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A RISK-BASED METHODOLOGY FOR FRESHWATER MANAGEMENT: MANAGING SALINE AND FRESHWATER INTERACTION IN THE RHINE-MEUSE ESTUARY IN THE NETHERLANDS

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ABSTRACT

Freshwater supply is of paramount importance to deltas everywhere around the world and is of substantial economic interest as well. Situations with water shortages, in which damage incurred owing to insufficient water, occur on regular basis. Water shortages will be more prevalent in future due to climate change, and resulting damage will increase due to the fact that droughts will become more severe and persistent and due to social-economic developments. In other words: the 'drought risk', defined as the product of the probability of a drought event happening multiplied by the consequences of the drought event, is increasing. Present-day decision-making processes in freshwater management are still very much based on deterministic considerations. There is a strong wish to make uncertainty and risks involved in freshwater management practice more explicit. This paper introduces an approach to help quantifying drought-related risks by considering jointly the probability of drought-related hazard events and the consequences of these hazard events. The potential of this risk-based approach is illustrated with a case study in the Netherlands, namely the Rhine-Meuse Estuary where water deficits frequently occur due to the joint occurrence of low river discharges and severe salt water intrusion.

Keywords: drought, water shortage, freshwater management, climate change, uncertainty, risk management

1. INTRODUCTION

In recent times it has been observed that delta regions world-wide encounter problems resulting from freshwater scarcity and corresponding deficits. Drought events in Europe in recent summers (for instance in Rhine River basin in the Netherlands in 2003, in the Po River Delta in Italy in 2012, in the Ebro River delta in Spain in 2005-2008 and 2012), and drought events outside Europe (in the Amazon River delta in 2005 and 2010, in the Sacramento-San Joaquim delta in California, USA in 1976, 1977, 1987-1994 and 2007-2009, and in the Yangtze river delta in China in 2006 and 2011) are just a few examples to demonstrate how vulnerable delta societies are to severe water scarcity.

Water scarcity may bring along negative consequences for various sectors, viz. agriculture, transport, industrial and energy, and may also induce problems for other societal interests such as nature, drinking water supply and public health. Large uncertainties in future climate change and socioeconomic developments impose an extra challenge on delta societies to prevent possible consequences arising from drought events in the future. Delta regions are expected to become more prone to periods of reduced water supply as average global temperatures rise. Due to climate change, droughts will become more severe and persistent (Forzieri et al., 2014, EEA, 2012 and EEA, 2009, see Figure 1).The impacts of droughts will become even more apparent as a result of socioeconomic developments entailing extra water consumption.

Freshwater scarcity in dry periods exhibits a large range of uncertainty resulting from inherent uncertain conditions, such as: river discharges, salt water intrusion and water storages in soil and in the surface water system. Additionally, the consequences of insufficient freshwater supply depend on the uncertain needs of the end users/sectors (and sometimes also on duration and seasonal period in which water shortage occurs). Future climate change and socio-economic developments make delta societies even more susceptible to water scarcity arising from drought events. Consequently, drought-risks are expected to increase, making water resource management decisions even more difficult than they already are. As a result, making decisions regarding freshwater assignment is becoming increasingly more complex.

Present-day decision-making in freshwater management is still very much based on deterministic considerations. For example, freshwater distribution is often executed according to a prearranged ranking system (a water hierarchy scheme), if a river discharge drops below a critical low level. This is in fact a fixed freshwater assignment, wherein damage and risks that would ensue as a consequence of drought is not considered. Various measures to cope with freshwater scarcity and to reduce damages due to deficits could be defined, including controlling water flows and salt water intrusion in major waterways, defining alternative water assignment rules, implementing local infrastructural solutions to supplement flows, and local adaptations by end-users. Whether these measures compensate damage resulting from deficits in a cost-efficient way remains rather unclear. In the present-day practice, these cost-benefit considerations are often not made explicit.

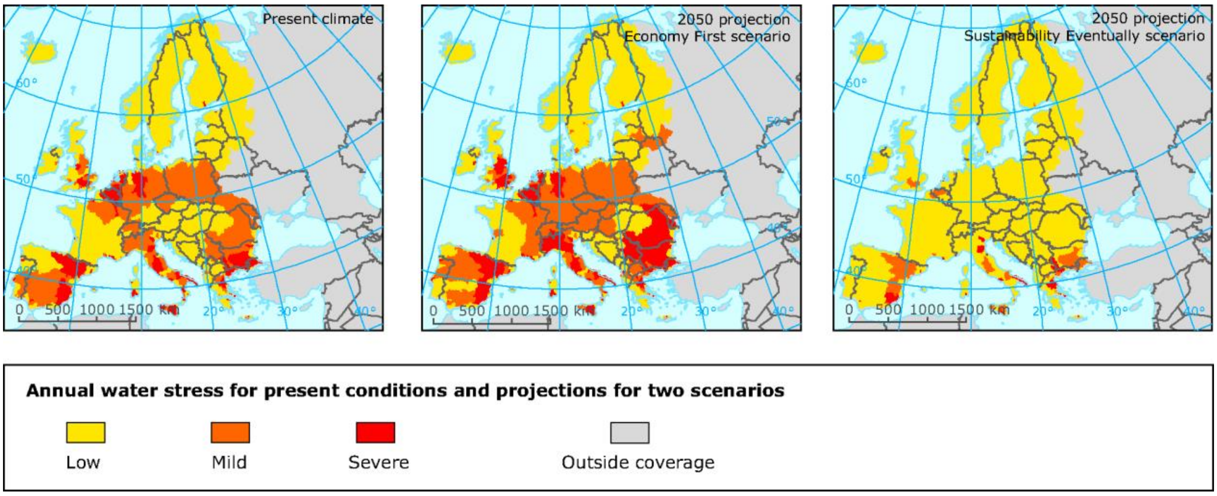

Figure 1. Annual water stress for present conditions and projections for two scenarios (EEA, 2012)

Consequently, there is a strong wish to make uncertainty and risks involved in freshwater management practice more explicit. This helps to determine the possible favourable or adverse impact of (prevention or mitigation) measures to cope with freshwater scarcity in terms of risk reduction. This paper presents the development of a methodology, enabling an assessment of drought-risks, in order to support decision making in freshwater management. The new methodology takes into account uncertainty and consequences resulting from inherent uncertain conditions, such as: (1) freshwater supply from river basins, salt water intrusion and freshwater storages in soil and in the surface water system, and (2) water needs of end users/sectors.

The risk-based methodology can help to

1. evaluate the impact of climate variability and socioeconomic developments on drought-related risks;
2. assess the cost-efficiency of measures to try to prevent water scarcity and mitigate drought damage; and in the end
3. develop strategies to better deal with drought-related risks.

The risk-based methodology is illustrated with a case study in the Netherlands, namely the Rhine-Meuse Estuary. In the Rhine-Meuse Estuary water deficits frequently occur due to the joint occurrence of low river discharges and severe salt water intrusion. The paper is organized as follow. Section 2 starts with an introduction of the risk-based methodology. Section 3 presents the results of the case study; conclusions and recommendations follow in Section 4.

2. METHODOLOGY FOR RISK-BASED FRESHWATER MANAGEMENT

2.1 Description of the methodology

As mentioned in Section 1, decision making in freshwater management is currently based on deterministic considerations. A risk-based approach to support freshwater management is rather new. As quantifying and dealing with risks has become already a more common practice in flood management (Jonkman et al., 2004, 2008, 2009, 2011; Douben et al. 2007, Stijnen et al. 2008), this experience is used when developing the risk-based approach for freshwater management. According to flood risks, drought risk is defined as the product of the probability of a drought event happening multiplied by the consequences of the drought event. In general, three major components can be distinguished in the risk-based approach: (a) risk assessment, (b) risk evaluation and (c) risk management.

Risk assessment is an important component in the risk-based approach as it forms the basis for risk evaluation and risk management. Figure 2 provides a conceptual framework for the quantification of drought-related risks resulting from water scarcity. The assessment of drought-related hazards will consist of a quantification of risks by considering the (i) probability of drought-related hazard events in the presence of current and possible future climate changes, (ii) the impact of these events on water supply/availability, (iii) the water demand of end users, (iv) the resulting water shortage and (v) the consequences for the various end-users, yielding (vi) a so-called risk profile. Quantification of uncertainties relating to ranges of possible future states of water shortage is necessary to obtain a better understanding of what might happen, and to be able to quantify consequences in terms of e.g. economic impacts, ecological damage, etc.

Freshwater scarcity reflects the imbalance that arises from an overexploitation of water resources, caused by water consumption being significantly higher than the natural availability (Van Loon and Van Lanen, 2013). Freshwater scarcity can bring along negative consequences for various end-users such as the agricultural, transport, industry and energy sectors, which all rely on sufficient freshwater. Water scarcity may also induce problems for other societal interests such as nature, drinking water supply and public health.

To determine the probability of occurrence of water shortage, information about water availability and consumption is required. Freshwater could be available from the main water system (i.e. river basins), from the regional water system (i.e. surface water and ground water system) and from the end-user itself (i.e. local facilities or water reservoirs). Regarding water availability it is important to determine the statistics of water supply of a certain water quantity and quality, at a certain location and at a certain point in time.

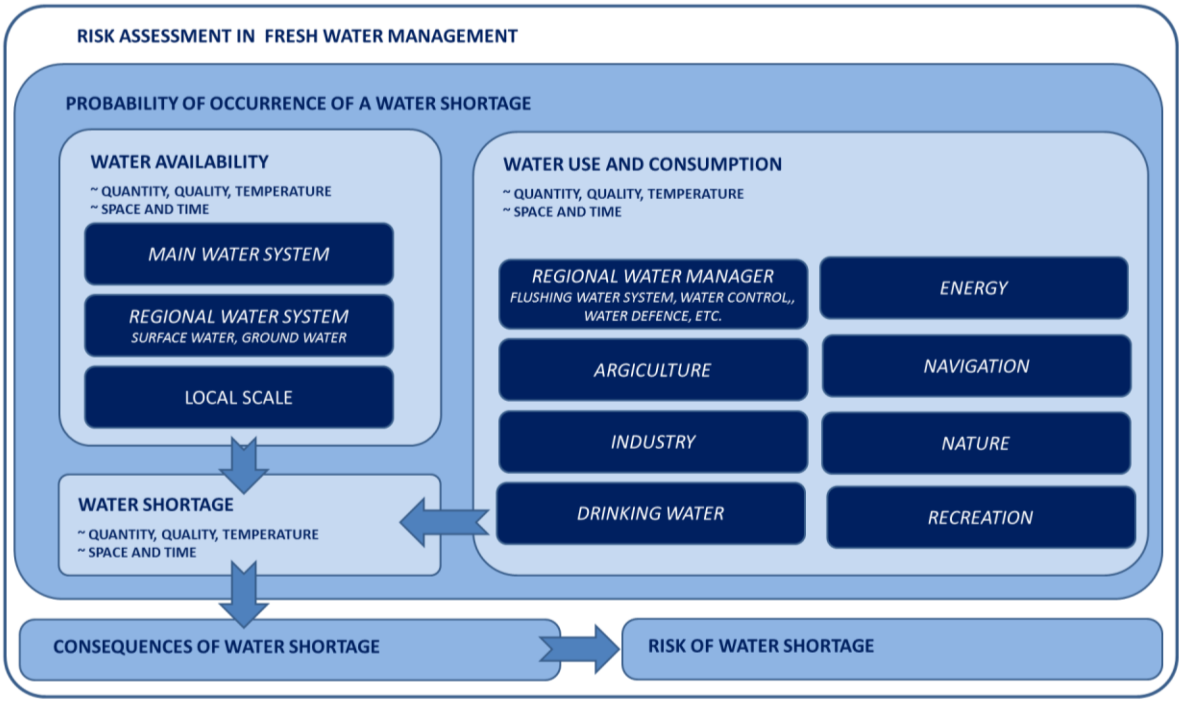

Figure 2. Conceptual framework for the quantification of risks resulting from freshwater shortage.

We recommend three techniques to derive the statistics of freshwater availability. The three of them are aimed at describing the water scarcity using multivariate probability distribution functions with the appropriate dependence patterns (Grimmett & Stirzaker, 1992, Shapiro & Wilcox, 1996, Coles & Tawn, 1991, Coles et al., 1999).

- Resampling techniques (Efron, 1982, Fan & Wang, 1996, Lall & Sharma, 1996, Rajagopalan & Lall, 1999). This approach turned out to be useful for assessing statistics of discharge events in the Rhine river. The Dutch KNMI developed a method to synthesize discharge time series (of thousands years duration) using Nearest Neighbour resampling of historical data about rainfall and evaporation events in the Rhine catchment.
- Dependence modelling through copulas. Copulas are actually multivariate probability distributions that allow flexible models for (complex) dependence patterns. State of the art techniques are described in Joe (2014). The approach could consist on assembling a (possibly complex) dependence structure for the random variables of interest through decomposing the joint distribution in bivariate pieces.
- Structured Expert Judgment (SEJ). The main feature of the classical model for SEJ is that experts are evaluated as uncertainty assessors through so called “seed” or “calibration” variables. Experts performing better on the set of seed variables will have higher weight on a pooled opinion. See for example Cooke (2008). Regarding to climate change, SEJ has been recently used to model future sea level rise from ice sheets (Bamber, 2013; Cooke, 2013).

Also, the statistics of the water demands by the various end-users need to be expressed. The water demand often exhibits a seasonal dependency and drought damage occurs only if during a certain seasonal period for a certain duration unsufficient water of certain quality is available. The probability of occurrence of water deficits can be combined with the consequences of water deficits, in order to determine the risks resulting from water shortage. It is still difficult to determine the consequences of water deficits. In principle, the degree end-users suffer from water deficits largely depends on (i) location, (ii) point in time of shortage, (iii) size and duration of the shortage, (iv) sensitivity of the end-user to shortage, (v) degree in which mitigation measures are possible and (vi) price-elasticity effects.

The resulting information about drought-related risks forms the basis of **risk evaluation**. The availability of freshwater required for drinking, agriculture, industries, ecosystems and subsistence will frequently be at stake. The risk-based approach enables an evaluation of the impact of climate variability and/or socioeconomic development on drought-related risks.

Risk assessment and evaluation can serve as a starting point for new **risk management** strategies, including risk adaptation and mitigation. The overall risks resulting from drought-related events can be reduced by measures at different scales: river basin, regional water system, and local. An inventory of measures to address water shortages is part of this step in the risk-based approach. First, individual measures should be identified and assessed at various scale levels such as (1) measures at river basin scale, (2) measures at regional scale or (3) measures at local scale. Next, risk management strategies can be defined, including combinations of these individual measures. A risk-based approach can subsequently help to assess the cost efficiency of counter measures to cope with droughts, which will help prioritise and choose operational and strategic actions and investments.

3. CASE STUDY

We demonstrate this risk-based methodology using the case study of the Rhine-Meuse Estuary in the Netherlands. The risk-based methodology is used to develop a salinity risk management model. The methodology helps to identify, qualify and evaluate the risk associated with salt water intrusion for adjacent regional water systems that extract water for multifunctional use (e.g. for agriculture, drinking water, industry, nature, ecology) from the Rhine-Meuse Estuary. The methodology enables to analyze the risk reducing effects of measures to cope with salt water intrusion. For the purpose of illustration, the impact of three measures to cope with salt water intrusion risks has been assessed.

3.1 Description of the case study

The Rhine-Meuse Estuary is a river delta in the Netherlands formed by the confluence of the Rhine and the Meuse. The Rhine-Meuse Estuary is a tidal area where the rivers Rhine and Meuse meet the North Sea. The Rhine-Meuse Estuary is affected by the marine influences of the North Sea and the riverine influences of the rivers Rhine and Meuse. The Rhine is a large river in Western Europe, with a total length of 1,320 km. It originates in the Alps in Switzerland as a snowmelt-fed mountain river and eventually debouches as a rain- and snowmelt-fed lowland river in the North Sea in the Netherlands. At the German - Netherlands border, the river splits into its three main branches: the Waal, the Nederrijn and the IJssel. The Nederrijn, further downstream called Lek, continues in Western direction and is connected to the Rotterdam port canal. The southern branch, the Waal, flows in western direction as well. Near Dordrecht it splits in several branches and feeds a large estuary with four interconnected branches. A smaller river, the Meuse is debouching in the same estuary. Figure 2 illustrates the location of the Rhine-Meuse Estuary.

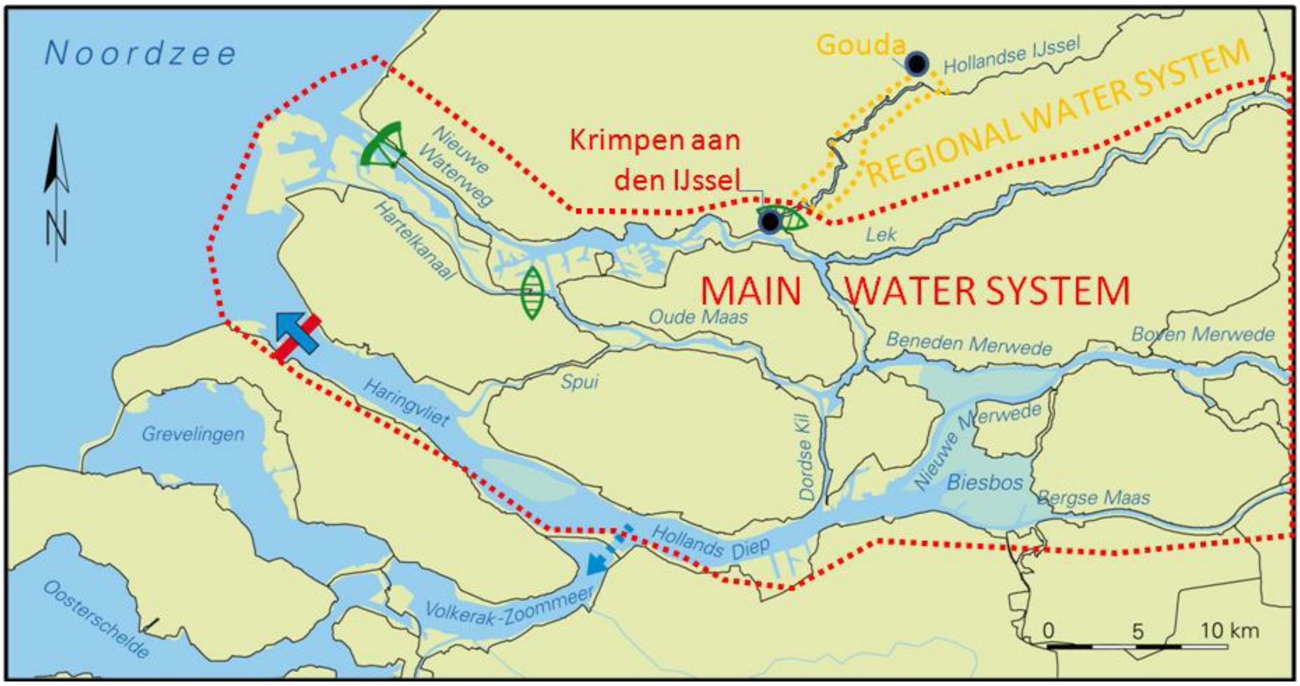

Figure 2. Study area: (1) the Rhine-Meuse Estuary, (2) two selected sub-areas (a subarea in the main water system and a subarea at the boundary of the main water system and an adjacent regional water system), (3) the location Krimpen aan ded IJssel and (4) the location Gouda.

The Rhine-Meuse Estuary is affected by salt water intrusion from the North Sea. The level of the salt water intrusion is related to the degree of mixing between the salt sea water and the fresh river water. In the Rhine-Meuse Estuary, salt sea water penetrates into the main water system via the Nieuwe Waterweg, the Nieuwe Maas and Oude Maas. The fresh water discharge of the rivers Rhine and Meuse acts as a counter pressure to prevent the penetration of the salt sea water during high tide. As a result of climate change, salt water intrusion will become more severe and persistent due to higher frequency of occurrence of low river discharges in combination with an expected sea level rise. The control of salinity concentrations is necessary to protect the fresh water inlets from salt water intrusion and to guarantee the supply of a certain water quantity and quality, at a certain location and at a certain point in time.

Within the Rhine-Meuse Estuary, we distinguish two different subareas, since the level of external salt water intrusion is location-specific.

- Main water system of the Rhine-Meuse Estuary (indicated by the red dotted lines in Fig. 2): 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.
- Regional water system adjacent to the Rhine-Meuse Estuary (Hollandse IJssel) (indicated by the yellow dotted lines in Fig. 2): locations in this area are not directly influenced by the upstream seaward flowing fresh river water. The Hollandse IJssel is an upper closed-off river branch that functions as a storage basin, with a slow variation of the physical processes over time. Salt water intrusion is affected by (1) the downstream inflow of water from the Rhine-

Meuse estuary and (2) the discharge of excess water and the extract of water for use in the adjacent regional water systems.

For our analyses we chose a location in each of these two subareas: (1) location '*Krimpen aan den IJssel'* (location where the main water system interacts with the Hollandsche IJssel and (2) location 'Gouda' (location where the Hollandse IJssel interacts with the regional catchment area of Water board Rijnland (i.e. fresh water inlet of the regional catchment). The two locations are indicated by the black dots in Figure 2.

3.2 Risk assessment

3.2.1 Model for hydraulics & salinity

We make use of a hydraulic Rhine model, which is based on the 1-D simulation package SOBEK. With this model, we make dynamic simulations, enabling us to compute the impact of river discharges Q and water levels h on Chloride concentrations in the Rhine-Meuse Estuary. The Rhine-Meuse Estuary is schematized in the SOBEK model as a network of branches and nodes, see Figure 3.

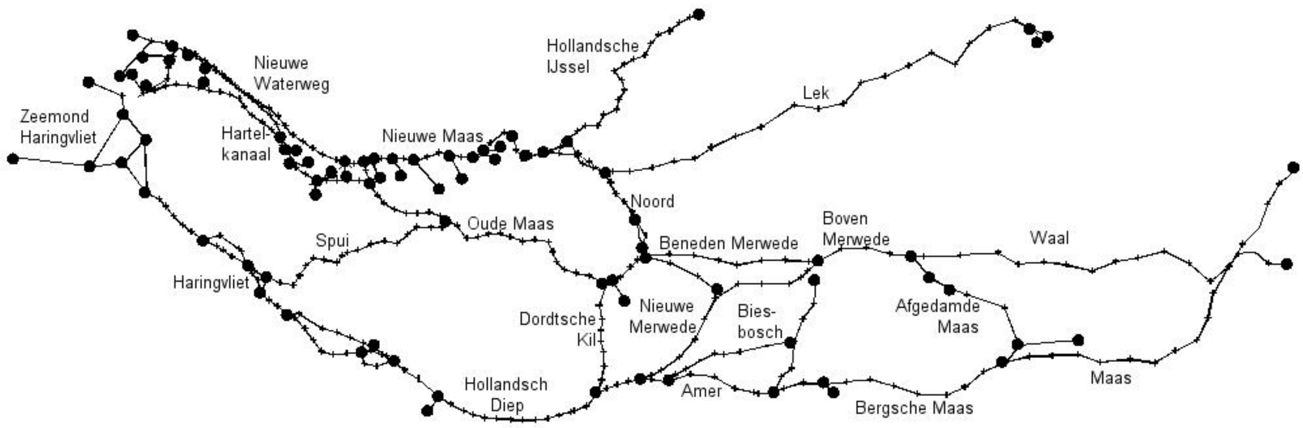

Figure 3. SOBEK model schematization of the Rhine-Meuse Estuary.

The SOBEK model simulates the salt concentration for each location in the Rhine-Meuse Estuary based on a large set of model boundary conditions. The following hydraulic boundary conditions are imposed: (1) discharge time series at the three upstream boundaries (i.e. Lek, Maas and Waal) and (2) water level time series (astronomical tide and water level set-up) at the three downstream boundaries (i.e. one at the Nieuwe Waterweg, and two at the Haringvliet sluices).

Each simulation is driven by a combination of conditions. The river discharge is discretized in 13 discharge time series with a peak/trough discharge (each with a variable duration) Q_i varying between 600, 700, 800, 900, 1.000, 1.200, 1.400, 1.600, 1.800, 2.000, 2.250, 2.500 and 4.000 m^3/s. The water level at the downstream boundary is composed of a standard astronomical tide and a water level set up Δh_j. For this water level set up 7 scenarios are distinguished: a water level set up Δh_j varying between 0 and 175 cm. This results in 91 combinations of river discharge time series and water level time series.

The maximum Chloride concentration at location '*Krimpen aan den IJssel'* and location 'Gouda' are computed for each combination of river discharge time series and water level time series. An example of the contour plot for location '*Krimpen aan den IJssel'* and for the location *'Gouda'* is presented in Figure 4 and Figure 5. The figures give insight into the contribution of the river discharge Q_i and the water level set-up Δh_j to the Chloride concentration $C_{i,j}$ at both locations.

The figures show that the Chloride concentration at location *'Krimpen aan den IJssel'* is influenced by both the river discharge and the water level set-up. The Chlority lines for location *'Gouda'* have a vertical course, indicating that the water level set-up does not significant contribute to the Chloride concentration. The Chloride concentration location *'Gouda'* highly depends on the river discharge.

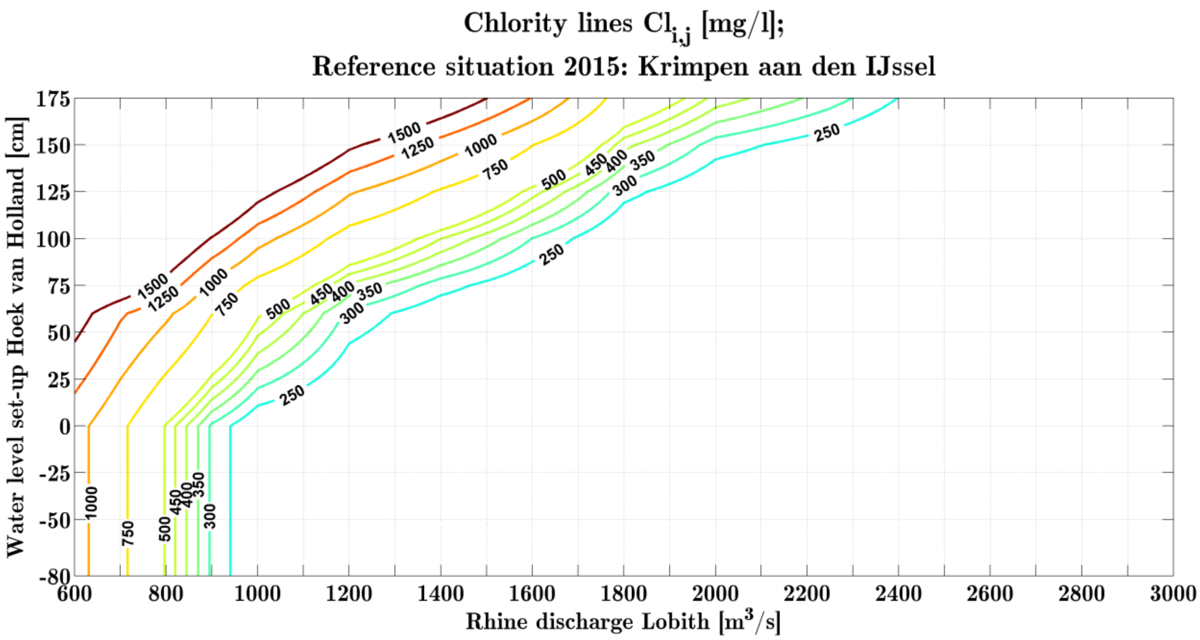

Figure 4. Contour plot of the Chloride concentrations at location 'Krimpen aan den IJssel' for the reference situation in 2015

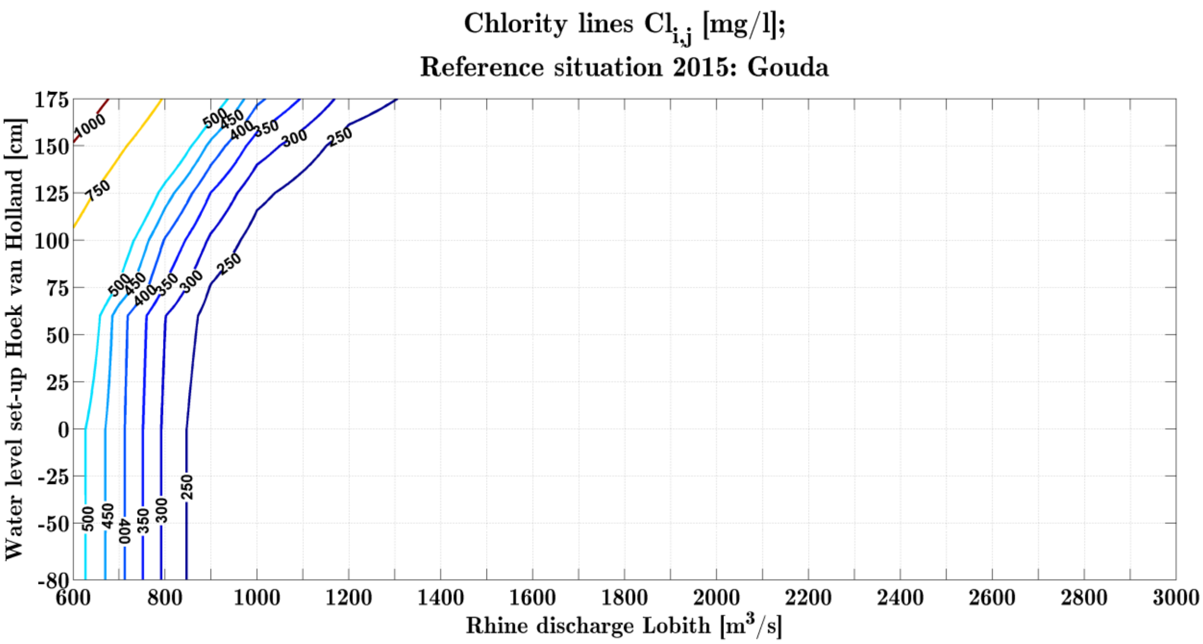

Figure 5. Contour plot of the Chloride concentrations at location 'Gouda' for the reference situation in 2015

3.2.2 Probabilistic model approach

For the case study a probabilistic model is developed to make the uncertainty in salt water intrusion (induced by uncertainty in river discharge and water level set-up due to a storm) more explicit. The contour plots of the Chloride concentration at location *'Krimpen aan den IJssel'* (Figure 4) and location *'Gouda'* (Figure 5) indicate that the tidal influence is more distinctive for the main system of the Rhine-Meuse Estuary, than for the Hollandse IJssel that functions as a storage basin. Therefore, two probabilistic models have been developed:

1. A tide and river dominated probabilistic model: locations where the salt water intrusion is jointly influenced by the river discharge Q_i and the water level set-up Δh_j
2. A river dominated probabilistic model: locations where the salt water intrusion is mostly influenced by the river discharge Q_i

The probabilistic model aims to derive the exceedance frequency of a certain Chloride concentration level and the exceedance duration in a given period, i.e. the summer season (1^{st} of April and 30^{th} of September). In the summer season (more specific in the months July and August), the Rijnland catchment highly depends on freshwater extraction from the Hollandse IJssel, since in this period water availability within the catchment is often low due to precipitation deficits. High Chloride concentration in the main water system will therefore induce fresh water management problems in this period. The situation becomes critical if the Chloride concentration Cl exceeds a concentration of 250 mg/l in the summer season.

Tide and river dominated probabilistic model

The momentaneous exceedance probability of the Chloride concentration Cl exceeding a concentration cl during a storm period of 36-hours can derived from the sum of the individual momentaneous probability densities $p(Cl_{i,j})$ of all conditions for which $Cl_{i,j}$ exceeds cl. The conditions (i.e. combination of river discharge Q_i and the water level set-up Δh_j) under which the Chloride concentration exceeds a certain level cl can be determined from the contour plots in Figure 4 and 5. The individual momentaneous probability density of the conditions that result in exceeding the concentration cl can be determined with the joint probability density functions of the river discharge Q_i and the water level set-up Δh_j. Figure 6 shows the probability density function of the river discharge Q_i and the probability density function of the water level set-up Δh_j. The probability density function of the river discharge Q_i has been derived from discharge records in the period 1900-2010. For the probability density function of the water level set-up Δh_j water level records from 1888 onwards has been used.

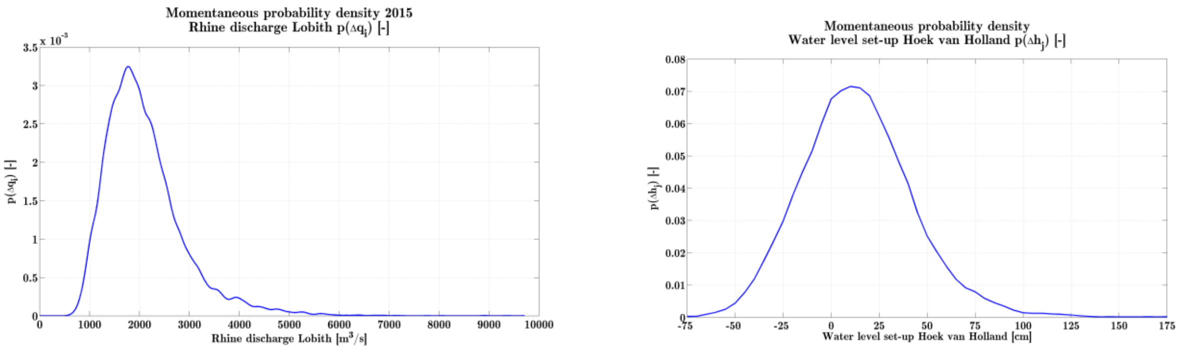

Figure 6. The probability density function of the river discharge $p(Q_i)$ and the probability density function of the water level set-up $p(\Delta h_j)$ for the reference situation in 2015

Figure 7 shows the joint momentaneous probability density function of the Chloride concentration $p(Cl_{i,j})$ for location *'Krimpen aan den IJssel'* for the reference situation in 2015 that could be determined using the probability density functions of river discharge and water level set-up and the SOBEK model simulations for a number of combination of river discharge and water level set-up.

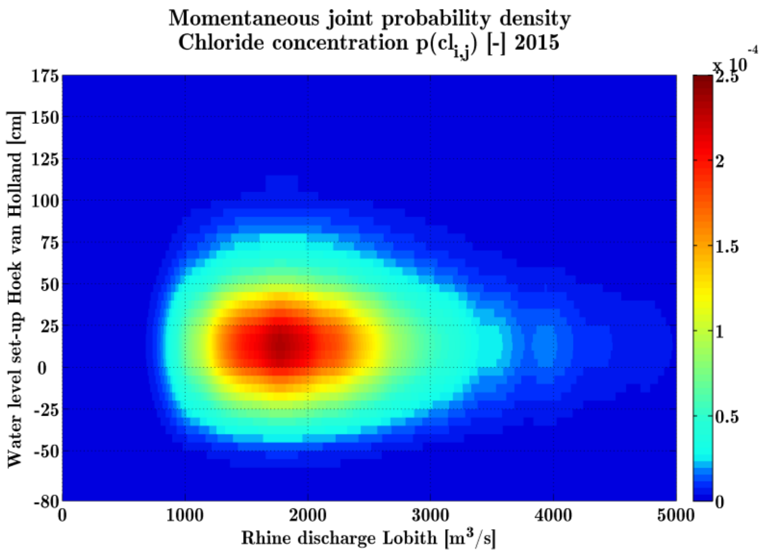

Figure 7. The joint momentaneous probability density of the Chloride concentration p(Cli,j) for location 'Krimpen aan den IJssel' for the reference situation in 2015

The exceedance frequency F(Cl>cl) can be derived by multiplying of the exceedance probability P(Cl>cl) with the number of possible storm periods per summer season N (i.e. 122 periods of 26 hours in a summer season). Figure 8 (left panel) shows the exceedance frequency curve of Chloride concentration for location *'Krimpen aan den IJssel'* for the reference situation in 2015.

The river dominated probabilistic model

At these locations the Chloride concentration is mostly influenced by the river discharge Q_i. The exceedance frequency F(Cl>cl) per year is equal to the non-exceedance frequency of the summer annual minima peak river discharge $F(Q_k<q_k)$, with $q_{k(i)}$ the river discharge that should not be exceeded to result in an exceedance of the Chloride concentration standard cl. Figure 8 (right panel) shows the exceedance frequency curve of Chloride concentration, for location *'Gouda'*, for the reference situation in 2015.

The exceedance duration $Dcl_{(i)}$ 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 $q_i = q_{k(i)}$. If for instance a Rhine discharge q_i of 1.000 m^3/s as 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 $Dcl_{(i)}$ of 10 days (=5/0,5).

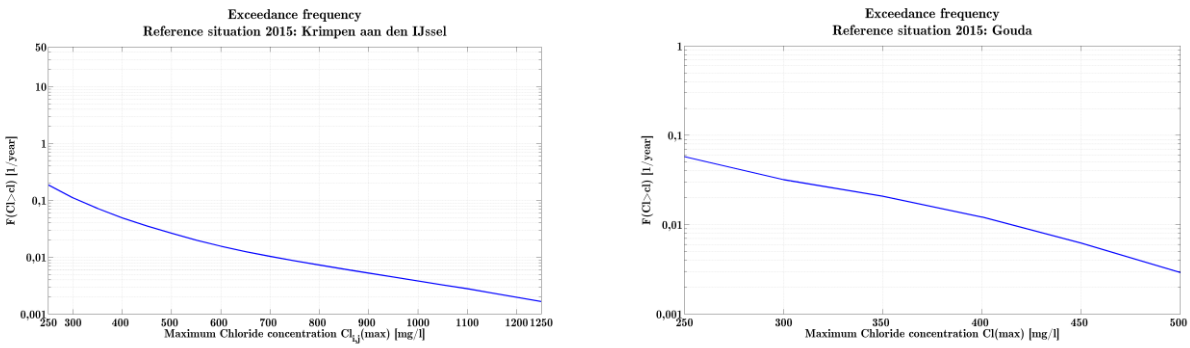

Figure 8. The exceedance frequency curve of the Chloride concentration level F(Cl>cl) for location 'Krimpen aan den IJssel' (left panel) and for location 'Gouda' (right panel) for the reference situation in 2015

3.2.3 Damage model

A quick-scan damage model is developed that aims to describe the relation between the salt water intrusion in the Hollandse IJssel and the agricultural drought damage for Rijnland in a highly simplified way. A full probabilistic damage model is extremely complex, due to both human intervention into the main and regional water system and the uncertainty of the variation in time and space of a system's water demand and water supply (i.e. caused by natural processes as temperature, precipitation and evaporation).

The quick scan model describes the agricultural damage AD of Rijnland's catchment as a function of the exceedance duration for varying exceedance frequencies F(Cl>cl). This model is based on three assumptions:

1. relation agricultural damage AD to the precipitation deficit ΔP
2. relation precipitation deficit ΔP to the discharge deficit ΔQ
3. relation discharge deficit ΔQ to the exceedance duration D_{Cl} of a Chloride concentration standard (i.e. 250 mg/l)

3.2.4 Salinity risk in present and future situation

We determined the salinity risk at the fresh water inlet at location 'Gouda'. 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 Gouda. Risk exists in many different forms, e.g. economical risk, social risk and environmental risk. Here we focus on salinity risk in terms of economic risk.

We expressed risk as:

1. yearly expected (YE) value of exceedance Duration for Chloride (D_{Cl}) concentration Cl > 250 mg/l (YED_{Cl} in days/year);
2. yearly expected (YE) value of agricultural drought damage (AD_{dr}) ($YEAD_{dr}$ in €/year).

The exceedance duration D_{Cl} is derived by a salinity probability model in Section 3.2.2. The corresponding economic consequences in terms of agricultural drought damage AD_{dr} derived with the damage model in Section 3.2.3.

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 $F(D_{Cl} > d_{cl})$ for varying exceedance durations D_{Cl}. Figure 9 shows the area that indicates the yearly expected duration YED_{Cl} for the reference situation in 2015 and the situation in 2050.

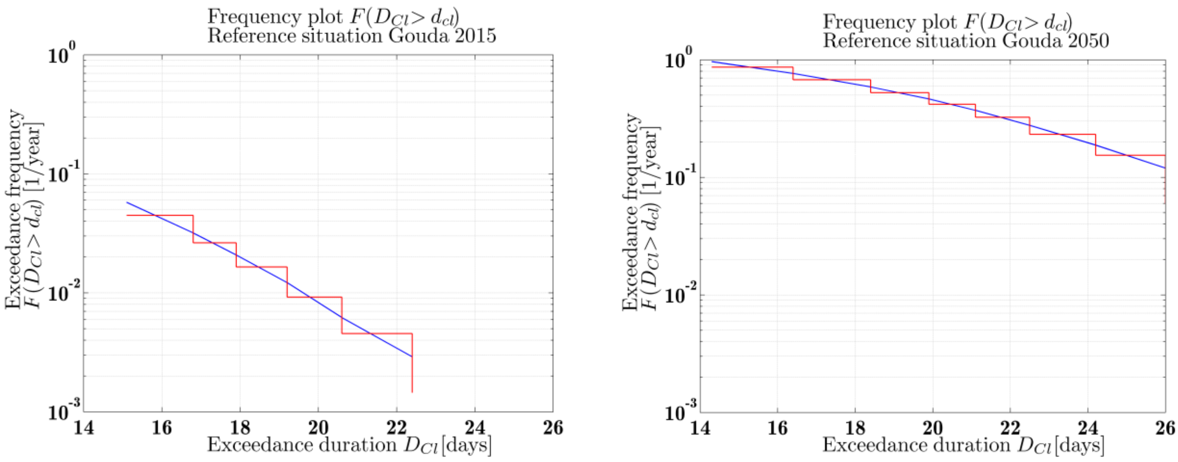

Figure 9. Frequency plot for the exceedance frequency F(DCl > dcl) for varying exceedance durations DCl for location 'Gouda' the reference situation in 2015 and the situation in 2050

The yearly expected exceedance duration YED_{Cl} can be derived by the following equation:

$$YED_{cl} = F_n \cdot D_{cl}(F_n) + (F_{n-1} - F_n) \cdot \frac{D_{cl}(F_{n-1}) - D_{cl}(F_n)}{2} + \ldots + (F_2 - F_1) \cdot \frac{D_{cl}(F_2) - D_{cl}(F_1)}{2}$$

In which YED_{Cl} is the yearly expected exceedance duration in days per year, $F_{1,n}$ is the exceedance frequency $F(D_{Cl} > d_{cl})$ in 1 per year for 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.

Table 1 gives the yearly expected exceedance duration YED_{Cl} derived for the reference situation in 2015 and the situation in 2050.

Location	Yearly expected exceedance duration YED_{Cl} [days/year]	
	2015	2050
Gouda	1.0	19.4

Table 1. Risk defined as yearly expected exceedance duration YEDCl for the reference situation in 2015 and the situation in 2050 for the location *'Gouda'*

The economical salinity risk can be expressed in a yearly expected agricultural damage YEAD in € per 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 10 shows the area that indicates the yearly expected agricultural damage value YEAD for the reference situation in 2015 and the situation in 2050.

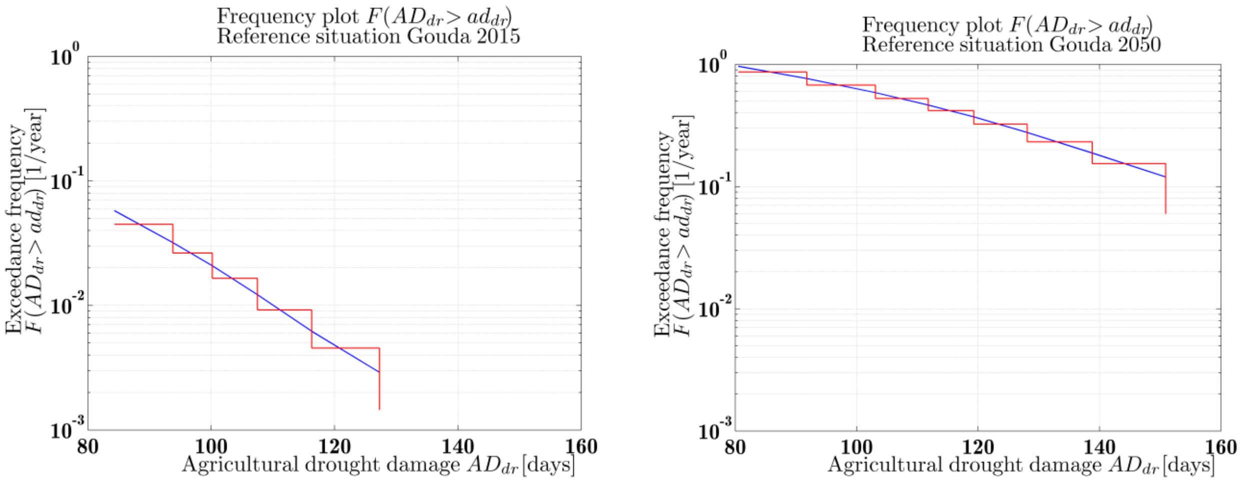

Figure 10. Frequency plot for the exceedance frequency F(ADdr > addr) for location 'Gouda' the reference situation in 2015 and the situation in 2050

The yearly expected exceedance duration YEAD can be derived by the following equation:

$$YEAD = F_n \cdot AD_{dr}(F_n) + (F_{n-1} - F_n) \cdot \frac{AD_{dr}(F_{n-1}) - AD_{dr}(F_n)}{2} + \ldots + (F_2 - F_1) \cdot \frac{AD_{dr}(F_2) - AD_{dr}(F_1)}{2}$$

In which YEAD is the yearly expected agricultural damage in € per year, $F_{1,n}$ is the exceedance frequency $F(AD_{dr} > ad_{dr})$ in 1 per year for 1 (largest frequency, smallest exceedance duration) to n (smallest frequency, largest exceedance duration), and $AD_{dr}(F_n)$ is the corresponding agricultural damage for each frequency.

Table 2 gives the yearly expected agricultural damage YEAD derived for the reference situation in 2015 and the situation in 2050.

Location	Yearly expected agricultural damage YEAD [10^6 €/year]	
	2015	2050
Gouda	5.7	109.9

Table 2. Risk defined as yearly expected agricultural damage YEAD for the reference situation in 2015 and the situation in 2050 for the location *'Gouda'*

3.3 Risk evaluation and risk management

The estimated risk in the reference situation in 2015 and the future situation in 2050 forms the basis for risk evaluation. If the salinity risk is unacceptable high, measures could be undertaken to reduce risks. Salinity risk can be reduced by means of (1) reducing the probability of external salinity or (2) by reducing the consequence of external salinity.

The probability of external salinity can be reduced by measures at river basin scale (i.e. intervention in the main water system), for instance by optimizing the distribution of fresh water flows over the Rhine branches, or by measures reducing salt water intrusion in the main water system. The consequence of external salinity can be reduced by measures in the regional catchment area, for instance relocation of cultivations to salinity prone areas.

We investigated the risk reducing effects of measures that aim to reduce the probability of external salinity. The impact of four measures has been investigated (see Figure 11):

1. Closure of one of the river branches that is in open connection with the North Sea, i.e. Spui;
2. Alternative distribution of fresh water flows over the Rhine branches: 10% extra discharge via the Lek;
3. Alternative distribution of fresh water flows over the Rhine branches: 25% extra discharge via the Lek;
4. Extra fresh water intake in the Lek to Rijnland's catchment: Krimpenerwaard route

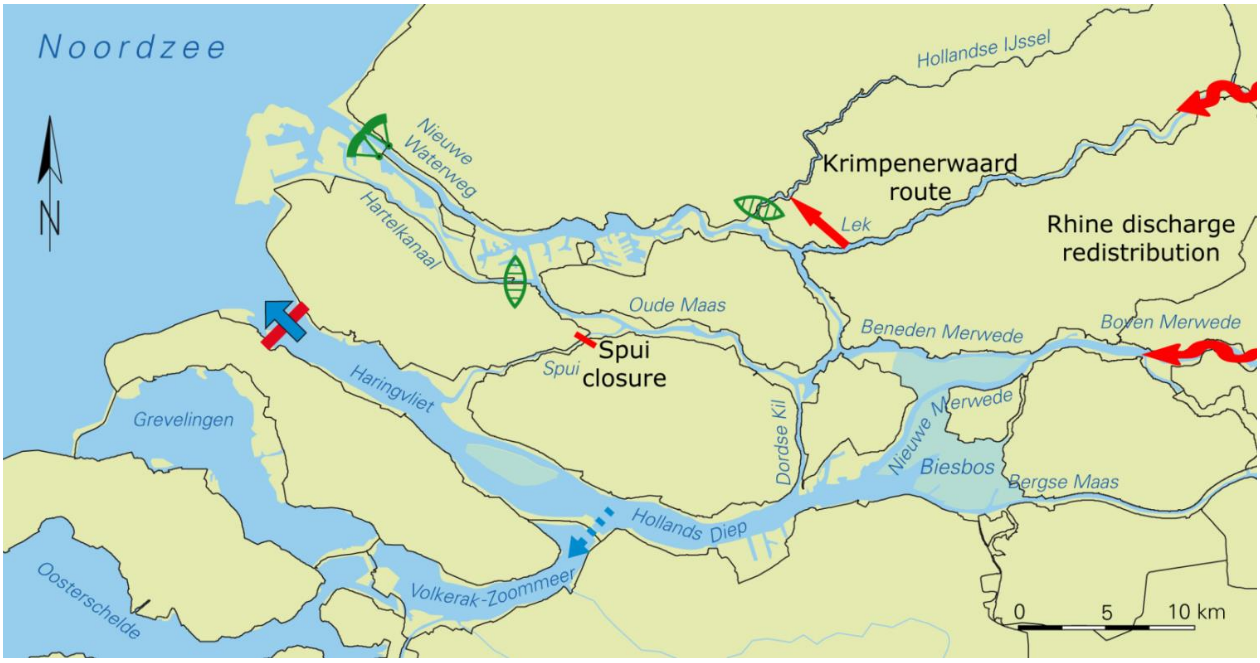

Figure 11. Measures to reduce the probability of external salinity at the fresh water intake at location 'Gouda': (1) Closure of one of the river branches that is in open connection with the North Sea, i.e. Spui, (2) alternative distribution of fresh water flows over the Rhine branches: 10% extra discharge via the Lek, (3) alternative distribution of fresh water flows over the Rhine branches: 25% extra discharge via the Lek and (4) extra fresh water intake in the Lek to Rijnland's catchment: Krimpenerwaard route.

Table 3 shows the impact of these measures on the yearly expected exceedance duration YED_{Cl} and the yearly expected agricultural damage $YEAD_{dr}$ for the situation in 2050.

This rises to the question whether the measures are attractive from a cost-benefit point of view. A cost-benefit analysis can be used to evaluate the benefits of the measures (a risk reduction) and the costs of the measures. If the benefits of a measure exceed the costs, the measure generates an increase of economic welfare and is indicated as attractive. A measure is unattractive, if the benefits are lower than the costs.

Measures to reduce probability of external salinity	Yearly expected exceedance duration YED_{CI} [days/year]	Yearly expected agricultural damage YEAD [10^6 €/year]
Spui closure	6.6	37.3
10% extra discharge via the Lek	5.4	30.3
10% extra discharge via the Lek	2.2	13.1
extra fresh water intake in Lek	6.6	37.3
Reference situation	19.4	109.9

Table 3. Risk defined as yearly expected agricultural damage YEAD for the reference situation in 2015 and the situation in 2050 for the location *'Gouda'* for the reference situation and for four measures to reduce the probability of external salinity at the fresh water intake

The economical salinity risk R is defined as a yearly expected agricultural damage in € per year. An investment I in € is a onetime cost. To make a comparison between the two, the yearly expected value of risk should be discounted over the investment's lifecycle time. For investments, we consider a time horizon of 50 years. The resulting present value of the yearly expected agricultural damage for this time horizon can be compared with the investment costs I to assess the cost-efficiency. If this present value is larger than the investment costs, the measure is costs-beneficial. Table 4 gives an overview of overview present value of salinity risk and the investment costs I of each measure.

The table shows that all measures are cost-effective. The extra fresh water intake in Lek (Krimpenerwaard route) is the best measure from economic point of view: the largest risk reduction of $2.316 \cdot 10^6$ € against to lowest investment costs I of $17 \cdot 10^6$ €.

Measures to reduce probability of external salinity	Present value of the yearly expected agricultural damage [10^6 €]	Investment costs I [10^6 €]
Spui closure	45	17
10% extra discharge via the Lek	651	250
10% extra discharge via the Lek	281	250
extra fresh water intake in Lek	801	100
Reference situation	2361	-

Table 4. An overview of overview present value of salinity risk Ri and the investment costs I of each measure

4. CONCLUSIONS AND RECOMMENDATIONS

Sufficient water supply that meets the required quality is of paramount importance to the well-being of the global population and is of substantial economic interest as well. According to current research regarding future climate change, it is likely that water shortages will be more prevalent in future. There is a strong need to make uncertainty, consequences and risks related to water availability, use and consumption more explicit. The risk-based approach as introduced in this paper could help to do so.

The risk-based approach directly addresses several issues that are of important economic and societal value:

- Reduction of drought risks and damage
  Water shortage may lead to restrictions in various functional purposes (viz. drinking water, agriculture, navigation, power plants, industry, nature and recreation). It may bring along also other points of concerns. If peat flood defense embankments lose too much moisture, the resulting decrease in the embankment's weight reduces its ability to hold back water. This can lead to failure of the peat embankment, which leads to flooding. Additionally, at decreased groundwater levels peat could oxidize irreversibly, resulting in more rapid subsidence and increased CO_2 emissions. The risk-based methodology will enable a proper assessment of trans-sectoral and trans-regional risks, as well as the assessment of feasible options to manage these risks. This can make delta regions across the world more resilient and less vulnerable for drought events.
- More cost-effective (decision making on) drought risk reduction strategies
  In drought prone areas various measures at different scales (river basin scale, regional water system, and local scale) can be undertaken to cope with water scarcity and to reduce drought-damage. The methodological approach will also enhance decision making as it helps to identify effective measures and strategies (combinations of measures) to reduce drought risks (considering trans-sectoral and trans-regional variations in drought risks). This will enable water managers to better anticipate water shortages and have an even better base for setting the precedence in the water distribution across the various regions and stakeholders.
- Better coordination and tuning between stakeholders in times of water scarcity
  Clear communication about the freshwater distribution and tuning between (1) managers of the main water system and (2) end-users (regional water systems and other end-users of freshwater) is of utmost importance. As drought situations will be more prevalent in future, it is important to clarify what one can expect from one-and-another during different circumstances. This counts for the freshwater availability from the main water system of a certain water quantity and quality, at a certain location and at a certain point in time. This gives end-users (managers of regional water systems and other end-users) an action perspective in respect of investments and measures to optimise their system and business operations (and also what residual risk they want to burden). Otherwise, it is also important that all end-users express their interest and their requirements. On the basis of joint information about water supply and requirements, managers of the main water system can decide on water distribution and anticipate on freshwater shortages.

The conclusions regarding the first two aspects have been demonstrated in the case study for the Rhine-Meuse Estuary in the Netherlands. The freshwater availability in the Rhine-Meuse Estuary will be more and more under pressure, due to the predicted effects of climate change. The risks associated with salt water intrusion, due to the joint occurrence of large consecutive periods of low discharges and severe salt water intrusion from the sea side and the consequences in terms of drought damage has been investigated. We have shown that resulting information about drought-related risks in the situation with and without measure can enable us to prioritise and predicate decisions. It helps to assess the cost-efficiency of measures to cope with droughts and define cost-efficient solutions through a cost benefit analysis.

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