,7	0,8	$_{0,3}$

Table 6-4: Exceedance duration $D_{Cl_{i,j}}$ simulated with the 1-dimensional Sobek model for each combination q_i , Δh_j for the reference situation of Krimpen aan den IJssel in 2015

¹³i.e. equal to $D_{Cl_{i,j}} \leq 36$ [hours]

The derived exceedance frequency F(Cl > cl) for the tidal situation yield an overestimation. In the tidal model overlapping exceedance periods are accounted twice, yielding an overestimation of the frequency (figure 6-31).



Figure 6-31: Explaination random allocated overlapping exceedance periods with duration $D_{Cl_{i,j}} > 36$ [hours]

The tide dominated salinity probability model is only applicable for the location Krimpen aan den IJssel for Rhine discharges $q_i > 1.000 \ [m^3/s]$. This concludes that since the tidedominated model is applied for all discharges q_i , the tide-dominated model derives incorrect exceedance frequencies.

- The river dominated salinity probability model is applied for the location Gouda in this research. The Chloride concentration $Cl > 250 \ [mg/l]$ for Rhine discharges $q_i \leq 845 \ [m^3/s]$ for the short-term situation of 2015 (see table 6-2). A discharge wave with peak discharge $q_k = 600 \ [m^3/s]$ non-exceeds a discharge $q = 845 \ [m^3/s]$ for $L_{q=845,q_k=600} = 14,8 \ [days]$, which approaches the computed exceedance duration $D_{Cl(250;q_k=600)}of_15,4$ [days] of the SOBEK model.
- The assumed variation in course of time of a discharge wave includes many uncertainties. Further statistical research should be conducted after the discharge variation in course of time for varying discharge waves with peak discharge q_k ; i.e. the shape of a discharge wave. It is desirable to establish reliable exceedance durations $D_{Cl(250)}$ that can be obtained by a reliable shape of a discharge wave.
- The statistical analysis assumed a single probability distribution of the low peak river discharges and high water level set-ups for all moments during the summer semester. However, the probability distributions vary thorough the summer semester. Low river discharges have their occurence mainly between August and October (see figure 6-8). So meaning that, further statistical research of q_i and Δh_j is recommended. For instance, statistics for bimonthly periods can be derived.

Chapter 7

Salinity damage model

7-1 Study context

This research investigates the possibilities of a probabilistic agricultural damage model that establishes the relation between the external salinity of the Hollandse IJssel and the Rijnland's agricultural drought damage.



Figure 7-1: Research outline: phase V salinity damage model

This relation is extremely complex to derive, due to the combination of human intervention into the main and regional water system and the uncertainty of the variation in course of time of a system's water demand and water supply¹. A quick scan model is developed that describes this relation by a very pragmatic simplified method. The quick scan model aims to express the exceedance frequency of Cl > 250 for varying exceedance duration $D_{Cl(250)}$ into Rijnland's agricultural damage AD_{dr} by an agricultural damage function. $D_{Cl(250)}$ is from now reported as D_{Cl} .

Rijnland's requirements concerning external water supply and further background theory of agricultural damage is outlined in section 7-2. Subsection 7-3 describes the drought characteristics, which are the basis for the agricultural damage model definition in section 7-4. Section 7-5 outlines the main conclusions of this chapter.

¹i.e. caused by the variation in course of time of natural processes as the temperature T, precipitation P, evaporation E

7-2 Context agricultural damage model definition

Agricultural damage of a water system can be correlated to the water demand of this system. Rijnland's water demand is the sum of the total water volume to guarantee:

- 1. waterlevel management;
- 2. salt flushing;
- 3. irrigation.

Agricultural damage can now be defined in terms of the requirements of Rijnland's external water supply of the Hollandse IJssel at Gouda:

- water quantity in terms of water volume $[m^3]$;
- water quality in terms of Chloride concentration [mg/l].

First of all, the Hollandse IJssel should deliver of a sufficient stored water volume. The second condition to satisfy is the required Chloride concentration cl, being at the very most 250 [mg/l]. Rijnland does not admit water containing a Chloride concentration above this threshold value. The refused water volume contributes to the total deficit of the water balance.

This study aims to derive the relative drought damage in accordance of the obstruction of the external water inlet at Gouda caused by an exceedance of the Chloride concentration standard of 250 [mg/l].

Subsections 7-2-1 and 7-2-2 give a general overview of the different types of agricultural damage and their contribution onto the agricultural yield reduction.

7-2-1 Type agricultural damage

Sufficient water quality and water quantity are the basis for damage prevention. Negative effects of an inbalanced water system have three type of agricultural damage to effect [31, 52]:

- drought damage;
- wet damage;
- salt damage.

A hydrologic dry year is subject to the negative effects of a water supply deficit; i.e. drought damage. Contrary, a hydrologic wet year is subject to the negative effects of a water supply surplus; i.e. wet damage. The system is subject to negative effects, if the water quality requirements of surface- and groundwater can not be met; i.e. salt damage. Appendix E gives an overview of the economical effects for each of these three types of agricultural damage.

Drought damage and salt damage are substitutable, since the agricultural sector prefers to eliminate salinated water of its system. If salinated water is admitted to Rijnland, the negative effects onto the groundwater are noticable as long as it takes to desalinate the groundwater; i.e. many years [52].
7-2-2 Yield reduction components

This investigations only focusses on the drought and salt damage components.

$$AD = \alpha_{dr}AD_{dr} + \alpha_{sa}AD_{sa} \tag{7-1}$$

Where AD is the total agricultural damage in $[10^6 \in]$, which is the sum of the drought damage component AD_{dr} in $[10^6 \in]$ and the salt damage component AD_{sa} in $[10^6 \in]$. α_{dr} [-] and α_{sa} [-] are the yield reduction factors for respectively the drought damage component AD_{dr} and the salt damage component AD_{sa} .

The drought damage function and the salt damage function are both crop type specific and depend on the crop's growth phase. The yield reduction factor is a crop type specific factor that distinguishes the yield loss due to drought α_{dr} and the yield loss due to salt α_{sa} . Grass, potatoes and mais are more drought sensitive compared to the more irrigated capital-intensive cults which are more salinity sensitive (figures F-1 and F-2). Appendix F gives an overview of Rijnland's crop cultivations with their potential market value and agricultural area. The growth phase is of importance for the yield reduction, since the effects of a water shortage have a larger impact during the growth than during the harvesting phase.

Drought damage increases with a decreasing actual evaporation E_{act} [mm] that is related to the potential evaporation E_{pot} [mm] (figure 7-2), since the crop's grow decreases if a crop can not evaporate optimal. Salt damage occurs due to the presence of salinated ground water at the crop's rootzone or due to the irrigation with salinated water. Salt damage increases with increasing Chloride concentrated ground- and surface water. Figure 7-3 presents an averaged salt damage function for these two causal salt damages.



Figure 7-2: Drought damage function [19]

Figure 7-3: Salt damage function [19]

Since salt damage is about 1 [%] of the drought damage in $[\in/ha]$, the total agricultural damage AD can be simply described as a function of the agricultural drought damage AD_{dr} :

$$AD \approx \alpha_{dr} AD_{dr}$$

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(7-2)

Drought damage characteristics 7-3

7-3-1 Drought indicators water balance

The agricultural damage can be determined on a national level and on a regional level. The extent of agricultural drought damage AD_{dr} is a function of the water demand V_d and the water supply V_s of a system:

$$AD_{dr} = f(V_s, V_d) \tag{7-3}$$

The water demand and water supply of a system result from balance of the individual in- and outflowing components. The waterbalance of a system defines the in- and outgoing flows of a system. This research analyses the water balance of two systems:

- 1. Main water system; i.e. the Dutch catchment area.
- 2. Regional water system; i.e. Rijnland's polder area.

DROUGHT INDICATORS WATER BALANCE

The water balance of the main water system exists of four main components that determine the water demand and the water supply:

 $\underbrace{\frac{\text{Precipitation } P \ [mm] \text{ and Evaporation } E \ [mm]}_{\text{Precipitation deficit } \Delta \ P \ [mm]}; \underbrace{\text{River inflow } Q_{in;c} \ [m^3]}_{\text{Discharge deficit } \Delta \ Q \ [m^3]} \text{ and River outflow } Q_{out;c} \ [m^3].$

The waterbalance for a regional polder system distinguishes from catchment area by the two components abstractions $Q_{in;p}$ $[m^3/s]$ and discharges $Q_{out;p}$ $[m^3/s]$; Precipitation P[mm] and Evaporation E[mm]; Polder abstraction $Q_{in;p}[m^3]$ and Polder discharge $Q_{out;p}[m^3]$.

Precipitation deficit $\Delta P [mm]$

The contribution of the remaining subcomponents is negligible [53]. Appendix G describes the general water balance and distinguishes the horizontal and vertical water balance.

Discharge deficit $\Delta Q \ [m^3]$

Two indicators can be assigned for drought impacts; the annual maximum precipitation deficit $\Delta P \ [mm]$ and the annual maximum discharge deficit $\Delta Q \ [m^3]$. The statistics of these two drought indicators will be analysed in subsection 7-3-2.

Large parts of the Netherlands can be supplied with river water in times of a precipitation deficit. since the amount of river water that flows through the Netherlands is on average 2,5 times as large as its receives from precipitation (see waterbalance in figure 4-5). The river discharge can compensate for a system's water shortage, caused by a precipitation deficit. A polder discharges its excessive water volume mainly during the winter semester, in case of a precipitation surplus.

7-3-2 Historical statistics of precipitation deficit and discharge deficit

In this study, each characteristic year will be characterized by the precipitation deficite ΔP and the discharge deficit ΔQ . At first a definition is given of these two indicators, from which 5 characteristic drought years are distinguished.

Precipitation deficit

The precipitation deficit is the difference between the the reference crop evaporation E_{ref} [mm]² and the precipitation P [mm], integrated over time between 01. April and the 30. September. The precipitation deficit is a measure for the soil's moisture content. A positive value of the precipitation deficit indicates a moisture shortage (vochtekort) and a negative value indicates a moisture surplus (vochtoverschot).



Figure 7-4: Evaporation and precipitation in the Netherlands for the period 1906-2000 between 01. April and 30. September [20]

The maximum precipitation deficit of 361 [mm] is observed in 1976. The upper limit of the precipitation deficit follows for a summer semester with no precipitation. Consequently, the precipitation deficit results from the reference evaporation and can have a maximum extent E of 600 [mm] (exceedance frequency once per 2.800 years) [20].

Discharge deficit

The discharge deficit of the river Rhine is based on daily discharge measurements at Lobith. The discharge deficit is determined by the decade averaged discharges intergrated over time between 01. April - 30. September, in case the decade averaged discharge is below a certain threshold value [21]. A threshold discharge of 1.800 $[m^3/s]$ is set, which corresponds to the 20 [%] quantile of the decade averaged discharge of the summer semester [20]. A lower threshold discharge should result in too many years with a zero discharge deficit.

The maximum possible discharge deficit can be derived for the lowest observed discharge in the period 1901-2010 of 713 $[m^3/s]$ integrated over a whole summer semester; i.e. ΔQ of 17, 2 * 10⁹ $[m^3]$. The maximum observed discharge deficit amounts 12, 1 * 10⁹ $[m^3]$ for the summer semester of the year 1921.

 $^{^2\}mathrm{The}$ grass reference evaporation is derived from temperature and sunshine duration at De Bilt by the Makkink formula

Trend precipitation deficit and discharge deficit

Figure 7-5 presents the precipitation deficit ΔP and the discharge deficit ΔQ in course of time. Beersma et al. [20] stated that there is no visible trend found in the data, but he concluded that the precipitation deficit and the discharge deficit are positive correlated. This research assumes the independency of the precipitation deficit and the discharge deficit. This will be later on clarified (section 7-4-4).



Figure 7-5: Top figure: Maximum precipitation deficit; bottom figure: Maximum discharge deficit for the period 1906-2000 between 01. April and 30. September [20]

Beersma et al. [21] assigns five historical years as 'characteristic drought years'. Each individual year can be distinguished by varying extents of the precipitation deficit and discharge deficit. Table 7-1 gives a qualitative indication of the five characteristic drought years.

Year	Precipitation	Discharge
	deficit	deficit
Average (1967)	small ΔP	small ΔQ
Moderate dry (1996)	moderate ΔP	moderate ΔQ
Dry (1949)	average ΔP	less large ΔQ
Very dry (1959)	less large ΔP	average ΔQ
Extreme dry (1976)	large ΔP	large ΔQ

Table 7-1: Characteristic drought year assigned by Beersma et al. [21], qualitative indication of the annual maximum precipitation deficit ΔP and the discharge deficit ΔQ

7-4 Quick scan model agricultural damage

This research aims to investigate the sensitivity of the economical effects caused by salinity of the Hollandse IJssel onto Rijnland's total agricultural drought damage. This section first argues why agricultural damage is complex to determine, which is the basic assumption for the development of a quick scan model. The model set-up is clarified by means of three assumed relations between the precipitation deficit, discharge deficit and the exceedance duration of a Chloride concentration $cl = 250 \ [mg/l]$.

7-4-1 Agricultural damage: a complex topic

The economical effects of external salinity are difficult to determine, since drought damage and salt damage are substitutable. This subsection discusses the complexity of a salinity agricultural damage model.

Regional water shortages of the soil's moisture and irrigation water are the result of a precipitation deficit in a dry year. The following three events underlie to the existing on regional water shortages in dry years:

- The Dutch main surface water system is not subject to water shortages, not even in extreme dry years. Agricultural drought damage in dry years is caused by the lack of sufficient regional small scale water supply systems and irrigational installations [52].
- Rijnland's current fresh water policy aims to implement salt flushing by fresh water and to refuse the intake of salinated water into the system [52]. The elimination of external water of the Hollandse IJssel contributes to an enlargement of Rijnland's water shortage.
- Alternative fresh water supply routes can functions as a calamity measure to compensate the water shortage; i.e. Kleinschalige Water Aanvoer route and the Tolhuissluis route described in section 1-4-2. An unsufficient capacity of measure³ or a policy discussion regarding the implementation of calamity measure⁴ contribute as well to a system's water shortage.

7-4-2 Quick scan model definition: agricultural damage function

Context

The precipitation deficit ΔP is an indicator for the agricultural drought damage AD_{dr} . Crops need a sufficient available groundwater volume to grow optimal. If the groundwater level is too low for the rootzone, the crop growth reduces.

Crops should be irrigated to compensate for the groundwater shortage. Irrigational water is available in regional water courses (i.e. ditches, streams etc.) and storage reservoirs. The available fresh water precipitation reserves that are stored in reservoirs, will be encroached first before external water is taken into the system. The water quality of the regional water courses depend on the external supplied water quality; i.e. the water quality of the Hollandse IJssel in case of Rijnland. The water quality and quantity are related to the discharge deficit ΔQ .

The agricultural drought damage AD_{dr} can be described by these two variables:

$$AD_{dr} = \beta_1 \Delta P + \beta_2 \Delta Q + \beta_3$$

(7-4)

Where AD_{dr} is the total agricultural drought damage between 01. April and 30. September as a function of the precipitation deficit ΔP and the discharge deficit ΔQ .

³The capacity of the Kleinschalige Water Aanvoer route was unsufficient to meets Rijnland's water demand in 2003.

 $^{^4}$ An evaluation of the implementation of the Tolhuissluis route in 2003 questioned the necessity of this measure.

Model definition

An agricultural damage function for Rijnland is derived that aims to express Rijnland's agricultural damage as a function of exceedance duration $D_{Cl(250)}$ for varying exceedance frequencies $F(Cl \leq cl)$. The model definition is stated below and the model derivation is clarified in the following subsections.

QUICK SCAN MODEL RIJNLAND'S AGRICULTURAL DAMAGE

Rijnland's agricultural damage function is defined as a function of the annual maximum precipitation deficit ΔP (assumption 1):

$$AD_{dr} = \beta_1 * (\Delta P)^2 + \beta_2 * (\Delta P) \tag{7-5}$$

Where β_1 and β_2 are the regression coefficients respectively expressed in $[10^6 \in /mm^2]$ and $[10^6 \in /mm^2]$.

The precipitation deficit ΔP can be related to discharge deficit ΔQ , based on the historical statistics of ΔP and ΔQ between 1906 and 2000 (assumption 2).

The duration $D_{Cl(250;q_k)}$ that the Chloride concentration of the Hollandse IJssel at Gouda will exceed a standard cl of 250 [mg/l] due to a discharge wave with peak value b_k . The duration $D_{Cl(250;q_k)}$ is from now abbreviated as D_{Cl} . D_{Cl} is related to the annual maximum discharge deficit ΔQ , since it is assumed that one single discharge wave with annual summer minima peak discharge q_k and peak duration b_k induces the exceedance of Chloride concentration standard cl^5 . (assumption 3).

$$D_{Cl(250)} \longrightarrow \Delta Q \longrightarrow \Delta P \longrightarrow AD_{dr}$$

Rijnland's agricultural damage AD_{dr} can be described as a relationship to the exceedance duration D_{Cl} via the following relations:

$$\Delta P = \varphi_1 \Delta Q + \varphi_2$$

$$\downarrow \quad \Delta Q = \gamma * D_{Cl}$$

$$\Delta P = \varphi_1 (\gamma * D_{Cl}) + \varphi_2$$

These relations can be combined with equation 7-5:

$$AD_{dr} = \beta_1 * [\varphi_1(\gamma * D_{Cl}) + \varphi_2]^2 + \beta_2 * [\varphi_1(\gamma * D_{Cl}) + \varphi_2]$$
(7-6)

which is equal to

$$AD_{dr} = 0,141D_{Cl}^2 + 4,8D_{Cl} + 19,1 \tag{7-7}$$

Where D_{Cl} is the exceedance duration in [days] and AD_{dr} is the agricultural drought damage in $[10^6 \in]$.

The three stated assumptions are the basis for the definition of the described quick scan model, which are clarified into the next subsections 7-4-3 till 7-4-5. Rijnland agricultural damage for the short-term situation (2015) and the long-term situation (2050) is presented in subsection 7-4-6.

7-4-3 Assumption 1: Relation A_{dr} to ΔP

This subsection derives the relation of Rijnland's agricultural damage AD_{dr} to the annual maximum precipitation deficit ΔP . At first, a short note is stated about the total agricultural damage function of the Netherlands as a joint function of the precipitation deficit and the discharge deficit. Based on this analysis, the agricultural damage indicators of Rijnland are analysed.

Agricultural drought damage function of the Netherlands

Beersma et al. [20] assessed the economical argicultural damage by derivating the 'failure regions'; i.e. rectangle defined by $(\Delta P > \Delta p, \Delta Q > \Delta q)$ in figure 7-6. All combinations $\Delta P_j, \Delta Q_j$ located in the rectangle are more extreme events, resulting in a larger economical agricultural damage.

The national agricultural drought damage can be described by the following equation:

$$AD_{dr} = \underbrace{5,15}_{\beta_1} \Delta P + \underbrace{0,0435}_{\beta_2} \Delta Q - \underbrace{258,2}_{\beta_3} \tag{7-8}$$

where the regression coefficient β_1 is expressed in $[10^6 \in /mm]$, β_2 in $[\in/m^3]$ and β_3 in $[10^6 \in]^6$. A regression line can be interpreted as a damage curve, which describes all combinations of the precipitation deficit and the discharge deficit with an equal agricultural damage level. The damage curves for the varying characteristic drought years clarify the individual contribution of the precipitation deficit and the discharge deficit to the total agricultural damage with a significance level of 10 [%]⁷.



Figure 7-6: Agricultural drought damage regression curves for the Netherlands, with the 'failure regions' ($\Delta P \ge \Delta p, \Delta Q \ge \Delta q$) derived by Beersma et al. [21]

⁶Standard errors respectively 0,66; 0,0174 and 113,7;

⁷The significance of the precipitation deficit is convincing (p-value of 0,00138), contrary to the significance contribution of the discharge deficit (p-value of 0,06505). The significance level is established at 10 [%], instead of the more justified 5 [%].

Year	Precipitation Discharge		Agricultural	Mean return	
	deficit deficit		damage	periods	
	[mm]	$[10^6 m^3]$	$[10^{6} \in]$	[year]	
Average (1967)	151	445	363	2,2	
Moderate dry (1996)	199	4.977	983	6,9	
Dry (1949)	226	9.402	1.233	17	
Very dry (1959)	352	5.373	1.740	55	
Extreme dry (1976)	361	10.851	2.143	110	

Table 7-2: Total agricultural damage of the Netherlands AD_{dr} for the five characteristic drought years; derived by Beersma et al. [21]

Agricultural drought damage function of Rijnland

An agricultural damage function can be derived for each regional area of the Netherlands, based on the estimated agricultural damage for the five characteristic drought years by Van Beek et al.⁸ [36]. Van Beek et al. determined the agricultural drought damage for 8 regions, all together covering the Netherlands. The damage figures of the region Zuid-Holland/Utrecht are assumed as the indicator of Rijnland's agricultural damage. This is appropriate since this research aims to expose the sensitivity of the agricultural damage.

Year	Precipitation	ipitation Discharge Agricultural		Mean return
	deficit	deficit	damage	periods
	[mm]	$[10^6 m^3]$	$[10^{6} \in]$	[year]
Average (1967)	151	445	20,2	2,5
Moderate dry (1996)	199	4.977	54,8	6,7
Dry (1949)	226	9.402	49,1	12
Very dry (1959)	352	5.373	74,2	71
Extreme dry (1976)	361	10.851	104,8	90

Table 7-3: Rijnland's agricultural damage AD_{dr} for the five characteristic drought year; derived by Van Beek et al. [36]

If the results of tables 7-2 and 7-3 are analysed, it can be concluded that contrary to the total agricultural drought damage of the Netherlands, Rijnland's agricultural damage does not linearly increase with increasing drought intensity. The year 1996 is indicated as a moderate dry year with a lower precipitation deficit and discharge deficit compared to the year 1949, but is described by a larger economical agricultural damage. This can be explained by the time variation of the maximum values of the precipitation deficit and the discharge deficit.

In this research, Rijnland's agricultural damage function will be defined as a function of the annual maximum precipitation deficit ΔP . A quadratic agricultural damage function gives a more likely description for the more extreme dry year, compared to a linear descriptive agricultural damage function (see figure 7-7):⁹

$$AD_{dr} = \underbrace{0,0003}_{\beta_1} \Delta P^2 + \underbrace{0,1612}_{\beta_2} \Delta P \tag{7-9}$$

With the regression coefficients $\beta_1 \ [10^6 \in /mm^2]$ and β_2 in $[10^6 \in /mm]$.

⁸The agricultural damage are determines with the use of the economical AGRICOM model (AGRI cultural COst Model), which is based on the hydrological results for the unsaturated zone. The AGRICOM model applies the damage concept for the financial crop yield loss [€/ha], based on the difference between the potential yield loss in a dry year and an average year [kg/ha] multiplied with the crop market price [€/kg]. See for further background appendix F.

 $^{^{9}}$ The relation is based on only annual values of five year, meaning that the relation is very unreliable.



Figure 7-7: Rijnland's agricultural drought damage as a function of the annual maximum precipitation deficit for the five characteristic drought years [21]

7-4-4 Assumption 2: Relation ΔQ to ΔP

This subsection derives the relation between the discharge deficit and the precipitation deficit. The mutual dependency of these two variables is analysed, from which a linear regression function is established.

The dependency of the precipitation deficit ΔP and the discharge deficit ΔQ is investigated by a graphical analysis of the correlation between these two parameters. Figure 7-8 shows the historical annual maximum precipitation deficit ΔP and discharge deficit ΔQ between 1906 and 2000 [20].



Figure 7-8: Correlation and dependency for the maximum precipitation deficit ΔP and the discharge deficit ΔQ for the period between 1906 - 2000 [20]

Two correlation areas can be distinguished in figure 7-8:

1. Independency of ΔP and ΔQ for: $\Delta P \leq 220 \ [mm]$ and $\Delta Q \leq 8 \ [10^9 m^3]$

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2. Dependency of ΔP and ΔQ for: $\Delta P > 220 \ [mm]$ and $\Delta Q > 5 \ [10^9 m^3]$

The derivation of the joint exceedance probability $P(\Delta P \leq \Delta p, \Delta Q \leq \Delta q)$ is discussed based on the individual exceedance probabilities $P(\Delta P \leq \Delta p)$ and $P(\Delta Q \leq \Delta q)$.

Precipitation deficit ΔP

The annual maximum precipitation deficit is best described by a Gumbel distribution, with location parameter μ of 115,2 [mm] and scale parameter σ of 49,7 [mm] derived by the maximum likelihood method¹⁰ by Beersma et al. [20]:

$$P(\Delta P \le \Delta p) = exp\left[-exp\frac{-(\Delta p - \mu)}{\sigma}\right]$$
(7-10)

Figure 7-9 gives an overview of the ordered historical annual maximum precipitation deficits with two fitted distributions. The Gumbel distribution properly fits the data best over the whole domain. The lognormal distribution gives a better description of the tail of the distribution. This research assumes the precipitation deficit Gumbel distributed, according to Beersma et al. [20].



Figure 7-9: Ordered historical observed annual maximum precipitation deficits between 1906 and 2000, with the fitted Lognormal and Gumbel distribution [20]

The annual maximum precipitation deficit $\Delta P > 200 \ [mm]$ does not represent a linear relation with the standardized Gumbel variate.

Discharge deficit ΔQ

The annual discharge deficit is also described by a Gumbel distribution with location parameter μ of 0,651 [10⁹m³] and scale parameter σ of 2,154 [10⁹m³].

$$P(\Delta Q \le \Delta q) = exp\left[-exp\frac{-(\Delta q - \mu)}{\sigma}\right]$$
(7-11)

 $^{^{10}{\}rm Maximum-Likelihood}$ method is a standard statistical method for the derivation of the parameter estimation for the most likely fit.

The discharge deficit is fitted to a Gumbel distribution and a square-root normal distribution, where both distributions are indistinguishable for discharge deficits ΔQ larger than 1,0 * 10⁹ [m^3].



Figure 7-10: Ordered historical observed annual maximum discharge deficits between 1906 and 2000, with the fitted square-root normal and Gumbel distribution [20]

Joint exceedance probability of ΔP and ΔQ

Drought events have theirs largest impact in case of both a large precipitation deficit and a large discharge deficit [20]. Therefore the joint exceedance probability of both deficits is of great interest.

The above defined univariate distributions of the precipitation deficit $P(\Delta P \leq \Delta p)$ and the discharge deficit $P(\Delta Q \leq \Delta q)$ should be combined into a bivariate probability distribution:

$$P(\Delta P \le \Delta p, \Delta Q \le \Delta q) \tag{7-12}$$

Beersma et al. [20] gives a further description of the statistical theoretical background of the joint probability distribution. The joint exceedance probability can be estimated as well for each data pair $(\Delta P_i, \Delta Q_i)$ by their plotting positions:

$$\hat{p}(\Delta P \ge \Delta p_l, \Delta Q \ge \Delta q_l) = \frac{\# \text{ pairs } (\Delta P_i, \Delta Q_i) \text{ with } \Delta P_i \ge \Delta P_l \text{ and } \Delta Q_i \ge \Delta Q_l}{C+1}$$
(7-13)

Where C is the total number of observations that the data set contains; i.e. C = 95 [-].

The joint exceedance probability for a historical characteric year with ΔP_i , ΔQ_i located on a certain damage curve (figure 7-6 is equal to number of pairs located above this damage curve divided by the total data counts in the data set C + 1. The characteristic drought year 1949 is the 3th most extreme event between 1906 and 2000 (C is 95 year), meaning that the precipitation deficit and the discharge deficit of 1949 have a joint exceedance probability $\hat{p}(\Delta P \ge \Delta p_i, \Delta Q \ge \Delta q_i)$ of 0,0521 [1/year]:

$$\hat{p}(\Delta P \ge \Delta p_i, \Delta Q \ge \Delta q_i) = \frac{2}{95+1} \tag{7-14}$$

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A precipitation deficit ΔP of 226,7 [mm] and a discharge deficit ΔQ of 9,2 * 10⁹ [m³] have an agricultural damage of 1.233 [10⁶ \in] to effect, with a return period T of about 19 [year] based on the empirical joint exceedance probability¹¹.

This empirical method is discussed for illustrational use, but will not be further implemented in this research. This research assumes a simplified situation that is described by the blue regression line in figure 7-8.

Linear regression function ΔP and ΔQ

This research focusses on the correlation of large precipitation deficit $\Delta P > 220 \ [mm]$ and large discharge deficit $\Delta Q > 5 \ [10^9 m^3]$; i.e. 2. defined correlation area, since the joint occurence of these two events has the largest drought impacts to result.

A linear regression function can describe the relation between the precipitation deficit ΔP and the discharge deficit ΔQ :

$$\Delta P = \varphi_1 \Delta Q + \varphi_2 \tag{7-15}$$

With φ_1 is $26, 3 * 10^{-9} \ [mm/m^3]$ and φ_2 is 100 [mm], based on the observed annual maximum precipitation deficit and discharge deficit between 1906 and 2000. The blue regression line in figure 7-8 is described by the regression function:

$$\Delta P = 26,3 * 10^{-9} \Delta Q + 100 \tag{7-16}$$

Theoretically, the probability density distribution of the precipitation deficit ΔP differs from the discharge deficit ΔQ over the summer semester. The precipitation deficit ΔP has its largest probability density in July and August and the discharge deficit ΔQ at the end of August and September. This assumed simplification is theoretical not justified.

7-4-5 Assumption 3: Relation D_{Cl} to ΔQ

This subsection derives a relation between the duration D_{Cl} that a Chloride concentration exceeds the standard cl of 250 [mg/l] and the annual maximum discharge deficit ΔQ . The derivation makes use of the assumptions regarding D_{Cl} and the discharge variation in course of time for a discharge wave.

The exceedance duration D_{Cl} that the Chloride concentration cl exceeds its standard of 250 [mg/l] at Gouda is only determined by the discharge variations in course of time. The influence of the water level set-up is minimal¹² and therefore for the definition of this agricultural damage sensitivity model negligible.

The exceedance of the Chloride concentration standard cl is assumed to be caused by one single trough discharge wave with peak value q_k during the summer semester. The exceedance frequency of Chloride concentration cl is equal to the non-exceedance frequency of the annual summer minima peak discharge q_k (see figure 6-5):

$$F(Cl \ge cl(q_k)) = F(Q_k \le q_k) \tag{7-17}$$

¹¹The return periods of the five characteristic drought years are derived by a theoretical joint exceedance probability distribution $P(\Delta P \ge \Delta p, \Delta Q \ge \Delta q)$, which differs for exceedance probabilities $\hat{p}(\Delta P_i, \Delta Q_i)$ for return periods larger than 10 [year] (figure 7 in [20])

¹²The water level set-up Δh [cm] only contributes to the variation of the Chloride concentration for value larger then 75 [cm], based on the simulation results of the one-dimensional SOBEK flow model. The probability density $p(\Delta h_i)$ is neglectable for water level set-up larger then 75 [cm]. See for further details chapter 6

The discharge deficit ΔQ can be assumed as a function of the exceedance duration D_{Cl} , since the annual minima summer discharge Q_{Summer} with peak value q_k is a measure for both the discharge deficit ΔQ and the exceedance duration D_{Cl} . Under the assumption that the exceedance of Chloride concentration standard cl for a duration D_{Cl} is caused by a single discharge wave with summer minima peak value q_k in year i that is a measure for the annual maximum discharge deficit ΔQ of year i.

$$F(Q_k \le q_k) \longrightarrow F(D_{Cl} \ge d_{cl}) \text{ and } F(\Delta Q \ge \Delta q)$$

(7-18)

The exceedance probability of the discharge deficit $P(\Delta Q > \Delta q)$ can be described by the Gumbel distribution (equation 7-11) or by the empirical relation for the plotting positions:

$$\hat{p}(\Delta Q_i) = \frac{\# \operatorname{rank} m \text{ of the observations } (\Delta Q_i)}{\operatorname{total} \# C \text{ of observations } + 1}$$
(7-19)

With m = 1 is the largest discharge deficit ΔQ in the observations between 1901 and 2009 (109year), which is the discharge deficit ΔQ of 12,3 * 10⁹ [m³] for the year 1921 and has a exceedance probability $P(\Delta Q > \Delta q)$ of once per 110 year; i.e. 0,0092 [1/year].

This research describes the exceedance probability of the discharge deficit $P(\Delta Q > \Delta q)$ by the empirical relation

The non-exceedance frequency of an annual summer minima peak discharge $F(Q_k \leq q_k)$ relates the exceedance duration D_{Cl} and the discharge deficit ΔQ via the factor γ :

$$D_{Cl} = \frac{\Delta Q}{\gamma} \tag{7-20}$$

The exceedance duration D_{Cl} of 15,1 [days] is caused by a trough discharge wave with peak value q_k of 845 $[m^3/s]$ with a non-exceedance frequency $F(Q_k \leq q_k)$ of 0,0577 [1/year]; i.e. about once per 17 [year]. This through discharge wave is related to a discharge deficit ΔQ with a once per 17 year non-exceedance frequency; i.e. ΔQ is 7, 4 * 10⁹ [m³]. Recall that $D_{Cl} = D_{Cl(250;q_k)}$.

Discharge	Non-exceedance	Exceedance	Discharge	Factor
	frequency	duration	deficit	
q_k	$F(Q_k \le q_k)$	D_{Cl}	ΔQ	γ
$[m^3/s]$	[1/year]	[days]	$[10^9 m^3]$	$[10^9 \ m^3/\text{days}]$
845	0,0577	15,1	7,4	0,49
790	0,0319	16,8	8,7	0,52
755	0,0208	17,9	10,5	0,58
715	0,0122	19,2	11,8	0,62
670	0,0062	20,6	12,8	0,62
620	0,0029	22,4	13,3	0,59

Table 7-4: Relation non-exceedance frequency of the exceedance duration D_{Cl} and the discharge deficit ΔQ via the factor γ

The factor γ has an average value of 0.57 [10⁹ m^3 /days](table 7-4) and therefore the discharge deficit ΔQ is described by the following function:

$$D_{Cl} = \frac{\Delta Q}{0,57} \tag{7-21}$$

7-4-6 Results Rijnland's agricultural damage

Rijnland's agricultural damage AD_{dr} can now be related to the exceedance duration D_{Cl} for varying exceedance frequencies of an annual summer minima peak discharge q_k that result in

Non-exceedance	Exceedance	Discharge	Precipitation	Agricultural
frequency	duration	deficit	deficit	damage
$F(Q_k \le q_k)$	D_{Cl}	ΔQ	ΔP	AD_{dr}
[1/year]	[days]	$[10^6 m^3]$	[mm]	$[10^{6} \in]$
0,0577	15,1	8,6	325,8	84,3
0,0319	16,8	$_{9,6}$	351,8	93,8
0,0208	17,9	10,2	368, 6	100,2
0,0122	19,2	10,9	387,5	107,5
0,0062	20,6	11,8	409,5	116,3
0.0029	22.4	12.8	436.0	127.3

F(Cl > cl) in [1/year]. Rijnland's agricultural damage AD_{dr} for the reference situation in 2015 is presented in table 7-5.

Table 7-5: Results quick scan model Rijnland's agricultural damage for the short-term situation of2015

The agricultural damage is determined as well for the long-term situation in 2050, based on the derived relations of the quick scan model for 2015. It is not of great relevance to adjust the derived relations of the short-term situation of 2015 to the long-term situation of 2050, since the developed quick scan model is a very pragmatic model and the limited amount of data $(AD_{dr} \text{ only} \text{ for 5 characteristic years})$ incorporates a high level of uncertainty. The results for the reference situation in 2050 are presented in table 7-6:

Non-exceedance frequency	Exceedance duration	Discharge deficit	Precipitation deficit	Agricultural damage
$F(Q_k \le q_k)$	D_{Cl}	ΔQ	ΔP	AD_{dr}
[1/year]	[days]	$[10^6 m^3]$	[mm]	$[10^{6} \in]$
0,9639	14,3	8,2	315,0	80,5
0,7649	16,4	9,4	346,3	91,8
0,5868	18,4	10,5	376,1	103,1
0,4644	19,9	11,3	398,2	111,8
0,3711	21,1	12,0	416,7	119,3
0,2767	22,5	12,8	438,0	128,1
0,1880	24,2	13,8	462,7	138,8
0,1196	26,0	14,8	489,8	150,9

Table 7-6: Results quick scan model Rijnland's agricultural damage for the long-term situation of 2050

7-5 Conclusions and discussions

A quick scan model for Rijnland's agricultural drought damage is developed that relates the exceedance duration D_{Cl} of Cl > 250 as a function of the annual maximum precipitation deficit ΔP and the discharge deficit ΔQ . The development of the quick scan model that derives Rijnland's agricultural damage has given the following insights:

- A direct relation between the exceedance duration D_{Cl} and Rijnland's agricultural damage AD_{dr} is complex to derive, due to the combined influence of human intervention into the system (control of fresh water distribution) and the time variation of the external salt water intrusion and the internal water supply and demand.
- The annual maximum precipitation deficit ΔP and the discharge deficit ΔQ can be assigned as the two indicators of a drought event. The joint occurrence of a large ΔP and a large ΔQ has an extreme drought to effect. The precipitation deficit has it largest probability

density in July and August and the discharge deficit has it largest probability density from August till September. This difference is neglected in this research. If not, the Rijnland's agricultural damage is less severe.

• The importance of the time variation of ΔP and ΔQ onto the economical effects of Rijnland's agricultural damage can be explained by the simulated Chloride concentrations along the Hollandse IJssel at Gouda. Simulations has been runned by an 1-dimensional Sobek flow model for the five characteristic drought years¹³ (figure 7-11 and table 7-7).



Figure 7-11: Simulated decade averaged Chloride concentration Cl in [mg/l] for the five characteristic year at Gouda 2015

Year	Precipitation	Discharge	Agricultural	Exceedance
	deficit	deficit	damage	duration
	ΔP	ΔQ	AD_{dr}	D_{Cl}
	[mm]	$[10^6 m^3]$	$[10^{6} \in]$	[days]
Average (1967)	151	445	20,2	0
Moderate dry (1996)	199	4.977	54,8	0
Dry (1949)	226	9.402	49,1	1x44
Very dry (1959)	352	5.373	74,2	3
Extreme dry (1976)	361	10.851	104,8	1x13 & 1x23

Table 7-7: Exceedance duration D_{Cl} for the five characteristic drought years derived for the summer semester 01. April - 30. September

Based on the simulated exceedance duration D_{Cl} it can be concluded that a long Chloride exceedance duration D_{Cl} only affects the damage level AD_{dr} if Rijnland's internal system is simulatenous subject to a water shortage and consequently Rijnland should take in external fresh water of the Holllandse IJssel. The year 1949 is subject to the longest exceedance duration, which resulted in a relatively low agricultural damage yield. Without a water shortage, Rijnland does not need to take in water.

Extended Sobek simulations should be executed to analyse the sensitivity of the annual time-variation of the maximum Chloride concentration Cl_{max} , the exceedance frequency F(Cl > cl) and the exceedance duration D_{Cl} for varying characteristic drought year onto Rijnland's agricultural drought damage AD_{dr} for varying characteristic drought years.

• Next to this, the uncertainty of the influence of the hydrologic conditions outside the crop growth season should be taken into account. The effects of a drought period will have a

¹³Provided by Deltares

reduced economical impact, if the previous months are characterized by an average to large amount of $\rm precipitation^{14}.$

- The results of the quick scan model suggest that the amount of Rijnland's agricultural damage $AD_{dr}(i)$ for a given exceedance duration $D_{Cl}(i)$ will not increase for the long-term situation in 2050, but the frequency of occurrence of a certain damage level $AD_{dr}(i)$ will strongly increase (tables 7-5 and 7-6).
- Further extended research of the quick scan model should be conducted to the dependency relation between the precipitation deficit ΔP and the discharge deficit ΔQ , in case the historical observations of ΔP and ΔQ are transformed to the predicted climate change effects of the KNMI'06 W+ scenario.

 $^{^{14}\}mathrm{Based}$ on the analysis of the drought characteristics of 1976 and 2003 in subsection 4-6

Chapter 8

Risk evaluation

8-1 Study context

This study aims to establish the salinity risk for a given set of scenarios (chapter 3), with salinity risk defined as the salinity probability times the salinity consequence. The determined salinity risk levels are the input for the risk evaluation phase of the risk analysis (figure 9-1).



Figure 8-1: Research outline: phase VI/VII Risk calculation and risk evaluation

A risk evaluation should investigate whether the determined salinity risk level is acceptable or not. Several decision making instruments are the basis for the risk evaluation phase. This research evaluates risk as an economic decision making problem, by means of two investment criteria:

- cost-effectiveness criteria;
- economic optimum risk level.

In the context of the drought event of 2003, it is questionable if the taken measures were costeffective. This can be analysed by an assessment of the total operation costs and the corresponding avoided damage. The drought impacts on the regional system of Mid-West Netherlands were prevented by the implementation of the measures: Kleinschalige Water Aanvoer route and the Tolhuissluis route. The total operation costs of these two measures were established at 800.000 $[\in]$. The implementation of these two measures can be stated as cost-effective, if the avoided damage is ascertained at least at 800.000 [\in]. The frequency of occurrence of a similar drought as 2003 is derived as a once per 10 [year] event; i.e. 0,10 [1/year]. In terms of risk, a minimal risk level of 2003 drought of 80.000 [\in /year] is required to indicate the implementation of the two measures as cost-effective.

It can as well be considered to accept the occurrence of drought events in the Netherlands. It can be investigated if drought is an public/private insurable risk.

This chapter describes the theory of a risk-based approach, which is implemented in this research. Chapter 9 assesses the risk-reducing effects of three measures.

8-1-1 Risk defined

Risk R is defined according to Kaplan et al. [22] as a set of scenarios s_i , each of which has a probability p_i and a consequence x_i :

$$R = \{\langle s_i, p_i, x_i \rangle\}, \text{ with } i = 1, 2, \dots, N$$
(8-1)

In relation to this research, the scenarios s_i are defined for varying exceedance durations $D_{Cl}(i)$, the probability p_i is the defined as the exceedance frequency $F(Cl > cl)^1$ for each exceedance duration $D_{Cl}(i)$ and the consequence x_i is indicated as the economical value of the agricultural drought damage AD_{dr} .

A risk curve describes the probability p_i and the consequences x_i for each scenario s_i . Every scenario results in a different risk level, expressed in a type of discrete staircase function. The actual risk should be regarded as a continuous function, i.e. a smoothed curve through the staircase curve, named the risk curve R(x) (figure 8-2).



Figure 8-2: Riskcurve [22]

8-2 Salinity risk: a yearly expected value

In the context of this research, salinity risk is defined as the probability of external salinity of the Hollandse IJssel at Gouda times the consequences of external salinity of the Hollandse IJssel at

¹If the salinity risk is based on the exceedance probability P(Cl > cl), it is highly likely that for P(Cl > cl) > 1/10 [year] multiple peaks of a discharge wave occur during a summer semester. The exceedance frequency F(Cl > cl) establishes the exceedance of the annual minima summer discharge q_k

Gouda. Risk exist in many different forms; e.g. economical risk, social risk, environmental risk. This study evaluates salinity risk in terms of economical risk. Risk can be expressed as an yearly expected value of:

- 1. exceedance duration D_{Cl} for Cl > 250 [mg/l]; i.e. YED_{Cl} in [days/year];
- 2. agricultural drought damage AD_{dr} ; i.e. $YEAD_{dr}$ in $[\notin/year]$.

The exceedance duration D_{Cl} is derived by a salinity probability model in chapter 6. The corresponding economical effects onto Rijnland's agricultural drougth damage AD_{dr} are established by a probabilistic quick scan model that derives a relation between the exceedance duration D_{Cl} and agricultural drougth damage AD_{dr} in chapter 7. The following two subsections 8-2-1 and 8-2-2 discuss the risk as a yearly expected value of D_{Cl} and AD_{dr} .

The next phases risk evaluation and risk reduction use the second method to define the economical risk; i.e. $YEAD_{dr}$ in [€/year].

8-2-1 Yearly expected exceedance duration *YED*_{Cl}

The yearly expected value of the exceedance duration for $Cl > 250 \ [mg/l]$ is equal to the area below the frequency plot for that presents the exceedance frequency $F(D_{Cl} > d_{cl})$ [1/year] for varying exceedance durations D_{Cl} [days]. Figure 8-3 and 8-4 show the area that indicates the yearly expected duration YED_{Cl} for respectively the short-term situation (2015) and the longterm situation (2050).



Figure 8-3: Frequency plot for the exceedance frequency $F(D_{Cl} > d_{cl})$ [1/year] for varying exceedance durations D_{Cl} [days] for the short-term situation (2015) of Gouda

Figure 8-4: Frequency plot for the exceedance frequency $F(D_{Cl} > d_{cl})$ [1/year] for varying exceedance durations D_{Cl} [days] for the long-term situation (2050) of Gouda

The yearly expected exceedance duration YED_{Cl} can be derived by the following equation: $YED_{Cl} = F_n * D_{Cl}(F_n) + (F_{n-1} - F_n) * \left(\frac{D_{Cl}(F_{n-1}) - D_{Cl}(F_n)}{2}\right) + \dots + (F_2 - F_1) * \left(\frac{D_{Cl}(F_2) - D_{Cl}(F_1)}{2}\right)$ (8-2)

Where YED_{Cl} is the yearly expected exceedance duration in [€/year], $F_{1,n}$ is the exceedance frequency $F(D_{Cl} > d_{cl})$ in [1/year] from 1 (largest frequency, smallest exceedance duration) to n (smallest frequency, largest exceedance duration) and $D_{Cl}(F_n)$ is the corresponding exceedance duration for each frequency.

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The general formula of the yearly expected value YEV defines the probability P_n from 1 (largest probability, smallest consequence) to n (smallest probability, largest consequence) instead of the exceedance frequency F_n . This research uses the exceedance frequency of a Chloride concentration cl; F(Cl > cl) [1/year], which is derived of the exceedance probability P(Cl > cl) via the Poisson distribution (see section 6-4-2).

The yearly expected exceedance duration YED_{Cl} is established for the short-term situation (2015) and the long-term situation (2050) by means of equation 8-2 in table 8-1:

Location	Yearly expected		
	exceedance duration		
	YED_{Cl}		
	[days/year]		
	2015 2050		
Gouda	1,0	19,4	

Table 8-1: Risk defined as yearly expected exceedance duration YED_{Cl} for the reference situation at Gouda in 2015 and 2050

8-2-2 Yearly expected agricultural damage

The economical salinity risk R can be expressed in an yearly expected agricultural damage value YEAD in [\in /year]. The yearly expected value of the agricultural damage is equal to the total area below the frequency curve of the agricultural damage AD_{dr} (figure 8-5 for the short-term situation (2015) and figure 8-6 for the long-term situation (2050)).



The yearly expected agricultural damage YEAD can be derived by the following equation: $YEAD = F_n * AD_{dr}(F_n) + (F_{n-1} - F_n) * \left(\frac{AD_{dr}(F_{n-1}) - AD_{dr}(F_n)}{2}\right) + \dots + (F_2 - F_1) * \left(\frac{AD_{dr}(F_2) - AD_{dr}(F_1)}{2}\right)$

Where YEAD is the yearly expected agricultural damage in [€/year], $F_{1,n}$ is the exceedance frequency $F(AD_{dr} > ad_{dr})$ in [1/year] from 1 (largest frequency, smallest damage) to n (smallest frequency, largest damage) and $AD_{dr}(F_n)$ is the corresponding agricultural damage value for each frequency.

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(8-3)

The yearly expected agricultural damage $YEAD_{dr}$ for the short-term situation (2015) and the long-term situation (2050) is shown in table 8-2:

Location	Yearly expected		
	agricultural damage		
	$YEAD_{dr}$		
	$[10^6 \in /year]$		
	2015 2050		
Gouda	5,7	109,9	

Table 8-2: Risk defined as yearly expected agricultural damage $YEAD_{dr}$ for the reference situationat Gouda in 2015 and 2050

8-3 Risk acceptance: economic decision problem

8-3-1 Risk attitudes

If the present reference situation will be maintained and no human intervention takes places, Rijnland is subject to an yearly expected agricultural damage of about 110 $[10^6 \\mbox{ } \mbox{ } \mbo$

Decision making processes are determined by the risk attitude of the decision makers. Risk attitude is defined as the attitude towards the investment costs and the agricultural damage reduction. The risk-attitudes are related to the way people perceive risk². There are three basic risk attitudes distinguished (figure 8-7)[54, 23]:

- 1. Risk-averse: investment costs are valued higher and agricultural damage is valued lower than they are;
- 2. Risk-neutral: investment costs an agricultural damage are valued at their present value;
- 3. Risk-prone:

investment costs are valued lower and agricultural damage is valued higher than they are;



Figure 8-7: Risk attitude spectrum; after [23]

²i.e. risk-averse, risk-tolerant or risk-seeking [23]

There are two instruments that can assess the profitability or the cost-effectiveness of a measure; i.e. a cost-benefit analysis and an economical optimization criteria. The applicability of these two instruments is discussed in the following subsections 8-3-2 and 8-3-3. This research investigates the risk reductional possibilities of three measures by means of a full risk assessment in chapter 9.

Risk reduction

If decision makers indicate the present risk level as unacceptable, the risk reductional possibilities will be investigated by means of evaluating the risk reducing effects of multiple measures. With an eye to a risk-neutral attitude, the costs and the benefits of the reference situation can be evaluated.

There exist two methods to reduce the risk:

- 1. reduce the probability of external salinity; $F(Cl > cl)_{(n)} > F(Cl > cl)_{(n+1)} \rightarrow$ intervention into the water system; e.g. redistribution of river water, reduces the exceedance frequency of external salinity of the Hollandse IJssel;
- 2. reduce the consequence of external salinity; $AD_{dr(n)} > AD_{dr(n+1)} \rightarrow$ adjustments of Rijnland's agricultural area; e.g. relocation of cultivations to salinity prone areas, reduces the agricultural damage AD_{dr} in times of salinity.

This research aims to reduce the risk of external salinity based on the first method; i.e. reducing the probability of external salinity onto the Hollandse IJssel.

8-3-2 Cost-benefit analysis

A cost-benefit analysis (abbreviated as CBA) evaluates the costs and benefits of a project. The aim of a CBA is to expose if a project will result in an increase of societal welfare; i.e. the societal benefits generated by the project should exceed the project's costs [54]. If the benefits exceed the costs, the project generates an increase of economic welfare and is indicated as attractive. A project is unattractive, if the benefits are lower than the costs [54].

\mathbf{Costs}

The costs of project are the sum of the investment cost, the management and maintenance costs. This research only considers the investment costs I in $[\in]$.

Benefits

The benefits of a measure exist of the avoided damage, which is defined as the risk reduction ΔR [\in]. The risk reduction ΔR is equal to the reduction of the yearly expected agricultural damage $\Delta Y EAD_{dr}$ discounted over a time horizon n [year].

The basic assumption of the cost-effectiveness principle is that the cost in the initial situation (r_{ef}) should exceed the total costs after completion of a project (i):

$$R_{ref} > I_i + R_i \tag{8-4}$$

The investment criteria for measure i can be defined as [54]:

$$I_i < \underbrace{R_{ref} - R_i}_{\Delta R_i} \tag{8-5}$$

Where ΔR_i is defined as the difference between the risks R_{ref} and R_i for respectively the reference situation and the situation after the implementation of measure *i*.

Appendix H outlines the different types of input effects of a CBA.

8-3-3 **Economical risk optimization**

The most cost-effective measure is the project for which the largest salinity safety level is found; i.e. largest risk reduction ΔR_i at the lowest investment costs I_i (figure 8-8):

$$\frac{d(I_i)}{d(\Delta R_i)} = 0$$
(8-6)



Figure 8-8: Economical optimum salinity safety level

Since this investigation focusses on the risk reduction by reducing the exceedance frequency F(Cl > cl), the measure with the lowest yearly expected exceedance duration YED_{cl} and so the yearly expected agricultural damage $YEAD_{dr}$ can be indicated as the most cost-effective measure.

The cost-effectiveness of three measures is analysed in chapter 9.

8-4 Salinity risk: present value

8-4-1 Theory

The economical salinity risk R is defined as an yearly expected agricultural damage in $[\in/year]$. An investment $I \in$ is an one-time cost. The yearly expected value of risk should be discounted over the investment's lifecycle time n [year] for the aim of the CBA.

The yearly expected agricultural damage can be expressed by its present value (abbreviated as PV), by which the total agricultural damage can be assessed for a certain period of n [year]. The PV is the value of total agricultural agricultural damage AD_{dr} after n [year], if each year (from 1 $\dots n$) the yearly expected agricultural damage $YEAD_{dr}$ will occur. The PV of the yearly expected agricultural damage $YEAD_{dr}$ for a finite time horizon can be derived by equation 8-7:

$$PV = Y E A D_{dr} * \left(1 - \frac{1}{(1+r)^n}\right) * \frac{1}{r}$$
(8-7)

Where PV is the present value of the yearly expected agricultural damage for n [year] in $[\in]$, $YEAD_{dr}$ is the yearly expected agricultural damage in [\in /year], r is the discount rate in [%] and n is time horizon or lifecycle in course of which the yearly expected agricultural damage should be discounted in [year].

The PV of the yearly expected agricultural damage $YEAD_{dr}$ can be derived as well for a infinite time horizon; i.e. $n = \infty$ by equation 8-8:

$$PV = \frac{YEAD_{dr}}{r} \tag{8-8}$$

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The selected discount rate r and the lifecycle n are of great relevance for the project evaluation. A higher discount rate r results into a lower PV of the yearly expected agricultural damage. A project that is evaluated based on a high discount rate r, assigns a project as less attractive in case of high investment costs at time t = 0 and reduced yearly expected agricultural damage distributed over a long future period t = 1...n.

The reduction of the total agricultural damage for n [year] can be evaluated to the investment costs of a possible measure with a lifecycle of n [year]. This next phase of the risk analysis evaluates the risk reduction ΔR in $[\in]$ of three measures that aim to reduce Rijnland's yearly expected agricultural damage $YEAD_{dr}$ in [€/year]. The Dutch government uses a design period of 50 [year] for the project evaluation of infrastructural measures, resulting in a time horizon n of 50 [year].

The discount rate r of 2,5 [%] (real risk-free)³ is adviced for infrastructural projects by the Dutch government (Eichenraam et al. [55]). A discount rate of 4 [%] has been recently applied in large water related infrastructural project⁴.

8-4-2 Evaluation present value reference situation 2015 and 2050

The PV of the yearly expected agricultural damage $YEAD_{dr}$ are established for a time horizon t = 50 [year] and for an infinite long time horizon $t = \infty$, each with disount rate r of 2,5 [%] and 4 [%] to expose the PV's sensitivity (table 8-3):

Time horizon	Discount rate	Present value	
t	r	I F	PV
[year]	[%]	[10 ⁶ €]	
		2015	2050
50	2,5	163	3.117
50	4	122	2.361
∞	2,5	228	4.396
∞	4	143	2.748

Table 8-3: The present value of salinity risk defined for the reference situation at Gouda in 2015 and 2050

The derived PV's are extremely large for the long-term situation of 2050, even for a discount rate of 4 [%]⁵. The large value of the yearly expected agricultural damage $YEAD_{dr}$ of about 110 [10⁶ \in] for the long-term situation, results from the high exceedance frequencies F(Cl > cl) [1/year]⁶ of a Chloride concentration $Cl > 250 \ [mg/l]$. The probabilistic model predicts an exceedance frequency F(Cl > 250) of once per year for an exceedance duration D_{Cl} of 14 [days] for 2050.

The quick scan agricultural damage model (chapter 7) presumes the dependency of the precipitation deficit ΔP and the discharge deficit ΔQ for large extents of ΔP and ΔQ , i.e. severe drought impacts. Besides that, the model assumes that the exceedance duration D_{Cl} and the annual discharge deficit ΔQ are related to the same discharge wave with annual summer minima peak discharge q_k . Therefore the yearly expected agricultural damage $YEAD_{dr}$ is relatively large, since it is assumed that Chloride concentration exceedance always goes along with a precipitation deficit ΔP .

³Inflation / economical growth g and a risk premium are neglected.

 $^{^4 \}rm Kosten-batenanalyse Waterkwaliteit Volkerak-Zoommeer; Kosten-batenanalyse voor Ruimte voor de Rivier; Wierringerrandmeer <math display="inline">[55]$

⁵Van Beek et al. establishes an $YEAD_{dr}$ of about 30 [10⁶ \in /year] for the long-term situation (2050), based on individual agricultural drought damage AD_{dr} which is computed for the five characteristic years with the use of the AGRICOM model [36].

⁶i.e. equal to $F(Q_k \leq q_k)$ [1/year]

The analysis of the variation of the Chloride concentration in course of time for each of the five characteristic drought years showed, that an increasing exceedance duration of $Cl > 250 \ [mg/l]$ does not directly correspond to an increasing agricultural drought damage AD_{dr} (see conclusions in section 7-5)⁷.

If this exceedance duration D_{Cl} simultaneously occurs with a precipitation deficit ΔP of 315 [mm], Rijnland is subject to an agricultural drought damage AD_{dr} of about 80 $[10^6 \in]$.

8-5 Conclusions

The risk evaluation gives the following insights:

- Salinity risk is defined as the probability of external salinity of the Hollandse IJssel at Gouda times the consequence of external salinity of the Hollandse IJssel at Gouda for the agricultural area of Rijnland. Salinity risk is expressed as a yearly expected value of for the short-term situation (2015) and the long-term situation (2050):
 - 1. exceedance duration D_{Cl} for Cl > 250 [mg/l]; i.e. YED_{Cl} in [days/year]; $YED_{Cl}(2015) = 1,0$ [days/year] $YED_{Cl}(2050) = 19,4$ [days/year]
 - 2. agricultural drougth damage AD_{dr} ; i.e. $YEAD_{dr}$ in [€/year]; $YEAD_{dr}(2015) = 5,7 [10^6 €/year]$ $YEAD_{dr}(2050) = 109,9 [10^6 €/year]$

The yearly expected value of the agricultural drought damage $YEAD_{dr}$ are relatively large for 2050. This is the effect of the high exceedance frequencies F(Cl > cl), for the exceedance of a Chloride concentration standard cl of 250 $[mg/l]^8$. The quick scan agricultural model assumes the relation between the exceedance duration D_{Cl} and the precipitation deficit ΔP , via the mutual relation with the discharge deficit ΔQ . So, the model assumes the simultaneous occurrence of D_{Cl} and ΔP . This underlies to the large yearly expected agricultural damage $YEAD_{dr}$ values for 2050, since large precipitation deficits ΔP has a large agricultural damage AD_{dr} to result.

• The assumed discount rate r and the lifecycle time n are of great relevance for the determination of the risk reduction and so the project evaluation. A project evaluation based on a higher discount rate r results in decreased risk reduction, consequently the project will be assigned as less attractive.

⁷The year 1949 was subject to a total exceedance duration D_{Cl} of 44 [days] that Cl > 250 and the year 1959 only to D_{Cl} of 3 [days] that Cl > 250, but the resulting agricultural drought damage AD_{dr} for Rijnland is established at 49 [10⁶ \in] in 1949 and 74 [10⁶ \in] in 1959

⁸An exceedance duration D_{Cl} for Cl > 250 of about 14 [days] corresponds with an once per year exceedance frequency F(Cl > 250) = 1 [1/year].

PART II CASE STUDY: SALINITY CONTROL RIJNLAND

Chapter 9

Risk reduction and control

9-1 Study context

A risk assessment incorporates the risk evaluation phase VII. This phase evaluates the established risk levels that are derived in the previous phase VI: risk, by means of decision making models. If decision makers assess the present risk level as unacceptable, the risk-reducing possibilities will be investigated by a new run of the risk analysis.



Figure 9-1: Research outline: phase VIII risk reduction and control

This research aims to study the economical salinity risks and evaluates the risk-reduction by means of economical investment criteria, which are used for the risk evaluation phase. The two examined criteria are the cost-effectiveness criteria and the economic optimum risk level, whose theory is discussed in the previous chapter 8.

This chapter will execute a risk analysis for three measures. Measures can be implemented that interfere in the international water system, national main water system and in the regional water system for the short-, mid- and long-term situation. Section 9-2 outlines these types of categorization to which measures can be addressed. Next to that, the side-effects of possible measures on the different water-related sectors¹ are discussed. Based on these theoretical categorization related to present drought studies, conceptual ideas of three types of measures are born. Section

¹i.e. agriculture, navigation, industry, drinking water and energy

9-3 to 9-5 give for each measure a conceptual system description and discussion of the technical feasibility. In section 9-6 are the probability and the consequences for each measure established, from where a measures' risk level will be evaluated in section 9-7.

9-2 Categorization drought measures

The Droogtestudie²[32] made a short list of possible measures and labelled each measure as auspicious or not. Measures in drought related studies can be distinguished by four ways:

Focus	Focus	Focus	Time horizon
water balance	intervention	Water system	
Decreasing water demand Increasing water supply	Accepting measureReactive measurePreventive measure	International water systemMain water systemRegional water system	 Short-term (2015) Long-term (2050)

Table 9-1:	Categorization	measures	drought	related	studies
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Conceptual ideas of these measures are born in recent studies [56, 43]. The project "Zoutbeperkende maatregelen Rijnmond"³ made a shortlist with auspicious measures to counteract external salt water intrusion [43]. This research will execute a risk analysis after the following three measures (overview in figure 9-2), that can be described by the following characterization:

1. Krimpenerwaard route;

Goal is to abstract fresh river water of the Lek that will be transported via the regional control area of the Krimpenerwaard polder towards the Hollandse IJssel were it will be discharged.

- Increasing water supply
- Reactive measures
- Main / regional water system
- Short-term (2015) and long-term (2050)

³i.e. in English salt reducing measures Rhine-Meuse Estuary

2. Optimization discharge distribution;

Goal is to optimize the Rhine discharge distribution over the rivers Waal and Pannerdens Kanaal to gain a seaward flowing larger Nederrijn/Lek discharge.

- Increasing water supply
- Preventive measures
- Main water system
- Long-term (2050)

3. Spui closure;

Goal is to optimize the seaward flowing fresh water volume of the Beneden Merwede via the Noord, Nieuwe Maas and Nieuwe Waterweg towards the North Sea.

- Increasing water supply
- Preventive measures
- Main water system
- Long-term (2050)

²i.e. in English Drought study

¹⁰⁶



Figure 9-2: Overview location of the three measures

9-3 Regional water system: Krimpenerwaard route

This measure focusses on an alternative fresh water supply route to the Hollandse IJssel. The following subsections 9-3-1 to 9-3-3 discuss the adaption of the present system to enable the operation of the measure Krimpenerwaard route.

9-3-1 Conceptual idea

Hydraulic Sobek simulations of the Chloride concentration variation in course of time for the year 2003 demonstrate that the entrance of the Hollandse IJssel was subject to increased Chloride concentrations till 3.000 [mg/l]. The Hollandse IJssel inlet will be subject to a Chloride concentration over 4.000 [mg/l], if the hydraulic conditions of the river discharge and the sea water level for 2003 are transformed to the KNMI'06 W+ climate change scenario. Besides, it is simulated that salt water will intrude onto the river Lek as far as the location Schoonhoven [56].

This research conducts a risk analysis for the measure Krimpenerwaard route. Alternative fresh water supply routes towards the Hollandse IJssel are under investigation. A high-opportunity measure is the water supply from the Lek via the Krimpenerwaard polder towards the Hollandse IJssel in combination with the Hollandse IJssel closure off. The simulatenous closure of the Hollandse IJssel flood defense is not included in this measure, since new insights indicate that the undesirable effects for the navigational sector⁴.

9-3-2 System description

The Krimpenerwaard polder is drained by three main pump houses (see figure 9-3).⁵ The Krimpenerwaard pump house is located along the Lek and draines the southern and eastern part of the polder. The Johan Veurink pump house at the Hollandse IJssel takes responsibility for the drainage of the western part of the polder. The remaining norther part is drained by the M. Verdoold pumphouse. The construction of a fourth pump house further upstream the river Lek can be necessary, based on the expected salt water intrusion upon to Schoonhoven [56].

⁴Personal note:V.A.W. Beijk (Rijkswaterstaat)

⁵The natural drainage flows out towards the Northwest, since the ground level declines with with 50 - 70 [cm] in northwestern direction. The water supply to the Krimpenerwaard polder is 63 [million m^3 /year] and the water discharge volume is 15 [million m^3 /year], averaged between 1991-2000



Figure 9-3: Overview Krimpenerwaard polder

9-3-3 Technical and economical feasibility

An overview of the present pumphouse characteristics should establish the technical feasibility of this present situation. A total pump capacity of 12,5 $[m^3/s]$ is available to discharge fresh water from the Krimpenerwaard onto the Hollandse IJssel. The total pump capacity along the Lek should be increased till at least 12,5 $[m^3/s]$ through the construction of an extra pump house upstream of Schoonhoven:

1. Veurink pump house

Two pump with a joint capacity of 300.000 [l/min], which corresponds with 5 $[m^3/s]$. The head difference between the polder and the Hollandse IJssel is 2,60 [m].

2. Verdoold pump house

Two pump with a joint capacity of 450.000 [l/min], which corresponds with 7,5 $[m^3/s]$. The head difference between the polder and the Hollandse IJssel is 2,80 [m].

3. Krimpenerwaard pump house

Two pump with a joint capacity of 400.000 [l/min], which corresponds with 6,7 $[m^3/s]$. The head difference between the Lek and the polder is 4,50 [m].

4. Schoonhoven pump house

Minimal required pump capacity of of 350.000 [l/min], which corresponds with 5,8 $[m^3/s]$. The head difference between the Lek and the polder is about 4,50 [m].

The effects of these current pumpcapacities are the input for the hydraulic Sobek simulaties. If the simulation results demonstrate an unsufficient reducing effect onto the salt water intrusion, new simulation should investigate the optimal pumpcapacity. The maximum available pumpcapacity is restricted by the storage capacity of the waterlopen of the Krimpenerwaard polder.

Investment costs

The Krimpenerwaard and Veurink pumphouses are recently set into operation. The construction of these pump houses is part of a large renovation project to upscale the capacity of the regional water system of the Krimpenerwaard. The costs of this measure are the sum of the construction costs of a fourth pump house and the costs for the widening of the regional main water courses and culverts.

The total investment costs I are estimated at 6 million $[\in]$ for the construction of a new pump house and 11 million $[\in]$ for the widening of the regional main water system [43].

9-4 Main water system: Discharge redistribution

This measure focusses on the optimization of the river discharge distribution over the Pannerdens Kanaal and river Waal at the Pannerdense Kop, to achieve a larger seaward flowing Nederrijn/Lek discharge. The following subsections 9-4-1 to 9-4-3 discuss the adaption of the present system to enable the discharge redistribution for the main water system.

9-4-1 Conceptual idea

The Rhine's discharge distribution over the rivers Lek and Waal has a large effect on the extent of salt water intrusion in the Rhine-Meuse Estuary (see section 5-4). The level of salt water intrusion is mainly contributed to the Rhine discharge $Q_f [m^3/s]$ for river-dominated locations that are not influenced by tidal effects $\Delta h_0 = 0 [cm]$; e.g. Gouda.

The variation of the Rhine and Lek discharge in course of time for the year 2003 is presented in figure 9-4. Extremely low values of the Lek discharge were observed during the drought period of 2003⁶, varying between 1 $[m^3/s]$ and 25 $[m^3/s]$. The weir policy S285 pursued by the weir of Driel aims to guarantee a minimum river discharge of 285 $[m^3/s]$ to the IJssel and restricts the Nederrijn/Lek discharge to 25 to 30 $[m^3/s]$, which is from now stated as the policy discharge distribution⁷.



Figure 9-4: Relation Rhine (Lobith) and Lek (Hagestein) discharge for the year 2003

Sobek simulations are conducted for both discharge distributions, to analyse the sensitivity of the river Lek discharge for the location Gouda. An exceedance of a Chloride concentration cl of 250 [mg/l] is caused by a Rhine discharge Q_f of respectively 620 and 850 $[m^3/s]^8$ for the policy discharge distribution and the historical observed discharge distribution.⁹

This statement asks for a more detailled study after the effects of a redistribution of the Rhine discharge.

9-4-2 System description

The discharge distribution can be controlled by different constructions. The cross-sectional flow area in situ the Pannerdense Kop can control the Rhine discharge over the river branches Waal

 $^{^{6}\}mathrm{i.e.}$ from mid of July to the beginning of October 2003

⁷ in case of a Rhine discharge of 600 $[m^3/s]$, a Lek discharge of 25 $[m^3/s]$ [16]

⁸i.e. remember the neglible tidal effects for Gouda and so the water level set-up $\Delta h = 0$ [cm].

⁹It can be assumed that either the Sobek model underestimates the Chloride concentrations or the policy Rhine discharge distribution for low discharges is not very likely.

and Pannerdens Kanaal. An interference of the cross-sectional flow area of the Rhine in situ the Pannerdense Kop can control the discharge division over the river branches Waal and Pannerdens Kanaal. The IJsselkop is a second location to regulate the Rhine discharge distribution over the branches Nederrijn/Lek and the IJssel.

The sensitivity of the Chloride concentration for the discharge distribution is investigated by the following two discharge distributions:

- 1. +10[%] Q_{Lek} & -10[%] Q_{Waal} Increase of 10 [%] of the Nederrijn/Lek discharge compensated by a decrease of 10 [%] of the Waal discharge (figure 9-5);
- 2. +25[%] Q_{Lek} & -25[%] Q_{Waal} Increase of 25 [%] of the Nederrijn/Lek discharge compensated by a decrease of 25 [%] of the Waal discharge (figure 9-6).

9-4-3 Technical and economical feasibility

The discharge division can be controlled at the junction of the Pannerdense Kop and the IJsselkop. A weir located at the Pannerdense Kop is able to reduce the Waal discharge and direct the extra discharge towards the Pannerdense Kanaal. A control system at the IJsselkop can only regulate the discharge over the Nederrijn/Lek and IJssel. In this case the desirable extra Nederrijn/Lek discharge should be compensated by a reduced IJssel discharge. A weir at the Pannerdense Kop can affect the discharge division at a wider control range of the total Rhine discharge (65/35 [%] instead of 22/11 [%]) and is therefore preferable. A disadvantage of the larger cross-sectional flow area at the Pannerdense Kop compared to the IJsselkop, is that it requires an increased weir size.

An adjustment of the discharge division for large Rhine discharges asks for an enlargement of the storage capacity of the river profile. In case of low Rhine discharges there are no interferences into the river profile needed. The main navigational routes should maintain a minimal flow depth, to avoid coagulation of the navigational sector. A minimal Rhine discharge Q_f of 1.020 $[m^3/s]$ (OLR) is required to guarantee the avoidance of limitations. An optimal navigation is not feasible for lower Rhine discharges, due to the reduced vessel transport load and so an required increase of the number of movements [32].



Figure 9-5: Redistribution discharge division by a reduction of 10 [%] Waal discharge and an increase of 10 [%] Lek discharge



Figure 9-6: Redistribution discharge division by a reduction of 25 [%] Waal discharge and an increase of 25 [%] Lek discharge

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This discharge distribution will be only preserved, in case of low Rhine discharges. An optimal discharge division for high Rhine discharge appeals a different discharge distribution. Extra storage capacity should be generated to preserve the large fresh water volumes of the Rhine. Therefore an increased discharge via the IJssel towards the IJsselmeer can be desirable in case the IJsselmeer can function as a large storage basin. A constructive intervention will be designed for the control of the total discharge regime. The risk evaluation is only adressed to the effect of low discharges onto the salt water intrusion

Investment costs

The investment costs I are estimated at 250 $[10^6 \in]$. This estimation is based on the constructional measurements of a control system.

9-5 Main water system: Spui closure

9-5-1 Conceptual idea

Backward salinity can have its occurence during a prolonged drought with low Rhine discharges. A simultaneous increased sea water level induces the salt water flow via the Nieuwe Waterweg towards the Oude Maas into the river branche Spui unto the Haringvliet and Hollands Diep. The term backward salinity is addressed to the backward directed flow into the Spui. Generally backward salinity has a short duration of about one or two tidal cycles.

A temporarily closure of the Spui with a flood defense is pointed as a high-opportunity measure. The effectivity of this measure onto the salt water intrusion in the Hollandse IJssel is investigated in this research. The basic assumption is that the Spui closure results in a larger seaward flowing river volume via the Oude Maas and the Nieuwe Maas to the Nieuwe Waterweg. Therefore a reduced effect onto the Chloride concentration along the Hollandse IJssel is predicted.

9-5-2 System description

Two fresh water inlets are located along the Spui; i.e Beerrenplaat and Bernisse. An exceedance of the Chloride concentration is undesirable at the location Bernisse, where a fresh water inlet of Voorne-Putten is situated. The control area of the Hollandse Delta applies a Chloride concentration standard cl of 200 [mg/l]. The inlet of Bernisse can guarantee a fresh water supply of 23.000 [l/s] to its hinterland for water level managemant, salt flushing and irrigation. Besides, the fresh water is further transported to the control area of Delfland by the Brielse Meerleiding. The capacity of this fresh water transport route is 4.000 [l/s].

The drinking water inlet of Beerenplaat is located at the Spui entrance. The drinking water supplier Evidance applies a maximum acceptable Chloride concentration of 150 [mg/l]. A Spui closure near the Oude Maas has the largest effect onto the guarantee of the fresh water supply for the both locations.

9-5-3 Technical and economical feasibility

A constructive design of a flood defense is based on the high water conditions. The hydraulic boundary conditions for the period 2006 - 2011 determine the design water level¹⁰ for a given water safety standard [47]. The Spui is situated between the dike ring areas 20 and 21, with primary

¹⁰i.e. in Dutch toetspeil



Figure 9-7: Situation inlet locations Beerenplaat and Bernisse along the river Branche Spui

flood defenses designed for a exceedance frequency of 1:4000 [year]. The equivalant design water level is $2,90 \ [+m \text{ NAP}]$.

The Spui has a flow width of 130 [m] near the junction with the Oude Maas and an averaged flow depth of -5,55 [+m NAP]. The flood defense should be designed onto a head difference of about 8,5 [m]. From a technical point of view, the flood defense should be designed for the location with the minimal cross-section. For the relevance of this study, the location of the flood defense is situated ahead of the fresh water inlet of Beerenplaat.

Investment costs

The investment costs I are estimated at 100 $[10^6 \in]$. This estimation is based on the constructional size of the Spui's flow width and head difference.

9-6 Risk

The yearly expected exceedance duration YED_{Cl} and the yearly expected agricultural damage $YEAD_{dr}$ are established for the long-term situation (2050) by means of respectively equations 8-2 and 8-3 and shown in table 9-2:

Measure for Gouda in 2050	Yearly expected	Yearly expected
	exceedance duration	agricultural damage
	$YED_{Cl(i)}$	$YEAD_{dr(i)}$
	[days / year]	$[10^6 \in / \text{ year}]$
Krimpenerwaard route	0,6	2,1
Rhine discharge distribution 10%	5,4	30,3
Rhine discharge distribution 25%	2,2	13,1
Spui closure	6,6	37,3
Reference situation <i>ref</i>	19,4	109,9

Table 9-2: Risk defined as yearly expected exceedance duration YED_{Cl} and the yearly expected agricultural damage $YEAD_{dr}$ for all three measures in relation to the reference situation for Gouda in 2050
9-7 Risk evaluation

A worst case scenario is presumed if the lowest risk reduction ΔR is computes, which is the case for a time horizon t of 50 [year] and discount rate r of 4 [%] (red labels in figure 9-3).

Measure for Gouda in 2050	Present value of salinity risk B_i [10 ⁶ \in]		Present value of salinity risk B_i [10 ⁶ ϵ]		Investment cost I [10 ⁶ \in]
Time horizon t	50 [year]		∞ [year]		
Discount rate r	2,5[%]	4,0[%]	2,5[%]	4,0[%]	
Krimpenerwaard route	60	45	84	53	17
Rhine discharge distribution 10%	859	651	1.212	758	250
Rhine discharge distribution 25%	372	281	524	328	250
Spui closure	1.058	801	1.492	933	100
Reference situation R_{ref}	3.117	2.361	4.396	2.748	-

Table 9-3: Risk evaluation; overview present value of salinity risk R_i and the investment costs I of each measure

All measures are cost-effective since for all measures counts:

$$I_i < \underbrace{R_{ref} - R_i}_{\Delta R_i} \tag{9-1}$$

Where ΔR_i is defined as the risks R_{ref} and R_i for respectively the reference situation and the situation after the implementation of measure *i*.

The Krimpenerwaard route is the economical optimum measure, with the largest risk reduction ΔR of 2.316 [10⁶ \in] against to lowest investment costs I of 17 [10⁶ \in].

$$\frac{d(I_i)}{d(\Delta R_i)} = 0,0073$$
(9-2)

Side-effects

Next to the economical investment criteria, the side-effects of measures should as well be incorporated:

» Krimpenerwaard route (calamity measure)

The Krimpenerwaard route is very attractive for both short-term and long-term, but it is questionable if the capacity of the Krimpenerwaard polder will be sufficient to transport the required water volumes for the long-term¹¹.

» Optimization discharge distribution (preventive measure)

The redistribution of the Rhine discharge is still cost-effective, but the least economic optimum of all three measures. This side-effects of this measure are of great relevance for the navigational sector, since the river Waal is the most important navigable waterway between the Rhine and the North Sea. An optimal navigation is not feasible for lower Rhine discharges, due to the reduced vessel transport load and so an required increase of the number of movements. Discussions arise which sector is prioritized in fresh water policies in times of drought, since drought damage is larger for the navigational sector compared to the agricultural sector.

» Spui closure (preventive measure)

The temporarily closure of the Spui is cost-effective, but the risk-reductional effects of this measure the lowest of the three measures. It is assumed that the salinity reduction of this measure is larger for locations along the Nieuwe Maas and Nieuwe Waterweg.

¹¹The long-term (2050) water demand of the Krimpenerwaard polder is not analysed in this study.

Chapter 10

Lessons learned

This research investigates the implementation of a probabilistic approach within the current fresh water policy of the Netherlands, which does not presume a risk-based decision-making. The main research goal of this thesis can be defined by two research objectives:

- 1. Develop a framework to assess the risks associated with external salt water intrusion into the Rhine-Meuse Estuary for the short term (2015) and the long-term (2050);
- 2. Evaluate measures to reduce the risk of external salinity for the long-term (2050), focussing on the optimization of the fresh water supply to the control area of Rijnland;

The research objectives are accomplished by the development of a salinity risk management model (chapter 2). The conclusions and recommendations for further research focus on the further development of the probabilistic salinity model and the quick scan agricultural damage model. The lack of sufficient data regarding continuous observed Chloride concentrations and agricultural damage calculations impose a causal high-level of uncertainty on this research.

10-1 Conclusions

- The extent of salt water intrusion depends on the mixing of salt sea water and fresh river water, which can be indicated by the tidal influences and riverine influences. The tidal influences describe the dispersive transport and the riverine influences describe the advective transport of dissolved salts.
- The dominance of the tide or river is location specific and determines the frequency [1/year] and the duration [days or 36-hour periods] of an exceedance period Cl > cl. The extent of external salt water intrusion is affected by the river-dominance for the location Gouda. The extent of external salt water intrusion is affected by the tide-dominance for the location Krimpen aan den IJssel, only for Rhine discharges $q_i > 1.000 [m^3/s]$. This concludes that since the tide-dominated model is applied for all discharges q_i , the tide-dominated model derives incorrect exceedance frequencies.
- The quick scan agricultural damage model assumes the relation between the exceedance duration D_{Cl} and the precipitation deficit ΔP , via the mutual relation with the discharge deficit ΔQ . So, the model assumes the simultaneous occurence of D_{Cl} and ΔP . This

underlies to the large yearly expected agricultural damage $YEAD_{dr}$ values for 2050, since large precipitation deficits ΔP has a large agricultural damage AD_{dr} to result.

- The annual maximum precipitation deficit and the discharge deficit are the two drought indicators, whose severity is a measure for the characterization of the drought. The maximum probability contribution of both indicators differs over the summer semester, which is neglected in this research. The annual maximum precipitation deficit has its largest probability density between June and August and the discharge deficit has its largest probability density between August and October.
- The results of the quick scan model suggest that the amount of Rijnland's agricultural damage $AD_{dr}(i)$ for a given exceedance duration $D_{Cl}(i)$ will not increase for the long-term situation in 2050, but the frequency of occurrence of a certain damage level $AD_{dr}(i)$ will strongly increase.
- Salinity risk is defined as the probability of external salinity of the Hollandse IJssel at Gouda times the consequence of external salinity of the Hollandse IJssel at Gouda for the agricultural area of Rijnland. The yearly expected value of the agricultural drought damage $YEAD_{dr}$ are relatively large for 2050. This is the effect of the high exceedance frequencies F(Cl > cl), for the exceedance of a Chloride concentration standard cl of 250 [mg/l].
- The assumed discount rate r and the lifecycle time n are of great relevance for the determination of the risk reduction and so the project evaluation. A project evaluation based on a higher discount rate r results in decreased risk reduction, consequently the project will be assigned as less attractive.

10-2 Recommendations

- The derivation of the exceedance probability of salinity is based on the development of two probabilistic models for tide-dominated locations and for river-dominated locations. The tide-dominated model is not applied for Krimpen aan den IJssel, which is actually not appropriate since the Krimpen aan den IJssel is a mixed tide/river-dominated location. Therefore a third probability model should be developed for locations with an equal contribution of the tide and the river, meaning that they are not tide- or river dominated.
- The assumed variation in course of time of a discharge wave includes many uncertainties. Further statistical research should be conducted after the discharge variation in course of time for varying discharge waves with peak discharge q_k ; i.e. the shape of a discharge wave. It is desirable to establish reliable exceedance durations $D_{Cl(250)}$ that can be obtained by a reliable shape of a discharge wave.
- The statistical analysis assumed a single probability distribution of the low peak river discharges and high water level set-ups for all moments during the summer semester. However, the probability distributions vary thorough the summer semester. Low river discharges have their occurrence mainly between August and October. So meaning that, further statistical research of q_i and Δh_j is recommended. For instance, statistics for bimonthly periods can be derived.
- Extended Sobek simulations should be executed to analyse the sensitivity of the annual time-variation of the maximum Chloride concentration Cl_{max} , the exceedance frequency F(Cl > cl) and the exceedance duration D_{Cl} for varying characteristic drought year onto Rijnland's agricultural drought damage AD_{dr} for varying characteristic drought years.
- The uncertainty of the influence of the hydrologic conditions outside the crop growth season should be taken into account in further research. The effects of a drought period will have a

reduced economical impact, if the previous months are characterized by an average to large amount of precipitation.

• Further extended research of the quick scan model should be conducted to the dependency relation between the precipitation deficit ΔP and the discharge deficit ΔQ , in case the historical observations of ΔP and ΔQ are transformed to the predicted climate change effects of the KNMI'06 W+ scenario.

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Appendix A

Regional measures Mid-West Netherlands in 2003

Two measures that aimed to provide Rijnland of sufficient fresh water, were implemented during the drought of 2003; Kleinschalige Water Aanvoer route (KWA) and the Tolhuissluis route (THS).

Figure A-1 gives a chronological overview of the events between 02. August and 10. October 2003.





Afterwards, discussions arise whether the operation of the two measures was cost-effective. The total operational costs of both measures were estimated at 870.000 Euro (figure A-2).



Figure A-2: Total operational cost of the Tolhuissluisroute measure and the KWA measure for all involved water board [24]

An overview of the fresh water inlets and the supply routes to provide Mid-West Netherlands of fresh water is given in figure A-3. A more detailled inpression of the supply routes of the KWA and the THS is shown respectively in figures A-3 and A-5.



Figure A-3: Overview fresh water inlets [25]



Figure A-4: Overview 'Kleinschalige Water Aanvoer' measure [26]



Figure A-5: Overview 'Tolhuissluis route' measure [27]

Appendix B

Estuary characteristics

B-1 Estuary characteristics

	Sea	Estuary	River
Shape	Basin	Funnel	Prismatic
Main hydraulic function	Storage	Storage and transport	Transport of water and
			sediments
Flow direction	No flow direction	Dual direction	Single downstream direc-
			tion
Bottom slope	No slope	no slope	Downward slope
Salinity	Salt	Brackish	Fresh
Wave type	Standing	Mixed	Progressive
Ecosystem	Nutrient poor, marine	High biomass productiv-	Nutrient rich, riverine
		ity, high biodiversity	

Table B-1: Comparison characteristics of a sea, estuary and river [28]

B-2 Gravitational circulation

Estuariene water contains a transitional density between seawater and freshwater. The salinity is defined as the total amount of solid material in grams contained in 1kg of seawater. Seawater has a salinity S varying between 34 and 36 [‰], leading to an average seawater density ρ_s of 1.025 - 1.030 $[kg/m^3]$. The North Sea contains a lower density ρ_s of 1.020 $[kg/m^3]$, as a result of the fresh water discharge. The river Rhine originates from the Swiss Alps, from where it consist of melting glacier and rain off water with a density ρ_w of 1.000 $[kg/m^3]$. Consequently a stratified system dominates the estuary, where the salt seawater intrudes under the outflowing fresh river water.

The density difference between two waterbodies induces a landward-directed hydraulic pressure gradient. Gravitational circulation is caused by the the increasing hydraulic pressure gradient with an increasing depth (see table B-2). A landward flow of dense seawater along the bottom is counteracted by the seaward flow of less dense riverwater along the surface.

INTERMEZZO: GRAVITATIONAL CIRCULATION

Hydrostatic forces balance the difference in water level Δh at the ends of the upstream and downstream ends of the salt intrusion length L. The two hydrostatic forces make equilibrium in the horizontal plane per unit width and are defined as:

$$F_1 = \frac{1}{2}\rho_1 g h_1^2$$
 with $\rho_1 = \rho$ (B-1)

$$F_2 = \frac{1}{2}\rho_2 gh_2^2 \quad \text{with} \quad \rho_2 = \rho + \Delta\rho \tag{B-2}$$

The equilibrium can be only fulfilled if the water level h1 > h2, since the density $\rho_2 > \rho_1$.

The generated momentum drives the gravitational circulation with the arm of the momentum $\frac{\Delta h}{3}$, since the two hydrostatic forces are of equal magnitude but function along a different line of action. The gravitational circulation drives vertical mixing processes. The moment per unit volume of water per unit width equals:

$$M = \frac{1}{12} \frac{d\rho}{dx} gh^2 \tag{B-3}$$



Figure B-1: The balance of hydrostatic pressure over a reach of salt water intrusion. After the hydrostatic forces make horizontal equilibrium, a momentum of forces remains driving vertical circulation and mixing [28]

Table B-2: Intermezzo: Gravitational circulation

Appendix C

Rhine and Meuse catchment area

C-1 Rhine catchment area

The Rhine originates from the Swiss Gotthard glacier and flows over a length of 1.320 [km] before discharging into the North Sea. The catchment area of the river Rhine has a surface area of 185.000 $[km^2]$, where only 25.000 $[km^2]$ belongs to the Netherlands. The Swiss part of the Rhine (Hochrhein in figure C-1) is mainly composed of ice water, resulting in high water levels during the spring and early summer season due to temperature rise. The German catchment area of the Rhine exists of a few tributary rivers, as the Neckar, Main and Moselle, that flow into the Rhine. These tributary rivers are mainly supplied by run-offs of the low lying German mountain area, causing high water levels in the winter. These two sources provide a annual averaged discharge of 2.200 $[m^3/s]$ and a lower summer averaged discharge of 1.985 $[m^3/s]$ at Lobith [57]. Due to the season flow pattern, low river discharges and water levels generally occur between August and October.

C-2 Meuse catchment area

The Meuse originates from the Plateau of Langres and flows over a length of 875 [km] before discharging in the North Sea (figure C-2). The catchment area of the Meuse covers 36.000 $[km^2]$. The river water is mainly composed of run-offs, causing high water levels in the winter and low water levels in the summer and early autumn. The Meuse flows over a length of 250 [km] within the Dutch catchment area with an annual average discharge of 230 $[m^3/s]$ and a summer discharge of 110 $[m^3/s]$, before discharging via the Bergsche Maas and the Nieuwe Waterweg in the North Sea.



Figure C-1: International catchment area of the river Rhine [29]



Figure C-2: International catchment area of the river Meuse [30]

Appendix D

Nationale Verdringingsreeks

Figure D-1 shows the National Verdringingsreeks, existing of four categories. Within categories 1 and 2 exist a prioritizing order and within categories 3 and 4 exist mutual prioritizing based on the least possible economical social damage.

Category 1	Category 2	Category 3	Category 4
Safety and the	Public facilities	Small-scale first-rate	Remaining interests;
prevention of		utilization	(both economical and
irreversible damage			environmental reflexion)
1 Stability of flood	1 Drinking water	* Temporarily irrigation	* Navigation
defenses	provision	of capital intensive	* Agriculture
		cults	
2 Settlement and	2 Energy provision	* Process water	* Nature (as long as no
subsidence (of peat			irreversible damage
and upland moor)			occurs)
3 Nature (committed to			* Industry
the soil			* Water leisure pursuits
characteristics)			
			* Lake fishing

Figure D-1: National Verdringingsreeks [5]

Category 1: Safety and prevention of irreversible damage

In case of water shortage, the highest priority has been addressed to the protection of flooding and the counteraction of irreversible damage (to natural resources). Water shortage in dry periods may lead to failure of flood defenses, as was the case in Wilnis in the summer of 2003. If the water level in the polder lowers, the peat layers of a dike body will dry out with the consequence of soil subsidence. Damage of natural resources can only be a result due to the water supply from outside the dikering or due to the drying out of beken and sloten.

Category 2: Public facilities

Sufficient drinking water and energy supply are socially important. Sufficient energy supply can be only guaranteed by sufficient cooling water. It might be surprising that drinking water has not the first priority since it is a matter of life and death. This choice has been based on the fact the problems due to the failure of flood defenses causes way larger problems than the insufficient drinking water. The storage volumes of drinking water are large enough to not expect any problems with respect to drinking water for human consumption. The energy supply has only a high priority if problems might be expected with the supply consistency. In case of any commercial interest, this has been included in category 4.

Category 3: Small-scale first-rate utilization

If there is the option to prevent a lot of damage with the use of a small water volume, this can be addressed to category 3. This category will be prioritized in case of preventing social consequences as firm bankruptcy, due to large scale damage. Examples are temporarily irrigation of expensive crops or the water use needed for the industry production.

Category 4: Remaining interest; Economical (environmental) decision

This category includes the remaining interests. Within this category takes place an economical evaluation, based as well on social criteria. The available water will be distributed to the sector with the most social damage may be prevented.

Appendix E

Description types of agricultural damage

The influence of the negative effects onto the occurence of agricultural damage will be described on the basis of these three types of damage [31]. A drought study for Mid-west Netherlands [31] derived an indication of the agricultural damage for varying drought characteristic years. This damage figures are based on the WB-21 climate change mid-scenario for 2050. These scenarios describe the former insights ahead of the KNMI'06 scenarios.

Drought damage

A yield reduction is the effect of a crop evaporation reduction. A decreased soil moisture puts a brake on the crop growth that can finally result in crop perishing. A drought damage function expressed drought damages as a function of the waterquantity deficit underlying to the evaporation reduction.



Figure E-1: Drought damage in $[\in/ha]$ for a characteristic dry year (1949) and an extreme dry year (1976) for the reference situation 2050 (based on WB-21 climate change mid-scenario) [31]

Wet damage

A yield reduction is the effect of a over saturated soil, due to excessive groundwater tables, excessive groundwater volume and a poor machinable agricultural areaal.



Figure E-2: Wet damage in [€/ha] and physical yield reduction in [%] for the reference situation 2050 (based on WB-21 climate change mid-scenario) [31]

Salt damage

A yield reduction is the effect of a excessive Chloride concentration at in the soil. Seepage and irrigation with salinated surface water are the two suppliers of salinated groundwater. A high osmotic soil pressure reduces the crop's ability of soil moisture absorption. A salt damage function expressed the salt damages as a function of the Chloride concentration present in the soil and in the surface water.



Figure E-3: Salt damage in [€/ha] for a characteristic dry year (1949) and an extreme dry year (1976) for the reference situation 2050 (based on WB-21 climate change mid-scenario) [31]

Salt damage is about 1 [%] of the drought damage in $[\in/ha]$. Salt damage is only a minor component of the total agricultural damage in a hydrologic dry year, since the current fresh water policy aims to implement salt flushing by fresh water and to refuse the intake of salinated water

into the system [52]. The damage effects of water supply surplus are slightly lower compared to the effects of a water supply deficit.

Description types of agricultural damage

Appendix F

Agricultural characteristics Rijnland

The location and object characteristics are the input for a damage assessment. The location and object characteristics of Rijnland subject to agricultural damage are the location of different agricultural areas and their crop type specific (object) characteristics.

The agricultural area of Rijnland is composed of six main crop cultivations, located within the whole control area (table F-1). An overview of the crop type specific market value of the potential yield concludes that bulb farming, glasshouse horticulture, floriculture and arboriculture have their largest contribution to Rijnland's agricultural yield.

Rijnland	Crop cultivation	Potential yield	Agricultural area
area		market value	
[-]	[-]	$[\in/ha]$	[ha]
Haarlemmermeerpolder	Mais	1.000	256,9
Haarlemmermeerpolder	Potatoes	2.500	2143,5
Polder de Noordplas	Mais	1.000	194
Polder de Noordplas	Potatoes	2.500	584,4
Bollengebied	Flower bulbs	20.000	3085,4
Aalsmeer	glasshouse horticulture	250.000	238
Roelofarendsveen (Alkemade)	glasshouse horticulture	250.000	142,3
Boskoop (Oude Rijn)	Floriculture	280.000	280
Boskoop (Oude Rijn)	Arboriculture*	225.000	280
Boskoop (Gouwe)	Floriculture	280.000	17
Boskoop (Gouwe)	Arboriculture*	225.000	17
Boskoop (Oude Rijn)	Floriculture	280.000	290
Boskoop (Oude Rijn)	Arboriculture*	225.000	290

Table F-1: Location and object characteristics of Rijnland indicated by the agricultural area in [ha] and the crop type specific potential yield market value [e/ha]; *) Arboriculture is the tree cultivation in the soil [58]

The yield reduction factor is a crop type specific factor that distinguishes the yield loss due to drought α_{dr} and the yield loss due to salt α_{sa} . Grass, potatoes and mais are more drought sensitive compared to the more irrigated capital-intensive cults which are more salinity sensitive (figures F-1 and F-2).



Figure F-1: Drought yield damage factor α_{dr} for the crop cultivations of Rijnland derived for the drought characterisitcs of 1949 and 1976 [31]



Figure F-2: Salt yield damage factor α_{sa} as a function of the Chloride concentration in the root zone for varying crop cultivations [32]

As stated before, drought damage and salt damage are substituable since salt damage includes only about 1 [%] of the total agricultural damage. The model takes into account the external available water quantity and water quality at the Hollandse IJssel, but excludes the water quality of the internal surface water. A farmer will not irrigate with salinated water, but the salt yield reduction factors of the AGRICOM model assume a summer semester continuous irrigation independable of Rijnland's water quality. The model includes the obstruction of the external water inlet at Gouda caused by unsufficient water quality conditions of the external water of the Hollandse IJssel [31].

Derivation economical loss of crop yield

Agricultural crop damage is defined as the reduction of the potential physical crop yield. The potential physical crop yield is the yield under optimal growth conditions, without negative influences through drought-, wet- or salt damage in [kg/ha]. The actual physical crop yield is real yield under the actual growth conditions. [33]. The agricultural sector presume an average actual crop yield, which is defined as the feasible crop yield once per two years. The financial crop yield loss in [€/ha] is the product of the crop market price in [€/kg] and the difference between the potential and the actual physical crop yield in [kg/ha].

The cost and benefits for the agricultural sector can be determined by the economical AGRICOM model (AGRI cultural Cost Model), which is based on the hydrological result for the unsaturated zone. Four economical damage concept can be distinguished [33]:

- 1. Loss of financial crop yield; 'Above average yield loss'
- 2. Loss of financial crop yield; 'Below average yield loss'
- 3. Loss of welfare
- 4. Loss of welfare adjusted for the production costs



Figure F-3: Economical agricultural damage concepts [33]

The current AGRICOM model applies a damage concept, where the financial crop yield loss in $[\in/ha]$ is the product of the crop market price in $[\in/kg]$ and the difference between the potential and the actual physical crop yield in [kg/ha] (left part figure F-3). This concept is described by two approximation; an above average yield loss (difference between the *potential* yield loss in a dry year and an average year) and a below average yield loss (difference between the *actual* yield loss in a dry year and an average year) (figure F-4).



Figure F-4: Two methods for the determination of the economical loss of the crop yield; Damage I is the above average yield loss and Damage II is the below average yield loss; PY is potential yield and AY is actual yield. [32]

New insights of Kind et al. [59] establish the economical agricultural damage is the loss of welfare, i.e. the sum of the consumers surplus and the producers surplus. A percentage of the loss of the financial crop yield can be averted on to the consumers, through the shift of market price between the actual and the potential crop yield (middle part figure F-3). A third damage concept takes the variation of the variable production costs into account. For instance a crop yield reduction in a dry year results in a welfare loss, which can be reduced by a decrease of the producers surplus through a change of the irrigational costs (right part figure F-3). The third concept minimizes the loss of total welfare.

Agricultural characteristics Rijnland

Appendix G

Water balance

A water balance describes all the ingoing and outgoing flows of a water cycle. A water system is a defined bounded domain with several appearances; e.g. ocean, river basin, polder etc. The general form of a water balance is based on the water budget concept [4]:

$$\frac{\Delta S}{\Delta t} = I(t) - O(t) \tag{G-1}$$

Where $\frac{\Delta S}{\Delta t}$ is the rate of change in storage of the considered control volume in the system over a finite time step $[m^3/s]$, I is the inflow $[m^3/s]$ and O is the outflow $[m^3/s]$.

A water balance gives insight if the water demand meets the water supply. If this situation exist, the water system is balanced and $\frac{\Delta S}{\Delta t} = 0$. Mostly the system is unbalanced, resulting in an increase $(\frac{\Delta S}{\Delta t} > 0)$ or a decrease $(\frac{\Delta S}{\Delta t} < 0)$ of the storage volume (see figure G-1).



Figure G-1: Overview water budget concept

In subsection 4-6 is the definition of a characteristic dry year introduced. The intensity of the drought is positive correlated with the water supply deficit. The water supply deficit will increase

with an increase severity of drought. This concept will be further implementated in chapter 7.

The general water balance can be further specified into a horizontal and a vertical water balance. These subbalances represent respectively the horizontal and the vertical flows of a water system.



Figure G-2: Human interference in the global water cycle; after [4]

The horizontal water balance refers to the supply (IN) and discharge (OUT) of water at the boundaries of the system.

$$\frac{\Delta S}{\Delta t} \leftrightarrow = Q(t) + C(t) \tag{G-2}$$

Where
$$C = U_s(t) + U_g(t) - R_s(t) - R_g(t) + H$$
 (G-3)

Where C is the net water consumption due to water use, which is the rainwater harvesting (H) plus the difference of the intakes from surface (U_s) and groundwater (U_g) and the return flows to surface (R_s) and groundwater (R_q) . Q is the runoff from land to a waterbody or ocean / sea.

The vertical water balance is mainly given by the difference between precipitation (P in $[m^3/s]$)and evaporation (E in $[m^3/s]$):

$$\frac{\Delta S}{\Delta t} \ddagger P(t) - E(t) \tag{G-4}$$

Where
$$E = T + I + O$$
 (G-5)

Where the total evaporation from land surface (E) is given by the sum of the transpiration (T), interception (I) and the open water evaporation (O).

Appendix H

Input effects Cost-Benefit Analysis

A cost-benefit analysis (abbreviated as CBA) evaluates the costs and benefits of a project. A CBA can take into account different types of effects, which can be classified to [60]:

(non-)monetary direct effects \leftrightarrow (non-)monetary indirect effects

This research will only incorporate economical effects; i.e. the direct and indirect monetary effects. The risk reductional effects of a measure are based on the investment costs and the maintenance and management costs of a measure. The maintenance and management costs are not evaluated within this research. An extended CBA can evaluate the following effects, which can be adressed to the stated four types of effects (table H-1):

	Monetary	Non-monetary
Direct	Investment civil structures	Safety
	Maintenance & management	Experience and social damage
	Tangible and economical damage	Spacial quality
	Shifting land-use	Environment
Indirect	Recreation	Social relocation effects
	Economical redistribution effects	Governmental variation

Table H-1: Example classification direct and indirect effects [61]

In the context of salinity studies, a clarification of the types of effects is given, to understand the wider notion of a CBA.

Direct vs. indirect effects

Direct effects come accrue directly to the watermanager and the contractor or the users. Investment costs and management- and maintance costs and the accompanying project benefits as e.g. extra safety, reduced damage, improved water quality can be characterized as direct effects. Indirect effects result from direct effects and mostly concerning suppliers and consumers of affected businesses. Indirect effects can be estimated with the use of the relation between the involved economical sectors, which is known as the multiplier. Indirect effect are known as well as multipliereffects. An example of an indirect effect is an economical loss in the region Rijnland due to the relocation of production factors to a less salinity-prone region B [61].

The distinction between a direct and an indirect effect can be understood with the following

example. A direct effect is the economical damage for a farmer due to an yield reduction of the crop cultivation. Because of the yield reduction, the consumer pays a higher price in the super-market. This is known as an indirect economical effect.

Monetary vs. Non-monetary effects

An economical evaluation can be executed, if all effects can be expressed with a monetary value. Drought and salt water intrusion result in monetary direct and indirect effects on the economical system. These effects can be expressed quantitative via a market price per unit per year. Monetary effects can be made comparable by the costs and benefits over the time.

Social and environmental effects are difficult to express in units and therefore not able to trade on the market. These effects are indicated as non-monetary effects.

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