A NEW SUIT FOR THE IJSSELMEER

Possibilities for facing the future needs of the lake by means of an optimized dynamic target water level

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SUMMARY

Problem definition

When looking into the future, the IJsselmeer is under climate change threats, both in the short term and, more considerably in the middle/long run (2050/2100). Sea level is expected to rise, making gravity discharge to the Waddenzee more difficult. Winters will be wetter, bringing more water into the system, and summer will be drier, endangering the satisfaction of water demand.

Research and meetings have been organized in order to tackle the situation as soon as possible and define rigorous measures towards a climate proof IJsselmeer. However, two main remarks can be made on the past studies, which are the starting point of the present research:

- The suggested strategies consider major structural measures which will completely change the shape of the IJsselmeergebied. What if the system is already flexible enough and able to face the future threats with only changes in its management (i.e. changes in target water levels)?
- The approach used to select the strategies to study and discuss with the stakeholders usually begins with the key role of experts and policy makers which design a set of promising options following their experience and intuitions. Without questioning the value of such approach, it is interesting to study how an optimization methodology can improve the selection of efficient alternatives for the stakeholder consultation.

Research Approach and Research questions

From these two starting issues, the present research strives to define for the IJsselmeer a dynamic target water level, which is variable over the whole year, by means of an optimization approach. The optimization uses a single objective function considering dikes safety and water demand. Most studies are skeptic on the ability of the present system to be flexible enough to cope with future climate scenarios. For this reason extra measures have been included in the optimization in case changes in target water levels are not enough to assure a climate proof IJsselmeer: a pumping station at the Afsluitdijk and early storage in March (i.e. different target water level).

The main research question asks for an evaluation of the optimization methodology used to define efficient alternatives for the IJsselmeer. The sub-question requires the assessment of the flexibility of the IJsselmeer towards a climate-proof system, and the definition of extra measures, if needed.

Research Methodology

First phase of the research is the investigation of the system and the stakes which have to be satisfied. Dienst IJsselmeergebied has been chosen as the problem owner, with two main interests, strictly prioritized: Safety of the dikes around the IJsselmeer (priority 1) and satisfaction of the water demand (priority 2).

In the second phase, the classes of actions considered in the research are formalized. Namely changes in target water levels, pump capacity at the Afsluitdijk and early storage in March.

In the third phase the indicators for the two stakes have been designed. According to the prioritization expressed, the indicators are combined into the single objective function which is used in the optimization. The indicators are defined as follow:

- Safety of the dikes in winter: for the winters 1952/1953, 1965/1966, 1987/1988, 1993/1994, 1994/1995, the peaks of the actual water level (mean + wind) should be equal or lower than the peaks in the same years from the modeled historical situation (reference). This is at the Roggebotsluizen. The indicator is the sum of the differences between the future condition and the reference, when such difference is higher than zero.
- Safety of the dikes in summer: two high boundaries have been selected for a safe summer system:
  - A conservative one, more realistic: maximum summer target water level +0.1mNAP.
  - An extreme one, used to explore the potentials of the IJsselmeer: mean water level in summer lower than +0.69mNAP.

  The indicator is the sum of the differences between the future condition and the reference, when such difference is higher than zero.
- Water Demand: Summer water level should never drop below -0.3mNAP, which is the threshold assuring free flow to the polders. The indicator is the sum of the water demands in summer, when the mean water level is lower than the threshold.

In the fourth phase, the model has been defined, together with the optimization algorithms. These algorithms are based on an evolutionary algorithm named: Differential Evolutions. A model of the IJsselmeer has been tailored in Matlab on the basis of the WINBOS model developed in SOBEK by Rijkswaterstaat. The time series used in the research, both for the past and the future scenarios, are also taken from WINBOS. The simulation horizon covers a period from 1951 till 1998.

In the fourth phase the optimization problems have been defined and run:

- Case 0: “optimization” of the sea level rise that the present system can bear. No climate scenario used (only sea level rise). The objective function has been designed on the indicator developed for winter safety of the dikes. The enlargement of the Lorentzsluizen has been included in the system.
- Case A: optimization of the winter target water level. W+2050 scenario has been used with rising sea levels (+0.025m, +0.05m, +0.1m, +0.125m, +0.15m, +0.175m, +0.2m). The objective function has been designed on the indicator developed for winter safety of the dikes. The enlargement of the Lorentzsluizen has been included in the system.

- Case B: optimization of the pump capacities. W+ scenario has been used with sea level rises of +0.20m and +0.35m. W+2100 scenario has been used with sea level rises of +0.30m, +0.80m, +0.55m, +1.2m. The objective function has been designed on the indicator developed for winter safety of the dikes. The enlargement of the Lorentzsluizen has been included in the system.
- Case C: optimization of the summer target water levels. The past time series have been used together with W+2050 and W+2100 scenarios. The objective function has been designed on the indicator developed for summer safety of the dikes and water demand. Optimizations have been executed both for the conservative and the extreme case.
- Case D: optimization of the summer target water levels, including early storage in March. The past time series have been used together with W+2050 and W+2100 scenarios. The objective function has been designed on the indicator developed for summer safety of the dikes and water demand. Optimizations have been executed both for the conservative and the extreme case.

Winter extreme event curves produced by the optimized alternatives are tested a posteriori with Hydra-VIJ. This is done in order to check safety of the dikes.

Results

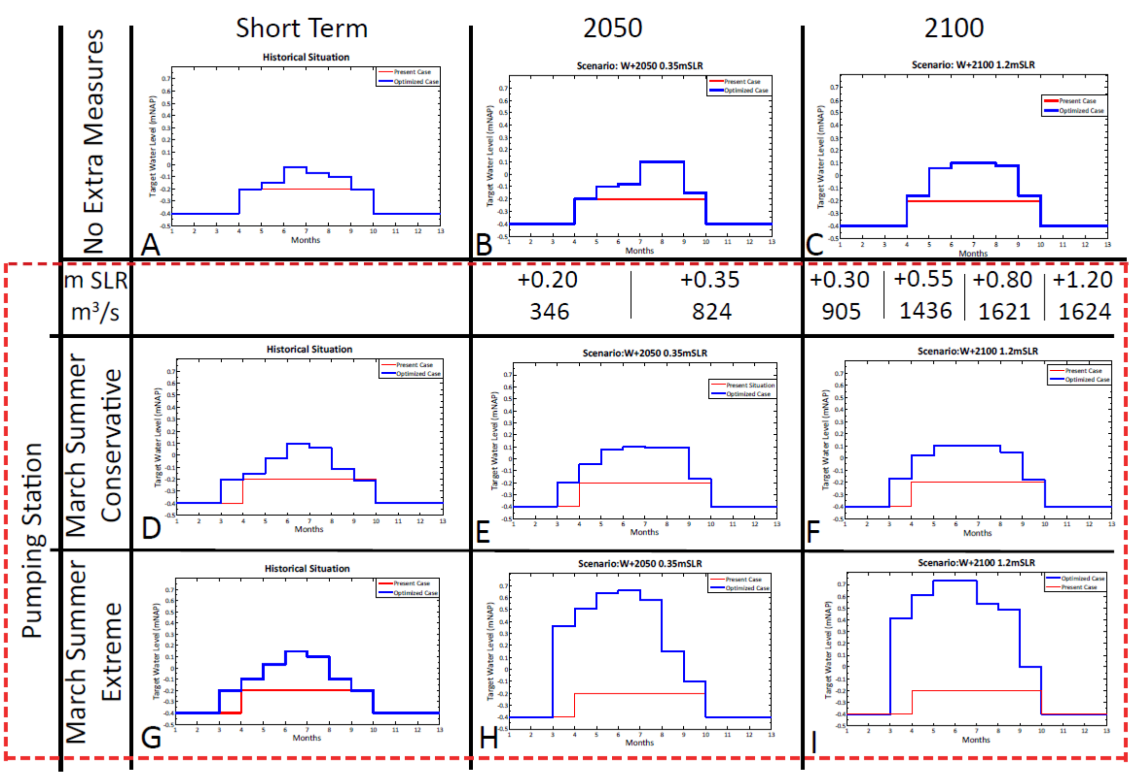

Figure i – Overview of the results

Figure i shows an overview of the results. Monthly target water levels are shown both for the present management (red) and the optimizations (blue). In particular it is interesting to notice that:

- Graphs B and C do not define a safe situation.
- Graphs A, D, E, F, G, H, I define a safe situation, either because extra measures are not needed (short term), or because a pump capacity at the Afsluitdijk is introduced.
- A generates a cut in half of the water deficit, while D and G reduced it to zero and 9%.
- B generates a water deficit close to the historical, while E reduces it to 85% and H to 5%.
- C and F generate a water deficit which is almost 2.5 times the historical, while I represents a cut in half.

Conclusions and Recommendations

A different planning of the target water level alone is not able to satisfy the needs of safety and water demand on the long term. As it is now, the IJsselmeer is flexible in the short term, but not enough to accommodate the impacts of longer horizons: extra measures are needed in order to define a climate proof system in 2050 and 2100. Pumping station at the Afsluitijk is an effective measure to guarantee safety for all the scenarios. Early storage in March is effective in the medium horizon (2050) but need high target water levels along the summer for the long term (2100). This might generate safety issues.

Even if applied on a simplified case, the use of an optimization methodology manages to define a realistic picture of the flexibility of the IJsselmeer, and retrieves efficient options for possible future strategies. For this reasons, the present research can be considered a successful implementation of an optimization approach for the IJsselmeer.

For the short term it is recommended to use the flexibility of the system, implementing the changes in summer target water levels which would allow deeper satisfaction of water demand.

For the medium/long term, options for early storage need to be investigated together with the summer target water levels needed to reduce water demand. This would probably require reinforcement of the dikes. Options for safety can be then defined for the new reinforced system, considering combinations of pumping station and raise of the dikes.

A more extensive and detailed optimization tool should be realized for the IJsselmeer, and applied for the definition of the measures above. In particular it is recommended to use a multi-objective analysis and to include costs in the definition of the indicators.

CONTENTS

1. INTRODUCTION

1.1. PROBLEM STATEMENT: THE FUTURE OF THE NETHERLANDS AND THE IJSSELMEER

The agreement is nowadays unanimous: the climate is changing. Even if we leave aside the discussion about the causes, there is scientific evidence on the fact that the future climate will be different from expected long term climate circles (van Drunen 2009). Scenarios of possible climate evolution, even if uncertain, have been prepared and discussed; for the Netherlands the Royal Meteorological Institute (KNMI) has produced in 2006 four local climate change scenarios (KNMI'06) (van den Hurk 2006), whose prediction have been confirmed by a later review in 2009 (Klein Tank 2009). There is an 80% chance that the evolution of Dutch climate will be within the predictions of those studies.
Furthermore, scientific research has proven that even if we will be able to implement significant reduction of greenhouse gas emissions (argued as the first cause of climate change), such process can not be stopped. Given the poor international agreement on limiting greenhouse gas emissions, it is important to realize that the best way to tackle future changes is to be able to adapt the system to the expected future situation: the Netherlands needs to be made climate-proof (van Drunen 2009). This is not only the opinion of the researchers but it is also shared by the policy makers; the path towards a climate-proof country is one of the key pillars of the National Water Plan (Ministerie van Verkeer en Waterstaat 2009), and the main objective of the Delta Commission (Deltacommissie 2008).
According to the KNMI'06 predictions, rises in worldwide temperature will affect the Netherlands with a rise of the sea level, rise of summer potential evaporation, wetter winters and dryer summers, conditions which will have consequences on many different sectors, from water management to energy consumption, from transport to public health, as well as on agriculture, nature, housing, infrastructure, recreation etc… (detailed description of climate change scenarios at Chapter 3.3).

As for the whole country, climate changes will affect also the "wet heart" ("natte hart") of the Netherlands: the IJsselmeergebied. In this area, and specifically in the IJsselmeer, the different sectors are sensitive in different ways to climate changes (van Drunen 2009):

- From a safety point of view too high winter water levels will be more frequent, increasing the flooding probability. Higher winter discharges in the Rhine will be the response to both increases in winter precipitations and less snowfall on the Alps due to rising of the temperature. Those will generate higher volumes flowing through the IJssel to the IJsselmeer, and increase flooding probability in the area. This danger is amplified by the expected sea level rise, which will make gravity discharges to the Waddenzee more difficult.

- Also satisfaction of the fresh water demand will be affected by the climate scenarios for those areas which rely on the IJsselmeer for water supply. During summer, demand for drinking water might rise a few percent, due to temperature rise and more frequent heat periods. Furthermore, agriculture might experience longer growing season and higher summer water demands due to longer soil water deficits. Even if it doubtful whether the water demand will grow (agriculture development depends also on market and land planning scenarios, and the possibilities for expansion of the sector seem limited in the Netherlands), the lower summer discharges of the Rhine, predicted by the climate scenarios, will surely pose problems on its satisfaction.
- The natural environment will surely suffer from rising temperatures of water and atmosphere, especially because wet and aquatic ecosystems are very sensitive to temperature changes.
- From the perspective of the transport sector, the occurrence of higher lake levels in winter and lower in summer, due to changes in Rhine discharges, can limit the number of vessels or their freight load. On the other side, shipping companies can benefit from shorter frozen periods in the IJsseelmeer, however such advantages can be considered less relevant.

The need for a change in the IJsselmeergebied is not only due to climate scenarios; Dutch society is constantly evolving, changing the needs on the system raised by the stakeholders who live with and from the lake and influencing directly the planning of the area. Socio-economic scenarios might raise issues on the management of the IJsselmeergebied, and should be taken into account in planning the future of the system.

In a broader vision there is need to make the IJsselmeergebied climate&socio-economic-proof, and such goal is made more challenging by the interactions of the effects of socio-economics and climate scenarios; climate changes will be experienced in the future: effects perceived as a danger today, might be harmless in the years to come because of socio-

BOX 1.1

The **IJsselmeergebied**: it is the water-land system in the center of the Netherlands which includes not only the IJsselmeer, the Markermeer, the Randmeren, Ketelmeer and Zwartemeer, but also the coasts and the neighboring areas to those water bodies. The term has been created mainly for managing proposes, in order to consider this strongly interconnected region as a whole.

The IJsselmeer is the largest lake in Western Europe, and it is an essential feature for life in the Netherlands.

The lake receives water from the IJssel and the neighboring polders; the Water Boards of Fryslan, Flevoland and Hollandse Noorderkwartier discharge their excess water to the lake by means of pumping stations. The same Water Boards collect fresh water from the IJsselmeer by free flow, when needed.

The main output of the IJsselmeer is to the Waddenzee, through two gravity gates at the Afsluitdijk: Stevinsluizen (in Den Oever) and Lorentzsluizen (at Kornwerderzand).

Detailed description of the system at chapter 2 economic changes and vice versa (van Drunen 2009).

Looking at the present status of the IJsselmeergebied, the problems above described do not seem particularly urgent or important; the present configuration of the system (structures and management) has not created, till now, big problems or complaints. The IJsselmeer and the neighboring water bodies have generally been safe, and served their functions in a satisfactory way.

Notwithstanding the truth of the previous statement, the problem *is* urgent and important when looking into the future prospective and considering the climatic and socio-economic scenarios.

First of all, the issue is *urgent* because well planned adaptation policies need to be discussed and designed in advance, in order to well evaluate their flexibility and costs (van Drunen 2009). Furthermore, the climate is changing rapidly (Deltacommissie 2008) and the system has experienced some past undesirable events which might suggest that the IJsselmeergebied has already little room to cope with extreme situations:

- 1976, a long dry period (from December 1975) has affected the whole Europe, generating severe droughts during summer which are still nowadays used as a reference for policy making purposes. It has been estimated that this event has, for the Netherlands, a return period of 110 years (European Comunity - Water Scarcity and Droughts Expert Network 2007).
- 1998, extreme high winter water levels have been registered in October/November 1998, with a peak of +0.52 NAP reached on November 6th, which, according to further analysis, corresponds to an event with a return period of 93 years. Extremely high rainfall, high IJssel discharge and strong Westerly winds have been the three main causes of the event, which caused flooding problems to many municipalities among which Medemblik, Enkhuizen and Wunseradiel (Ministerie van Verkeer en Waterstaat - Directoraat Generaal Rijkswaterstaat - Directie IJsselmeergebied 1999).

Secondly, the issue is *important*, because the IJsselmeergebied represents a key element in Dutch life and economy; many people, interests and investments are linked to good performances of the system, stakes which need to be protected. Among the most important functions of the area, the IJsselmeergebied is a safety buffer for the water coming from the IJssel and the neighboring polders, fresh water supplier, migration spot for birds, home to many different ecosystems, site for commercial and recreational shipping. In the last century, the pulsing Dutch society has been growing with and around those water bodies, creating such big network of uses, benefits and dependencies, that it is nowadays not possible to imagine the Netherlands without the IJsselmeer, the “wet heart” of the country. Furthermore, there is evidence to state that the role of the area will become more and more crucial in the future, since has been indicated as the best option for storing fresh water in order to prevent droughts (van Beek 2008).

1.2. PAST RECOMMENDATIONS/RESEARCHES

1.2.1. RESEARCHES REVIEW

In this view of a climate&socio-economic-proof IJsselmeergebied, recommendations, meetings and preliminary plans have been already organized by the Dutch government and Rijkswaterstaat, with the objective to raise the questions and discuss with the stakeholders the future of the "wet heart" of the Netherlands.

2008, Delta Commission (Veerman Commission)
Established in 2007, the Dutch government asked to the so called "Second Delta Commission" to come up with recommendations on how to protect the Netherlands from climate changes, i.e. how to build a climate-proof country (Deltacommissie 2008). The outcome is a report presenting 12 recommendations for the future of the country, with concrete measures up to 2050, a vision for 2100 and long term options beyond 2100. Also costs to implement such recommendations have been estimated.
Regarding the IJsselmeergebied, a rise of the water level of maximum 1.5m is suggested for the IJsselmeer after 2050. This situation would allow sufficient fresh water supply in times of droughts and gravity discharge to the Wadden Sea. The level in the Markermeer will not be raised.

The last National Water Plan (2009), which is the formal government plan for national water policies for the period 2009-2015, has been already inspired by the Delta Commission: it represents the very first government's elaboration of the twelve recommendations into policies. Also in this document a climate&socio-economic-proof Netherlands is crucial: "[…] we want future generations to be able to enjoy the Netherlands as a safe and affluent land of water, we have to find answers in new developments in climate, demography and economy, and invest in sustainable water management" (Ministerie van Verkeer en Waterstaat 2009).

2010, Exploration of water level management options for the IJsselmeer - short/long term (Voorverkenning korte-lange termijn peilbesluitIjsselmeer)
From September 2009 till March 2010, three meeting have been organized by the Ministry of Transport, Public Works and Water Management together with a selection of stakeholders, in order to discuss possible measures and consequences for the IJsselmeergebied. Changes in target water level have been widely discussed, with the goal of assuring safety and sufficient fresh water supply both on the long and the short term. Since the Deltaprogramma has not started yet discussing the water policies in the IJsselmeergebied beyond 2015, the meetings have been organized with the main objective of collecting knowledge and understandings on the system from the point of view of the different stakeholders, in order to build a solid background on which the Deltaprogramma can base its planning for the next National Water Plan, specifically for the IJsselmeergebied (Rijkswaterstaat Waterdienst 2010) (Deltaprogramma IJsselmeergebied 2010).

The outcome of the consultation is a set of four possible strategies for the target water level of the IJsselmeer on the short and long horizons, together with the discussion of extra measures needed to keep the system safe, effects of the different choices and knowledge gaps. Appendix A contains a short summary of the outcome of the meetings, the proposed strategies and the mitigation measures needed.

1.2.2. ANALYSIS OF THE PAST RECOMMENDATION/RESEARCHES

Strategies and measures for a socio-economical & climate proof IJsselmeergebied proposed by the above consultation processes are outcomes of very important and established decision making approaches: experts' inquiry and stakeholders' involvement. Experts and researchers (as the Delta Commission) have studied possible solutions which have been later on discussed and developed with the stakeholders. Both steps are essential for successful planning, the opinion of the researchers and the experts gives scientific value to the selected measures, sizes them according to the needs and helps defining and quantifying the negative effects of the different strategies. Involvement of stakeholders is essential to build consensus on the possible interventions, investigating the parties which could oppose the different measures, understanding their reasons and defining the suited solution together with the ones which will experience the consequences. Furthermore, there is often no rigid border between experts and stakeholders. Defining and agreeing on future measures together with the ones which know and live with the system, is the way towards a successful plan.

Notwithstanding the value of the consultations, two remarks can be raised, respectively on the methodology used and the set of measures proposed:

– The approach used to select the strategies to study and discuss with the stakeholders usually begins with the key role of experts and policy makers which design a set of promising options, following their experience and intuitions. Such alternatives are then tested in order to enlighten impacts on the system, and negotiated with the stakeholders, establishing decisional loops which eventually bring to shared solutions. It can be said that the way experts select the

> BOX 1.2
> **Pareto Efficiency** is the concept which in the present research is intended when talking about efficient alternatives. In a Multi Objective problem all the alternatives A which are *pareto efficient*, are the ones for which there is no other alternative B which has better performances than A on at least one objective while keeping the same performance on all the others. This means that ordering the efficient alternatives implies making an explicit preference between the objectives, being no more a technical but a political issue [115].
> Optimization algorithms are the tools which can be successfully used to define the pareto efficient alternatives.

starting alternatives focuses on the measures itself: options are well specified and detailed, already complete in their mind, designed according their experience. From the nature of the approach, the starting alternative selected by the experts are necessary biased and suboptimal. Biased because such can be their view, opinion and experience, facing difficulties in considering all the multiple stakeholders in the picture. Suboptimal because it is the outcome of a human inventory of possible strategies. It is not possible to manually compare many different (many thousand) detailed measures (human mind gets lost while comparing pros and cons of too many alternatives). For this reason the selected strategies are chosen from a restricted pool of options, which might not include more interesting and efficient alternatives.

It is important to notice that the selection of the alternatives to bring to the attention of the stakeholders is an extremely important phase, which can strongly influence the outcome of the decision making process.

What if many other combination of measures are possible which can be interesting, cheaper and more efficient than the ones under examination (in terms of satisfaction of stakeholders' needs)? How can we drastically enlarge the number of different alternatives to consider, selecting and bringing to the attention of the stakeholders the ones which are actually most efficient because chosen from many thousands of different options?

- The measures proposed will completely change the shape of the IJsselmeergebied; it is easy to understand that raising the water level of the IJsselmeer by 1,5m as suggested by the Delta Commission, will totally change the equilibrium of the system and influence all the users along the lake. Furthermore measures are needed to actually implement a maximum water level increase of 1,5m after 2050 (Deltacommissie 2008). In fact all options are very demanding in terms of infrastructures needed to keep the system safe and compensations measures planned to repair the losses of ecological value and land use outside the dikes (see Appendix A). Such infrastructures are expensive and inflexible, while impact of climate is still only defined within a range (see Chapter 3.3). What if climate change will not be as severe as expected, or delayed, and the Netherlands discovers that dike reinforcement and drastic increase of water level of the IJsselmeer, are not needed, or could be better tailored on the needs? What if the system is flexible enough and already able to cope with the climate changes for some decades, if only more efficiently managed? How to investigate such flexibility in time, in relation with climate change, and define the potentials of the present system?

These are the questions which have been the primordial motor of the present research, together with the belief that another approach to the problem is possible: shifting the focus from the measures to the objectives, helps finding more efficient solutions to bring to the negotiation phase, selected among a much larger pool of options (i.e. tens of thousands). Furthermore, the way to tackle the uncertain climate changes is the implementation of flexible measures, which are able to adapt to different scenarios. Investigating the flexibility which already exists in the system, is the best way to adapt it to our needs in the near future (until it is possible); in this way more strategic decisions and labor intensive measures (i.e. rising of the dikes or building a pumping station) may be postponed to times where more information is available and climate effects on the system are clearer, so that the right choice is taken at the right time.

1.3. THE RESEARCH

1.3.1. DEFINITION OF THE RESEARCH

The present research investigates in the same direction of the ones presented above, looking for possible approaches and solutions towards a socio-economic&climate proof IJsselmeergebied. As mentioned before, it moves its first steps from the drawbacks on the methodology and the typology of measures adopted so far to tackle the problem. To cope with the drawbacks mentioned above, this study adopts the following strategies:

- As for the methodology, an approach is applied which uses optimization strategies to investigate the most efficient alternatives to discuss with the stakeholders. Stepping back from the definition of a well defined solution, a class of measure is consider instead of single particular measures, together with the declaration of the objectives of the system. It is not stated that the spring target level should be raised till 1.30, 0.60 or 0.20 mNAP (which are specific measures - as stated by the strategies presented in appendix A). Spring target water level is simply allowed to change (class of measures) and only extreme boundaries are defined, together with the objectives on the system (safety, water demand etc..). The most suitable alternatives are then defined through an optimization algorithm which strives to minimize (or maximize) the objectives, leading to the most efficient solutions.

  > BOX 1.3
  > CONTRAINT 1, *single objective function,* the optimization will be performed on a single objective function which will represent the objective of the decision maker (DIJ). *Discussed at 3.2 and 4.1.*
  > CONSTRAINT 2, *stakes subjected to optimization: safety of the dikes and water demand being the main concern of the decision maker.* Given the complexity of the system, possible measures are optimized taking into account only safety of dikes and water demand. Therefore the objective function of the optimization will be only defined on those stakes. For the other stakes in the IJsselmeergebied, impacts of the measures resulting from the optimization will be discussed a posteriori. *Discussed at 4.1.*

  Given the complexity of the IJsselmeergebied, the problem subjected to optimization is defined under a number of constraints shaping a workable *test case* which can be tackled with the simple tools and the time framework of the present research. Many constraints will be clarified later on in the research; however it is important to state now that the optimization problem will involve a *single objective function,* which defines the objective of a single *decision maker*, namely the Dienst

IJsselmeegebied (DIJ), management authority of the area. In particular the decision maker is interested in satisfying *only* safety of the dikes and water demand, which will be the two stakes included in the optimization. Reasons for such choice will be discussed later on in the research.

- As for the measures to consider, the starting point is the conviction that structural changes in the system might be very expensive and inflexible, while the IJsselmeergebied might have already, within the existing structures, the capability and flexibility to adapt to the future threats and needs.

  For this reason, as a first step, no extra (structural) measures will be taken into account: the research strives for defining for the IJsselmeer a dynamic target water level over the year which could *alone* satisfy the objective of the problem owner and create a socio-economic&climate proof system. The aim is to investigate whether a new IJsselmeer is possible, with no physical differences in the system, but which is able to face the future because differently used. It will be the same IJsselmeer, just with a new suit.

> BOX 1.4
> CONSTRAINT 3, *possible measures: changes in target water level only.* Since an important objective is to prove the flexibility of the IJsselmeergebied, at first, only management measures will be taken into account. Options for pumping stations and a different strategy in March will be discussed in a second stage. *Discussed at 1.3.3.*

Experts are skeptical on solutions which only lie on changes in target water levels (Deltaprogramma IJsselmeergebied 2010; Rijkswaterstaat Waterdienst 2010), stating that big infrastructural measures, being either dike reinforcement or pumping station at the Afsluitdijk, are needed in the long term. In the present research, when changes in the target water level only are not enough to assure the requirements of the system, extra measures are taken into account. For reasons which will be clarified later, the only extra measures considered in the present study are the installation of a pumping station at the Afsluitdijk (to cope with safety), and a change in the management strategy of March, considered as a summer month (to cope with water demand). The

> BOX 1.5
> CONSTRAINT 4, *no socio-economical scenarios*. Due to time constraints of the research only climate scenarios will be investigated. From now on the desirable condition for the future of the system is a “climate proof IJsselmeergebied”. *Discussed at 3.3.*
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> CONSTRAINT 5, *IJsselmeer only.* Due to time constraints of the research the spatial boundaries of the study will focus on the IJsselmeer alone, leaving out the Markermeer and the Randmeren. From now on, the area under study is the IJsselmeer, and not the whole IJsselmeergebied. *Discussed at 4.1.5*

second could fall within the range of the management strategies, since it consists only in a change of the target water level of March. However, changing management strategy of the month is a measure which falls out of the present management of the IJsselmeergebied, where March is treated as a winter month. Moreover it is still not clear the effect which such choice would have on the safety of the system, therefore the implementation of the strategy could need reinforcement of the dikes, hence structural measures.
The same optimization methodology will be used to size the pump capacity needed and asses a new target water level for March.

As a result of the two points above, this research strives to define for the IJsselmeer a dynamic target water level which is variable through the whole year by means of an optimization approach which uses a single objective function considering dikes safety and water demand, the main interests of the problem owner and decision maker of the system the Dienst IJsselmeergebied (DIJ). The research explores the flexibility of the system and defines for each month the target which better satisfy the considered stakes and gives to the Netherlands a "natte hart" which is climate proof. It is relevant to notice that such target water level trajectory is defined exactly on the needs expressed by the stakes considered, avoiding in this way over-dimensioning the system. The outcome is a set of monthly (12) target levels, which in theory can be different each month.

As it will be clear after the analysis of the stakes of the system, the problem is complex, both on social and computational aspects; in the present research the issue is significantly simplified, in order to fit the tools and the time framework of a Master Thesis. All the constraints and assumptions used in the present research will shape what is called *test case*: a simplified, but still close to real IJsselmeergebied problem, which will be tackled by the present research with an optimization approach. Given this, even though the outcome will be qualitative realistic, the research can not provide quantitative exact solutions and alternatives ready to be discussed with the stakeholders. The IJsselmeer problem in real life is far more complex than the test case analyzed in this work.
For this reason, the first and high level objective of the study is to define a methodology based on the optimization of the test case, and to investigate whether such approach gives new ideas and still unexplored alternatives for the future management of the IJsselmeergebied. This research does not have the challenging ambition of getting to an optimum solution; nevertheless it might suggest efficient alternatives which have fallen so far out of the attention of the experts. Although referring to a simplified test case, if with the use of just a simple model and an optimization algorithm together with the definition of few essential stakes and only one objective function, one can profitably explore the possibilities of the present system, and define promising future alternatives so far disregarded, then *it is interesting to use more extensively in the future an optimization approach in order to support the selection of efficient alternatives to negotiate with the stakeholders*.

If the method shows good understanding of the IJsselmeer even for such a simplified case, then it can be worthwhile to investigate such approach and define more close to reality solutions.

In the course of this report, constraints of the research (both on the system and the optimization) are clarified and justified, so that from one hand the test case is defined step by step, and from the other the problem can be made more complex and closer to the real case at wish, while using the same approach and tools. Simplifications are made where there is a knowledge gap (more research would be needed to close it and take more factors into account) or the issue would make the problem too complex for the present research.

As guidance for the reader, justifications and reasons behind the assumed constraints will be discussed when describing the methodology. However orange text boxes are present along the report when there is need to express such constraints before its discussion for the understanding of the research. As it can be notice, this has been already the case for boxes 1.3, 1.4, 1.5; the motivation which brought to such choices will be argued while discussing the test case, however their statement is already important for the definition of the research goal.

1.3.2. RESEARCH GOALS AND RESEACH QUESTION

According the above description, the main goals of the research are the follow:

1. *High level*, investigate the feasibility, simplicity and benefits of a methodology based on an optimization approach on dikes safety and water demand, for exploring measures towards a climate proof IJsselmeer.
2. *Low level,* for the Ijsselmeer (test case):
    a. define for the different scenarios a set of monthly target water level which can best generate a climate proof IJsselmeer, satisfying dikes safety and water demand objectives;
    b. define a set of monthly target water level and extra measures which can best generate a climate proof IJsselmeer for those scenarios where the flexibility of the present system is not enough to meet the objectives of dikes safety and water demand only by means of changes in the target water level;
    c. on the base of the selected measure, asses the flexibility of the present situation to adapt to future scenarios, satisfying dikes safety and water demand objectives;

As mentioned before, the low levels objectives do not have only meaning per se, since the answers can not be applied in real life as they are, but are necessary to fulfill the high level goal. When the methodology used in this research proves to be feasible and simple giving a good support for decision making, then as an answer to the high level

objective, it can be said that such approach is interesting for analyzing efficient alternatives for the future of the IJsselmeer. In this case, it is true if the research is able to give deep insight on the system and suggest new alternatives to bring into the discussion with the stakeholders, even if the problem has been simplified considerably.
On the other hand, necessary condition for the research to show the potentials of the methodology are qualitative interesting and realistic answers to the low level objectives, so that the results of the optimization of the test case can be also used as reliable indications of the behavior of the system under different alternatives, especially in the view of further research and application of optimization algorithms.

High and low level objectives translate respectively to the two research question of the research:

Can a different planning of the target water level alone give an answer to the long term needs for dikes safety and water demand of the IJsselmeer, and if not which other measures can help improve the situation?

Can a research methodology based on optimization strategies be a useful tool for defining efficient alternatives for the future management of the IJsselmeer?

Once goals and research questions are clear, it is also important to define what will be considered a satisfactory answer. Table 1.1 defines requirements of the conclusions in order to fulfill the objective and positively answer the research questions.

A positive answer to the first research question is built on the hypothesis that if realistic and interesting alternatives are obtained in a time and knowledge framework of a Master Thesis, the procedure can be considered feasible.

Research goal	*Goal fulfilled when:*	*Positive answer to Research Question when:*
1.High level	Carrying on the research has given insight on the applicability and benefits of an optimization approach for finding efficient alternatives for the IJseelmeer case	Answers to goals 1.a.b.c are realistic and the use of an optimization approach has given new information on efficient alternatives towards a climate proof Ijsselmeer
2.Low level a	Monthly (12) target water level are defined for a climate proof Ijsselmeer, which satisfy dikes safety and water demand needs with the present configuration of the system in different scenarios.	Changes in the target water levels alone are sufficient to make the Ijsselmeer climate proof and satisfy dikes safety and water demand objectives in future scenarios.
2.Low level b	Monthly (12) target water level are defined for a climate proof Ijsselmeer together with the dimensions of the extra needed measures, when the present system is not flexible enough to satisfy dikes safety and water demand needs.	
2.Low level c	Definition of the conditions when the present configuration of the system fails to meet the dikes safety and water demand objectives even with different target water levels	

Table 1.1 – Requirements for the conclusions to fulfill the goal

1.3.3. REASONS BEHIND THE RESEARCH

Why such research?

The research joins the already big number of studies which investigate possible future strategies for the IJsselmeer; together with the report of the Delta Commission and the “Exploration of water level management options for the IJsselmeer”, it answers to the necessity to design a climate proof IJsselmeer.

As mentioned before, strategies used to define the measures to be discussed and negotiated with the stakeholders are often defined by the experts end the effects computed on the base on the knowledge of the system; there is a lack of trust and use of optimization approach in the management of the IJsselmeer, in fact optimization algorithms have hardly been used in exploring possible solutions to the rising problems of the system.
With no doubt the opinion of the experts is important, however using a methodology which starts from the definition of the desired performances of the lake and selects an efficient set of alternatives by means of an optimization algorithm might be able to discover options which have fallen out of the imagination of the experts. This is especially because the system is complex; many stakeholders express different and contrasting needs on the IJsselmeer, so that it is easy to lose the complete picture of the problem.

It is important to realize that the present research is not in contrast with past recommendations, and has absolutely no intention of decrying their approach and methodology. On the contrary this study strives for adding value to the past work towards a climate proof IJsselmeer. The introduction of a strategy based on an optimization approach, might help the decision making process, because higher would be the variety of the alternatives proposed to the stakeholders during the consultation. As already mentioned, experts’ opinion and stakeholders’ consultation are essential planning approaches, however they would surely gain effectiveness if based on measures selected via optimization processes instead of pure expert experience.
An optimization approach is based on indicators specified together with the stakeholders, so that their wishes and objectives are immediately clarified and stand at the base of the selected strategies, already on an early stage. This can considerably smooth the stakeholders’ consultation process, and led easier to shared solutions. Furthermore an optimization approach is able to detect and discard on an early stage inefficient options, i.e. measures which are technically less satisfactory than others because bring less benefit under all the objectives considered. Eliminating inefficient options brings the discussion to purely political considerations: all the selected strategies are equally efficient, but they satisfy in different degrees the stakeholders which have contrasting objectives. Choosing one measure instead of another is then a matter of prioritizing the different interests and negotiating between the stakeholders, which is far from the scope of a purely technical research.

On the other way around an optimization approach allows to explore a bigger pool of alternative (many thousands) so that efficient alternatives which have fallen out of the imagination of the experts are more probable to be included.
Finally an optimization approach would help sizing the measures according to the needs, avoiding expensive over estimation of the strategy.
It is important to mention that the experience of the experts has sill a key function in the process, leading and managing the consultation (i.e. by supporting the stakeholders in the definition of their objectives).

To summarize, the optimization approach used in the present research can offer a precious help if integrated to the strategies traditionally used for decision making; selecting the options to discuss in the stakeholders' consultation trough a methodology based on optimization, the alternatives will be efficient and already oriented on actors' wishes, smoothing the process and the outcome.
The present research is therefore justified by the little research and trust so far given to optimization approaches, together with the belief of its important contribution to the future of the IJsselmeer, and in general to the decision making process.

Why such measures?

It is important to notice that the class of measures under study in the present research represents the first constraint of the problem. Only changes in target water level have been taken into consideration (with additional measures when changes are not able to meet the requirements). This does not mean that it is the only option. In theory, the set of actions which can be subjected to optimization can be bigger, including all the measures which are thought to be useful for the purpose of the project. It is then legitimate to wonder why such constraint has been chosen.
In the report addressing the causes of the high water levels reached in 1998 (Ministerie van Verkeer en Waterstaat - Directoraat Generaal Rijkswaterstaat - Directie IJsselmeergebied 1999), several options have been suggested as measures to prevent flooding and safety issues in the future. These suggestions have been already inspiring previous researches (de Jong 2010), and the same holds for the present one. However, only few of the suggested options have been considered in this study.

Changes in target water levels (winter and summer) is the main class of measures considered in the present research. There mainly two reasons why this choice has been made.

- First of all, as already mentioned, this might be a very *cheap* option; if the system is flexible enough to cope with climate changes by means of only management measures, no structural infrastructure has to be build, and the solution is free. In the case that extra measures are needed, investigating changes in target water level is also very interesting, since can give indication on the time when changes in management are not effective anymore and the system needs structural measures. This information allows policy makers to postpone expensive measures to the right time in the future, when more information on changes in climate will be available. In this way money can be saved in the present, and better used in the future, because more efficiently spent. The essential underlying hypothesis is that the target water level moves within the *indifference space* i.e. changes in target water level are considered which keep the system as it is now, notwithstanding the climate pressure (for instance keep the system as safe as in the present, so that no rising of the dikes is needed and keep the water demand served).

– Secondly it is a *flexible* option; this is an important issue, as the Delta commission stated "Flexibility is essential: it is important to stay abreast of developments, to keep our knowledge up to date, continually assessing our plans and modifying them where necessary" (Deltacommissie 2008). If no structural measures are built, the system remains the same as now, and changes in the management can be gradually implemented along with the experienced climate change, shaping the system exactly as needed. This is a flexible system, which can adapt to real changes in climate; on the other side if structural changes are implemented, it is not possible to step back, even if the climate threats will be less intensive than expected.

Pumping Stations; as mentioned before, installing pumping stations at the Afsluitdijk is the only extra measure which will be taken into account when changes in target water level alone are not sufficient to guarantee a climate proof IJsselmeer.
It is an interesting option because it keeps the situation as it is (same target water level), and does not affect all the stakes which are linked with the IJsselmeergebied: stakeholders will experience the system as it is in the present. This is the main reason why such measure has been taken into account in the present research; it is a strategy in line with changes in target water level because it is a measure which keeps the system within the *indifference space*, so modeling and optimization of a pumping station is straightforward in the frame of the research.
Also such option is not very popular between experts and policy makers. The main objection is the size of the pump needed: it has been estimated that a capacity of 1500/2000 m^3/s is needed to keep the present regime of water level in a W+2100 scenario, while the biggest European pump in IJmuiden (NL) has a capacity of 260 m^3/s (Verhoeven 2009). Since this option has the advantage of keeping the system as it is in the present (i.e. very little extra compensation measures are needed), it is interesting to investigate it trough an optimization approach, in order to understand the order of magnitude needed by the capacity of the pump, and analyze the advantages of applying an optimization algorithm.
Doubts over such option have been raised on the sustainability and the costs of the project; a pumping station has investments and operational costs, generating high energy consumption. Also it is not flexible.

Change in management strategy of March; dry years are dangerous for water demand both because the demand is higher, but also because there is less water available. It is easy to imagine that changes in target water levels are not effective in order to build the

needed buffer for the satisfaction of the water demand, if not enough inflow comes into the IJsselmeergebied.
This means that the configuration of the system might be a limiting factor in dry years, when the water entering the system is too little to provide satisfaction of the water demand: no matter how high is the target water level will be set, there is not enough water.
A solution within the frame of the present research, is allowing the system to start storing water earlier in the year, which would mean considering March as a summer month, and permitting a higher target water level. In such case more water is available to build the needed buffer. This seems a promising strategy and will be taken into account as an extra measure to help the system to cope with satisfaction of the water demand when the present configuration is not flexible enough.
Even if promising, safety problems are likely to limit a rise of the target water level in March due to the wind conditions. It is far from the purpose of this study to assess safety of March in case of higher target water levels, however, researches from the Meteorological Dutch Institute (KNMI) has shown that the chance of strong winds in such month is lower than in the rest of the winter (Rijkswaterstaat RIZA 2005). In general little research has been done in order to assess the storm characteristics of March, which has always been treated as a winter month.

Growing with the sea; is the main option suggested by the previous researches presented above. It is not taken into account in this study because it brings impacts whose estimation falls outside the present research (see appendix A), and generate a too complex optimization problem.

Enlarge gravity discharge capacity; this option is not taken into account in the present research firstly because already planned for the IJsselmeergebied (further investigation is not needed at this point), and secondly because its effectiveness decreases with sea level rise, being an uninteresting strategy for the long term (de Jong 2010).

Use of forecasts, using weather forecast to predict periods of high water income to the lake, might lead to the decision of temporally lowering the target water level, discharging more water to the Waddenzee, and creating a buffer which could be able to store the extra income, and avoid risky situations.
This option is very interesting; it would give to the system a greater dynamism, being able to respond to the actual situation, gaining in flexibility and efficiency. From a computational point of view this would mean to formulate the optimization problem every time step with new forecast information, in order to define the target water level at the next time step according to the information available. The time constraints of the research are such that is not possible to include this strategy into the study, however its investigation would be very straightforward and easy to implement starting from the tools developed in this study. In fact, investigation of the benefits of use of forecasts to manage the system is the first recommendation for further research.

As a final remark it should be stated that the present research mainly investigates the methodology and the measures described above because not much research has been done in this direction. It is far from the will of the author to suggest that such methodology and measures are better than the ones traditionally used. However they are certainly less popular among the studies on the IJsselmeer, and this makes their investigation interesting.

1.3.4. STRUCTURE OF THE RESEACH AND THE REPORT

The research has been approached taking inspiration from the procedure proposed by Rodolfo Soncini Sessa for Participatory and Integrated Planning (PIP) [114]. Section 3.1 describes the steps of the procedure used in the present research.

Chapter 2 and 3 contain the background information needed in order to approach the research. At first one can assume that the system under optimization is the real one, with all its complexities; description of the complete system will be provided in section 2.1, while the description of the stakes in the IJsselmeergebied and their objectives will be the subject of section 2.2.

As mentioned above, in section 3.1 the steps of the methodology will be clarified, while section 3.2 will be dedicated to the description of the optimization algorithms and the constraints on the optimization. Description of the scenarios is the subject of section 3.3.

Once the background knowledge is provided, chapter 4 contains the description of the work done within the research in order to fulfill the goals and answer to the research questions. In the chapter, the problem is analyzed, reduced to the test case, and structured for its optimization. The PIP is applied to structure and define the optimization problem. While proceeding with the PIP, constraints on the system will be clarified till the definition of the test case.

Chapter 5 will present the results, while conclusions and recommendations will be provided in chapter 6.

2. THE IJSSELMEERGEBIED

2.1. AREA DESCRIPTION

The IJsselmeergebied is the water/land system in the center of the Netherlands composed not only by the main open water bodies IJsselmeer, Markermeer and Veluwerandmeren, but also by all the land and the inland water networks which are connected with the lakes. Land and water generate together a strongly interconnected system, which needs to be considered in its joined complexity when managed.

Given the extremely connected Dutch water network, it is easy to understand that the IJsselmeergebied might actually include a big portion of the country. Checking the list of the stakeholders invited to the consultation for the exploration of water level management options for the IJsselmeer [111], it is possible to find 45 municipalities, 6 provinces (Flevoland, Fryslan, Gelderland, Noord-Holland, Overijssel and Utrecht) and 11 Water Boards (Groot Salland, Reest en Wieden, Regge en Dinkel, Vallei & Eem, Veluwe, Zuiderzeeland, Fryslan, Amstel Gooi en Vecht, Hunze en Aa's, Noorderzijlvest, Hollands Noorderkwartier). Given this fact, the extension of the IJsselmeergebied is indeed consistent, Figure 2.1 and Figure 2.2 show in red its borders if considering the provinces or the Water Boards invited to the consultation. Figure 2.2 is more indicative, as Water Boards are water management units and give a better indication of interconnected water systems; anyway it represents an overestimation of the IJsselmeergebied, since some areas are included which are not connected with the system (i.e. the islands in the north sea).

Figure 2.1 – Borders considering provinces

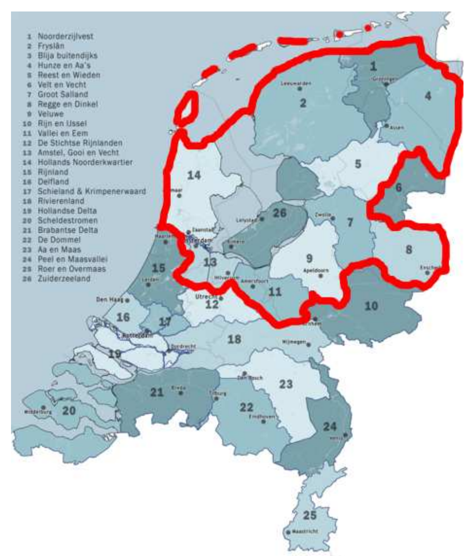

Figure 2.2 – Borders considering water boards

Given the extension of the IJsselmeergebied, it is easy to imagine that it represents an important feature of the Netherlands; a large part of the population is affected by its management and relies on the proper functioning of the system. This is the reason why the IJsselmeergebied is usually referred to as wet hearth of the country (het natte hart); this unique system, as the heart, pulses together with the Dutch society.

In winter, when water is abundant, the water bodies which compose the IJsselmeergebied are essential for the safety of the Netherlands, receiving excess water from the neighboring polders. While in summer, when the water is scarce, they provide large part of the country with fresh water, used for irrigation, drinking water, cooling water for power plants and volumes needed to keep the inland Dutch water system at the required status (fundamental for safety of the structures and ecological quality). Being part of the European Birds Directive “Natura 2000”, the IJsselmeergebied has also a strategic ecological value for birds’ migratory routes. Commercial shipping routes give to the area a high economical value and a key function for goods trading. Last but not least the IJsselmeergebied contributes to the quality of living, being home to many recreational activities and associations.

2.1.1. OPEN WATER BODIES

The open water bodies can be considered the core of the IJsselmeergebied. With a total wet surface of approximately 2000 Km^2, they lap the shores of 6 provincies (Flevoland, Fryslan, Gelderland, Noord-Holland, Overijssel and Utrecht) and are confined at the North-Western side by the Afsluitdijk.

The first step towards the present configuration of the IJsselmeergebied, which earlier was salty because part of the Waddenzee, has been implemented in 1932 with the construction of the Afsluitdijk, a 32 Km barrier which isolates the area from the open sea. However the present set up of the system has been completed in the 1975, when the Houtribdijk has been built and the Markermeer separated from the IJsselmeer. According to the internal dikes and gates, the lakes within the JIsselmeergebied can be divided in three compartments [109 – 110]: the IJsselmeer (light blue - including Ketelmeer en Zwarte Meer) the Markermeer/IJmeer (purple - including Gooi-Eemmeer) and the Veluwerandmeren (green). Figure 2.3 shows the three compartments.

Figure 2.3 – Compartments of the IJsselmeergebied

Ijsselmeer compartment

The Ijsselmeer compartment, limited at the South-Western side by the Houtribdijk and at the North-Western by the Afsluitdijk, is the largest lake in Western Europe with a surface of approximately

1200 Km^2, if including also the Ketelmeer, the Zwatemeer, and the Vossemeer. The four lakes can be considered a unique body from the water management point of view, since they are interconnected and variations in water level are strongly related (van Overloop ; Kuijper 2009). The IJsselmeer receives water not only from the neighboring polders, but also from the rivers JIssel and the Vecht, the main inflows to the IJsselmeergebied. For this reason it is more subjected to high water levels than the other compartments (not including the wind effect). Water levels in the compartment can be regulated by discharging water to the Waddenzee through the gates at the Afsluitdijk: Stevinsluizen and Lorentzsluisen. Water is discharged by gravity at low tide. High levels are almost exclusively in the winter: in that period discharge by gravity to the Waddenzee is made more difficult by the storms and wind influence, so that water has to be stored within the IJsselmeer. Furthermore higher inflows occur in winter, both from the river IJssel and the polders which have to discharge their excess water. The highest water level registered has been 0.52 mNAP in 1998; those events are usually the result of a period of 1 to 3 weeks which the inflow (from the IJssel, Vecht and regional supply) is greater than the outlet to the sea (through the gates in the Afsluitdijk). High water levels are usually measured a few days after the maximum discharge of the Jssel (Kuijper 2009).

Markermeer compartment

The Markermeer compartment, limited at the North-Eastern side by the Houtribdijk, at the South-East side by the Nijkerkernauw gate and connected to the Noordzeekanaal through the Oranjesluizen, is composed by the Markermeer, the Gouwzee, the IJmeer, the Gooimeer, the Eemmeer and the Nijkerkernauw. All together has a surface of approximately 740 km^2.

The Markermeer has no comparable large inflow of river water as the IJsselmeer. The most relevant supply is the water coming from the Nijkerkernauw gate via Eemmeer Gooimeer and the IJmeer. Winter excess water is discharged to the Waddenzee through the IJsselmeer. The gates at the Houtribdijk, Krabbergatsluizen and Houtribsluizen, regulate the exchanges between the two lakes, however it is generally very low.

The Oranjesluizen at Schellingwoude are used for flushing towards the Noordzeekanaal when the water quality of the Markermeer deteriorates (van Overloop ; Kuijper 2009).

Veluwerandmeren

The Veluwerandmeren consist of the water bodies between Nijkersluizen and Roggebotsluis, namely Wolderwijd, the Veluwmeer and the Drontermeer. All together the compartment has a surface area of 60 km^2. The level in the Randmeren can be controlled by the Roggebotsluizen (to IJsselmeer) and the Nijkerkersluizen (to Markermeer). Since the removal of the Hardersluis in 2002, these waters bodies are in open connection to each other (van Overloop ; Kuijper 2009).

2.1.2. STRUCTURES

The different lakes are connected to each other, to the land and to the water bodies outside the IJsselmeergebied through a wide range of structures. Dikes, pumps, gates, locks, measurement locations assure the achievement of the planned management, allowing water to flow within the system according to the needs. In the following paragraphs, the relevant structures in the vision of the present research are described.

Dams

The main dams in the IJsselmeergebied are the Afsluitdijk and the Houtribdijk. The first one has been realized in 1932, it connects Den Oever with Kornwerderzand and separates the Ijsselmeer from the Waddenzee. Connection between the lake and the sea is assured trough two gravity sluice gates, Stevinsluizen and Lorentzsluisen, which are only used one way to discharge water to the Waddenzee. The Afsluitdijk has been the first structure towards the present configuration of the IJsselmeergebied, initializing the process of transforming the area from a salt water system to a fresh water system.
In 1975 the Markermeer has been divided from the IJsselmeer by means of the Houtribdijk; it connects Lelystad with Enkhuizen, and exchange of water between the two biggest lakes of the IJsselmeergebied is assured by two sluice gates, Krabbergatsluizen and Houtribsluizen. Water can flow in both ways.

Gates

There are 5 main sluice gates in the IJsselmeergebied (van Overloop):

- *Lorentzsluizen* are located at Kornwerderzand in the North of the IJsselmeer in the Afsluitdijk. There are 10 undershot gates, each 12 meter wide. Their function is discharge water from the IJsselmeer to the Waddenzee. The total flow area when the gates are completely opened is 480 m^2, therefore the maximum opening is 4 meters (the gates have rectangular openings). The complex consists of:
    - Sluices, composed by two buildings, each with five culverts (tubes which operate to discharge water at low tide, by gravity) discharging water from the IJsselmeer into the Wadden Sea.
    - Locks, one large and one small lock which lie east of the sluices. The locks permit the navigation between the Waddenzee and the IJsselmeer.
- *Stevinssluizen* are located at Den Oever in the North-West of the IJsselmeer in the Afsluitdijk. The complex comprises 15 undershot gates that are each 12 meter wide.The total flow area when the gates are completely opened is 720 m^2. This means the maximum opening is 4 meters. The complex is identical to the Lorentzsluizen.
- *Krabbergatsluizen* are located in the West of the IJsselmeer in the Houtribdijk. In order to discharge water from the IJsselmeer to the Markerkmeer, two undershot gates are available of each 18 meter width. The crest level of the gates is at -4.50

mNAP. There are locks to let boats pass from Ijsselmeer to Merkemeer and vice versa.

- *Houtribsluizen* are located in the Houtribdijk in the South of the IJsselmeer and discharges to the Markermeer. There are six undershot gates (each 18 meter wide). The crest level of the gates is at -4.50 mNAP. The maximum capacity of the complex is 1000 m^3/s. There are locks to let boat pass from IJsselmeer to Markermeer and vice versa.
- *Roggebotsluizen* can discharge water in two ways, through the discharge gates and through the locks. The discharge gates consist of 2 round culverts that can be closed off by gates. The diameter is 1.8 meter. This can, mathematically, be replaced by a square culvert of approximately 1.6 by 1.6 meter. The crest level of the culverts is at -1.85 mNAP.
  The lock is 10 meter wide and has its crest level at -4.40 mNAP.

Sluice gates and locks are also located all around the coast of the lakes within the IJsselmeergebied in order to allow fresh water withdrawal from the polders and shipping from and to the inland.

Pumps

Pumping stations are located all around the coasts of the lakes, with the function of discharging excess water from the land to the open water bodies in wet periods. Some more are located more internally, but still having the IJsselmeer or the Markermeer as the final collector.

Water level measuring stations

Measurements of the water levels are monitored including wave heights caused by wind at four locations in the IJsselmeergebied. These measurements are then weighted into a representative average level (van Overloop).

Weather measuring station

The Centrale Meldpost IJsselmeer (CMIJ) is located at the Houtribsluizen in Lelystad (Ministerie van Verkeer en Waterstaat 2003). At CMIJ, information of the national weather is elaborated. Each hour, a new forecast of the situation in the IJsselmeer and the Markermeer is made. The focus is on navigation and through Mari-phone radio forecasts are send out to all ships in the area.

Wave measuring stations

Wave heights are measured in the IJsselmeer at five location: near Gaasterland (2x), near Enkhuizen (2x) and at the Rotterdam Hoek. Instead at the Markermeer there are no measuring locations for waves (Ministerie van Verkeer en Waterstaat 2003).

2.1.3. WATER BALANCE & INFLUENCING PHENOMENA

In order to understand the functioning of the system it is necessary to define the fluxes of water which regulate the volumes in the lakes, together with the phenomena, such as tide and wind, which have a direct influence on the water balance of the IJsselmeergebied.

Inflow

There are different inflows to the system:

- The discharge of the *IJssel* supplies approximately 70% of the water inflow to the IJsselmeergebied, with a mean discharge of 400 m^3 / s (van Overloop). At high discharges the flow of the IJssel is approximately 15% of the discharge of the Rhine, while at low Rhine flow a discharge of 285 m^3 / s is assured for the IJssel through the use of the weir at Driel. However when the Rhine discharge drops under 1300 m^3 / s, then such minimal flow can not be assured anymore (Meijer 2009).
- A number of regional rivers also flow into the system, including the *Overijsselse Vecht* into the Zwartemeer, the *Hierdense Beek* to the Ketelmeer through the Veluwemeer and the Drontermeer and the *Eem* (Kuijper 2009). Their discharge is not measured but expressed as a percentage of the discharge of the IJssel (0-1.5) according to rainfall and soil moisture condition (Meijer 2009). Their average cumulative flow is about 165 m^3 / s (Kramer 2008)
- Direct *precipitation* on the open water is also an important inflow component.
- The water managers of water boards in the surrounding areas pump excess water from the polders into the IJsselmeergebied. Water is also exchanged through the locks (Meijer 2009). At maximum capacity (after an extreme storm event), approximately 200 m^3/s is pumped from regional water board Zuiderzeeland, 45 m^3/s from Hoogheemraadschap Holland Noorderkwartier and 70 m^3/s from Fryslân (total inflow of 315 m^3/s) (van Overloop).

In total the IJsselmeergebied drains an area of approximately 20.000 Km^2, including large part of the Northen Netherlands and a small portion of Germany. Figure 2.4 shows the catchment area of the system (Deltaprogramma IJsselmeergebied 2010).

Figure 2.4 – catchment of the IJsselmeergebied

Outflow

Water leaves the system through different ways:

- Water mainly leaves the IJsselmeergebied discharged by gravity through the *gates at the Afsluitdijk*. Lorentzsluizen and Stevinssluizen are opened when the water level in the IJsselmeer is higher than the target water level. Since water is discharged by gravity, the water level in the IJsselmeer must be higher than the water level in the Waddenzee, this is true for instance at low tide, so that time of flushing is mainly determined by the astronomical tide and influenced by the winds, which determine the actual water level in the lake and at the sea (Meijer 2009). The elevation difference between the two water levels determines the amount of possible discharge (the larger the difference, the higher the discharge) until the maximum capacity of the gates.
- Through the *Oranjesluizen* water can be discharged to the North Sea via the Noordzeekanaal, through the gates at IJmuiden. This is generally done to flush the channel and prevent salt water intrusion (Meijer 2009).
- From the IJsselmeer water is subtracted as *fresh water supply* (drinking water, agriculture, supply for inland water systems etc…). Fresh water demand is higher in the summer months of May (18%), June (21%), July (22%) and August (22%) while limited in the months of April (9%) and September (8%). Also in this case discharge to the polders takes place under gravity; the water level of the lake should be higher than a certain threshold (Meijer 2009).
- *Evaporatio*n and *seepage* to the low-lying reclaimed lands, also contribute to water losses from the system. Evaporation is in the order of millimeters per day, but given the large surface of the lakes, the volumes are relevant (Meijer 2009).

Astronomical tide

As already mentioned discharge of excess water to the Waddenzee is only possible when the actual water level is higher that the sea water level. When the sea level is too high, water has to be kept in the IJsselmeer until free flow is possible again. Determining the fluctuations of the sea water level, the astronomical tide plays then a key role for the timing of the discharge.

Wind

Actual water levels both at the sea and at the lake side are strongly influenced by the weather conditions, especially wind, which can generate either a positive or a negative setup.
In winter the dominant wind blows from the North-West, so that there is often a negative setup at Lorentzsluizen and Stevinssluizen which limits water discharge by gravity. This is also because the same weather condition creates the opposite situation at the Waddenzee side of the dam.

Figure 2.5 shows a typical situation at the Afsluitdijk, where the blue and light blue lines show the discharge possibilities trough the dam. As it can be noticed, both the astronomical tide and the wind effect are relevant; the general sinusoidal sea water level is given by the tide, but the actual water level (the one which determines real discharge possibilities) is also influenced by the storms.
Limitations for discharge trough the Afsluitdijk is one of the main reasons for high water levels in the IJsselmeer.

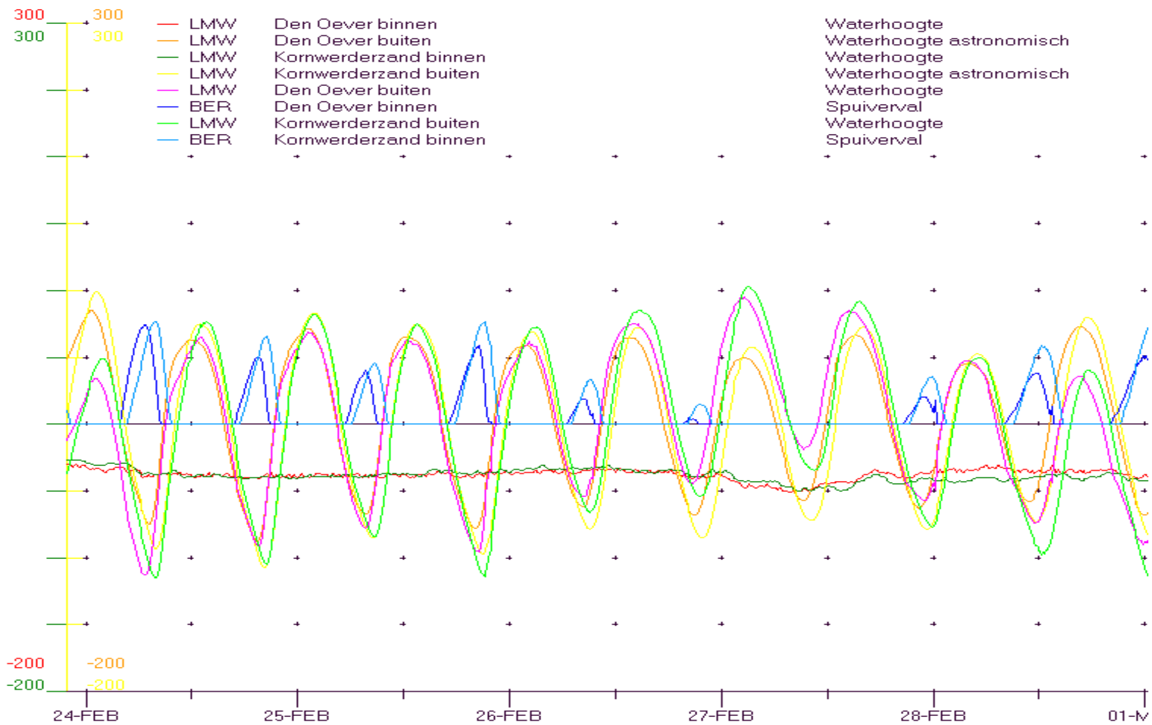

Figure 2.5 – Discharge possibilities at the Afsluitdijk

On the other side of the lake, at the Ketelmeer and Zwartemeer, the situation is the other way around; positive wind set up might let the water level rise up to 3 meters.
In general two typology of location can be found In the IJsselmeergebied: wind or water level dominated. In the first case the actual water level is more influenced by the wind effect and wind setup (usually located in the South-Eastern side of the area where wind effect gets stronger due to the possibility of the wind to blow on the flat lake surface). At water level dominated sites the influence of the wind in determining the actual water level is lower.

In summer, the winds are much milder, and blow typically from Eastern direction. Wind setup has relevant consequences also in this case; the water level at the Frisian coast is lowered, while raised along North Holland. As a result, satisfaction of fresh water supply is often more difficult at the Eastern coasts of the IJsselmeer (Rijkswaterstaat Waterdienst 2010).

2.1.4. OPERATIONAL WATER MANAGEMENT (TARGET WATER LEVEL)

As mentioned before the open water bodies of the IJsselmeergebied receive the excess water from the neighboring polders in wet periods, while providing fresh water especially in dry periods. Water exchanges between lake and land are, in general, perfectly tuned to satisfy the needs of the population, and the IJsselmeer is a precious buffer both in times of excess (water discharged to the lake) and shortage (fresh water taken from the lake).

In order to best satisfy the double buffer function mentioned above, target water levels of the three water bodies have been defined; the system tries to bring the water level to the target by discharging to the Waddenzee when the level is too high, or closing the gates and storing the water when it is too low (Kuijper 2009). Rijkswaterstaat is responsible for management of the water level in the IJsselmeergebied.
The present management of the target water levels is shown in Table 2.1:

Watersysteem	Streefpeil winter (m+NAP)	Overgang winterstreefpeil naar zomerstreefpeil	Streefpeil zomer (m+NAP)	Overgang zomerstreefpeil naar winterstreefpeil
IJsselmeer	-0,40	20 maart - 10 april	-0,20	20 september – 10 oktober
Markermeer	-0,40	15 maart – 15 april	-0,20	20 september – 15 oktober
Veluwerandmeren	-0,30	7 maart – 1 april	-0,05	15 oktober – 1 november

Table 2.1 – Management of the IJsselmeeergebied

There are different targets for summer and winter, because different objectives have to be met. The considerations which played a role in planning the targets are:

- The whole year the target should be sufficiently high above the level in the Waddenzee, to assure adequate discharge by gravity.
- The whole year the target should be high enough to guarantee shipping.
- Low target in the winter to assure adequate safety of the dikes.
- Low target in the winter to facilitate pumping of excess water from the polders.
- Higher target in the summer to assure water supply to the polders by gravity.

It should be noticed that the target water level does not always coincide with the actual water level. Especially in winter the inflows are much higher than the possibility the system has to discharge the water through the gates at the Afsluitdijk, so that actual water level are often much higher than the desired ones. On the other hand, lower inflow in summer allows the system to keep the water levels close to the target.

Figure 2.6 shows the main structures and flows which define the water balance of the IJsselmeergebied.

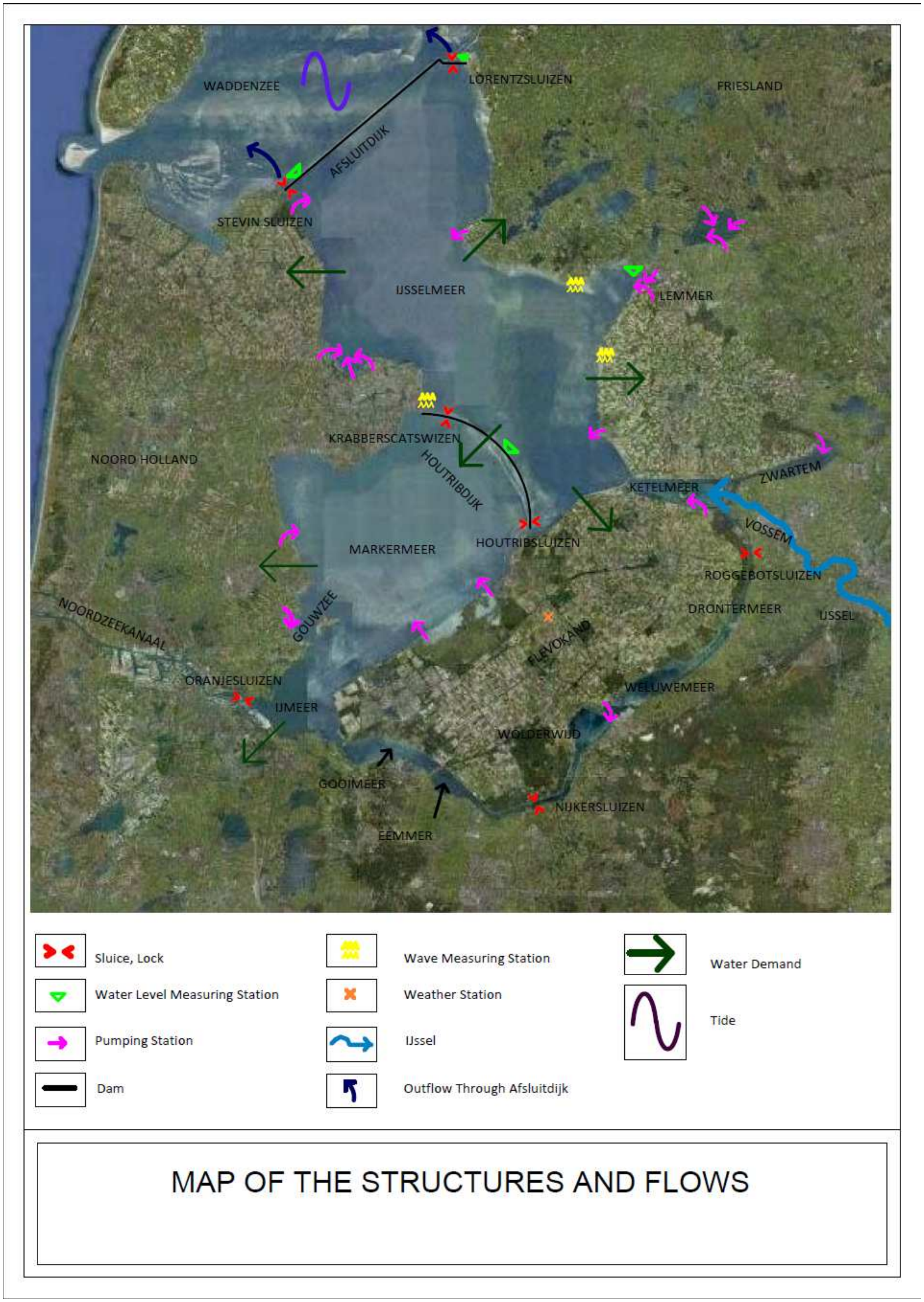

Figure 2.6 – Main structures and flow in the IJsselmeergebied

2.2. STAKES ANALYSIS

Once it has been discussed which are the physical features of the IJsselmeergebied and how it works, it is important to understand the social set up of the system. Who manages the system as well as who "uses" it, how it is used and which are the objectives of the users. Analysis of the stakeholders and their stakes is crucial for successful problem solving (Enserink 2010), and in the present research it is fundamental in order to define the objectives on the system, and structure the objective functions on which an optimization can be based. Furthermore it gives insight on the contrasts and common interests which rise from the different stakes on the IJsselmeergebied, and allows an evaluation of the impacts of the selected alternatives on the different stakes.

A detailed analysis of the single stakeholders falls outside of the purpose of the research, especially for its extension with respect to the time constraints of this research; nevertheless it is fundamental for the quality of the work. For this reason such analysis will be performed on a higher level, defining the objective of the stakes which exist on the system, stakes which group the interests of the single stakeholders.

> BOX 2.1
> CONSTRAINT 6, *Stakes analysis instead of stakeholders' analysis.* Analysis of the single stakeholders is not subject of this research; the objectives which are considered in the system will be addressed as high level stakes, in which the stakeholders can be grouped*. Discussed at 2.2.*

Since the present research strives for an optimum target water level which would result in a climate proof IJsselmeer, special attention will be given in order to relate the objectives of the different stakes to the desired water levels, i.e. the water levels which would satisfy the needs of the different stakes. In this vision objectives are defined in a more operational way into the desired water level fluctuations, so that it is possible to:

- Translate them in objective functions for the optimization, which evaluate the actual water level produced by the different alternatives according to the needs of the stakes (if the stakes are part of the optimization of the system).
- Understand effects of the measures on the stakes which have been left out from the optimization, comparing actual water level produced by the optimized measures with the objectives of the stake.

In line with the previous works and reports which study the options towards a climate proof IJsselmeergebied, the stakes which will be analyzed in the present research are: safety of the dikes, fresh water demand, ecology, commercial shipping, recreation, inland water management (Binnendijkswaterbeheer) and water management outside the dikes (Buitendijkswaterbeheer). Furthermore the Dienst IJsslemeergebied, problem owner and decision maker in the system has to be added into the picture.

2.2.1. DIENST IJSSELMEERGEBIED (DIJ) – RIJKSWATERSTAAT

Rijkswaterstaat is the authority which manages and develops both transportation and water networks in the Netherlands, on behalf of the Ministry of Infrastructure and Environment. The management of the IJsselmeergebied, like all the other waterways and lakes in the country, falls under its duty, specifically under the IJsselmeergebied Department of Rijkswaterstaat (Dienst IJsselmeergebied).

The Dienst IJsselmeergebied is one of the 10 regional departments of Rijswaterstaat, responsible for maintenance, management and construction of the main infrastructures in the region, as well as for the practical implementation of water policies. The Dienst IJsselmeergebied works in line with the national water policies (e.g. National Water Plan) and in solid collaboration with the local authorities and organizations.

Being the manager of the area and the authority which has to assure a good functioning of the system for the whole country and specifically for the users, the Dienst IJsselmeergebied has the objective of implementing a good management of the area, now and under future scenarios, which can satisfy the desires of all the stakes. Given the definition of the problem in the introduction (chapter 1.1), the objective of the Dienst IJsselmeergebied can be expressed as the achievement of a climate-proof IJsselmeergebied, while gaining the broadest consensus within the stakeholders on the selected measures.

> BOX 2.2
> OBJECTIVE FOR DIENST IJSSELMEERGEBIED (*decision maker)*: climate-proof IJsselmeergebied, while gaining the broadest consensus within the stakeholders on the selected measures.

2.2.2. SAFETY OF THE DIKES

In the areas of the Netherlands below the sea level, the flood defense is provided by a system of dikes which protects the hinterland against flooding(Kuijper 2009). The dikes have a security level expressed as a probability of occurrence per year of the failure event. The same holds for the IJsselmeergebied; neighboring areas which are lower than the water level, are protected by dikes. Around the Ijsselmeergebied, security standards vary between 1/1250 and 1/10.000 per year. The standards have been defined around 50 years ago according to the damage that a flood event would cause in the area (Rijksoverheid 2008).

Threats from the water bodies of the IJsselmeergebied to the safety of dikes are due to the combination of three different phenomena, shown in Figure 2.7 (Deltaprogramma IJsselmeergebied 2010):

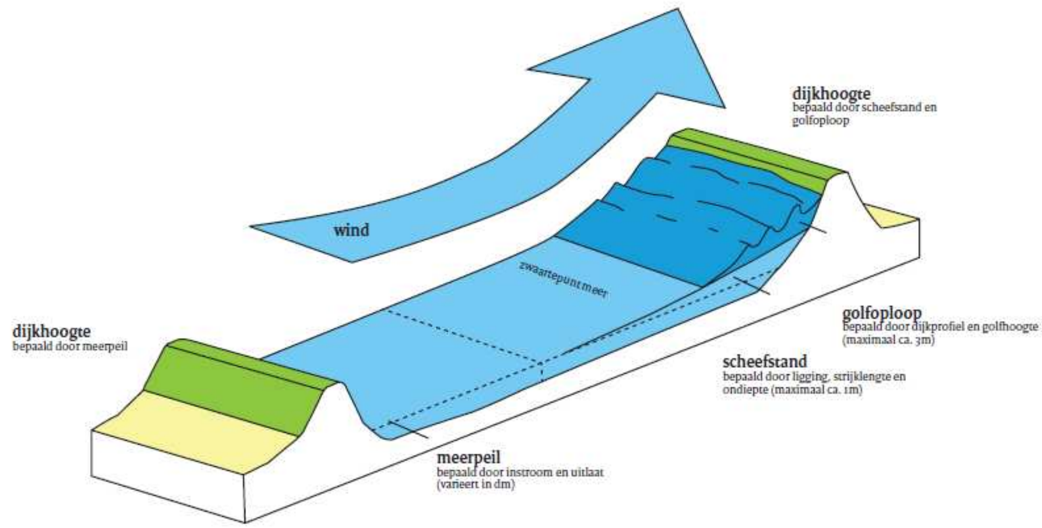

Figure 2.7 – Phenomena influencing safety of the dikes

- The average water level in the lake, determined by the inflows and outflows.
- The wind setup, due to wind influence.
- The waves, due to wind influence.

As it can be seen in Figure 2.8, the average water level might be only a minimal part of the total local water level. This is true for locations which are wind dominated, and it is easy to imagine that measures which control the mean water level might be very ineffective from a safety point of view.

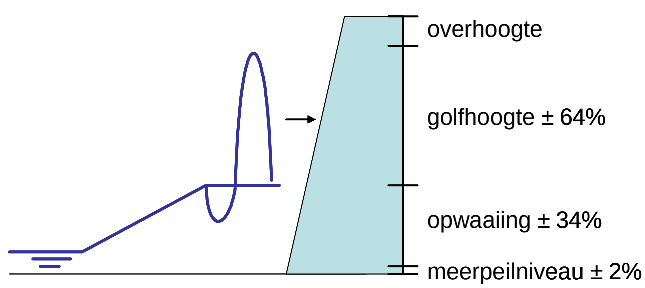

Figure 2.8 – Realtive importance of the different Phenomena

Given the local variability of wind influence, discussed in paragraph 2.1.3., the height of the dikes is also locally defined on the base of statistics of the mean water level and wind, shape of the dike and standard to be respected. Dikes height is reviewed every 5 years, the latest standards are the Hydraulische Randvoorwaarden 2006 (HR 2006), which uses the software Hydra-M and Hydra-Q for the statistical analysis at the IJsselmeer and Markermeer. Extreme event analysis is performed considering mean water level and wind statistics together. The design water level (toetspeil) is read in correspondence with the return period which coincides with the safety standard of the location. Furthermore the design dike height (hydraulische belsting niveau, HBN) is computed considering wave effect and shape of the dike (Ministerie van Verkeer en Waterstaat 2007).

It is important to notice that the HR2006 prescribes the design features which dikes around the IJsselmeergebied should have in order to comply with the safety standard. In general some dikes are over-dimensioned, some dikes respect the standards and others

need to be upgraded. Given this, the present system subject to its historical water levels, is not safe. The peak in 1998 is a good example of an unsafe historical situation.
Furthermore calculations are all referred to the winter period (October-March).

Given the lower inflow from the IJssel and the milder winds, statistics for summer water levels and winds hardly been considered for safety issues concerning the dikes. However, summer storms are not uncommon and safety issues regarding the dikes can happen also in summer time.
Depending on the summer target water level, summer storms can be a threat for the dike safety, and flooding can occur. In general, little research has been done on summer safety. There is agreement on stating that a rise of 50cm of the summer target water level from the present winter target level (till +0.1mNAP), does not represent a threat for safety of the dikes. This is confirmed by the difference between toetspeil needed for summer and winter in the present condition, which is minimum 50cm. However it has been shown that even a rise of the target water level till 0.6mNAP has no influence on the safety of the dikes (Kramer 2008).
It is important to see the two boundaries in the correct perspective, a safe rise till +0.1mNAP is certainly a more shared indication among the experts, while higher target water levels have been considered unrealistic (Meijer 2009).

Objective

The objective related to this stake is to keep the system at the correct safety standard in winter as well in summer under the future scenarios.

Operational objective

In a more operational way, when performing an extreme event analysis of the water levels at a certain location (considering mean water level and wind effect) the water level with return time corresponding to the safety standard at that location should be equal or lower than the toetspeil on which the dike has been designed (prescribed by HR 2006); i.e. in the future scenarios, if a dike has been designed to resist an extreme even of 1 mNAP with an annual frequency of 1/10000, the water level with return period 1/10000 years should equal or be lower than 1 mNAP.

BOX 2.3
OBJECTIVE FOR SAFETY OF THE DIKES: satisfaction of the safety standards location per location (both for summer and winter), in the present and under future scenarios.

2.2.3. FRESH WATER DEMAND

[The lakes within the IJsselmeergebied are the largest freshwater basin of the Netherlands (Rijksoverheid 2008); they supply directly or indirectly over 30% of the water needs of the country (a total are of 12950 Km^2). Figure 2.9 relates each region with the relative supplier.

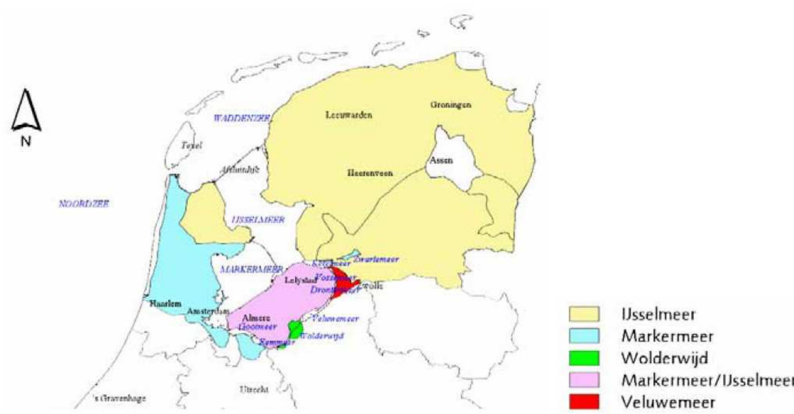

Figure 2.9 – Areas supplied by the different compartments

Fresh water is used for many purposes among which agriculture, ecology and safety. Drinking water is also an important demand, about a million of people rely on the IJsselmmeer, which affects, however, more the quality than the quantity of water required.
Water is usually delivered by gravity to the users, but some mobile emergency pumps can be used in times when gravity flow is impossible. This has important consequences on the fresh water availability; in volumes fresh water in the IJsselmeergebied is abundant, however only a restricted buffer of such water is available to use, when the water level drops under a certain threshold and water can not be delivered by gravity anymore, then there is a deficit.

Each sector has different demands in terms of quality, quantity and timing; in normal conditions demands are all satisfied, while are subjected to a priority rank in times of shortage.

Figure 2.10 – Priority of the different water demands

Namely the different uses involved with their priority are (Kuijper 2009); see Figure 2.10):

- Maintenance of the target water level of the main inland system – Boezem – in order to keep the dikes and structures inland safe and stable. Prevention of irreversible ecological damage due to prolonged dehydration (Safety/Ecological emergency - Priority 1).
- Drinking water and cooling water for power plants, vital and socially important supply for people (drinking and energy). (Urban water demand-Priority 2).
- All the other use: flushing the system for ecology purposes (salinity intrusion), and water demand at the districts (agriculture, stability at the districts etc…). (Ecology, Agriculture, safety of the districts etc… priority 4). Social and economical consideration are used to set a priority within the different sectors.

Priority 3 is missing, because this includes problems with a high impact, which can be solved with a low use of water (i.e. irrigation of capital intensive crops). Also extreme and sudden dangerous situations (irreversible environmental damage for example) can climb the priority order.

Objective

The objective related to fresh water demand is its satisfaction under future scenarios.

Operational objective

In a more operational way, under future scenarios, free flow to inland water system should be guaranteed, i.e. water levels should never drop under the threshold which would make it impossible.

BOX 2.4
OBJECTIVE FOR FRESH WATER DEMAND: Satisfaction of the water demand in the present and under future scenarios, i.e. keep free flow to inland systems.

2.2.4. ECOLOGY

Improvement of ecological quality has different meanings in the IJsselmeergebied, from water quality, to the safeguard of ecosystems, biodiversity, and the multitude of animals and vegetation which live in the area.

With regard to the ecological quality, the IJsselmeergebied, falls into two very important directive of the European community:

- WFD (Water Framework Directive), which prescribes the definition and implementation of water quality objectives for the European water bodies. Since water quality is not modeled in the present research, the WFD will not have any prescription on the ecological objective of the present research.

– Natura2000, (European Birds Directive), which sets different objectives for the developing of the bird population in the area, in terms of number of existing species and number of individuals per specie. In order to reach the objectives defined by "Natura2000" the ecosystem should be favorable for the needs of the different species. These needs translate into requirements in terms of water quality, extensions of breeding areas, water level fluctuations and all the other elements which can influence the quality of the ecosystem.
  Figure 2.11 shows the areas protected by the directive.

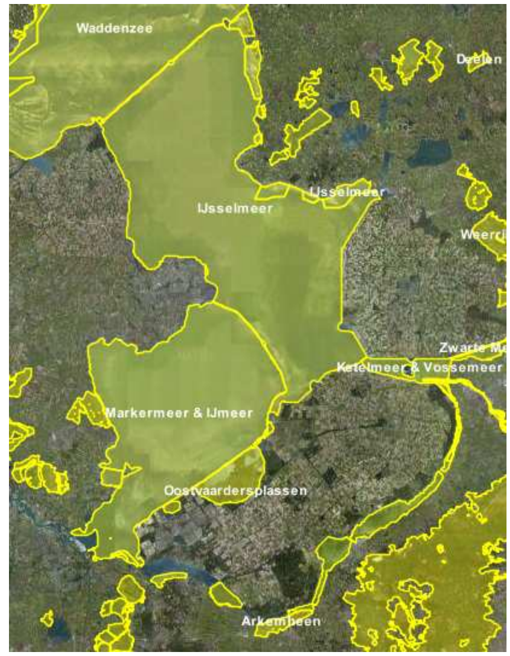

Figure 2.11 – Areas of ecological interest

In the framework of the present research, ecological aspects which are discussed are the ones which can be influenced by changes of the target water levels and the consequential daily water levels. No water quality issue is considered, even though chemical and physical quality is essential for ecological objectives.

BOX 2.5
CONSTRAINT 7, *No analysis of water quality.* The IJsselmeergebied is only analyzed on water quantities issues; assessment of water quality is left out of the present research.

Research has shown that seasonal water level fluctuations, produced in the IJsselmeergebied by a dynamic and more natural target water level, may be beneficial for the littoral vegetation and ecosystems (Lammens 2007).
The improvements of ecological quality and ecosystems related to adopting more natural water level fluctuations in the IJsselmeergebied are mainly referred to the benefits which will be produced for reed breeding birds. Reed breeding birds migrate to the IJsselmeergebied in their route between Siberia and Africa, during breeding period (early spring – February/June) if conditions for breeding are favorable. In such prospective, extended and partially submerged reed area are needed in order to build their nests during the breeding period. Water level fluctuations over the year strongly influence the growth of the reed, and the possibility for the birds to build their nests in the IJsselmeergebied. In particular more natural fluctuations, together with land-water transitions, might enhance the extension and health of reed, and consequently the number of birds migrating to the IJsselmeergebied.

It is important to realize that fluctuation of water levels might harm other species or ecosystems. Different species of birds (eating plants, fish or mussels) live in the IJsselmeergebied the whole year. According to an expert[1], only water plants eating birds (like swans) might be affected by water level fluctuations. They are present all year, and they eat water plants so that the water levels should not be too high for too many days in a row, otherwise the food can not be reached (plants are too deep). However those animals can still adapt to changes in water levels from 30-70 cm, due to their long neck.

Under these conditions, improving ecological quality by means of more natural water level fluctuations means creating favorable conditions for the reed to grow and the reed breeding birds to come to the area. This goes in the direction of the implementation of the Natura2000 directive.

Characteristics of the fluctuations

First of all it is important to notice that the IJsselmeer and the Markermeer can be described as large water tabs with relatively little land-water transitions. However reed development need gentle coasts. Natural water level fluctuations will improve the ecological quality of the lake, but only after implementing large-scale land-water transitions (i.e. major morphological changes): the two aspects are both required in order to reach ecological objectives (Meijer 2009).

In areas where water-land transitions are present, expansion of reed can be obtained if:

- There is a peak in spring of 20/50 cm over the ground; this is the perfect situation for birds to build their nests over semi-submerged reed.
- In late summer, from July, some areas dry out for 2/3 months; so that reed roots can expand at open air, enlarging the area.
- In winter land should be submerged (also with just little water) so that reed roots do not freeze.

Figure 2.12 shows a potential yearly pattern. The red dotted line represents the land-water transition. It is important to notice that it is not a feasible solution to keep the summer water level lower than the present winter level because such situation would generate droughts which would damage other ecological compartments. A simple solution would be to switch summer and winter target water level, with a spring peak.

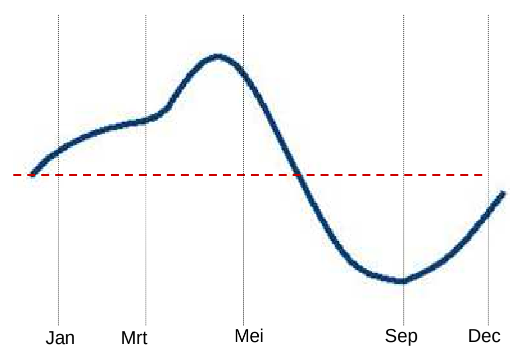

Figure 2.12 – Potential yearly fluctuations for ecological quality

[1] Dominique Bokeloh – Natuur Monumentum

This pattern is optimal for environmental considerations when it does not occur every year with the same amplification. In other natural lakes the differences between summer and winter average change year by year: it can be usually of 1 meter, but every three year can be of 1.5 to 2 meters and every ten years of 3 meters. Also, if reed health is strong, the above features of water level fluctuations can now and then not be verified, without damage to the plants (Meijer 2009).

Regarding the IJsselmeergebied, the absence of extensive land-water transitions, causes the ineffectiveness of water level fluctuations, towards ecological goals. For this reason there are skepticisms in including ecological objectives into the target water level management.

Objective

The ecological objective requires developing the lake into a more natural, sweet, dynamic shallow lake, favorable for development of reeds and reed breeding birds.

BOX 2.6
OBJECTIVE FOR ECOLOGY: development of the lake into more natural, sweet, dynamic shallow lake, favorable for reed growth and migration of reed breeding birds.

2.2.5. COMMERCIAL SHIPPING

Commercial shipping is an important economical activity in the IJsselmeergebied; the main route links Amsterdam and Lemmer through the Houtribsluizen (purple in the figure), but also connections to the Waddenzee experience a consistent number of cargos (Meijer 2009). Figure 2.13 shows the main shipping routes in the IJsselmeergebied.

Key factors for commercial shipping are both the loads which can be carried with one single trip, and the number of trips possible. Higher loads and faster trips are desirable because they increase the revenues of shipping companies. Water levels in the IJsselmeergebied influence both factors: from one side the depth of

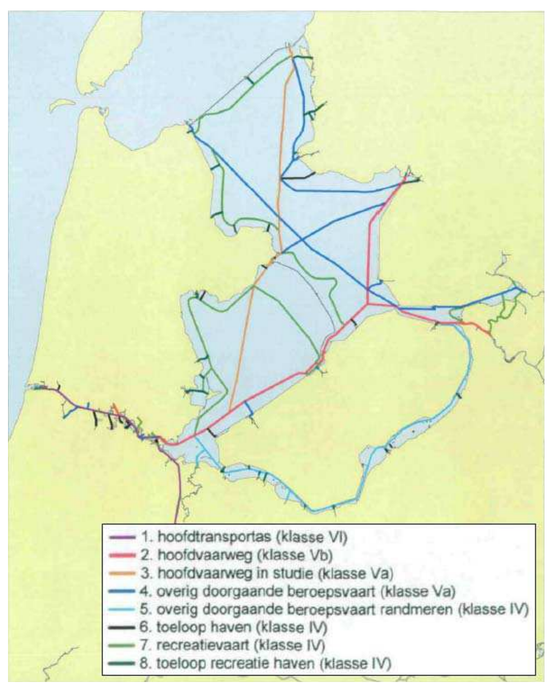

Figure 2.13 – Main shipping routes

the water determines the maximum possible load for ships and from the other water levels influence the waiting times at locks and bridges.
Given this two important criteria, there are different features to consider when thinking of desired water levels for commercial shipping.

Bridges height

The height of bridges might be an important limitation to commercial shipping in relation with water level changes. A raise in water levels have a negative effect when passing both under movable bridges: waiting times are prolonged, increasing the total travel time of the cargo.

Locks

When water levels drop down, problems arise for commercial shipping at locks where the water level is too low to allow many ships at the same time or full load. This would cause longer waiting times or limitations to cargo loads. Also if the water level between the two water bodies differs too much, longer waiting times are experienced to overcome bigger differences.

Water depth

Lower water levels and consequently lower depths can bring damage to the commercial shipping sector. It can lead to a longer travel times because ships have higher hydraulic resistances. As a consequence, shipping companies should either use more energy in order to maintain the boat speed or lighter cargos. Depending on the choice, smaller depths lead to additional travel time, less loading or higher energy consumptions.

Objective

The general objective of the commercial shipping is to have a water level regime which could allow full load of cargos and little waiting times at the structures, in order to increase their revenues.

Operational objective

Large fluctuations of water levels are not appreciated by the commercial shipping sector, a more stable water level would be preferable because it creates a more reliable environment for shipping.
However shipping companies can adjust to a certain range of water level fluctuation with little economical losses. The definition of the range outside which high damage start to be perceived by the sector, depends on the dimensions and the type of the ships which access fairways. At the present situation several studies have assumed the following boundaries (Meijer 2009):

- Low boundary of -0.4 mNAP, assuming a necessary depth of 4m and a position of the lock threshold at -4.4mNAP.
- No high boundary, assuming that damage for shipping companies due to higher waiting times at movable bridges, can be neglected.

However it can be argued that navigation channels through the lake have been dredged in order to comply with the needed depths. Lowering the water level can be easily counteracted by further dredging.
This is certainly a simplified definition of the objective, mainly due to knowledge gap on the problem.

> BOX 2.7
> OBJECTIVE FOR COMMERCIAL SHIPPING: a water system which could allow full load of cargos and little waiting times at the structures, in order not to lower the present shipping revenues.

2.2.6. RECREATION

Given the natural, cultural and historical value of the IJsselmeergebied, the area is an important site for many different recreational activities, contributing in this way with the quality of life of the inhabitants (Deltaprogramma IJsselmeergebied 2010).
The main recreational activities are water related, such as recreational shipping, water sports, swimming and fishing. In the last decades, camping sites, holiday villages, resorts and recreational use of the shores are strongly developing, attracting not only local tourists, but also people from all over the country. These trends are expected to be confirmed also in the future, determining an increasing recreational pressure on the IJsselmeergebied (Meijer 2009).
Changes in water level regimes directly influence the recreational activities, altering its possibilities and producing less attractive conditions. Furthermore the present infrastructure has been adjusted to the present water level management, therefore any change is likely to create nuisance.

Objective

Objective of the recreational sector is to keep a water level regime which preserves the present infrastructure, beaches and leisure activities.

Operational objective

Requirements on water levels from the recreational sector depend on the leisure activity which is taken under consideration (Meijer 2009):
- For recreational shipping and water sports, rising of water levels might generate longer waiting times at bridges and locks, and problems at the harbors. On the other

side, water level reduction will bring down the navigable surface and create problems at harbor accessibility.

However some impacts are considered negligible; many of the ships can already not navigate outside the main channels, and would still be able to do it even with considerable water level decrease. Furthermore the increase of waiting time at structures has been considered not significant.

More relevant is the accessibility of the harbors' facilities; in general no problems are faced when the mean water level stay within +0.20m and -0.60m with respect to the present summer target water level.

- Beaches for swimming disappear if the water level is too high, and unpleasant mud layers come out when the level drops too much. In general small inundations with no big consequences happen with a water level rise of +0.2m, while many of the beaches disappear if the rise is about +0.4m (reference: summer target water level).
- Recreational facilities experience inundation problems with rise of target water level, however information on the thresholds are not available.

Notwithstanding the above figures, still little is known about water level regimes required by recreational activities.

BOX 2.8
OBJECTIVE FOR RECREATION: a water level regime which preserves the present infrastructure, beaches and leisure activities.

2.2.7. INLAND WATER MANAGEMENT (Binnendijkswaterbeheer)

Changes in water level management in the IJsselmeergebied have important consequences on all the inland systems which are dependent and/or connected with the lakes from a water management point of view (Meijer 2009).

There are mainly two issues:

- When water levels in the IJssselmeergebied drop too much, free flow for fresh water supply to inland is not guaranteed anymore, and severe drought can happen (especially because this situation is typical of water scarce period).
- When water levels in the IJsselmeergebied are too high, problems arise for the neighboring areas to pump excess water into the lake, causing water logging (especially because this situation is typical of wet periods).

Since the first problem has been already considered under the water demand stake (paragraph 2.2.2), this section deals only with the second issue.

In general excess water from the polders around the lakes is pumped into the open water bodies in order to keep the inland water system well drained and at the desired water level. When the head rise is higher, more energy has to be used to pump the same amount of water, until the point that the pumping station is not able to overcome the difference between the inland water system and the lake. At this point water logging happens. Water logging is accepted by the water boards; measures are implemented in order to limit the damage, which is in any case lower than upgrading the pumping stations. However, when changes in target water level in the IJsselmeergbied are severe, new pump capacity might be needed in relation with the water head changes. It is intuitive to understand that this situation is undesirable by the water boards around the area.

Objective

Water boards along the lakes want to keep the inland water system properly drained, without the need of expanding their pumping capacity.

Operational objective

It can be assumed that with a target water level rise of 0.3m over the present summer level (up till +0.1mNAP), all the pumping station can still guarantee the safety of the system, be it with higher energy consumption (Meijer 2009).

BOX 2.9
OBJECTIVE FOR INLAND WATER MANAGEMENT: drainage of the inland water system, with no the need of expanding pumping capacity.

2.2.8. WATER MANAGEMENT OUTSIDE THE DIKES (Buitendijkswaterbeheer)

Within the IJsselmeergebied there are plans for housing, offices, recreation facilities and wind power production, promoted both by the government and the private sector. They are usually small scale projects, especially in the areas of Amsterdam, Almere and Lelystad (Kuijper 2009).

Objective

Specific objectives and desired water levels depend on the features of the location, therefore it is not easy to define a common operational objective. However it is easy to imagine that they might suffer from inundation problems when target water levels are too high, so that the objective is to prevent them.

BOX 2.10
OBJECTIVE FOR WATER MANAGEMENT OUTSIDE THE DIKES: no inundations due to high water levels in the lakes.

Figure 2.14 shows the main stakes of the IJsselmeergebied on the map of the area.

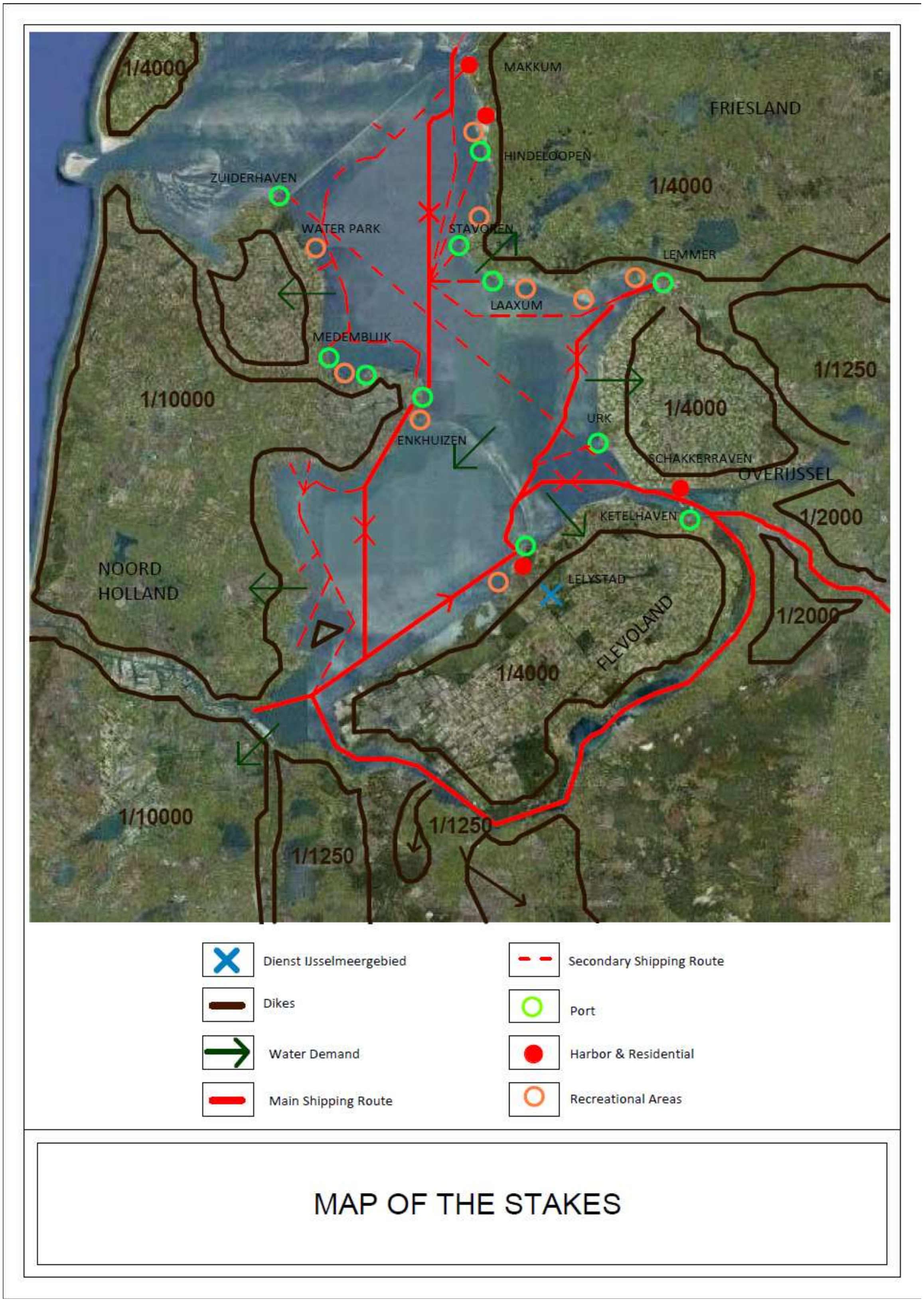

Figure 2.14 – Map of the stakes

3. METHODOLOGY: BACKGROUND OF THE RESEACH

3.1. DEFINITION OF THE METHODOLOGY

As mentioned before, the research has been approached taking inspiration from the procedure proposed by Rodolfo Soncini Sessa, Participatory and Integrated Planning (PIP) (Castelletti 2005).
In the literature there are many different methodologies for system engineering, which are suited to support decision making processes in multi actor systems. There are mainly two reasons why the PIP has been chosen in the present research:

- The PIP exactly covers the operational and technical level of the present study. Some techniques focus on a more strategic level, with the objective of defining the interactions between the stakeholders and the contrasts or synergies between their objectives. On the other hand the PIP considers the importance of a stakeholder analysis, but gets also more opretional, defining a methodology which aims at the definition of the practical measures needed to satisfy the objectives. In the present research the strategic analysis of the whole system is left aside, in favor of the definition of measures towards a climate proof system, even if simplified. For this reason the PIP has been considered suitable for the present work.
- As it will be clear in the following paragraphs, the PIP procedure includes a phase (4 – design of the alternatives) which perfectly suits the aim of the present research. In such step a simplified system is assumed and subjected to optimization in order to design efficient alternatives to bring to the stakeholder consultation. As stated in the introduction, this is exactly the role which the present research wants to give to an optimization methodology: using a simplified case (test case) to give support to the stakeholder consultation.

That is the main reason why the PIP has been chosen as the methodology for the present research, it recommends to design the alternatives for stakeholder negotiation with an approach based on the optimization of a simplified Project Problem (the test case of the present research) rather than purely experts consultation, which is exactly what has been considered missing in the previous researches on the alternatives for a climate-proof IJsselmeergebied (see chapter 1.2).

From the words of its authors "the PIP procedure is a 9 phases procedure that, starting from the identification of the goals of the planning activity, ends with a negotiation process among the stakeholders that produces a set of compromise alternatives to be submitted to the decision maker(s) for the final political decision".

The procedure takes initial inspiration from the Integrated Water Resources Management (IWRM) paradigm, which prescribes a holistic and participatory approach for water resources management. However, in order to put into practice the IWRM concepts, there is need of data collection and procedures which are able to generate a solid Decision Support Systems at the service of policy makers. While little effort has been spend in defining a suitable methodological approach, the PIP is a first attempt to fill this gap, and build a procedure which is able to support the IWRM paradigm.

3.1.1. THE STEPS OF THE PIP PROCEDURE

The PIP is a procedure in the sense that strongly involves human beings into the decisions at each step; the people who compose the system under analysis are called to make judgments and agree on the choices to make in order to proceed towards shared measures; furthermore it is recursive because while proceeding, new knowledge and insight in the problem is gained and it might be necessary to change and reshape the decisions made at the previous steps. Figure 3.1 shows the scheme of the PIP as described by the authors.

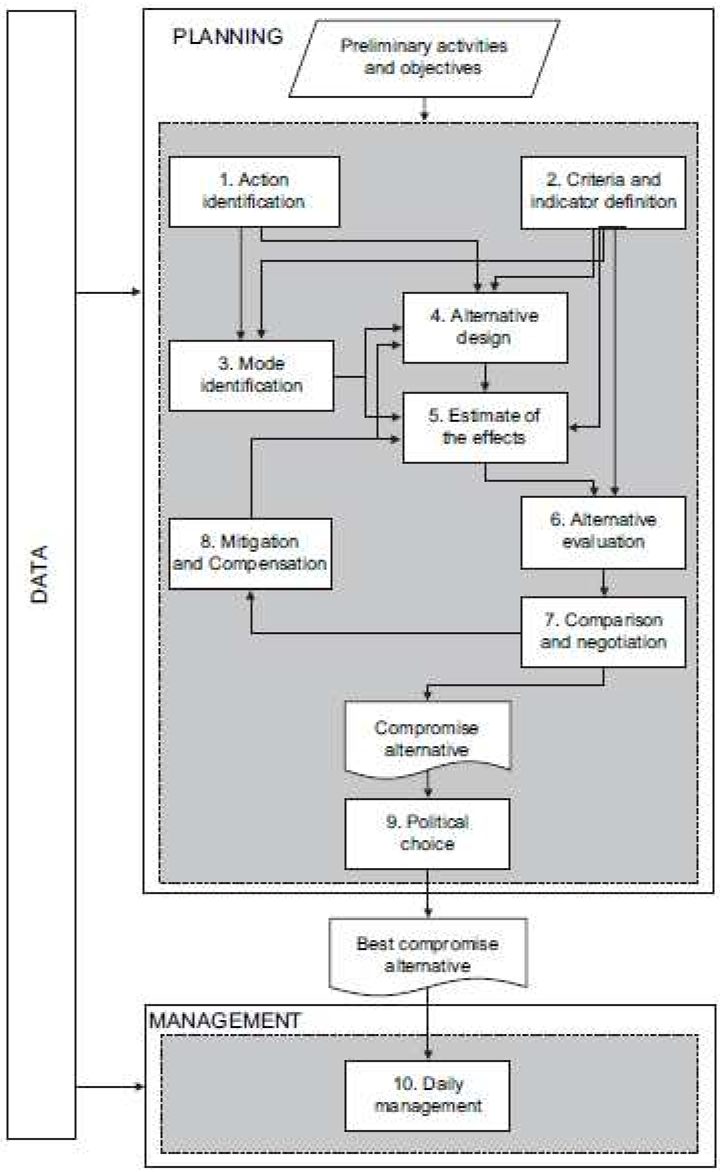

Figure 3.1 - scheme of the PIP

Step 0, *preliminary activities and objective*

In this preliminary phase there is need to define the objectives which the project has to address; for their definition it is essential to identify:

- The wishes and the objectives of the problem owner, the decision maker and the stakeholders involved in the study area.
- The normative context and the relative relevance of the different actors, in order to define how the different objectives will be taken into account during the analysis.

Furthermore the boundaries in time and space of the water system have to be defined together with the scenarios adopted to describe the future.

Step 1, *identification of actions*

Actions and measures which are thought to be functional in order to pursuit the objectives of the project have to be selected, bearing in mind the objectives of the stakeholders. More precisely classes of action or measure have to be chosen, which can be later on fully specified by their parameterization.

Step 2, *identification of criteria and indicators*

Evaluation criteria are necessary in order to evaluate the performances of the different alternatives and their effects according to the different stakes in the system. Those criteria express the desires and the judgments of the relative stakes, and have to be defined together with the stakeholders.
In the framework of the PIP, starting from the high level criteria/objectives of the stakes, there is need to define measurable criteria (leaf criteria) which can be calculated from the state of the system produced by each measure. Therefore a set of quantitative indicators have to be designed for each evaluation criteria.
The out come of this phase is a set of indicators defined for each stake and derived from the objectives of the stake itself.

Step 3, *model identification*

In order to define the consequences which would be produced if the different set of measures would be implemented, it is necessary to define a model which describes the cause-effect relations in the system. The model should therefore calculate the outputs of the system (values of the indicators) on the base of on the inputs (implemented measures and driving forces of the system/scenarios).
The choice of the type of model and its level of spatial and temporal detail and extension, strongly depends on the previous steps of the PIP: the definition of the objectives, the indicators and the measures considered.
Even if not mandatory, a model is in general mathematically formalized, with a fix structure (conceptualization) and fixed values for the parameters (calibration).

Step 4, *design of the alternatives*

Once the model has been defined together with the indicators, the time has come to select the alternatives to be evaluated, discussed and negotiated in the following phases of the procedure. An alternative is a combined set of the possible classes of actions and measures identified at step 2, defined in their instances (quantification of the actions and measures).

In theory the complete set of alternatives is made of all the possible combinations of the actions and measures defined at step 1. However it would be impossible to examine all of them in the next phases of the procedure, therefore it is important to define the "most interesting" ones to be further analyzed.

Different approaches are possible at this phase:

- Traditionally the selected alternatives are designed by the experts' experience, or suggested by the stakeholders (see chapter 1.2).
- In more complex systems, it is useful to define an optimization problem, called *Project Problem*, which selects efficient alternatives for the stakeholders consultation, i.e. Pareto optimal. The project problem considers only *Projects Stakeholders* and optimizes the system on their *Project Indicators,* using a *Project Scenarios* and a *Project Horizon*, i.e. simplifies the problem considering only its relevant features.

  The definition of a simplified Project Problem is necessary when the complete problem is too complicated to be used to select efficient alternatives (e.g. would lead to too long computational time for its optimization).

  The solution of the Project Problem by means of an optimization algorithm retrieves the set of efficient alternatives to be analyzed in the following phases. In this context a set of efficient alternatives is such if all the alternatives are Pareto dominant (see Box 1.2). Basically, given the Project Stakes, the optimization problem removes all the dominated alternatives which are not interesting for the stakeholders.

  It is relevant to notice that the set of selected alternatives strongly depends on the definition of the Project Problem and the selection of the Project Stakeholders. The definition of the Project Problem has to be carried on carefully with all the stakeholders and experts; however such choices can be revised iteratively if the analysis of the following phases shows other relevant issues disregarded in the formulation of the Project Problem.

The use of either one or the other approach (or both together) will provide at the end of the phase a set of relevant alternatives which will be negotiated with the stakeholders after the estimation and the evaluation of their effects. The *zero alternative,* which is the case in which no action or measure is implemented (the system stays as it is), has to be added for evaluation to the selected set of alternatives.

Step 5, *estimate of the effects*

After the identification of the efficient alternatives under study, it is necessary to estimate their effects on the system, i.e. define the values of the indicators when each alternative is implemented.
In a dynamic system the estimation of the effects of one alternative is the result of its model simulation over a time horizon. Such time horizon has to be long enough to include mean and extreme situations, so that the alternative can be evaluated for different conditions of the system, allowing a complete judgment.
The estimation of the effects can be performed under the historical scenario as well as different future scenarios. The first has the advantage of allowing comparison between what happened in the past and what would have happened if the alternative would been implemented at the beginning of the time horizon. This gives immediate perception of the potentials of the alternative. The use of future scenarios allows evaluation of the alternative in the decades to come.
The outcome of this phase is the *matrix of effects*, which summarizes the impacts of the selected alternatives on the different stakeholders.

Step 6, *evaluation of the alternatives*

The values of the indicators found at the previous phase are a measure of the effects of the different alternatives regarding a certain criterion; however the satisfaction that the stakeholders express on the values of such indicators is not always directly proportional with the indicator itself.
There is therefore need to translate the indicators in a dimensionless index which expresses the satisfaction of the stake (usually in a scale from 0 to 1); this can be done by a *partial value function*.
Once a unique dimensionless index for each stake has been given to each alternative, all the alternatives can be ordered from the most satisfying; of course orders are different from stake to stake, because different are the indexes used for the evaluation.

If the Decision maker is unique, the optimum alternative is the one which scores the best according to its index. When the decision makers are more, or more stakes have an influence on the decision a negotiation is needed to define the most shared alternative.

Step 7, *comparison and negotiation of the alternatives*

The objective of this phase is to find among the alternatives under study the one which represents an acceptable compromise by all the stakeholders and does not encounter the opposition of any of them.
The ideal situation, a win-win alternative which satisfies all the stakes, rarely happens. The phase ends with a set of alternatives which have the broadest consensus, together with the list of the stakes in favor and against.

Step 8, *mitigation and compensation*

If some of the alternatives selected in the previous phase have the consensus of a large group of stakes but not all of them, it is interesting to investigate if there are some mitigation or compensation actions which might help to enlarge the consensus also to the unsatisfied stakes.
This actually means designing a new set of actions which include the mitigation and compensation measures identified in this phase. Once defined, the actions have to be integrated in the procedure, which starts again from step 4. Iterations are possible until it is not possible to identify new mitigations or compensation actions which might expand the consensus.
The outcome of this phase is *the set of the compromise alternatives* together with the list of the stakes in favor and against.

Step 9, *political choice*

At the final step the decision maker has the duty to decide which the best compromise is; the alternative which will be implemented in the system.

3.1.2. PIP AND THE TEST CASE

Given the single decision maker, and the single objective function of the optimization problem in the present research (see Box 1.3 constraint 1), the test case makes use of the steps of the PIP which go from 0 (preliminary activities and objective) to 5 (estimation of the effects):

- with a single decision maker there is no need of the phases from the negotiation on (7-9) because *the best compromise alternative* can be selected by the DIJ according to its objective;
- With a single objective function, there is not need of step 6 because *the best compromise alternative* corresponds to the alternative which minimizes the objective function.

In fact the test case defined in the present research *is* a Project Problem: they both are a simplification of the system, which considers the main features of the IJsselmeergebied and few stakes in order to identify efficient alternatives to be proposed to the stakeholders' consultation. The only difference is that in the test case the objective function is unique (even though considering two different stakes, see box 1.3 constraint 2), so that it optimization will not generate a set of Pareto efficient alternatives, but *the* efficient alternative, which minimizes the objective of the DIJ.

Since the test case has only one objective function and suggests *the* efficient alternative, it is not suited, as it is, to design alternatives for stakeholders' consultations. By

definition, during a negotiation, more than one efficient option has to be discussed, considering a Multi Objective problem.
However, this is not the objective of the present research, which rather strives for investigating the benefits of an approach based on optimization for proposing efficient alternatives to the negotiation phase. In this vision if *the* efficient alternative, solution of the test case, reveals new possible strategies for a climate proof IJsselmeergebied which have not been considered without an optimization tool, then the benefits of its use are straightforward.

3.2. DEFINITION AND CONSTRAINTS OF THE OPTIMIZATION ALGORITHM

When talking about optimization it is important to realize that there is not a unique definition of the optimization setup, but many different optimization algorithms exist with different characteristics, suited for different problems.
For this reason the choice of the optimization algorithm is very important and has to take into considerations the features of the problem to optimize, the kind of actions considered and the objectives. The optimization algorithm has a strong influence on the results of the research, shaping their value, applicability and limitations. Furthermore, the computational time of the optimization process and the effective possibility to find an optimum solution, strongly depends both on the structure of the model and the optimization algorithm, and the interactions between the two.

> BOX 3.1
> HYPOTHESIS 1, *stakeholders and decision maker behave rationally. Discussed in 3.2.*

Before describing the optimization algorithms it is important to state that the present research assumes that the stakeholders (and most important the decision maker) behave rationally. This means that the preference of the stakeholders can be expressed by an objective function, which is used to optimize the system. Furthermore the alternatives can be strictly ordered according to the value assumed by the objective, and such order represents the ranking of its satisfaction. This hypothesis it is fundamental in order to consider the alternatives resulting from the optimization the ones which the best represent the wishes of the stakeholders.
It can be argued that this is not always the case, because it happens that the stakeholders show preferences on the measures which are in contrast with the outcome of the optimization. In such cases the objective function has to be redesigned according to the new collected information (Beroggi 1999).

The first important constraint of the optimization problem analyzed in the present research, is the use of a *single objective function* (see Box 1.3 constraint 1). This aspect is important because the choice of the optimization algorithm strongly depends on the number of objective functions to be optimized. Once again the choice has been assumed in order to define a simple and manageable test case from the computational point of view. Consequences of this strategy will be discussed later on in the research.

In the present research two different optimization strategies have been used:

- For the optimization of the objectives regarding the safety of the dikes (definition of winter target levels and eventually pump capacity) a *Differential Evolutions* algorithm has been selected (Storn 1997), using the tool developed by R. Storn (1997, International Computer Science Institute, Berkely) and improved by N.J. de Vos (October 2007,TUDelft) and S. Weijs (February 2009, TUDelft).
- For the optimization of the objectives regarding the water demand, an optimization tool has been designed ad-hoc in the present research. In the report such procedure is refereed as *Lexicographic Algorithm* for its similarities with the technique generally used in the context of multi-objective problem decomposition [115].

3.2.1. DIFFERENTIAL EVOLUTIONS

Algorithm description

Differential Evolution is a relatively recent heuristic algorithm developed by K. Price and R. Storn in order to optimize problems over a continuous domain. DE falls under the family of Evolutionary Algorithm, which perform the optimization inspired on biological evolution.

The selection of the best option is done through in the definition of subsequent generations (G) of alternatives, each composed by a population of NP different strategies. From one generation to another the members of the population are created from the ones which performed best in the previous generation, allowing some random selection. This is done in order to assure the exploration of the whole space of the alternatives, avoiding falling into some local minimum.

From one generation to another the evolution is performed in three phases:

- Mutation: definition of a member of the next generation as a combination of three random members of the previous one. The combination is done as follow:

  $$I_{NEW}=P_{OLD}+F(A_{OLD}-B_{OLD})$$

  Where: I_{NEW} is the new member of the population;
  P_{OLD} is the parent member from the old population;
  A_{OLD} and B_{OLD} are other two random members of the old population
  F is an amplification factor $\in$ [0,2];
- Crossover: exchanging elements of the different members of the new generation;
- Selection: comparison of each new member of the population with the "parent" in the old one, according to the value scored in the objective function. The new member is kept only if performs better then the parent.

More detailed information on the algorithm can be found in literature (Storn 1997).

Advantages and Disadvantages

DE is a very powerful optimization algorithm in case of single objective function. It has been proved to be robust in the application of many non linear problems. Furthermore it has good converging properties towards the global minimum.
However, the algorithm as it is provides the optimum alternative with no information on the others which have been tested. For this reason it provides weak guidance towards the understanding of the results.

Reasons for its selection in the present research

The differential evolution algorithm has been used in the present research for its broad applicability, good convergence to a global minimum and possibility to analyze continuous spaces. All those qualities are especially enhanced in a single objective function problem, which is the case of the present study. Furthermore a DE algorithm is able to handle non-differentiable and non linear objective functions.
For these reasons, at first, it has been considered a good choice in order to tackle the complexity of the Test Case, especially in the vision of including a statistical analysis of the winter water levels into the optimization.

With the impossibility to include a reliable extreme event analysis of the winter water levels into the optimization, the objective function simplified considerably. For the analysis of the optimization problems described in paragraph 4.5, the use of such powerful algorithm is not strictly necessary. Simpler methods can get the same result, with less computational times. However, due to time constraints, the DE algorithm has been applied in the definition of the winter target water level and the pump capacity.

3.2.2. LEXICOGRAPHIC OPTIMIZATION

Algorithm Description

For the definition of the summer target water level, the DE algorithm has been proven to lead to excessively long computational times and unclear relation between the alternatives and the objectives. In particular it is difficult to understand how the objective evolves with the different measures, since only the optimum alternative is given as result.
A much simpler algorithm has been developed following a lexicographic approach. Lexicographic methods are generally used to deal in a simple way with multi-objective problems. In such situations the optimum solution is obtained by defining a prioritization between the objectives. Alternatives are optimized first according to the high priority objective, defining a set of optimum measures. A subset of those

alternatives is then defined by optimizing according to the lower priority objective, and the procedure is iterated until the objective with lowest priority.

The same approach has been used in the present research considering a prioritization between the summer months. Starting from April till September, the target water level of each month has been minimized, and then fixed for the optimization of the following ones. As a starting point a maximum target water level has been considered for the months May till September. The optimum target water level for April is then defined selecting the value which minimizes the objective. In the algorithm all the target water levels within the possible range have been tested, considering a step of 1cm. The possible range is defined by the safety of the system in summer (see paragraph 4.3.1). Once the optimum target water level for April is defined, such value is fixed, and the target water level in May is optimized. The procedure is repeated until the definition of the optimum target water level in September.

Advantages and Disadvantages

The main advantage of the algorithm is its simplicity. This method allows the user to better control the optimization process and have a direct experience on the effects of the different target water level on the objectives. This is because the algorithm keeps memory of the objective obtained by all the different alternatives tested in the optimization procedure. Figure 3.2 shows a typical graph which can be produce trough the use of such algorithm.

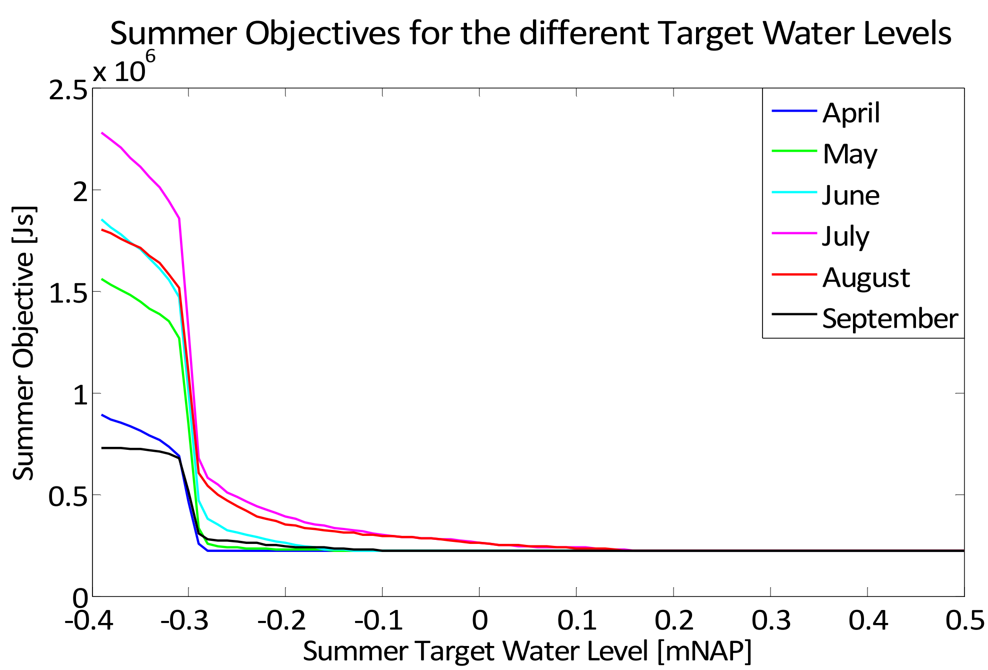

Figure 3.2 – Summer objective for different target water levels

As it can be noticed, it is straightforward from the figure to check for each month which is the target water level which minimizes the water deficit. Furthermore it gives a direct idea of how the objective is influenced by changes in target water levels.

However, even if able to find an optimum, such algorithm can not assure to find the global one. In fact the optimum depends on the prioritization order assumed for the analysis of the months. An exhaustive analysis should include the analysis of all possible ordering of the months, because changing the order, the optimum target water level may differ, as well as the objective. In the present research only the chronological order has been used during the optimization. Therefore, it is important to realize that other solutions than the one presented might be equally good and efficient. The lexicographic algorithm used in the present study is not an exhaustive procedure.

Reasons for its selection in the present research

Moving from the DE to a lexicographic algorithm has gained in simplicity and controllability of the optimization algorithm. This is the main reason for such choice in the case of the summer months. Also, it is believed that using a lexicographic algorithm still gives interesting results even without assuring the detection of a global optimum.

3.2.3. OVERALL COSTRAINTS ON THE OPTIMIZATION

The value and limitations of the optimization does not depend only on the algorithm used, but also on the features of the system subjected to optimization and the information used in the optimization procedure. Two important constraints have to be specified for the present research, which applies:

– A *deterministic optimization*. The optimization will be computed on the basis of the historical inputs, used as they are and modified according to the different climate scenarios. The driving forces/inputs of the system (inflows, tide, wind etc…) are therefore deterministic values (one exact value each time step), no stochastic

> BOX 3.2
> CONSTRAINT 8, *a deterministic optimization*, the optimization of the system will be performed using deterministic series of the driving forces/inputs of the system (inflows, tide, wind etc…). Namely the historical series, as it is and updated according the climate scenarios selected. *Discussed at 3.2.3.*
> CONSTRAINT 9, *an off line optimization*, forecasts will not be considered in the previous research and the optimization will be performed on the whole available horizon (1951-1998, 48 years). *Discussed at 3.2.3.*

analysis of the data will be done in order to generalize the inputs, assuming that the available time series are long enough to be representative of the phenomena (available: 1951-1998, 48 years)[2].

This choice brings limitations to the optimization of the test case, especially regarding the analysis of the uncertainty of the results and the impacts of the alternatives, which is missing from the present research. Using a stochastic definition of the inputs has the advantage of including both mean and extreme events together with their specific probability of occurrence, so that the alternative are tested and selected in a wide range of situations. However, this makes the problem very complex both for its definition and the resulting computational time. The choice of a deterministic approach is justified by the intend to keep the test case simple and the hypothesis that the time series used represent a good range of the possible situations (both mean and extreme cases)[3].

> BOX 3.3
> HYPOTHESIS 2, *time series of 48 years are representative of both the mean and the extreme situations in the system*, making use of a deterministic optimization in the present research, the underlying hypothesis is that the series used ere well representative of the whole range of behaviors of the system. *Discussed at 3.2.3.*

– An *off line optimization*: the optimization is performed on the whole horizon, the outcome of the research is a set of target water levels valid for the whole year and for the whole time window of the optimization. No use of on line forecasts (weather etc…) will be considered in the present study.

This choice has been made in a view of analyzing the system with growing complexity. As a first analysis an off line optimization is easier to define and manage because there is no use of forecasts. However, switching to an online approach is very easy when the offline problem has been defined: the same problem needs to be solved for a shorter time horizon (generally as long as the predictions) including the available forecasts (weather, special situations etc…). This option is not under study in the present research, but will be discussed as promising future research.

3.3. DEFINITION OF THE SCENARIOS

When looking into future strategies, it is necessary to define suitable scenarios which describe the future evolutions of the system which are interesting under the present research. Different scenarios can be considered.

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[2] In general the set of data is not homogeneous, because in 1975 the features of the system changed with the construction of Houtribdijk. However, within the research, the series are made homogeneous by the use of the model (WINBOS), Historical boundary conditions are applied on the present configuration of the system.

[3] It is important to realize that this hypothesis is in general not verified and dangerous to assume. This is because 50 years is too short with respect to return times of 1/2000 or 1/10000 years.

Climate

Climate scenarios have been intensively studied and discussed. Since climate changes are the key problems for the future of the IJsselmeergebied (see Chapter 1.1) they have to be taken into account in the present research.
Since their publication by the Royal Meteorological Institute, the KNMI '06 scenarios for climate change in the Netherlands are the reference tool for taking into account climate change into planning and policy making projects in the Netherlands. The same predictions for climate change have been used in the present research, in order to rely on trusted scenarios and be in line with the past studies, allowing continuity and room for comparison with the findings of this and past researches.

Agriculture/Water demand

Definitions of agricultural trends are especially important for forecasting water demand. One can imagine that with dryer summers, water demand scenarios might increase in the future, however this is partially true, since the sector is sensitive to many different scenarios (not only climatic) among which international cooperation, market liberalization etc. Furthermore possibilities for expansion of the agricultural sector are limited by environmental and animal welfare policies. Markets are also becoming saturated and the cultivated area in the Netherlands is shrinking (van Drunen 2009).

Socio-economic scenarios

As stated in the introduction (see Chapter 1.1), socio-economic scenarios are fundamental for policy making. Changes in the society and in the economical settings of the country may strongly influence the stakes on the system, drastically changing the judgments on the measures. However, as stated by constraint 4 (see box 1.5), the use of socio-economic scenarios falls outside the present research, due to time constraints and their high uncertainty.

3.3.1. CLIMATE KNMI '06 SCENARIOS

Climate scenarios are *relevant, plausible* and *internally consistent* pictures of how the climate may look in the future (IPCC, 2001). On these guidelines, the KNMI '06 scenarios have been prepared combining information from global and regional climate models, and then downscaling to the Dutch situation using local observations (van den Hurk 2006; Klein Tank 2009).
Even if widely used, it must be specified that climate projections suffer from many sources of uncertainties. First of all evolution of human and natural forcing on the climate is difficult to predict. Furthermore it is not clear how the climate will response to future atmospheric concentrations and the internal variability of the climate is difficult to predict. Finally, the quality of climate-models is still limited due to limited computer resources. The way to deal with such uncertainties is by using ensemble of model

simulations, i.e. modeling the phenomena with different initial conditions and even different models in order to assess uncertainties. However, it is clear that it is not possible to assure absolute certainty on the scenarios.

The KNMI ’06 predictions consist in four different scenarios, which differ for temperature rise and changes in atmospheric circulations; the four scenarios refer to two different time horizons, 2050 and 2100. Changes in temperature generate either a Warm (W) or Moderate (G) scenario, while changes in atmospheric circulation can be either weak or strong (+). Figure 3.3, taken from the KNMI’06 report, summarizes the four different scenarios for 2050: G, G+, W, W+.

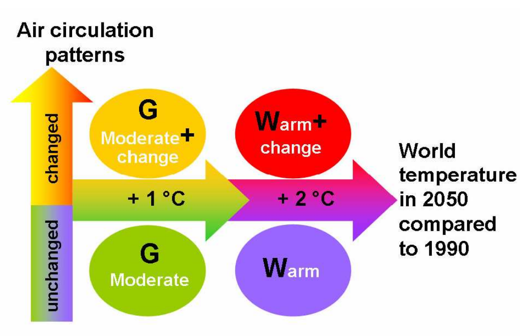

Figure 3.3 – The four scenarios from the KNMI’06

Changes in precipitation, evaporation and wind have been computed following the above cited scenarios, while a different approach has been chosen for sea level rise. In this case, changes in atmospheric patterns have not been considered relevant because they have a local influence, so that only two scenarios are defined: high global temperature and low global temperature. Sea level scenarios are given both for 2050 and 2100.
The outcomes of the KNMI ’06 scenarios are the following (van den Hurk 2006):

- Precipitation: winter experiences an increase in precipitation due to higher precipitation on wet days whose frequency changes are small. On the other hand summer precipitation decreases due to less wet days, while precipitation on wet days is almost unchanged.
- Potential evaporation (summer): summers experience an increase in potential evaporation, to which contribute both increase in temperature and changes in circulation patterns.
- Wind: daily mean wind speeds are expected to increase from the southwest direction, while changes from the northwest direction are more ambiguous, models tend to predict no changes or even reductions. Such situation is somehow confirmed by wind measurements: Even if trends are often not consistent among the different Dutch measuring stations, a decrease of moderate and strong wind can be observed from the analysis of the measurements between 1962 and 2002.

– Sea level: sea levels experience increases of different magnitudes and uncertainties for both of the scenarios (high and low global temperature). Changes refer to the target years 2050 and 2100 in respect to 1990.

The exact values describing climate change according to KNMI'06 scenarios are shown in Table 3.1:

Variable	G	G+	W	W+
summertime values				
mean temperature (K)	+0.9	+1.4	+1.7	+2.8
yearly warmest day (K)	+1.0	+1.9	+2.1	+3.8
mean precipitation (%)	+2.8	-9.5	+5.5	-19.0
wet day frequency (%)	-1.6	-9.6	-3.3	-19.3
precipitation on wet day (%)	+4.6	+0.1	+9.1	+0.3
10yr return level daily precipitation sum (%)	+13	+5	+27	+10
potential evaporation (%)	+3.4	+7.6	+6.8	+15.2
wintertime values				
mean temperature (K)	+0.9	+1.1	+1.8	+2.3
yearly coldest day (K)	+1.0	+1.5	+2.1	+2.9
mean precipitation (%)	+3.6	+7.0	+7.3	+14.2
wet day frequency (%)	+0.1	+0.9	+0.2	+1.9
precipitation on wet day (%)	+3.6	+6.0	+7.1	+12.1
10yr return level 10-day precipitation sum (%)	+4	+6	+8	+12
yearly maximum daily mean wind speed (%)	0	+2	-1	+4

Sea level sensitivity	low scenario		high scenario	
year (ΔTG since 1990)	*2050 (+1 °C)*	*2100 (+2 °C)*	*2050 (+2 °C)*	*2100 (+4 °C)*
Low	15	35	20	40
High	25	60	35	85

Table 3.1 – Description of the climate scenarios

More recent studies have been analyzed and summarized in a review of the KNMI '06 scenarios (Klein Tank 2009), which confirms the validity of the reliability of the 2006 findings. Under the present knowledge, there is no reason to update the KNMI '06 scenarios.

However, reduction of self-gravitation of ice, due to mass losses, has been recently introduced in the calculation for sea level rise, bringing little changes for the 2100 scenarios (Dr. C.A. Katsman, 55th Colloquium "Recent advances in Water Resources", presentation, TUDelft). Reduction of self-gravitation generates a decrease of predicted sea level rise for the high scenario with target year 2100. Increases from 30 to 80 cm are more accurate than 40 to 85.

Long term prediction of sea level rise is the most controversial issue on climate change scenarios. The Delta Commission used in its recommendations the KNMI '06 scenarios, with the exception to predictions for 2100. At the target year, a sea level rise of 55 to 120 cm has been considered more plausible. Given the relevance of the study of the Delta Commission, their scenarios have been also tested in the present research.

3.3.2. WATER DEMAND SCENARIO: PAWN TOOL

The PAWN tool (Policy Analysis for Water in the Netherlands), already adopted in the past for studies on drought issues, has been used by Deltares in order to define water demand scenarios in the whole Netherlands under the climate scenario W+2050 (Meijer 2010). With the PAWN tool the water demand per decade (10 days) is calculated separately for the different uses of fresh water in the Netherlands.

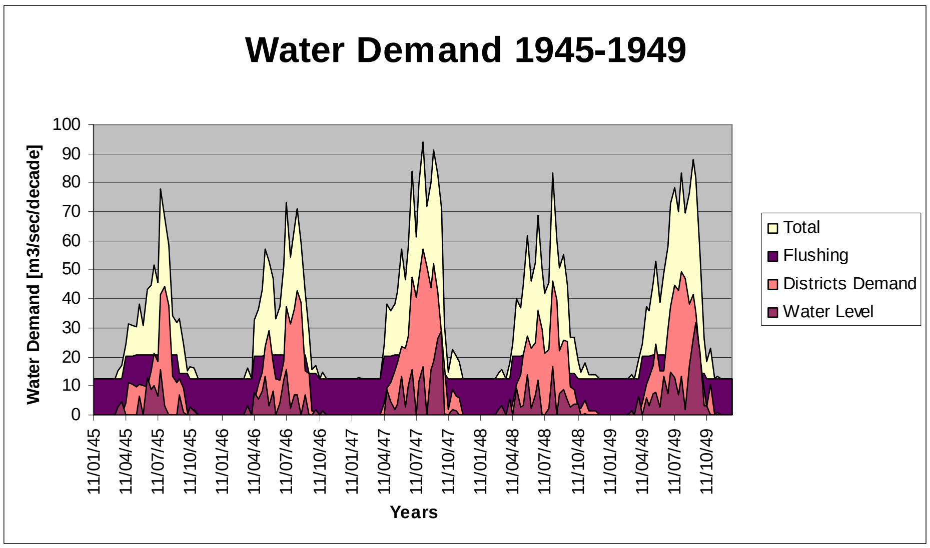

Figure 3.4 – Distribution of the three uses

The tool integrates climate scenarios (KNMI '06 W+ 2050) and three models:

- Nagrom, modelling deep groundwater.
- Mozart, modelling shallow groundwater.
- Distributiemodel (distributed model, DM), modeling the main surface water system.

The three main uses includes into the simulations of the PAWN tool are:

- Water used to flush the *main inland water system*.
- Water used to keep the water level in the *main inland water system* at the desired target (for safety reasons).
- All the other water demands to the districts (irrigation, drinking water, cooling the power plants), including the demands for safety and flushing of the districts.

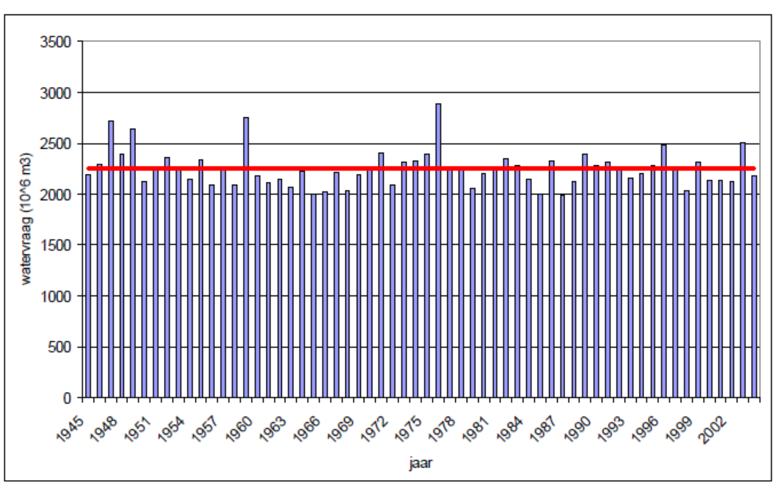

Figure 3.4 shows the distribution of the three uses in the sampling period 1945-1949.

Figure 3.5 shows the total water demand under the W+2050 scenario; it is possible to notice the higher

Figure 3.5 – Total water demand under W+2050

demand in the years 1947, 1947, 1859, 1976, already known as dry years. Even though the years in the graph refer to the past time series (1945-2005), demands are calculated under the W+2050 scenario, so that they represent the future scenario.

Figure 3.6 shows the map of the areas served from each water body in the IJsselmeergebied, as modeled in the PAWN tool.

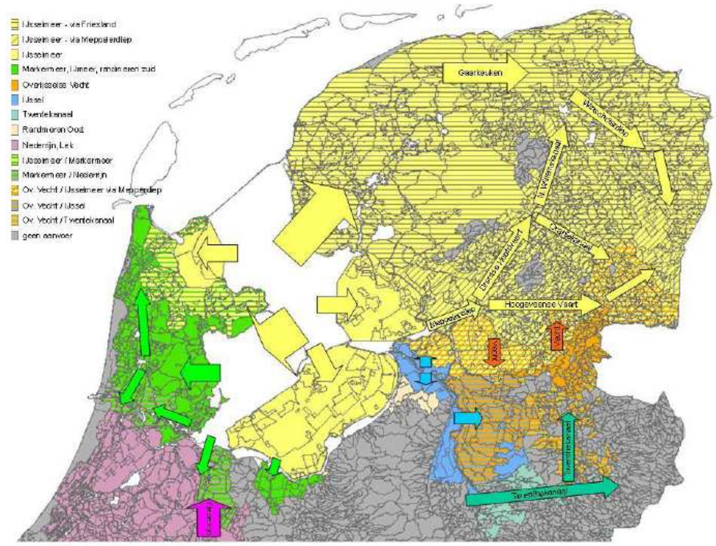

Figure 3.6 – areas served by each water body as modeled in PAWN

4. THE TEST CASE

4.1. PRELIMINARY ACTIVITIES AND OBJECTIVE

4.1.1. PREFACE

In the introduction (paragraph 1.1), the problem has been stated for the whole Netherlands and in particular the IJsselmeergebied. Climate is changing differently than the expected long term climate circles; most probably bringing higher temperatures, sea level rise, dryer summers and wetter winters, consequently influencing discharges from the incoming rivers, possibility for discharging to the sea by free flow and water availability. Combination of those events will lead to significant problems for the Netherlands, and specifically for the IJsselmeergebied, in terms of safety (flooding, stability of dikes) and freshwater supply. In order to cope with those threats, there is need to define a climate-proof IJsselmeergebied. From the point of view of the decision maker, measures have to be implemented which are able to guarantee the present functions of the system under climate change, while gaining the broadest consensus among the stakes which might directly or indirectly be influenced.

4.1.2. NORMATIVE FRAMEWORK, DECISION MAKER

As stated in paragraph 2.2.1 the Dienst IJsselmeergebied is responsible for maintenance, management and construction of the main infrastructures in the region, as well as for the practical implementation of water policies.
Being the manager of the area, the only authority (under the supervision of Rijkswaterstaat and Ministry of Infrastructure and Environment) which has the duty and the power to approve and implement water policies and infrastructures in order to assure a good functioning of the IJsselmeergebied for the Dutch society, the Dienst IJsselmeergebied is only *decision maker* of the tests case.
This has important consequences for its definition:

- The objective of the test case is inherited directly from the definition of the objective of the decision maker;
- The evaluation of the measures towards the definition of the optimal alternative is performed according to the judgments and prioritizing criteria expressed by the decision maker.

4.1.3. TOWARDS THE DEFINITION OF THE OBJECTIVE OF THE TEST CASE: STAKES AND PRIORITIES

Taken from paragraph 2.2.1, the objective of the decision maker (DIJ), and consequently of the Test Case is:

THE DEFINITION OF A CLIMATE-PROOF IJSSELMEERGEBIED, WHILE GAINING THE BROADEST CONSENSUS WITHIN THE STAKEHOLDERS ON THE SELECTED MEASURES

A climate proof IJsselmeer would guarantee that the functions related to *all* the stakes in the area are preserved under the future scenarios, so that the DIJ would need to analyze all the stakes in the area and inherit their objectives into its goal.
However, in the present research, it is not possible to consider all the stakes of the system in the optimization procedure, therefore different stakes have to be taken into consideration on different levels.

This is mainly because, from a computational point of view, it is impossible to deal with the complexity of the problem when the objectives of all the stakes are included in the optimization algorithm. This is especially true in the present research where, as stated at constraint 1 (see box 1.3), the objective function has to be unique.
Only some stakes, with their objectives, will be taken into consideration in computing the optimum and selecting the efficient alternatives; for others, the selected solutions will be only tested after the optimization in order to understand the impacts.
This is also the strategy used in the PIP in the definition of the Project Problem (paragraph 3.1.1.), which corresponds to the Test Case of the present research: the system is simplified and only some relevant stakes will be considered in the optimization process used to select efficient alternatives for the next phases of the consultation, for the others effects are evaluated a posteriori (Soncini-Sessa 2007).

According to the above considerations, the stakes can be divided in two different groups:

- Project Stakes (P): which have fundamental stakes in the system which the decision maker has to take into account and inherit in its goals for a climate proof-IJsselmeer. Their objectives will concur in the definition of the test case objective and they will be taken into account in the optimization problem.
- Impact Stakes (I): whose objectives are not part of the optimization process, and therefore not considered in the test case objective. However, those stakes are relevant enough to need an evaluation of the consequences of the efficient actions selected trough optimization.

As stated by the constraint 2 (see box 1.3), the stakes which will subject of the optimization in the present research are *safety of the dikes* and f*resh water demand*. They have been chosen for the optimization, because they represent the main concern of the policy makers regarding

BOX 4.1
CONSTRAINT 6, *safety of the dikes (P1) has higher priority than satisfaction of fresh water demand (P2); all the other stakes have lower priority (P3)*. Such hierarchy between the two project stakes has been assumed due to the single objective of the optimization and has been suggested by the conclusions of the Delta commission. *Discussed at 4.1.3.*

future scenarios, as is confirmed by the high number of reports and studies on the subject, and especially by the Delta Commission, which states in its document: "[cit] Water safety is the center of this report, and includes both flood protection and securing fresh water supplies. Achieving water safety prevents causalities and social disruption, while avoiding damage to our economy, landscape, nature, culture and reputation." (Deltacommissie 2008).

Furthermore, given the single objective formulation of the optimization problem (constraint 1 Box 1.3) it is necessary to define a priority between the two stakes subjected to optimization. The Delta commission states that safety is the highest priority, so that in the present research safety of the dikes is considered a more important stake than fresh water demand. In this way, satisfaction of the second comes only after the satisfaction of dike safety standards.

All the other stakes discussed in chapter 2.2 will be addressed as impact stakes, and therefore not included directly in the definition of the test case objective and the optimization. When possible, according to the information available on the operational desires of the stakes, evaluation of the impacts of the selected alternatives will be given with the help of indicators developed for the stakes. Otherwise the discussion will be based on comparison between the high level objectives defined in chapter 2.2 and the water level regime produced by the selected alternatives.
However, important issue for the decision maker is to gain the broadest consensus between the stakes left out of the optimization. Impact stakeholders can indirectly be represented by this aspect of the objective, which however has the lowest priority.

Table 4.1 shows how the stakes have been divided into the two categories:

Project Stakes (P)	Impact Stakes (I)
Safety of the dikes (both in winter and summer) (P1) Water demand (P2)	Ecology Commercial Shipping Recreation Inland water management (Safety) Water management outside the dikes (safety)

Table 4.1 – Project and impact stakeholders

For a detailed description of the stakes and definition of their objectives see chapter 2.2.

4.1.4. OBJECTIVE OF THE TEST CASE

The formulation of the objective of the Test Case given at the beginning of the previous paragraph is too general, in the sense that it is vague what actually "climate-proof" means in the framework of the test case.

However different degree of involvement and prioritization has been specified for the Test Case in the previous section, so that, given the choice of the project stakes (P), the impact stakes (I), and their prioritization, a climate-proof IJsselmeer is such when it *satisfies first the objectives of safety of the dikes and secondly the water demand under the threats of climate change. Furthermore, under the hypothesis of satisfaction of the project stakes, it is important to gain the broadest consensus on the measures among the stakes which have not been included in the objective of the test case (impact stakes)*.

Given this definition, the objective of the decision maker and the Test Case can be further specified with the use of the goals of the selected project stakes (P), together with the need of gaining consensus.

Box 4.2 summarized the redefined objective of the test case:

BOX 4.2
OBJECTIVE OF THE TEST CASE:
A climate-proof IJsselmeer under the climate scenarios selected.

i.e.

1. Satisfaction of the safety standards location per location (both for summer and winter), in the present and under the climate scenario selected (see box 2.3);
2. Satisfaction of the water demand in the present and under the climate scenarios selected (see box 2.4);
3. Acquisition of the broadest consensus among the impact stakes.

The order of the numbering represents also the priority of the three objectives.

4.1.5. BOUNDARIES OF THE TEST CASE

- Time, the research strives to find a solution, within the possible measures, for the management of the IJsselmeer in the future. In many of the cited reports, time horizon selected is 2050 and 2100. This will be also the case for the present research.
  However important understanding on the potential of the methodology can be obtained by optimizing on the past series and confront what historically happened, with what could have happened if a similar approach would have been used before.
  For this reasons, *the test case will look into optimized measures both for the past and long time future horizon 2050 and 2100.*
  As it will become clear with the explanation of the model, the available data series cover the years from 1951 till 1998 (48 years); the data series regarding the future

scenarios will be derived from the available historical series modified according to the prescriptions of the KNMI'06 and updates.

- Space, as stated by constraint 5 (see box 1.5), the IJ*sselmeer* alone defines the spatial boundaries of the test case. Other components of the IJsselmeergebied (Markermeer, Randmeren, neighbor polders etc…) will not be part of the analysis and will not be modeled.
  This is because, if more state variables are defined in the model of the system (other water bodies, polders etc…), the computational time increases by 10^n with respect to the case of only one state variable, when n is the number or state variables (Soncini-Sessa 2007). Given the need of keeping the computational time of the model of the system low, the use of only one state variable has been defined as a limit.

4.1.6. SCENARIOS

Different scenarios have been selected for the test case, Table 4.2 shows the overview:

Horizon	Climate			Water demand
	sea level rise	Rhine and minor rivers discharge, precipitation, evaporation, pumping form neighboring polders	wind	
2050	W+2050	W+2050	none	W+2050
2100	W+2100 Delta commission	W+2100	none	W+2050

Table 4.2 – Scenarios used in the test case

Many of the studies and reports on the future of the IJsselmeergebied consider the most extreme scenario as the reference on which to define the measures. In the present research, the same choice has been made in order to be in line with the past studies. The analysis of the worst case has the advantage of investigating which would be the worst option.
Furthermore, a review of the KNMI '06 produced in 2009 (Klein Tank 2009) cit. observed that "in recent years the average temperature in the Netherlands is rising faster than the global average and extreme high temperatures are occurring more frequently". This gives room for justification for using the warmer scenarios (W, W+), which describe the current situation best.

Also the scenarios adopted by the Delta commission for sea level rise with horizon 2100 have been included in the research, in order to be in line with the past studies. This scenario predicts a higher sea level rise.

Regarding wind, North-Western wind is dominant on the IJsselmeer. As mentioned, it is responsible to storm surges in the North Sea and low water levels in the IJsselmeer at the Afsluitdijk, reducing possibilities for gravitational discharge and rising risk within the

lake. Past measurements and KNMI '06 predictions for wind do not give reason to expect changes in North-Western wind and risks of North Sea surges. For this reason no wind scenarios are taken into account in the present research.
On the other hand more intense South-Western wind might even have positive influence on gravity discharge of the system at the Afsluitdijk. However, such scenario is too poorly defined to be taken into account in the present research (van den Hurk 2006).

BOX 4.2
HYPOTHESIS 2, *Water demand does not change from scenario W+2050 and W+2100*. Due to data availability the same water demand has been used for the two different time horizons. *Discussed at 4.1.6.*

For water demand, the only available information is the scenarios provided by Deltares and calculated by the PAWN tool (see paragraph 3.3.2) under climate change conditions KNMI '06(W+2050).
In the present research the same scenarios have been used for the time horizon 2100, assuming that water demand does not change considerably from 2050 to 2100, also considering that agricultural development of the Netherlands will be limited in the next centuries (as argued in chapter 3.3).
This might be, in general, not true, because even if the agricultural extension of the country remains the same, a dryer climate would result in a higher water demand and more important, other demands concur in the definition of the total water demand (see paragraph 3.3.2.).

4.2. IDENTIFICATION OF ACTIONS

4.2.1. MEASURES TO INVESTIGATE

Once the objective of the project has been specified in an exhaustive way, it is necessary to make an inventory of all the possible measures which are available to reach such goals. Such list, which usually is the result of a brainstorming, should be discussed and generated together with the experts and the stakeholders.
In theory, no action should be excluded from the list; the procedure itself will eliminate the ineffective options. However, some are not feasible, or too expensive, so they are left out in order not to load the computational procedure: a synthesis phase follows the creative brainstorming. One should anyway keep in mind that the final set of actions will be strongly dependent on the choices in this phase (Soncini-Sessa 2007).

As specified in the introduction (see constraint 3 in box 1.4), in the present research, the *only* class of actions which will be considered are changes in the target water level of the IJsselmeer; a set of 12 target water levels, one for each month is the outcome of the optimization of the test case. In theory, each month can have a different target level.

BOX 4.3
CLASS OF MEASURE: 12 target water levels, one for each month.

It is important to notice that there will be *no* changes in the management of the sluices (management is not part of the optimization); gates will still follow the present policy depending on the target water level, the actual water level, and sea level. The present management prescribes to open the gates at their maximum when gravity flow to the Waddenzee is possible and the water level is higher than the target water level.

BOX 4.4
CONSTRAINT 11, a *planning and not a management problem*. The control functions of the structures (gates at the Waddensea), and the management of the pumping station at the Afsluitdijk will not be subjected to optimization. For the first, the present management will be kept, while for the second, the pumping station works always a full capacity. *Discussed at 4.2.1.*

As stated in the introduction (see constraint 3 in box 1.4), the *only* class of extra measures which is considered in the research is a pumping station at the Afsluitdijk and a change of the management strategy of March (considered as a summer month). Such actions are only taken into account when the system is not flexible enough to be climate proof with only changes in the target water level. The outcome of the optimization of the test case with pumping station at the Afsluitdijk, is the capacity of the pumping station.

BOX 4.5
CLASS OF MEASURE: pumping station at the Afsluitdijk.

Again it is important to notices that the management of the pumping station is not part of the optimization. In the present research, the following management is assumed for the pump: in the event that that the water level is higher than the target water level, but discharging by gravity is not possible, pumps are assumed to work at full capacity, regardless the difference between sea level and lake level. Implications of such choice will be discussed later on in the research.
The outcome of the optimization of the test case considering March as a summer month is a new target water level for March, to be included in the class of measures defined in box 4.3.

BOX 4.6
CLASS OF MEASURE: target water level for March.

Instances of the measures

Classes of measures have to be specified by the instances which shape them in actual measures which can be implemented. In the case of the present research, values have to be given to the 12 target water level and the pump capacity (if needed in the scenario). The parameters of the measures can be collected in the following vector:

$$\mathbf{u}^p = [u_{jan}, u_{feb}, u_{mar}, u_{apr}, u_{may}, u_{jun}, u_{jul}, u_{aug}, u_{sept}, u_{oct}, u_{nov}, u_{dec}, u_{pump}]$$

4.2.2. PLANNED MEASURES

Enlargement of Lorentzsluizen, has not been implemented on the system yet, but has been already planned; works will start in 2013, with end in 2016 (Ministerie van Verkeer en Waterstaat 2010). The recommended size of the new gate is a width of 165m with a lower threshold of -6.5m (Vlag 2002). The structure has been designed in order to make the system safe up till 2050 considering a mean sea level rise of 60 cm per century. This means that the structure will is able to face 0.23m of sea level rise. Such measure will be considered implemented in the system for optimizations over a time horizon later than the expected realization date (2016).

4.3. IDENTIFICATION OF CRITERIA AND INDICATORS

(Soncini-Sessa 2007)In order to asses and compare the effects of the alternatives, it is necessary to define a set of *criteria* which decision maker and stakeholders can use to order the alternatives, and select the optimum $\mathbf{u}^p$.

In chapter 2.2, objectives have been associated to each stake. The stakes' objectives are the starting point of the present phase; they are high level *criteria*, which need to be specified, simplified and made operational, by understanding which are the physical characteristics of the systems desired by the different stakes. In this phase, starting from the objectives of the stakes, it is necessary to answer to the question "What exactly does the stake want?"(Enserink 2010).

Criteria are made operational into *indexes* which measure (which implies for indexes being mathematical expressions) the effects of an alternative on a sector, and make explicit the relation between the stake criterion

> BOX 4.7
> **Selection of the criteria and indicators** should be performed together with the stakeholders, in order to be significant, reliable and trusted by the actors. However in the present research time constraints have made impossible such approach, so that meeting have been organized with experts in the sectors, considered a good mirror of the wishes of the different stakes.

and the state of the system. They associate a value to an action in order to understand the satisfaction of a sector regarding that alternative. Indexes are function of the state of the system produced by a certain action and indirectly they are function of the action itself.

It is often not easy to directly formulate an index from the high level criteria (sector objectives) due to its general form. For this reason they are often translated and divided on lower levels criteria: each group of lower level criteria *defines* the higher level (Enserink 2010). Many different levels are possible until the lowest (*leaf criterion*) can be easily measurable. The measurable expression of the leaf criterion is an *indicator*. The objective tree defined from the sector objective (high level criterion) till the definition of the indicators builds up the *evaluation hierarchy* of the stake.
"Defining an evaluation hierarchy is mainly a problem of finding the right words" (Enserink 2010). The analyst has to be able to define the objectives of the stakes in a simpler way, getting to the mathematical formulation of the indicators. There are simple rules which an evaluation hierarchy should satisfy:

- Objectives should be described by a noun phrase which indicates the desired state;
- Connections between higher and lower levels criteria denote definition relations, the lower level criteria explains the meaning of the higher one;
- Each criterion Y should be defined by zero or at least two lower level criteria Y1 Y2 etc... When no lower level criterion exists, then it is considered operational enough to be easily translated in an indicator. If only one lower level criterion Y exist, then it can substitute the higher level criterion X.
- The lowest level criteria (leaf criterion) should be operational and easy to translate into measurable indicators.

In the practice of impacts estimation, indicators are often translated into economical values. Such technique is popular because many theories are available on monetization of impacts and the approach allows comparison of different kind of damages and sectors. Furthermore talking about costs is a very effective way to hit the experience of the stakeholders, which otherwise might face problem in understanding the entity of the damages produced from the different alternatives.
However, in the present research no cost estimation will be provided to any index, but effects will be mainly evaluated with respect to the modeled historical situation. Also in this case is possible to capture the understanding of the stakeholders in an effective way; impacts will be related to events which happened in the past, and have been experienced on firsthand.

> BOX 4.8
> CONSTRAINT 12, *no costs estimation.* Impacts of the different alternative on the stakes will be based on the water level regimes produced, and evaluated by comparing them to the modeled historical situation. *Discussed at 4.3.*

This choice is also possible because comparison of impacts between different stakes is not needed, since a strict prioritization has been defined. Also measures under study are virtually free, since changes in target water levels do not cause any extra operational costs (provided the range in which impact is zero). However it is important to recognize that is a limit when considering extra measures as a pumping station or changes in water management strategies of March, which might need extra dike reinforcement for safety.

In the present phase, indicators are designed for each stake through the definition of their evaluation hierarchy:

4.3.1. DECISION MAKER (DIJ)

The subject of the optimization is the objective of the decision maker. The indicators related to the stake will firstly define the satisfaction of the decision maker, but will also concur in the definition of the objective function for the optimization.
Given the fact that such indicators will be included in the optimization of the system, indicators have to be representative of the desires of the stakes, but also be simple in order to lead to feasible computational times. This second requirement plays indeed an important role in the definition of the indicators for the problem owner. For instance in assessing the safety of the dikes, is not possible to include a complete statistical analysis into the optimization and a *proxy indicator* is needed (see following paragraph).
The evaluation hierarchy of the stake is shows in figure 4.1.

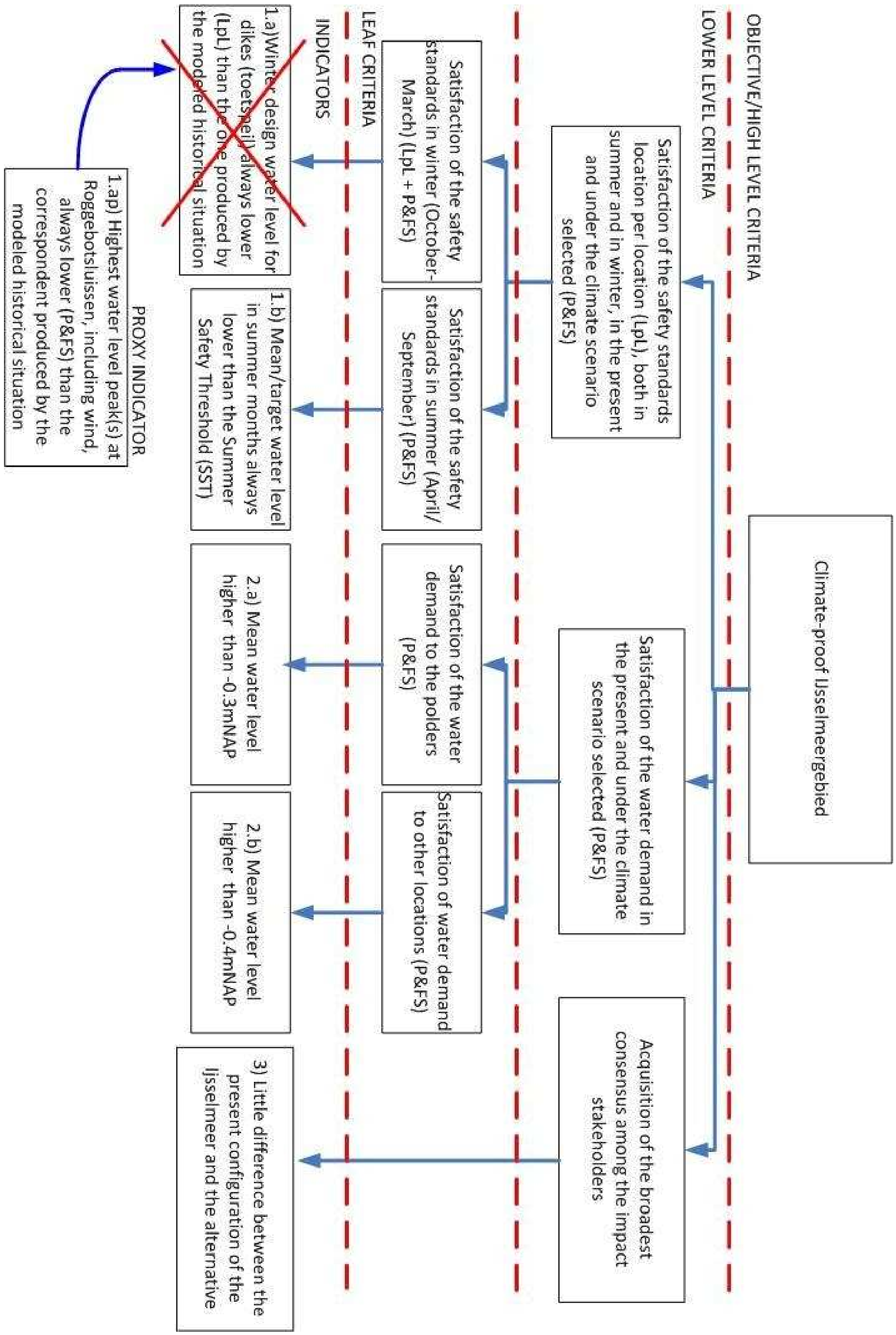

Figure 4.1 – Evaluation hierarchy of the decision maker (DIJ)

Winter Safety

Satisfaction of the safety standards location per location (LpL), both in summer and in winter, in the present and under the climate scenario selected (P&FS);

> BOX 4.9
> HYPOTHESIS 3, *the HR2006 design features are met by entire dike ring around the IJsselmeer.* Therefore, if there are no changes in the required design water level, because the dikes remain the same as in the present, historical instances of water level (both mean and actual) represent a comparison term in order to define a safe situation*. Discussed at 4.3.1.*

As stated in paragraph 2.2, the historical time series in the IJsselmeer do not define a safe situation, because not all the dikes comply with the features prescribed by the HR2006 calculations. However an important hypothesis stands at the base of the definition of the leaf criteria for this sector: the HR2006 design features are met by an entire dike ring around the IJsselmeer. If this is true, the past time series of the water levels in the lake can be used as a term to compare the outputs generated by the different alternatives in the future in order to define safe situations: *an alternative is safe if it performs as the historical in an extreme event analysis.*

Hypothesis 3 is assumed for practical reasons, because it has been impossible to include a reliable statistical analysis into the optimization. Therefore a proxy indicator is used to assess the safety of the system, and the historical series have been used as a reference. However, it is important to realize the danger of such assumption (see paragraph 2.2)

> BOX 4.10
> HYPOTHESIS 4, *Indicators designed on the modeled historical series, in order to have conformity of the results. Discussed at 4.3.1.*

It is also important to specify that the historical series used to design the indicators are the simulations performed by the model described in paragraph 4.4, used in combination with the past time series and the present management. The research makes no use of measured water levels. In order to assure conformity of the results, it uses the same modeling tool to define past and future conditions of the system.

The stake objective can be defined as:

1.a) *Satisfaction of the safety standards in winter (October-March) location per location in the present and under the climate scenario selected (LpL + P&FS)*;
The winter mean water level regime produced by the alternatives can be statistically analyzed, defining the extreme events curve. Such curve, combined with wind statistical analysis, produces in turn the extreme event curve of the actual water level. For the return period correspondent to the safety standard of the dikes, the extreme actual water level should be equal or lower than the design water level (toetspeil) prescribed by the HR 2006 in each location around the lake. In this way the system keeps the same safety as the present.

Even if this is the more natural leaf criterion on which to design the indicator, problems have been encountered both in the introduction of a reliable statistical analysis of wind and mean water levels and in the use of the Hydra tools into the optimization. (See Appendix B – Problems in introducing reliable statistical analysis into the optimization, and reasons for the definition of a proxy indicator).

For this reason a *proxy leaf criterion* has been used, which can lead to the definition of a simpler and usable indicator which does not represents exactly the original leaf criterion, but is believed to be a good indication of its satisfaction.

The proxy leaf criterion (1.ap) states that, in the present and under the future scenarios, the highest peak(s) in actual water level at Roggebotsluizen (including mean water level and wind) should be lower than the correspondent ones verified in the past.

This definition loses the distributed analysis of safety along the IJsselmeer, in favor of a local evaluation at the Roggebotsluizen. Also it does not performs an extreme event analysis, but simply uses the peaks(s) happening during the horizon as a good indications of the extreme events. Two hypotheses are at the base of the use of the proxy criterion:

> BOX 4.11
> HYPOTHESIS 5, *controlling the highest peak(s) of the actual water levels (mean water level + wind) at Roggebotsluizen, where the wind effect is strongest, results into a safe situation for all the other locations in the IJsselmeer. Discussed at 4.3.1.*
> HYPOTHESIS 6, *extreme events happening at Roggebotsluizen during the time horizon are representative for extreme situations. Discussed at 4.3.1.*

– regarding the first issue, Roggebotsluizen is used as reference, because in the South-Eastern part of the lake, wind influence is the strongest, (see paragraph 2.1.3.), so that can be assumed that controlling the actual water levels at this extreme location would result in a safer situation for the entire IJsselmeer, where the wind influence is lower[4].
– regarding the second issues, the analysis and control of more than one extreme peak over the time horizon has been considered significant in order to train the alternatives on different kind of events, and make them robust from a statistical point of view. The underlying hypothesis is that the events happening during the time horizon are representative for extreme situations,

> BOX 4.12
> CONSTRAINT 13, *a single target water level for the whole winter.* In the optimization of the test case, when talking about winter target water level, only one value will be assumed for the whole period October-March. $u_W=u_{jan}=u_{feb}=u_{mar}=u_{oct}=u_{nov}=u_{dec}$. *Discussed at 4.3.1 and appendix B.*

[4] It is important to relalize that such assumption is in general not true. Different are the features of the locations around the lake, so that different factors influence the safety (wind, water levels).

introducing some statistical information on the definition of the optimum alternatives[5].

Given the form of the indicator, especially its definition on single peaks which can happen in different winter months, a constraint is needed in this case. Only one target water level can be defined for the whole winter, so that referring to paragraph 4.2.1. $u_W=u_{jan}=u_{feb}=u_{mar}=u_{oct}=u_{nov}=u_{dec}$. This choice has been also forced by the impossibility to define a monthly statistical approach. This issue is further discussed in appendix B.

The first step for the mathematical formalization of the proxy indicator, is the definition of the peaks at Roggebotsluizen which need to be controlled. An analysis has been performed on the actual water levels at the location, comparing the historical series with the ones produced under an extreme scenario (W+2100), in order to identify the most dangerous situations. The following years have been selected for the relevance of their winter peaks in the historical series:

- Winter 1952/1853, with a peak of 2.110 mNAP [$WSTh_{52/53}$];
- Winter 1965/1966, with a peak of 1.065 mNAP [$WSTh_{65/66}$];
- Winter 1987/1988, with a peak of 0.896 mNAP [$WSTh_{87/88}$];
- Winter 1993/1994, with a peak of 1.104 mNAP [$WSTh_{93/94}$];
- Winter 1994/1995, with a peak of 1.137 mNAP [$WSTh_{94/95}$];

The selected peaks have different nature. The first one (1952/1953) is the highest in the whole series, however it is very short and characterized by a low mean water level; it is mainly wind driven. The others are lower, but longer, characterized by high water levels in the extreme scenario; mainly water level driven (notice the red series in figure 4.2). Figure 4.2 shows the historical series of actual water levels at Roggebotsluizen in comparison with the series produced by a W+ scenario, marked in red circles are the peaks under examination.

[5] See footnote 3

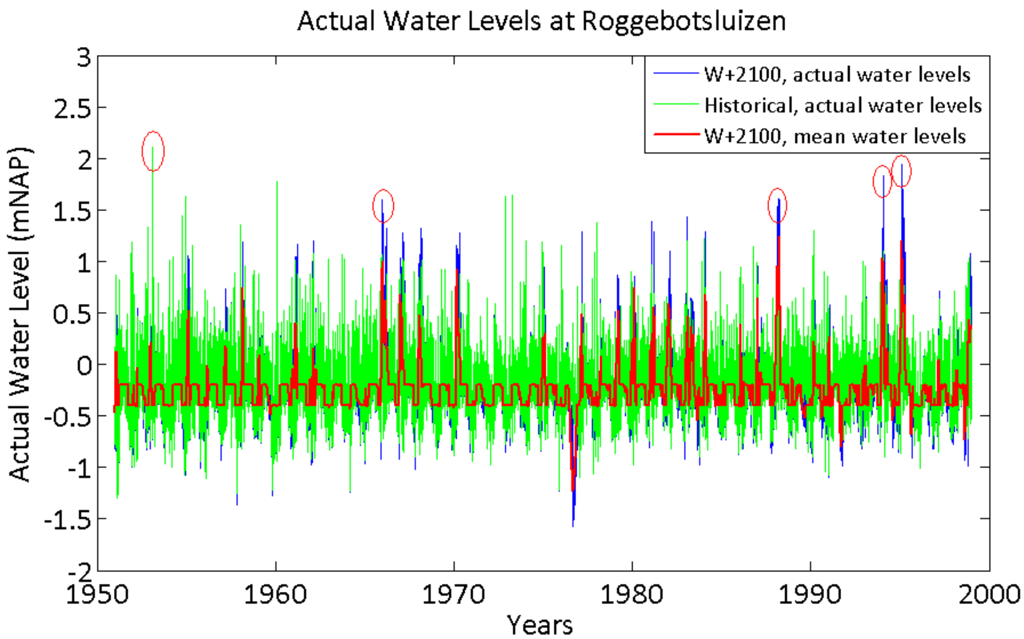

Figure 4.2 – Actual water levels at Roggebotsluizen

As it can be noticed, the peak in winter 1952/1953 is already present in the historical series, because of the wind. The other peaks are only present in the W+2100 scenario, due to the high water levels.

For each winter defined above, the difference between the highest peak and the reference taken from the historical situation is measured. When under the current alternative the peak is higher than the threshold, then the differences are summed up in the indicator i_{SW}. Mathematically it is defined as following:

$$i_{SW} = i_{52/53} + i_{65/66} + i_{87/88} + i_{93/94} + i_{94/95}$$

$$i_{52/53} = \max[\max(HRb_t) - WSTh_{52/53}, 0] \quad \text{where} \quad t \in winter(52/53)$$
$$i_{65/66} = \max[\max(HRb_t) - WSTh_{65/66}, 0] \quad \text{where} \quad t \in winter(65/66)$$
$$i_{87/88} = \max[\max(HRb_t) - WSTh_{87/88}, 0] \quad \text{where} \quad t \in winter(87/88)$$
$$i_{93/94} = \max[\max(HRb_t) - WSTh_{93/94}, 0] \quad \text{where} \quad t \in winter(93/94)$$
$$i_{94/95} = \max[\max(HRb_t) - WSTh_{94/95}, 0] \quad \text{where} \quad t \in winter(94/95)$$

Where:

i_{SW}, indicator for safety of dikes in winter [m];

$i_{Wyy/yy}$, indicator for safety of the dikes in the reference winters (yy/yy, year of reference) [m];

HRb_t, actual water levels at Roggebotsluzen [mNAP];

$WSTh_{yy/yy}$, winter safety threshold [mNAP];

1.b) Satisfaction of the safety standards in summer (April/September) in the present and under the climate scenario selected (P&FS); the following hypothesis has been formulized in the definition of the indicator: as wind strength at summer are much lower than in winter, its influence can be disregarded when assessing safety of the dikes in summer months[6]. For this reason the analysis of mean water levels, not including wind effect, is sufficient to assess safety of the dikes from April till September.

> BOX 4.13
> HYPOTHESIS 7, *wind influence can be disregarded when assessing safety of the dikes in summer months (March-September) due to its lower strength than winter. Discussed at 4.3.1.*

In order for the IJsselmeer to be safe, the water level during summer should not reach levels which generate dangerous situations for the safety of the dikes. There is therefore need to define a summer safety threshold (SSTh) which should limit either the maximum mean water level or the maximum target water level allowed from March till October.

As summer is characterized by low water income from the IJssel, from the neighboring polders and milder winds, little research has been carried out on safety of the IJsselmeer from April till September, because it generally does not represent an issue. There is still not a shared procedure which can asses the danger of high mean water levels in summer in relation with summer winds (Meijer 2009). For this reason two different cases have been defined as boundaries for the summer mean water levels, taking into consideration both a conservative and realistic condition and a more extreme one (see paragraph 2.2). The cases are as follow:

- *Extreme case:* $SSTh_{EX}$ is the water level which corresponds to a return period of 1/500 in the statistical analysis of the historical winter extreme mean water levels. It represents a boundary on the mean water level. A safety standard of 1/500 has been assumed because it corresponds to a safe choice with respect to the lowest safety standard of the dikes in the IJsselmeer (1/1250). In the present research, this corresponds to a $SSTh_{EX}$=+0.69mNAP, which is comparable to the maximum water level rise allowable according to expert judgments reported in [7] (+0.6mNAP).

  This choice comes from Hypothesis 5: if wind effect can be disregarded, than the safety threshold in summer is given by the extreme mean water level with return period equal to the safety standard of the dike (here 1/500 to have some safety margin).
- *Conservative case:* as suggested in paragraph 2.2, the extreme threshold has been considered unrealistic, especially because wind can not totally be disregarded leading to an unsafe condition. Experts agree on the fact that a

[6] This is in general not true, After May wind influence is lower but not negligible. This is also the reason of assuming two different cases: a conservative and an extreme one.

maximum rise of the target water level till +0.1mNAP is more realistic. For this case a $SSTh_{SF}$=+0.10mNAP has also been selected as a boundary for the target water level.

It is importance to notice that there is a difference in considering a boundary for the target water level and for the main water level. Under the present conditions, the constraints are similar, given the prolonged possibility for discharge to the Waddenzee. However, with extreme sea level rise, a constraint on the target water level might fail in controlling the mean water level. There is therefore need to check the mean water level when using $SSTh_{SF}$

Also, it is important to see the two cases in the right perspective. The extreme case neglects the influence of summer winds, defining a boundary which is unrealistic, but however interesting to investigate. In fact adopting such hypothesis allows exploration of the physical limits of the system. On the other hand, the conservative case shortens the field of action, but surely defines a realistic alternative.

The missing step for the mathematical formalization of the indicator is the definition of the $SSTh_{EX}$. Figure 4.3 shows the extreme event curve of the mean water level (modeled). The value corresponding to a return time of 1/500 is the $SSTh_{EX}$=0.69mNAP.

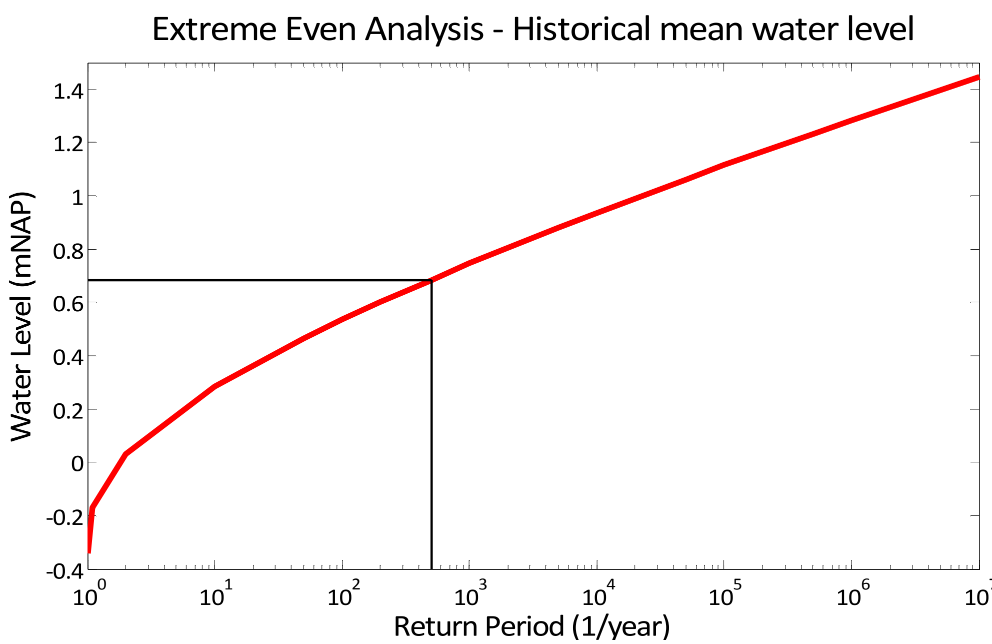

Figure 4.3 – Extreme event curve for the hystorical situation

For an accurate description of the statistical tools used in the research, refer to paragraph 4.3.2, where the indicator is designed for the safety of the dike.

In the extreme case, for each summer month the highest water level in the whole series is selected and checked with the SSTh. When the water level is higher than the threshold, the differences are summed up in the indicator i_{SSEX}. Mathematically it is defined as following:

$$i_{SSEX} = i_{sap} + i_{smm} + i_{sjn} + i_{sjl} + i_{sag} + i_{ss}$$

$$i_{sap} = \max[\max(HIJ_t) - SSTh_{EX}, 0] \qquad \text{where } t \in \forall \text{April}$$
$$i_{sap} = \max[\max(HIJ_t) - SSTh_{EX}, 0] \qquad \text{where } t \in \forall \text{May}$$
$$i_{sap} = \max[\max(HIJ_t) - SSTh_{EX}, 0] \qquad \text{where } t \in \forall \text{June}$$
$$i_{sap} = \max[\max(HIJ_t) - SSTh_{EX}, 0] \qquad \text{where } t \in \forall \text{July}$$
$$i_{sap} = \max[\max(HIJ_t) - SSTh_{EX}, 0] \qquad \text{where } t \in \forall \text{August}$$
$$i_{sap} = \max[\max(HIJ_t) - SSTh_{EX}, 0] \qquad \text{where } t \in \forall \text{September}$$

Where:

i_{SSEX}, indicator for safety in the summer [m];
i_{smonth}, indicator for safety in each summer month [m];
HIJ_t, mean water level of the IJsselmeer, in the reference summer month [mNAP];
$SSTh_{EX}$, summer safety threshold for the extreme case [mNAP];

In the conservative case, no indicator is defined. $SSTh_{SF}$ define the higher boundary for the possible target water level to test in the optimization so that the algorithm can not consider options higher than the threshold. In those cases the following limitation holds:

$$u_{apr} \in U[-0.4;0.1]$$
$$u_{may} \in U[-0.4;0.1]$$
$$u_{jun} \in U[-0.4;0.1]$$
$$u_{jul} \in U[-0.4;0.1]$$
$$u_{aug} \in U[-0.4;0.1]$$
$$u_{sept} \in U[-0.4;0.1]$$

Water Demand

Satisfaction of the water demand in the present and under the climate scenario selected (P&FS); as stated in paragraph 3.3.2. The scenario used for the water demand defines the volumes required by the different functions, flushing, safety and water for the districts. The intakes around the lake, all working by gravity, have different threshold levels (levels under which gravity flow is not possible anymore). In the present research, an analysis diversified by the use and the location of the intakes is not possible. Therefore, as a hypothesis, water demand serves only one common function (disregarding diversification of interests between the users) and only through one service location (disregarding the presence of different intakes with different features).

The only distinction has been made on the destination of the water demand; some volumes are required to the inland (to the polders), others to satisfy flushing requirements to other destinations (in the case of the IJsselmeer, mainly to the Waddenzee through the Afsluitdijk, for flushing to prevent salt intrusion). Given this, the objective can be defined as:

> BOX 4.14
> HYPOTHESIS 8, *there is no distinction between the different functions which define the total water demand, and the intake is unique.* Water demand is modeled as requested by a unique user, and supplied at a unique intake. *Discussed at 4.3.1.*

2.a) Satisfaction of the water demand to the polders (P&FS); this includes water required for flushing, safety and needs of the districts in the neighboring land. Taking inspiration from the operational objective defined for water demand at 2.2.3., the mean water levels should never drop under the threshold which makes gravity flow to the polders impossible.

The first step for the mathematical formalization of the indicator is the definition of the threshold under which free flow to the polders is not possible anymore, WDPTh.
Given the need of 20/30cm of head difference for the free flow to supply sufficient capacity in dry summers, and the intake to the Frisian boezem at -0.52 mNAP (at Lemmer the major inlet is located), a mean water level in the IJsselmeer of -0.3mNAP is needed in order to supply the fresh water demand (WDPTh=-0.3mNAP) (Meijer 2009).
The official intake level is actually at -0.4 mNAP, but water managers protested, because capacity reduces already at higher levels. Moreover, as a result of wind from eastern direction (as is usually the case in dry and warm summers when demands are highest), the water level is lower near Friesland and higher near Noord-Holland.

Given the water demand to the polders, at each time step, a deficit equal to the water demand is assumed when the modeled mean water level in the IJsselmeer is lower than -0.3 mNAP. In all the other cases the deficit is zero. Deficits are then summed up in the indicator i_{WDP} the indicator is mathematically defined as following:

$$i_{WDP} = \sum_{t=1}^{t=T} Dp_t$$

Where:

$$Dp_t = \begin{cases} 0 & \text{if } HIJ_t < WDPTh \\ Qdp_t & \text{if } HIJ_t \geq WDPTh \end{cases} \qquad t = 1,2,\ldots,T-1$$

Where:

I_{WDP}, indicator for water deficit to the polders [m^3/s];
Dp_t, deficit to the polders at the time step t [m^3/s];
Qdp_t, water demand to the polders at time step t [m^3/s];
HIJ_t, Mean water level in the IJsselmeer [mNAP];
WDPTh, Threshold for free flow to the polders [mNAP];
T, total number of time steps;

2.b) Satisfaction of water demand to other locations (P&FS); the same holds for the water demand to other locations. The mean water level should never drop under the threshold which makes gravity flow to the Waddenzee impossible.

The case of water required for flushing to the Waddenzee is identical to the one for the polders. However, a different threshold is defined. In this case, free flow is assured if the mean water level in the IJsselmeer is higher than –0.4 mNAP (WDWh=- 0.4mNAP). It is important to notice that the case is simplified in the sense that flushing by gravity to the Waddenzee does not depend only on the mean water level of the IJsselmeer, but also on the one of the sea. However, such approximation has been considered having little consequences on the estimation of the water deficit. This is also because an evaluation of the alternatives for satisfaction of water demand to the Waddenzee is easy to perform given the fact that the demand is constant the whole year and equal to 10 m^3/s.

Given the water required for flushing to the Waddenzee, a deficit equal to the water demand is assumed when the mean water level in the IJsselmeer is lower than -0.4 mNAP. In all the other cases, the deficit is zero. Deficits are then summed up in the indicator i_{WDW}. The indicator is mathematically defined as following:

$$i_{WDW} = \sum_{t=1}^{t=T} Dw_t$$

Where:

$$Dw_t = \begin{cases} 0 & \text{if } HIJ_t < WDWTh \\ Qdw_t & \text{if } HIJ_t \geq WDWTh \end{cases} \qquad t = 1,2,...,T-1$$

Where:

I_{WDW} indicator for water deficit to the Waddenzee [m^3/s];
Dw_t, deficit to the Waddenzee at the time step t [m^3/s];
Qdw_t, water demand to the Waddenzee at time step t [m^3/s];
HIJ_t, mean water level in the IJsselmeer [mNAP];
WDWTh, threshold for free flow to the Waddenzee [mNAP];
T, total number of time steps;

Broadest consensus

3) *acquisition of the broadest consensus among the impact stakeholders;* This objective might in general be applied to any decision making process: a broad consensus on the alternative to implement is the ultimate goal of planning, because it guarantees the success of project. Many ways are possible to define and measure the consensus of the stakeholders; however in the present research this objective is specified in a very simple way.

The basic idea is that once safety and water demand have been optimized, a set of multiple alternatives might come out, which equally satisfy the two stakes. How to choose then? Bearing in mind that there are many other stakes in the system which have not been considered in the optimization of the test case, it is assumed that they are used to the system as it is. They dislike changes (this is true for navigation, recreation, water management outside the dikes etc…). The optimum solution is chosen, selecting the alternative which is closer to the present configuration of the system, minimizing the difference between the measures and the IJsselmeer as it is today.

The formulation of the indicator depends on the measure considered. When changes in target water level are analyzed, the indicator i_{TG} is the square of the difference between the new and the present target water level. While sizing the pump capacity, the indicator i_{PUMP} is the capacity itself (considering that in the represent situation the pump capacity is zero).

The indicators are mathematically defined as following:

$$i_{TG} = (tg_{new} - tg_{pr})^2$$

Where:

I_{TG}, indicator for minimum changes in target water level [m^2];
tg_{new}, new target water level [mNAP];
tg_{pr}, present target water level [mNAP];

$$i_{PUMP} = Pcap$$

Where:

I_{PUMP}, indicator for minimum changes in pump capacity [m^3/s];
Pcap, pump capacity [m^3/s];

The above indicators concur in the definition of the objective function used in the optimization. Once the optimum alternative has been selected, there is need to assess its impacts on the stakes (in an *"a posteriori"* analysis). Since in this case the indicators do not have to be implemented in an optimization, proxy indicators and assumptions used to make the objective function workable will be left out, and the assessment will use the indicators of the sectors in their complexity.

4.3.2. SAFETY OF THE DIKES

The evaluation hierarchy of the stakes is shown in Figure 4.4, which is a subpart of the evaluation hierarchy of the problem owner shown in Figure 4.1.

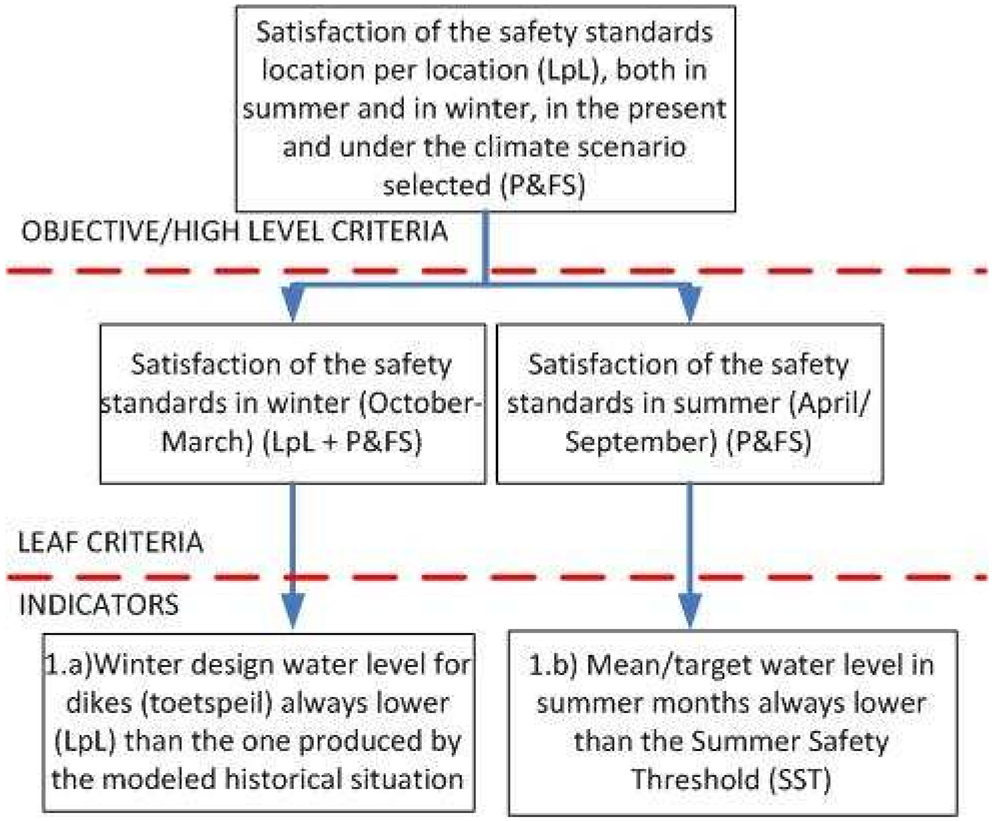

Figure 4.4 – Evaluation hierarchy for safety

In this paragraph there is need to describe the indicator for winter safety, which assumes a different and more complete formulation than the one used in the optimization and defined in paragraph 4.3.1.

As for the indicators for summer safety, no further discussion is needed. Equation *[cite the equation]* holds for assessing safety when assuming the extreme case. Regarding the conservative case, its satisfaction has been transformed in a boundary condition for the target water level, so that alternatives are safe by definition.

Satisfaction of the safety standards in winter (October-March) location per location in the present and under the climate scenario selected (LpL + P&FS);

The effects on safety of the dikes produced by the selected alternatives are assessed with the use of Hydra-Vij; a probabilistic tool developed by *Rijkswaterstaat RIZA* and *HKV lijn in water* used for calculating the design characteristics of the dike ring in the

IJssel and Vecht delta. The version used in the present research is Hydra-Vij 2.2.3. in combination with the database of the dikes location and features in the IJsselmeer.
Given the statistical analysis of the mean water level in the lake (extreme event curve), the software calculates the design water level (and design height) of the dikes in several locations, by its combination with local wind statistics.

Alternatives selected through the optimization problem modify the mean water level regime of the IJsselmeer. The winter statistics of the mean water level produced by the different alternatives are given as inputs to the software and, as an outcome, the design water level (toetspeil) is read and confronted with the present requirements.

The statistical tool used to define the extreme event curve of the mean water level in the IJsselmeer, is the one proposed by Blaakman (Blaakman 1999) in the framework of the Boertien commission, which was asked to review the assumptions on which the toetspeil has to be defined. The same methodology has been applied also in other past researches (Kramer 2008; de Jong 2010).
The year maxima of the mean water level (modeled) are fit to four different statistical models:

- Gumbel distribution;
- Normal distribution;
- Gamma distribution;
- Rayleigh distribution;

The mean of the four distributions is assumed to be the extreme event curve (work line) and used as input to Hydra-Vij. Figure 4.5 shows an example (Kramer 2008) of how the work line is derived from the four statistical models, the light blue line is the one used as input for Hydra-Vij.

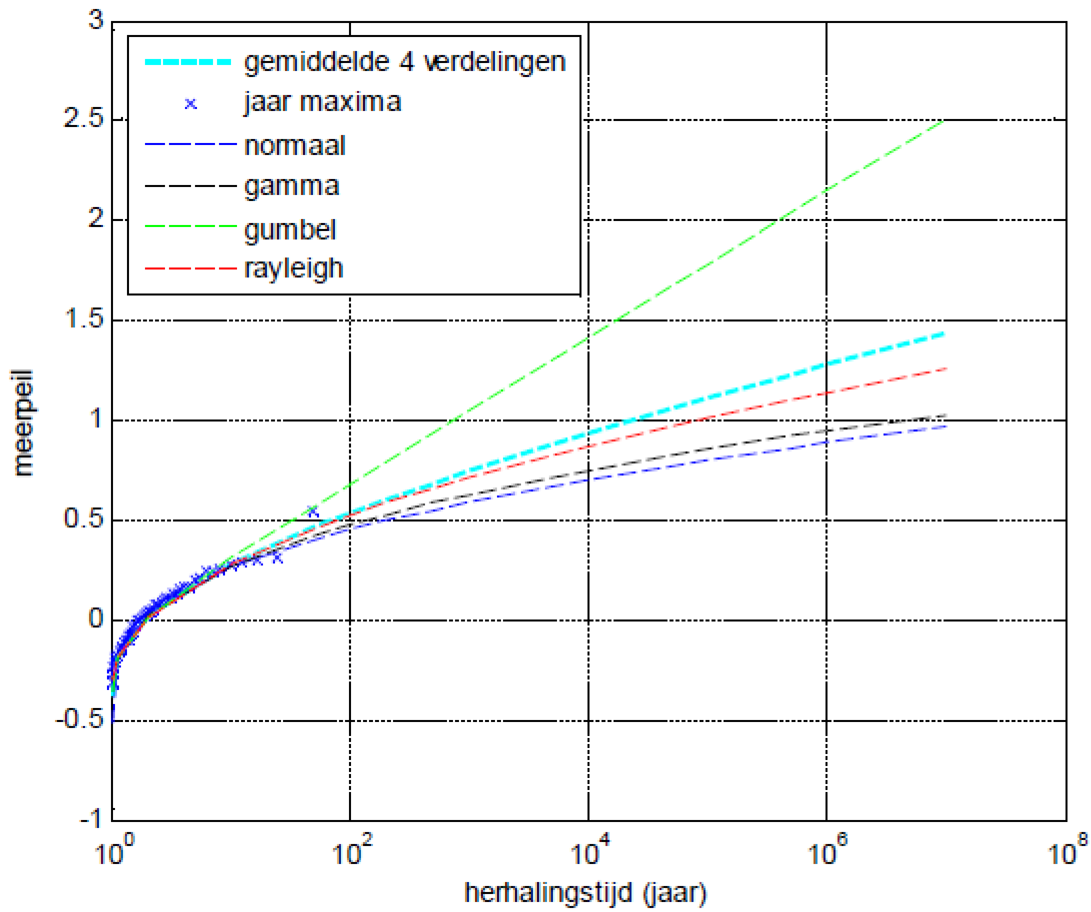

Figure 4.5 – Example of the four distributions

The choice of the statistical method suggested by Blaakman, assures reliability and continuity of the analysis being in line with the methodology of the previous studies and allowing comparison of the alternatives with past researches.

In the present research, not all the locations around the IJsselmeer have been tested for safety. Due to time constraints, 14 locations have been selected, choosing both water level and wind dominated areas of the IJsselmeer (see paragraph 2.1.3. *wind*), in order to assess the alternatives in both conditions.
Table 4.3 shows the selected locations with the correspondent toetspeil and the typology (wind or water level dominated); the first column shows the design water level as reported in the HR2006 report (Ministerie van Verkeer en Waterstaat 2007), while in the second, the toetpeilen are taken from the calculations of Blaakman (Blaakman 1999), performed by using the above defined methodology for defining the extreme mean water level curve.

LOCATION	HR 2006 [113]	Blaakaman [120]	Type of location
02A Zeughoek Noord	1	1,12	Water Level
F037 Makkum	1,4	1,51	Wind
F125 Workum Gele Strand	1,2	1,27	Wind
F202 Hinderlopen	1	1,13	Water Level
F292 Stavoren	1	1,03	Water Level
F351 Laaxum	1	1,02	Water Level
L006 Lemsterbaai	2	1,97	Wind
N195 Westermeerdijk	1,5	1,51	Wind
N290 Westermeerdijk	1,9	1,94	Wind
F115 Ketelmeerdijk	2,5	2,44	Wind
F235 IJsselmeerdijk	1,8	1,81	Wind
H-IJM086 Houtribdijk	1,6	1,66	Wind
07A-Enkhuizen	1,1	1,11	Water Level
05C Andijk Noorderdijk	1,1	1,11	Water Level

Table 4.3 – Location selected for evaluation of impacts on safety

Figure 4.6 shows the location of the selected test areas in the IJsselmeer. The selection of the locations has been done in line with the choices made in previous research (de Jong 2010), also in this case, in order to allow continuity and comparison of the alternatives suggested.

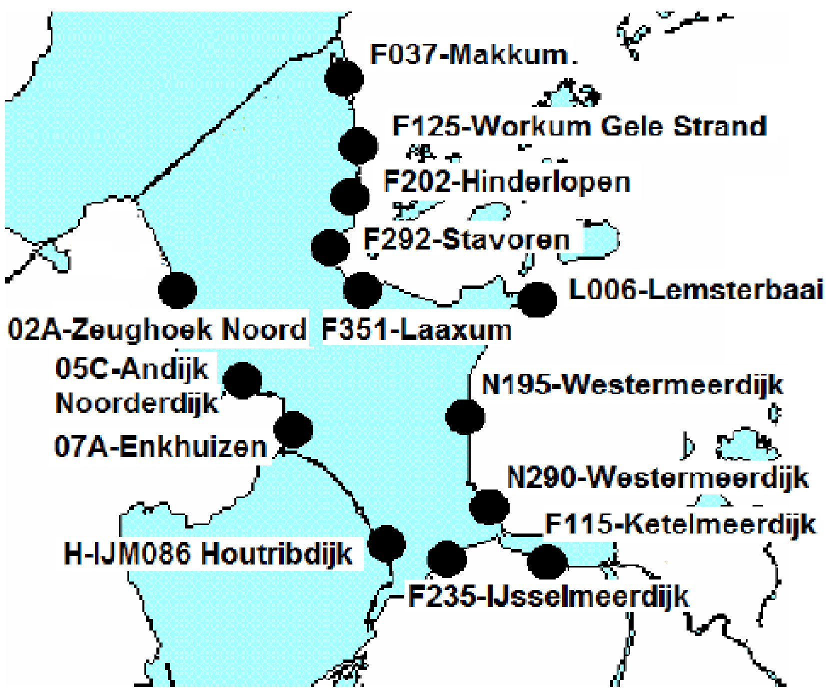

Figure 4.6 – Map of the location selected for evaluation of impacts on safety

An alternative can be considered safe with respect to the winter period, if its toetspeil calculated through Hydra-Vij and the methodology above defined, is equal or lower to the toetspeil calculated from the modeled historical situation. This should hold for any of the selected locations.
Again, in line with the hypothesis 13 (box 4.12), the modeled historical series of the mean water level is considered as a reference for the alternatives.

4.3.3 WATER DEMAND

For this stake see paragraph 4.3.1. – *water demand*, where the definition of the indicators for water demand is defined as part of the objective of the problem owner. The specific evaluation hierarchy is shown in Figure 4.6, subpart of Figure 4.1.

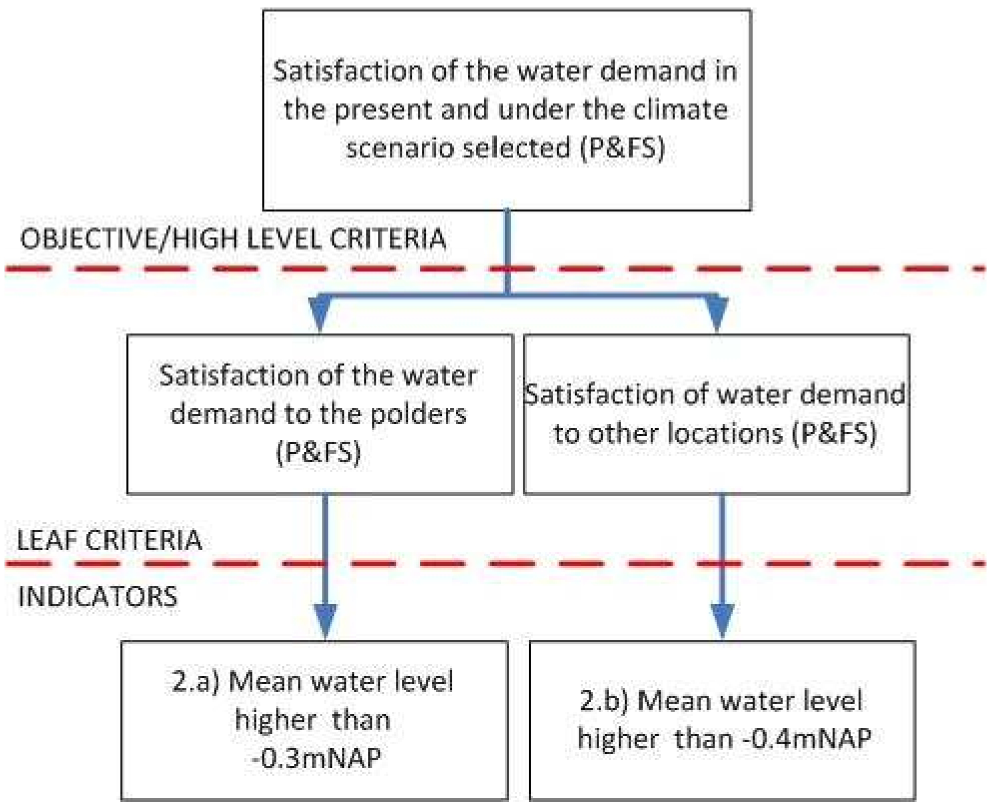

Figure 4.6 – Evaluation hierarchy for water demand

4.3.4 COMMERCIAL SHIPPING

As stated in chapter 2.2.5, the objective of the commercial shipping is *a water system which could allow full load of cargos and little waiting times at the structures, in order to increase shipping revenues.* Commercial shipping can adjust to broad water level fluctuations, also with the help of extra dredging if needed. However, from the review of several reports (Meijer 2009), a low threshold of ShTh=-0.4mNAP is often used to assess undesired water level fluctuations, due to the limitations on cargo load. Since the indicator for commercial shipping is only one, there is no definition of evaluation hierarchy in this case.

On the modeled horizon, the number of time steps during which the mean water level is lower than ShTh (-0.4mNAP) is used as an indicator for supporting the analysis of the impacts of the selected alternatives.
The mathematical formulation of the indicator is as follow:

$$i_{sh} = \sum_{t=1}^{t=T} Sh_t$$

Where:

$$Sh_t = \begin{cases} 1 \text{ if } HIJ_t \geq ShTh \\ 0 \text{ if } HIJ_t < ShTh \end{cases}$$

Where:

i_{sh}, indicator for commercial shipping [-];
Sh_t, step indicator for commercial shipping [-];
HIJ_t, mean water level of the IJseelmeer [mNAP];
ShTh, threshold for commercial shipping [mNAP];
T, total number of time steps;

4.3.5 RECREATION

As state in paragraph 2.2.6, the objective of the stake is a *water level regime which preserves the present infrastructure, beaches and leisure activities.* On the base of the available information, two main aspects concur in the definition of the indicator for recreation: accessibility of leisure harbors, and accessibility of beaches. The evaluation hierarchy is shown in figure 4.7. For the discussion over the threshold assumed in the indicators see paragraph 2.2.6.

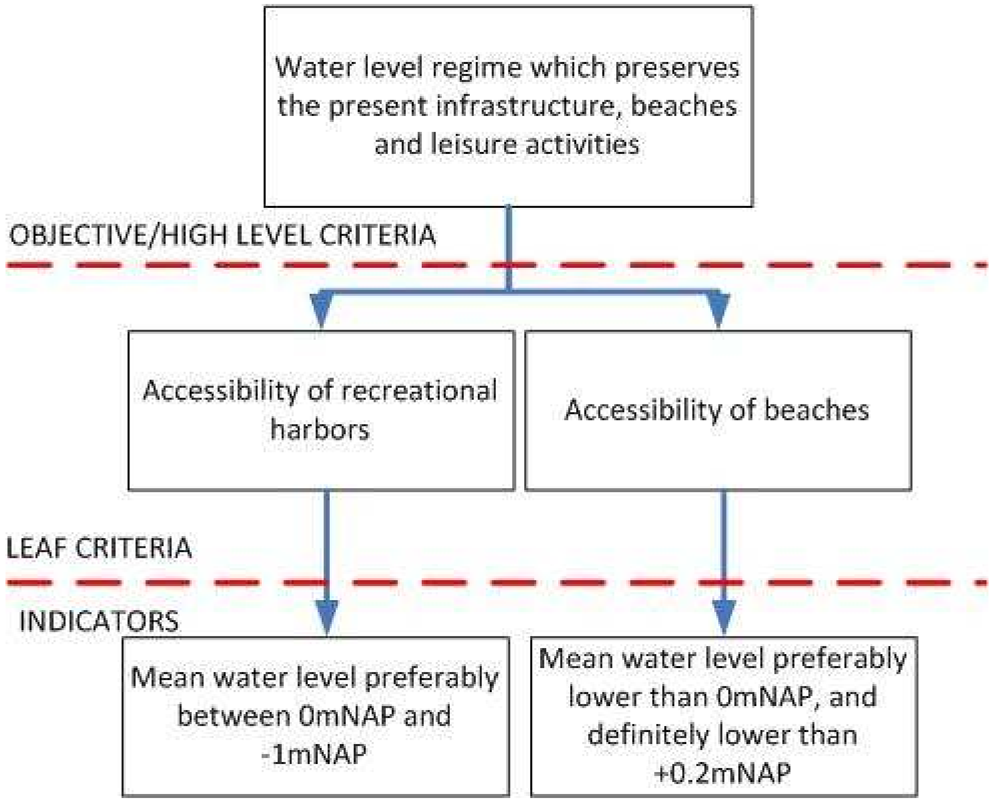

Figure 4.7 – Evaluation hierarchy for recreation

For recreation, the summer period is considered more relevant (March-September), so that, given the modeled time series, the three indicators can be defined:

- i_L, number of time steps during summer when the mean water level is lower than the RLTh=-1mNAP;
- i_H, number of time steps during summer when the mean water level higher than the RHTh=+0mNAP and lower than RHHTh=0.2mNAP;
- i_{HH}, number of time steps during summer when the mean water level higher than the RHHTh=0.2mNAP;

The mathematical formulation of the indicators is as follow:

$$i_L = \sum_{t=1}^{t=T} RL_t \quad \text{where } t \in \text{summer}$$

$$i_H = \sum_{t=1}^{t=T} RH_t \quad \text{where } t \in \text{summer}$$

$$i_{HH} = \sum_{t=1}^{t=T} RHH_t \quad \text{where } t \in \text{summer}$$

Where:

$$RL_t = \begin{cases} 1 \text{ if } HIJ_t < RLTh \\ 0 \text{ if } HIJ_t \geq RLTh \end{cases} \qquad \text{where } t \in \text{summer}$$

$$RH_t = \begin{cases} 1 \text{ if } RHTh < HIJ_t \leq RHHTh \\ 0 \text{ if } HIJ_t \leq RHTh \Lambda HIJ_t > RHHTh \end{cases} \quad \text{where } t \in \text{summer}$$

$$RHH_t = \begin{cases} 1 \text{ if } HIJ_t > RHHTh \\ 0 \text{ if } HIJ_t \geq RHHTh \end{cases} \quad \text{where } t \in \text{summer}$$

Where:

I_L, indicator for accessibility of recreational harbors [-];
I_H, indicator for accessibility of beaches [-];
I_{HH}, high indicator for accessibility of beaches [-];
RL_t, step indicator for accessibility of recreational harbors [-];
RH_t, step indicator for accessibility of beaches [-];
RHH_t, step indicator for high accessibility of beaches [-];
HIJ_t, mean water level of the IJseelmeer [mNAP];
RLTh, threshold for accessibility of recreational harbors [mNAP];
RHTh, threshold for accessibility of beaches [mNAP];
RHHTh, threshold for high accessibility of beaches [mNAP];
T, total number of time steps;

On the base of the lower importance of the RHTh, the tree indicators will concur in the definition of the global index for the sector according the following weights:

$$I_R = i_L + 0.5\ i_H + i_{HH}$$

4.3.6 INLAND WATER MANAGEMENT

As stated in 2.2.7, the objective of the stake is drainage of the inland water system, with out the need of expanding pumping capacity. According to the available information, this is assured until a water level of IWMTh=+0.1mNAP.

Given the main need of drainage of the neighboring polders during winter months, the indicator for the stake is defined as the number of time steps during the modeled winter period in which the mean water level is higher than 0.1mNAP. The mathematical formulation of the indicator is as follow:

$$i_{IWM} = \sum_{t=1}^{t=T} IWM_t \quad \text{where } t \in \text{winter}$$

Where:

$$IWM_t = \begin{cases} 1 \text{ if } HIJ_t > IWMTh \\ 0 \text{ if } HIJ_t \leq IWMTh \end{cases} \quad \text{where } t \in \text{winter}$$

Where:

I_{IWM}, indicator for inland water management [-];
IWM_t, step indicator for inland water management [-];
HIJ_t, mean water level of the IJseelmeer [mNAP];

IWMTh, threshold for inland water management [mNAP];
T, total number of time steps;

Since the indicator for inland water management is only one, there is no definition of evaluation hierarchy in this case.

4.3.7 WATER MANAGEMENT OUTSIDE THE DIKES AND ECOLOGY

No mathematical indicator has been designed for ecology and the areas outside the dikes. In both cases the development of a proper index would have need investigation which is outside the scope of the research. Evaluation of the impacts of the selected alternatives will be given by pure comparison of the water level regime produced and the objectives expressed by the stakeholders.

4.3.8 FINAL REMARK ON THE DEFINITION OF THE INDICATORS

Given the division in Project and Impact stakes (see paragraph 4.1.3), the definition of the indicators has a different purpose according to the class each stake belongs to.
More research, attention and detailed definition is given to the Project Stakes (4.2.1-4.3.3), which have to be accurate both when concurring in the definition of the objective function and when needed to asses the selected alternatives. This is because they are the stakes which define a climate-proof IJsselmeer for the test case.
The indicators for the impact stakes are only defined with the purpose of supporting the evaluation of the impacts of the selected alternatives. Due to their simplification, they have little absolute value in assessing the impacts, but can only be used as tools to help relative evaluation between the results. This is especially true because they assume that the damage for the stake only depends on the crossing of the threshold, while the amount by which such limit is passed has no influence. This might be in general not true.

Indicators defined for the decision maker (paragraph 4.3.1) are used in section 4.5.1 for the definition of the optimization problems and the objective functions. The results of the optimizations are shown in 5.1. The indicators defined for all the other stakes (paragraph 4.3.1-4.3.6) are the base of the evaluation phase described in 4.5.2. Results are shown in 5.2.

4.4. MODEL IDENTIFICATION

A mathematical model of the system is needed in order to represents the dynamics of the IJsselmeer and estimate the values of the indicators in correspondence with the different alternatives.

In the present study, a model for the IJsselmeer has been programmed ad-hoc in Matlab®, on the basis of the SOBEK Bekken model. SOBEK Bekken is the flow modeling tool of WINBOS, a water balance decision support system commissioned in the nineties by Rikswaterstaat. WINBOS has been developed in order to analyze different strategies in the IJsselmeergebied under climate scenarios and includes different modules which mainly assess water safety and ecology, but also recreation, commercial shipping, fishing, drinking water, agriculture etc… The main compartments included in the tool are the Jsselmeer, the Markermeer and the Randmeren, together with the Noordzeekanaal and the Amsterdam-Rijnkanaal.

There are different reasons why it has been necessary to reformulate the model in Matlab® environment:

- In the framework of the present study, it is fundamental that the model is simple and able to simulate the water levels produced by a single alternative with little computational time. The lower the simulation time of one alternative, the higher the number of alternatives which can be simulated, and the lower the time needed to find the optimum. If the model is not fast enough, the whole optimization can fail, leading to impracticable computational time.

  The SOBEK Bekken includes compartments which are not relevant in the framework of the present study. State variables are calculated also for the Markermeer and the Randmeren, increasing computational time. Furthermore, being the optimization tool developed in Matlab®, its interaction with SOBEK could slow down the process.
- SOBEK Bekken does not include possibilities to assess droughts, so that in previous studies it has been recommended to use a modeling tool which could integrate such aspect [19].

The model developed in the present study tries to tackle such drawbacks, defining a fast and accurate tool, which however builds its basis on the SOBEK Bekken model, in order to have a reliable reference, used in previous studies [7-19-106].

4.4.1 CASUAL NETWORK AND STATE TRANSITION EQUATION

The modeling tool developed in the present research is a mass balance model of the IJsselmeer. Coherently with the SOBEK Bekken model, the IJseelmeer has been modeled as a box, with a constant surface and depth. The surface has been assumed to be As=1.182 10^9 m^2. The other compartments of the IJsselmeergebied are disregarded, and the only state variable is the water level of the lake.

The model is deterministic, has a time step of 1 hour, and uses for the external driving forces the time series taken from the SOBEK Bekken model, both for the past situation and for the future scenarios (W+2050 and W+2100). Since the SOBEK Bekken model is defined for a time horizon from 1/1/1951 till 31/12/1998, such is the time horizon of the present model, with a total of T=420.768 time steps [hours].

The state variable is the water level of the IJsselmeer in mNAP, described with the following equation:

$$HIJ_{t+1} = f(HIJ_t, \mathbf{w}_t, \mathbf{u}^p) \qquad t = 1,2,...,T-1$$

Where:

HIJ, state variable, water level in the IJseelmeer (mNAP);

w, external driving forces, i.e. wind (velocity and direction), sea water level, discharge from the IJssel, water demand to the polders, water demand to the Waddenzee, lateral flow, fluxes from the Markermeer and from the Veluwemeer;

$\mathbf{u}^p$, decision variables, defined in box 4.3, 4.5, 4.6;

In order to understand the form of the function f, Figure 4.8 shows the casual network of the model which links the inputs with the definition of the state.

Where:

Wvd, wind direction [degrees] and velocity [m/s];
Hw, water level of the Waddenzee [mNAP];
Qdp, water demand to the polders [m^3/s];
Qdw, water demand to the Waddenzee [m^3/s];
QIJ, discharge from the IJssel [m^3/s];
Qlt, lateral flow [m^3/s];
Fv_ij, net flow from the Veluwemeer [m^3/s];
Fm_ij, net flow from the Markermeer [m^3/s];
Hst(L), wind set up at the different structures[m], depends on the location L;
Qawd, actual water demand [m^3/s];
Ht, target water level [mNAP];
u, decision variable [-];
Qwp, potential discharge to the Waddenzee [m^3/s];
Qw, actual discharge to the Waddenzee[m^3/s];

Definition of the different variables will be provided in the following paragraphs.

As can be noticed all the variables are defined for the time step t, this is because a deterministic model has been used in the present research. All the components which contribute to the definition of the state at the time step t+1, are precisely known at the time step t, so that the future state variable can be precisely defined. The following paragraphs consider the different variables of the casual network, making explicit the equations, until the definition of the state transition equation.

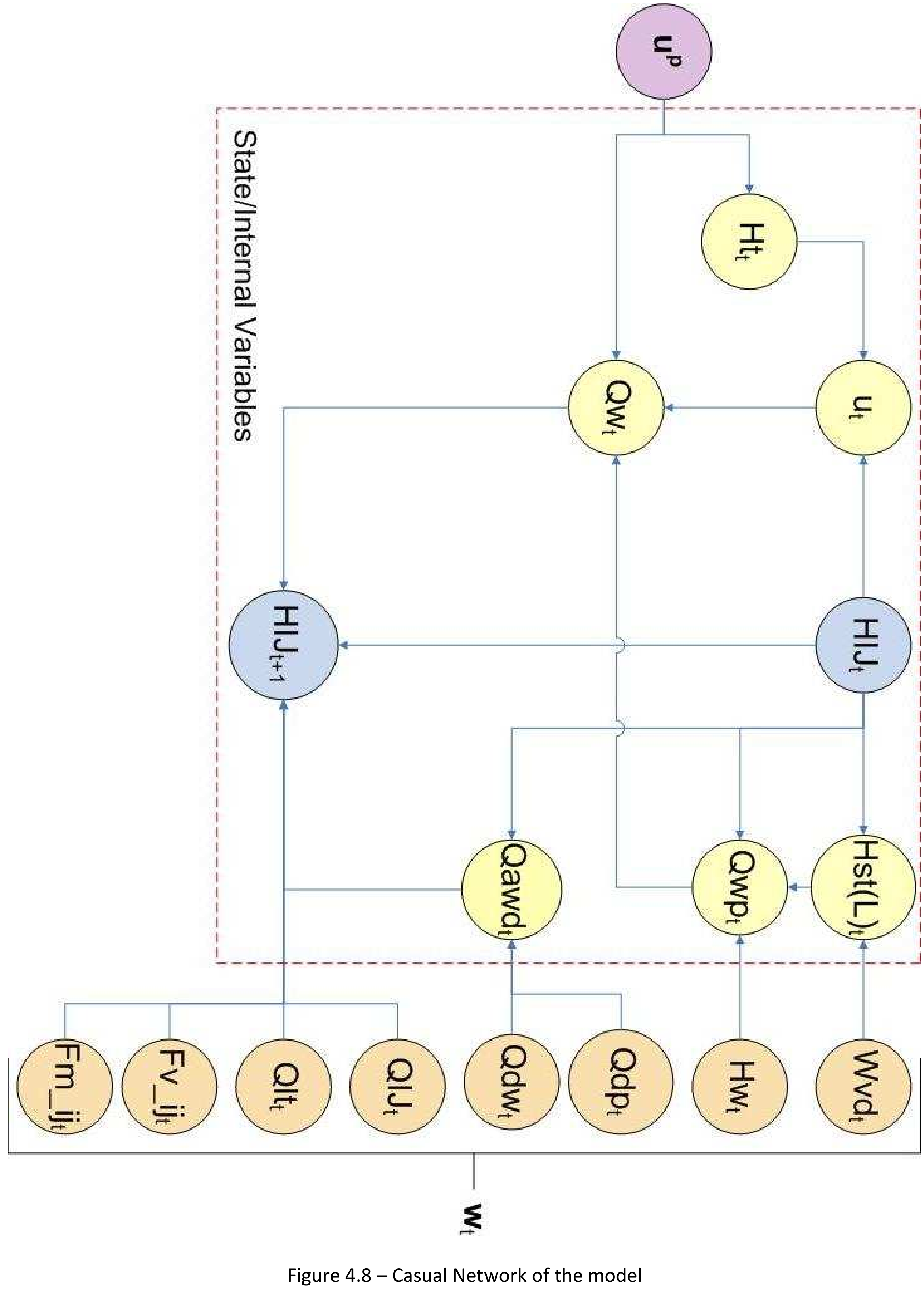

Figure 4.8 – Casual Network of the model

4.4.2 EXTERNAL DRIVING FORCES

Wind - Wvd

Hourly wind directions and velocities have been taken from the SOBEK Bekken model and used to define the wind setup at 3 locations: Lorentzsluizen, Stevinsluizen and Roggebotsluizen.

Since there are no future scenarios defined for the wind, the same series will be used both to model the historical situation and the future scenarios for the Ijsselmeer.

Water level at the Waddenzee – Hw

The time series of the hourly water level at the Waddenzee has been taken from the SOBEK Bekken model, where they are expressed in mNAP.

For the future scenarios, absolute sea level rise in meters has been added hourly to the historical water levels.

Discharge from the IJssel – QIJ

The time series of the daily discharge from the IJssel has been taken from the SOBEK Bekken model, where they are expressed in m^3/s. In order to be used with an hourly time step, the time series has been interpolated.

For the future scenarios the IJssel discharge has been change accordingly to the monthly percentages variation expected for the river Rhine in the scenarios W+2050 and W+2100. Assuming that in the future the discharge of the IJssel will still represent the 15% of the Rhine, the percentages in Table 4.4 (Verhoeven 2009), can be used to define the future inflow to the IJsselmeer.

maand	T2050 W+	T2100 W+
januari	14.3	26.3
februari	18.1	35.1
maart	16.1	33.4
april	11.9	25.1
mei	1.7	5.1
juni	-11.8	-21.5
juli	-24.4	-43.2
augustus	-34.3	-57.0
september	-37.3	-61.9
oktober	-32.9	-56.4
november	-17.9	-32.9
december	2.5	4.1

Table 4.4 – Monthly changes of the discharge of the IJssel for the different scenarios [%]

Lateral flow - Qlt

The time series of the daily lateral inflow has been taken from the SOBEK Bekken model, where they are expressed in m^3/s. In order to be used with an hourly time step, the time series has been interpolated.

In the SOBEK Bekken model, the lateral inflow is a net inflow to the IJsselmeer which includes several incoming and outgoing fluxes. Namely rain, evaporation, discharge from the Vecht and the volumes pumped from the neighboring polders in times of excess of water.

For the future scenarios, evaporation and rain have been changed according to the expected monthly percentage variations. Table 4.5 and 4.6 (Verhoeven 2009) show the percentages used to update the fluxes:

maand	T2050 W+	T2100 W+
januari	14.7	29.4
februari	15.3	30.6
maart	14.3	28.6
april	7.8	15.7
mei	-3.8	-7.7
juni	-14.6	-29.1
juli	-21.2	-42.4
augustus	-21.4	-42.9
september	-16.3	-32.6
oktober	-5.7	-11.4
november	4.0	8.0
december	12.5	25.1

Table 4.5 – Monthly changes in rain[%]

maand	T2050 W+	T2100 W+
januari	0.0	0.0
februari	0.3	0.7
maart	3.0	6.0
april	6.0	12.0
mei	9.3	18.5
juni	13.8	27.6
juli	15.3	30.6
augustus	15.8	31.7
september	13.2	26.4
oktober	10.0	20.0
november	6.6	13.1
december	0.4	0.8

Table 4.6 – Monthly changes in evaporation [%]

The time series used in the different climate scenarios for the lateral inflow have not developed within the present research. As for the time series of the historical situation they have been taken from the SOBEK Bekken model.

Water Demand - Qdp and Qdw

The water demand per decade has been taken from the time series developed by Deltares with the use of PAWN tool, and interpolated in order to define it on an hourly time step. In the vision of the definition of the indictors, it has been divided in two components:

- Qwdp: water demand to the polders;
- Qwdws: water demand to the Waddenzee;

Such demands are defined for the scenario W+2050, and used both for the simulation of the historical situation and the future ones (W+2050 and W+2100).

Net flows from the Marekermeer and Veluwemeer – Fm_ij F_ij

In the SOBEK Bekken model the IJsselmeer is linked with the Markermeer and the Veluwemeer, so that fluxes are exchanged between the water bodies according to the relative water levels. However, in the model used in the present research, such compartments are not included.
The historical net fluxes between the IJsselmeer and the lakes have been added as external driving forces. This is done in order to minimize the losses of those volumes which can not be modeled in the present research.

The same fluxes are also used in the different future scenarios (W+2050 and W+2100).

The assumption is questionable because the actual fluxes depend on the relative water levels in the lakes. Since changes in target water levels of the IJsselmeer are discussed in the framework of the present research, the volumes exchanged in the past will be different from the ones which happen in the modeled future scenarios. However, compared to the other fluxes (from the IJssel and the lateral fluxes), the volumes exchanged with the Markermeer and the Veluwemeer are small fraction on the entire time series (1/10000), therefore have little influence on the simulations.

4.4.3 TARGET WATER LEVEL

The target water level at each time step HT_t, is defined on the base of the decision variable u^p. The decision variable defines the target water level for each month.

From this information the target water level for the whole simulation horizon is defined by assuming a constant water level for each month, equal to the value defined by u^p. In his way the time series of the target water levels is stepwise.

4.4.4 ACTUAL WATER DEMAND

Given the water demands to the Polders and the Waddenzee, the actual water demand which can be satisfied by the IJsselmeer, is defined by the water level of the lake. Only if the mean water level is higher than the needed threshold for free flow (WDPTh and WDWh), the volumes required can leave the IJsselmeer.

The actual water demand at the time step t can be defined as:

$$\mathrm{Qawd}_t = \mathrm{Qdp}_t * \mathrm{cfp}_t + \mathrm{Qdw}_t * \mathrm{cfw}_t \qquad t = 1,2,...,T-1$$

Where:

Qawd_t, actual water demand at the time step t [m^3/s];
Qdp_t, water demand to polders at the time step t [m^3/s];
Qdw_t, water demand to the Waddenzee at the time step t [m^3/s];
cfp_t, coefficient to polders at the time step t [m^3/s];
cfw_t, coefficient to Waddenzee at the time step t [m^3/s];

Defined as:

$$\mathrm{cfp}_t = \begin{cases} 1 & \text{if } \mathrm{HIJ}_t \geq \mathrm{WDPTh} \\ 0 & \text{if } \mathrm{HIJ}_t < \mathrm{WDPTh} \end{cases} \qquad t = 1,2,...,T-1$$

$$\mathrm{cfw}_t = \begin{cases} 1 & \text{if } \mathrm{HIJ}_t \geq \mathrm{WDWTh} \\ 0 & \text{if } \mathrm{HIJ}_t < \mathrm{WDWTh} \end{cases} \qquad t = 1,2,...,T-1$$

The actual water demand is then subtracted to the IJsselmeer, while the part which could not be satisfied defines the deficit (see paragraph 4.3.1).

4.4.5 DISCHARGE TO THE WADDENZEE - Qw

The discharge to the Waddenzee is the main output of the IJsselmeer, it is defined in different ways according to the features of the system.

No pumping station at the Afsluitdijk

For the cases where the discharge to the Waddenzee is only by gravity, the definition of the volumes to be discharged follows the following steps:

a.1) Definition of the wind set up at the Lorentzsluizen and Stevinsluizen. Wind setup is defined given the wind direction, the wind velocity and the mean water level at the IJsselmeer:

$$Hst(L)_t = \frac{c(Wd_t, L)(Wv_t)^{a(Wd_t, L)}}{(h_0(Wd_t, L) + HIJ_t)^{b(Wd_t, L)}} \qquad t = 1,2,...,T-1$$

Where:

$Hst(L)_t$, wind set up for the time step t at location L [m];
Wd_t, wind direction at the time step t [degrees];
Wv_t, wind velocity at the time step t [m/s];
HIJ_t, mean water level at the time step t [mNAP];

The parameters a, b, c and h_0 are function of the different locations and the wind directions. They are defined according to Tables XX-XX, in appendix C.

The same equation is used to define the wind set up at Roggebotsluizen, used to calculate the indicator for safety of the dikes in winter i_{SW}.

a.2) Definition of the potential gravity discharges through the gates, by means of the equation for submerged orifices:

$$Qwp(L)_t = c(L)\mu(L)W_{cr}(L)h_{OP}(L)\sqrt{2g[\max((HIJ_t + Hst(L)_t - Hw_t), 0)]} \qquad t = 1,2,...,T-1$$

Where:

$Qwp(L)_t$, potential gravity discharge at location L for the time step t [m^3/s];
c(L), lateral contraction coefficient for at location L [-];
$\mu(L)$, contraction coefficient for location (L) [-];
$W_{cr}(L)$, crest width for location L [m];
$h_{op}(L)$, opening height for location L [m];
g, gravitation acceleration [m^2/s];
HIJ_t, mean water level in the IJsselmeer for the time step t [mNAP];
$Hst(L)_t$, wind set up for the time step t at location L [m];
Hw_t, water level of the Waddenzee at time step t [mNAP];

Discharge is only possible if the actual water level at the structures (mean water level plus wind set up), is higher than the water level in the Waddenzee. If that is the case, the discharge is proportional to the square root of the difference in water levels, and to the characteristics of the structure.

The parameters depend on the location, and have been taken from the SOBEK Bekken model. Table 4.7 shows the values used in the model:

Parameter	Unit	Lorentzsluizen	Stevinsluizen
c	[-]	0.88	0.88
μ	[-]	0.66	0.66
W_{cr}	[m]	120/270	180
h_{op}	[m]	6.9	6.9

Table 4.7 – Parameters for the sluices at the Afsluitdijk

The different sizes in width of Lorentzsluizen refer to the present structure and the one after the enlargement (Verhoeven 2009).

b.1) Definition of the management decision. Depending on the relation between mean water level and target water level, water needs to be discharged or stored into the IJsselmeer. The decision variable u can be calculated as follow:

$$u_t = \begin{cases} 1 \text{ if } HIJ_t > HT_t + 0.001 \\ 0 \text{ if } HIJ_t < HT_t - 0.001 \end{cases} \qquad t = 1,2,...,T-1$$

Where:

u_t, decision variable at time step t [-];
HIJ_t, mean water level in the IJsselmeer for the time step t [mNAP];
HT_t, target water level in the IJsselmeer for the time step t [mNAP];

Discharge is needed (u_t=1) if the water level is one millimeter higher than the target, avoided (u_t=0) if the water level is one millimeter below the target.

The actual discharge to the Waddenzee is then defined by multiplying the potential discharge by the decision variable:

$$Qw(L)_t = Qwp(L)_t * u_t \qquad t = 1,2,...,T-1$$

Where:

$Qw(L)_t$,actual discharge to the Waddenzee at location L for the time step t[m^3/s];
$Qwp(L)_t$, potential gravity discharge at location L for the time step t [m^3/s];
u_t, decision variable at time step t [-];

Both $Qwp(L)_t$ and u_t can be limiting factors, if discharge by gravity is not possible or the mean water level is lower than the target.

The total discharge to the Waddenzee is then the sum of the discharges at the two gates:

$$Qw_t = Qw(Lr)_t + Qw(St)_t \qquad t = 1,2,...,T-1$$

Where:

Qw_t, total actual discharge to the Waddenzee for the time step t [m^3/s];
$Qw(Lr)_t$, stands for Lorentzsluizen;
$Qw(St\,)_t$ stands for Stevinsluizen;

Pumping station at the Afsluitdijk

When a pumping station is installed at the Afsluitdijk, it is only used when the decision variable suggests discharging the excess water, but gravity discharge is not possible because the water level at the Waddenzee is higher than the one at the IJsselmeer. In such case the discharge to the Waddenzee it is assumed to be equal to the capacity of the pumping station:

$$Qw_t = Pcap \quad \text{if } (u_t = 1)\Lambda(Qwp(Lr)_t = 0)\Lambda(Qwp(St)_t = 0) \qquad t = 1,2,...,T-1$$

Where:

Qw_t, total actual discharge to the Waddenzee for the time step t [m^3/s];
Pcap, pump capacity [m^3/s];
$Qwp(Lr/St)_t$, potential gravity discharge at Lorentzsluizen and Stevinsluizen for the time step t [m^3/s];

All the previous steps (a.1, a.2, b.1) are the same also in case of a pumping station at the Afsluitdijk.

4.4.6 MASS BALANCE – THE STATE TRANSITION EQUATION (f)

Once all the input and output fluxes have been defined, the mean water level at the following step t+1, can be calculated through the mass balance equation:

$$HIJ_{t+1} = HIJ_t + (QIJ_t + Qlt_t + Fm\_ij_t + Fv\_ij_t - Qawd_t - Qw_t) * \Delta t / As \qquad t = 1,2,...,T-1$$

Where:

HIJ_{t+1}, mean water level at the following time step [mNAP];
HIJ_t, mean water level at time step t [mNAP];
QIJ_t, discharge from the IJssel at time step t [m^3/s];
Qlt_t, lateral flow at time step t [m^3/s];
Fv_ij_t, net flow from the Veluwemeer at time step t [m^3/s];
Fm_ij_t, net flow from the Markermeer at time step t[m^3/s];

$Qawd_t$, actual water demand at time step t [m^3/s];
Qw_t, actual discharge to the Waddenzee at time step t [m^3/s];
Δt, seconds in a time step (3600s) [s];
As, surface of the lake [m^2];

Through the mass balance equation the model is able to simulate the mean water level of the IJsselmeer for the whole time horizon, estimating the effects of the different alternatives.

4.5. DESIGNOF THE ALTERNATIVES

4.5.1. THE OPTIMIZATION

Once indicators and the model have been specified, there is first need to structure the optimization problem of the test case and build the objective function.
In both tasks the prioritization of the objectives expressed by the decision maker is a fundamental guide in order to define the approach which best satisfies its wishes.

Structure of the optimization problem

Given the strict prioritization of the objectives, a lexicographic approach is used in order to define the best option. This means that the test case is optimized according to the following steps:

– firstly, the optimum alternatives for safety in the *winter* (1.a) have been defined considering only the winter months, through the indicator i_{SW}. Between equally performing options, the optimum has been defined through the indicator i_{TG} or i_{PUMP} depending on the alternatives considered;
– secondly, given the best measures for winter, the optimum alternative for the summer months (1.b 2.a 2.b) is defined through the optimization of the satisfaction of *summer* water demand, using indicator i_{SS} and i_{WDP}. Between equally performing options, the optimum has been defined through the indicator i_{TG}.
In the optimization, only summer water demand is considered. This is because the alternatives for the winter are already defined at the previous step of the

> BOX 4.15
> **Optimization of Water Demand** is based only on the indicator $\mathbf{i_{WDP}}$ defined in chapter 4.3.1, calculated on **Summer Months**. This is because the strategies for the winter moths are defined on the basis of the optimization problems defined on safety of the dikes, due to the prioritization of the stakes. For this reason the winter deficit is fixed, and changes in summer target water level can not influence them. Also i_{WDW} is not used in the optimization because has a less strict threshold than i_{WDP}, which is then considered representative also for water demand to the Waddenzee. *Discussed in 4.5.1.*

optimization (safety of the dikes). Winter deficit is fixed due to the fixed target water level from October till March.

It is relevant to notice that in the optimizations there is no use of the indicator i_{WDW} designed to assess satisfaction of water demand to the Afsluitdijk. This is because the threshold for the satisfaction of its free flow is 10cm lower than the one for water demand to the polders. Its objective is satisfied by the optimization of i_{WDP}, which represents a stricter constraint. i_{WDW} is used when evaluating the optimum alternative according the satisfaction of water demand.

In the following paragraphs the single optimization problems are described:

Winter Safety, optimization 0: definition of the maximum SLR

In order to comply with the goal of the research there is firstly need to understand which climate changes the system is able to face in the short term, with no threats for the safety of the dikes. This optimization is important to assess the present flexibility of the system from a safety point of view.

No scenario is used in this case, the present system is “optimized” with respect to the sea level rise, i.e. looking for the maximum sea level rise which can guarantee a safe configuration of the system.

The optimization has been performed with and without the enlargement of the Lorentzsluizen.

Safety Winter 0		
	Case 0a	Case 0b
Climate Scenario	none	
Enlargement Lorentzsluizen	no	yes

Table 4.8 – Optimization 0

The optimization tool used is the Differential evolution algorithm (see paragraph 3.2.1).

The outcome of the optimization, is the maximum sea level rise which can be faced by the system in the short term, the results is shown in paragraph 5.1.1.

Winter Safety, optimization A: definition of a safe winter target level

Firstly, the only measures considered are changes in the winter target level in order to assure safety in the different future scenarios. This is in line with constraint 3 (box 1.3), and complies with the goals of the research (2.b and 2.c). The optimization is important to assess the present flexibility of the system from a safety point of view.

In all the scenarios the enlargement of the Lorentzsluizen has been taken into account.

The scenario used in this case is W+2050, with different sea level rise shown in Table 4.9:

Safety Winter A							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Climate Scenario	W+2050						
Sea Level Rise (m)	+0.025	+0.05	+0.1	+0.125	+0.15	+0.175	+0.20

Table 4.9 – Optimization A

No optimization of the historical case is presented. This is because the optimization results in no changes from the present configuration of the system (winter target water level -0.4mNAP). This has been indeed checked.
The use of a climate scenario W+2050 in combination with the selected sea level rises, can sound as a strange choice. As stated in the KNMI '06 (see 3.3.1), the minimum expected sea level rise with a W+2050 scenario is 0.20cm, while cases from 1 to 7 consider lower changes. This choice has been made for analyzing an extreme case; Changes on precipitation, evaporation and Rhine discharge patterns are gradual from the present till 2050. For this reason, considering the most extreme change which can happen till 2050 (W+2050) and a gradual increment of the sea level rise, the situation in the time horizon present-2050 is assessed taking into consideration the most extreme situation.

The optimization tool used is the Differential evolution algorithm (see paragraph 3.2.1).

The indicators used in this case to define the objective function are:
- i_{SW}, but only considering the peak in the winter of 1952/1953;
- i_{TG}, in order to be as close as possible to the present winter target level.

They combine in the definition of the objective function J_W as follow:

$$J_W=10^4 i_{SW}+10^2 i_{TG}$$

The weights are designed in order to express the prioritization of the stakes; i_{TG} assumes relevance once i_{SW} is satisfied (i_{SW}=0).

The outcome of the optimization is the optimum winter target level which can assure safety in the different scenarios: $u^p= [u_w]$.

The optimum alternative u^{p*} is the one which solves the following problem:

$$J(u^{p*}) = \min_{u^p}(J_w)$$

The results are shown in paragraph 5.1.1.

Winter Safety, optimization B: definition of the optimum pump capacity

In line with constraint 3 (box 1.4), and in order to comply with the goals of the research (2.b), there is need to size a pumping station at the Afsluitdijk for the climate scenarios stronger than W+2050 and sea level rise of 0.15m. This is because, as it can be seen at 5.1.1., the IJsselmeer, as it is now, is not safe anymore when the sea rises more than 0.15m and a climate scenario W+ is taken into account. Therefore extra measures have to be taken into consideration.
This optimization is interesting in order to define which extra measures are needed to keep the system safe for longer time horizons.

In all the scenarios, the enlargement of the Lorentzsluizen has been taken into account. The target water level used for the winter period in the optimization is the present one: -0.4mNAP.

The scenarios used in this case are W+2050 and W+2100, with different sea level rise shown in Table 4.10:

Safety Winter B							
	Case5b	Case 7	Case 8	Case 9	Case10	Case11	Case12
Climate Scenario	W+2050			W+2100			
Sea Level Rise (m)	+0.15	+0.20	+0.35	+0.30	+0.80	+0.55	+1.20

Table 4.10 – Optimization B

No optimization of the historical case is presented. This is the optimization results in no changes from the present configuration of the system (no pump needed). This has been indeed checked.
The scenarios of the cases are designed according to the possible boundaries of uncertainty prescribed by KNMI'06 (case 7-10), while the sea level rises assumed by the Delta commission are taken in consideration for case 11 and 12. Case 5b is the boundary case with the previous optimization (Winter Safety A). Sea level rise is assumed, which could be still coped by the present situation (0.15m) in order to understand the corresponding pumping capacity needed.

The optimization tool used is the Differential evolution algorithm (see paragraph 3.2.1).

The indicators used in this case to define the objective function are:
- i_{SW}, considering all the 5 selected peaks ('52/'53, '65/'66, '87/'88, '93/'94, '94/'95);
- i_{PUMP}, in order to select the lowest possible pump capacity.

They combine in the definition of the objective function J_W as follow:

$$J_W=10^5 i_{SW}+10^{-2} i_{PUMP}$$

The weights are designed in order to express the prioritization of the stakes; i_{PUMP} assumes relevance once i_{SW} is satisfied (i_{SW}=0).

The outcome of the optimization is the optimum pump capacity in the different scenario selected: u^p =[u_{PUMP}].

The optimum alternative u^{p*} is the one which solves the following problem:

$$J(u^{p*}) = \min_{u^p}(J_w)$$

The results are shown in paragraph 5.1.2.

Summer Safety and Water Demand – base case, optimization C: definition of the optimum summer target water level

Once the optimum alternatives for the safety of the dikes have been defined through the definition of the winter target levels and the pump capacity needed at the Afsluitdijk, the optimum summer target levels needed for satisfaction of the water demand have to be designed. The cases under study are taken from the previous optimizations.

In all the scenarios, the enlargement of the Lorentzsluizen has been taken into account.

The scenarios used in this case are W+2050 and W+2100 with different sea level rise and the winter measures shown in Table 4.11:

Summer safety and water demand – base case								
	Hist	Case5	Case7	Case8	Case9	Case10	Case11	Case12
Climate Scenario	0	W+2050			W+2100			
Sea Level Rise (m)	0	+0.15	+0.20	+0.35	+0.30	+0.80	+0.55	+1.20
Winter target water level (mNAP)	-0.4	-0.48	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Pump capacity (m^3/s)	0	0	346	824	905	1621	1436	1644

Table 4.11 – Optimization C

The historical case (Hist) has been added to the study in order to understand if a summer setup for the target water levels can be found which could have performed better than the past.
All the cases are computed both in the framework of the extreme case and the conservative case for summer safety (see 4.3.1). In the extreme case, since it has been noticed as the major influence of the driest year 1976, two optimizations have been defined:

- *total* optimization: minimizing the water deficit in the whole series, using i_{WDP} as defined so far;
- *partial* optimization: minimizing the water deficit in the whole series except in the summer 1976, considering therefore $i_{WDP1976}$, which is equal to i_{WDP}, except from the fact that no deficit of 1976 is included.

Comparison of the two can give insight in the contribution of the driest year to the definition of the optimum target water level, and especially to the extra storage needed to satisfy the demand in the driest year.

The optimization tool used is the Lexicographic algorithm (see paragraph 3.2.2).

The indicators used in this case to define the objective function are:
- i_{SSEX}, in order to define a safe system;
- i_{WDP}, in order to minimize summer water demand;

As specified, i_{WDP} does only consider summer months (April-September).
The indicators combine in the definition of the objective function J_S as follow:

$$Js=10^9 i_{SSEX}+i_{WDP}$$

The weights are designed in order to express the prioritization of the stakes; i_{WDP} assumes relevance once i_{SS} is satisfied (i_{SS}=0).

In order to define a satisfactory minimization of the water deficit, the minimum which can be achieved from the system with changes in summer target water levels is defined by simulating the case in which all the summer months have maximum target water level. This varies according to the two different cases assumed:
- extreme case, the minimum achievable water deficit is assessed by assuming a target water level of +0.8mNAP in all the summer months;
- conservative case, the minimum achievable water deficit is assessed by assuming a target water level of +0.1mNAP in all the summer months;

In this way it is possible to define the minimum water deficit that the system is able to provide, given the winter management of the IJsselmeer.
The optimum is selected by the lexicographic algorithm by a choosing minimum target water level which keeps the deficit in the range of 1% of the minimum achievable (see the description of the optimization algorithm 3.2.2.).

For each case, the outcomes of the optimization are three set of target water level for summer months, one for each optimization problem:
- Extreme case for the whole time series (total): $\mathbf{u}^p$ =[u_{apr}, u_{may}, $u_{jun,}$ u_{jul}, u_{aug}, u_{sept}, u_{oct}];
- Extreme case for the time series with no 1976 (partial): $\mathbf{u}^p$ =[u_{apr}, u_{may}, $u_{jun,}$ u_{jul}, u_{aug}, u_{sept}, u_{oct}];

– Conservative case: $\mathbf{u}^p$ =[u_{apr}, u_{may}, $u_{jun,}$ u_{jul}, u_{aug}, u_{sept}, u_{oct}].

The optimum alternative $\mathbf{u}^{p*}$ is the one which solves the following problem:

$$J(\mathbf{u}^{p^*}) = \min_{\mathbf{u}^p}(J_S)$$

The results are shown in paragraph 5.1.3. They include the summer target water level together with the winter ones selected at previous optimizations.

Summer Safety and Water Demand – Mach Summer, optimization D: definition of the optimum summer target water level

In line with constraint 3 (box 1.3), and in order to comply with the goals of the research (2.b), there is need define a new set of target water level through the year considering March as a summer Month. This is because from the result of the previous optimizations, looking at the time series of the deficits, it can be noticed that the selected alternatives have difficulties to cope with the water demand of the driest year already in the present, and more drastically from 2050. In none of the cases there is a complete satisfaction of the water demand in 1976, and in long term scenarios, summer water levels are designed mainly on the deficit of the other years (see paragraph 5.1.3). However the selected alternatives are the best possible, they score the lowest possible deficit, and further rising of the target water level does not provide any better satisfaction of the demand (see paragraph 5.1.3). This means that the system is the limiting factor for water demand, therefore extra measures have to be taken into consideration.

This optimization is interesting in order to define which extra measures are needed for a better satisfaction of the water demand for longer time horizons.

For this reason it is assumed that March can be treated as a summer month. This is to explore the possibilities of the system of satisfying the water demand, when early storage is implemented.

The problem is formulated exactly like the previous one, in terms of assumptions, cases and definition of the objective function. The only difference is the outcome of the optimization, which in this case will include also the definition of the March target water level.

For each case, the outcomes of the optimization are three set of target water level for summer months plus March, one for each optimization problem:

– Extreme case for the whole time series (total): $\mathbf{u}^p$=[u_{mar}, u_{apr}, u_{may}, $u_{jun,}$ u_{jul}, u_{aug}, u_{sept}, u_{oct}];

- Extreme case for the time series, no 1976 (partial): $\mathbf{u}^p$=[u_{mar}, u_{apr}, u_{may}, $u_{jun,}$ u_{jul}, u_{aug}, u_{sept}, u_{oct}];
- Conservative case: $\mathbf{u}^p$=[u_{mar}, u_{apr}, u_{may}, $u_{jun,}$ u_{jul}, u_{aug}, u_{sept}, u_{oct}].

The optimum alternative $\mathbf{u}^{p*}$ is the one which solves the following problem:

$$J(\mathbf{u}^{p^*}) = \min_{\mathbf{u}^p}(J_S)$$

The results are shown in paragraph 5.1.4. They include the summer target water level together with the winter ones selected at previous optimizations.

4.5.2. ESTIMATION OF THE IMPACTS

Once the optimization problems have defined the optimum alternatives for all the cases, there is need to assess their impacts on the different sectors. Given the large number of optimization cases, in order to keep the estimation of the impacts simple, only some cases will be tested. In particular there will be no evaluation of the effects produced by the partial optimization of the extreme cases for the optimization of the summer target water level.

Regarding the water demand, estimation of the impacts will be performed both considering March a winter and a summer month. Only the cases when March is a winter moth will be discussed for the evaluation of the impact stakes (ecology, commercial shipping, recreation, inland water management and water management outside the dikes).

Impacts and their discussion are provided in chapter 5.2.

5. RESULTS AND DISCUSSION OF THE IMPACTS

The results of the optimizations defined in paragraph 4.5 are shown in the following sections. In section 5.1, the pump capacities and optimized target water levels obtained for the different cases are presented and discussed. Section 5.2 discusses the impacts of the selected alternatives on the single stakes, considering their specific indicators, when defined.

5.1. RESULTS OF THE OPTIMIZATION OF THE TEST CASE

5.1.1 WINTER SAFETY 0 AND A: DEFINITION OF A SAFE WINTER TARGET LEVEL

The maximum sea level rise that the present configuration of the system can face has been defined trough the optimization problem 0.

- case 0a, with no enlargement of the Lorentzsluizen; there is no margin for sea level rise,
- case 0b, after the implementation of the new measure; sea level can rise of 0.12 m with no consequences for the safety of the dikes.

Regarding the case 0a, it is important to notice that the indicator has been defined on the performance of the system as it is; it is understandable that any change of the external forces (in this case sea level rise) brings to un unsafe conditions if no measures are implemented. With respect to the case 0b, the enlargement of the Lorentzsluizen has been designed in order to keep the system safe with a sea level rise up to 0.23m (see paragraph 4.2.2). In the present research it has been found that the possible margin is only the half (0.12m). Differences could be due to the simplification used in the definition of the test case, but mainly the definition of the indicator for safety. In the optimization, a proxy indicator has been deigned In order to assess the safety of the system during winter months; according to the results of the problem 0, it seems that such indicator is too strict, keeping the IJsselmeer on the safe side.

The optimized winter target water levels for satisfaction of the safety of the dikes are shown in Table 5.1.

Safety Winter A							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Climate Scenario	W+2050						
Sea Level Rise (m)	+0.025	+0.05	+0.1	+0.125	+0.15	+0.175	+0.20
u_w (mNAP)	-0.4	-0.4	-0.41	-0.44	-0.48	-0.46	-0.43
J_W	0	0	0.01	0.16	0.64	150.36	310.09

Table 5.1 – Results optimization A

The optimized alternatives show that changes in target water level can guarantee safety of the system for winter months until a sea level rise of 0.15m, considering a climate scenario W+2050. It is important to notice that the system taken into consideration in this optimization problem includes already the enlargement of Lorentzsluizen.

According to the analysis, the target water level in winter can be left unchanged untill a sea level rise of 0.1m. After that, it suggests using a lower target until a sea level rise of 0.15m. At this point a target water level in winter of -0.48mNAP would be needed in order to have a safe IJsselmeer.
Such strategy suggests moving to lower target water levels in winter in order to gain more buffer to accommodate winter peaks. However, it is clear that this is only a temporary solution; for higher sea level rise, changes in target water levels are not effective anymore, and the system is unsafe even if more buffer is allowed. For instance, with a sea level rise of +0.20 m (case 7) the optimum target water level is -0.43 mNAP, which generates a peak in the winter ‘52/’53 which is 3.1cm higher than the historical peaks (from the definition of J_W). Lower target water levels are ineffective, they generate the same peak. Higher produce even higher ones.
This is because lowering the target water level is very ineffective alternative in order to satisfy the safety of the system for the whole winter. The first peak of the winter might be lower if there is more room for water in the IJsselmeer. However, the same peak brings immediately the system to a condition of high water level, and the following peaks happen on a system which has no more buffer, so that the measure adopted has no more effect. The limit of such strategy is indeed its short durability along the winter.

It must be noticed that such measure has even much less effectiveness than what seems from the results of the optimization. It can not be said that lowering the target water level can cope alone with safety issues until a sea level rise of 0.15m, because in the formulation of the problem, the enlargement of the Lorentzsluizen has been considered. The influence of this structure on the safety of the system has much more influence than lowering the target water level, so that the system can be safe for such long horizon mainly because of the structural measure which will be realized in 2016.
When the enlargement of the Lorentzsluizen is not considered in the system and the optimization is run with no climate change scenario, except sea level rise, lowering the target water level can cope only with 0.025m raise (simulation performed but not included in the report).

5.1.2 WINTER SAFETY B: DEFINITION OF THE OPTIMUM PUMP CAPACITY

A pump, in contrast to the gravity gates, does not have the above mentioned disadvantage at lowered target levels and is therefore considered a potential interesting measure in this research. The optimized pump capacities needed at the Afsluitdijk are shown in Table 5.2 and Figure 5.1.

Safety Winter B							
	Case5b	Case 7	Case 8	Case 9	Case10	Case11	Case12
Climate Scenario	W+2050			W+2100			
Sea Level Rise (m)	+0.15	+0.20	+0.35	+0.30	+0.80	+0.55	+1.20
u_w (m^3/s)	198	346	824	905	1621	1436	1644
J_W	1.98	3.46	8.24	9.05	16.21	14.36	16.44

Table 5.2 – Results optimization B

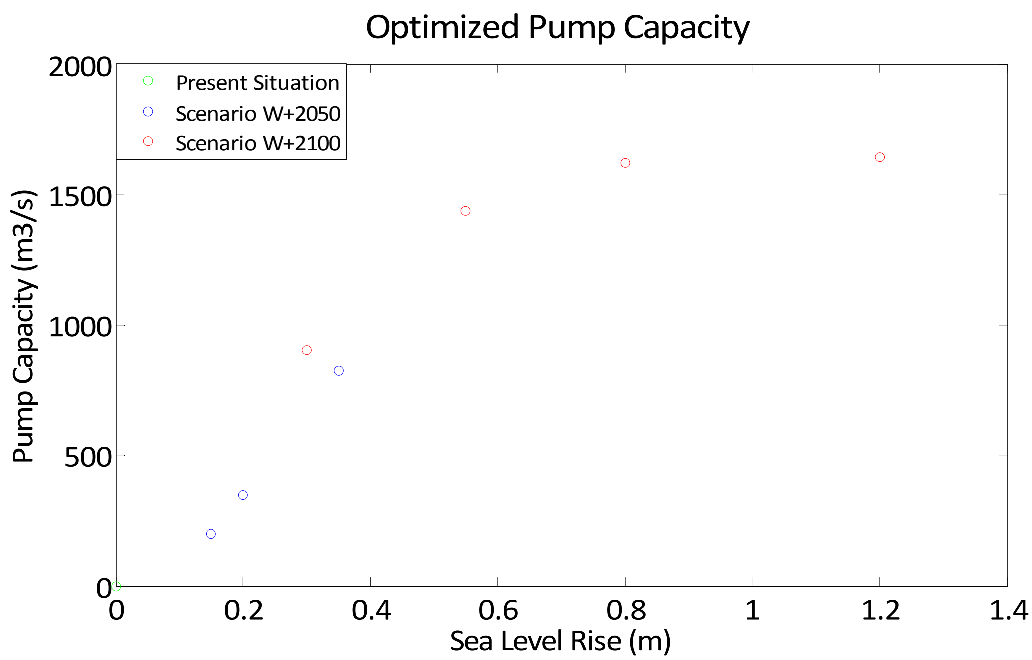

Figure 5.1 – Results optimization B

The pump capacity needed is represented relatively to the sea level rise. The relative influence between the sea level rise scenario and the other climate features (Rhine discharge, evaporation and precipitation) can be checked confronting blue and red dots.

Figure 5.1 shows that the pump capacity needed with sea level rise is S shaped. It rises sharply for intermediate sea level rises (0.1-0.6 mSLR), and gets to an asymptote for higher (>0.70 mSLR). This graph is very useful in order to understand the impact of investing in pumping stations for the far and near future. From the result of the optimization it can be said that a pumping station at the Afsluidijk is a very effective solution in the long term, because the capacity needed stabilizes for high sea level rises; no more investments are needed after a certain level. However, its application can be opposed for lower scenarios, since the capacity needed grows fast with the sea level rise (a high capacity is needed to cope already with 0.2 mSLR).

The stabilization of the needed capacity can be explained by the fact that, in the simulated alternatives, sea level grows, but the same scenario is kept for the inflow of water (see for instance the red dots in Figure 5.1: sea level rises, but the climate scenario considered is always W+2100). With the same inflow, rising of the sea makes discharge by gravity more difficult and more frequent use of the pumping station in necessary, until a point when gravity discharge is possible in only few cases. In this situation the pump works almost continuously, and further sea level rise does not influence that much the needed capacity, because few are the cases which still use gravity flow. However, if the inflow scenarios change, higher peaks happen and the pump capacity has to be raised again (the asymptote raises).
It can be said that in the long term (sea level rise more than 0.7m), a pumping station is a robust investment in order to keep the present safety standard with respect with sea level rise, while higher capacities might be consequentially needed with higher inflow scenarios. However, it can be noticed that the size of the pumping station is much less influenced by climate changes in the inflow than sea level rise. Looking at Figure 5.1 the jump in pump capacity between cases 5b 7 and 8 is only due to sea level rise, and it is definitely higher than between case 8 and 9, due to change in climate scenario (from W+2050 to W+2100). This has been observed also in other researches (Verhoeven 2009). Therefore, pumping stations manage to be robust also to changes in inflow scenarios, because they are little affected.

On the other hand the previous remarks do not consider use costs; indeed if pumps have to be used to face a growing hydraulic jump (IJsselmeer-Waddensea), more energy has to be used, and sea level rise has an influence on the cost of the pump also in the long term.

Finally the values of the pump capacities found through the optimization are in line with the ranges observed in previous studies (Verhoeven 2009).

Deeper details on the impacts on safety of the dikes produced by a pumping station at the Afsluitdijk are discussed in paragraph 5.2.1., where the safety of the different strategies is assessed with the use of statistical tools.

5.1.3 SUMMER SAFETY AND WATER DEMAND – BASE CASE OPTIMIZATION C: DEFINITION OF THE OPTIMUM SUMMER TARGET WATER LEVEL

The optimum target water levels are shown in this section (and in the next one 5.1.4) case by case. The different cases consider the measures discussed in 5.1.1 and 5.1.2, i.e. for the winter months they inherit the options selected from the optimization of safety of the dikes (in terms of pump capacity needed and winter target levels).
In this section, discussion will be based only on summer deficits, since summer deficits have been the subject of the optimization. For the volumes of deficit produced in the different cases, see Table XX in paragraph 5.2.2. The water deficits produced by the

different alternatives will be defined in terms of percentage related to the same typology of deficit in the historical modeled case. This means that:

- For deficits in the summer periods in the whole time series, percentages refers to the summer deficit in the whole time series of the historical modeled case;
- For deficit in the summer 1976, percentages refer to the summer deficit in 1976 of the historical modeled case;
- For the deficits in all the summers except 1976, percentages refer to the deficit experienced in the historical modeled case in all the summers but 1976;

Comparison between the different assumptions (i.e. extreme versus safe case) and discussion of the total deficit (considering also winter) will be the subject of paragraph 5.2.2, where the alternatives will be deeply analyzed from the point of view of the satisfaction of the water demand.

Historical Situation – extreme & conservative case

Figure 5.2 shows the optimum target water level for the whole year in the historical situation, while Table 5.3 reports the values.

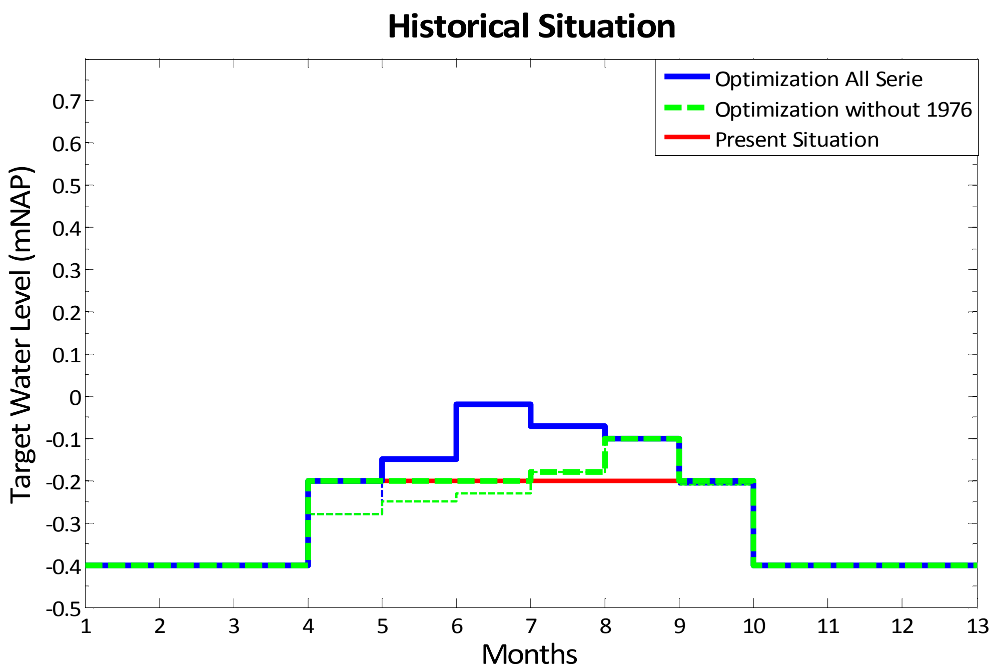

Figure 5.2 – Optimum target water level – March winter – historical situation – Extr&Cons

Extreme&Conservative	Winter	April	May	June	July	August	September
	Hist (mNAP)						
Total	-0.4	-0.20	-0.15	-0.02	-0.07	-0.10	-0.20
Partial (no1976)	-0.4	-0.20	-0.20	-0.20	-0.18	-0.10	-0.20

Table 5.3 – Optimum target water level – March winter – historical situation

The thinner lines are the lowest target water level needed to gain the minimum deficit; because of the desire of being as close as possible to the present management, summer target water level are equal to -0.2mNAP when possible. However it is important to realize that the identical deficit can be produced with a lower target water level (thick and thin line has exactly the same deficit).

As it can be read from the table, in no month, the target water level crosses the safe limit of 0.1mNAP, therefore the safe case coincides with the extreme case (total).

The target water level resulting from the total optimization (blue line) has a summer deficit which is 52% of the historical deficit. This means that its use in the past would have reduced the deficit in summer periods by half from 1951 till 1998 with respect to the water shortage experienced with the present management (red line). In particular the deficit in summer 1976 would have been the 50% of the historical deficit in the same year, while in all the other years it would have been reduced by 45%.

With respect to the differences between the total and the partial optimization, water deficit for the year 1967 are shown in Table 5.4, reporting the percentage of the deficit in the total optimization with respect to the one in the partial one. For the two cases the deficit in all the rest of the time series is the same, therefore the ratio between the two shows the advantage of adopting one instead of the other alternative.

Deficit Summer '67 (Mm^3)	Total (blue)	Partial (green)	%
Historical situation	0.20	0.43	47

Table 5.4 – Total VS partial optimization – March winter – historical situation

Given the safe limit of +0.1mNAP for maximum summer target water level, the alternative found through total optimization is a good choice both for safety and satisfaction of the water demand, therefore there is no reason to adopt the solution defined through the partial optimization. In fact it definitely performs worse in satisfying the summer water demand, while gaining little from a safety point of view.

Case 5/7/8 extreme: W+2050 0.15SLR/0.20SLR/0.35SLR

Figure 5.3 shows the optimum target water level considering the extreme boundary for case 5; while Figure 5.4, represents case 7. Between the two, the main difference is in the winter target water level, while little differences can be noticed in summer. Being case 8 similar to the other two cases, no figure is reported. However, Table 5.5 reports the values for all the target water levels.

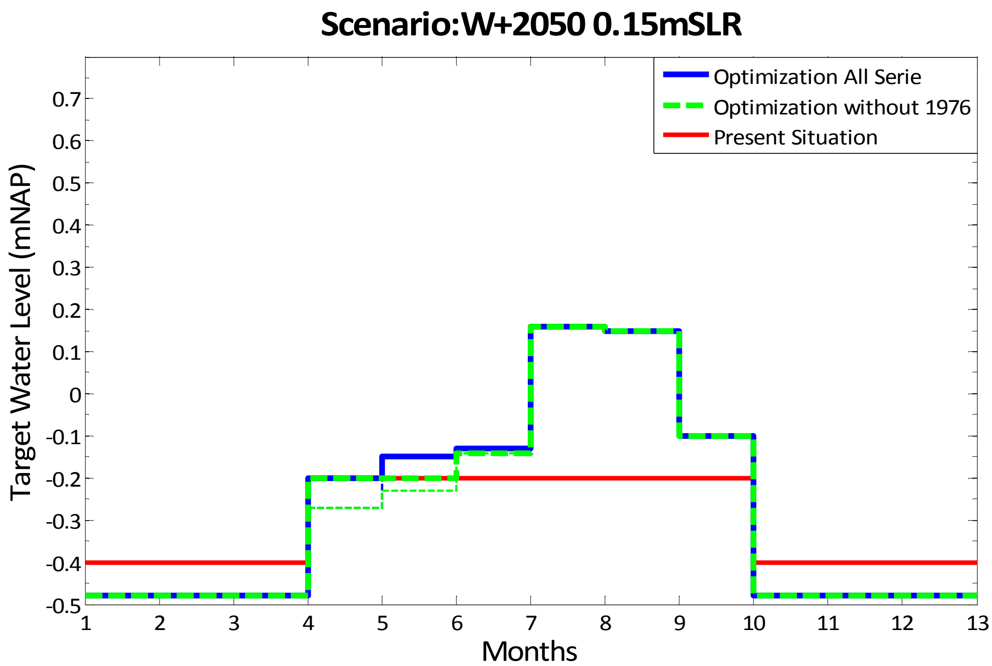

Figure 5.3 – Optimum target water level – March winter – case 5 – Extr

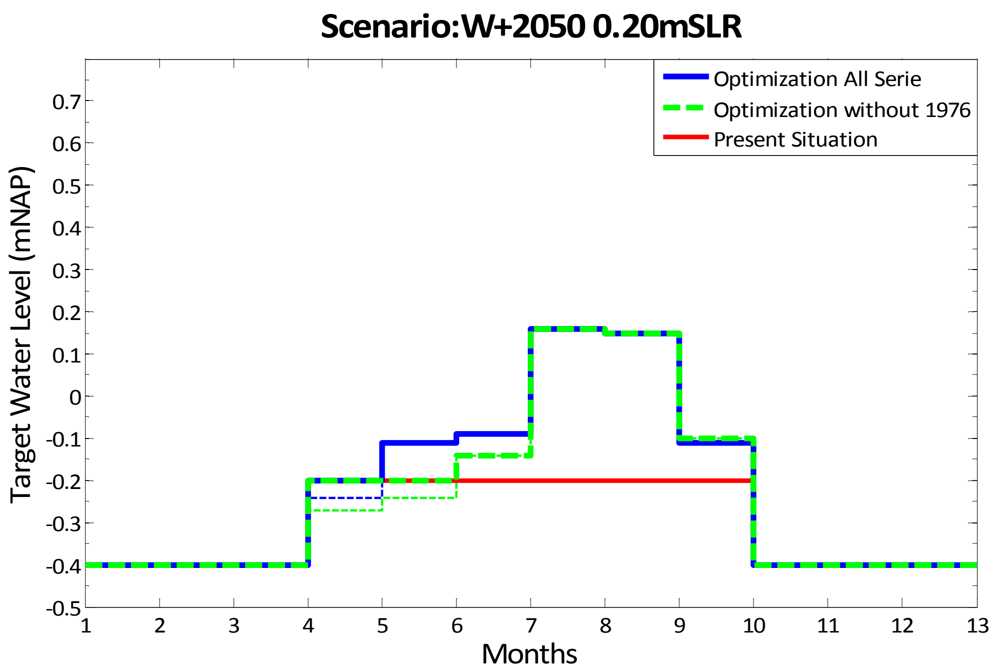

Figure 5.4 – Optimum target water level – March winter – case 7 – Extr

Extreme	Winter	April	May	June	July	August	September
	Case 5 (mNAP)						
Total	-0.48	-0.20	-0.15	-0.13	0.16	0.15	-0.10
Partial(no1976)	-0.48	-0.20	-0.20	-0.14	0.16	0.15	-0.10
	Case 7 (mNAP)						
Total	-0.4	-0.20	-0.11	-0.09	0.16	0.15	-0.11
Partial(no1976)	-0.4	-0.20	-0.20	-0.14	0.16	0.15	-0.10
	Case 8 (mNAP)						
Total	-0.4	-0.20	-0.11	-0.09	0.17	0.15	-0.10
Partial(no1976)	-0.4	-0.20	-0.20	-0.15	0.1600	0.15	-0.11

Table 5.5 – Optimum target water level – March winter – case 5/7/8

Again the thinner lines show the lowest needed target water level to gain the minimum deficit.

The target water level resulting from the total optimization (blue line) in case 5 has a summer deficit which is 132% of the historical deficit. This means that the system under such management fails in keeping the water deficit in the future close to the historical one. In particular the deficit in summer 1976 has a big influence, since it is the 144% of the historical deficit in that year, while in all the other years it is still close to the historical one being its 109%.

Different is the situation for case 7 and 8, where the total water deficit in summer months is the 106% of the historical situation, mainly caused by a raise of the deficit in 1976 (+35%), compensated with an halving of the deficit in all the other summers (-50%). In this case, such strategy is able to define a water deficit for 2050 which is comparable with the one experienced in the past.

Water deficit for the year 1976 are shown in Table 5.6, reporting the percentage of the deficit in the total optimization with respect with the one in the partial one. For the two cases the deficit in all the rest of the time series is the same. Therefore, the ratio between the two shows the advantage of adopting one instead of the other alternative.

Deficit Summer '67 (Mm^3)	Total (blue)	Partial (green)	%
Case 5	0.57	0.60	95
Case 7	0.54	0.58	93
Case 8	0.54	0.58	93

Table 5.6 – Total VS partial optimization – March winter – case 5/7/8

As it can be seen from Figures 5.3 and 5.4, the target water level defined through a partial optimization does not differ that much from the one defined by the total. This can be seen also in Table 5.6, where the difference in deficit between the two is only 5-7%. In both cases, the target in July/August gets to +0.15/+0.16mNAP, generating the same threats for safety, while the total optimization is slightly higher in May and June, but does not reach the safe limit of +0.1mNAP. For this reason the target water levels identified by the total optimization are preferable, because they generate a slightly lower deficit and do not differ from a safety point of view from the ones defined in the partial.

Such similarity between the two cases is due to the fact that, with the climate scenario W+2050, other years then 1976 start to be considerably dry; even leaving out the driest year from the optimization, this situation leads to the need of high target water levels in order to cope with water shortage in the other years. A test is performed on case 15, with a lower target water level in July and August: +0.1mNAP in both cases, instead of +0.15 and +0.16 mNAP (in line with the conservative constraint). This set of target water levels generates a higher deficit in the early nineties, as can be seen in Figure 5.5, where the deficit is compared with the one produced by the total optimization.

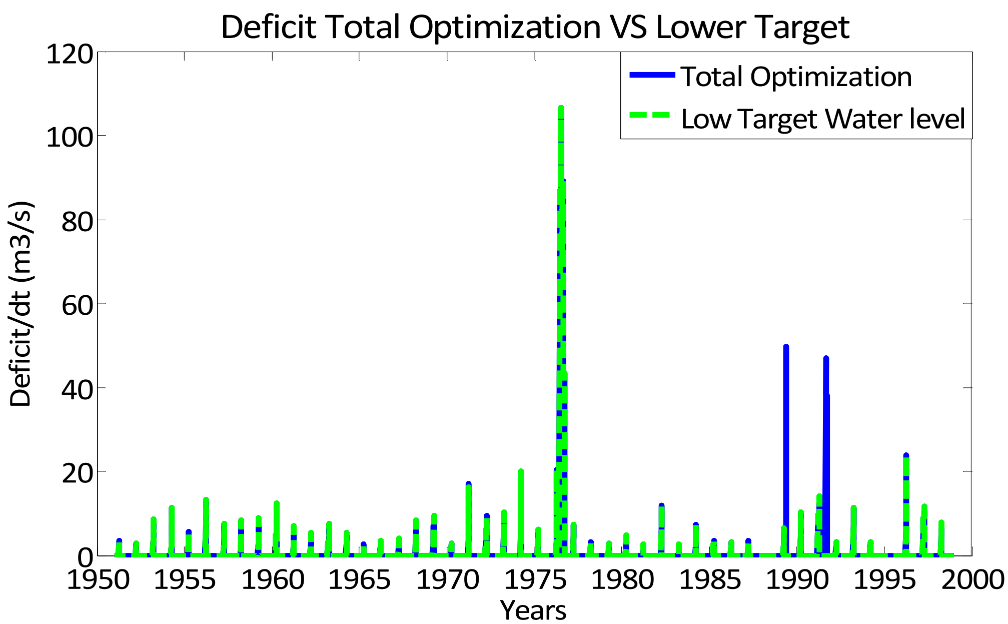

Figure 5.5 – Total optimization VS lower target

This means that, on one hand the influence of the dry years other than 1976 gets stronger, while assuming future climate scenario. On the other, the system has little room to cope with the driest year, since the target water level is mainly driven by the needs of the other years, also when optimizing on the whole series.

Special discussion is needed for case 5. It is evident that it creates a worse condition than cases 7 and 8, even if the same climate scenario has been used. This is because of the winter target water level. The strategy adopts a target water level of -0.48mNAP in order to cope with safety in the winter. This situation is very inconvenient for satisfaction of the water demand, because storing of water for summer starts from a lower level, so that low buffers for water demand can be set up in dry years. It has been already noticed how lowering of the winter target water level is not effective for guarantee safety in the winter, now it can also be added that such strategy harms water demand satisfaction in the summer.

It is interesting to notice that in May and June the target water level is lower for case 5 than for cases 7 and 8 when considering the total optimization. This can be explained by considering that, given the winter target water level, there is a maximum until which the water level can raise in 1976, due to the available inflow. This maximum is lower in case 5 than in case 7 and 8 (this is the reason for the higher deficit in 1976), so that rising the target water level is not effective.

Case 5/7/8 conservative: W+2050 0.15SLR/0.20SLR/0.35SLR

Figure 5.6 shows the optimum target water level considering the conservative boundary for case 5, while Figure 5.7, represents case 7. Also in this case between the two, the main difference is in the winter target water level, while little differences can be noticed in summer. Being case 8 similar to the other two cases, no figure is reported. However, Table 5.7 reports the values for all the target water levels.

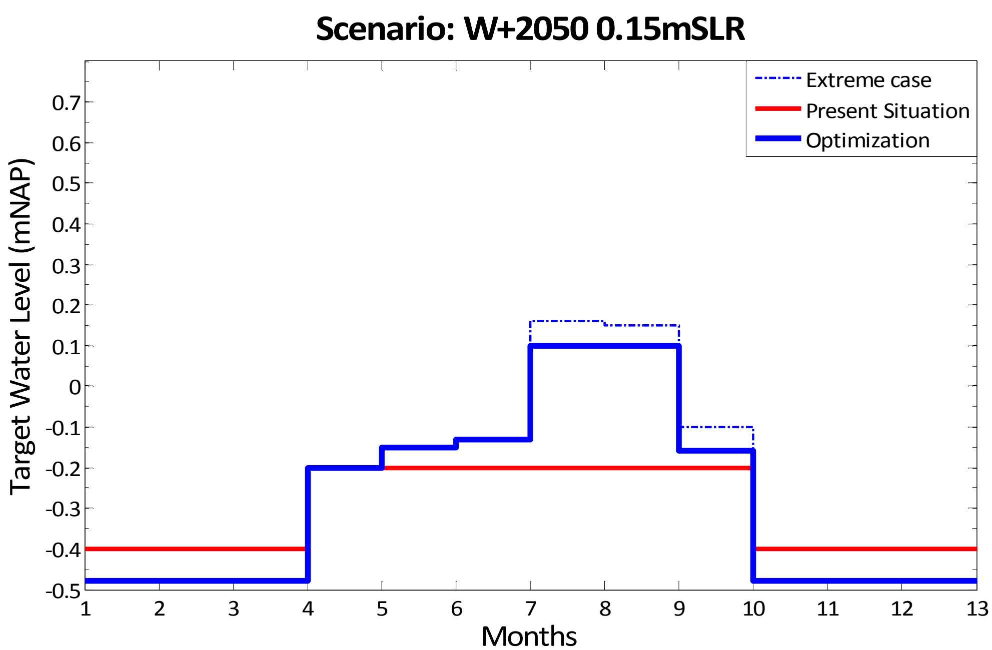

Figure 5.6 – Optimum target water level – March winter – case 5 – Cons

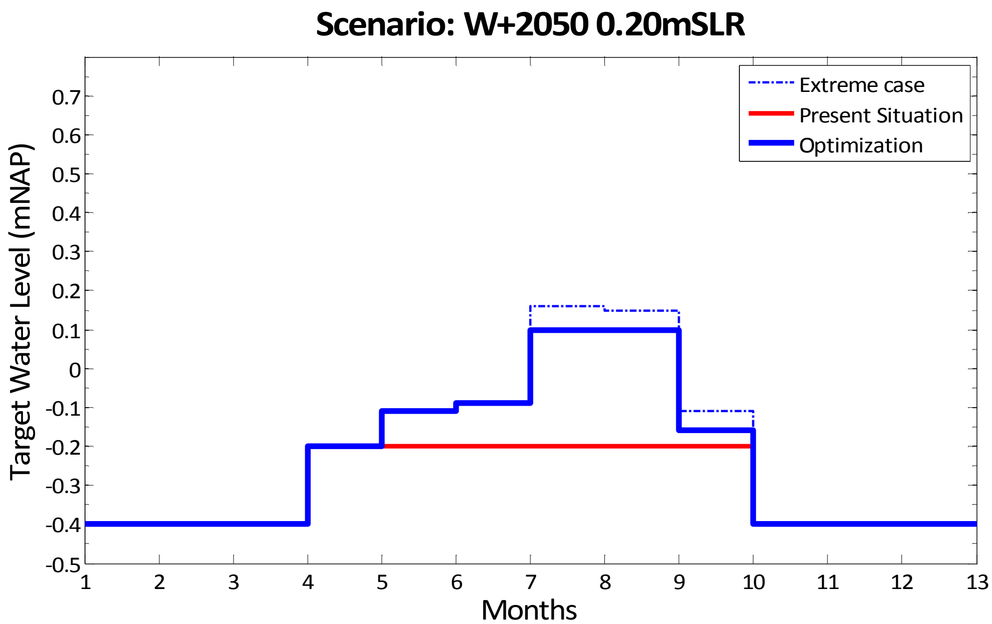

Figure 5.7 – Optimum target water level – March winter – case 7 – Cons

Conservative	Winter	April	May	June	July	August	September
Total	Case 5 (mNAP)						
	-0.48	-0.20	-0.15	-0.13	0.10	0.10	-0.16
	Case 7 (mNAP)						
	-0.4	-0.20	-0.11	-0.09	0.10	0.10	-0.16
	Case 8 (mNAP)						
	-0.4	-0.20	-0.10	-0.08	0.10	0.10	-0.15

Table 5.7 – Optimum target water level – March winter – case 5/7/8 – Cons

The optimization considering the conservative boundary generates a deficit in summers which is 140% of the historical one for case 5, and 113% for case 7 and 8. Considering the driest year, the summer deficit is 44% higher in case 5, while 35% higher in the other two cases. Again the reduction is mainly in the other years, but only for cases 7 and 8 (-28%), while for case 5 there is a raise of 30%. Percentages are close to the extreme cases. In fact not much difference can be seen in the target water levels.

The thinner dotted line represents the target water level for the same case considering the extreme boundary (shown in the previous paragraph). Figure 5.5 shows the deficit produced by a situation similar to the conservative case 15 (blue), in comparison with the one given by the extreme case 15 (green). It is interesting to notice that the two differ from the deficit produced in years other than 1976, while they have the same deficit in the driest year. Therefore the conservative case performs worse in satisfying the water demand in years other than the driest, while for the driest year, both approaches can not do much to satisfy the water demand.
It is relevant to notice that also in September the target water level in the conservative case is lower than the extreme one, even if in both case the conservative threshold of

+0.1mNAP has not been crossed. This means that, given the minimum deficit which can be achieved in such situation, having a higher target water level in September does not improve the performances of the optimum alternative.

Again case 5 performs badly in satisfying the water demand. The reasons are linked with the winter target level adopted and have been discussed in the previous paragraph.

Case 9/10/11/12 extreme: W+2100 0.30SLR/0.80SLR/0.55SLR/1.2SLR

Figure 5.8 shows the optimum target water level considering the extreme boundary for case 9. Being case 10, 11 and 12 similar to 9, no figure is reported. However, Table 5.8 reports the values for all the target water levels.

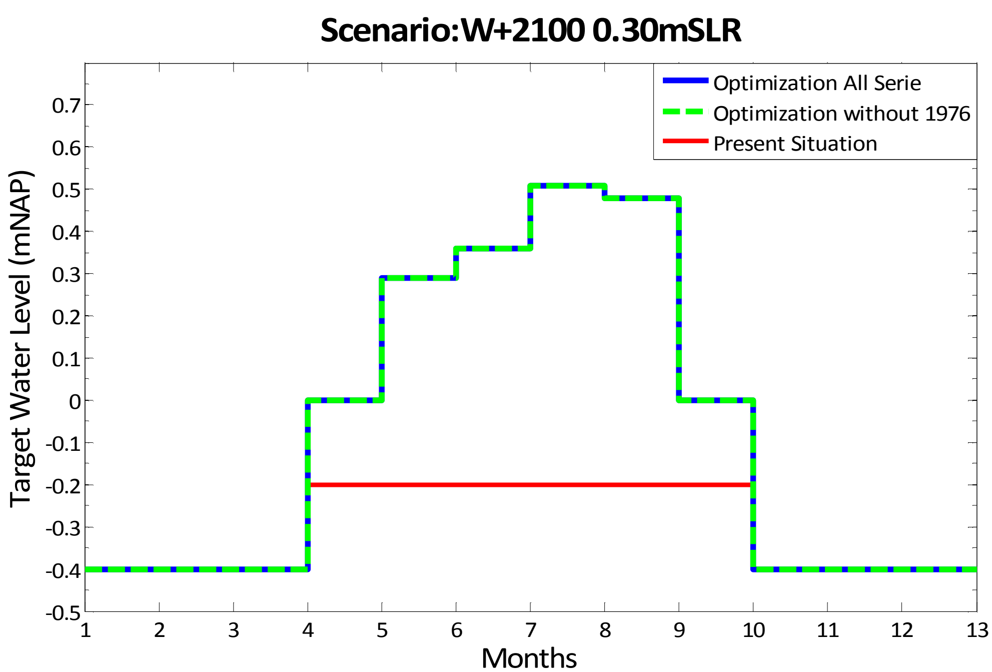

Figure 5.8 – Optimum target water level – March winter – case 9 – Extr

In all the four cases the deficit produced in summer is 108% of the historical deficit. This means that adopting such set up for target water level keeps the deficit also in 2100 in the range of the historical one. In all the cases there is an increment of 43% in the deficit of 1976, while a decrease of 57% in the summer deficit of all the other years.

Extreme	Winter	April	May	June	July	August	September
	Case 9 (mNAP)						
Total	-0.4	0	0.29	0.36	0.51	0.48	0
Partial(no1976)	-0.4	0	0.29	0.36	0.51	0.48	0
	Case 10 (mNAP)						
Total	-0.4	0	0.29	0.36	0.51	0.49	0
Partial(no1976)	-0.4	0	0.29	0.36	0.51	0.49	0
	Case 11 (mNAP)						
Total	-0.4	0.01	0.29	0.37	0.51	0.50	0.02
Partial(no1976)	-0.4	0.01	0.29	0.37	0.51	0.50	0.02
	Case 12 (mNAP)						
Total	-0.4	0	0.31	0.36	0.51	0.50	0
Partial(no1976)	-0.4	0	0.29	0.36	0.51	0.48	0

Table 5.8 – Optimum target water level – March winter – case 9/10/11/12 – Extr

As can be seen from the figure and the table, there is no difference between performing the optimization on the whole series or leaving out 1976. In both optimization and for all the cases there is a deficit on 1967 of 0.57 Mm^3 of water. This is because the optimization designs for this scenario the target water level only on the deficits in the years other than the driest, because for 1976 the system is not able to have efficient strategies.
It can be noticed that the target water level is at the limit of the safety condition for the extreme case.

Case 9/10/11/12 conservative: W+2100 0.30SLR/0.80SLR/0.55SLR/1.2SLR

Figure 5.9 shows the optimum target water level considering the conservative boundary for case 10. Being case 9, 11 and 12 similar to 10, no figure is reported. However, Table 5.9 reports the values for all the target water levels.

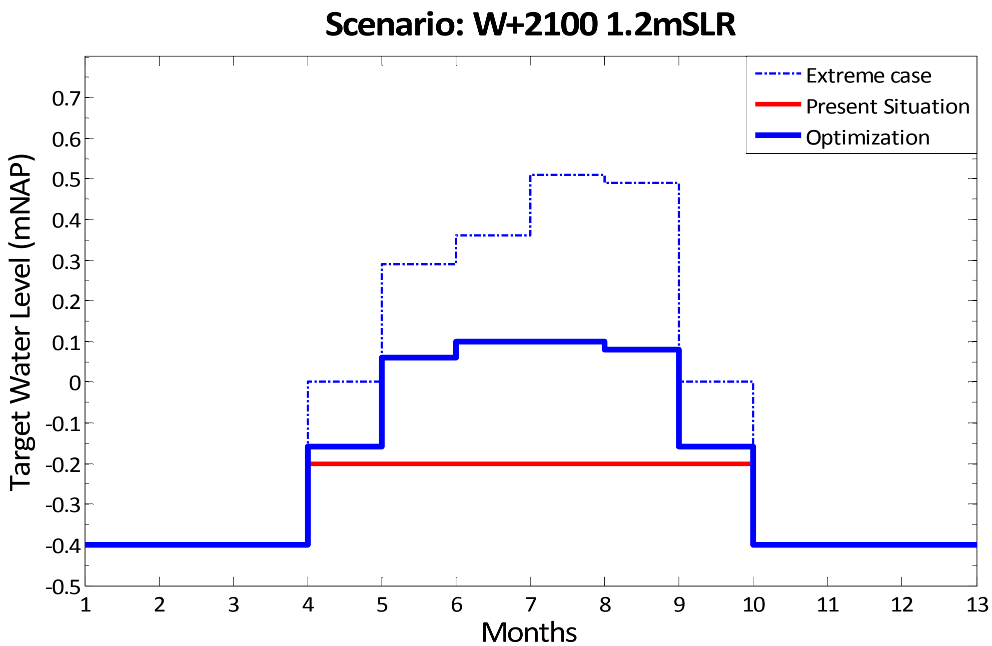

Figure 5.9 – Optimum target water level – March winter – case 9 – Cons

Conservative	Winter	April	May	June	July	August	September
Total	Case 9 (mNAP)						
	-0.4	-0.1900	0.1000	0.1000	0.1000	0.0500	-0.1800
	Case 10 (mNAP)						
	-0.4	-0.1700	0.0900	0.1000	0.1000	0.0600	-0.1800
	Case 11 (mNAP)						
	-0.4	-0.1600	0.0600	0.1000	0.1000	0.0800	-0.1600
	Case 12 (mNAP)						
	-0.4	-0.2000	0.0300	0.1000	0.1000	0.0500	-0.1700

Table 5.9 – Optimum target water level – March winter – case 9/10/11/12 – Cons

The summer deficit produced by the above alternatives is 258% of the historical deficit, with an increase of 43% of the deficit in 1976 and of 473% for all the other years.

The thinner dotted line represents the target water level for the same case considering the extreme boundary (shown in the previous paragraph). The only difference from the extreme case is the satisfaction of the water demand in years other than 1976. Regarding the driest year, the extreme and conservative case perform exactly the same, as a confirmation that the system is not able to cope which such event and the optimized target water levels for the extreme case are only designed on the rest of the series.

It can be said that applying a conservative strategy for the target water levels in summer does not influence the deficit in the driest year, but is not able to satisfy water demand in the others, which, with a climate scenario, are more critical.

Concluding remarks

Observing the whole set of the selected alternatives, two remarks should be done:

- First of all, as already mentioned, the present configuration of the system is not able to cope with the water demand in the driest year already for the present situation and more drastically since 2050. Other measures have to be thought of, if such situation needs to be improved. This is actually the starting point for the optimization problem D. In line with the possible measures in the framework of the present research, a situation is investigated which allows March target water level to rise, as a summer month. This would allow earlier water entering the system, and more possibilities for satisfaction of the water demand in extreme situations.
- Secondly sea level rise has no influence on satisfaction of the water demand. The target water levels found through the optimization only change due to inflow climate scenarios, and are practically the same for changes in sea level rise. This is easily understandable and was easily predictable, since water demand is connected with the availability of water, and in theory would not experience damage if all the water is stored. Therefore, there is no influence from the discharges possible to the Waddensea, due to sea level rise (This holds also for the results of the optimization D).

Performances of the selected alternative

It is important to evaluate the performances of the selected alternatives according to the limit of the system (see paragraph 4.5.1); i.e. the minimum deficit obtainable with changes in target water level. For this reason, comparison is needed for the summer deficits for water demand to the polders (i_{WDP} only in summer periods), between the selected alternatives and a situation with the highest target water level for all the summer months.

Table 5.10 shows the percentage which the difference represents on the minimum obtainable deficit.

Extreme	Historical case	Case 5	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
	%							
Total	0	0	0	0.4	0.2	0	0	0.15
Patial	0	0	0	0	0.1	0	0	0.4

Conservative	Historical case	Case 5	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
	%							
Total	--	0	0	0.1	0	0	0	0

Table 5.10 – performances of the optimization

As it can be seen, the alternatives presented manage to keep the deficit in the range of 1% with respect to the minimum obtainable deficit. This means that rising the target water level further than as showed, does not give any improvement on the satisfaction of the water demand.

5.1.4 SUMMER SAFETY AND WATER DEMAND – MACH SUMMER, OPTIMIZATION D: DEFINITION OF THE OPTIMUM SUMMER TARGET WATER LEVEL

Historical Situation – extreme & conservative case

Figure 5.10 shows the optimum target water level for the whole year in the historical situation, regarding the extreme case. Table 5.11 reports the values. Again the thinner lines are the lowest target water level needed to gain the minimum deficit.

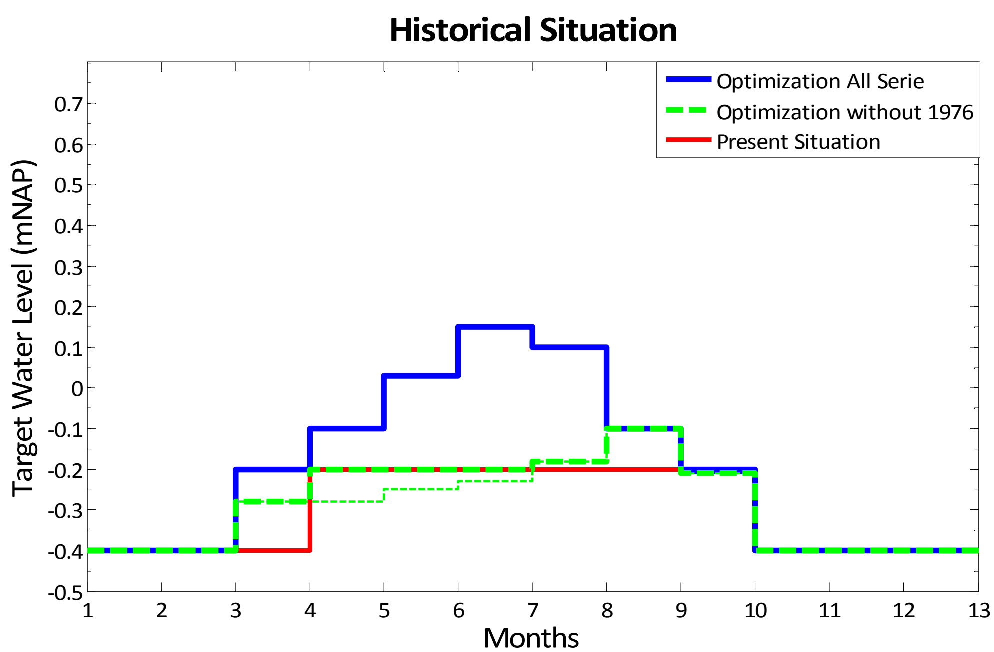

Figure 5.10– Optimum target water level – March summer – historical situation – Extr

The target water level resulting from the total optimization (blue line) has a summer deficit of zero. This means that its use in the past would have generated no deficit in the time horizon 1951-1998.

Water deficit for the year 1976 are shown in Table 5.12, reporting the percentage of the deficit in the total optimization with respect with the one in the partial one. As mentioned, the total optimization is in this case able to satisfy all the water demand, also in the driest year, while in the partial case, there is still some deficit, which is however lower than the one shown for the correspondent case when March is considered a winter month. Both for the partial and the total case the deficit in the rest of the years is zero.

Deficit Summer '67	Total (blue)	Partial (green)	%
Historical situation (Mm^3)	0	0.41	0

Table 5.12 – Total VS partial optimization – March summer – historical situation

Figure 5.11 shows the optimum target water level for the whole year in the historical situation, regarding the conservative case. Table 5.11 reports the values.

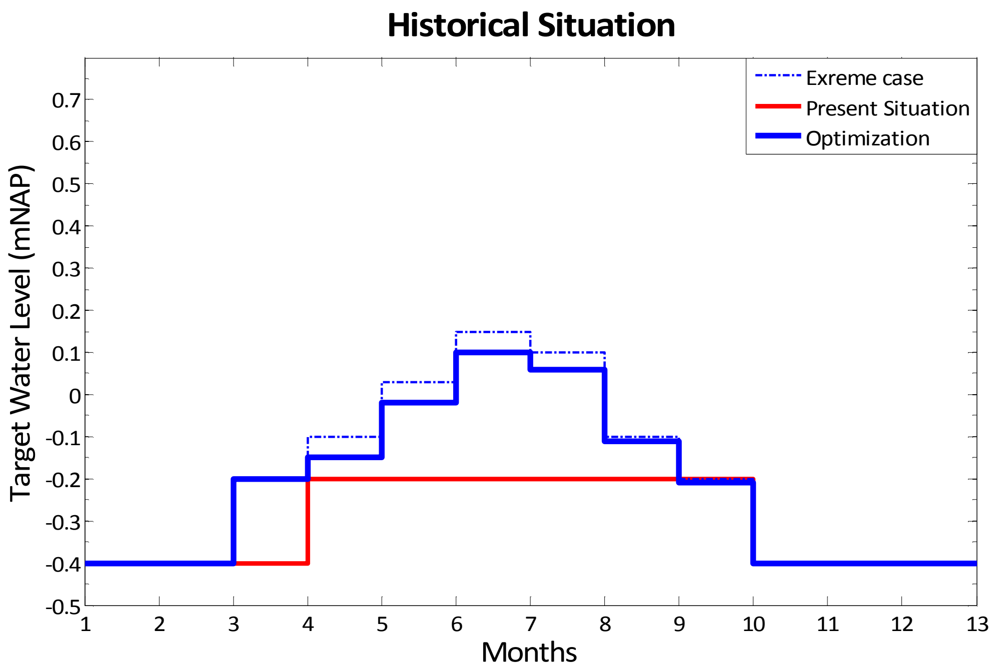

Figure 5.11– Optimum target water level – March summer – historical situation – Cons

	Winter	March	April	May	June	July	August	September
Extreme	Hist (mNAP)							
Total	-0.4	-0.20	-0.10	0.03	0.15	0.10	-0.10	-0.20
Partial(no1976)	-0.4	-0.20	-0.20	-0.20	-0.20	-0.18	-0.10	-0.20
Conservative	Hist (mNAP)							
Total	-0.4	-0.20	-0.15	-0.02	0.10	0.06	-0.11	-0.21

Table 5.11– Optimum target water level – March summer – historical situation – Cons&Extr

The thinner dotted line represents the target water level for the same case considering the extreme boundary (Figure 5.11). In this case the summer deficit on the whole time horizon is 9% of the historical deficit, mainly given by the deficit on 1976 (13% of the historical one).

According to the optimization, starting to store water from March is a good option for satisfaction of the water demand, also in extreme dry periods.

In the extreme case, a maximum target water level of +0.15mNAP is needed in June to completely satisfy the water demand. Given the amount of rise, compared with the

advantage gained in satisfying the water demand, there is no reason to prefer the target water level suggested by the partial optimization.
However, the results from the conservative case can give a more realistic view of the advantages of letting the target water level rise in March. Given the little differences with the extreme case, a good satisfaction of the water demand can be indeed defined also assuming a conservative case.

With respect to the historical situation, the assumption of considering March as a summer month is promising, because it allows both safety and profound satisfaction of the water demand.
It is important to specify that this is true if bringing the March target water level to -0.2mNAP is safe.

Case 5/7/8 extreme: W+2050 0.15SLR/0.20SLR/0.35SLR

Figure 5.12 shows the optimum target water level considering the extreme boundary for case 5; while Figure 5.13, represents case 7. Between the two, the main difference is in the winter target water level and the target water level in March, while little difference can be noticed in the other summer months. Being case 8 similar to case 7, no figure is reported. However, Table 5.13 reports the values for all the target water levels.

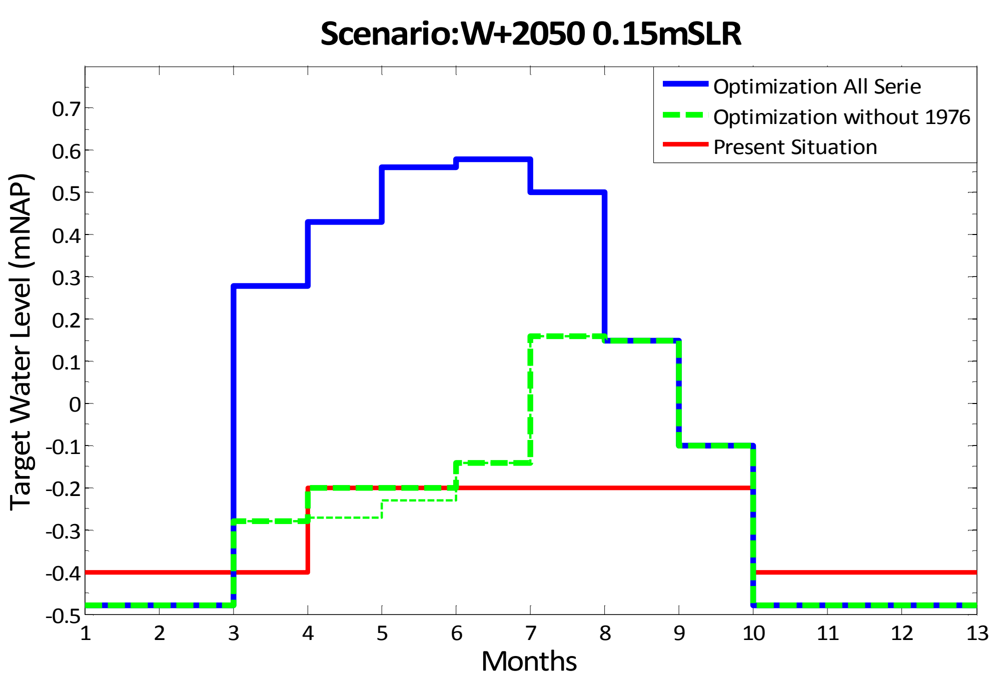

Figure 5.12 – Optimum target water level – March summer – case 5 – Extr

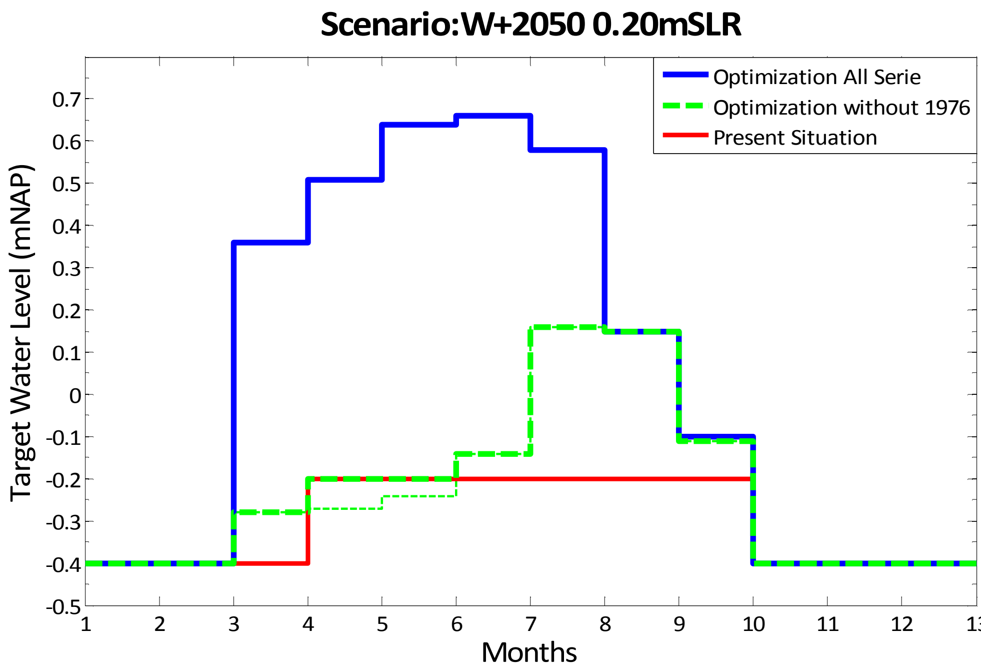

Figure 5.13 – Optimum target water level – March summer – case 7 – Extr

Extreme	Winter	March	April	May	June	July	August	September
	Case 5 (mNAP)							
Total	-0.4	0.28	0.43	0.5	0.58	0.50	0.15	-0.20
Partial(no1976)	-0.4	-0.20	-0.20	-0.20	-0.14	0.16	0.15	-0.10
	Case 5 (mNAP)							
Total	-0.4	0.36	0.51	0.64	0.66	0.58	0.15	-0.20
Partial(no1976)	-0.4	-0.20	-0.20	-0.20	-0.14	0.16	0.15	-0.20
	Case 6 (mNAP)							
Total	-0.4	0.35	0.50	0.64	0.65	0.57	0.15	-0.11
Partial(no1976)	-0.4	-0.20	-0.20	-0.20	-0.15	0.16	0.15	-0.20

Table 5.13 – Optimum target water level – March summer – case 5/7/8 – Extr

Again the thinner lines show the lowest needed target water level to gain the minimum deficit.

The target water level resulting from the total optimization (blue line) for the case 5 has a summer deficit which is 17% of the historical deficit. In particular the deficit in summer 1976 (26% of the historical case) is the only influence, since in all the other years the deficit is zero.

Better is the situation for case 7 and 8, where the total water deficit in summer months is respectively 4% and 6% of the historical situation. Also in those cases, there is no deficit in years other than 1976, while the summer deficit in the driest year is 7% of the historical deficit.

Water deficit for the year 1976 are shown in Table 5.14, reporting the percentage of the deficit in the total optimization with respect to the one in the partial one. For the two cases, the deficit in all the rest of the time series is the same and equal to zero (there is only deficit in 1976). Therefore the ratio between the two shows the advantage of adopting one instead of the other alternative.

Deficit Summer '67 (Mm^3)	Total (blue)	Partial (green)	%
Case 5	0.10	0.57	18
Case 7	0.03	0.57	5
Case 8	0.03	0.57	5

Table 5.14 – Total VS partial optimization – March summer – case 5/7/8

It is remarkable that the satisfaction of the summer water demand for the year 1976 leads to very high target water levels. If those are acceptable within the hypothesis of the extreme case, in a realistic way, it can not be said that a target water level in March of +0.36mNAP is safe. In such vision, the analysis of the conservative case gives a more realistic assessment of the effectiveness of raising the March target water level to cope with water demand.
Also, it is important to notice that the partial optimization defines a set of target water levels which is identical to the one found for the same cases in the optimization problem C (March winter month), except for a water level in March which is higher. This brings two important considerations:

- the high target water levels in the total optimization are only needed to tackle the water demand in 1976. The alternative selected in the partial one is sufficient to bring the water deficit of all the other years to zero.
- a higher water level in March is able to satisfy the water deficit which happened in the same cases at the optimization problem C, while all the other targets might be kept the same. This means that the summer deficit which the previous case has not been able to control happens only in the beginning of April. It is only due to the time lap that the system needs to adapt from the winter target level to the one of April.

Again the ineffectiveness of case 5 can be noticed, even if, in this case, positive indexes of satisfaction of the water demand are due to the use of March as a summer month.

Case 5/7/8 conservative: W+2050 0.15SLR/0.20SLR/0.35SLR

Figure 5.14 shows the optimum target water level considering the extreme boundary for case 5, while Figure 5.15, represents case 7. Also in this case, between the two, the main difference is in the winter target water level, while little differences can be noticed in summer, except for the target water level in March. Being case 8 similar to the other two cases, no figure is reported. However, Table 5.15 reports the values for all the target water levels.

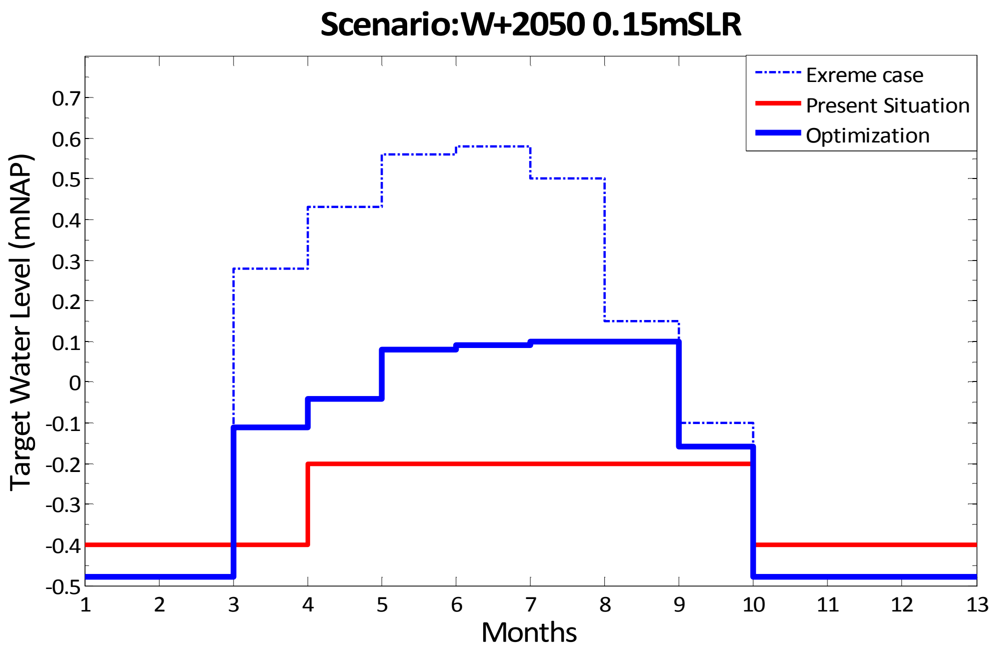

Figure 5.14 – Optimum target water level – March summer – case 5 – Cons

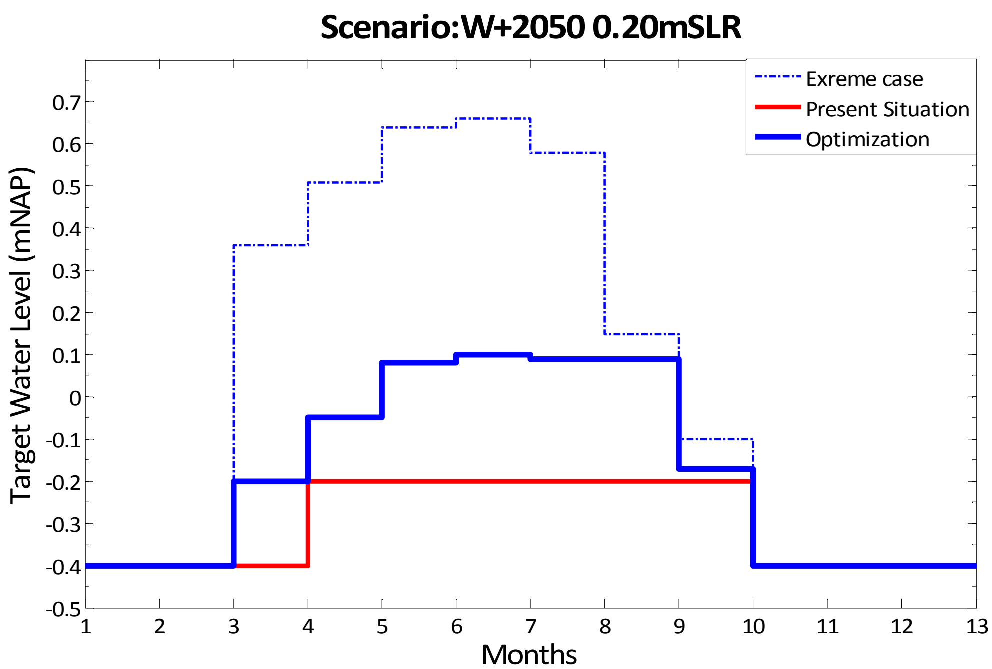

Figure 5.15 – Optimum target water level – March summer – case 7 – Cons

Conservative	Winter	March	April	May	June	July	August	September
	Case 5 mNAP							
Total	-0.4	-0.11	-0.04	0.08	0.09	0.10	0.10	-0.16
	Case 7 mNAP							
Total	-0.4	-0.20	-0.05	0.08	0.10	0.09	0.09	-0.17
	Case 8 mNAP							
Total	-0.4	-0.17	-0.03	0.10	0.10	0.10	0.09	-0.16

Table 5.15 – Optimum target water level – March summer – case 5/7/8 – Cons

The thinner dotted line represents the target water level for the same case considering the extreme boundary (shown in the previous paragraph).

The target water level resulting from the conservative case 5 has a summer deficit which is 82% of the historical deficit. In particular the deficit in summer 1976 is higher (115% of the historical case), while important reduction is possible on the other years (-79%).

Slightly better is the situation for case 7 and 8, where the total water deficit in summer months is respectively the 81% of the historical situation. Deficit in 1976 is still increasing (112% of the historical case), while on the other years it decreases to 21% of the historical summer deficit on the same years.

This case represents a more realistic estimation of the benefits of increasing the target water level in March. The alternatives are safe and allow the system to improve the historical summer deficit. This is however true for average/slightly dry years, whereas for the most extreme year, also this configuration fails to keep the deficit at the present rate, generating an increase of 12%. This case loses many of the benefits that the extreme case gained on allowing higher March water levels, due to the target water level constraint to +0.1mNAP. However, it performs better than the partial optimization of the extreme case, whose total summer deficit is the 94%of the historical one. This means that the target water level in Figure 5.14 and 5.15 are able to tackle some water demand in 1976, which the green (partial) target water level in Figure 5.12 and 5.13 do not perform by definition.

Case 9/10/11 extreme: W+2100 0.30SLR/0.80SLR/0.55SLR

Figure 5.16 shows the optimum target water level considering the extreme boundary for case 9. Being case 10 and 11 similar to 9, no figure is reported. However, Table 5.16 reports the values for all the target water levels.

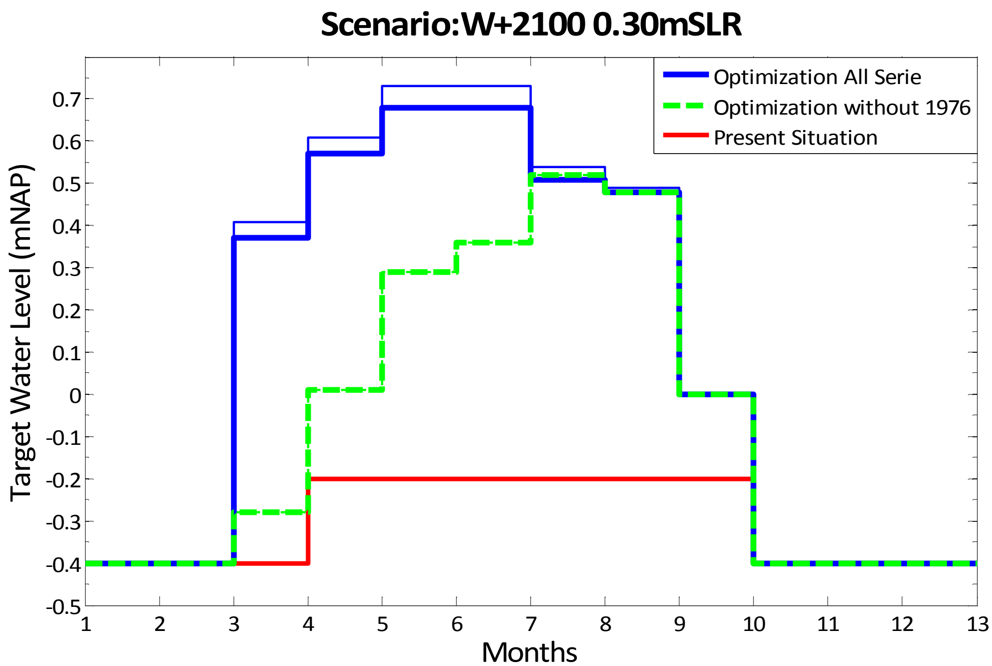

Figure 5.16 – Optimum target water level – March summer – case 9 – Extr

Extreme	Winter	March	April	May	June	July	August	September
	Case 9 (mNAP)							
Total	-0.4	0.37	0.57	0.68	0.68	0.51	0.48	0
Partial(no1976)	-0.4	-0.20	0.01	0.29	0.36	0.52	0.48	0
	Case 10 (mNAP)							
Total	-0.4	0.35	0.55	0.65	0.65	0.52	0.50	0
Partial(no1976)	-0.4	-0.20	0	0.29	0.36	0.51	0.49	0
	Case 11 (mNAP)							
Total	-0.4	0.37	0.58	0.65	0.65	0.51	0.49	0
Partial(no1976)	-0.4	-0.20	0.01	0.29	0.37	0.51	0.48	0

Table 5.16 – Optimum target water level – March summer – case 9/10/11 – Extr

It can be noticed that case 12 has not been included in the results. This is because the optimization has not been able to find a safe solution which was interesting from a water demand satisfaction point of view. This is mainly due to the use of a high target level in March, in combination with the highest scenario.

Again, the thinner doted line shows the lowest needed target water level to gain the minimum deficit.

The thinner solid line shows the target water level needed to achieve the minimum deficit possible from the system. However, given the summer safety threshold for the extreme case ($SSTh_{EX}$) this configuration generates water levels higher than +0.69mNAP,

and is therefore unsafe. The thick lines are the allowed safe target water level, under the assumptions of the extreme case.
With respect to the total optimization, the alternatives selected generate a total summer deficit which is around the 43% of the historical deficit for summer months. Again, there is no deficit in the years other than 1976, which has a water deficit around 67% of the historical deficit. The extreme case is then able to keep the deficit lower than the one historically experienced, also for a time horizon untill 2100. However, as in the previous scenarios, target water levels are extremely high.

Water deficit for the year 1976 are shown in Table 5.17, reporting the percentage of the deficit in the total optimization with respect with the one in the partial one. For the two cases, the deficit in all the rest of the time series is the same and equal to zero (there is only deficit in 1976), therefore the ratio between the two shows the advantage of adopting one instead of the other alternative.

Deficit Summer ‘67 (Mm^3)	Total (blue)	Partial (green)	%
Case 9	0.27	0.53	51
Case 10	0.28	0.53	53
Case 11	0.28	0.53	53

Table 5.17 – Total VS partial optimization – March summer – case 9/10/11

The increase of the target water level obtained by the partial optimization is indicative for the increasingly dry years, which happen when considering more extreme scenarios.

Due to the high target water level produced by both the total and the partial optimization, none of the two can be accepted, because they are unsafe. The conservative case gives certainly a more realistic way of the possibilities and the advantages of considering March a summer month.

Case 9/10/11 conservative: W+2100 0.30SLR/0.80SLR/0.55SLR

Figure 5.17 shows the optimum target water level considering the conservative boundary for case 9. Being case 10 and 11 similar to 9, no figure is reported. However, Table 5.18 reports the values for all the target water levels.

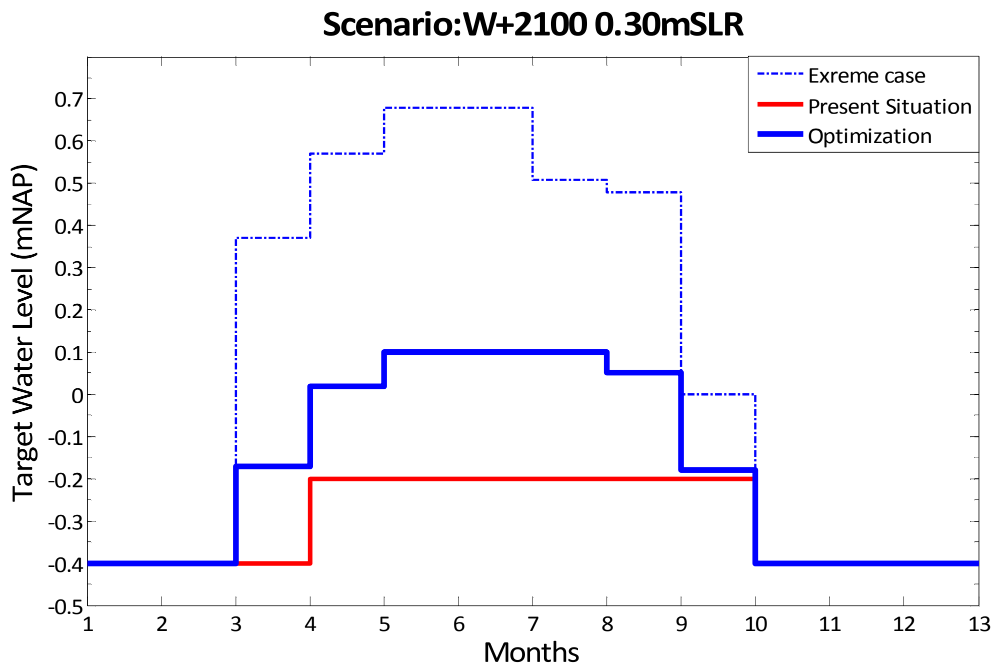

Figure 5.17 – Optimum target water level – March summer – case 9 – Cons

Conservative	Winter	March	April	May	June	July	August	September
	Case 9 mNAP							
Total	-0.4	-0.17	0.02	0.10	0.10	0.10	0.05	-0.18
	Case 10 mNAP							
Total	-0.4	-0.17	-0.02	0.09	0.10	0.10	0.06	-0.18
	Case 11 mNAP							
Total	-0.4	-0.20	0	0.09	0.10	0.10	0.07	-0.15

Table 5.18 – Optimum target water level – March summer – case 9/10/11 – Cons

The thinner dotted line represents the target water level for the same case considering the extreme boundary (shown in the previous paragraph).

The deficit in the whole summer period for cases 9 10 and 11 is 234% of the historical one on the whole series. There is an increase of 30% of the deficit in the summer of 1976, while in all the other summers the deficits of the analyzed cases are the 430% of the historical ones.
As already mentioned, this alternative represents a more realistic case than the ones defined in the extreme case. In this view, it is essential to mention that performances of the alternatives are only 10% less that the same cases defined through the optimization C, i.e. March a winter month.

From this it can be said that rising the March target water level is not a robust strategy to assure water demand in the long term.

Performances of the selected alternative

Again it is important to evaluate the performances of the selected alternatives according to the limit of the system (see paragraph 4.5.1); i.e. the minimum deficit obtainable with changes in target water level. The same analysis has been done as for the results of the optimization C.

Table 5.19 shows the percentage which the difference represents, on the minimum obtainable deficit.

Extreme	Historical case	Case5	Case7	Case8	Case9	Case10	Case11
	%						
Total	0	0	0	0	--	--	--
Patial	0	0	0	0	--	--	--

Conservative	Historical case	Case5	Case7	Case8	Case9	Case10	Case11
	%						
Total	0	0	0.26	0	0	0	0

Table 5.19 – performances of the optimization

It can be noticed that no comparison can be made for cases 9, 10 and 11 for the extreme situation. This is because, as can be seen from Figure 5.16 the minimum achievable (thin dotted line) leads to a target water level which is unsafe according to the assumptions (mean water level goes higher than +0.69mNAP). For this reason the optimum alternative shows a lower target level (thick line), but also a higher deficit. The deficit of the selected alternative is double compared to the minimum achievable.

Also, it is important to notice that, for the extreme case, a deficit happens only in 1976; the selected alternatives are able to reduce the deficit on the other years to zero. This is not the case for the conservative condition.

5.1.5 OVERVIEW OF THE RESULTS

Figure 5.18 shows an overview of the results. Monthly target water levels are shown both for the present management (red) and the optimizations (blue). As argued above, it is interesting to notice that:

- Graphs B and C do not define a safe situation.
- Graphs A, D, E, F, G, H, I define a safe situation, either because extra measures are not needed (short term), or because a pump capacity at the Afsluitdijk is introduced.
- A generates a cut in half of the water deficit (52%), while D and G reduced it to zero and 9%.

– B generates a water deficit close to the historical (113%), while E reduces it to 82% and H to 5%.
– C and F generate a water deficit which is almost 2.5 times the historical, while I represents a cut in half (43%).

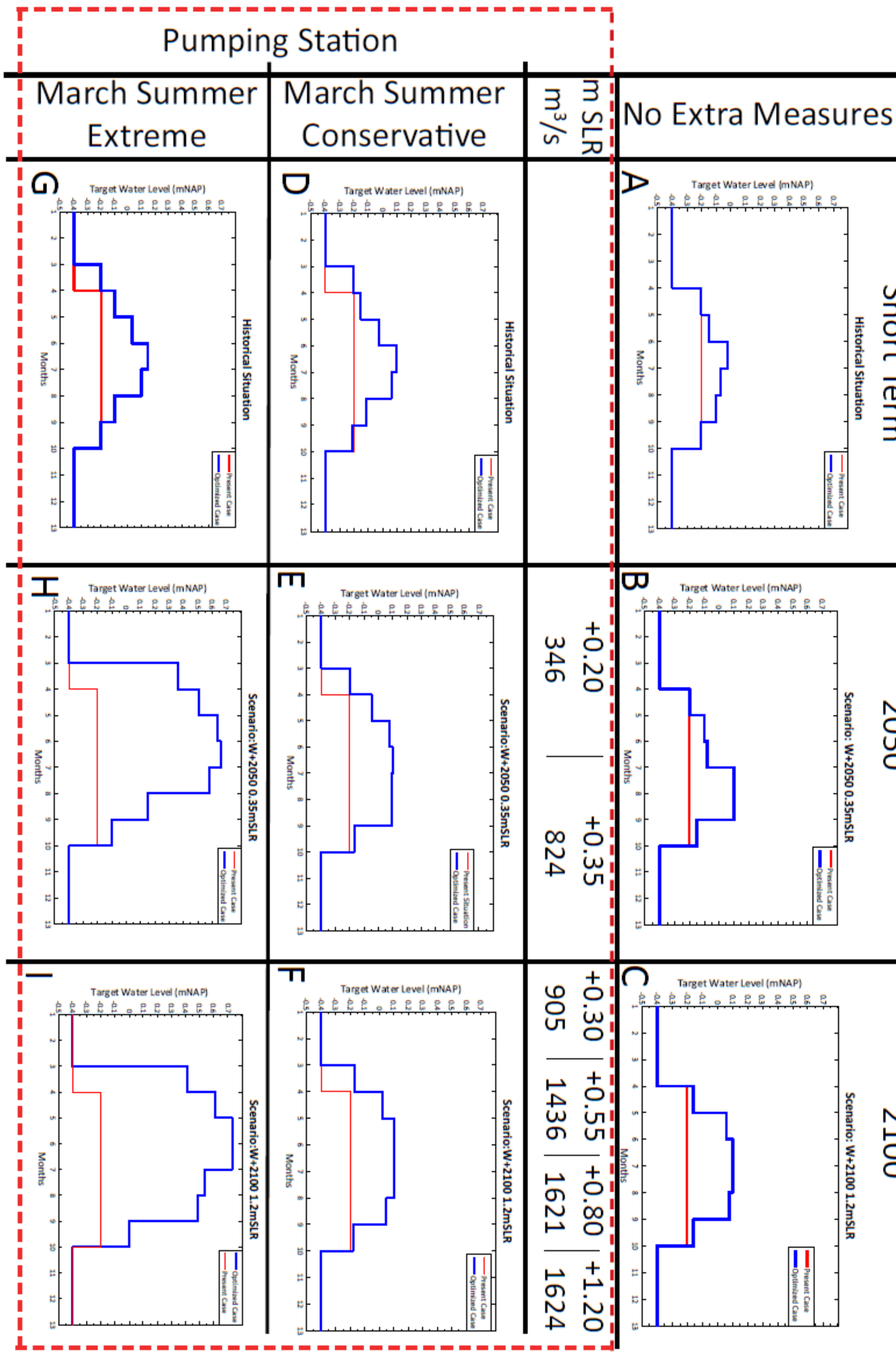

Figure 5.18 – Overview of the results

5.2. ESTIMATION OF THE IMPACTS

The alternatives shown in chapter 5.2 will now be evaluated according to the impacts they have on the different stakes.

5.2.1. SAFETY OF THE DIKES

Regarding the safety for the selected alternatives, two issues have to be checked: safety in winter and in summer (see paragraph 4.3.2).

Satisfaction of the safety standards in winter (October-March) location per location in the present and under the climate scenario selected (LpL + P&FS);

Taken from the optimization problems 0, A and B, seven cases have led to interesting optimum alternatives, which have to be assessed for the safety they produce in winter months. Table 5.20 shows a recap of the different cases:

	Climate scenario	Winter target water level m NAP	Pump capacity m^3/s
Case 0b	None for inflow 0.12mSLR	-0.40	0
Case 5	W+2050 0.15mSLR	-0.48	0
Case 7	W+2050 0.20mSLR	-0.40	346
Case 8	W+2050 0.35mSLR	-0.40	824
Case 9	W+2100 0.30mSLR	-0.40	905
Case 10	W+2100 0.80mSLR	-0.40	1621
Case 11	W+2100 0.55mSLR	-0.40	1436
Case12	W+2100 1.2mSLR	-0.40	1644

Table 5.20 – results of the different cases (safety)

For all the selected alternatives, the winter extreme event analysis has been performed according to the methodology described in paragraph 4.3.2, and the curves obtained have been tested with Hydra-Vij.
For all the selected locations, new toetspeilen have been defined, which can be confronted with the ones produced by the historical situation modeled. Table 5.21 shows the results of the evaluation:

LOCATION	Hist Case	Case 0b	Case 5	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
		mNAP							
02A Zeughoek Noord	1,049	0,907	1,027	0,946	0,849	0,909	0,575	0,660	0,569
F037 Makkum	1,575	1,541	1,589	1,538	1,491	1,493	1,413	1,428	1,412
F125 Workum G. Strand	1,325	1,261	1,331	1,269	1,201	1,220	1,096	1,118	1,094
F202 Hinderlopen	1,165	1,057	1,157	1,081	0,992	1,039	0,813	0,857	0,811
F292 Stavoren	1,047	0,911	1,030	0,944	0,850	0,914	0,569	0,656	0,564
F351 Laaxum	1,045	0,914	1,031	0,946	0,852	0,917	0,572	0,658	0,567
L006 Lemsterbaai	2,035	2,018	2,050	2,010	1,981	1,975	1,914	1,926	1,913
N195 Westermeerdijk	1,584	1,554	1,600	1,549	1,504	1,503	1,422	1,438	1,421
N290 Westermeerdijk	2,011	1,993	2,027	1,985	1,952	1,946	1,881	1,894	1,879
F115 Ketelmeerdijk	2,508	2,494	2,522	2,485	2,460	2,453	2,398	2,409	2,397
F235 IJsselmeerdijk	1,884	1,864	1,900	1,856	1,823	1,817	1,749	1,763	1,748
H-IJM086 Houtribdijk*	1,726	1,700	1,742	1,694	1,651	1,648	1,571	1,586	1,569
07A-Enkhuizen*	1,121	0,978	1,096	1,012	0,925	0,993	0,623	0,716	0,618
05C Andijk Noorderdijk*	1,126	0,972	1,101	1,015	0,919	0,987	0,616	0,712	0,611

Table 5.21 – toetspeilen produced by the different cases

Figure 5.19 shows the differences in toetspeil between the historical situation modeled and the different cases. A positive value represents a reduction of the toetspeil needed, hence a safer situation, while a negative value shows a more dangerous situation for safety.

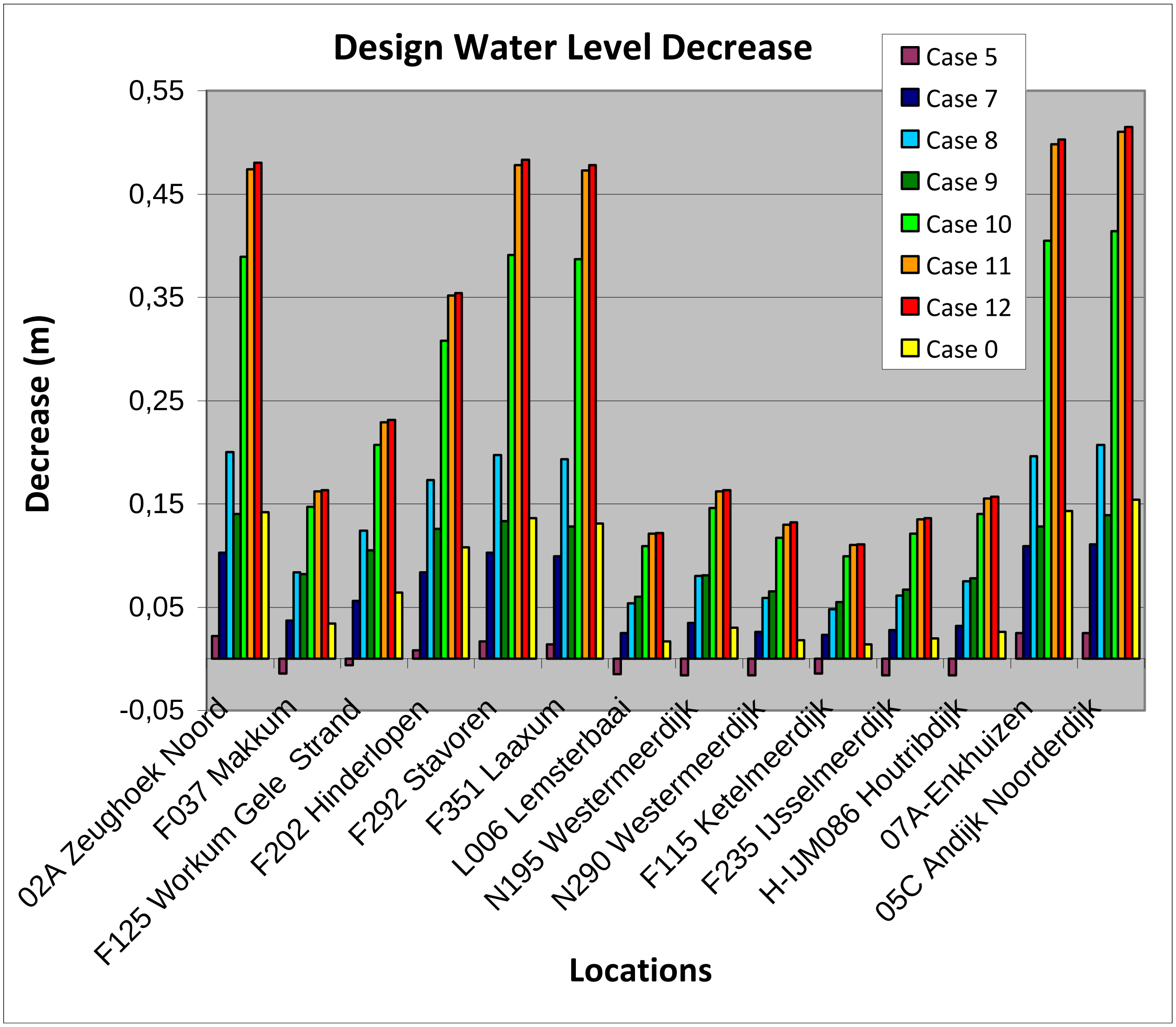

Figure 5.19 – Differences Historical toetspeilen and toetspeilen of the different cases

From Figure 5.19, different aspects can be discussed:

- Case 0b, according to the evaluation trough Hydra-Vij, it can be confirmed that the proxy indicator on which the safety is optimized is too strict. With the enlargement of the Lorentzsluizzen, the system can definitely cope with higher sea level rise than the 0.12m find through optimization 0b, since the toetspeilen found in the evaluation are safer than the historical modeled situation.
- Case 5, with the implementation of a lower winter target level in order to assure more buffer for peaks, generates a more dangerous situation for the safety of the dikes. This is not true for all the locations, but especially for the wind dominated ones, where the water level regime produced by the alternative is not low enough in order to guarantee a safe superposition by the wind.

This is a further confirmation of what is noticed in paragraph 5.1.1. Lowering the winter target level is not an effective solution to guarantee safety of the system in the future scenarios.

- Cases 7-12, with the implementation of a pumping station at the Afsluitdijk, define a safe situation in all the alternatives, by lowering the toetspeil in all the locations (both wind and water level dominated). It can be notice that the influence is stronger on water level dominated locations; while in the others, being wind dominated, controlling mean water level fluctuation has a lower impact, as expected.

It is definitely interesting to notice that the higher the pump capacity, the more the system gains in safety. This suggests that the pump capacities defined through the optimization are slightly over-dimensioned, and even lower capacities can assure a safe system. This can be explained by the fact that size of the pumps have been defined on 5 extreme peaks, while they are active in reducing also lower peaks in the series. By reducing the lower peaks the system is safer. This is because, combining the statistics of the mean water level with the wind statistics, less probable is the combination of wind and water levels which can put the system in danger. In an extreme case, the highest peaks can even be higher than in the past, if lower and more frequent peaks are lower.

Satisfaction of the safety standards in summer (April/September) in the present and under the climate scenario selected (P&FS);

As for satisfaction of the summer safety, the two cases can be discussed separately:

- Extreme case, within the hypothesis of the case, all the selected alternatives are safe for summer months. This is true, because the objectives functions have been designed in a way that only safe solutions can come out of the optimization; i.e. all the alternatives guarantee a mean summer water level which is lower than the $SSTh_{EX}$, and hence are safe according to the hypothesis on the case.
- Conservative case, within the hypothesis of the case, all the selected alternatives are safe for summer months, i.e. all the resulting target water level are never higher than +0.1mNAP.

  However, a further check is needed in this case. As mentioned in 4.3.1., a condition on the target water level (as posed in this case) does not assure an actual water level within the safety range. This is because the actual water level depends on the real possibilities for discharging to the Waddenzee, which might be limited by external conditions (sea level, wind etc…).

  However, in all the cases, the alternatives are safe for summer months, because they manage to keep the summer water level at the target in all the scenarios. In case 5, this is possible because sea level rise is still limited. In more extreme scenarios, such as cases 7-12, this is true, thanks to the pump integrated in the system used to keep the IJsselmeer safe in the winter. Pumps can be used also in summer, allowing the water level to be close to the target. Figure 5.20 shows a modeled year in case 19. As can be noticed the water levels in summer are able to follow the target.

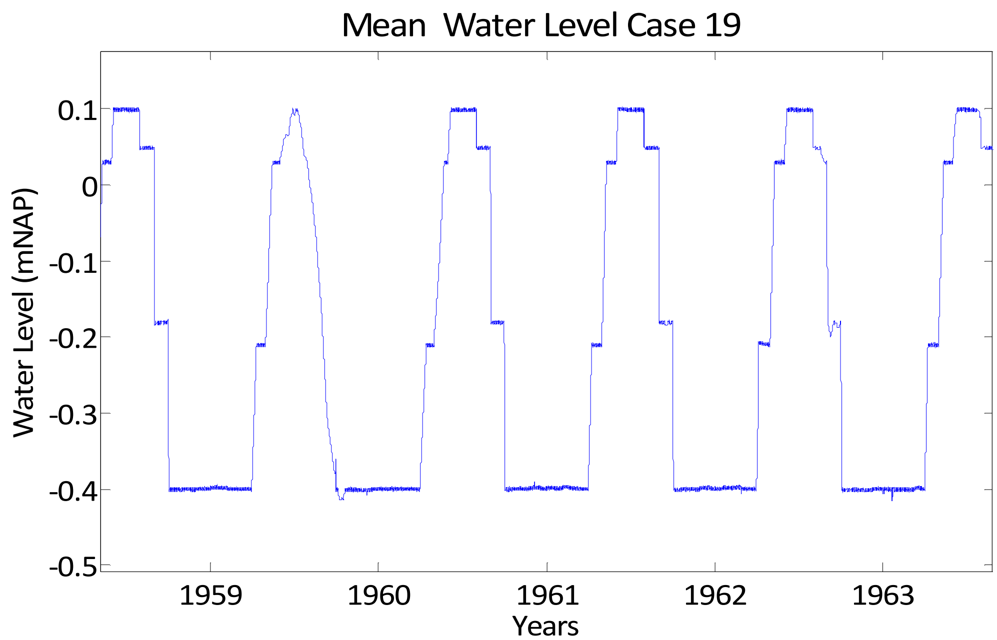

Figure 5.20 – Mean water level for case 19

Therefore all the alternatives shown in chapter 5.1 are safe in summer months, under the specific hypothesis.

5.2.2. WATER DEMAND

Table 5.22 and 5.23 show the deficit produced by the different alternatives shown in paragraph 5.1.3 and 5.1.4. The first presents the impacts of alternatives selected in the optimization problem C (March is considered a winter month), while the second shows the deficits produced by the alternatives resulting from the optimization problem D (March is considered a summer month). Deficits are in Mm^3 and refer to the whole time series of the simulation from the 1st of January 1951 till the 31st of December 1998 (if not differently specified)

.

The first three columns refer to the total deficit, considering both winter and summers. Here, the deficit is given for the water demand to the polders and to the Waddensea separately, and together.

The last three columns refer only to summer deficit (April-September), which has been the time window on which the objective function for water demand has been designed. Those have been discussed while showing the results in paragraphs 5.1.3 and 5.1.4. In the Tables, the summer deficit for the whole time series is presented together with the deficit for only the driest summer (1976) and for all the summers except the driest.

Case		Whole Year			Summers		
		Polders	Waddensea	Total	Whole	1976	No 1976
		Water Deficit Mm^3					
	Historical	2.38	1.45	3.84	0.61	0.40	0.21
March Winter Month	Opt Historical	2.10	1.45	3.55	0.32	0.20	0.12
	5 Extreme	2.57	4.11	6.68	0.81	0.57	0.23
	5 Conservative	2.64	4.13	6.77	0.85	0.57	0.28
	7 Extreme	2.61	1.74	4.35	0.64	0.54	0.11
	7 Conservative	2.68	1.75	4.42	0.69	0.54	0.15
	8 Extreme	2.80	1.80	4.60	0.64	0.54	0.11
	8 Conservative	2.68	1.75	4.42	0.69	0.54	0.15
	9 Extreme	2.84	2.17	5.00	0.66	0.57	0.09
	9 Conservative	3.82	2.24	6.06	1.58	0.57	1.01
	10 Extreme	2.95	3.26	6.21	0.66	0.57	0.09
	10 Conservative	3.93	3.36	7.29	1.57	0.57	1.00
	11 Extreme	2.92	2.93	5.85	0.66	0.57	0.09
	11 Conservative	3.89	3.01	6.90	1.57	0.57	1.00
	12 Extreme	2.95	3.29	6.24	0.66	0.57	0.09
	12 Conservative	3.94	3.38	7.32	1.58	0.57	1.01

Table 5.22 – Summer deficit for the different alternatives – March winter

	Case	Whole Year			Summers		
		Polders	Waddensea	Total	Whole	1976	No 1976
		Water Deficit Mm^3					
	Historical	2.38	1.45	3.84	0.61	0.40	0.21
March Summer Month	Opt Historical Ext	1.44	1.13	2.56	0.00	0.00	0.00
	Opt Historical Conservative	1.50	1.12	2.62	0.06	0.05	0.00
	5 Extreme	1.55	3.18	4.73	0.10	0.10	0.00
	5 Conservative	1.97	3.23	5.20	0.50	0.46	0.04
	7 Extreme	1.63	1.32	2.95	0.03	0.03	0.00
	7 Conservative	2.13	1.38	3.51	0.50	0.45	0.05
	8 Extreme	1.82	1.39	3.21	0.03	0.03	0.00
	8 Conservative	2.30	1.44	3.74	0.49	0.45	0.05
	9 Extreme	2.05	1.76	3.82	0.27	0.27	0.00
	9 Conservative	3.29	1.87	5.17	1.44	0.52	0.92
	10 Extreme	2.17	2.72	4.89	0.28	0.28	0.00
	10 Conservative	3.39	2.85	6.24	1.43	0.52	0.91
	11 Extreme	2.12	2.44	4.56	0.25	0.25	0.00
	11 Conservative	3.35	2.57	5.92	1.42	0.52	0.91

Table 5.22 – Summer deficit for the different alternatives – March summer

The separate cases have been discussed already in paragraph 5.1.3 and 5.1.4. Here a broader vision on the alternatives is provided, analyzing and recalling the different strategies by climate change scenarios: past/present climate, W+2050 and W+2100. Case 5, already mentioned as an ineffective alternative, will be left out of the discussion and discussed later.

- *Past/Short term.* With no changes in the climate scenario, the system is able to efficiently reduce the water deficit in a safe way. Both with the present management, or more efficiently allowing March target water level to raise. Changes in target water levels during summer are able to reduce the historical deficit to half (Figure 5.2) or even to zero (Figure 5.10). This last option needs a higher target water level in March, and a target water level in June of +0.15mNAP. The safer version (Figure 5.11) however, reduces the deficit considerably (9% of the historical deficit).

- *W+2050*. In an extreme scenario with horizon 2050, the system is not able to cope with the deficit in its driest year due to the little inflow into the system. However, the target water level can be raised in July and August in order to tackle the deficit in other years, which are now drier due to climate change (Figure 5.4). This would need to get to a target water level of +0.16mNAP. However, the safer version (Figure 5.7), gives a similar satisfaction of the demand. Both strategies are able to keep the deficit in the summer months close to the past deficit (+9%/+13%).

  Allowing March target water level to rise is an effective alternative to tackle deficit in the driest year (Figure 5.13) which reduces to 26% of the historical one, and brings the total summer deficit down to 5% of the historical one. However, this happens only with a rise in the target water level up to +0.66mNAP (and to +0.36mNAP in March). In a realistic perspective, this is not acceptable. The conservative version of the case (Figure 5.15) brings the maximum target water level down to +0.1mNAP. With this configuration, the system fails in controlling the deficit in 1976, but the overall deficit in summer years reduces to 81% of the historical case.
- *W+2100*. In an extreme scenario with horizon 2100, the system fails again to cope with the deficit demand in the driest year. Furthermore, water demands in other dry years need now a target water level up to +0.51mNAP (Figure 5.8) in order to keep the deficit in the same range as the historical one (109% of the historic summer deficit). In a more realistic view, such option is not safe; water levels have to be lowered (Figure 5.9), but in this case the deficit in summer months is almost 2.5 times the historical one.

  Allowing a higher target water level in March is still an effective solution (even if it is less than in the horizon 2050), which manages to halve the deficit of the historical case (figure 5.16). However, an unfeasible target water level of +0.65mNAP is needed. The conservative option (Figure 5.17) rises again the summer deficit to almost 2.5 times the historical one.

Given this overview, it is easier to discuss the different strategies used in optimizing the water demand.

Extreme vs conservative cases

As discussed in paragraph 4.3.1, there is little knowledge on the exact water level configuration which assures safety of the dikes in summer. For this reason, two different strategies have been assumed in the optimization: a conservative option which limits the target water level to +0.1mNAP, and a more extreme one which allows water to reach +0.69mNAP.

From the analysis of the results, it is possible to asses which are the consequences of assuming the different hypothesis. The solutions of the extreme and the conservative cases differ more when considering longer horizons, hence stronger climate change scenarios. This is because the extreme strategy assumes that the system has higher flexibility, and, when needed, goes to higher target water level. This is very interesting in

order to explore the possibilities and the hard limits of the IJsselmeer for the satisfaction of the water demand. In a broader perspective, it considers the system in summer time as if the satisfaction of the water demand has a higher priority than safety. It selects the alternatives which might be unsafe, but are better in controlling the deficit of fresh water supply.
On the other hand, the conservative strategy brings back the possible solutions to the ones which are feasible, allowing a more realistic assessment of the alternatives selected by the optimization.

The use of the two hypothesis in combination, allows a complete analysis of the ways in which the satisfaction of the water demand can be tackled in the IJsselmeer; exploring the higher boundaries of the system, while keeping an eye on what can actually be implemented. This is actually the perspective to follow when assessing the results:

- Extreme strategy are more an indication of what could be possible, which are the furthest limits of the IJsselmeer in satisfaction of fresh water demand and which measures would be needed to overcome them.
- Conservative strategies are realistic indication of what can be implemented, considering the present (limited) flexibility of the system.

March winter month vs March summer month

Also in this case, little knowledge is available on the real possibilities for the March target water level to rise. Studies suggest that such option could be possible (Verhoeven 2009). Others recommend further research on the topic (Deltaprogramma IJsselmeergebied 2010). As mentioned, it is not the purpose of this study to discuss which target water level can be reached, or to argue if such measure is really feasible within the present configuration of the system.

From the analysis of the extreme strategies, it is shown that the IJsselmeer as it is now, is simply not able to cope with the water demand in the driest year for long horizons. If good options are possible for the present climate (see figure 5.2), rises of target water level, no matter how high, fail to satisfy the water demand in the year 1976, when considering the climate scenario W+2050 and W+2100. It has been shown that high target water levels suggested by the optimization of the extreme case (see Figure 5.4 and 5.8), are mainly due to tackle (successfully) water demand in years which become drier with the proceeding of the climate scenarios, while the deficit in 1976 stays unsolved.
Regarding water deficit in years other than 1976, from the analysis of the extreme cases, the IJsselmeer seems having good potentials (see Figures 5.4 and 5.8). However, bringing the possibilities to a more realistic perspective, only with a climate change W+2050, the prescribed target water changes are feasible and lead to a satisfactory situation (see figure 5.7), while for a longer horizon the more realistic alternative (see Figure 5.9) does not guarantee an acceptable deficit.

As confirmed by the results, the problem of the present configuration of the IJsselmeer in facing the most extreme dry year, is due to the fact that in such case too little water enters the system and it is not possible to build up the needed buffer for the satisfaction of the water demand. In order to help the system in facing also the most extreme dry year, there is need to allow more water entering the IJsselmeer, which can be done by anticipating the period from which the water is stored, and keep in the lake also some of the inflow from March. This would mean, from an operational point of view, allowing a higher target water level in March. Optimization D has been therefore introduced in order to tackle the deficit also in 1976.

Allowing a higher target water level in March seems a very promising measure in the present climate. With a March rise to the present summer target water level (-0.2mNAP), the water demand in 1976 can be completely satisfied, and even considering the conservative condition, the gain is extremely interesting (see Figures 5.10 and 5.11). However, when considering long term scenarios, the effectiveness of the strategy reduces from a practical point of view. This means that the advantages are still high, are much higher only in the extreme case; there is a need of high target water levels along the summer in order to preserve the buffer for water demand in the driest year. Such target water levels, at the present configuration of the system, are definitely not safe (see Figures 5.13 and 5.16). When defining a more realistic case, advantages of the strategy can still be experience in the scenario W+2050, but a higher target level in March loses its function on longer terms, generating a deficit really close to the case in which March target water level is kept at -0.4mNAP.

From the result of the optimization, it can be said that allowing early storage of water is effective in the short term, but needs consequent higher target water levels in the summer months while considering longer horizons.

Total deficit (whole year)

So far, the discussion has been based on the deficit during summer months. However, water demand is present the whole year around, so that the whole deficit has to be assessed in order to complete the evaluation of the selected alternatives.

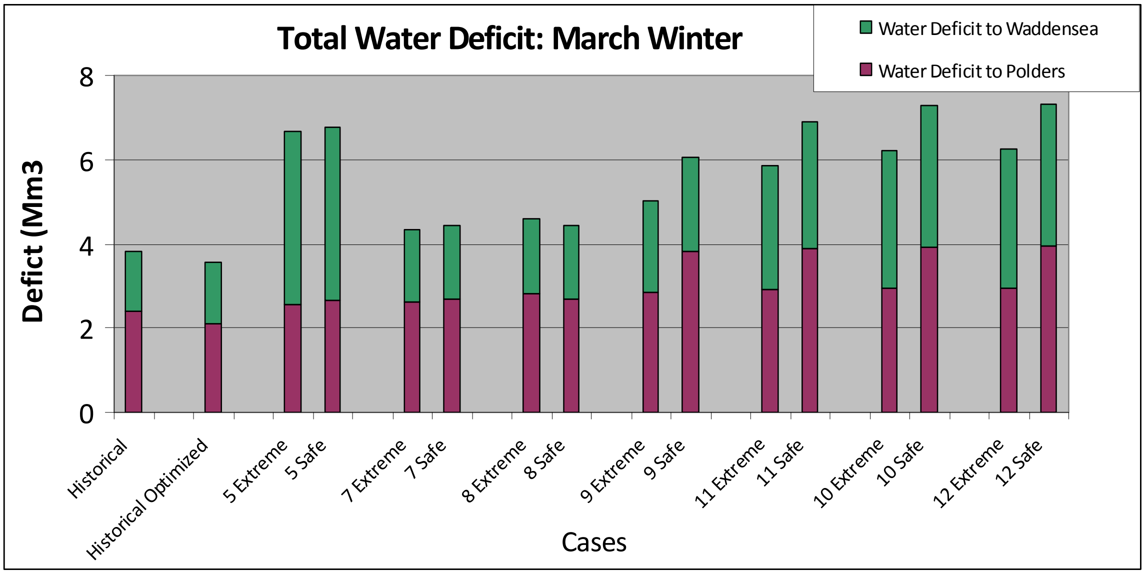

Figure 5.21 – Total water deficit – March winter

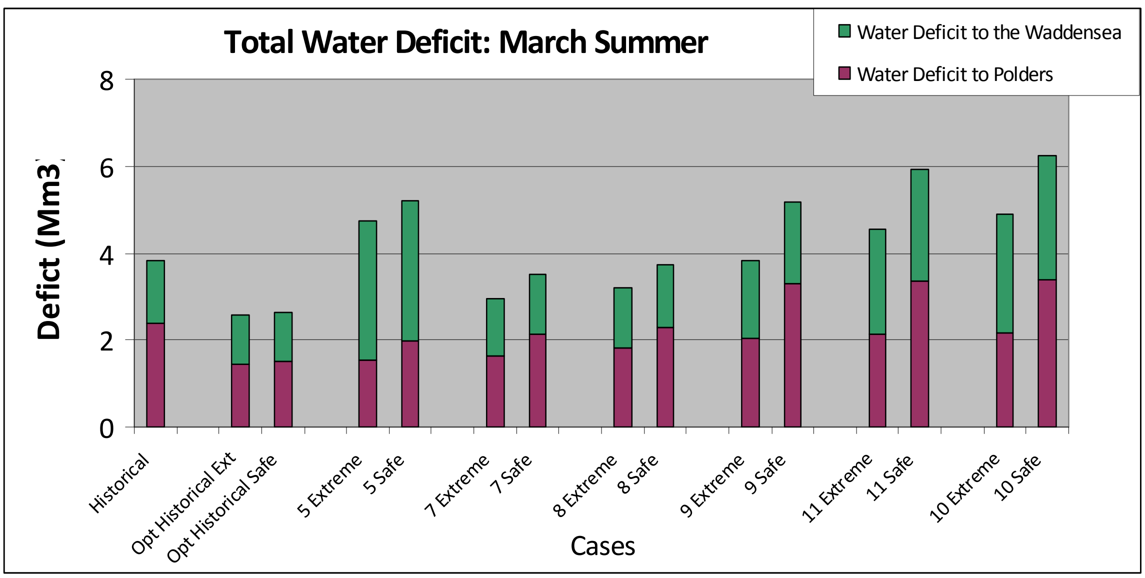

Figure 5.22 – Total water deficit – March summer

The two components of the water deficit are shown in Figures 5.21 and 5.22. Different remarks can be made from these figures:

– As already noticed before, and confirmed by the values in the total deficit, case 5 is not effective for the satisfaction of the water demand. It generates in a short term situation a deficit which is comparable with the long term scenarios of W+2100. This aspect is even made worse in the total water demand due to the fresh water required for flushing to the Waddenzee (green in the graph). This is needed also in the winter and requires a water level higher than -0.4mNAP. It can be imagined that case 5 with a winter target level of -0.48 mNAP opposes such demand. In fact, looking at the total water deficit for the polders, case 5 does not perform much worse than case 7 and 8. However when adding the deficit to the Waddenzee, the difference is relevant.

- Looking at the deficit for the polders, the trends confirm what has been said considering only the summer water deficit. However, it is surprising that the alternatives discussed in the previous paragraphs have less impact on the total deficit than what expected. This can be explained by the fact that summer deficits are only a little fraction of the total missing water (e.g. only $1/4^{th}$ in the historical case), so that measures for reducing summer water shortage are less effective when considering the whole year. This is also surprising.
- The little fraction of the summer deficits can be explained by the fact that measures and attention has been already given to summer situation in order to minimize water scarcity when the demand is higher (target water level of +0.2mNAP). While for the winter not much can be done, because the management is driven by safety issues, so that the deficit is higher. In this sense it is surprising to notice that from case 7 till 12, the total water deficit increases with the sea level rise, while no impact of such type have been noticed when observing only summer deficits. It is believed that this happens more due to the rise in the pump capacity than the rise of the sea level. The use of pumping helps the system keeping to the target water level, which in the studied cases is exactly -0.4mNAP. A section of the winter water level is shown for the historical situation, case 9 and 12 in Figure 5.23. As can be noticed the use of the pumps allows the system to stay closer to -0.4mNAP, so that winter discharge to the Polders (for flushing) and to the Waddenzee is made more difficult.

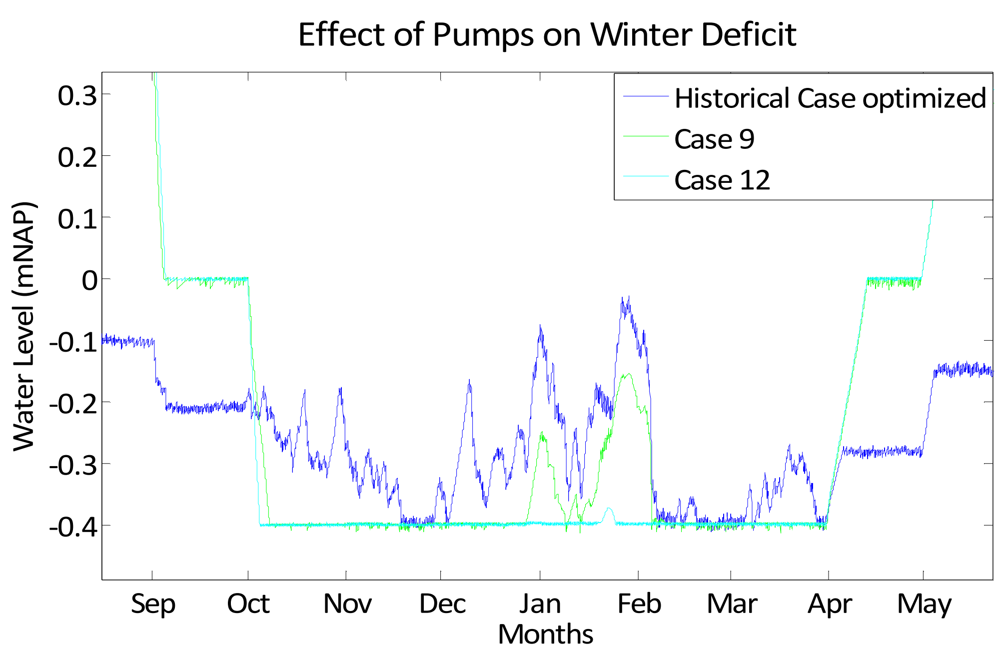

Figure 5.23 – Effects of pump on winter mean water levels

One last remark has to be made on water deficit happening at the boarders of the summer period: March and October. Looking at the water demand, it is not uncommon to find demand already in March and until October. However, being considered winter months, they have a lower prioritization than safety. It is true that being already wetter months than summer, water demand is not high. However, it is important to acknowledge them while talking about water deficit on the whole year. In the present research, due to the strict prioritization considered, they have not been used for the definition of the indicator. However, for March, water deficit has been reduced while considering the month as in summer. For October, an higher target water level than the one defined in the presented alternative would help reducing the deficit, but just because of the time lap that the system would need to go from a summer to a winter target water level. More research is needed for both months in order to check the possibilities for higher target water levels in order to reduce water deficit.

5.2.3. ECOLOGY

No indicator has been developed for the present stake, so that evaluation of the effects is qualitative given by the visual analysis of the target water level. This is possible for summer months because in such period the system is generally able to keep the actual water level close to the target, as shown in Figure 5.20.
From the results of the different optimization problems (figures in paragraph 5.1), it can be noticed that:

- There is no peak in early spring, while the peak is generally in middle/late summer (June/August).
- In late summer the target water level does not drops under the winter water level.

Given these features it can be concluded that the alternatives selected in the present research are not suitable for the development of the IJsselmeer into a more natural dynamic shallow lake. In particular the absence of a spring peak does not allow the reed breeding birds to safely build their nests on the semi-submerged vegetation. Furthermore the high water levels in late summer oppose the expansion of the reed, so that the migration areas can not develop as needed.

Further research is needed to define indicators for ecology. This would help understanding the possibility of the integration of such stake with the objective posed by water demand and safety.
It is necessary to remember that land/water transition areas are strictly needed in order for the water level fluctuations to be effective for the ecological status of the lake. At the present state of the IJsselmeer, little littoral areas have the needed characteristics. Their implementation and position, especially relatively to the water level fluctuations of the lake, might be a strategic issue to enhance ecological quality in the IJsselmeer.

5.2.4. COMERCIAL SHIPPING

The evaluation of the impacts of the rsults on commercial shipping is performed with the help of the indicator i_{sh}, defined in paragraph 4.3.4. Table 5.23 shows the value of the indicator in the different cases. The values represent the number of time steps when the water level is lower than -0.4mNAP. Also the percentage which each case represents on the present situation is reported in the table.

	Time steps	%
Historical	40383	
Optimized Historical Situation	40378	100
Case 12 Extreme	114237	283
Case 12 Conservative	114599	284
Case 14 Extreme	48467	120
Case 14 Conservative	48532	120
Case 15 Extreme	49980	124
Case 15 Conservative	48532	120
Case 16 Extreme	60220	149
Case 16 Conservative	62217	154
Case 18 Extreme	81348	201
Case 18 Conservative	93265	231
Case 17 Extreme	90644	224
Case 17 Conservative	93265	231
Case 19 Extreme	91487	227
Case 19 Conservative	93265	231

Table 5.23 – Commercial shipping indicator in the different cases

The optimization of the summer target water level has little effect on navigation. In fact the historical optimized case scores as the present management.
On the other hand, the winter management of the IJsselmeer has a more relevant influence on the stake. In case 12, with a winter target water level of -0.48, there is a consistent damage to the commercial shipping sector. This could have been expected, since the system tries to keep the water level lower then the shipping threshold.
In cases 14-19, with the installation of a pumping station at the Afsluitdijk, the system is able to better control the winter water levels, and keep them closer to the target. Since the target coincides with the navigation threshold, this generates damage to the commercial shipping, since the water levels in winter will be more frequently close to the threshold. The damage is proportional with the capacity of the pump, since higher capacities better control water levels.
It can be noticed that the extreme cases score slightly better than the conservative ones. This is because in the transition from summer to winter, the system takes longer to evacuate excess water (higher target water levels) and the winter target is reached later.

However, it is important to mention that the in the case of commercial shipping, water levels lower than -0.4 mNAP represent a minor problem since the channels can be dredged. On the other hand, every year, one or two ships sink because of wave action. Such aspect, which is not considered in the present research, has higher influence on the stake.

5.2.5. RECREATION

The evaluation of the impacts of the results on recreation is performed with the help of the indicators i_l, i_h and i_{hh} defined in paragraph 4.3.5. All together they concur in the formulation of i_R. Table 5.24 shows the value of the indicator in the different cases. Also the percentage which each case represents on the present situation is reported in the table (when relevant).

	i_h	i_{hh}	i_l	i_R	
				Timesteps	%
HIstorical Situation	289	41	0	186	
Optimized Historical situation	607	41	0	345	186
Case 12 Extreme	51835	58	0	25976	
Case 12 Conservative	51224	53	0	25665	
Case 14 Extreme	56265	48	0	28181	
Case 14 Conservative	55057	48	0	27577	
Case 15 Extreme	55854	66	0	27993	
Case 15 Conservative	55057	48	0	27577	
Case 16 Extreme	32524	117814	922	134998	
Case 16 Conservative	111735	83	922	56873	
Case 17 Extreme	33373	118876	920	136483	
Case 17 Conservative	114321	156	920	58237	
Case 18 Extreme	57796	119420	919	149237	
Case 18 Conservative	114321	156	920	58237	
Case 19 Extreme	33863	119425	918	137275	
Case 19 Conservative	114321	156	920	58237	

Table 5.24 – Recreation indicator in the different cases

From the analysis of i_h and i_{hh}, changes in the summer target water levels are detrimental for the recreational quality of the beaches around the IJsselmeer. This has a much lower effect in the short term, but the impacts are higher with the measures considered for the long term.

The results shown by the values of the indicators are in line with the expectations. High impacts are related to the high summer target water levels needed to satisfy the water demand in the medium/long term. The higher boundary is especially passed in the extreme cases for the long term measures. The conservative approach manages to keep the impacts low.

From the analysis of i_l, there is danger for the accessibility of the harbors only when the system is not able to cope with the driest year. This is the case of the long term scenarios, when in 1976 the water level drops considerably due to intense evaporation.

5.2.6. INLAND WATER MANAGEMENT

The evaluation of the impacts of the results on inland water management is performed with the help of the indicators i_{IWM}, defined in paragraph 4.3.6. Table 5.25 shows the value of the indicator in the different cases. The values represent the number of time steps during winter when the water level is higher than 0.1 mNAP. Also the percentage which each case represents on the present situation is reported in the table.

i_{IWM}	Timesteps	%
Present Situation	2987	
Optimized present situation	2987	100
Case 12 Extreme	3407	114
Case 12 Conservative	3407	114
Case 14 Extreme	1988	67
Case 14 Conservative	1988	67
Case 15 Extreme	1118	37
Case 15 Conservative	1988	67
Case 16 Extreme	936	31
Case 16 Conservative	936	31
Case 17 Extreme	372	12
Case 17 Conservative	371	12
Case 18 Extreme	468	16
Case 18 Conservative	371	12
Case 19 Extreme	371	12
Case 19 Conservative	371	12

Table 5.25 – Inland water management indicator in the different cases

From the analysis of the indicator it can be seen that the installation of a pumping station at the Afsluitdijk improves the water management in the polders around the IJsselmeer. In particular water logging is expected to decrease generating benefits for the neighboring water boards. This is because, as noticed before, a pumping station actively reduces both the highest and the lower peaks, so that there are fewer chances for the mean water level to get higher than 0.1 mNAP.

Again this is not the case for strategy 12, where water logging is actually expected to increase.

5.2.7. WATER MANAGEMENT OUTSIDE THE DIKES

No indicator has been developed for such stake, also because the effects of high water levels in the IJsselmeer vary location by location with regard to the structures outside the dikes. From the analysis done for recreation at paragraph 5.2.5, it is evident that there are effects from the strategies selected in the present research. However more research is needed in order to better understand the impacts.
It can be however said that the present situation is already critical in the IJsselmeergebied. In the Markermeer, close to the town of Uitdam, a camping has been flooded regularly in the last 12 years.

5.2.8. FINAL REMARKS ON THE RESULTS

Impacts of the optimization on the results

As mention in chapter 3.2, the optimization algorithms used have an important impact on the methodology. Impacts can be both on the time needed to find the optimum alternative and on the quality of the optimum. In this second case limitations from the algorithm might lead to the identification of a local optimum, instead of a global one, i.e. identification of sub-optimal alternatives.

For what concerns the DE algorithm, there are no doubts on its capability of finding a global optimum within the framework of the present research. Also computing times have not been a limiting factor. However, the same result could have been obtained by simpler algorithms and shorter computing times. In this case there are no major impacts on the results, but more research should be done in order to define a more suitable optimization algorithm.

In the case of the lexicographic algorithm, the results have to be considered with care. Since the algorithm considered in the present research is not exhaustive, there are possibilities that the same minima can be obtained by different configurations of the summer target water levels. The fact that the selected alternatives have minima which correspond with the ones achievable with the highest configuration of the target water levels, assures that the solution is not suboptimal. However, it is important to realize that the set of optimum alternatives might be larger.

Impacts on the design of the indicators on the results

The optimization of the test case has been performed on the basis of the indicators defined for the objectives of the different stakes. Their design is fundamental for the optimization process and their influence huge on the results. If they are badly defined or they badly represent the objectives of the stake, can lead to misleading results, making the optimization meaningless.

Given this, the definition of the indicators is maybe one of the most complex and important phase of the whole procedure, requiring not only analytical skills but also some creativity and empathy in order to understand correctly the needs of the stakeholders and translate them into mathematical indicators.

A good example in the framework of the present research is the definition of the proxy indicator for safety of dikes. As discussed in Appendix B, it has not been possible to introduce a reliable statistical analysis into the optimization, so that a proxy indicator has been designed in order to keep the peaks in actual water levels down to the past events. Such indicator has been proved to be too strict in assessing the safety of the system as shown in the results of the optimizations 0 and B (see paragraph 5.1.1 and 5.2.1). This brought to the definition of slightly over dimensioned pumps and definition of a lower flexibility of the present system for coping with safety in the short term.

Impacts of the use of a single objective function

As mentioned in paragraph 1.3.3, a methodology based on an optimization approach can be useful in order to bring efficient and stakeholder oriented alternatives to the stakeholder consultation. This is true only if the outcome of the optimization is a set of multiple alternatives, all efficient but satisfying on a different degree the actors involved. Only in this case a negotiation can be carried towards the selection of the best compromise.
However, in the present research, the use of a single objective produces as an outcome a single optimum alternative. Under such condition there are no possibilities for a stakeholder consultation.

As the present research uses only a simplified test case in order to understand the benefits of an approach based on optimization, the use of a single objective does not limit the value of the results. However, it is important to realize that the application of an optimization methodology on a real case would need a multi objective approach. This is fundamental in order to gain practical advantages in the decision making process.

6. CONCLUSIONS AND RECOMMENDATIONS

From the definition of the objectives and the features of the test case (4.1), through the specification of the measures to consider (4.2), the indicators for their evaluation (4.3) and the model for their test (4.4), the PIP procedure has supported the present study until the definition of efficient alternatives and the discussion of their effects (4.5-5). The present chapter discusses how the whole procedure contributes to the fulfillment of the research goals and to the answer to the research questions. Paragraph 6.1 contains a recap of the goals of the study and the research question. Fulfillment of the goals and their discussion in relation with the results is provided in paragraph 6.2, while in 6.3 answers are given to the research questions. Finally, paragraph 6.4 is dedicated to the discussion of the recommendations.

6.1. RECAP OF THE GOALS OF THE STUDY AND THE RESEARCH QUESTIONS

As defined in Chapter 1.3.2 the goals of the study are:

1. *High level*, investigate the feasibility, simplicity and benefits of a methodology based on an optimization approach on dikes safety and water demand, for exploring measures towards a climate proof IJsselmeer.
2. *Low level,* for the IJsselmeer (test case):
    a. define for the different scenarios a set of monthly target water level which can best generate a climate proof IJsselmeer, satisfying dikes safety and water demand objectives;
    b. define a set of monthly target water levels and extra measures which can best generate a climate proof IJsselmeer for those scenarios, where the flexibility of the present system is not enough to meet the objectives of dikes safety and water demand, only by means of changes in the target water level;
    c. on the base of the selected measure, asses the flexibility of the present situation to adapt to future scenarios, satisfying dikes safety and water demand objectives;

High and low level objectives translate respectively in the two research questions of the research:

Can a different planning of the target water level alone give an answer to the long term needs for dikes safety and water demand of the IJsselmeer, and if not which other measures can help improve the situation?

Can a research methodology based on optimization strategies be a useful tool for defining efficient alternatives for the future management of the IJsselmeer?

6.2. DISCUSSION OF THE GOALS OF THE RESEARCH

In the present paragraph, a discussion is provided for the three sub goals of the low level objective of the research (2.a, 2.b, 2.c). This prepares the ground for the discussion of the two goals (1 and 2), which will be provided in paragraph 6.3 as the answers to the correspondent research questions. Note that all numbers given below are the result of a profound research, but still need to be considered as (best) estimates.

6.1.1. GOAL 2.A - MONTHLY TARGET WATER LEVEL WHICH CAN BEST GENERATE A CLIMATE PROOF IJSSELMEER

With no extra measures, a climate proof IJsselmeer can be only defined on a short term horizon. Considering no climate change in the inflow, sea level rise up to +0.12m and including the enlargement at Lorentzsluizen, the optimum monthly target water levels can be defined as shown in table 6.1:

Optimum target water level (short term no extra measures)	Winter	April	May	June	July	August	September
	mNAP						
	-0.4	-0.20	-0.15	-0.02	-0.07	-0.10	-0.20

Table 6.1 – Optimum target water level, goal 2.a

This configuration is safe until a sea level rise of 0.12mNAP as defined through case 0b, optimization 0 (and maybe further, see paragraph 5.2.8). As defined through the optimization of the historical case (Hist - optimization C – Figure 5.2), such strategy provides a cut into half of the water deficit with respect to the historical water shortage, reducing effectively both deficit in the driest year and in the whole series. Furthermore, it is safe with respect to the summer period.

In the short term, water deficit could be further reduced to zero by changing the strategy in March, and allowing early storage of water. However, given the good flexibility that the IJsselmeer has to tackle water demand without considering such extra measure, and given the uncertainty of its effect on safety, allowing early storage is not needed in the short term.
Of course this may depend on more political strategies and the real effects on safety of the extra measure, which might lead to the choice of the case Hist as came out from the optimization D (both the extreme and the conservative case – Figure 5.10 and 5.11). However, those considerations fall outside of the purpose of the study.

Considering long term scenarios (W+2050), the system as it is, does not have room for the definition of a climate proof management of the target water level, especially when dealing with safety of the dikes.
From a safety point of view, an attempt has been made with case 5 (optimization A), but the only option is to lower the target water level, which has been proven to be an ineffective alternative. It produces an unsafe condition at the wind dominated location, it is not robust to large increase of sea level rise, and is also detrimental for the satisfaction of the water demand.
From a water demand point of view, the discussion is more open, since with changes in management of the summer target water level, it is possible to keep the deficit in a scenario W+2050 within the range of the historical one (case 7 and 8 both extreme and conservative cases – Figure 5.4 and 5.2). However, such strategies fail in tackle the driest year and extra measures might be needed, if there is the wish to further control water deficit.

6.1.2. GOAL 2.B MONTHLY TARGET WATER LEVEL AND EXTRA MEASURES WHICH CAN BEST GENERATE A CLIMATE PROOF

In order to define a climate proof IJsselmeer for long term scenarios, there is a need to define extra measures which help the system satisfy safety of the dikes and water demand.

For a climate scenario W+2050, the optimum setup is defined as follows:

Sea level rise	Pump Capacity	Winter	March	April	May	June	July	August	September
m	m^3/s	mNAP							
+0.20	346	-0.4	-0.17	-0.03	0.10	0.10	0.10	0.09	-0.16
+0.35	824	-0.4	-0.17	-0.03	0.10	0.10	0.10	0.09	-0.16

A pump at the Afsluitdijk is needed in order to keep the system at the required safety standard during winter time. Capacities have been defined through the optimization problem B.
Regarding the satisfaction of the water demand, a lower water deficit than the one historically experienced can be gained if the March target water level is allowed to be raised untill the present summer one, in order to allow early storage of water. The target water levels have been defined with the optimization of cases 7 and 8 through the optimization problem D (see Figure 5.15).

Extra storage in March can also be avoided, and March kept a winter month (optimization of case 7 and 8 through problem C – Figure 5.7), but then the deficit experienced is more that the historical one, even if slightly. Again, the choice between the two falls outside of the purpose of this research. Here the best option for water demand has been presented, while still keeping an eye on the other alternative.

When considering a scenario W+2100, again is not possible to define a climate proof IJsselmeer, given the extra measure taken into account.
Differently than before, the limiting factor in this case is not the safety of the system in the winter. Pump capacities needed for a safe IJsselmeer have been defined for the most extreme scenario and have been proven to be effective in keeping the correct safety standards.
Satisfaction of the water demand is now an issue. Considering the present configuration of the system, and the maximum target water level reachable in the summer, water shortages rise in such a way that the IJsselmeer can not be considered climate proof anymore, even with an early March storage. Alone, it is not an effective measure to tackle water deficit in such long horizon, other measures or strategies are needed in order to enhance the benefits of early water storage.

6.1.3. GOAL 2.C ASSES THE FLEXIBILITY OF THE PRESENT SITUATION TO ADAPT TO FUTURE SCENARIOS

From the above considerations, it can be concluded that the IJsselmeer has very good potential for being climate proof in the short term, but extra measures are definitely needed to assure safety and satisfaction of the water supply when considering longer horizons (2050 and 2100).

In a short term safety is assured mainly by the implementation of the enlargement of Lorentzsluizen, while changes in target water levels are mostly ineffective. Regarding the satisfaction of the water demand, the IJsselmeer is flexible enough to allow changes of summer target water levels, which can efficiently tackle water scarcity in dry years, with no extra measures needed.

6.3. ANSWERS TO THE RESEARCH QUESTIONS

On the base of the discussion of the goals of the research, answers can be given on the two main research questions. In particular it is important to remember that the second one represents the main goal of the research: answer to the goals and the first research question create the basis on which its answer can be given.

Can a different planning of the target water level alone give an answer to the long term needs for dikes safety and water demand of the IJsselmeer, and if not which other measures can help improve the situation?

According to the present study, a different planning of the target water level is not able to satisfy the needs of safety and water demand in a long term. As it is now, the

IJsselmeer is not flexible enough to accommodate the impact of stronger scenarios: extra measures are needed to define a climate proof system.

Two different measures have been assessed in the present study in order to upgrade the IJsselmeer and allow a climate proof system on long term horizons.

Pumping station at the Afsluitdijk

The research shows that the use of a pumping station to discharge water to the Waddenzee is an effective measure to guarantee a safe IJsselmeer in the long term. This is because it has been shown that it is always possible to define a pump capacity which is able to keep the system at the present safety level.

However, the main limiting issue is the practical implementation of such capacities. As showed in the present research, the needed pumping station is multiple times larger than the largest pump currently used in the Netherlands (IJmuiden, 260 m^3/s).Also operational costs and use of energy have been often mentioned as drawback of such option.

In medium/long terms (2050 – sea level rise 0-0.6m), the capacities needed to keep the system safe rise considerably with the rise of the sea level. However, it has been noticed that such measure is very robust when considering longer horizons and higher sea level rises (2100 – sea level rise >0.6m).In fact needed capacities stabilize, and are no more influenced by further rises of the sea. Furthermore, it has been observed that the influence of the inflow scenarios on the design of the measure is minor, so that such strategy can really allow a safe and climate robust IJsselmeer when looking in a long prospective.

It is important to mention that there are evidences to state that the capacities defined in the present research are oversized with respect to the real needs; this is true because of two reasons:

- The proxy indicator defined for the optimization is very strict, assessing the benefits of the pumps only on high peaks, while it is effective also on low ones. A safe situation can be surely defined with lower pump capacities than the ones showed in the present research.
- The use of a simple management of the pumps. More attention in the definition of the management strategies of the pump can surely make a much more efficient use of the structures. Lower capacities might suffice to get the same safety standards.

Early March water storage

The research shows that allowing storage of water in March is a very effective measure to tackle water shortage even in the driest year. However, given the present configuration of the system, this is definitely true for a short term, has less effectiveness for a horizon of 2050, but fails for longer ones (2100).

The comparison between the extreme and conservative cases gives the key to interpreting this phenomenon. For long term scenarios, in order for an early storage to effectively tackle deficit in the driest year, there is a need of higher target water levels in the rest of the summer months. Considering a conservative threshold, this is presently not possible because of safety reasons during summer.

The main issue for preventing deficit is to being able to start storing water in the system at the right moment, in order to build up the needed buffer. Therefore, if water demands need to be satisfied for longer horizons, there is definitely a need to allow early storage, hence there will be no water in the system to prevent deficit. However, this is only effective if higher target water levels are allowed in summer. At the present state of the system, if the conservative boundary is confirmed to be the maximum allowable safe target water level in summer, there is need to extra reinforcement of the dikes for the satisfaction of the water demand.

Can a research methodology based on optimization strategies be a useful tool for defining efficient alternatives for the future management of the IJsselmeer?

Given the analysis of the system and the results provided by this study, the present research can be considered a successful implementation of an optimization approach for the IJsselmeer case.
This can be stated because the work has been able, on one hand, to retrieve a reliable picture of the flexibility of the IJsselmeer and on the other, to size the possible measures on the real needs of the system and in this way identifying efficient alternatives.

Although referring to a simplified test case, the use of just a simple model and an optimization algorithm, together with the definition of few essential stakes and only one objective function, has been able to draw a complete picture of the potentials and the flexibility of the IJsselmeer in the different scenarios, both in satisfying the water demand and the safety standards. And most important, such picture is realistic because it is in line with the other studies and the present beliefs on the real possibilities of the IJsselmeer.

Furthermore there are good clues to identify the potentials of such methodology in the definition of efficient alternatives to discuss with the stakeholders.

- *Definition of the optimum target water level for the satisfaction of the water demand in the short term*. The optimization approach has been able to identify a configuration which can provide a cut in half of the historical deficit, with no need for extra measures. Furthermore, it provides an improvement with respect to the strategies which are presently proposed for such time horizon. There is no need to reach a high target water level in all the summer months, or in early spring when the chances of storm are still high, but the same deficit can be gained with lower levels in April/May and July/September, and the peak in June. This configuration is efficient because avoids over dimension of the system, which in this case can harm the summer safety of the IJsselmeer. Allowing higher target water levels only when needed, lowers the probability that high level can happen during summer storm, enhancing safety.

- *Exploration of the effectiveness of early storage*. Given the essential role of such measure in the long term satisfaction of water demand, the optimization procedure has been able to define which kind of water levels are needed along the summer months in order for such alternative to be effective. Hence, which kind of extra measures would be needed to support such levels. The methodology shows very good potentials in detecting the target water levels needed for the effective timing of early storage, together with the management requirements to support such measure (timing of the target water levels needed to define the efficient buffer).

Furthermore the procedure has been able to give a reliable and safe indication of the size of the pump capacities needed.

Given the time constraints and the background along which the research has been developed, the implementation of an optimization procedure for decision support system in the IJsselmeer is certainly *feasible*. Indeed it can be argued if such approach is simple to implement. According to the experience gained on the work, the definition of the indicators has been the most challenging task, and especially for the case of the IJsselmeer, the introduction of a reliable statistical analysis in the optimization is not straightforward. Also, the analyzed test case is very simplified; challenges in the use of such approach might increase when considering a more complex case of the IJsselmeer. However, what is certainly true is that once a model for the system and indicators for the stakes have been defined, the resulting tool is very versatile, and can be used to test and investigate many different hypothesis on the needed measures. Finally, as shown above, the procedure is certainly *beneficial*. In the present research, the optimization methodology has been able to explore the potentials of the IJselmeer and most important to define efficient alternatives avoiding over-dimensioning of the system. Efficient alternatives are a key base of a successful stakeholder consultation.

6.4. RECOMMENDATIONS

Given the results of the research and the conclusion which have been drawn, a number of recommendations follow from the present study. Recommendations can be divided in three categories:

- Practical recommendations for future measures to implement in the IJsselmeer;
- Recommendations for further research on an optimization tool for the IJsselmeer;
- General recommendations on the use of optimization tools into the decision making process;

6.4.1 PRACTICAL RECOMMENDATIONS FOR FUTURE RESEARCH AND MEASURES TO IMPLEMENT IN THE IJSSELMEER

1. For the short term, finalize the enlargement of the Lorentzsluizen, which is able to give good room for satisfaction of safety.
2. For the short term, raise the target water levels in summer months in order to allow satisfaction of water demand.
3. Investigate the possibility for the system, in the short term, to accommodate early storage in March, with no need to strengthen the dikes. This could further reduce the water deficit in the near future.
4. Improve the present statistical analysis for safety in winter months. This should be done by defining a procedure which can assess the different months separately, and allow evaluation of different target water levels for each winter month. In this way there might be possibilities for months like February or March to have slightly higher target water level, and allow early storage with no threats for winter safety. This would be very beneficial for satisfaction of the water demand. In such perspective, a peak over threshold analysis seems a good option to assess extreme events which are related to different target water levels.
5. Define an official strategy for assessing summer safety. On the short term, this is needed in order to define the possibility of the present system to safely bear higher target water level (related to recommendation 2). On the medium/long term, assessing summer safety will be fundamental, since profound satisfaction of the water demand is only possible with higher target water levels in summer.
6. Define a statistical methodology in order to assess the desired level of satisfaction of the water demand in the future. Measures can then be defined which comply with the required level. Complete elimination of the deficit might require intensive measures. On the other hand, accepting some degree of deficit (as has been done in the past), might need considerably less infrastructure, but still be satisfactory. After all, droughts hit the whole Europe and the Netherlands can be already far ahead of the other countries by just limiting the impacts.
7. For medium/long term (2050 and 2100), investigate possible extra measures which can assure safety of the system in the long run.
8. Regarding recommendation 7, do not focus the studies only on one typology of measure (i.e. rising of the dikes or pumping station at the Afsluitdijk). Keep the different possibilities open, and integrate the different strategies, in order to define an option which is able to inherit the benefits of the two different measures, and compensate for the drawbacks. Namely:
    - Raising of the dikes: allows the lake to grow with the sea level rise and permits discharge by gravity (free and sustainable). Allows early storage of water, and possibilities for the summer target water level to reach the needed buffer for the long term satisfaction of the water demand.
    - Pumping station: is a robust solution for long term sea level rise. Allows effective lowering of the toetspeilen around the IJsselmeer, by controlling also lower peaks. Is able to keep the water level regime close

to the present configuration, so that climate change has little effect on the other stakes around the IJsselmeer.

It is interesting how the benefits of one measure coincide with the drawbacks of the other.

9. For medium and long term, reinforce the dikes in order to allow higher summer target water levels, and more effective satisfaction of the water demand. This must be done in line with recommendation 5 and 6.
10. For the medium, but especially for the long term, investigate options for early storage of water, as the only efficient way to tackle water demand. In this view, two strategies are possible:
    - Allow early storage on March, which is however not enough for longer term scenarios (has probably less impact on safety);
    - Allow early storage on winter months, raising the winter target water level (has an important impact on safety);

    In the medium/long term, there might be room for both, with respect to the implementation of recommendation 9.
11. Consider in the analysis of the water deficit also the water demand in winter and especially in March and October. Measures have been so far taken to tackle water demand during summer, while it has an impact all over the year. Measure for winter periods suggested at recommendation 7 and 8 should then consider also winter water demand.

To summarize, in the short term the system is flexible enough to assure a climate proof IJsselmeer. After the enlargement of the Lorentzsluizen, there is no need of other structural measures, and changes in target water level can profitably assure satisfaction of water demand. This is a good option to implement flexible interventions in the short term, and have some more room to plan medium/long term measures. In this way structural measures can be postponed in their realization, when there will be more knowledge on the climate scenarios.

This is similar to strategy 4, in appendix A. However, a more efficient evolution of the target water levels has been defined for summer months by means of an optimization approach.

For the medium/long term, reinforcement of the dikes is certainly needed in order to permit higher target water level in summer and tackle the water demand in an efficient way. This measure might give more room to early storage in order to further enhance the satisfaction of the water demand.

The reinforcement needed for water demand, can certainly give room to safety of the winter, however it is probably not enough to assure safety long terms. Further measures are needed. The recommendation is to define the minimum needed strengthening of dikes according to water demand needs. Then consider the new system and the new safety assured in winter months. Further measures for safety can then be planned combined different strategies, as suggested in recommendation 6.

The basic idea is that winter target water levels as defined in options strategy 1, 2 and 3, appendix A, are over-dimensioned in order to satisfy water demand, so not strictly needed. This is because winter safety of the system can be assured by different set of measures, combining dike reinforcement and pumping station, in a more beneficial and efficient way.

6.4.2 RECOMMENDATIONS FOR FURTHER RESEARCH ON AN OPTIMIZATION TOOL FOR THE IJSSELMEER

12. Given the feasibility, simplicity and benefits of the analysis, it is recommended to build a more extensive and detailed optimization tool for the IJsselmeer. This might involve intense work in a first phase, but will define a decision making support instrument which will be durable and useful in the decades to come. Starting from the present research, some constraints can be removed in order to define a more accurate set up of the problem:
13. From a single, to a multi objective system. This is a fundamental improvement that the present research needs, in order to fulfill the primordial scope of the optimization tool. Stakeholder consultation can be positively influenced by an optimization approach, only if it is possible to present and discuss different efficient alternatives, evaluated according to different objectives. No discussion is possible if only one solution is presented, as in the case of the present study, so that the methodology has little benefits on a real decision making problem.
14. From a deterministic to a statistical approach. The definition of a statistical model, fed by statistical time series, would allow a more reliable definition of the optimum alternatives. This is because the information of the past time series can be generalized, being better able to consider extreme events in the optimization. Furthermore, with a formalized definition of the statistical tools used to assess safety and water demand (recommendation 4-5-6), it will be possible to insert such analysis into the optimization.
15. From a pure planning to a management problem. With the optimization of the management of the structures, along with the measures to implement, the system can be used at its best, allowing more flexibility. In particular this is interesting when looking at the option of a pumping station at the Afsluitdijk. Its management can also be subjected to optimization.
16. From an offline to an online optimization problem. Shortening the time horizon and including the use of forecasts can considerably improve the quality of the optimization. However, this holds for management and flexible measures (target water level, management of the pumping stations), while has obviously no effect on structural and permanent measures.
17. Costs included into the objective functions. Especially when different expensive strategies have to be chosen, estimation of costs can help defining the efficient options. In this sense looking for the best configuration between raising the dikes, installing a pumping station or a combination of both, can substantially benefit from a cost analysis.

If implementing recommendations 13-17 can define a more complete and efficient optimization tool, it is important to realize that problems might arise from their implementations. If the problem gets too complicated, computational time becomes prohibitive.

18. The above recommendations have to be implemented into the optimization tool for the IJsselmeer making sure that the problem is still manageable.

19. Application of the optimization tool to asses the recommendations in paragraph 6.4.1. In particular:
    - Further analysis of the short term, recommendation 2/3;
    - Definition of the optimum strategy to tackle safety in the long term, considering both a pumping station and raising of the dikes. Use of cost functions is recommended, recommendation 7/8;
    - Definition of the target water level during summer and the early storage needed to tackle water demand in the long term, recommendation 9/10.

6.4.3 GENERAL RECOMMENDATIONS ON THE USE OF OPTIMIZATION TOOLS INTO THE DECISION MAKING PROCESS

20. Extend the approach and build an optimization tool on other water systems of the Netherlands, eventually interconnected, in order to improve the decision making process. This will be the most natural way to proceed if a more complete optimization tool built for the IJsselmeer proves to be interesting in order to define possible options to bring to the stakeholders consultation and if the definition of the best compromised alternative is enhanced and facilitated by such methodology. Furthermore, when more systems are connected and subjected together to optimization, the space of the possible alternatives enlarges, and there is definitive gain in flexibility. It is however important to keep in mind the complexity which is introduced in the system, when considering such broader water systems. Complexity should never be such that problems are faced from the computational point of view.

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APPENDIXES

APPENDIX A - Exploration of water level management options for the IJsselmeer - short/long term – Outcome of the consultation

The outcome of the consultation held with the stakeholders of the IJsselmeergebied from September 2009 till March 2010 is summarized in Figure A.1 (Deltaprogramma IJsselmeergebied 2010; Rijkswaterstaat Waterdienst 2010). Four possible visions for the future target water level of the IJsselmeer have been defined, based on the situation in approximately 100 years and with 1.30 cm sea level rise.
The strategies have been designed analyzing their consequences on safety, impacts on the surrounding areas (fresh water demand), ecology and use of space.

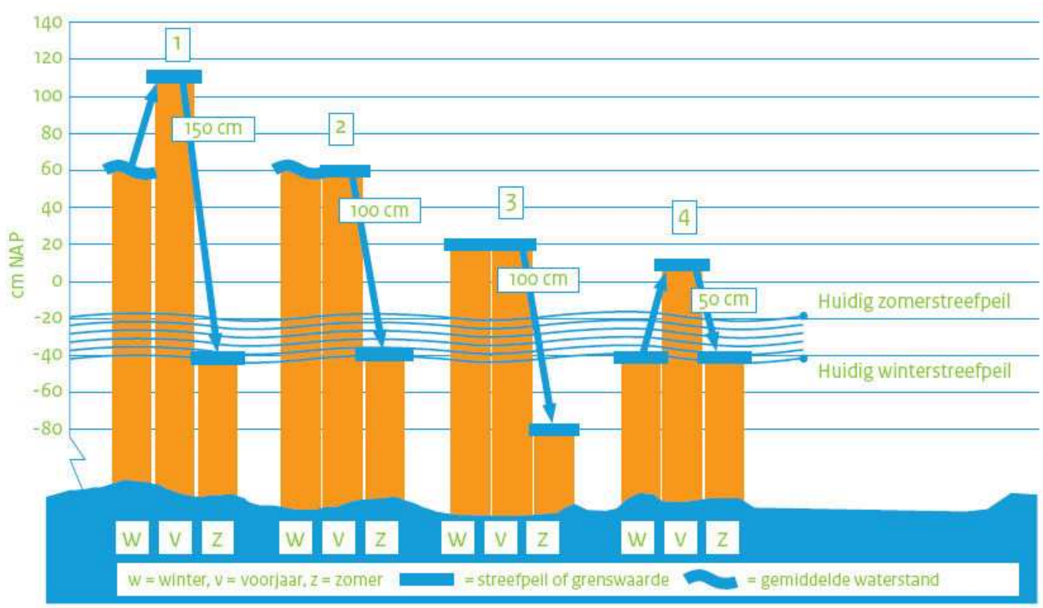

Figure A.1 – Possible strategies for the IJsselmeer

- *Strategy 1* (Implementation of the recommendation from the Delta Commission). The average winter water level can rise up till 0.60 NAP (+1m), with further increase in spring to a target water level of 1.10 NAP (+1.50m from winter target, as suggested by the Delta Commission). In late summer, the target water level can drop down to the present winter target level (-0.4 NAP). This strategy will allow sufficient buffer for summer water demand and for sufficient head for gravity discharge in winter.
- *Strategy 2*, same as the previous, with less spring buffer. Spring target water level remains as the winter one, 0.60 NAP (+1m in spring instead of +1.5m with respect to the winter target).

- *Strategy 3*, the target water level in winter and spring rise only till 0.2 NAP (+ 0.60m from the winter target), but in late summer it drops down till -0.80 NAP. This will still allow 1m buffer for fresh supply water in summer, as in the previous case.
- *Strategy 4*, close to the present water management of the area, and addressed as the short term strategy. In spring, the target water level rises till 0.1 NAP (+ 50cm from the winter target), dropping down to -0.40 NAP in late summer. In this case no changes are made for the winter target water level, and only 50cm of buffer are available for summer fresh water demand.

During the consultations, it has become clear that also small changes in water level management have undesirable effects on the system. For this reason, in all the four strategies, there is need of a set of measures to mitigate or compensate negative impacts. Both impacts and extra measures have been discussed during the meetings.

Negative effects can be observed on:

- *Safety*. Requirements on dike height depend on average water level and on the wind. According to the position of the dike along the IJsselmeer, the two factors have different influence, so that an increase of the mean water level can locally lead to different kind of reinforcements. However it can be said that for strategies 1 and 2 intensive reinforcements are needed, estimated around 300km of dikes which need to be raised by 1.5/2 meters. Interventions needed for strategy 3 are much less, which requires raises only up to 1m. No big interventions are needed for strategy 4. However it is important to define when in spring the target water level can be raised i.e. defining the end of the storm season.

  It needs to be noticed that such measures might even be more intense, when considering the recommendation of increasing safety by a factor of 10, suggested by the Delta Committee.
- *Impacts on the surrounding areas.* With a higher water level draining water to the IJsselmeer will be more difficult: problems will be faced at the inflow of the IJssel-Vecht delta, but also when water boards have to discharge excess water to the IJsselmeer.

  The four strategies will provide a different buffer for fresh water in summer; it is still not clear which of the options better meets the future water demands also in dry years and whether such buffers are overestimated or not. Reservation of fresh water in the IJsselmeer is abundant, but water is provided under gravity. When the water level drops too much, supply will not be possible anymore; this can be a problem for instance in strategy 3.

  Changes in water levels will influence the groundwater in the surrounding areas; from one side, higher water levels can cause increasing seepage pressure and saline intrusion, while on the other lower levels may generate stability problems at foundations in urban areas (wooden piles can dry out and rot).
- *Impacts on ecology*. Changes in water levels will have impacts on the existing ecosystem, which have to adapt to new conditions. In general, it has been argued

that all the different strategies, even if in different degree, are at odds with the existing nature preservation strategies.

- *Use of space.* There is not a precise inventory of the impacts of the different strategies on use of space, but beyond any doubt, many areas outside the dikes will face inundation problems, compromising the use of industrial activities, agricultural, residential and recreational areas.

Mitigation measures have to be shaped on the different strategies and the changes in water level brought into the system:

- *Strategy 1* is the one with the highest water level rise, causing severe flooding in the areas outside the dikes and serious worsening of the safety of the area. Many of the activities outside the dikes have to be replaced, and dikes considerably reinforced, not only around the lake, but also at the IJssel inflow. Pumping stations with higher capacity have to be installed at the polders, in order to get rid of the excess water and nature compensation project have to be promoted on land.
- *Strategy 2.* In this case, interventions are very similar to the previous strategy, but the water level reached in spring is lower, so that the needed measures are on a smaller scale.
- *Strategy 3*. Dike reinforcement needed along the coast and especially at the inflow of the IJssel are in this case much smaller than the other two strategies. Some areas outside the dikes, the ones with high value, can still hold their functions with small protective measures, ecological value can be enhanced and extra pumping capacity is not needed to get rid of excess water from the polders. However, due to the fact that the water level drops so low in summer, pumps are needed to withdraw freshwater, since gravity flow can not be applied under -0.3m NAP. Furthermore, in order to cope with sea level rise, in the future a pump is probably needed at the Afsluitdijk.
- *Strategy 4*, is the closest to the present situation, so that very little mitigation measures are needed. Namely the only negative effect is the inundation of about 40% of the area outside the dikes, due to the higher water level in spring. This has been mainly thought of as a short term strategy; if applied on a longer horizon, a pumping station would be needed at the Afsluitdijk, as an extra measure to guarantee the proper discharge to the Waddenzee, also with sea level rise.

APPENDIX B – Problems in introducing reliable statistical analysis into the optimization, and reasons for the definition of a proxy indicator

The winter safety of the dikes is tested trough the combined analysis of extreme events (mean water level and wind) in winter months. For this reason the most natural indicator in order to define a safe alternative is defined on the statistics produced by the new target water level regime.

With respect to the wind statistics, the extensive computational time and the complexity of the calculations needed to perform a statistical analysis combined with the mean water level, opposes its introduction into the optimization algorithm. In this sense a complete analysis is only possible a posteriori, as it is performed with the use of the Hydra-Vij software.

On the other side, a statistical analysis of the mean winter target water level has been at first considered into the optimization algorithm. This is because it seemed the natural way to keep part of the statistics into the definition of the indicator. In line with previous researches (Kramer 2008; de Jong 2010), the statistical tool used to design the indicator is one proposed by Blaakman (Blaakman 1999) and described in paragraph 4.3.2. However, several problems have been encountered:

- It is not straightforward to define which extreme event curve can be considered safe and which not. Whether the new situation should have extreme water levels lower then the present for all return periods, or for some, and if so which ones.
- Changes in target water level strongly influence the extreme event curve for short return periods, and through extrapolation, for high return periods. Results of such influence often contradict the common sense, since higher target water levels generate safer conditions for longer return periods. This is believed to happen purely due to extrapolation.
- If a different target water level is considered for each month, then a different statistical analysis has to be done monthly. This is because, starting from different set points, series of different months can not be treated together because incommensurable. If this is the case, the data on which each extreme event analysis is performed is 1/6th of the data available if considering the whole winter. It is then questionable whether the methodology proposed by Blaakman is still defining a proper statistic or not.

As a confirmation of the relevance of the problems posed by those issues, the results of the optimizations using DE algorithm did not manage to give any satisfactory result. The causes can be identified into the lack of data for the statistics, the effect of extrapolation, and the difficulty in defining a comparison with the past situation.

These reasons brought to the definition of a proxy indicator, and the assumption of a unique winter target water level (constraint 8, box XX).

APPENDIX C – Wind Parameters

In the present appendix, the parameters used for modeling wind effect at the structures are reported. Namely a(Wd,L), b(Wd,L), c(Wd,L), h_0(Wd,L).

Stevinsluizen:

Wind direction [degrees]	a	b	c	h_0
0-14	1,89	1	-0.00490	4.5
15-44	1,89	1	0.00033	4.5
45-74	1,89	1	0.00547	4.5
75-104	1,89	1	0.00914	4.5
105-134	1,89	1	0.01037	4.5
135-164	1,89	1	0.00882	4.5
165-194	1,89	1	0.00490	4.5
195-224	1,89	1	-0.00033	4.5
225-254	1,89	1	-0.00547	4.5
255-284	1,89	1	-0.00914	4.5
285-314	1,89	1	-0.01037	4.5
315-344	1,89	1	-0.00882	4.5
345-360	1,89	1	-0.00490	4.5

Lorentzsluizen:

Wind direction [degrees]	a	b	c	h_0
0-14	2,05	1	-0.00715	4.5
15-44	2,05	1	-0.00591	4.5
45-74	2,05	1	-0.00308	4.5
75-104	2,05	1	0.00058	4.5
105-134	2,05	1	0.00407	4.5
135-164	2,05	1	0.00648	4.5
165-194	2,05	1	0.00715	4.5
195-224	2,05	1	0.00591	4.5
225-254	2,05	1	0.00308	4.5
255-284	2,05	1	-0.00058	4.5
285-314	2,05	1	-0.00407	4.5
315-344	2,05	1	-0.00648	4.5
345-360	2,05	1	-0.00715	4.5

Roggebotsluizen:

Wind direction [degrees]	a	b	c	h_0
0-14	1,76	0,6	0.01346	4.5
15-44	1,87	0,6	0.00404	4.5
45-74	1,94	0,6	-0.00186	4.5
75-104	1,92	0,6	-0.00603	4.5
105-134	1,69	0,6	-0.01804	4.5
135-164	1,81	0,6	-0.01279	4.5
165-194	1,95	0,6	-0.00652	4.5
195-224	1,89	0,6	-0.00257	4.5
225-254	2,17	0,6	-0.00164	4.5
255-284	1,83	0,6	0.01153	4.5
285-314	1,75	0,6	0.01850	4.5
315-344	1,73	0,6	0.01953	4.5
345-360	1,76	0,6	0.01346	4.5