Once in a (technical) lifetime

Assessing the influence of interdependence and climate change uncertainty on the decision-making process for the renewal of hydraulic infrastructure. A case study at Zoutkamp

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TU Delft

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by

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Preface

Before you lies the final version of my thesis project. This was written for the completion of the MSc TIL. I started in April, worked through the summer and after 7,5 months i can finally say that i'm finished. I'm not big in making speeches but i would like to take this opportunity to say thank you, words that may otherwise be left unsaid. I would like to thank Jaap en Jan Anne for their supervision. While you kept honest and let me know when things were not good or unclair, you always made me feel confident that I would make it to the end. Also, I would like to thank Bert for the positive way in which you led the meetings with the supervising committee.
Finally, I would like to thank Mark, who gave me a chance to come to TAUW as an intern and thanks to you I have a job there. I wish you a speedy recovery.

Erik Hadders
Groningen, September 2021

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1 Introduction

1.1. Context of the research

Infrastructures age. In the Netherlands, a large portion of the hydraulic infrastructure (such as weirs and pumping stations) has been built between the 1920's and the 1960's (Willems et al., 2016). When this infrastructure is built, the common technical lifetime of this infrastructure is between 80-100 years. This indicates that in the coming years, a large part of the hydraulic infrastructure will reach the end of its technical lifetime and will need to be renewed. The research institute TNO (2021) confirms this in a prognosis of the status of Dutch civil infrastructure.
Next to the end of a structure's technical lifetime, biophysical change and socioeconomic change are drivers that influence the moment at which the functional end-of-lifetime of a structure is reached (van der Vlist et al., 2015). The impact of climate change in recent years regarding drought and extreme precipitation have caused a consensus that a shift in water management strategy is needed to cope with these impacts (UVW, 2020). A different functioning of the hydraulic infrastructure is part of the new strategy.

When the technical or functional lifetime of hydraulic infrastructure has come to an end, the decision has to be made on what to do with that piece of infrastructure. When infrastructure needs to be renewed it presents a 'once in a lifetime opportunity' to try to restructure the system so that it meets new goals (Vuren et al., 2015).
To reach those new goals (or to continue reaching the old goals if that is deemed sufficient), design alternatives are created. This is often done in the exploration phase of a project (Rijkswaterstaat, 2021). Between those alternatives a choice will be made for the preferred design alternative, after which the project moves on to the realization of the infrastructure.
In the daily practice, the choice options are evaluated with numerical and monetary models, such as (Social) Cost-Benefit Analysis ((S)CBA) (e.g. Mouter et al., 2013; Jones et al., 2014), Life Cycle Assessment (LCA) (e.g. Grubert and Stokes-Draut, 2020; Byrne et al., 2017), and Multi-Criteria Analysis (MCA) (e.g. Hajkowicz and Collins, 2007).Combinations of methods have also been created (e.g. Gühnemann et al., 2012). Especially the SCBA has become popular in decision-making (Wortelboer et al., 2012), but it is subject to an ongoing discussion about its desired impact and its limitations (Mouter et al., 2013).
These methods aim to assign a value to a project, after which a choice can be made based on the scores of the alternatives. Which alternative is chosen does not have to be the alternative with the highest score in the Netherlands, but in practice it often is (Mouter et al., 2013).

In creating the design alternatives and subsequently in deciding between them, there are factors that complicate the process. When a hydraulic structure is built, it is desired that it functions as intended for its complete technical lifetime. As said, a common technical lifetime is 80-100 years. This can be considered as long-term, which brings a high level of uncertainty into play about its functioning in the future (Pot et al., 2018). The precise impact of climate change is unknown, future technologies can make the current technology redundant, and socioeconomic changes can have an impact on the de-

mand towards infrastructure (Haasnoot et al., 2013).
Including long-term uncertainty is not a standard obligation in researching design alternatives (Machiels et al., 2020). But even if decision-makers have the best of intentions to incorporate long-term uncertainty into the design and evaluation of water infrastructure, Brown et al. (2020) note that a ‘classic’ CBA cannot accurately include uncertainty into its process, because the historic probabilities on for example precipitation or drought do not apply anymore in the changing climate. This can in fact be said for any 'ex-ante' model that makes use of probabilities.
To support decision-making regarding hydraulic infrastructure in light of long-term uncertainty, several researchers recommend the application of the theory of adaptivity to the planning of infrastructure renewal (e.g. Busscher et al., 2014; Hui et al., 2018). With adaptive planning, a long-term strategy is set after which short-term decisions are made within that long-term vision. This allows for flexibility in the future when circumstances or technologies change. This theory has been incorporated into some decision-support frameworks (e.g. Gersonius et al., 2013; Pot, 2019; Brown et al., 2020). These allow for quantitative comparison of design alternatives in light of long-term uncertainty.

Another factor that complicates the process of hydraulic infrastructure renewal, is the matter of interdependence. In an infrastructure system, one piece affects the larger whole (Brown, 2014). This is especially the case for hydraulic infrastructure. The interdependencies of hydraulic infrastructure work in two ways.
The first is functional interdependence of a structure towards the other structures. When for example the capacity of a pumping station in a polder is expanded, it can pump more water to the polder river one level higher. This level is in turn also regulated by a pumping station. The capacity expansion of the first pumping station will then likely lead to a faster reaching of the second pumping station's maximum capacity, accelerating the moment at which the second pumping station needs to be renewed. What complicates this is the fact that hydraulic infrastructure is managed on multiple organizational levels. Through the water system the structures (or assets) always interact in a network of different assets (Zandvoort & van der Vlist, 2020). Those organizational levels often display interest for just their lane of work (Neef et al., 2020), which causes the interdependencies of hydraulic infrastructure across different levels to be overlooked or ignored.
The second interdependence of hydraulic infrastructure is the interdependence with its surroundings. When for example a weir is raised at a point in a river to secure groundwater levels, this will at least temporary lead to dehydration of the water system downstream. This has impacts on among others ecology and agriculture.
The degree to which extent these interdependencies play a role, depends on the development of climate change, which is uncertain. In order to make an informed decision about hydraulic infrastructure renewal, it is important that the influence of structures on other structures is taken into account (Vuren et al., 2015). If this is ignored, then an intervention that seems like a good idea might eventually lead to higher costs for prematurely renewing structures elsewhere in the system because of that intervention.

1.2. Research problem

The research problem is that there is not yet a way to take interdependence into account when deciding between design alternatives, and to analyse how this might influence the decision on the preferred design alternative. The mentioned adaptive frameworks in the previous section treat the renewal of a hydraulic structure as if it is an isolated piece of infrastructure, without influence from and on the environment in which it operates. The effects of hydraulic infrastructure renewal are not yet incorporated into the adaptive decision-supporting frameworks. The only framework that looks at functional interdependencies of hydraulic infrastructure is the framework of Vuren et al. (2015). This remains however limited to an indication of a positive or negative influence on the functional lifetime of other structures. But the interdependencies do determine - now and in the future - whether a structure functions satisfactory; if a structure negatively influences the functional lifetime of other structures you can argue that is does not function satisfactory, even if it does what it is designed to do. And since hydraulic infrastructure renewal is a capital-intensive venture (TNO, 2021), it is important that a structure functions as intended for its complete technical lifetime. This means that long-term uncertainties, such as climate change and the effect of climate change on interdependence, have to be taken into account.

1.3. Research objective

The objective of this research is to explore to which extent the incorporation of climate change and interdependence into the decision-making process influences the resulting preferred design alternative. The goal is to look at the tipping points. Under which conditions does incorporating interdependence into adaptive decision-making lead to a different choice of the preferred design alternative, as opposed to not incorporating them? In addition, which interdependencies are the most important?
Within a single case study, this research will compare the conducted analyses and following decisions regarding a project of hydraulic infrastructure renewal with the results that follow from analysis in which interdependencies are looked at as well. Following from this analysis the findings will be put in a proposal for a decision-support framework.

The goal of the research and the sub-goals that were presented in the previous paragraph have resulted in the following research questions.

1.3.1. Main research question

The main research question that will be answered is:

To which extent does incorporating climate change uncertainty and interdependence influence decision-making for the renewal of hydraulic infrastructure?

1.3.2. Sub-questions

To answer the main research questions, several sub-questions have been formulated. These are the following:

1. *What are the possible ways presented in the literature to deal with long-term climate change uncertainty in designing hydraulic infrastructure?*
2. *What is available in the literature regarding decision-making for the renewal of hydraulic infrastructure?*
3. *How can interdependence be incorporated into the decision-making process?*
4. *How do the costs of the design alternatives compare?*
5. *What is the impact on decision-making?*
6. *How could a decision-support framework that takes climate change uncertainty and interdependence into account look?*

These questions have been answered with a set of methods such as literature research and interviews, which will be discussed in chapter 2. The decision-making process of the renewal of a pumping station has been used as a single case study in order to answer the research questions.

1.4. Scope of the research

In this section, the concepts that are of importance will be demarcated to indicate the scope under which the research will be performed.

1.4.1. Hydraulic Infrastructure

Hydraulic infrastructure is - even though it presents a convergence from the overarching concept of infrastructure - a broad term. Hydraulic infrastructure represents the physical structures built into water systems, with the aim to control water levels, allow for economic activities (such as shipping across water levels) or decrease flood risks. Examples of hydraulic infrastructure are weirs, sluices, dykes or pumping stations. Each category is built with different motives, and serves different purposes. Together they form the infrastructure in a particular water system.
Depending on what piece of hydraulic infrastructure is renewed, different interdependencies play a role. For example, changing a sluice will impact mostly the functioning of the rest of the hydraulic infrastructure regarding economic activity and shipping. For larger ships to pass through a sluice, up-

and downstream navigation for ships needs to be expanded as well. While a weir will also have an impact on the navigability of a river (both for ships and animals) it will as well have impact on water levels and all hydrological effects that follow from it.
To try to take all these functions and interdependencies into account, can lead to an infinitely complex research. This research presents a first sketch for considering interdependence in deciding on hydraulic infrastructure renewal. Therefore, the hydraulic infrastructure that will be considered will only be the infrastructure that is present in the case study that will be selected. On the single case study research Section 2.3.1 will elaborate. The hydraulic infrastructure that is not present in the system in which the case operates will be ignored. In the Discussion chapter the possible application of the found results and conclusions on ignored categories of hydraulic infrastructure will be discussed.

1.4.2. Interdependence

Interdependence is defined as follows: The fact of depending on each other (Cambridge, 2021). The term also refers to the idea that everything in nature is connected to and depends on every other thing. This means that for hydraulic infrastructure, an enormous list of interdependencies could be created, since the water that it works with influences the natural processes in the area which is in turn interdependent with every other thing in nature. From this list, many interdependencies will be so small that their influence is not or barely noticeable. This research will focus on the two levels of interdependence: functional and environmental.
For functional interdependence the emphasis will be on the influence that a hydraulic structure has on the functional lifetime that the other structures in the system have left. This form of interdependence is defined by Petit et al. (2015) as ”a bidirectional relationship between two assets where the operations of Asset A affect the operations of Asset B, and the operations of Asset B then affect the operations of Asset A”. This influence can positively or negatively affect the lifetime of the infrastructures, depending on the intervention that will be done.
For the environmental interdependence, it will depend on the case which factors will be taken into account. The project that serves as a case study will have objectives that are met by the intervention. These objectives could for example be increasing the navigability of the water system for fish, or to keep the groundwater levels at a certain level. The objectives that the selected case wishes to fulfill, and local interdependencies that have been identified will be taken into account in this research. The rest will be ignored.

1.4.3. Long-term

Throughout this research, there will be spoken of ’long-term’. long-term uncertainty and the fact that hydraulic infrastructure is planned for the long term are two examples. However, long-term can mean anything; ten years, a hundred years, a thousand years?
In this research when the long term is spoken of, it refers to the period that is as long as the average technical lifetime of hydraulic infrastructure. This is approximately a period of 60 to 120 years (TNO, 2021).

1.4.4. Use of scenarios

To assess the impact of climate change, scenarios will be used. In the first subsection of the literature review, there is commented on the accuracy and the uncertainty regarding the latest scenarios. They are however at the moment the most accurate ones available. For this study, the climate scenarios of the KNMI (2014b) will be used as a reference. They are the translation of the findings of the IPCC to the impact of climate change on the Netherlands. These four scenarios are used to assess the performance of the renewed structure on its own, but also in relation to the other structures.

1.5. Report outline

The next chapter will discuss the methods that are used to execute this research and to answer the research questions. Chapter 3 presents the obtained results from the first two sub-questions. In chapter 4 the case study will be presented and chapter 5 discusses the construction of the framework as well as the validation of it. The final chapter 6 presents the conclusion and discussion of the research.

2 Methodology

In this chapter, the proposed methods to answer the research questions will be discussed. This will be discussed per sub-question.

Below in Figure 2.1 the flow of the research can be seen. For each component of the research the aim is presented, as well as the methods to reach this goal.

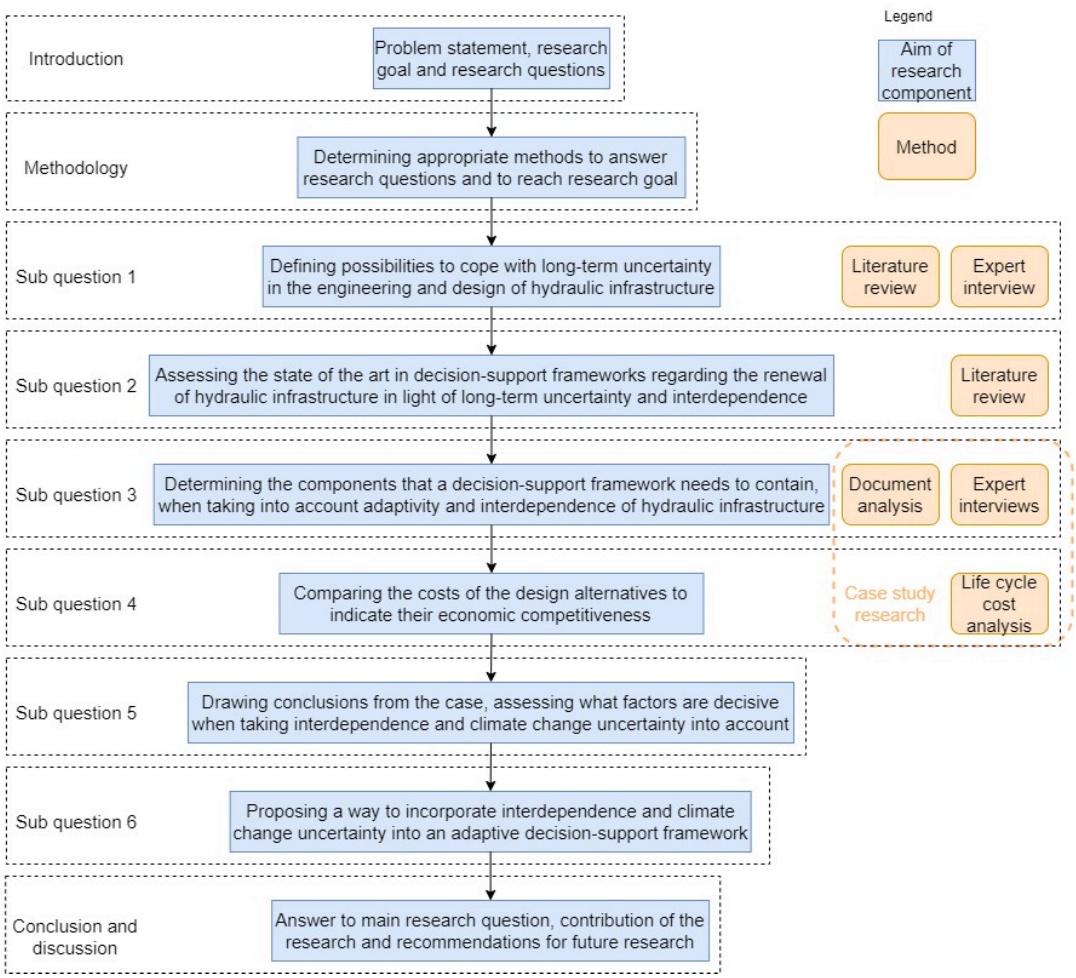


Figure 2.1: Representation of the research flow and the used methods

2.1. Methods for sub-question 1

What are the possible ways to deal with long-term uncertainty in designing hydraulic infrastructure?

The goal of sub-question 1 is to look at the ‘engineering side’ of the renewal of hydraulic infrastructure, and to see what possibilities are available to cope with long-term uncertainty. A distinction can be made between adaptive (with the possibility to alter components if needed) and non-adaptive (‘build it once and build it big’) design alternatives (Smet, 2017). The found ways to incorporate adaptivity into the design have been used to create additional design alternatives on top of the ones that were already present in the case study in chapter 6. These should according to literature be better equipped to deal with long-term uncertainty regarding climate change than the alternatives that were already there.

A literature study was conducted to answer this sub-question. Literature has been searched on the search engines Scopus and Web of Science. Main keywords to find literature were: hydraulic infrastructure uncertainty, water infrastructure uncertainty, adaptive infrastructure design.
Two methods have been used to expand the found body of literature: snowballing and citation searching. Snowballing refers to the usage of the reference list of a relevant paper that is found. The papers that it cites may also be relevant (RUG, 2021). Where snowballing goes back in time – the cited papers can only be from before the publication of that particular paper – citation searching goes forward. You can check which newer papers have cited that particular paper since it has been published. This may lead to relevant, more recent papers on the subject. To answer sub-question 1, 12 relevant papers have been found.

In addition to the literature study, an expert interview is conducted. The person that is interviewed is Dr. ing. Mark Voorendt. Mark Voorendt is a teacher at the TU Delft in the field of hydraulic structures and integrated design, at the department of Hydraulic Engineering in the faculty of civil engineering. This interview served as addition and verification for the information that has been found in the literature study, which is why only one person is interviewed for this sub-question. An addition to the literature review in the form of an interview is needed because only 12 relevant papers have been found and cited. The view of an expert helps in processing the information the right way. The reason why Dr. Voorendt is interviewed is because he is specialized in multi functional water-barriers. The case study has a multi functional nature (a regional water barrier, a pumping station, a sluice with a monumental status and a road that goes across it are all combined into one project) which makes Dr. Voorendt a fitting expert to interview.
The interview method of choice is a semi-structured interview. A semi-structured interview approach is preferred to a structured interview. This is because a semi-structured interview provides for a more open response and a possibility to explore certain statements by the interviewee that might be interesting (Clifford et al., 2016). This is of course done within the boundaries of the subject and the interview does adhere to an interview guide. This interview guide can be found in Appendix B. The transcript of the interview is not included in the appendix, but it is available on request.

2.2. Methods for sub-question 2

What is available in the literature regarding adaptivity and decision-support frameworks for the renewal of hydraulic infrastructure?

Sub-question 2 aims to provide an overview of the decision-supporting frameworks that are discussed in scientific literature with respect to the theory of adaptivity as a means to take uncertainty about climate change and socioeconomic development into account. Also, it is determined to what extent the influence of the structures on the other structures in the literature is taken into account.

This question is answered with literature research. Literature has been searched on the search engines Scopus and Web of Science. Main keywords to find literature were: adaptive decision making, decision-support uncertainty. Again, the search methods of snowballing and citation searching have been used. To answer sub-question 2, 26 relevant articles have been found.

2.3. Methods for sub-question 3

How can interdependence be incorporated into the decision-making process?

The goal of this research question is to go through a decision-making process that does incorporate interdependence and to see how the outcome of that process will differ from the outcome of the process that was run through in the original process. This has been done within the boundaries of the case study that is the new pumping station the H.D. Louwes in Zoutkamp. Additional design alternatives have been created, and the relevant interdependencies identified. All design alternatives are evaluated in terms of their influence on those interdependencies. Then, a new preferred design alternative with respect to interdependence and climate change uncertainty was selected.

2.3.1. Single case study research

This research has been performed under the scope of a single case study. In a single case study, the research allows for exploration and understanding of complex issues, through close examination of data within a specific context (Zainal, 2007). Yin (1981) defines case study research as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used." Because a single case study research very closely examines one real-life application of a theory, there are researchers that state that the findings of case study research can be difficult to generalize in a broader context (e.g. Verschuren and Doorewaard, 1998). Flyvbjerg (2006) however states that one can often generalize on the basis of a single case. It depends on the choice of the case.

The choice to perform this research as case study research is made because incorporating interdependence explicitly into the decision-making process is a new approach. Since it is a new approach, the research has an exploratory nature to see how interdependence and climate change uncertainty could be taken into account when deciding on hydraulic infrastructure renewal. And because of this exploring nature, the 'boundaries between phenomenon and context' that Yin (1981) mentions are not yet clear.
Interdependence is very difficult to evaluate without a case. This is because without the real world application that a case presents, the influence of infrastructure on interdependence is zero. To determine the factors that make up a category of interdependence, you need a case to see which factors play a role. After that is clear, the theoretical interdependence can be distilled from its degree of influence that is caused by the circumstances that are part of the case study.

2.3.2. Case selection

The case is a hydraulic infrastructure renewal project in the Netherlands, the pumping station H.D. Louwes in Zoutkamp. The reason to look at the Netherlands is that it's a country that has a very high average population density, of 512 persons living on a square kilometer (Worldbank, 2018). This density causes the fact that spatial planning in the Netherlands is a longstanding tradition that has to optimally use every available square meter. Renewing infrastructure has to take into account this scarcity of available space. In the Netherlands, many hydraulic structures such as weirs and pumping stations have been built between the 1920's and the 1960's (Willems et al., 2016). These structures function as components or assets in a Large Technical System that is the entire Dutch water network. These assets are aging and reaching the end of their technical lifetime. Furthermore, the Netherlands are experiencing drier summers and also extreme precipitation, which is cause for the ministry of I&M to announce extra funds for climate-adaptational measures (KNMI, 2018; UVW, 2020). These measures should create a shift in management strategies, going from discharging water as soon as possible to retaining water for periods of drought.

To select a case that is representative for the population, the same objectives as random sampling apply (Seawright & Gerring, 2008): 1) a representative sample and 2) useful variation on the dimensions of theoretical interest. For this research, a representative sample will mean a project of hydraulic infrastructure renewal. Useful variation on the dimensions of theoretical interest means for this research that multiple design alternatives have been created between which a choice has made. Furthermore, this indicates that the case needs to be situated in a system or sequence of hydraulic structures. This is necessary because otherwise there would be no functional interdependencies to analyze.

The case that has been chosen is the project of renewal of pumping station H.D. Louwes in Zoutkamp, in the province of Groningen. Its broad context will be elaborated on in section 4.1. It is a suitable case because it adheres to the two objectives that have just been mentioned. It is a project of hydraulic infrastructure renewal, which makes it representative. Also, there is a useful variation on the dimensions of theoretical interest. Already three design alternatives have been made from which the preferred design alternative was chosen. Furthermore, this research has created two additional alternatives which gives a total of 5 alternatives from which the new preferred design alternative has been selected. Additionally, the case is situated in both a sequence and a system of hydraulic infrastructure. This means there is sufficient functional interdependence, and that objective 2 of random sampling is also fulfilled.

2.3.3. Context of the case study

First, the context of the case has been sketched. Where is the project situated and what system does it operate in? Also, the problem that has been the cause for intervention is discussed, along with its proposed solution. The methods for this section are real world documents analysis, along with two open interviews. The interviewees are presented in Table 2.1.

Table 2.1: The two interviewees that were used complementary to the document analysis for context about the project and the possible present interdependence.

Name	Function	Company
Harry Grevers	Project manager	TAUW
Arne Roelevink	Hydrologist	Waterschap Noorderzijlvest

Harry Grevers is project manager on the project of the H.D. Louwes for the advisory company TAUW. He and his team are responsible for the development of the preferred design alternative into a prototype design, and after that into a detailed design. He knows everything there is to know about the design of the pumping station and its requirements.
Arne Roelevink is hydrologist for the water authority Noorderzijlvest and is an expert on hydrological matters within the Electra bosom.
Together these two interviews are considered a good addition to the document analysis for a comprehensive picture of the area. An open interview was chosen because there were not yet specific questions to be asked, but the context of the project needed to be discussed.

The documents that have been analysed can be distinguished into two categories. The first is general information about the water system that regional water authority Noorderzijlvest governs. These documents are listed in Table 2.2. Additional information about the water system has been obtained via contacts at Noorderzijlvest through their public viewer GeoWeb and the GIS shapefile with all water levels.

Table 2.2: Used documents of the first category

Title	Author	Year
Droge Voeten 2050	Waterschap Noorderzijlvest & Arcadis	2014
Beleid peilbeheer en peilbesluiten	Waterschap Noorderzijlvest	2018
Waterkeringbeheerplan	Waterschap Noorderzijlvest	2019
Jaarplan 2021. Inclusief meerjarige doorkijk	Waterschap Noorderzijlvest	2021

The second category consists of the documents that have been created by several advisory companies and Noorderzijlvest itself before and during the exploration phase of the project. The information in them describes the identified problem of the water system, as well as the proposed solution with the three present design alternatives. These documents have been made available to this research by both Noorderzijlvest as advisory company TAUW. The documents that have been used can be seen in Table 2.3.

Table 2.3: Used documents of the second category

Title	Author	Year
Droge Voeten 2050	Waterschap Noorderzijlvest & Arcadis	2014
Maatregelenstudie Droge Voeten 2050. Herberekeningen effectiviteit maatregelenpakketten	Arcadis	2016
Gemaal H.D. Louwes. Samenvatting Oriëntatiefase	Arcadis	2018
Capaciteitsuitbreiding gemaal HD Louwes. Haalbaarheidsstudie basisvariant	Witteveen & Bos	2019
Capaciteitsuitbreiding gemaal HD Louwes. Haalbaarheidsstudie voorkeursvariant	Witteveen & Bos	2019
Offerte aanvraag Nadere uitwerking VKA 'Nieuwe Waterwerken Zoutkamp	Waterschap Noorderzijlvest	2020

2.3.4. Identifying interdependence

After the context was described, the relevant interdependencies have been identified, for which the current and newly created design alternatives have been evaluated. These interdependencies have been collected by myself.
Three interdependencies have been identified. There may be more interdependencies that can be of influence within the water system (for example fish migration might be an interdependence as well), but these three are assumed to be the most important ones. That is because these three can be seen as universal interdependencies that are present in any (polder) water system. Furhtermore, these three interdependencies have been selected because they are not actually new. They are quite general water system management indicators that do structure the creation of design alternatives to some degree. They have however not yet been used as distinctive categories that are used to differentiate the design alternatives with.
The first interdependence (sequential interdependence) is described in literature (Vuren et al. (2015); Vuren et al. (2015); Zandvoort and van der Vlist (2020)). The second interdependence (balance interdependence) is derived from the underlying problem that has been the cause for intervention at the H.D. Louwes, through document analysis and an open interview with the responsible project leader of the H.D. Louwes project at consultancy firm TAUW. The third interdependence (environmental interdependence) is derived from the fact that the core business of a pumping station is regulating water levels, as well as an open interview with a hydrologist at Noorderzijlvest who was involved with the development of the Droge Voeten 2050 study.

2.3.5. Creating new design alternatives

New design alternatives are created that serve as an addition to the design alternatives that are already present. The new ones have been created by me, based on the principles of adaptivity and the answers that have been found on sub-question 1. This has been done with the KNMI'14 scenarios in mind, which will be discussed later in this chapter. The requirements for water safety are met with the new design alternatives. The requirements that are set by water authority Noorderzijlvest are listed, and have been acknowledged as a given. Navigability has been left out of the design. The reason for this is that the navigability is largely done for recreational purposes. During extreme weather events there will almost no recreational persons be navigating the waterways.

2.3.6. Evaluating the design alternatives

Both the current and the new alternatives are evaluated for two aspects: their adaptivity and their influence on the identified interdependence. Evaluating their adaptivity has been done by me, based on the present literature that can be found in sub-question 2.

Evaluating the design alternatives in terms of their influence on the identified interdependence has been done by experts.

In order to assess design alternatives' performance and influence on interdependence across their lifetime, we need to look into the future. How will the weather behave in 80 years? Do the design alternatives still do their job correctly? Or will there be so much rain in the future that the capacity of the new pumping station is too low?
Climate change is a factor that makes this more difficult. In a stationary climate, probabilities of certain precipitation- or drought events are known. If a pumping station is able to handle a downpour that occurs once every hundred years, then it will be too in the future. Due to climate change, those probabilities are no longer valid. The 'once in a hundred years downpour' can occur more often, and the actual new 'once in a hundred years downpour' can be much heavier.

In order to be able to account for the changing climate, scenarios are widely used. For the Netherlands, the best scenarios to use are the KNMI (2014b) scenarios. These are the translation of the worldwide IPCC (2014) climate change scenarios for the Netherlands. During the writing of this research, the next IPCC (2021) report has come out. It will however take until 2023 until the KNMI has made new local scenarios out of this 6th assessment report (KNMI, 2021). That is why for this research the KNMI (2014b) are still relevant.

The four scenarios that form the KNMI'14 scenarios can be seen in Figure 2.2. They are based on a rise in the global temperature and a change in the air current pattern. The rise in global temperature is represented by the large letters in the scenarios. The two classes are moderate (G) and Warm (W). The G-scenario assumes a rise in global temperature of +1 degree celcius in 2050, and +1.5 degrees in 2085. The H-scenario assumes a +2 degrees rise in 2050 and a +3.5 degrees rise in 2085. scenarios run up to the year 2100 in the forecast. But it represents 30-year averages, which means that 2071-2100 is the furthest sight-year period for which the year 2085 is used to refer to this period. The reference period to which the effects of the scenarios are compared is the climate period of 1981 - 2010.
The change in air current patterns is represented by the small letters in the scenarios. The two classes are low value (L) and high value (H).

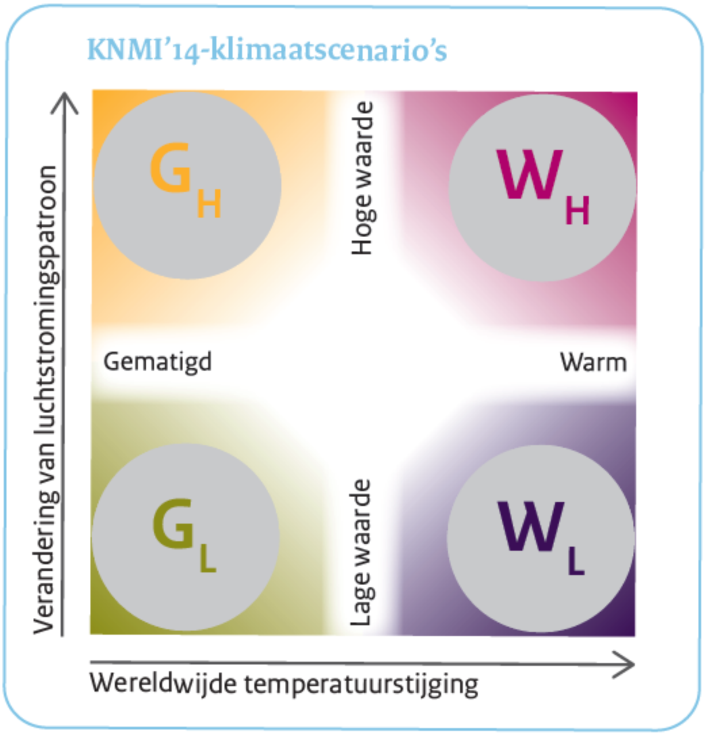


Figure 2.2: The KNMI'14 climate scenarios (KNMI, 2014a)

For the assessment of the influence of the climate scenarios on the water system, these scenarios are translated into precipitation-statistics by the STOWA foundation. With the volume, location of occurrance and duration stochastically determined the influence of extreme events in a water system can be calculated in a hydrological model. Noorderzijlvest has such a model. Design alternatives could be inserted and then their performance under a certain scenario could be calculated.
Quantitatively evaluating the design alternatives for the four scenarios would be the best option, giving the most reliable results. However, for the influence of the alternatives on the interdependencies the entire water system needs to be calculated, and is still subject to many uncertainties such as the assumption of no interventions anywhere else in the system but the one intervention that is analyzed, during the interview with Arne Roelevink of Noorderzijlvest it has turned out that this is a too complex task to complete within a Master thesis scope.

This is why the design alternatives have been evaluated in a qualitative manner. The influence of the six design alternatives on the three interdependencies has been evaluated by experts. During interview sessions of an hour with each expert, scores have been assigned to the alternatives. This has been done to not only assign a relatively simplistic score to the alternatives, but to also find out the reasons behind those scores. The experts that have been interviewed are the following:

Table 2.4: Experts that have evaluated the design alternatives

Name	**Function**	**Company**
Harry Grevers	Project manager	TAUW
Erik Korterink	Design leader	TAUW
Rob Bos	Technical Manager	Waterschap Noorderzijlvest
Eddi Ottens	Stakeholder Manager	Waterschap Noorderzijlvest

For each of the three interdependencies, a question has been formulated to which the experts were to answer with a score, which was discussed in the interview. The interviews were conducted in dutch. The three (translated) questions based on which the scores were assigned, are:

- Sequential interdependence: What is the influence of this design alternative on the moment that the infrastructure of the Lauwersmeer or the Cleveringsluizen needs to be altered or upgraded? Is this moment being expedited (- -, negative effect) or pushed back (+ +, positive effect)?

- Balance interdependence: What is the influence of this design alternative on the balance in the water system? Does water in the management area of the HD Louwes flow elsewhere (- -) or does it flow nicely towards the HD Louwes pumping station (+ +)?

- Environmental interdependence: What is the influence of this alternative on the manageability of the water level in the Electra bosom? (Also think about letting water in) Does the manageability of the water level get worse (- -) or better (+ +)?

All design alternatives have been assigned one score per interdependence. Two of the three newly created design alternatives, the Engineering and Modular alternative, are two alternatives that have been created with the aim of being adaptive. This means that depending on the actual development of climate change, these alternatives have different sizes and configurations. The interviewees have been asked to take this into account when assigning a score.

The scoring is done with a five-point scale, going from - - (very negative influence) to + + (very positive influence). The expert session is done one-on-one, where the expert is asked to motivate the reason behind the given score. These scores are filled in on a scorecard per interviewee. These filled-out scorecards can be seen in Appendix C.
At the beginning of the interview, a Powerpoint presentation has been given by me to tell about the research, what the interdependencies are and how to score, and to guide the interview. The slides of this presentation can be seen in Appendix C.

2.3.7. Selecting the preferred design alternative with respect to interdependence and climate change uncertainty

Once the possible solutions have been identified and all their interdependencies have been evaluated in light of long-term uncertainty, the solution that performs the best has been selected. The solution that performs the best is the one that still serves the initial problem that has been the motivation for renewal, and that has the most positive influence on the interdependencies. For each design alternative, the average of the 4 expert-assigned scores per interdependence will be calculated to determine the alternatives' overall influence on that interdependence. These scores will be presented in the final summarizing table. In the final table, each design alternative will have an average, on how well it performs across all three interdependencies. This final average shows which design alternative has the highest, which means that that design alternative performs the best when looking at its influence on interdependence.

2.4. Methods for sub-question 4

How do the costs of the design alternatives compare?

Next to the influence of the design alternatives in interdependence, do costs play a role in the selection of the preferred design alternative. One could make very nice and fancy alternatives that are very adaptive and resilient to any kind of climate change, but are they realistic options to implement? Can they compete, cost-wise, with the current design alternatives? To check this, an indicative cost calculation has been made.
This calculation regards the Life Cycle Costs of the design alternatives. In TAUW (2021), the variable costs that go along with different pump systems are analysed. They are split up into components that have investment costs, maintenance costs and a lifetime. The pump that has been chosen to use in the design of the pumping station is the horizontal pump, as was mentioned in one of the interviews. This pump type has been used in the calculation of the life cycle costs as well. The costs of each component can be seen in Table 2.5.

From this list of components, there are some that are dependent on the size of the pumping station and some that are not. The E-installation, PLC and hydraulic unit are independent of the size of the pumping station.
The pump, hatch and valve are dependent on the number of pumps that are installed. For three pumps, one would need $3 * €400.000 + 3 * €40.000 + 3 * €50.000 = €1.470.000$ in investment costs.
The civil construction below and above ground is also dependent on the number of pumps in the station, but their costs are not as linear as the pump, valve and hatch. For a pumping station with 4 pumping bays instead of 3 the civil construction costs are approximately 15% higher, as was discussed in one of the interviews.

Table 2.5: Costs and lifetime of the different components of the pumping station

Component	**Investment costs (€)**	**Yearly maintenance costs (€)**	**Lifetime (years)**
Pump incl. drive	400,000	2,500	30/60
Hatch	40,000	50	60
Valve	50,000	50	60
E-installation	1,500,000	500	30
PLC (hard- and sofware)	50,000	250	15
Hydraulic unit	150,000	500	30
Civil construction below ground	2,500,000	0	100
Civil construction above ground	500,000	800	100

The life cycle costs of the design alternatives have been calculated under three scenarios, which are based on the calculation that water authority Noorderzijlvest has used to determine the needed

capacity of the pumping station (Arcadis, 2016).
This calculation states that for the W_L-scenario for the year 2070, the needed capacity is 1600 m^3/minute. This means that the capacity-calculation has been done for the pumping station on the half of its lifetime, for a moderate-high scenario. So, climate change could turn out less heavy (the G_L- or G_H-scenario) or even heavier (the W_H-scenario). Based on this data, three rudimentary scenarios are developed to give an indication of how the costs would shift under different outcomes of climate change. These scenarios are the High, Low, and Middle scenario.

The Middle scenario assumes that the persons who calculated the capacity for the HD Louwes were exactly right: for its entire lifetime, so up to 2121, the maximum needed capacity is 1600 m^3/minute.
The Low scenario assumes that the calculations came to an exaggerated conclusion. For its entire lifetime, the HD Louwes only needs a capacity of 1000 m^3/minute. This is the same capacity as it theoretically has right now, but 300 m^3/minute higher than the practical capacity it has.
The High scenario assumes that the calculated capacity is not enough. Up to 2121, the capacity that will be needed is 2100 m^3/minute.
The increase of capacity is represented linearly, starting in 2021 at the highest capacity that the HD Louwes has pumped: 700 m^3/minute. From there the needed capacity goes up linearly towards the maximum needed capacity in 2121. The development of the scenarios can be seen in Figure 2.3.

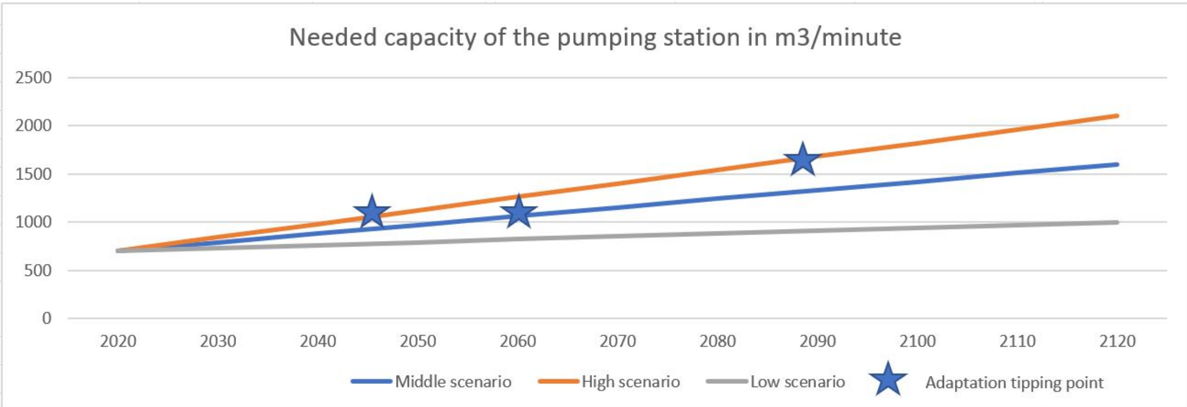


Figure 2.3: Development of the needed capacity in the different scenarios

In the development of the climate and the corresponding needed capacity, there are two moments where an adaptation tipping point will be reached. This concept will be further explained in subsection 3.4.1. These tipping points represent the moment when the current capacity of a pumping station is no longer enough. This happens when the needed capacity passes 1066 m^3/minute and 1600 m^3/minute. When this tipping point occurs, adaptation of the design alternatives is needed because the current capacity of (some of) the design alternatives is no longer sufficient. What the consequences of this are for the costs, is discussed in section 6.3.

For the calculation of the life cycle costs, two basic assumptions have been made. These are the following:

- Components that are part of the navigation lock or the sluice will not be considered in this calculation. Only components that relate to the pumping station are considered.
- Provisions to pump or let water back into the water system will not be considered in this calculation. The adaptation tipping points for such provisions are too fuzzy to determine, since they largely depend on policy decisions in the future regarding the water level on both sides of the pumping station, next to climate change.
  Only the basic job of the pumping station, pumping water out of the system, is considered in this calculation.
- It is assumed that the design alternatives will function as intended for their complete technical lifetime. Calamities or faster deterioration are not considered.

For the detailed calculations, some additional assumptions have been made. These are listed in section 6.3.

The results of this cost indication are coupled with the results from the scores of the alternatives with respect to interdependence. The goal is not to provide a detailed cost overview that is completely accurate, but to indicate whether the alternatives are on a comparable level with each other, and to see where costs can be saved.

2.5. Methods for sub-question 5

What is the impact on decision-making?

The aim of this question is to draw conclusions from the previous two sub-questions. Is there another design alternative that has come out as the most preferable? And what is the cause of that difference? The aspects that turned out to be distinctive are discussed.

2.6. Methods for sub-question 6

How could a decision-support framework that takes climate change uncertainty and interdependence into account look?

The goal of this research question is to propose a decision-support tool that could be used in other projects of pumping station renewal. The interdependencies that have been identified and the factors that are distinctive for those interdependencies are included, as well as the comparison of the costs. These will be presented in a conceptual model. The tool should be able to take the influence of hydraulic infrastructure on the selected interdependencies into account. With the framework, it will be possible to assess the functioning of design alternatives not only on their isolated functioning, but on their function regarding the other infrastructure as well, in light of long-term climate change uncertainty. The aim of the framework is to also be applicable in other projects of hydraulic infrastructure renewal, which means that the framework will generalize the findings from the research, if possible. The framework provides a handle on the important factors that should be considered when deciding on hydraulic infrastructure renewal. Costs are part of this consideration, but the costs of the different alternatives are complementary to interdependence, instead of the end goal of the framework. Also, it should help determine what drives a tipping point towards the choice for another alternative.
This framework is a proposal of how such a tool could look like, and which steps should be taken into account. It has not been evaluated for its generalizability.

3

Literature review

This chapter presents the results from the first two sub research questions:

1. *What are the possible ways to deal with long-term uncertainty in designing hydraulic infrastructure?*
2. *What is available in the literature regarding adaptivity and decision-support frameworks for the renewal of hydraulic infrastructure?*

Both of these will be answered with a literature review. Additionally, sub-question one will be supplemented with an interview.

3.1. Uncertainty regarding climate change impacts on the Dutch water system

The Intergovernmental Panel on Climate Change (IPCC) addresses the uncertainty about the impacts of climate change in their reports, of which the 5th report is the most recent (IPCC, 2014). It defines uncertainty as a lack of complete information, as well as incomplete knowledge or disagreement on what is known and knowable. To indicate how confident they are that the picture they present will happen, two indicators are used: How much evidence there is (limited, robust, medium) and how much agreement there is amongst cooperating researchers (low, high, medium). With robust evidence and high agreement, the IPCC (2014) states that the freshwater related risks of climate change increase significantly with increasing greenhouse gas concentrations. By the end of the 21st century, the number of people exposed to the equivalent of a 20th century 'once in a hundred years' river flood is three times as large when emissions continue to rise.

The reports present concise information about the impacts of climate change on, amongst others, fresh water resources. However, if one wants to know the impact on the Dutch water system, there are two issues. The first one is the high scale at which the IPCC operates. The findings that are presented are global findings, at the most detailed level looking at continents. The exact impact on the Dutch water system is not clear from the IPCC reports. The second issue refers to modeling. With each report (IPCC 1, IPCC 2, etc) the precision in modeling of climate change impacts improves, also in quantifying uncertainties. In this fifth report, for different levels of emissions, the differences in impacts are shown. However, what the levels of emissions will be in the next hundred years is completely dependent on the (lack of) effort to reduce those emissions. The climate agreements such as the climate agreement of Paris (UNFCCC, 2015) give some grip to see what the emissions could be, but there are many countries lagging behind in the reduction of emissions, amongst which is the Netherlands (HUMAN, 2021). This makes it uncertain what the impact of climate change on the Dutch water system will be. Furthermore, while the IPCC constantly improves its modeling skills, there is still some critique on its uncertainties from academics (Kundzewicz et al., 2018).

On a national level, the Dutch weather institute KNMI has constructed climate scenarios that translate the IPCC outcomes to its implications for the Netherlands (KNMI, 2014b). Four scenarios have been created as corner points between which climate change will most likely happen. For all four scenarios, warmer winters and summers are expected, as well as an increase of (extreme) precipitation during the winter. Also, the intensity of extreme precipitation in the summer will increase. This does create a direction for water managers to focus on in the future, but the actual impact is dependent on the scenario. However, the actual development of climate change remains unknown. 4 years after the construction of the scenarios, the KNMI released an article that stated that summers in the future might even be drier than anticipated (KNMI, 2018).
This combination of not knowing what the emission levels will be in the future with the already present uncertainty with respect to modeling the future creates a high level of uncertainty that planners, engineers and decision-makers need to be aware of.

3.2. Interdependent infrastructure

In an infrastructure system, there is always a matter of interdependence. Assets in the system are connected to the larger whole (Brown, 2014). Disruptions or improvements on a part of the infrastructure system will have effects on the entire system. In transport infrastructure, an example is spillback where congestion in one part (or link) of the infrastructure system will also hinder the flow on other roads (Knoop et al., 2008). In other infrastructures this is referred to as 'cascading failures'. Another transport infrastructure example is when the quality of one road is improved, it will attract more users and other parts of the system will become less used.
In hydraulic infrastructure systems, there is naturally a matter of interdependence as well. The assets that make up the infrastructure system (e.g. pumping stations, weirs, and sluices) are connected through waterways and disruptions or interventions do not only influence the asset that is disrupted or improved, but they influence every part of the system to some degree. Efforts to prevent flooding in one location might lead to extra inundation elsewhere in the system (Wang et al., 2018). Or a pumping station with a high capacity can pump away so much water that it actually partially does the work for another pumping station as well, which can lead to problems elsewhere in the water system (this issue is cause for intervention in the case study in chapter 4).

The fact that (hydraulic) infrastructure systems are interdependent is not new. In assessment of infrastructure systems robustness or resilience this is addressed (e.g. Baroud et al. (2015)). However, it is of growing importance. The cause of this is climate change (Val et al., 2019). Climate change is likely to lead to an increase in extreme weather phenomena (Trenberth, 2011). The actual probabilities of those extreme weather events to happen are difficult to calculate, because it depends on the actual extent of global and local warming of the temperature. More and higher extremities make interdependent infrastructure systems more vulnerable (Wilbanks and Fernandez, 2014; Val et al., 2019). During heavier extreme weather events interdependencies that may not have been thought of when implementing hydraulic infrastructure renewal, or that were not considered an issue, may become an issue. When increasing the capacity of a pumping station, the next pumping station downstream may at the moment still be sufficient to meet safety standards for flooding. But in the case of more and heavier precipitation due to climate change, the pumping station downstream may not be able to handle the extra volume of water that is pumped up by the new pumping station, on top of the water in its own polder bosom. This can result in flooding, damages and cascading impacts across the infrastructure system (Undorf et al., 2020). For hydraulic infrastructure renewal, it is growingly important that the intended design solution does not only solve the local issue. While this is still important of course, the effects of that particular solution should be assessed with regards to the possible implications of climate change. This way one can be confident that the intended intervention does not cause or even worsen problems elsewhere during extreme weather events.

3.3. Sub-question 1: Possible ways to deal with long-term uncertainty in designing hydraulic infrastructure

This section presents the answer to the first sub-question. It looks at the different possibilities that are available in the literature regarding engineering solutions to deal with long-term uncertainty. The first concept that is discussed is Options Theory, the second concept is modularity.

3.3.1. Options theory

A possibility to be able to adapt to unforeseen changes in the future when designing and implementing hydraulic infrastructure is to make use of Options theory. The concept of financial options has been used and modified to serve (hydraulic) infrastructure renewal tasks. This is the so-called Real Options theory, which later has been modified again into Engineering Options (Smet, 2017).

Real Options (RO) analysis provides a rational means to decide on the most effective options to maintain expected performance of the system and when to implement these options (Gersonius et al., 2013). On a strategic level, the placement of possible interventions across time has similarities with Adaptive infrastructure planning, which will be further elaborated on in section 3.4.
RO has originated from financial stock options. An option gives the holder the right to buy or sell a share for a previously set price at or before a predetermined moment in time. This provides the opportunity for the option-holder to wait and see how the external processes develop. If the share price increases, the option-holder can still buy the shares for the previously lower price. The option-holder can also decide to do nothing, and only lose the initial purchasing cost of the option. This strategy makes sense in an environment where uncertainty plays a large role; if there is no uncertainty about the future, then an option would make no sense to buy since the investor can already confidently buy or not buy.

This concept of financial options has been modified to 'real' options, which encompasses 'real world' investments, such as investments in infrastructure projects. Trigeorgis (1996) defines RO as "the right but not the obligation to change a project in the face of uncertainty" (pp 124). This approach provides a more dynamic way of looking at projects, where they are traditionally static of nature: Invest in this pumping station or not, where the investment does not change.
While this does create a more flexible environment for investment decisions for (hydraulic) infrastructure projects, the focus of RO is on managerial and strategic thinking. 'Real In Options' (RIO) analyses are the application of RO to infrastructure (re)development projects, where the options relate to the technical characteristics of a system (de Neufville, 2004). RIO has been used to quantify the added value of building flexibility into infrastructure systems. This way it can be found out which of the flexibilities are worth their added additional cost to the construction cost of the project. An example of such flexibilities is disconnecting back roof drainage, upsizing storage facilities in an urban drainage system (Gersonius et al., 2013).
While RIO presents a way to assess the value of built in flexibilities in hydraulic infrastructure, it is mainly concerned with infrastructure systems as the article of Gersonius et al. (2013) illustrates. In for example an urban drainage system there are many small parts that can be quite easily replaced. When looking at a single piece of hydraulic infrastructure, it can be more difficult. A pumping station needs to have a certain minimum capacity, and accounting for future uncertainty most likely results in simply oversizing the facility. This is not a very cost-effective solution. Smet (2017) refers to this approach to hydraulic infrastructure design as "build it once and build it big" (pp 6). Dr. ing. Voorendt refers to the oversizing of the facilities as an ethical paradox. The oversizing of facilities is often regarded as an ethical approach because you will definitely be safe. Dr. Voorendt argues that this can also be seen as unethical, because all the extra money spent on safety margins that you do not need could have been spent usefully elsewhere, increasing safety. In order to be more cost-effective, it is better to be flexible.

So the Real In Options approach looks at the technical aspects on a system-level. Another distinction in Real Options is RO 'on' Projects and RO 'in' Projects (Martins et al., 2015). RO 'on' projects deals with the infrastructure as one system, and is generally applied when market factors are responsible for the largest part of the present uncertainty. RO 'in' projects refers to the specific planning and design of separate infrastructures. This looks more on the technical side instead of the investment side. These names look so much like each other that the term Engineering Options has been coined to avoid confusion (Smet, 2017). This is the same as RO 'in' Projects, and it is also similar to the concept of 'flexibility in design' (Chester & Allenby, 2019). In a proactive way, the technical components of a single structure are thought of when considering long-term uncertainty. For example: if the pumping capacity may need to be increased in the future, how do I design the pumping station right now so that will be possible? A possibility, as Dr. Voorendt mentions, is building an extra pumping bay, but not installing a pump. It could be 30 of 40 years before you need that extra pump. Not installing it yet will save on maintenance costs, and there could be much better pumps available for the same amount of money when the time is there to install it.

Thinking in Engineering Options requires a proactive attitude to see which options can be purchased beforehand. It is not realistic to simply include options for all possible scenarios, since that might even be more expensive than building a non-adaptive/flexible design and to modify that in the future. Thorough analysis is needed to assess which uncertainties play a role at the location of the asset that will be built or renewed. For the prevailing uncertainties, the cost-effectiveness of the options should be weighed with scenarios. In how many scenarios is there a need for realizing the option (heightening the levee), and how much does it cost? Also, how much will it cost if the option is not built in beforehand? This trade-off can be analysed and based on this analysis the choice can be made what to implement. Several researchers (e.g. Woodward et al., 2014; Hino and Hall, 2017) have compared a flexible strategy with options with inflexible, static approaches to water management issues. Hino and Hall (2017) conclude socioeconomic scenarios do not have very much influence on what the protection level should be of flood-risk management infrastructure. Climate change scenarios however do have a strong influence. For the flood protection costs and benefits, they state that the upfront investment of flexible options in infrastructure design is justified. Woodward et al. (2014) found that investment strategies that took both managerial and physical options into account performed better than those that only considered managerial flexibility. de Neufville et al. (2011) states that flexible designs allow system managers to build small initially, which can create tremendous savings - far greater than the cost of enabling the flexibility.

3.3.2. Modularity

In order to create Engineering Options that are cheap and efficient, modularity of hydraulic infrastructure design can play a role. Hydraulic infrastructure is custom built. For a pumping station, an analysis will be conducted on the needed pumping capacity. An architect will create a design that fits in the surroundings of the location and an engineer makes sure it works. While this has its advantages, it comes at the expense of flexibility. It is a project with a start and a finish that will look and function this way for the next 100 years. Successful infrastructure in the twenty-first century needs to be agile and flexible (Chester & Allenby, 2019). Modularity and economy of numbers in infrastructure design can provide the flexibility that is desired when creating Engineering Options (Dahlgren et al., 2013). The engineering options can be custom made as well, but standardized modules are likely to be cheaper, if they are mass-produced. For a pumping station this can refer to prefabricated pumping bays or prefabricated pumping engines. If a certain capacity for a pumping station is needed, the required number of bays and engines can simply be ordered. Extra bays could be installed without engines as an engineering option. If needed, the engines can easily be installed. One could also simply reserve extra space next to the station if the need for capacity expansion arises. Then an additional module can be installed relatively cheap.
This does however ask for preparations beforehand. Dr. Voorendt notes that you cannot simply add or remove modules as you wish, but that this can only happen within the boundaries of what the foundation can handle. So if one would like to create a modular pumping station, where for example extra pumping modules can be added later, then the foundation needs to be able to carry this expansion. A proactive approach is needed to research the range of capacities that the pumping station might need in the future, and to create a proper foundation.

According to Wuni and Shen (2019), construction has to adhere to some factors for modular construction to be preferable over the traditional approach. These include a skilled labour force that can manufacture and install the modules, as well as a skilled management team. While knowledge and skill is inevitably important for the correct installation and management of modular infrastructure, it is not a deal-breaker, since every field of production and construction needs skill and experience. It can however be a signal that workers need to be educated to work with modular infrastructure. When thinking about the amount of hydraulic infrastructure that needs to be renewed in the coming decades, it may very well be a good investment to focus on standard, mass-produced modules. These investments can in the long-term be cheaper than creating custom solutions for every renewal project.

The matter of investing beforehand is not limited to a skilled workforce. For modular infrastructure to be economically competitive, it relies on mass production of modules which makes them relatively cheap. For mass production to be worth the upfront investment costs, there needs to be a sufficient demand for those modules. When looking at the upcoming renewal task in the Netherlands (TNO, 2021) and perhaps in other countries (the recent flooding in parts of Belgium, Germany and the Netherlands this summer may be an incentive for new watermanagement strategies to prevent damage and fatalities in the future), one can expect a high demand. This does however ask for a completely different approach to building of hydraulic infrastructure. The decision needs to be made to switch from custom built infrastructure at each project to implementing these mass-produced modules. This is quite a big decision to make, which may encounter resistance from regional governments which will be hampered in their independence, as well as from market parties that profit from the custom building of each piece of infrastructure. Also the mass production and distribution of the modular infrastructure need to be set up from scratch, which requires a very large and costly supply-chain operation, from which the profits will only become clear over the course of years.

3.3.3. Answer to sub-question 1

In literature about flexibility towards (hydraulic) infrastructure design, the bulk of the literature is focused on modeling and decision-support frameworks that advocate a flexible or adaptive management of hydraulic infrastructure, instead of looking at flexibility in the civil engineering of the structure itself (e.g. Guthrie, 2019). Regarding flexibility, there are two main concepts that can contribute to the agile and flexible infrastructure that is needed in the twenty-first century, according to Chester and Allenby (2019). These are Engineering Options, which presents a clarification from the overlapping terminology in the research field of Real Options. Modularity is the second concept. Modularity which stands for standardized units that are mass-produced and that can easily be installed together, can help to create proactive Engineering Options that are relatively cheap and easy to implement. It does however ask for a completely new approach and logistical chain for it to be economically viable.

The sub-question *what are the possible ways to deal with long-term uncertainty in designing hydraulic infrastructure?* can be answered as follows: by proactively thinking about the performance that a hydraulic structure needs to deliver across its complete technical lifetime, and how that may differ from the function and performance that it has at the moment of construction, Engineering Options can be developed. These can either be custom made or modular units, which depends on what fits better in the situation in which the project is located.
Next to the adaptive design alternatives that include engineering options, static/ non-adaptive design alternatives may still be better. It is important to develop both and to assess what is a better fit in that situation. This is dependent on the cost, as well as on the local consequences of uncertain climate change.

3.4. Sub-question 2: Decision-support frameworks for the renewal of hydraulic infrastructure

This section answers the second sub research question, with the use of a literature review. First, it is discussed when the moment of renewal of hydraulic infrastructure comes to light. When the need for renewal has become apparent, strategies and alternatives for the renewal have to be created. The second paragraph elaborates on how this can best be done, and what factors need to be taken into account. Finally, once enough strategies and design alternatives have been created, the final decision has to be made on which intervention is going to take place. The last paragraph discusses how this decision can best be made, and what decision-support tools there are. A conclusion will in the end answer the sub question.

3.4.1. Determining the moment of renewal of hydraulic infrastructure

At the foundation of every project of (hydraulic) infrastructure renewal, lays the decision that the infrastructure in question needs to be renewed. It has been deemed unfit to continue the way it has done until now. This decision can be caused by many events, for example an inspection that shows that the structure does not adhere to current or future safety standards. This decision, or moment in time, is referred to as an *Adaptation Tipping Point* (Kwadijk et al., 2010). When an adaptation tipping point has been reached, it means that a different management strategy is needed. It can be useful for efficient and cost-effective hydraulic infrastructure management to estimate when adaptation tipping points are likely to be reached in the future. This allows for proactive and preventive thinking about renewal options. But how can you determine when an adaptation tipping point will be reached?

The first to introduce this concept are Kwadijk et al. (2010). Under different climate change scenarios the effectiveness of water management strategies is assessed. The moment in time where the water management strategy is not sufficient anymore to adhere to the set standards or goals, a tipping point has been reached. In light of hydraulic infrastructure the concept of adaptation tipping points has been expanded by van der Vlist et al. (2015) to also include structural deterioration and socioeconomic developments as drivers to reach a tipping point. Brown et al. (2020) use the same principle, but they have reformulated a driver as 'utility of losses' and a tipping point as a 'threshold that the utility has to pass' that indicates the need for transformation of a structure.
Kallen et al. (2013) have created a method to actually estimate when a tipping point will occur. The functional lifetime is estimated with scenarios, the technical lifetime with a probabilistic model. There is a difference in the methods because the technical end-of-life of structures is largely known. When a pumping station is built, it is aimed to last 100 years. Due to individual differences such as the speed of the degeneration of concrete, a probability density function can be determined for the technical end-of-life. The functional end-of-life is more fuzzy, dependent on factors that are much more uncertain and for which it is very difficult to find a proper probability density function. That is why scenarios are used for the functional end-of-life. They conclude that the functional end-of-life will in most of the cases sooner be reached than the technical end-of-life. van Vuren et al. (2017) have developed a more sophisticated way to estimate the functional end-of-life. This can be calculated for each structure in the water system, if the correct data is available.

The above paragraph shows that the moment at which hydraulic infrastructure is in need of renewal can be estimated. The next step is determining what type of renewal you want to implement. The next paragraph will look into this matter.

3.4.2. Determining the possible types of interventions

When an adaptation tipping point has been reached, it is clear that something needs to be done. But how can you determine *what* to do? Given the long technical lifetime of hydraulic infrastructure, long-term uncertainty arises. For efficient investments, it is desirable that the built infrastructure functions as intended for its complete technical lifetime.

In the spatial planning domain, the proposed mechanism to cope with uncertainty is the theory of adaptivity (e.g. Gupta et al., 2016; Rauws and De Roo, 2016) as mentioned in the introduction. With adaptive planning, a long-term strategy is set after which short-term decisions are made within that long-term vision. This allows the decision-maker to adjust to unforeseen changes, and to use the most recent knowledge available at that moment. The practice of creating boundaries within which a number of spatial developments is allowed to happen as time progresses, has many suitable applications in urban development. In for example a neighborhood there is time for zonal development. The concept of adaptivity can be analogously explained with the journey of a ship Rahman et al. (2008). Before the journey, the destination is determined and the rough course is set. Upon embarking on the journey circumstances (like the weather) can change. So, the policy - the specific route - is changed along the way. Some contingency plans may already be ready for some unpredictable events. The ultimate goal remains unchanged.
An adaptive policy would include a systematic method to monitor the environment and to gather information. Over time, pieces of policy would be implemented. The moment for adaptation can be determined by signposts, that signal certain change when it passes a threshold (Raso et al., 2019). In

spatial and infrastructure planning, these policies that can be implemented over time can be viewed in *Dynamic Adaptive Policy Pathways* (Haasnoot et al., 2013). Figure 3.1 presents a visualization of these pathways.

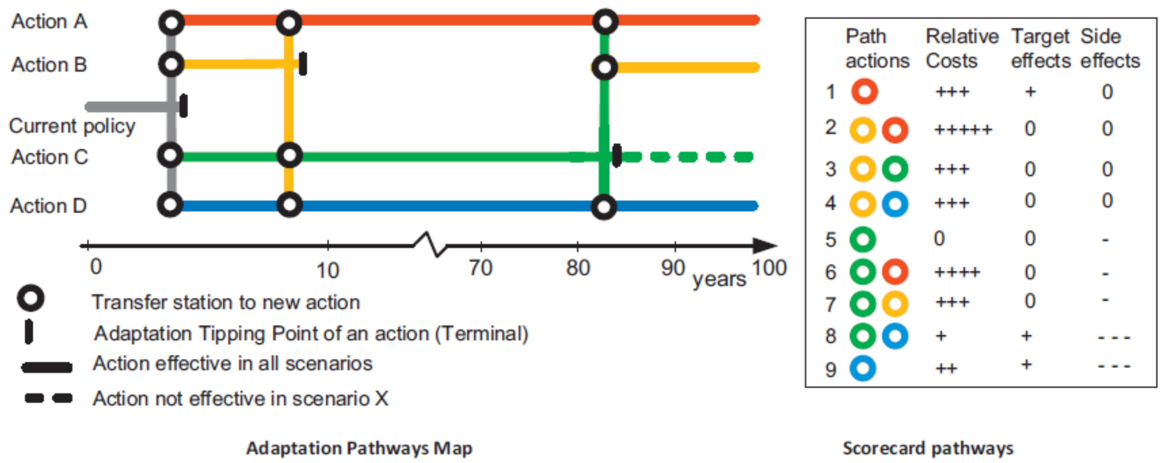


Figure 3.1: Adaptation Pathways (Haasnoot et al., 2013)

The long-term objective can be something like staying below a flood-risk threshold or above a certain groundwater level. To reach the goal different actions are created. Then their effectiveness in the future can be assessed with scenarios. Some policies may be effective under all scenarios, which are likely to be large and robust solutions. These do probably however cost more and may be less desired by the public because of their appearance. Some policies may turn out not to be effective anymore to reach the long-term objective under certain scenarios. Then an adaptation tipping point will be reached and a transfer to a different policy is needed. These transfers form the pathways in which there can be switched between policies. The relative cost of these pathways can be assessed. Relative cost does not have to be monetary, part of it can also be the opinion of the public for example. Based on that, the most desired pathway can be specified.

For hydraulic infrastructure planning, most planning frameworks that are presented in the literature are based on adaptation tipping points and *Dynamic Adaptive Policy Pathways* (e.g. Bernardini et al., 2014; Vuren et al., 2015; Restemeyer et al., 2017). Dynamic adaptive policy pathways are the translation of the theory of adaptivity (adaptive policymaking) to a strategic plan for hydraulic infrastructure management. Constructing the pathways provides insight into the different possibilities for intervention. These possibilities work on three levels.
The first one is the most classical one, which are the design alternatives for an intervention (*what* are we going to do). These are most often on the location where the hydraulic structure that is in need of renewal is situated. In a *project-based* approach (Busscher et al., 2014) this is the most dominant one. A renewal task of hydraulic infrastructure is considered as an isolated project with a start- and end date, focused on renewing the structure on that spot for just the purpose that has been identified. Adaptive planning presents a *programme-oriented* approach, where a broader view on the possible options is maintained to serve the programme (flood risk management or groundwater preservation). The second and third level of intervention are more programme-oriented. The second level refers to the location of the intervention (*where* are we going to do something). Is the same location still the best location for an intervention to solve the specified issue? The third and last level refers to the moment of intervention (*when* are we going to do something). Perhaps a small reparation to deal with the urgent issues is sufficient for now, and can a large-scale renovation better be done later. The moment that an Engineering Option is added is also one of these short-term actions. The location is predetermined, as well as the type of intervention. The moment of adding this Option can vary.
An issue with the implementation of a programme-oriented approach is the matter of costs. A project has a clear start and an end, in between which the costs and income are clear. A programme has a more continuous character of management. Costs that are made can be fuzzier, which creates the

risk of excessive costs. Furthermore, keeping a continuous programme running across time will cost more anyway than a temporary project. For the progrmme-oriented approach to be accepted, the higher costs need to be substantiated, and it needs to become clear that it may be cheaper in the end because of the money that does not have to be spent for large adjustments due to unforeseen circumstances. A matter of a single asset that needs to be renewed can be viewed as a 'mini-programme' instead of a project of renewal. This perspective may save costs in the long run.

When creating (adaptive or non-adaptive) design alternatives, interdependence plays a role as well. As explained in section 3.2, this has to a certain extent always been a factor that needs to be taken into account in (hydraulic) infrastructure planning. Just as increasing the capacity of a highway segment will lead to a bottleneck at the location where the road becomes narrower again, does increasing the capacity of a pumping station lead to a higher discharging demand of the pumping or discharge station downstream. Efforts to prevent flooding in one location may lead to extra inundation in another location (Wang et al., 2018). However, the changing climate is responsible for the fact that interdependence is becoming more important than it was before.
In a climate that is stationary, the rate of occurrence of extreme weather events is known, and is lower than in the changing climate in which we live (Val et al., 2019). The changing climate is the cause for interdependent infrastructure systems to become more vulnerable (Wilbanks & Fernandez, 2014). During heavier extreme weather events, interdependencies that may not have been thought of when implementing hydraulic infrastructure renewal, may become a problem. When increasing the capacity of a pumping station, the next pumping station downstream may at the moment still be sufficient to meet safety standards for flooding. But in the case of more and heavier precipitation due to climate change, the pumping station downstream may not be able to handle the extra volume of water that is pumped up by the new pumping station, on top of the water from its own polder bosom. This can result in flooding, damages, and cascading impacts across the interdependent infrastructure system (Undorf et al., 2020). When coming up with solution directions for the renewal of hydraulic infrastructure, it is important that the interdependence of that particular piece of infrastructure with the larger system is taken into account, also when selecting a preferred design alternative.

The next paragraph discusses the availability of options to evaluate the created design alternatives, and how one can choose the alternative that is the best fit for the needed renewal at hand.

3.4.3. Adaptive decision-support frameworks for the renewal of hydraulic infrastructure

The above section presented the theory of adaptivity with regards to hydraulic infrastructure renewal, as well as the need to address interdependence in the design of alternatives. Critical notes towards the paradigm of adaptivity are given by Smet (2017), who calls this type of management a reactive 'wait-and-see'-mentality, and Pot et al. (2018), who says that the frameworks that are created in literature are more concerned with how alternatives should be explored, instead of how specific solutions are chosen. The persons responsible for a renewal project are in need of clear decision-support tools based on which they can confidently choose an alternative or a pathway.

In literature the question of addressing uncertainty in decision-support frameworks has been addressed in the last decade. Pot et al. (2018) and Pot (2019) evaluated forward-looking decisions, in other words to what extent decision-makers consider the future when making investments. From policy analysis, a framework has been created that helps shape forward looking plans. Scenarios play an important role in preparing for the future.
The use of scenarios is found in most of the literature that aims to build adaptivity into the decision-making process. The reason for this is because of climate change, probabilistic occurrences of natural phenomena are not accurate anymore. If the climate changes, then the historic rate of occurrence of for example heavy droughts does not say anything anymore about its rate of occurrence in the future. Gersonius et al. (2013) acknowledge this fact, but they still use a probability density function in order to determine the value of flexibility in infrastructure design. The reason why is because they expect future knowledge to adjust the probability distributions in the future. While this may be true, it may also be not important anymore in the future since the infrastructure will then already be built, based on the value that is assigned with the current probability densities. All other articles discussed in this section

make use of scenarios.

Most of the adaptive decision-support frameworks are based on the notion of adaptation pathways, discussed in the above section (Vuren et al., 2015; Pot, 2019; Haasnoot et al., 2020; Brown et al., 2020). Haasnoot et al. (2020) have adapted their own adaptation pathways model to also be able to monetarily compare different pathways, instead of the more rudimentary comparison of relative costs. Their adjusted model can be seen in Figure 3.2

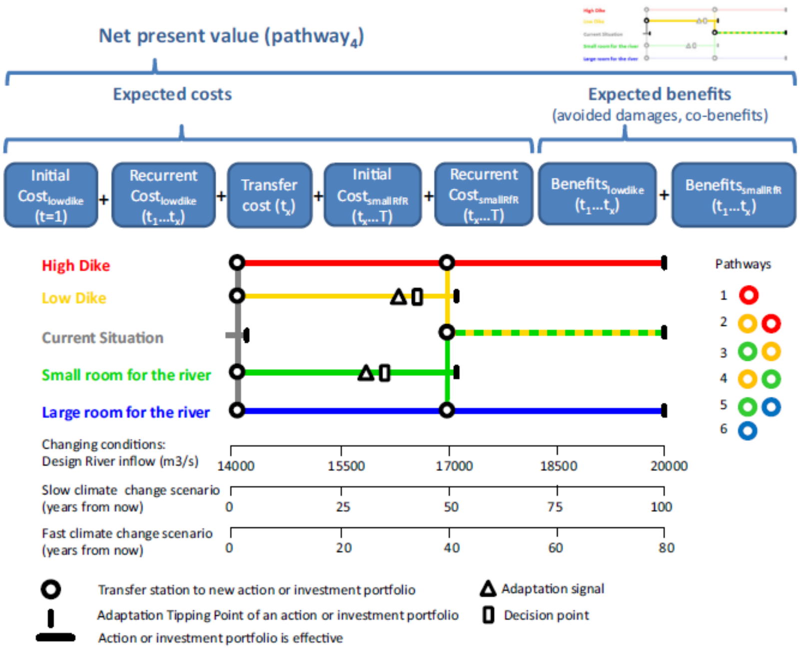


Figure 3.2: Economic evaluation of Adaptation Pathways (Haasnoot et al., 2020)

Pot (2019) does not present a monetary model, but specify a set of criteria that decision-makers should take into account. Brown et al. (2020) present a numerical framework, based on utility. The performance of the system is monitored, and when the utility passes a threshold then transformation of the system design is initiated. This is actually simply another way of saying when an adaptation tipping point has been reached and a new policy or action needs to be implemented.

There are also decision-support frameworks that are not based on adaptation pathways but that do aim to be adaptive and flexible. These are based on Options Theory (Gersonius et al., 2013; Yzer et al., 2014; Smet, 2017; Hino and Hall, 2017; Woodward et al., 2014). This concept has already been discussed in the previous sub-question, and the general idea is to proactively seek out functions or expansions of the infrastructure that may be needed in the future. An 'option' can be acquired through engineering flexibility into the design or by keeping the option in mind during the water management in the future. The cited decision-support frameworks are used to compare flexible/ adaptive designs or strategies with non-flexible designs. From this comparison it can be assessed which strategy or intervention is the best fit for the specified problem. It does not always have to mean that flexible alternatives are better. It can still be that a non-flexible alternative performs quite well in the given scenarios, and that any costs of renewing the structure in the future are still less than creating a fancy, flexible solution right now.

As discussed in the above paragraph, does interdependence play an increasing role in the resilience of hydraulic infrastructure systems, due to climate change. Because of this increasing importance, it was stressed that when creating design alternatives and when deciding between those alternatives, the relevant interdependencies need to be taken into account. From the literature regarding decision-support frameworks discussed here, the conclusion can be drawn that this is not the case. The infrastructure that is to be renewed is treated as an isolated piece of infrastructure when the decision is made for the preferred design alternative. The performance of the new asset itself is solely looked at, and what these possible interventions mean for the rest of the infrastructure system in terms of interdependencies is ignored. Vuren et al. (2015) are the only ones that look at the influence of an intervention on the functional lifetime of other infrastructures in the system, be it only if there is a positive or negative influence. While this is a start, a more detailed approach is needed to accurately assess an intervention's influence on the rest of the system. van Vuren et al. (2017) have created a way to determine the functional end-of-life of hydraulic structures, as mentioned in subsection 3.4.1. This can be used to assess the influence of interdependencies of design alternatives in light of climate change.

3.4.4. Answer to sub-question 2

This sub-question has explored the literature that is available regarding hydraulic infrastructure renewal, and how a decision on what kind of intervention to implement can be made or supported. The moment at which the functional end-of-life of a hydraulic structure is reached can be determined using the concept of *Adaptation Tipping Points*. van Vuren et al. (2017) have created a method that can estimate the number of functional years that are left.

When an adaptation tipping point has been reached, strategies for the renewal of the hydraulic infrastructure can be created with the use of *Dynamic Adaptive Policy Pathways*. This provides a framework in which the long-term functioning of hydraulic infrastructure is the goal. As time progresses the long-term uncertainty becomes less uncertain and with that new knowledge adaptations between possible actions or alternatives can be made. Dynamic adaptive policy pathways, and adaptive planning in general, help create design alternatives that can vary in the moment of renewal, the location of renewal, and the type of renewal.

With adaptive decision-support frameworks, the created alternatives for the renewal task can be compared with each other and based on that comparison the desired alternative or pathway of alternatives can be selected. There are numerical and monetary frameworks available that can help justify an investment. Some are based on adaptation pathways where a sequence of possible interventions is compared. Other frameworks are based on *Real/Engineering options* where flexible engineering is compared with non-flexible engineering, as well as flexible management strategies versus non-flexible strategies.

So, there is a present body of literature regarding the renewal of hydraulic infrastructure and what the best practices are. One thing that is however overlooked is the interdependence of one hydraulic structure with the rest of the infrastructure. Renewal tasks and the literature that discusses it focuses on the performance of hydraulic infrastructure itself. Does this one structure fit in the long-term strategy and how does it function in light of long-term uncertainty? The influence of the new structure on the rest of the infrastructure does however influence the performance of the entire water system and may create bottleneck situations elsewhere.

3.5. Conclusion

From the literature review in this chapter, it can be concluded that there are several ways to deal with long-term uncertainty regarding the renewal of hydraulic infrastructure on different levels of implementation. On the design and engineering level, flexibility can be built into the design alternatives with Engineering Options and modularity providing flexibility to adapt to future needs. This is more costly in the initial stage but this pays off when the structure needs to be adapted. Deciding between adaptive and non-adaptive design alternatives can be done with several decision-support frameworks, based on Options Theory or Adaptive Pathways. There are some differences between these two paradigms but they also have a lot in common, which is strategically placing investments over time and thinking about the functioning of a structure over its complete technical lifetime. Based on the findings in this chapter, the new design alternatives have been created to be more flexible to cope with future uncertainties.

From this review it has become clear that the interdependence of hydraulic infrastructure is an aspect that is yet to be incorporated into decision making. This research aims to contribute to that with

the case study that is presented in the next chapters. Due to the large amount of literature present that advocates adaptive decision-making, the choice has been made based on this chapter to incorporate interdependence into an adaptive decision-support framework.
The found ways to design flexible design alternatives from sub-question 1 have been used to create additional design alternatives that do contain flexibility. When the relevant interdependencies are identified, then the influence of the found design alternatives on these interdependencies in the water system can be determined. Then it is assessed what this means for the selection of the preferred design alternative.

4

Case study description: Pumping station H.D. Louwes at Zoutkamp

In this chapter, the case study will be discussed. First, the case and its background will be introduced. Then the process that has led up to the current preferred design alternative is discussed. Next, the relevant interdependencies are presented, and for each interdependence will its presence in the water system of the H.D. Louwes be discussed.

4.1. Background of the case study

Zoutkamp is a village in the north of the Netherlands, in the province of Groningen. It is situated right behind the former sea dike. Behind this dike lies the Lauwersmeer, a former estuary that has been closed off from the sea in 1969 and that is now a freshwater lake. The Lauwersmeer serves multiple purposes: It is a national park with protected nature and touristic value, and it serves as a water buffer towards which parts of the provinces of Groningen, Drenthe and Friesland pump water from their polders. Situated in the dike that separates the Lauwersmeer from the sea is a sluice complex. During low tide, the sluice gates can be opened if necessary and excess water is discharged into the sea. The pumping station 'H.D. Louwes', built in 1973, is one of the two pumping stations on the side of Groningen that pumps the water from the hinterland into the Lauwersmeer. Its capacity has been deemed too low, and construction works are required to increase it.

4.1.1. The water system in which the H.D. Louwes operates

The water system in which the H.D. Louwes operates is completely governed by the Regional Water Authority Noorderzijlvest. It covers the western part of the province of Groningen and the northwestern part of the province of Drenthe. The H.D. Louwes operates in the Electra polder bosom, which is named after the former regional water authority Electra which has merged into Noorderzijlvest.
The Electra bosom is situated completely below sea-level. Because of subsidence of the land, it has been divided into three layers (also called shells). Starting from the lowest layers, water keeps getting pumped up a layer until it is pumped into the Lauwersmeer, after which it can be discharged into the Wadden sea. The H.D. Louwes pumping station is situated on the third layer, at the edge of the Lauwersmeer. Figure 4.1 shows a map of the water system that is the responsibility of water authority Noorderzijlvest, and the different layers. A schematic overview of the Electra bosom and its layers can be seen in Figure 4.2.
Next to the H.D. Louwes there is another pumping station that pumps water from the third layer into the Lauwersmeer. This is the Waterwolf, which is located at the hamlet of Electra. It has been built in 1920 and it is a historical monument. It is situated in the Reitdiep river, which is the largest river (a former sea arm) that connects the city of Groningen and the Lauwersmeer.

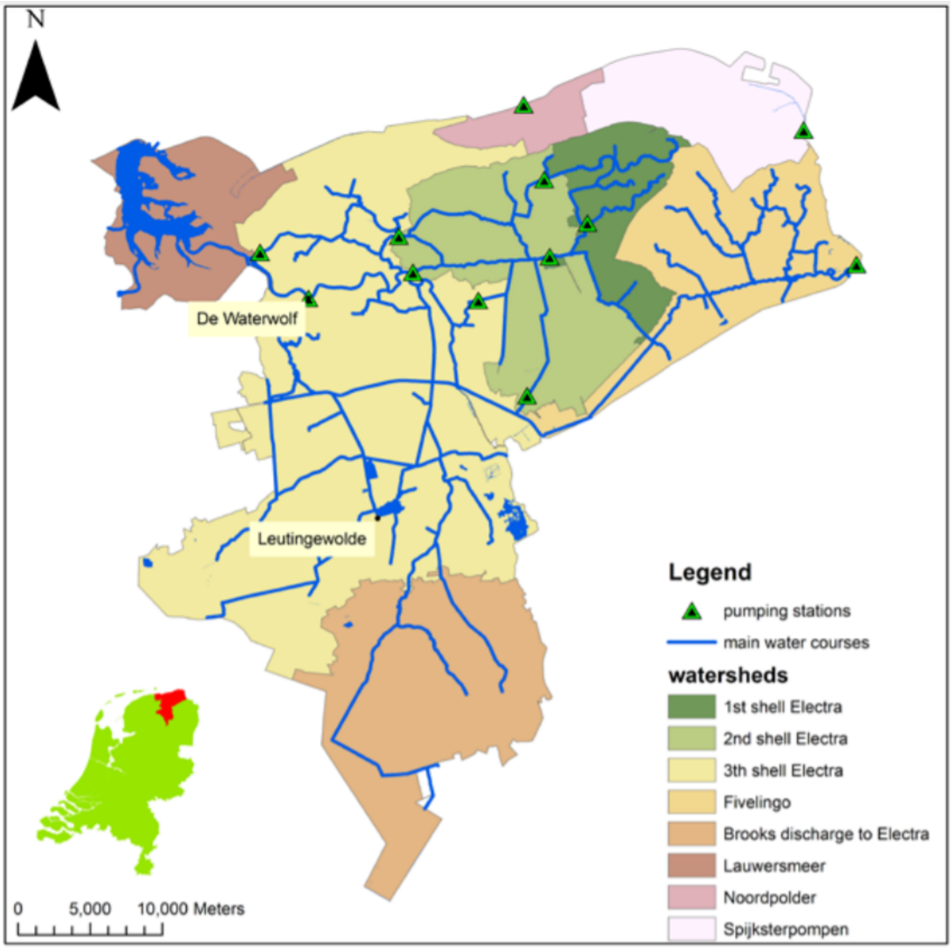


Figure 4.1: Map of the different polder bosoms that are the responsibility of water authority Noorderzijlvest (Deltares, 2015). The Fivelingo, Noordpolder and Spijksterpompen areas do not discharge into the Lauwersmeer and are not part of the Electra bosom. The displayed name of Leutingewolde is not relevant for this research and can be ignored.

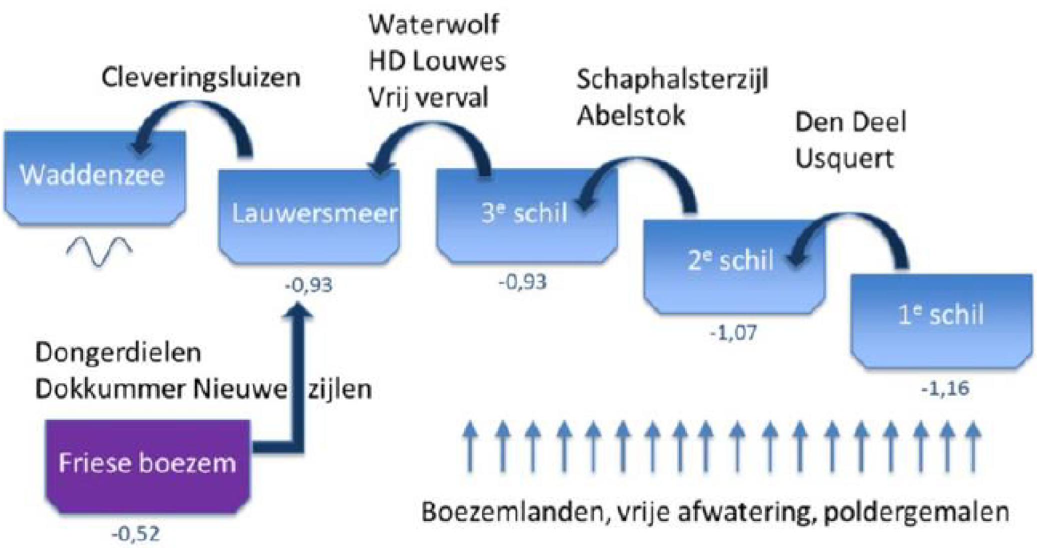


Figure 4.2: The layers of the Electra polder bosom (W. Noorderzijlvest, 2020)

4.1.2. The problem

In order to remain resilient against the changing climate, Noorderzijlvest has performed a study in collaboration with water authority Hunze en Aas and consultancy firm Arcadis in which the measures that need to be taken in light of climate change are shown (Arcadis, 2014). This study has shown that in the southern part of the third layer (the large green area on the map), the situation will not meet the standards anymore for certain calculated events. The pumping station the Waterwolf has a high capacity of 4500 m^3/ minute (NGS, 2021), which should be sufficient. The issue however, is that when there are extreme precipitation events, water will flow from the northern part of the bosom (which is the responsibility of the H.D. Louwes) towards the Reitdiep, where it is pumped away by the Waterwolf. These parts are connected with a small river, which causes this skewness in the discharge of water. Figure 4.3 shows a map of the situation.
In order for the Waterwolf to pump away the water from the correct area, the intention is to create a structure in the problematic river that can be closed during situations in which pumping is needed. The H.D. Louwes pumping station will then be fully responsible again for the northern part of the third layer. But for it to do that, its capacity needs to be increased to 1600 m3/minute (Arcadis, 2018). The watershed for which the H.D. Louwes is responsible can be seen in Figure 4.4.

The problem stated above is illustrative of the growing importance of interdependencies as the climate changes. The Waterwolf has been built in 1920, and the H.D. Louwes in 1973. The course of the rivers has not changed since. This means that this skewness in discharging has been present since 1973. For almost 50 years this has never been an issue until the consequences of climate change for the Electrabosom were calculated. Now it turns out that because the Waterwolf partially does the work for the H.D. Louwes, and part of the area which is the Waterwolf's own responsibility is not in agreement with safety norms anymore when looking at the precipitation in the future and measures need to be taken.
The H.D. Louwes is almost 50 years old. With the design age of pumping stations of approximately 100 years, it will have only served for half its intended lifetime. If the discharging interdependence of these two pumping stations had been known before the H.D. Louwes was built, it may have led to other intervention choices which would serve for its complete intended lifetime, or at least longer than half.

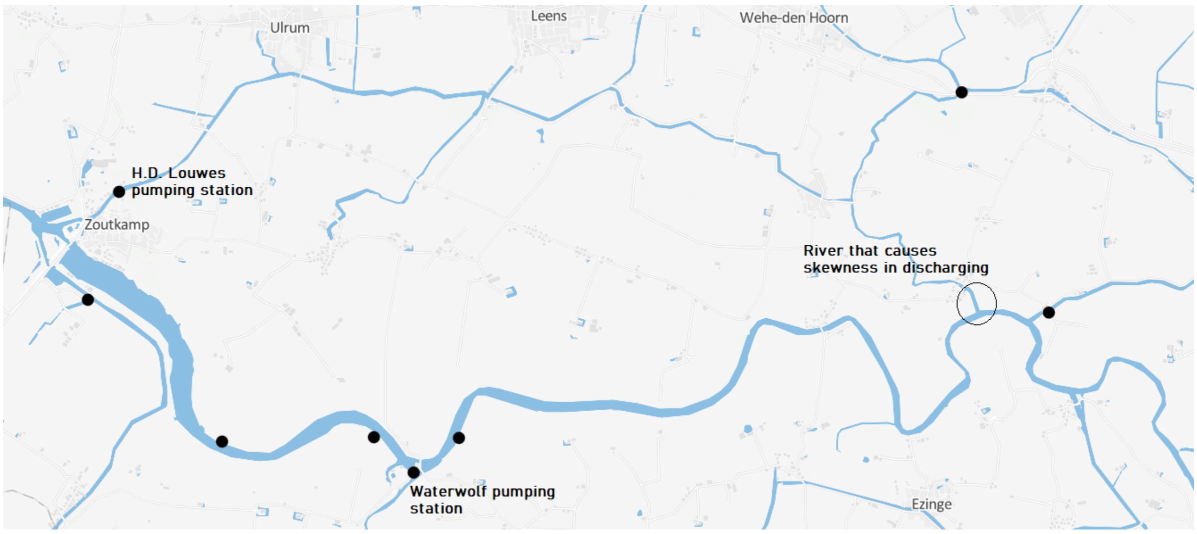


Figure 4.3: The situation that causes the skewness in discharging

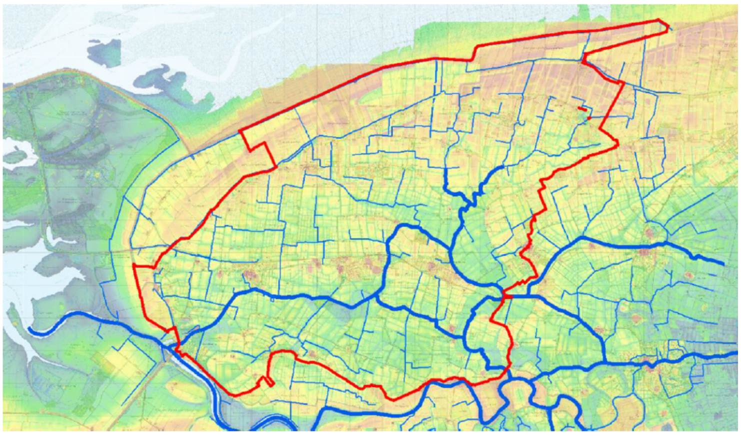


Figure 4.4: The water system in the third bosom layer for which the H.D. Louwes is the pumping station towards the Lauwersmeer (Arcadis, 2018)

4.1.3. The current situation at the H.D. Louwes

The H.D. Louwes pumping station is situated in the Hunsingo-channel. It has a theoretical pumping capacity of 1000 m^3 per minute, which in practice is never utilized because the building will suffer from vibrations that can cause damage (Arcadis, 2018). The actual capacity that was measured during the period of high water in 2012 was 708 m^3/minute. The water is pumped into the channel which goes through the monumental Hunsingo sluice, which is situated in the former sea dike and is always opened, into the Lauwersmeer. The needed capacity expansion will not fit within the current building. Next to the pumping station, there is a sluice which is part of the dike system around the Lauwersmeer, and which needs to be closed when the pumping station is in operation. An identified issue with this is that this poses a barrier for navigability for boats because this barrier is closed on between 20 - 40 days in the boating season. There have been ideas to transform this sluice into a navigation lock but because of a lack of money, this has never been realized. Figure 4.5 shows the location of the current pumping station. The regional dike system around the Lauwersmeer is undergoing construction as well. The pumping station is part of it, and from there the dike goes through the village of Zoutkamp. These regional dikes are too low and need to be heightened. The issue however is that heightening the street that functions as water barrier to a height of 1,40 meters +NAP evokes local resistance.

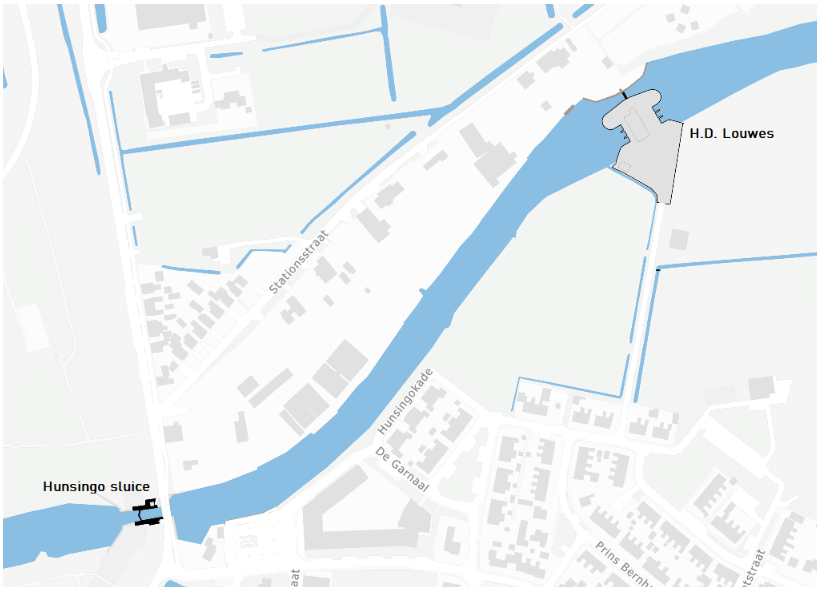


Figure 4.5: The location of the current H.D. Louwes pumping station in Zoutkamp

4.2. The proposed solution

In order to realize the needed extra capacity, three design alternatives have initially been developed in the exploration phase between which a choice has been made (Arcadis, 2018). These are the original design alternatives and they will be discussed in this section. The design alternatives that have been created additionally for this research will be presented in the next chapter. All three alternatives include a provision for closing of the river Kromme Raken near Schouwerzijl, the river that is discussed before as an issue for proper water discharge.

4.2.1. Design alternative 1

The first design alternative is the most basic one: The pumping station will get a higher capacity at the location that it is situated at the moment. The sluice will remain a sluice. The regional water barrier around the Lauwersmeer will keep going through the town of Zoutkamp. The existing building will have to be demolished and built up new. This is because there is no space for the expanded capacity. Also, the regional water barrier goes through the building and the floor is too low according to the safety standards for the regional water barrier. A schematic representation of the first design alternative can be seen in Figure 4.6.

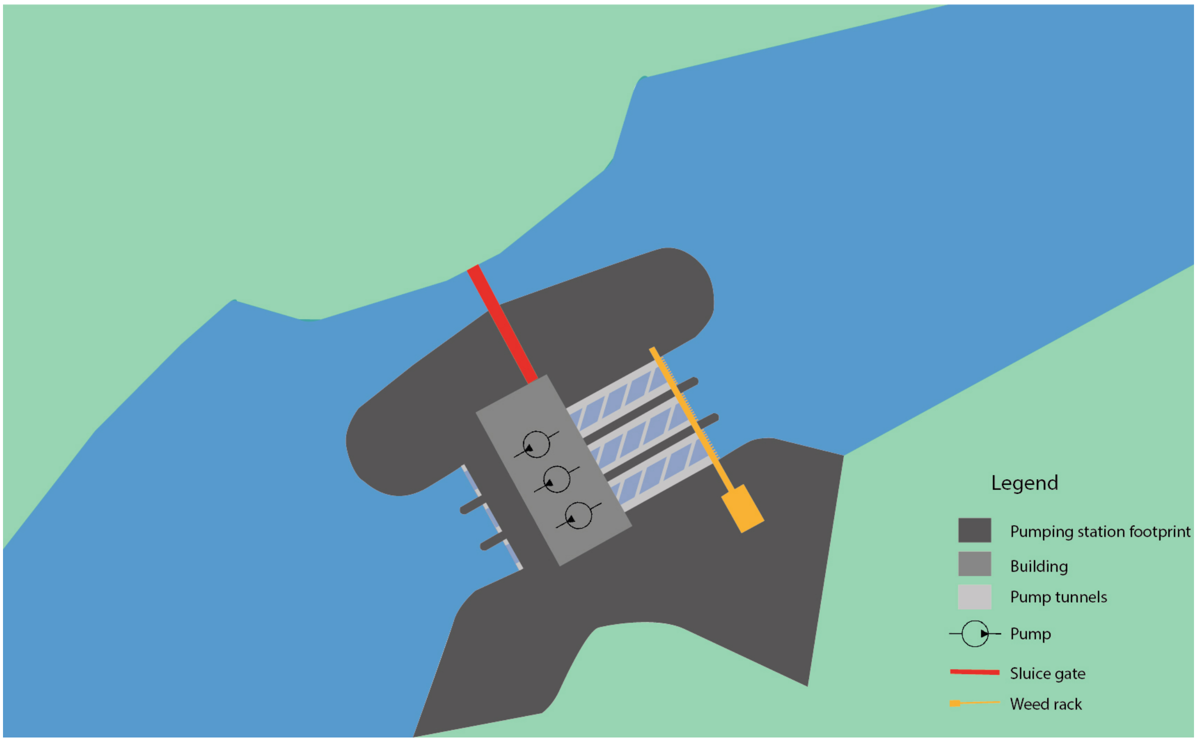


Figure 4.6: Schematic representation of design alternative 1 (own production).

4.2.2. Design alternative 2

Design alternative 2 is quite similar to alternative 1. The existing building will be demolished and a pumping station with the needed capacity will be built at the same location. In addition, the sluice will be converted to a navigation lock. This will solve the bottleneck issue of the navigability of the Hunsingo channel when the pumping station is in operation; boats can still go through the lock. A schematic representation of the second design alternative can be seen in Figure 4.7

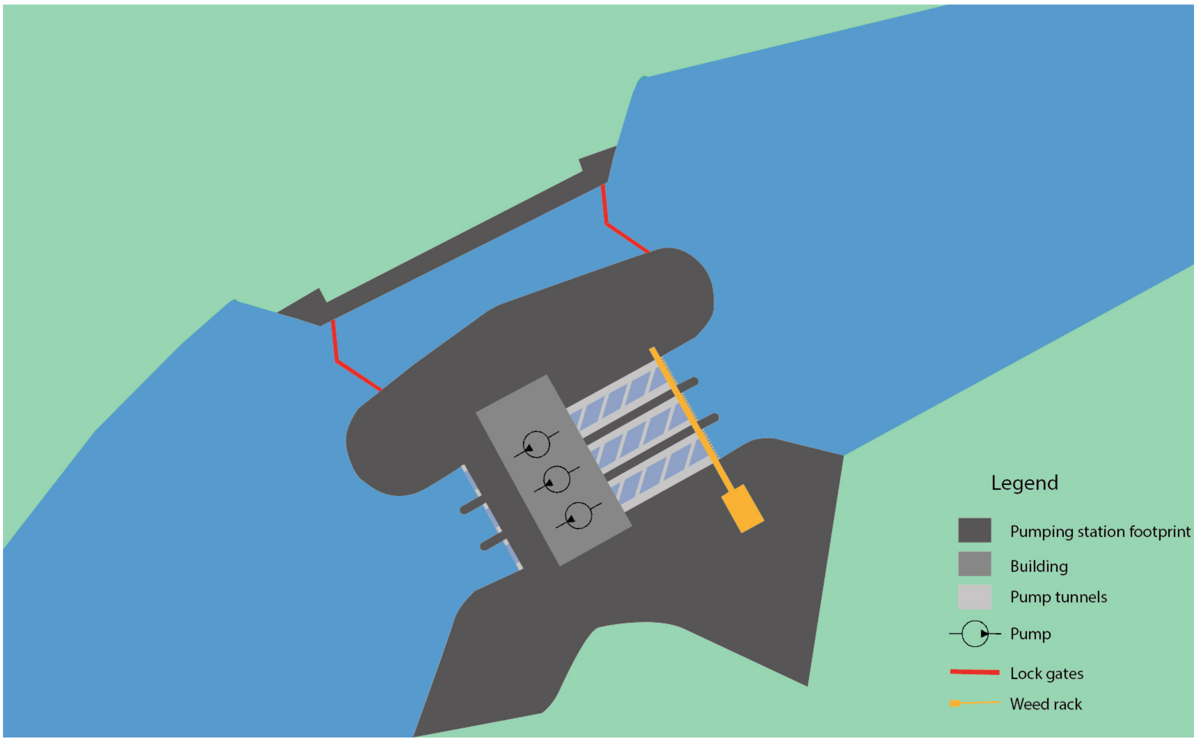


Figure 4.7: Schematic representation of design alternative 2 (own production).

4.2.3. Design alternative 3 - the preferred design alternative by Noorderzijlvest

The third design alternative that has been developed is also the preferred design alternative by Noorderzijlvest. Next to the monumental Hunsingo sluice, a new pumping station will be built into the former sea dike. The former sea dike will regain its water-repelling function, as it will function as the regional water barrier around the Lauwersmeer. The regional dikes through the village will expire. The Hunsingo sluice will be refurbished and transformed into a navigation lock. Even though this is a more expensive design alternative, it has the preference because it combines several issues at play. A visual representation can be seen in Figure 4.8

The decision-making process that led to the choice of this design alternative did not depend on tools such as a cost-benefit analysis. The analyses that were done beforehand determined the necessary capacity of 1600 m^3/minute. All three design alternatives have that capacity, and in terms of water-safety benefits, design alternative 1 would have been chosen, since it is the cheapest. Design alternative 3 is the most expensive option, but still it is the preferred one. This is because, as said, it combines several issues at play and it will be relatively cheap to handle these issues right now instead of later. These opportunities can enhance livability and touristic opportunities in the area. The fact that this alternative is the most expensive does not mean that water authority Noorderzijlvest pays all that money. The project of renewal for the pumping station facilitates the combined construction, but the local municipality, province and other stakeholders have to pay their part (Noorderzijlvest, 2021b).

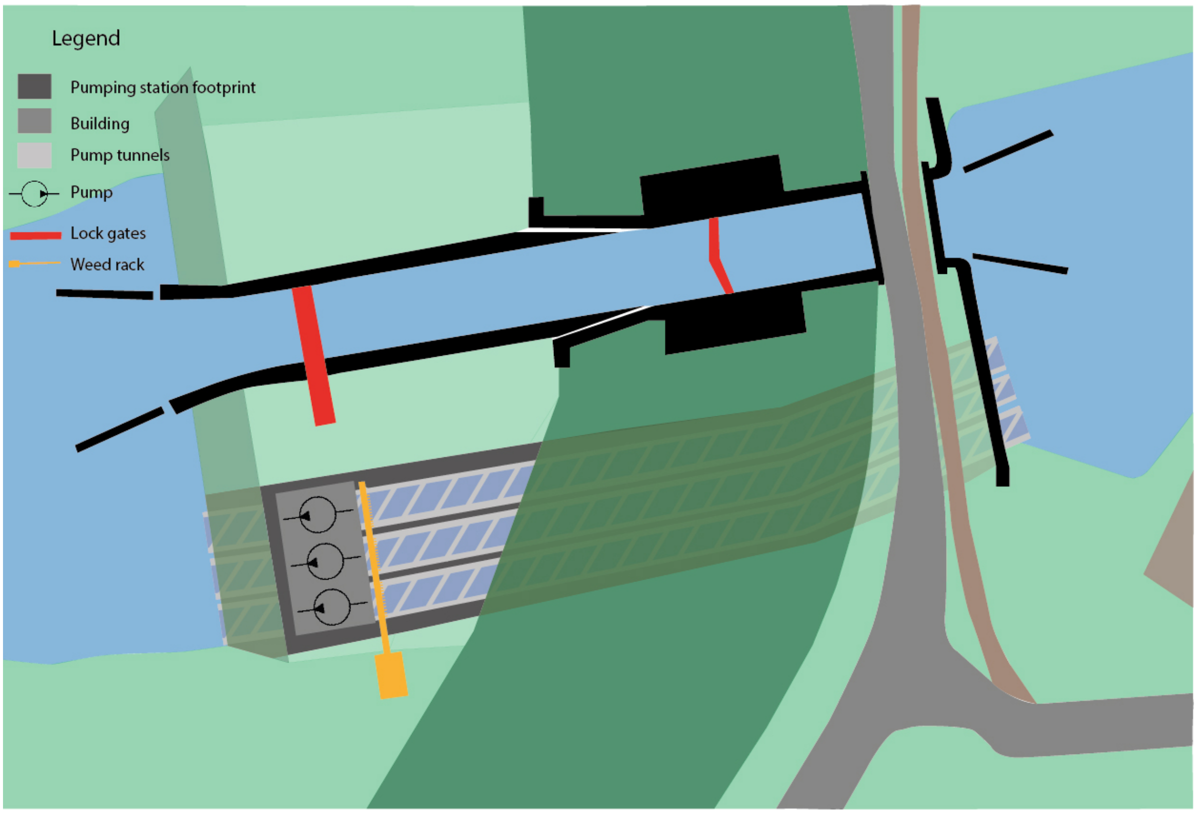


Figure 4.8: Schematic representation of design alternative 3 (own production).

5

Identifying interdependence and creating new design alternatives

In this chapter, the items that will be used in the analysis are presented. First, the relevant interdependencies will be discussed, as well as their presence in the Electra polder system. Then the new design alternatives that have been created are displayed.

5.1. Identifying interdependence

In order to be able to take interdependence into account when looking at the renewal of hydraulic infrastructures, the relevant interdependencies need to be identified first. This will be done in this section. As mentioned in subsection 2.3.4 have these interdependencies been collected through literature, interviews and document analysis.
For hydraulic infrastructure, the different kinds of interdependence have not been coined yet in literature. Vuren et al. (2015) refer to this interdependence as the influence on the functional lifetime, which can be translated into functional interdependence. However, all three interdependencies that will be mentioned are of influence on the functioning of a pumping station, which makes them three sub-categories of functional interdependence. That is why in the following paragraph new names will be given to the interdependencies.

While there are more interdependencies that can be identified (fish migration across the water system for example is also influenced by such a renewal task), only three interdependencies are presented below. This is because these three came floating up when researching literature and researching the context of this case study. How they were found is explained at each separate interdependence. They can be seen as universal interdependencies that are present in any (polder) water system, which makes them the most important to consider first. They are not new, they are quite general water system management indicators for which there already is knowledge. They have however not yet been used as integrated factors for hydraulic infrastructure renewal.

After they are discussed in their general presence, in the next paragraphs these interdependencies will be discussed more in detail within the case study. This discussion will treat the water system (all layers of the Electra-bosom) as it is now, which means without implementation of the renewal of the H.D. Louwes yet. The goal is to draw a picture of how the identified interdependencies are present in this system. Later on in this chapter, the influence of the created design alternatives on these interdependencies will be analysed.

5.1.1. Relevant interdependencies

In a water system, there are several interdependencies present that will change when a renewal of hydraulic infrastructure is implemented. There is some difference between water systems as well; a polder system such as the one in this case study functions differently from for example a river that flows freely from a higher elevation towards the sea. There are differences in the present infrastructure in those systems, and different water management goals. New interventions serve those goals and they influence the interdependencies.

In a water system that is comprised of polders, pumping stations are the most important pieces of infrastructure. Without them, the lowest parts of the polders would simply fill with water, since a polder system transports the water upwards, against its natural flow. The polder system in this case study consists of 3 layers, as mentioned before. These layers are instated because there is a difference in height of the land present. This difference is increasing because of land subsidence due to natural gas extraction in the area.
These three layers cause a sequential way of pumping away water. The water in the first layer is pumped up with pumping stations towards the second layer, where it is the responsibility of the pumping stations of the second layer, on top of the water that is already present in the second layer. This continues to happen until the water has reached the sea.
Each pumping station has a certain capacity. If a new pumping station is implemented, it is sized on the amount of water in its own hinterland (the layer in which it operates plus the lower layers) that needs to be pumped away. However, this resizing also has its implications for the next pumping station(s) or infrastructure in the sequence, which need to be able to cope with the extra water.
This kind of interdependence will be called **Sequential interdependence**. As with the other interdependencies it is not a new phenomenon, but in light of climate change uncertainty it may become an issue in the future. This interdependence is mainly described in literature when the matter of interdependence is discussed (Vuren et al., 2015; van Vuren et al., 2017; Zandvoort and van der Vlist, 2020).

The second kind of interdependence is present *within* a polder layer or bosom. In the area of the layer, the waterways are connected to each other. If there are multiple pumping stations present, the pumping station that is the most powerful might create a flow of water towards itself (differences in land height can contribute to this happening). This may cause issues elsewhere in the system if there is not a proper balance between the pumping stations.
This kind of interdependence will be called **Balance interdependence**. This interdependence has been the cause of the planned interventions. The presented documents in subsection 2.3.3 plus the in subsection 2.3.3 mentioned open interview with the project leader at engineering company TAUW that provided context of the project have been the sources for this interdependence.
The Waterwolf is so powerful that it partially does the H.D. Louwes' job as well. This creates an imbalance across the third layer of the Electrabosom. This imbalance is cause for problems in another part of the third layer when applying new precipitation patterns due to climate change. Creating a separate system in the north for which the H.D. Louwes is the only responsible pumping station should restore the balance in the system.

The above two kinds of interdependence are both types of *functional* interdependence, as discussed in the Introduction. To some extent, there is also an interaction between them. An example: Based on the water balance in the second layer, the choice can be made to which part of the third layer most of the water will be pumped. This balance can be changed according to the desired flow of the water. This in turn has an influence on the respective sequential interdependence of the pumping stations.

The third and last kind of interdependence that is considered relevant is **Environmental interdependence**. What is meant with environmental interdependence is the influence of the water level in the system on it environment. There is a water level that is considered ideal for the different kinds of land use that are present in the water system such as nature and agriculture (the respective ideal water levels are not necessarily the same). This level is artificially preserved by the water level managers (peilbeheerders). The infrastructure that is needed for the water levels is managed by pumping stations, as well as (small) weirs. When looking at the changing climate, how can this level be preserved if there is more precipitation? Will the pumping stations run at low power for a very long time? or how will the system react in the case of extreme drought? Is the infrastructure capable of dealing with drought? The current freshwater supply basin in times of extreme drought for the regional water authority Noorderzijlvest is the IJsselmeer (Noorderzijlvest, 2019). Perhaps could the Lauwersmeer also be used for such purposes, if the infrastructure and the system are equipped accordingly.
This interdependence is derived from the fact that regulating the water level is the core business of a

pumping station, and from the open interview that was mentioned in subsection 2.3.3, with a hydrologist at water authority Noorderzijlvest that provided context.

5.1.2. Sequential Interdependence in the Electra system

As discussed in the previous paragraph, is sequential interdependence the influence of the asset that will be renewed on the other assets in the sequence. As said before and as shown in Figure 4.2, does the sequence of the Electrabosom comprise of three layers. These layers use pumping stations to transport water to the next layer. When transporting water to the sea in the final step, discharging sluices are used. In Table 5.1 the pumping stations are listed, together with relevant information that can be used for assessing the influence of renewal on the pumping stations (Noorderzijlvest, 2021a).

Table 5.1: The pumping stations that are in sequence in the Electra bosom system

Name of pumping station	Type	Location	Construction year	Capacity (m^3/min.)
Usquert	Drain pump	Border of 1st to 2nd layer	2014	160
Den Deel	Drain pump	Border of 1st to 2nd layer	1993	630
Schaphalsterzijl	Drain pump	Border of 2nd to 3rd layer	2004	1125
Abelstok	Drain pump	Border of 2nd to 3rd layer	2006	600
H.D. Louwes	Drain pump	Border of 3rd layer to Lauwersmeer	1973	1000
Waterwolf	Drain pump	Border of 3rd layer to Lauwersmeer	1920	4500
R.J. Cleveringsluizen	Discharge sluice	Sea dike	1969	≈120.000

This is not all present infrastructure that is present in the Electra bosom system. There are many culverts that connect the waterways, under-drainage pumps, and feed pumps that play a role in maintaining the water level. However, for sequential interdependence, the role of these pieces of infrastructure is very small. That is why they are not considered here.

Downstream of the H.D. Louwes are the R.J. Cleveringsluizen, the discharging sluice complex that discharges water from the Lauwersmeer into the sea. It has a capacity of 120.000 m^3/minute. With the capacity of 4500 of the Waterwolf, 1600 of the intended new H.D. Louwes and 900 from Friesland, 7000m^3/minute is needed. This means that in terms of remaining capacity there is not a problem. The issue however with the discharging sluices is that they can only discharge during low tide. With sea-level rise as a consequence of climate change, the window for discharge is getting smaller. This means that either all water needs to be discharged quickly when the sea-level is low enough, or there needs to be a possibility to pump up water when the sea-level is higher than the location of the sluice tunnels. In the G_L and G_H scenario, the sea-level rise will be somewhere between +0.25 and +0.60 meter above the reference level, which is 0.03 meter +NAP. in the W_L and W_H scenario this is between +0.45 and +0.80 meter. Along with a smaller window of opportunity for discharge, the sea level rise is also responsible for closing off the discharge pipes completely during storms that cause the water level of the sea to rise. These storms can coincide with heavy rains on the landside, which causes an impossibility for discharge while water keeps coming into the Lauwersmeer from the polders. This has caused issues in the recent past (DvhN, 2017). For this reason, the regional water barriers around the Lauwersmeer are being heightened, of which the preferred design alternative is a part, with its replacement and the restoration of the former seadikes water-retaining function. Interventions at the pumping station affect the filling of the Lauwersmeer. The extent of this impact is discussed in section 6.2.

5.1.3. Balance interdependence in the Electra system (3rd layer)

The phenomenon of balance interdependence refers the balance in the discharging of water in a polder water system. Does each pumping station or discharge sluice move away the water from the right areas? Is there a place in the water system where water is not pumped away efficiently? Does an intervention interfere with the balance in the system? This kind of interdependence occurs *within* a polder bosom. In the case of the H.D. Louwes, this is the third layer of the Electrabosom.

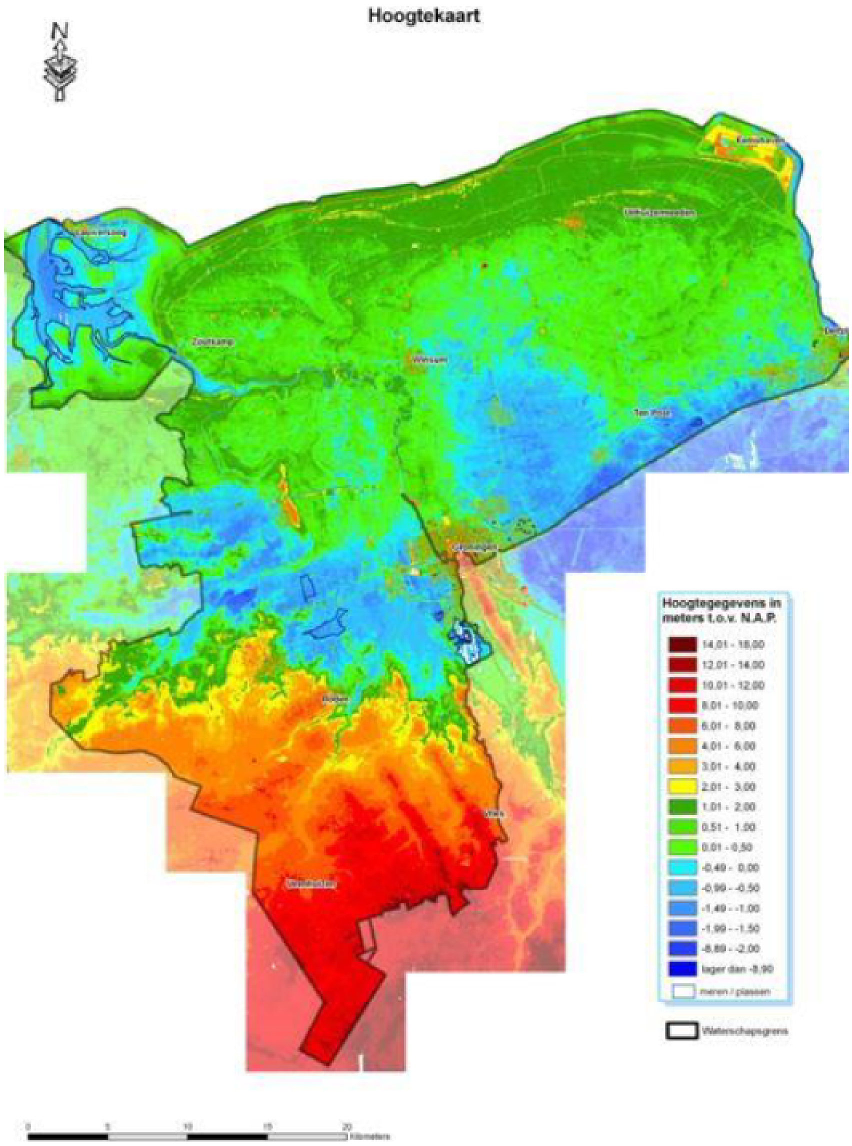


Figure 5.1: Land height map (Noorderzijlvest, 2019)

Within the third layer of the Electrabosom, there is quite some height difference present, as can be seen in Figure 5.1, the height map of the water system that Noorderzijlvest governs. The southern part of the third layer is part of the plateau of Drenthe with heights up to 15m +NAP. From there the water flows in a northern direction towards where the third layer has the lowest altitude. This is where the nature reserve area the Onlanden is located, which is a nature reserve area and an overflow area. Also, in the lowest part of the layer is the southern Westerkwartier. The southern Westerkwartier is the place where the imbalance in the system right now will cause problems, which is why there has been chosen for the renewal of the H.D. Louwes. North from this low area is an area which is higher and where some channels are located, being the Hoendiep, the Starkenborgh channel and the Aduarderdiep. The water from these channels all flows towards the Reitdiep river, in which the Waterwolf

pumping station is responsible for pumping away the water into the Lauwersmeer.
The H.D. Louwes is the second pumping station in the third layer, which is located in the Hunsingo channel in the northern part of the third layer. It is intended that all water north of the Reitdiep flows towards the Hunsingo channel, after which it will be pumped away towards the Lauwersmeer by the H.D. Louwes, if needed. There is one waterway that connects the Hunsingo channel with the Reitdiep, and that is the river the Kromme Raken.

Next to pumping stations whose objective is to pump water away, there are also pumping stations that are designed to pump water into the system. At the edges of the third layer, for example towards the sea, elevation goes up. The main use of land is agriculture, which needs enough water for the crops to grow. For this purpose, the 'summer-circuit' of pumping stations is present, which pumps water up from the central waterways towards the higher located crop fields.

As said before, there is at this moment an imbalance within the water system that is the third layer. During high water levels, water flows south towards the pumping area of the Waterwolf. The flow of water from the northern part prevents the Waterwolf from pumping away water from the southern part of the layer, which can cause problems during extreme precipitation events.

The original preferred design alternative should solve the problem of balance interdependence between the H.D. Louwes and the Waterwolf. Creating the separation in the Kromme Raken river separates the northern from the southern part, creating two separate water systems in the third layer. Both water systems have just one pumping station responsible for the discharge of water towards the Lauwersmeer. However, the preferred design alternative also creates a navigation lock in the place where a weir lock used to be which was open most of the time. This closes the flow of water from the Lauwersmeer into the area during the summer, if necessary. This could have an impact on the supply of water by the summer circuit.

5.1.4. Environmental interdependence in the Electra system (3rd layer)

Just as balance interdependence, is environmental interdependence a phenomenon that occurs within a polder bosom of layer. For the third layer of the Electrabosom, the maintained water level is -0.93 +NAP at the pumping stations Waterwolf an H.D. Louwes. This level is maintained (a margin below or above is permitted) by water level managers who steer on the operation of pumping stations. Also, there are (small) areas where pumps automatically pump away water. There are however some differences within the third layer. This can be seen in Figure 5.2

As mentioned before and visible in Figure 5.1, there is quite some difference in the elevation of the land. There are different small areas that have a preferred water level. For the southern part of the third layer, the differences are the largest. The water from the plateau of Drenthe flows via rivers into the tub that is the lowest area of the third layer. This is the Onlanden, Leekstermeer and the Marumerlage. On the plateau of Drenthe there are many small areas with their own desired water level. This is maintained through present infrastructure such as weirs, since there is a flow of water present from high to low.
There are not many pumping stations in the southern area of the third layer. The ones that are present pump away small quantities of water into the waterways that flow unhindered towards areas as the Onlanden or the Leekstermeer. On the northside of this low area, the pumping towards the Waterwolf starts. As said are these lowest areas nature and overflow areas, so a relatively high water level is permitted. (for example: -0.7 meter +NAP where the land height is between -0.9m +NAP and -0.5m +NAP in the Onlanden, which means that parts are constantly inundated. For a wetland this is desired.) Going further north the main land use is meadows for cattle (Landschapsmonitor, 2019). The vast majority of the desired water level areas is -0.93m+NAP, with some areas up to +0.8 and -1.6m +NAP. Starting from the Reitdiep going north the main land use changes to agriculture. The large area which has -0.93m+ NAP as desired water level stretches out into this area as well. North of this land the water level goes up to -0.35+NAP for some small areas. This indicates that between meadows and agriculture there is not much difference needed in the water level. The land uses in the Electrabosom can be seen in Figure 5.3.

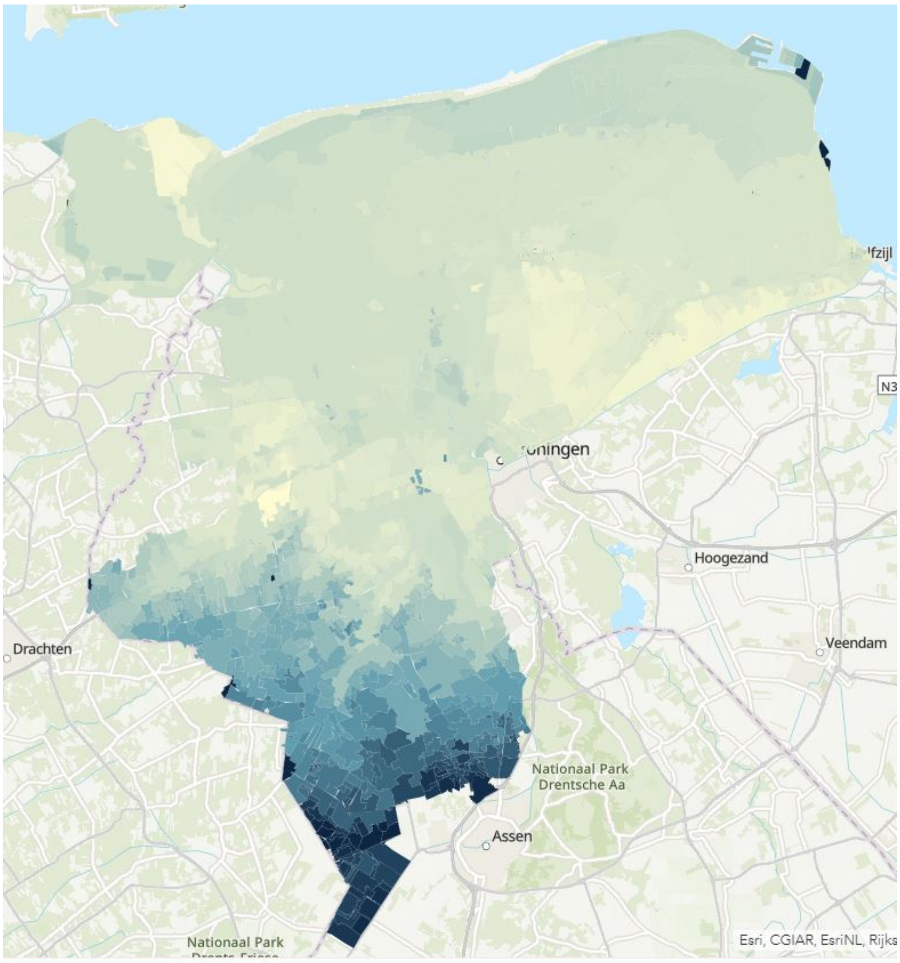


Figure 5.2: Difference in the height of the desired water levels in the Noorderzijlvest area

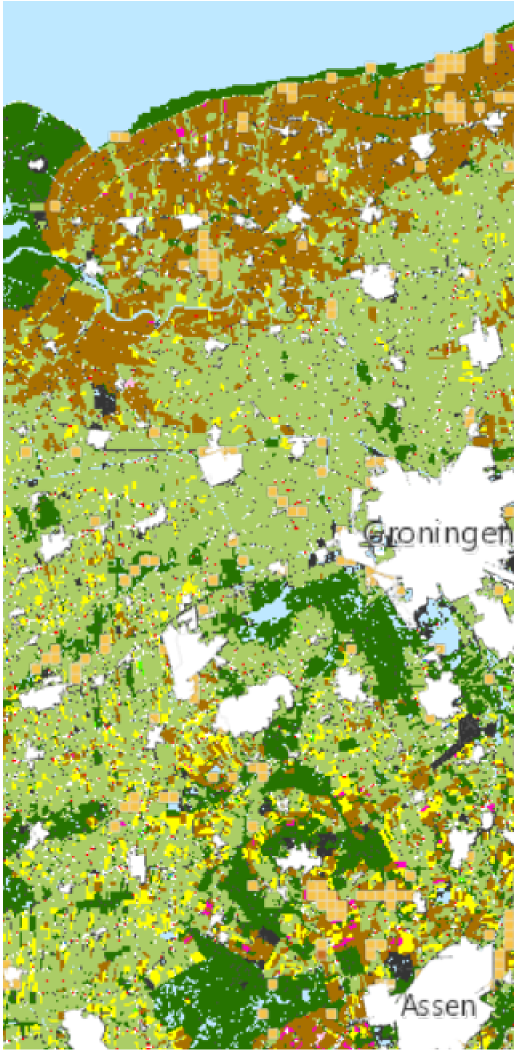


Figure 5.3: Land use in the Electrabosom (Landschapsmonitor, 2019). Brown is agriculture, light green is meadows, dark green is nature, yellow is corn and white is residential area.

5.2. New design alternatives

In this section, the new design alternatives will be created. These new design alternatives are based on the ways to incorporate flexibility and adaptivity into the design of hydraulic structures and the management of the water system, found in chapter 3. After these new alternatives have been created, they will be evaluated as well in terms of their adaptivity and their influence on the identified interdependencies, just as the original design alternatives. According to the literature, these new alternatives should be better suitable to cope with climate change uncertainty than the original design alternatives. The analyses in the next chapter will determine if that is also the case for interdependence.

5.2.1. Requirements

Water authority Noorderzijlvest has specified requirements for the design of the pumping station, with respect to water safety and the operation and lifetime of the construction. These requirements are fixed and do not leave room for interpretation. Regarding water safety, these requirements are:

- The minimum capacity of pumping station HD Louwes needs to be 1600 m^3/minute
- The pumping system needs to be operable up to a water level of 0.40m +NAP
- The minimum height of the regional water barriers needs to be at least 1.40m +NAP
- The lock needs to have a double-repelling function: it also needs to be suitable as a water barrier during lower water levels on the Lauwersmeer than in the Electrabosom
- The maximum low-water level on the Lauwersmeer is -1.20m +NAP
- The velocity of the current must not be higher than 0,5 m/s

These requirements are a consequence of the need to adhere to the 1:100 safety norms in the future. For example for the 1600 m^3/minute capacity, this is as a result from the capacity calculation (Arcadis, 2018), which assumes the W_L-scenario for the sight year 2070.

For the creation of the new design alternatives, this research observes these and acknowledges these requirements as a given. However, for the capacity of the pumping station, a more flexible approach is chosen. As mentioned, is the capacity requirement based on a scenario for a sight year. This means that for the current situation, capacity expansion is not yet necessary. The closing of the Kromme Raken is however a necessity that already needs to be taken. According to calculations of Arcadis (2016) will the quays in the southwest of the third layer already fail in a 1:100 event in 2025 if the northern part isn't separated from the southern part. The closing provision is included in all design alternatives, and will not be mentioned at the individual design alternatives.
For the creation of the new design alternatives, the choice is made to increase capacity according to the needs in the more near future, as long as the 1:100 norm is adhered to.

The new design alternatives will be based on the answers to sub-questions 1 and 2 that have been found in chapter 3. They will be designed according to the theory of adaptivity.
The first step in adaptive hydraulic infrastructure management is the long-term goal. In the case study, the long-term goal is water safety in the polder: the infrastructure must be able to handle a water level that occurs once every 100 years (1:100) (Arcadis, 2014). The amount of rain that is associated with a 1:100 water level, will change in the future because of climate change. How much it will change depends on the actual degree of climate change, represented in the different climate scenarios. In the existing design alternatives, the capacity is fixed to be able to accommodate a 1:100 event in 2070. In the new design alternatives, there is room for adjustment to adapt to the changing intensity of a 1:100 event.

5.2.2. The Engineering Options alternative

Below, in Table 5.2 and Figure 5.4 the specifications and a schematic overview of the first new design alternative, the Engineering Options alternative, can be seen. First the conceptual lay-out of the pumping station will be discussed within the context of the theoretical concept that it is modeled after. Then, its needed capacity will be discussed, as well as when and how its capacity can be expanded.

Table 5.2: Specifications of the Engineering Options alternative

Location	Southwest of the Hunsingo sluice
Sluice type	Navigation Lock
Initial capacity	1066 m^3/minute
Capacity expandable to	2132 m^3/minute
Freshwater flowback option	Backward pump

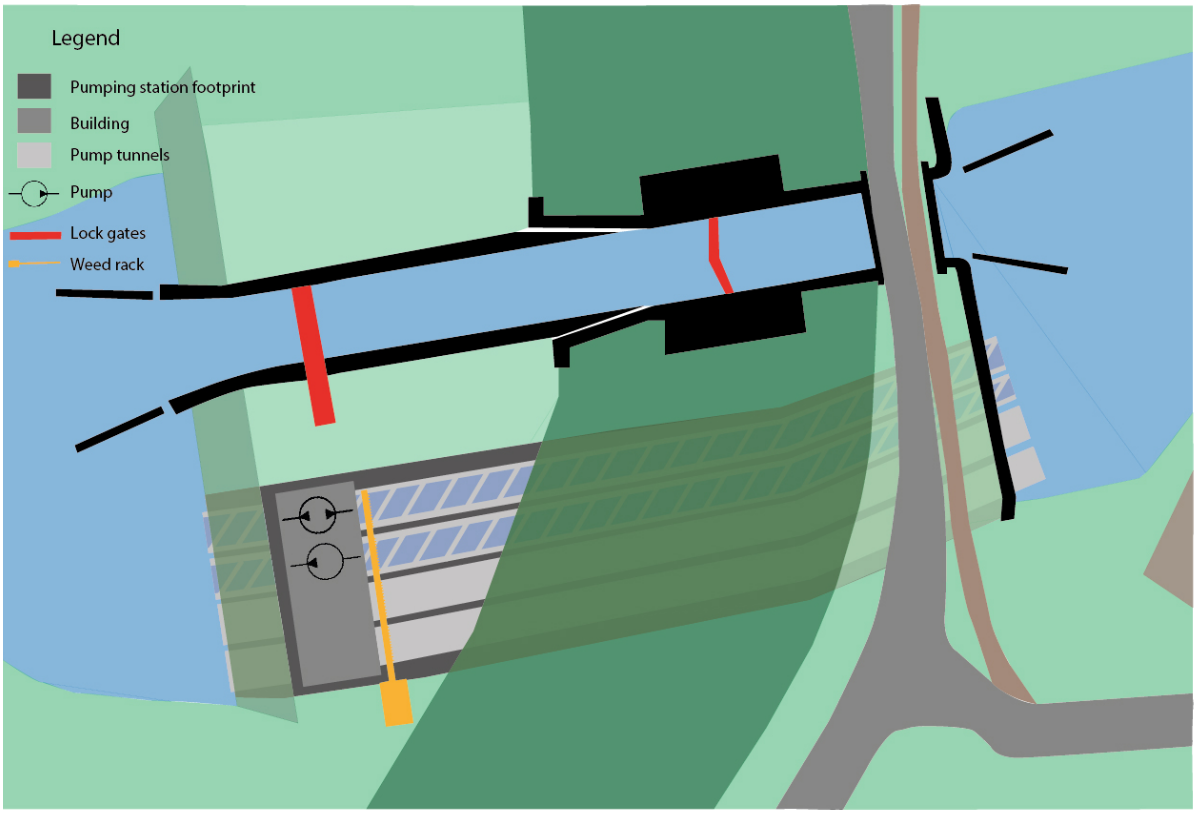


Figure 5.4: Schematic representation of the Engineering Options alternative (own production)

The Engineering Options alternative is based on the concept of Engineering Options. From the literature review, this has come forward as a promising way to proactively account for uncertainty regarding climate change and the interdependence that results from that climate change. The design alternative will be as Smet (2017) describes, and that Dr. Voorendt has mentioned as well: A pumping station will be fully built with four bays, but there will be 2 extra pumping bays where no pump will be installed yet. Each installed pump has a capacity of 533 m^3/minute, so the initial capacity of the pumping station is 1066 m^3/minute, slightly higher than the theoretical capacity of the current pumping station, but almost 300 m^3/minute higher than the measured capacity of the current pumping station.
This alternative is relatively similar to the 3rd existing design alternative. It will be located next to the monumental sluice as well, reinstating the water-retaining function of the former sea dike and transforming the sluice into a navigation lock.
A difference between this new alternative and the existing 3rd alternative, next to the extra bays, is that the new pumping station will provide a possibility to pump water back into the 3rd layer from the Lauwersmeer. Currently, fresh water is brought into the system through Friesland from the IJsselmeer, in periods of drought (Noorderzijlvest, 2019). Making the sluice into a navigation lock separates the Lauwersmeer from the 3rd layer. This provides an opportunity for a difference in water levels, where the Lauwersmeer can also function as a freshwater supply closer to home during dry periods. If the water levels for both the Lauwersmeer and the third layer is -0.93m +NAP then the lock can be opened to let water freely flow back. But if there is a difference between the levels then a pumping provision is

desired. The backward pumping provision will be the same pump as the forward pumps, meaning that it will have a capacity of m^3/minute.

The capacity of this new pumping station must be able to handle a 1:100 event for at least the next 20 years. The capacity should be as high as it is right now, which theoretically is 1000 m^3/minute. One pump has a capacity of 533 m^3/minute (Witteveen & Bos, 2019), which means that 2 pumps need to be installed. The two empty bays can add up to a total capacity of 2132 m^3/minute. This is more than the designed capacity of the current capacity. This may be needed if the precipitation after 2070 becomes even heavier. One added pump reaches the same capacity as the three original design alternatives. The moment to install an extra pump is determined by a signpost for adaptation (Raso et al., 2019). This signpost means that an adaptation tipping point is approaching. A tipping point is reached when the current policy is no longer sufficient to meet the long-term goal. This means that it will be reached when the current capacity is no longer able to handle a 1:100 event. When the pumping station is adapted at the exact moment that the tipping point is reached, you have a period where you do not adhere to the safety norms, also because the adaptation of the pumping station needs to be planned and contracted, which will cost some time. So, the signpost functions as a safety margin. When the 1:100 event in ten years exceeds the capacity of the pumping station, then the signpost is reached and should preparations start to insert an extra pump.

5.2.3. The Modular alternative

In Table 5.3 and Figure 5.5 the specifications and a schematic overview of the second new design alternative, the Modular alternative, can be seen. First the conceptual lay-out of the pumping station will be discussed within the context of the theoretical concept that it is modeled after. Then, its needed capacity will be discussed, as well as when and how its capacity can be expanded.

The second new design alternative, the Modular alternative, is based on the concept of modularity that came forward in the literature review. This is based on the assumption that these modules are available in the market, and that there is knowledge and skill to work with these modules. To be able to add modules in the future, the foundation of this design alternative needs to be oversized so it will still have the strength to bear the additions. A pumping module would ideally consist of a pump and a pumping bay, already put together.
As the initial situation, a very basic pumping station consisting of 2 modules of 533 m^3/minute can be constructed to maintain the current present capacity. It will as well be situated west of the former seadike, next to the monumental sluice. The sluice will also be made into a navigation lock.

Table 5.3: Specifications of the Modular alternative

Location	Southwest of the Hunsingo sluice
Sluice type	Navigation Lock
Initial capacity	1066 m^3/minute
Capacity expandable to	2132 m^3/minute
Freshwater flowback option	Through open navigation lock, backward pumping module possible in the future

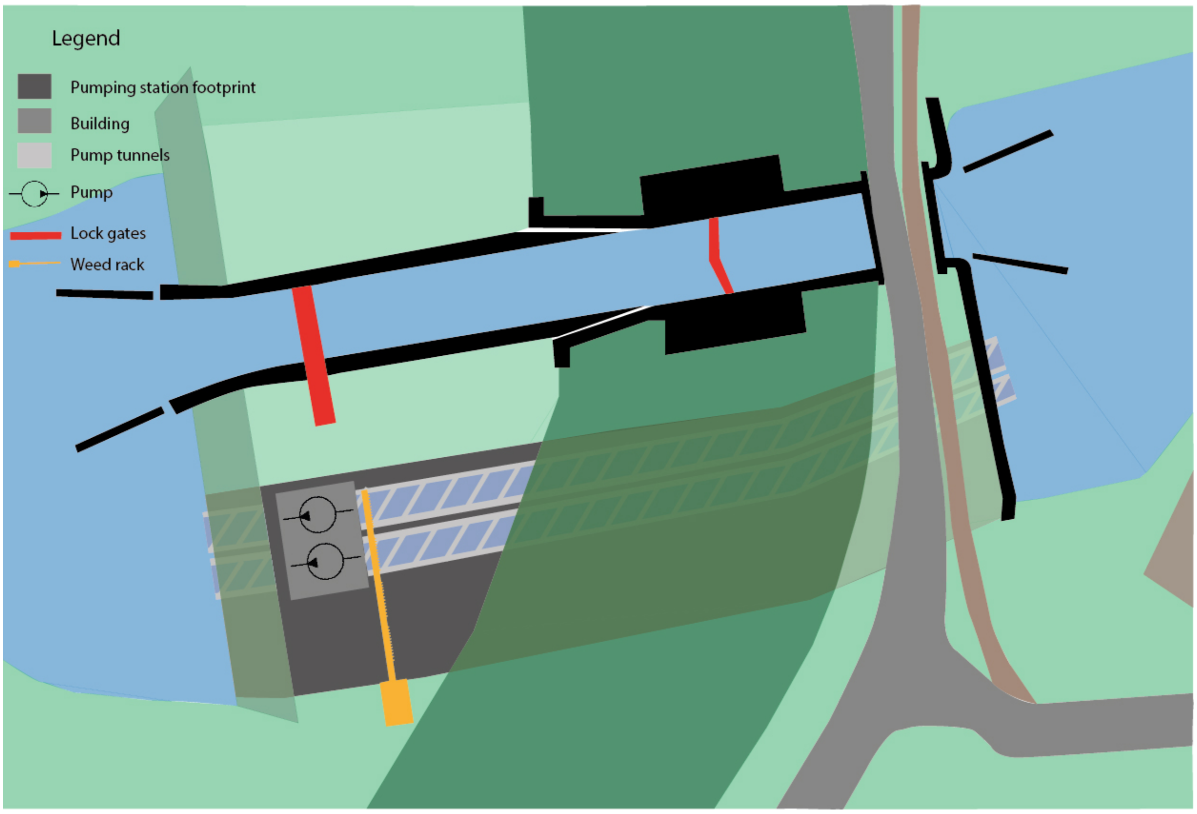


Figure 5.5: Schematic representation of the Modular alternative (own production)

This design alternative will at first be an oversized foundation with 2 modules that will be able to handle a 1:100 event for at least the next 20 years, approximately. This is the same capacity as mentioned in the previous paragraph for the Engineering Options alternative.
The backward pump will not yet be built. This can be another module that can be added if the drought turns out to be so severe that more freshwater is needed. The same kind of adaptation signpost can be used: if the amount of water needed to handle a 1:100 drought event in ten years is higher than the amount of water that can be let back into the system through the lock, then the backward pumping module needs to be installed.

This design alternative provides safety and the possibility to explore other solutions. If the adaptation tipping point is in sight (the same tipping point as new alternative 1, if the capacity needed to handle a 1:100 event 10 years from now is larger than the current capacity), then a wide range of possibilities can be explored. Adding an extra module can be a last resort, if other solutions are not sufficient. Efforts to increase water safety while preserving the water have a preference because this can be of benefit in later periods of drought. These efforts can be floodplains, or perhaps increasing pumping capacity at the location where flooding will occur. This will be a trade-off between the costs and effectiveness of screwing on the extra module on the pumping station, and the costs and effectiveness of other local interventions.

An additional note for both the Engineering Options and Modular design alternatives is the fact that you can be too late in increasing capacity or implementing other interventions. A 1:100 event may get heavier faster, and there may not be very much time to increase capacity. A discussion point is that you can accept the fact that once every hundred years there may be some floods. With increasingly extreme precipitation patterns one can argue that you cannot be safe for everything. The important thing is that high damages and the safety of people is ensured. Other than that, it may not be such a big problem that there is a little inundation here and there. The choice can be made to accept a higher risk of inundation, and instead of increasing capacity spending that money on preventing damages or injury in the case of an extreme event.

5.2.4. The Big alternative

Below, in Table 5.4 and Figure 5.6, the specifications and a schematic overview of the third new design alternative, the Big alternative, can be seen.

Table 5.4: Specifications of the Big alternative

Location	Southwest of the Hunsingo sluice
Sluice type	Navigation Lock
Initial capacity	2132 m^3/minute
Capacity expandable to	Not expandable m^3/minute
Freshwater flowback option	Backward pump

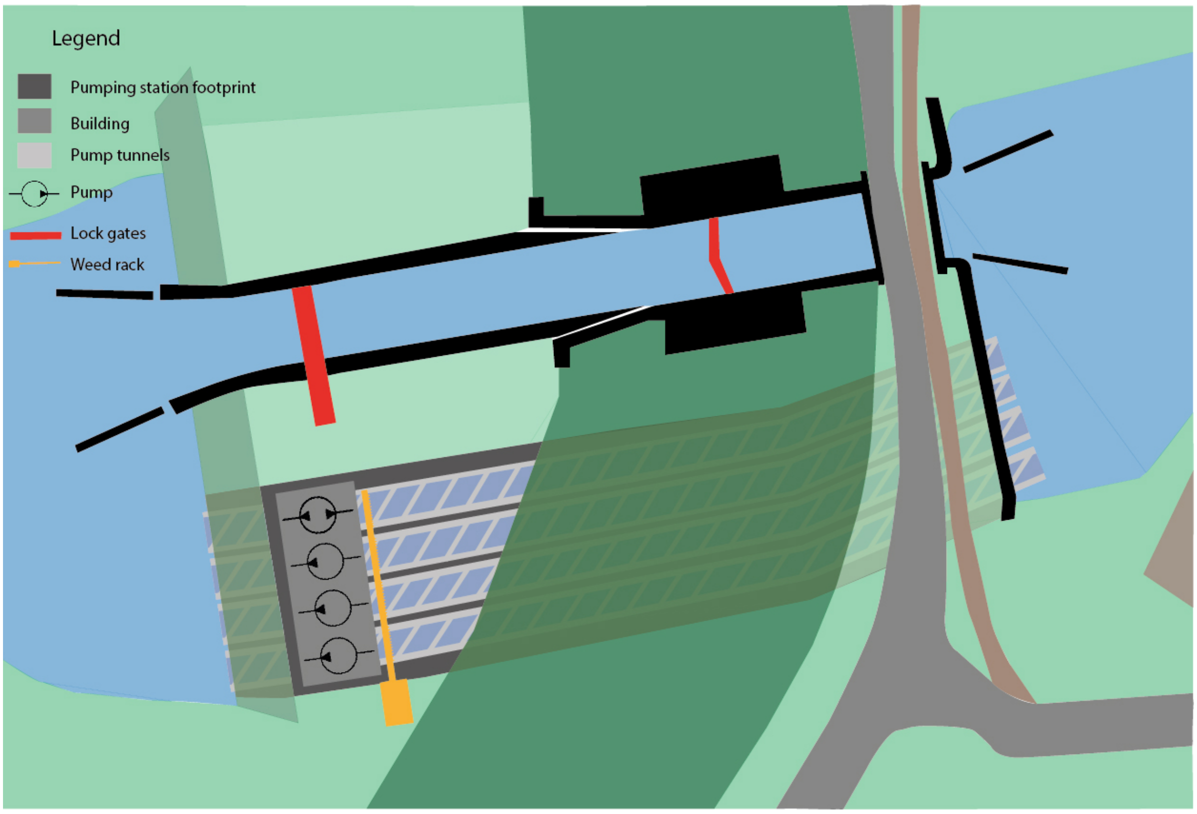


Figure 5.6: Schematic representation of the Big alternative (own production)

The third and final new design alternative is one that will be used as a comparison. What if you do 'build it once and build it big'? How would those costs compare to a smaller alternative or alternatives with investments spread through time? That is why this alternative is included. It has a capacity of 2132 m^3/minute, and a backward pumping provision. With a capacity this high it is likely to be able to handle extreme precipitation events in all climate scenarios. The backward pumping provision can help combat drought if that turns out to be necessary. It will consist of 4 pumping bays in which four pumps with each a capacity of 533 m^3/minute will be installed. The location of this alternative is as well on the west side of the dike and the sluice will be transformed into a navigation lock. This alternative can be described as the 'all-inclusive' package.

6 Assessment of the design alternatives with respect to adaptivity and interdependence

This chapter is comprised of three sections. The first section compares the adaptive capacity of the original design alternatives with the new design alternatives. The new design alternatives are created to be adaptive, so their assessment has a positive outcome. It is however still listed to serve as comparison to the original design alternatives and each other, and to illustrate how their adaptive capacity will work.
The second section evaluates the influence of the design alternatives on interdependence. Here sub-question 3 will be answered: *How can interdependence be incorporated into the decision-making process?* A decision making process has been gone through that does incorporate interdependence to see whether the choice of preferred design alternative will be different, and what causes that.
The third section answers sub-question 4: *How do the costs of the design alternatives compare?* The life cycle costs of the design alternatives are analysed and compared, to see which one is economically the most competitive alternative.
Lastly, the conclusion of this chapter will answer sub-question 5: *What is the impact on decision-making?*
For clarification, the specifications of all 6 design alternatives are listed in Table 6.1 below. The original design alternatives are numbered, the new alternatives are listed by their names.

Table 6.1: Overview of the specifications of all design alternatives

	1	**2**	**3**	**Engineering Options**	**Modular**	**Big**
Location	Old location	Old location	Southwest of the Hunsingo sluice	Southwest of the Hunsingo sluice	Southwest of the Hunsingo sluice	Southwest of the Hunsingo sluice
Sluice type	Weir sluice	Navigation lock	Navigation lock	Navigation lock	Navigation lock	Navigation lock
Initial capacity (m^3/ minute)	1600	1600	1600	1066	1066	2132
Capacity expandable to	Not expandable	Not expandable	Not expandable	2132	2132	Not expandable
Freshwater flowback option	Through opened navigation lock	Through opened navigation lock	Through opened navigation lock	Backward pump	Through opened navigation lock	Backward pump

6.1. Assessment the adaptivity of the design alternatives

In this section, adaptivity of the original design alternatives will be assessed. Are they able to adjust to changing circumstances? Then, the same will be done for the new design alternatives. Two of the new alternatives are designed to be adaptive, so they will illustrate what that difference means.

6.1.1. Assessing the adaptivity of the original design alternatives

As discussed in chapter 3, is the theory of adaptivity a way to deal with long-term uncertainty when it comes to the renewal of hydraulic infrastructure. A long-term goal or vision is set, after which short term actions can be undertaken when uncertainties become known, such as future precipitation patterns. These actions can be represented in Dynamic Adaptive Policy Pathways, such as in Figure 3.1 (Haasnoot et al., 2013). When uncertainties become more certain, a transfer can be made to a different action. This way the long-term goal will still be achieved. Additional to these pathways there are different kinds of adaptive interventions. A problem does not have to be solved in the here and now, when the problem is detected. Keeping a broad perspective on the possible options may lead to solving the problem by intervening somewhere else in the system, or at a later moment in time. This requires less focus on projects of renewal, but more on programmes of watermanagement (Busscher et al., 2014). The *what, where, when* of interventions together with dynamic adaptive pathways are the core of the theory of adaptivity.

For water authority Noorderzijlvest, the long-term vision is remaining safe from water under climate change.
For this purpose the study Droge Voeten 2050 has been initiated. In this study the long-term vision has been made specific: Being able to cope with water levels that occur once in 100 years. The identified problem that lead to the renewal of the pumping station at Zoutkamp is a result from this study. For the problem that is detected in the Electra bosom, three design alternatives have been developed that should be an effective action to reach the long-term vision, as discussed in section 4.2. Figure 6.1 shows the design alternatives, represented as dynamic adaptive pathways. All three design alternatives contain the closing provision in the Kromme Raken, which is why it has been left out of this figure.

Figure 6.1: The original design alternatives represented in Adaptation Pathways.

This figure shows that design alternative 2 and 3 can not be considered adaptive alternatives. There is nowhere a possibility to adapt the course, once it has been set. Design alternative 1, which is the building of a new pumping station at the current location, and doing nothing with the present sluice, does contain one adaptive aspect. The sluice that is there at the moment would not be altered in this design alternative. This means that if the pumping station will start pumping, this sluice is closed. This hampers the navigability of the channel by boats. If there is less water in the future than anticipated on, and the pumping station almost never has to pump, then this sluice will stay opened, being a free waterway for boats. This is better for the navigability of the channel than a navigation lock which is still a barrier.
However, if more rain falls and the pumping station needs to pump more often, then the sluice will also be closed more often. This can reach a point where the decision can be made to eventually change the sluice into a navigation lock. This is the transfer point to design alternative 2. With the navigation lock, the navigability of the channel is no longer dependent on the operations of the H.D. Louwes.

Both design alternative 2 and 3 contain the creation of a navigation lock. If less rain will fall or the pumping station is not in operation, perhaps both doors of the navigation lock can be opened to create a free passage. This is possible because the third layer of the Electra polder and the Lauwersmeer both have the same water level of -0.93m +NAP. You are however stuck with a more expensive navigation lock that doesn't fulfill its function for most of the time. If more rain falls, it may prove to be worth the investment Looking at the climate scenarios this is likely, because all 4 scenarios predict an increase in yearly precipitation. Furthermore, a provision to close the Kromme Raken during high water will be built anyway. One might argue that the barrier for navigability will just be moved to another location.

The adaptive capacity of alternative 1 refers to the navigability of the channel by boats, be it simply because it is the most basic option where functions can be added later. When you build more elaborate structures from the start, you cannot go back. Building a basic solution where functions can be added later is an important aspect of adaptive planning: Do right now what is necessary, and wait and see what the future brings.
When looking at adaptivity with regards to the discharging of water towards the Lauwersmeer, all three alternatives are the same. Arcadis (2018) determined that a capacity of 1600m^3 per minute is needed, which all three design alternatives have. These new pumping stations will be custom built, which means that there is no possibility for expanding the capacity in the future, if there are heavier rains.

The choice for increasing the capacity of the H.D. Louwes and separating the northern and the southern water system in the third layer does fit into adaptive thinking. The problem in the water system will occur in the southwest of the layer. Recognizing the underlying problem of balance interdependence lead to a solution that is likely to be more robust than simply increasing the pumping capacity in the southwest of the system. If that would have been done then the imbalance in the system would still remain and that might still have lead to flooding. So adaptive thinking and interdependence has been thought of nicely when looking at the problem, but it has not been thought of when looking at the structure of the pumping station itself. For effective handling of long-term uncertainty and interdependence, this research argues that adaptivity on both the level of the water system and the level of the intervention itself is important.

The final remark about the adaptivity of the design alternatives is that the long-term vision is not that long term. The study of Droge Voeten 2050 aims at (as the name implies) at water safety in 2050, which is less than 30 years away. The furthest sight year is 2070. The new H.D. Louwes will be designed to stand for a hundred years (Witteveen & Bos, 2019). This will mean that it will have reached the end of its technical lifetime approximately in 2120, if no calamities occur. This means that for half of the H.D. Louwes' lifetime, there has not been though of what might happen and how the administrators can adapt to circumstances that might happen then.

6.1.2. Assessing the adaptivity of the new design alternatives

In Figure 6.2 below the adaptation pathways of the Engineering Options alternative can be seen. Based on different scenarios, different pathways can be travelled. Based on the Droge Voeten 2050 study (Arcadis, 2014), its recalculations (Arcadis, 2016) and the calculations based on which the capacity of the original design alternatives is calculated (Arcadis, 2018), some assumptions can be made with regard to the scenarios. The newly built pumping station in its most basic form will have a capacity of 1066 m^3/minute. This is 358 m^3/minute higher than H.D. Louwes' current highest measured actual capacity. Together with the closing provision in the Kromme Raken, can this alternative be regarded sufficient in the most moderate scenario G_L for the sight year 2085.
However, if the future climate change turns out to move in the direction of the heavier scenarios, an adaptation signpost may be reached and the capacity may need to be expanded. This is when an additional pump can be installed in one of the empty bays. A capacity of 1600 m^3/minute was deemed necessary for the original design alternatives to be safe until at least 2070. This has been determined based on the W_L-scenario. This indicates that up until the W_L-scenario, the pathway with one additional pump suffices.
For the most extreme scenario that is available now, there is the final option with both empty pumping bays filled with a pump. The total capacity will be 2132 m^3/minute, higher than thought necessary thus far. Based on the new IPCC report, this may not be an unrealistic option (Trouw, 2021).
The backward pumping provision is included in the description of the alternative for completeness' sake. It is the same for all variants, and it does not have an influence on the pumping station's ability to handle extreme precipitation events. It can however be needed to combat drought during the summer, which is why it is part of the design alternative.

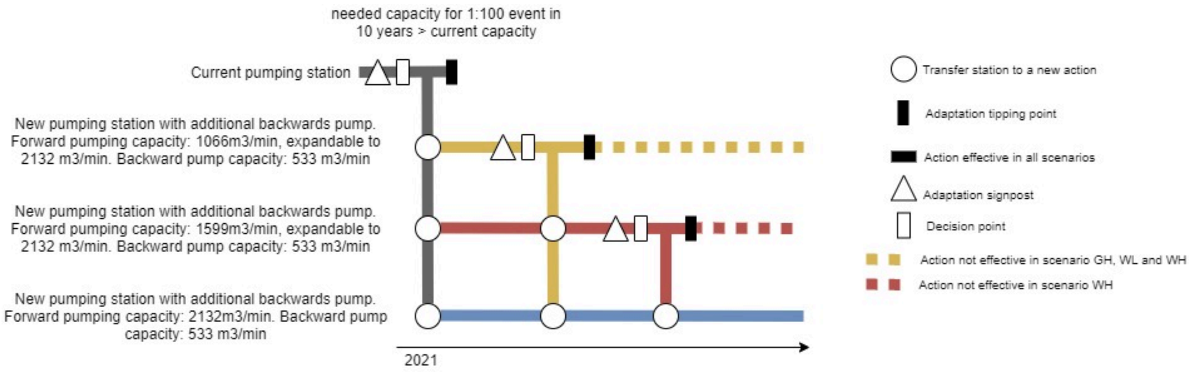


Figure 6.2: Adaptation pathways of the Engineering Options alternative

Looking at this design alternative it can be determined that there is adaptivity present. The capacity of the pumping station can relatively easy be expanded by installing an extra pump in an empty bay, when it turns out that in the near future more capacity is needed. By taking these possibilities into account beforehand, you are better prepared for future developments which are at the moment uncertain. Also money can be saved in the short term on maintenance for the pumps that are not yet installed and that are not yet necessary. Creating a margin above the capacity that is needed now, provides room for expanding the capacity without having to build an entire new facility when the capacity turns out to be too low.
However, there are also some downsides with regards to the adaptivity. Looking at the *what, where and when* of interventions it becomes clear that the *what* and *where* are already fixed: expanding capacity of the pumping station at the location where the new pumping station will be built. Only the *when* is still variable, depending on the actual progression of climate change. Other interventions such as creating watersheds elsewhere in the system can be done, there is nothing that forbids that, but this can be more expensive than installing the extra pump, since the preparations for installing extra pumps have already been made. Also it can feel like a waste when other interventions are implemented when the empty extra pumping bays are laying there, waiting to be used.
Evaluating the adaptivity of this alternative it can be concluded that it is an adaptive design alternative, which is capable of adapting to changing future circumstances in the climate. This alternative does however limit the possibilities of adaptation to simply expanding the capacity.

Figure 6.3 shows the adaptation pathways for the Modular alternative. A note here is that the backward pumping module is not considered here. That is because this feature does not have an influence on the ability of the pumping station or the system to cope with extreme precipitation events. It will therefore not contribute to the postponing or expediting of the adaptation signpost and is left out. It can of course still be installed, if drought is becoming severe. In the description of the design alternative it is mentioned that when an adaptation signpost is reached, a wide range of possibilities can be explored. Examples can be creating buffer areas or building water barriers. What all these options are goes beyond the scope of this research. They are listed as a pathway as *water-retaining interventions within the water system*. They are shared under this collective name because their common denominator is that they provide safety while allowing the water to be retained within the water system.
When looking at the forward-pumping capacity of this fifth design alternative, it can be noted that the most basic version, with two forward-pumping modules, is basically the same as the most basic version of the Engineering Options alternative. It is expected that this will be a sufficient solution under the G_L-scenario. When the climate turns out to evolve according to one of the more heavy scenarios, an adaptation signpost will be reached somewhere in the future. Then the aforementioned trade-off between the addition of an extra module and the water-retaining interventions in the water system needs to be assessed. When going directly to an increased capacity of 1599 m^3/minute then the scenarios G_L, G_H and W_L are covered. But it can be more effective to locally create some water-retaining measures. For this research, based on the documents mentioned in the previous paragraph, the assumption is made that a pumping capacity of 1066 m^3/minute and local water-retaining measures is sufficient to function under the G_H-scenario.
The decision could also be made to skip the water-retaining interventions and go straight to a capacity

of 1599 m^3/minute, as said, then the W_L-scenario is covered as well. In the W_H-scenario this may still not be enough, leading again to the choice between an increased capacity and water-retaining measures. It is assumed for this research, for a means of comparing the alternatives with each other, that a capacity of 1599 m^3/minute and water-retaining measures is sufficient to handle 1:100 precipitation events in the year 2085 under the W_H-scenario. There is still enough foundation to add a fourth module in a worst-case situation where the precipitation will become even more extreme than the current scenarios predict.

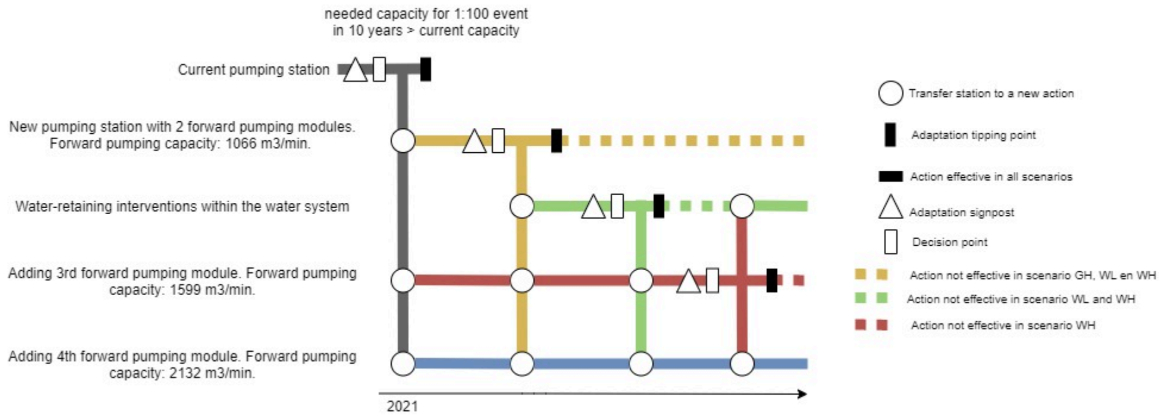


Figure 6.3: Adaptation pathways of the Modular alternative

This design alternative can be regarded the most adaptive. Next to the possibilities for increasing the capacity, which can be done to adapt to the developing climate, it provides the opportunity to customize the water system so it will function optimally for the lowest amount of money. Instead of simply expanding capacity, other measures can be taken in the system that may be more efficient in terms of cost and achievement of water safety. This trade-off can be made at the moment an adaptation signpost is reached. The *what, where and when* of adaptive interventions is more open to newly gained insights in the future for the best option.
This design alternative does however also have a downside. By continuously keeping all options open there is a risk of becoming ambivalent and indecisive, which is what Smet (2017) and Pot (2019) refer to as 'reactive' and a 'wait-and-see' attitude. The chances are higher that upgrades to the system or the pumping station are too late, due to meticulously exploring every option. This can be combated by coming into action as soon as the adaptation signpost is reached, and setting a deadline for the decision point.

The third new design alternative, the Big alternative, is not adaptive. All options are included beforehand, and there is no room for expansion or other adjustments. It is also not meant to be adaptive, but to function no matter the outcome of climate change with a one-time investment. Its adaptation pathway would simply be one straight line.

6.2. Evaluating the influence of the original and new design alternatives on interdependence

In this section, the third sub research question is answered: *How can interdependence be incorporated into the decision-making process?*
To answer this question, the results of the scoring sessions with the experts are presented. These scoring sessions are carried out according to the method specified in subsection 2.3.6. For each interdependence they assessed the influence of the design alternatives on that interdependence. As discussed in subsection 2.3.6, each interdependence was accompanied by a question that should be answered. This question is listed at each subsection for each interdependence. Each alternative has been assigned one score per interdependence. Next to the scores are the reasons behind the scores very important because these reasons have led to the identification of distinctive factors that make up an interdependence.

6.2.1. Influence of the design alternatives on Sequential Interdependence

The first interdependence is also the one whose scores differ the most among the respondents. An overview can be seen in Figure 6.4. The question that was answered in the scoring session for this interdependence is:

What is the influence of this design alternative on the moment that the infrastructure of the Lauwersmeer or the Cleveringsluizen needs to be altered or upgraded? Is this moment being expedited (- -, negative effect) or pushed back (+ +, positive effect)?

Sequential	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Average
1	- -	- -	- -	-	-1,75
2	-	- -	- -	-	-1,5
3	+ +	-	+	+ +	+1
Engineering Options	+	0	+	+ +	+1
Modular	0	0	+	+ +	+0,75
Big	+	-	+	+	+0,5

Figure 6.4: Overview of the scores assigned to the alternatives with respect to their influence on sequential interdependence

Where the respondents do agree is the fact that the first two design alternatives - the two which are situated at the same location as the current pumping station - have a negative influence on this type of interdependence. This has to do with two factors: the existence of a bottleneck at the old location and the reinforcement of the regional water barriers.

The problem of the bottleneck is as follows: If the new pumping station with a capacity of 1600 m^3/minute is built at the same location as the current pumping station, then it will naturally pump much more water towards the Lauwersmeer. However, between the Lauwersmeer and this location of the pumping station, the old sluice is still situated. This sluice is the only way through the former sea-dike for the water, and it is quite narrow with 8 meters wide. If the capacity is increased then this will create a bottleneck which will congest the water. This is likely to cause inundation or water flow speeds which are too high. To solve this issue, either the banks of the channel need to be heightened or extra passages for the water through the dike have to be created. This effectively causes the need for infrastructure renewal which is a negative effect.

The regional water barriers around the Lauwersmeer are cause for a negative effect of the first two alternatives, and for a positive effect for other alternatives. Recently, the regional water barriers around the Lauwersmeer have been reinforced. These barriers are now able to retain water levels of the lake that are 40 cm higher than before. The only part where these water barriers have not been reinforced yet is at the town of Zoutkamp. The H.D. Louwes is right now a part of this barrier system, and the current barriers go through the town where streets function as water barriers. If the pumping station is built at the same location as the old pumping station, that this will mean that the barriers through the town still need to be reinforced. This would be a complex task to raise streets, and it would not land well within the community of the town. This has led to a negative effect of the first two design alternatives on the infrastructure.
Moving the pumping station to the new location has two benefits in this regard. The former sea-dike will function as the regional water barrier from now on. This means that you don't have to break out streets and go through a complex project anymore. This is a positive effect. Second, the former sea-dike is approximately 5 meters +NAP high and still stable. The required height for the regional water barriers is 1.40 meters +NAP. This means that for the part where the former sea-dike is the regional water barrier,

it never has to be heightened anymore, only its stability needs to be monitored. This is another positive effect, which is applicable to design alternative 3, Engineering Options, Modular and Big.

Lastly, there is the effect of the increased capacity on the Lauwersmeer and the Cleveringsluizen. With an increase of water that will be pumped into the Lauwersmeer and the fewer possibilities for discharging water into the sea due to sea level rise, this might be cause for placing a pump in the Cleveringsluizen or maybe heightening the regional water barriers again. This aspect led to different interpretations among the respondents. They did all acknowledge that this issue is present, but its importance is assessed differently. For example, one respondent (R2) said that it is at least not a positive influence and that the higher the capacity of the pumping station, the more negative it would be. Which is why this respondent scored alternative 3 and the Big alternative more negative than the adaptive Engineering Options and Modular alternatives. The other perspective was given by respondent 3, who stated that the new regional water barriers are already able to retain 40 cm higher water levels, and that this is of no influence on the Cleveringsluizen, no matter the capacity of the pumping station. The Lauwersmeer can hold enough water to wait for the next moment of free discharge to the sea.

6.2.2. Influence of the design alternatives on Balance Interdependence

As can be seen in Figure 6.5, there is quite a lot of consensus between the respondents, and the scores of the alternatives are also very similar. The question that was answered in the scoring session for this interdependence is:

What is the of this design alternative on the balance in the water system? Does water in the management area of the H.D. Louwes flow elsewhere (- -) or does it flow nicely towards the H.D. Louwes pumping station (+ +)?

Balance	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Average
1	-	+	+	+	+0,5
2	-	+	+	+	+0,5
3	+	+	+	+ +	+1,25
Engineering Options	+	+	+	+	+1
Modular	+	+	+	+	+1
Big	+	+	+	+	+1

Figure 6.5: Overview of the scores assigned to the alternatives with respect to their influence on balance interdependence

The most important aspect that is a positive influence on the balance within the third layer of the Electrabosom is the closing provision in the river the Kromme Raken. This is included in all 6 alternatives. With this closing provision, the northern and the southern part of the bosom can be separated from each other during extreme circumstances. This ensures an optimal working of the two pumping stations in the bosom, without having a flow of water from north to south, causing problems there. During the interviews, the question was asked whether a permanent closing provision would be better, where the northern and the southern part are separate for good. All respondents argued that a flexible solution is preferable, since that provides the opportunity to play with the water system and to be able to better anticipate on unforeseen circumstances in an uncertain future. For example during maintenance of one of the two pumping stations, or very local precipitation, these two pumping stations can still be connected through the open river and work together. During circumstances where it’s better to have each pumping station work alone, the closing provision will be closed. For the new H.D. Louwes, the respondents did not yet advocate a flexible solution, even though the arguments behind it are the same - being able to better anticipate an uncertain future.

Since the imbalance in the third layer of the bosom was the reason behind the renewal of the H.D. Louwes, the question arose whether it has been checked if there are any other imbalances in the management area of the H.D. Louwes. None of the respondents actually knew if that was the case. On the other hand, this imbalance would have been the same for all alternatives, which does not cause them to differ from each other. Respondent 4 did mention that with a higher capacity of the pumping station, problems may arise with the supply of water towards the pumping station, because the channel would then be too narrow. the Engineering Options alternative and Modular alternative would have a slight advantage because you can grow towards the high capacity of 2100 m^3/minute which gives you the opportunity to check whether an expansion influences the balance. Since the Modular alternative states that before an extra module is placed, other options should be explored within the water system, it's possible to first broaden the channel to see what impact that would have and then later consider an expansion of capacity.

6.2.3. Influence of the design alternatives on Environmental Interdependence

The assigned scores by the experts on the influence of the design alterntives on environmental interdependence can be seen in Figure 6.6. The question that was answered in the scoring session for this interdependence is:

What is the influence of this alternative on the manageability of the water level in the Electra bosom? (Also think about letting water in) Does the manageability of the water level get worse (- -) or better (+ +)?

Environmental	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Average
1	- -	0	0	-	-0,75
2	0	-	+	-	-0,25
3	+	+	+	+	+1
Engineering Options	+ +	+ +	+ +	+ +	+2
Modular	+	+	+ +	+ +	+1,5
Big	+ +	+ +	+ +	+	+1,75

Figure 6.6: Overview of the scores assigned to the alternatives with respect to their influence on environmental interdependence

Quite similar to sequential interdependence, does the old location cause the first two design alternatives to receive some negative scores. Also there are some neutral scores. For the first design alternative, the main reason for its low scores is the fact that it still consists of a sluice instead of a navigation lock. With a sluice, the aim is to only be closed when the pumping station is in operation. The underlying assumption here is that when there is a sluice instead of a navigation lock, then the Lauwersmeer and the third layer of the bosom will have the same water level that will be maintained. The current situation would be recreated, which means that the grip on the manageability of the water levels stays the same. One could also argue that if the manageability is the same while the climate changes, then your grip becomes less, causing a negative influence instead of a neutral one.
A navigation lock which the other alternatives have, provide the possibility for differences in water levels on both sides. This is why alternative 2 scores a little better than 1. A downside of the old location is the same bottleneck situation that was mentioned with sequential interdependence. In the stretch of channel between the pumping station and the sluice a higher water level can not be maintained, since floodings might occur in the village. This means that you can be less flexible with your water level.

Next to the type of sluice that is part of the pumping station, is the capacity of the pumping station also a determining factor of the manageability of the water level in the sense of managing the water level by pumping excess water out of the system. Looking at it this way, this means that a higher capacity is simply better, when ignoring the costs. Which is why the design alternatives with a capacity that is expandable up to 2100 m^3/minute (the Engineering Options and Modular alternative) and the Big alternative whose capacity is already at 2100 m^3/minute score the best to that respect. The pumps are able to pump at a lower capacity, so if you have a very high capacity, you can slow down if you don't need to pump at full power, and gear up wen you do.

With environmental interdependence the matter of drought also plays a role. During dry and hot summers, the water level in the bosom can become too low, which is damaging to both nature and agriculture. Being able to let water into the system is thus also a vital part of keeping the water levels between the safety margins. the Engineering Options and Big alternative contain a backwards pumping provision. These alternatives have a clear advantage when water needs to go back into the system, because they can do that no matter what the water level on the Lauwersmeer is. the Modular alternative does not yet have it, but such a module could be installed if the drought turns out to become quite severe during the summer. This means that the Modular alternative still has some advantage over alternative 2 and 3.
The alternatives with a navigation lock have a lock which will be completely open in normal circumstances. If the same water level is maintained on both sides, then the Electrabosom can regulate its own water levels with sweet water from the Lauwersmeer. If the Lauwersmeer as a higher water level then the navigation lock can let water in through a rinket solution. This is possible for alternative 2 and 3 (and the Modular alternative, as long as the backwards module is not added). If the water level on the Lauwersmeer is lower than the bosom, then no water can be let into the bosom.
Design alternative 1 is the least preferable in this regard. Only when the sluice is opened then water can flow back. In all other possibilities with a difference in water levels no water can be let back into the bosom.

The above paragraphs concerning environmental interdependence contain many *ifs*. If the water level on the Lauwersmeer is higher, if it is lower, and so on. This is because the way the water level in the future will be managed, largely influences how the design alternatives perform and in their turn influence this type of interdependence. The issue is however that there is uncertainty present regarding the governance of the Lauwersmeer and the water level that corresponds with it. At the moment a pilot called the Rietproef is carried out, in which the water level of the Lauwersmeer is kept at -0.52 m NAP instead of -0.93m NAP for eight weeks in the months of Februari and March. This done to improve the ecology of the Lauwersmeer. Next to that, some respondent mentioned that there are also thoughts about a lower water level during the summer. There can be many motives for altering the water level, if its for ecology, agriculture or tourism. The issue is that nothing is definitive yet.
Trying to cope with this uncertainty can lead to two outcomes: creating a pumping station that is able to manage the water level in the bosom properly, no matter what the outcome of the plans with the water on the Lauwersmeer may be. Or to ignore the plans, since they are not certain yet anyway. For both stances there are good arguments, for example the costs of trying to cope with every little uncertainty. The latter stance has been the case with the H.D. Louwes. The plans are not certain, they may never happen, so lets assume that for the coming 100 years the water level on the Lauwersmeer and the Electrabosom stay the same. It may however be wise to indicate how likely some plans are and to anticipate on them, otherwise the polder might dry out in the summer.

6.2.4. Determination of the best performing design alternative with respect to interdependence (answer to sub-question 3)

As can be seen in the previous section, are the average scores calculated per interdependence. These are the averages of the scores of the four experts per alternative. Figure 6.7 shows the final summarizing table, with the averages per interdependence. The right column presents the average score of the alternatives across all three interdependencies.

Total	Sequential	Balance	Environmental	Average
1	-1,75	+0,5	-0,75	-0,67
2	-1,5	+0,5	-0,25	-0,42
3	+1	+1,25	+1	+1,08
Engineering Options	+1	+1	+2	+1,33
Modular	+0,75	+1	+1,5	+1,08
Big	+0,5	+1	+1,75	+1,08

Figure 6.7: Overview of the average scores of the design alternatives for the interdependencies

From this table it can be concluded that the Engineering Options alternative is the design alternative which has the most positive influence on the interdependencies. It performs slightly better than alternative 3, Modular and Big. Alternative 1 and 2 perform the worst, with a negative total average. With balance interdependence it does not score better than the others but with sequential and environmental it does. With environmental interdependence it has the advantage of being able to adapt all the way to a capacity of 2100 m^3/minute, which provides a good grip on the water level in the case of excess water. Also its backward pumping provision helps combat drought.
These are also properties that the Modular alternative can have. However it does score a little lower than the Engineering Options alternative. The reason for this is that the Engineering Options alternative is already quite equipped. Increasing capacity is relatively easy. For the Modular alternative, each addition to the pumping station requires a significant construction effort, which is why it's favored less by the experts.
The Big alternative also scores quite high. Since it is an 'all-inclusive' alternative and costs are not yet considered, this can be expected. The point where it loses to the Engineering Options alternative is that its size can cause negative sequential impacts and its static nature is considered a slight disadvantage.
Design alternative 3 is also just short of being the best. The reason for this is that its capacity can not be expanded easily if needed, since it is no adaptive alternative. Also there are limited options to let water back into the bosom with this alternative.

While the Engineering Options alternative is deemed the best performing alternative in terms of its influence on the interdependencies, this does not necessarily mean that it is the preferred design alternative. Since it is a hypothetical alternative, it needs to be calculated in terms of its functioning, its possibility for real-world application needs be determined and its costs need to be calculated before it can be considered as an actual alternative.
That being said, this does show the potential of adaptive design solutions, even for a static field of pumping stations which are meant to last for a century.

6.3. Life cycle costs of the design alternatives

In this section, the fourth sub-question is anwered: *How do the costs of the design alternatives compare?*
The life cycle costs of the design alternatives are presented. From the previous section it has become clear that the Engineering Options alternative is the preferred design alternative with respect to interdependence, but it can be wise to check whether the costs of this design alternative are somewhat reasonable.

The development of the needed capacity in the different climate scenarios and the adaptation tipping points that result from them has been shown already, but for completeness sake it can be seen in

Figure 6.8 below as well.

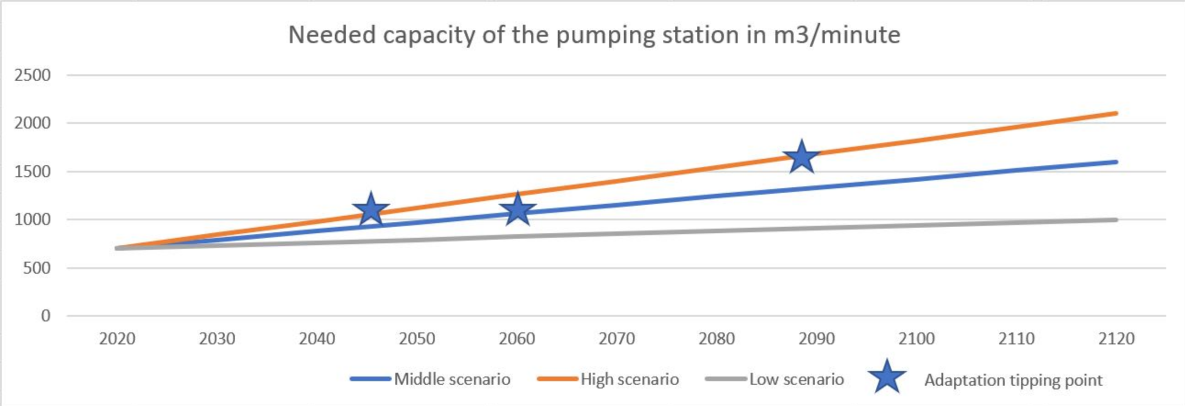


Figure 6.8: Development of the needed capacity in the different scenarios

For the calculation of the costs, the costs and lifetime of the different components listed in section 2.4 are used to determine the costs of the different alternatives. Some additional detailed assumptions have been made on top of the general assumptions listed in section 2.4. These are the following:

- Design alternative 1, 2 and 3 have the same costs, since they all three are non-adaptive alternatives with the same intended layout and a fixed capacity of 1600 m^3/minute.
- For pumps, the most conservative lifetime is assumed. This means that every 30 years, the pumps need to be replaced. For the other components, the lifetime is not variable.
- Yearly maintenance costs for the civil construction above ground do not change with the size of the facility, but stay at €800 per year for each design alternative.
- For the non-adaptive design alternatives 1, 2, 3 and the Big alternative, it is assumed that when their capacity is no longer sufficient a new pumping station needs to be built. The investment costs for the new pumping station are assumed to be the same as for the initial investment costs.
- For the Engineering Options and Big alternative and, the costs for civil construction above and below ground are assumed to be 15% higher than for alternative 1, 2 and 3.
- For the Modular alternative, the civil below ground are assumed to be the same as design alternative 1, 2 and 3. For each expansion, 15 % of these costs are added. This is because a large foundation will already be placed but the pumping bays are part of the pumping module that can be added later.
  The civil construction costs above ground are assumed to be 15% lower than design alternative 1, 2 and 3 . For expansion of the civil construction above ground, 15% of the reference costs are added for each expansion.

The results of the cost calculations are discussed in the next paragraphs.

6.3.1. Low scenario

The low scenario states that up until 2121, a capacity of 1000 m^3/minute is needed. This means that there are no adaptation tipping points that will be reached for the entire lifetime of the alternatives. For all design alternatives goes that what was built initially in 2021 is sufficient, and no expansions are needed. For all alternatives the life cycle costs consist of the investment costs, maintenance costs and periodical replacement costs of the components. The results can be seen in Table 6.2, where the costs are compared to the original preferred design alternative (which is design alternative 3) and the Big alternative, which is the 'all-inclusive' variant for comparison. The costs are rounded to tenths of a million euro, and the percentages are rounded to integers.

Table 6.2: Life cycle costs of the design alternatives for the Low scenario

Alternative	Life cycle costs	Relative difference to original preferred design alternative (3)	Relative difference to the Big alternative
1	€16,5 million	-	-13%
2	€16,5 million	-	-13%
3	€16,5 million	-	-13%
Engineering Options	€15,0 million	-9%	-21%
Modular	€14,4 million	-13%	-24%
Big	€19,0 million	+13%	-

Since only a capacity of 1000 m^3/minute is needed, are design alternatives 1, 2, 3, and the Big alternative oversized. They contain pumps that are redundant, but which do need maintenance every year and which do need to be replaced every 30 years. Design alternative is the most expensive, since it contains four pumps where alternative 1, 2 and 3 have three. the Big alternative also has a larger facility which causes higher costs.
the Engineering Options and Modular alternative only have two pumps, which is still enough capacity for this scenario. Relative to the original preferred design alternative, this saves somewhere around 10% of the costs. The difference between the Engineering Options and the Modular alternative is that the Engineering Options alternative has a large facility, the same size as the Big alternative. This causes higher civil construction costs. the Modular alternative only has an oversized foundation, 2 pumping modules and thus a smaller facility, which saves in civil construction costs which causes this alternative to be the cheapest in the low scenario. Relative to the Big alternative it's even 24% less expensive.

6.3.2. Middle scenario

The middle scenario states that up until 2121, a capacity of 1600 m^3/minute is needed. For design alternative 1, 2 and 3 this means that they have exactly the right capacity to be operational for the complete technical lifetime of the pumping station. the Big alternative still has excess capacity.
For the Engineering Options and the Modular alternative, an adaptation tipping point occurs. In 2060, the capacity of 1066 m^3/minute that they have with two pumps is no longer enough. This means they have to be adapted. For the Engineering Options alternative, the facility is already large enough so only an extra pump costing €400,000 needs to be installed along with a hatch and a valve of €40,000 and €50,000, after which the maintenance costs for that pump will also start to count. the Modular alternative needs to build a pumping module, which costs €400,000 for the pump, €40,000 for the hatch, €50,000 for the valve, €375,000 for the civil construction below ground and €75,000 for the expansion of the above ground facility. The final life cycle costs can be seen in Table 6.3

Table 6.3: Life cycle costs of the design alternatives for the Middle scenario

Alternative	Life cycle costs	Relative difference to original preferred design alternative (3)	Relative difference to the Big alternative
1	€16,5 million	-	-13%
2	€16,5 million	-	-13%
3	€16,5 million	-	-13%
Engineering Options	€16,0 million	-3%	-16%
Modular	€15,9 million	-4%	-16%
Big	€19,0 million	+13%	-

In this scenario, the differences are getting smaller. Alternative 1, 2 and 3 are built for this capacity, and they are quite close to the cheapest Engineering Options and Modular alternatives. The difference is that alternative 1, 2 and 3 still have a redundant pump that you don't need for almost 40 years but that you do have to pay for.
The difference between the Engineering Options and Modular alternative lies again in the costs for civil construction. the Engineering Options alternative is equipped to accommodate four pumps, which

means that more civil construction costs have been spent up front. The Modular alternative has been expanded to three pumping modules in 2060, which means that it will have spent a little bit less money on the construction, hence the small difference.
the Big alternative is still much more expensive than the rest, on average 15% more expensive. Renewing and maintaining pumps that you don't need for a hundred years puts quite a heavy strain on the budget.

6.3.3. High scenario

The high scenario states that up until 2121, a capacity of 2100 m^3/minute will be needed. A consequence of this high needed capacity is that there are two adaptation tipping points that will occur. The first in 2045, when the Engineering Options and the Modular alternative need to expand their capacity to 1600 m^3/minute, just as in the Middle scenario. The second tipping point is passed in 2090. Then 1600 m^3/minute is no longer enough, and all alternatives except the Big alternative need to be expanded. the Big alternative's capacity is 2132 m^3/minute so it is still safe.

Design alternative 1, 2 and 3 have a fixed capacity of 1600 m^3/minute. This means that the first tipping point in 2045 does not apply to them, since that one crosses the threshold of 1066 m^3/minute. So up until 2090, they are good. However in 2090, a higher capacity than 1600 m^3/minute is needed. These pumping stations are not expandable or flexible. This means that alternative 1, 2 and 3's functional end-of-life will arrive prematurely and that they need to be replaced with new pumping stations. As stated in the assumptions, when a new pumping station needs to be built, the initial investment costs are also the investment costs for the new pumping station. This means that everything has to be bought new in 2090 from the civil construction below ground to the E-installation. Components that are in the middle of their lifetime will have to be removed and new components are installed, starting their cycle in 2090. A total of €6,4 million has to be invested again in 2090 to accommodate the needed higher capacity.

the Engineering Options alternative needs to undertake action in both adaptation tipping points in 2045 and 2090. Its facility is already equipped to handle a capacity up to 2132 m^3/minute, so the only costs that have to be made are the purchasing costs of the new pump, hatch and valve and the maintenance costs from the moment they are installed. So for the Engineering Options alternative there is €490,000 investment costs in 2045 and €490,000 investment costs in 2090.

the Modular alternative needs to undertake action in both adaptation tipping points in 2045 and 2090 as well. Both in 2045 and in 2090 an additional pumping module needs to be added. This brings costs for the pump, hatch, valve, the civil construction above ground and the civil construction below ground. In total €940,000 has to be invested in each adaptation tipping point.
The total life cycle costs can be seen in Table 6.4.

Table 6.4: Life cycle costs of the design alternatives for the High scenario

Alternative	Life cycle costs	Relative difference to original preferred design alternative (3)	Relative difference to the Big alternative
1	€19,8 million	-	+4%
2	€19,8 million	-	+4%
3	€19,8 million	-	+4%
Engineering Options	€17,0 million	-14%	-11%
Modular	€17,4 million	-12%	-9%
Big	€19,0 million	-4%	-

One thing that stands out in this costs overview is that it has been stated that €6,4 million needed to be invested in the building of a new pumping station for alternative 1, 2 and 3. However, the total costs are only approximately 3,3 million euros higher. The reason for this is that the renewal costs of components was interrupted, and the lifetime of the new components of the new pumping station can last another 30 years (except for the E-installation which has to be replaced once more). So some

money is saved there. Nevertheless, are design alternative 1, 2 and 3 still the most expensive ones in this high scenario, due to the fact that they were too small and not adaptive.
The cheapest alternative here is the Engineering Options alternative. The Modular alternative was cheaper in the previous scenarios but the higher costs for expansion did cause it to become more expensive if such an expansion needs to be done more than once. the Engineering Options alternative as said has a large building which was already ready for the higher capacity.
The Big alternative already had the capacity of 2132 m^3/minute since the beginning. Having that capacity from the beginning turns out to be 11% and 9% more expensive than adding the extra capacity later in the Engineering Options and the Modular alternative. Since the Big alternative does not need expansion, it is now a better alternative than alternative 1, 2 and 3 when looking at the costs. The Big alternative is now 4% less expensive.

6.3.4. Answer to sub-question 4

Table 6.5 shows the overview of the costs of the different alternatives.

Table 6.5: Overview of the life cycle costs of the different alternatives

Alternative	Low	Middle	High
1	€16,5 million	€16,5 million	€19,8 million
2	€16,5 million	€16,5 million	€19,8 million
3	€16,5 million	€16,5 million	€19,8 million
Engineering Options	€15,0 million	€16,0 million	€17,0 million
Modular	€14,4 million	€15,9 million	€17,4 million
Big	€19,0 million	€19,0 million	€19,0 million

What can be concluded from this rudimentary calculation is that economically, adaptive design alternatives are quite competitive to static alternatives. The added cost of preparing the pumping station beforehand so capacity can be added later, is lower than keeping an oversized pumping station operational for its complete lifetime. It is also less expensive than building a completely new pumping station when the capacity is not enough anymore.
One could argue that this large difference in costs is because in the calculation, the shortest lifetime of the pumps was assumed, of 30 years. This causes extra investment on the part of the non-adaptive alternatives, while the adaptive alternatives have very low costs because they have less pumps and don't need to spend €400,000 per pump every 30 years. To check whether this really is the cause of the fact that the Engineering Options and the Modular alternative consistently cheaper, the same calculations have been done, but with the lifetime of the pumps assumed the most lenient, being 60 years. The results of this calculation can be seen in Figure 6.9.

	Low	relative difference to current preferred design alternative (3)	relative difference to alternative 6	Middle	relative difference to current preferred design alternative (3)	relative difference to alternative 6	High	relative difference to current preferred design alternative (3)	relative difference to alternative 6
1	€ 14,2 million	0%	-11%	€ 14,2 million	0%	-11%	€ 18,6 million	0%	18%
2	€ 14,2 million	0%	-11%	€ 14,2 million	0%	-11%	€ 18,6 million	0%	18%
3	€ 14,2 million	0%	-11%	€ 14,2 million	0%	-11%	€ 18,6 million	0%	18%
Engineering Options	€ 13,4 million	-6%	-16%	€ 14,0 million	-1%	-12%	€ 15,0 million	-19%	-5%
Modular	€ 12,9 million	-9%	-19%	€ 13,9 million	-2%	-12%	€ 15,4 million	-17%	-3%
Big	€ 15,8 milion	11%	0%	€ 15,8 million	11%	0%	€ 15,8 million	-15%	0%

Figure 6.9: life cycle cost calculation with a pump lifetime of 60 years

This figure shows that the longer lifetime makes some differences smaller, and some differences larger. For the low scenario, the Engineering Options and the Modular alternative are still 6% and 9% cheaper than alternative 1, 2 and 3. In the middle scenarios, the differences are very small between the first 5 alternatives. Such a small amount of difference in cost may advocate for the non-adaptive alternatives, since you build them once and then you're done. You don't need to meddle in the pumping

station anymore, where you do need to meddle in the Engineering Options and Modular alternative. It's likely that the 1% or 2% costs you save for the Engineering Options alternative and Modular alternative will be lost in the preparation for the expansion of their capacity.
In the high scenario, the differences are actually bigger than before. The reason for this is that with a longer lifetime of components, it is less efficient to replace components in the middle of their lifetime. With a short lifetime there is a constant cycle of replacement with which you are able to play. With a long lifetime that is not as easy and removing and building a part new in the middle of the old components' lifetime, hurts extra much.

A final note is about the Modular alternative. It has been created in Chapter 5 as a modular design alternative. As stated in Chapter 3, is there not yet a supply chain and a culture of modular pumping stations present. This causes the prices of the 'pumping modules' to be the same prices as the custom made components in the other alternatives. When such a culture and supply chain would be available and there existed prefabricated pumping modules, then the prices of these modules would likely be lower, resulting in a cheaper the Modular alternative.

6.4. Conclusion (answer to sub-question 5)

The fifth sub-question is *What is the impact on decision-making?* When combining the results of the cost indication and the influence of the design alternatives on interdependence, a strong case can be made for the adaptive design alternatives. the Engineering Options alternative scores the best on the interdependence, and the best in the high scenario for costs. the Modular alternative has a shared second place for interdependence, but scores the best in the low and middle cost-scenario. Being able to adapt to changing circumstances and only expanding capacity when needed can potentially save money, and has the best influence on interdependence in this case.

This shows that there is an influence on decision-making. With approximately the same amount of money design alternatives can be created that are better suitable to account for climate change uncertainty and that have a good influence on interdependence. The fact that climate change uncertainty is accounted for advocates for more inherently flexible design alternatives, combined with concerning the *what*, *where* and *when* of hydraulic infrastructure renewal that is also part of adaptive policymaking. Accounting for interdependence also advocates the choice of more flexible design alternatives, since the development of the interdependencies ans the resulting influence of the design alternatives on those interdependencies is dependent on the development of climate change.

Taking interdependence into account has another impact on decision-making. During the scoring sessions, it turned out that a majority of the items that arose as factors that make up the interdependencies were items that was already thought of before when making the design alternatives. For example the relocation of the pumping station was done with the idea in mind that it would save a lot of work for the regional water barriers through the town of Zoutkamp. Interdependence was already a part of the decision-making process, but in a more dormant, implicit way. Taking interdependence into account makes these considerations explicit, and shows where the differences between the alternatives for all interdependencies are. Doing so makes sure that all interdependencies are considered before making a final decision. If needed, the design alternatives can be altered if the outcome of the process indicates issues with certain interdependencies.

7

Proposing a framework

From the results of the case study that has been performed in the previous chapter, this chapter proposes a decision-support framework. It answer the sixth sub-question: *How could a decision-support framework that takes climate change uncertainty and interdependence into account look?*
The created framework can be seen in Figure 7.1.

The framework is a conceptual representation of the research process that has been conducted in this research. The steps that have been taken, and the factors that have been found to influence the outcome of those steps are integrated in the framework. The findings of this research have been presented in a general manner. This has been done with the purpose of creating a decision-support framework that is applicable on other projects of renewal of pumping stations in a polder system as well.

The rest of this chapter will walk through the framework. Each section presents an intermediate process step (or steps) and in those sections the aspects that have been found, what needs to be kept in mind and the limitations of that part of the framework are discussed.

7.1. Adaptation tipping point

The start of a renewal project of hydraulic infrastructure is an Adaptation tipping point. Here it is recognized that the way things are going are not sufficient to meet safety standards in the future anymore. This tipping point can be influenced by structural deterioration, biophysical change and socioeconomic change (van der Vlist et al., 2015). These factors have not been a subject to this research, but are listed in literature and accepted as a given.

For the HD Louwes pumping station, all three of these factors have played a part to some extent in the reaching of the tipping point. Biophysical change, since the changing climate magnified the imbalance in the water system, causing problems elsewhere in the system; structural deterioration because the current pumping station is not capable anymore to reach its full theoretical capacity of 1000 m^3/minute; and socioeconomic change because there is a need for keeping the water system accessible and navigable.

7.2. Creation of design alternatives

After an adaptaion tipping point has been reached, you need to decide what you want to implement. This leads to the process of which the preferred design alternative is the result. For a design alternative to be the preferred one, first a set of design alternatives need to be created. These can be both adaptive and non-adaptive. The design alternatives that will be developed need to adhere to certain requirements. Requirements can come from certain stakeholder demands of wishes which in case of the HD Louwes is for example that the new pumping station should not overshadow the monumental sluice that is present. Furthermore does a pumping station have a desired function, which also leads to requirements for the capacity, for example. The budget is also an important factor that influences

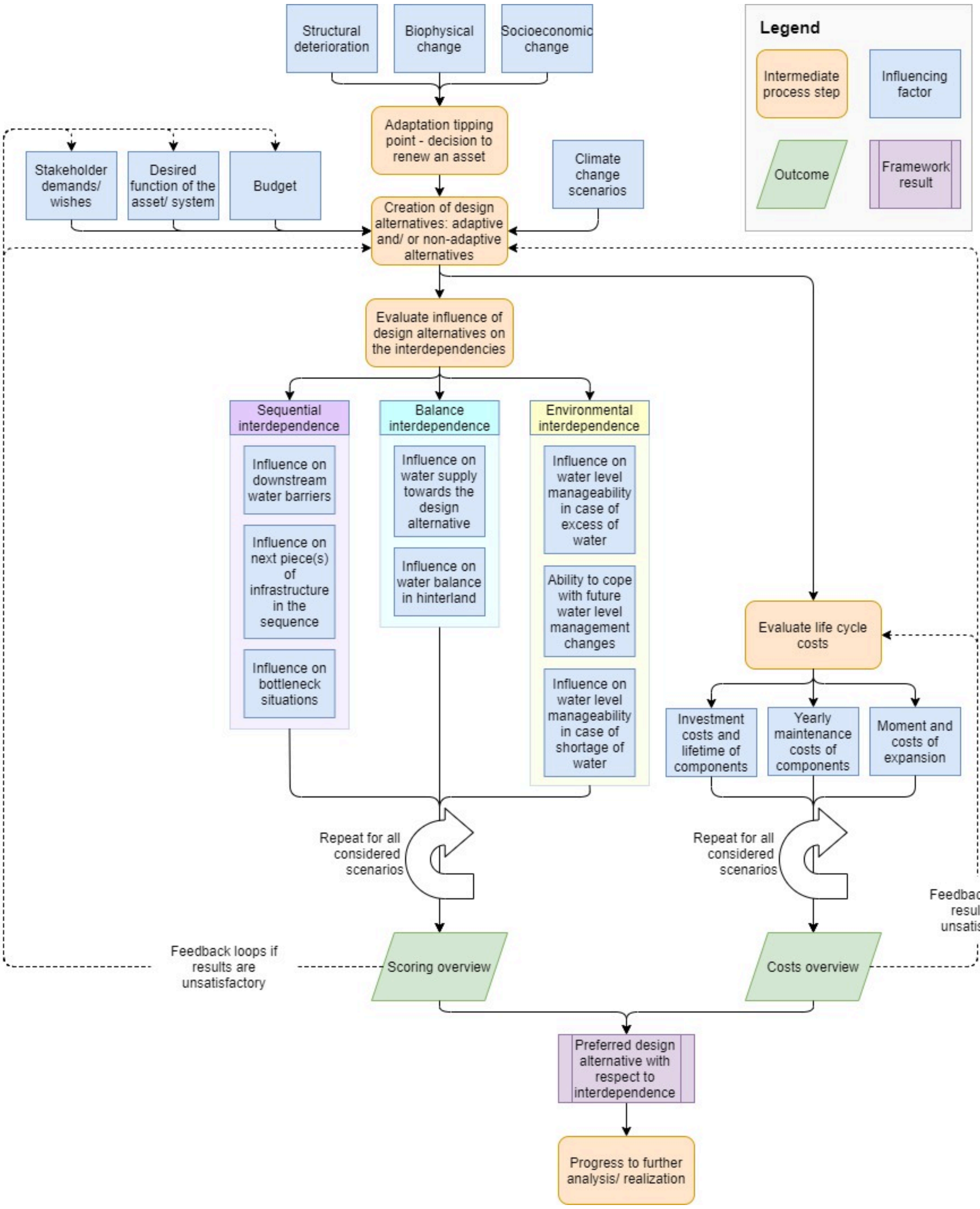


Figure 7.1: The framework (own production)

the design alternatives.
A pumping station functions for a hundred years and it needs to be able to pump enough water away so the polder remains dry enough, This means that a pumping station needs to operate under a changing climate. The extent to which the climate is expected to change influences the requirements of the design alternatives, the most important one being the capacity.

7.2.1. Non-adaptive design alternatives

Non-adaptive design alternatives are design alternatives that you build now and that you expect to operate in the same manner for the next hundred years. With respect to climate change, a climate scenario that is conceived as realistic/ average/ worst case is assumed, and the dimensions of the alternative are created accordingly. Non-adaptive alternatives are difficult to alter in the future if needed, since they are custom built for that specific set of requirements. All investment costs are due at the start of the project, and at the end-of-life of its components

7.2.2. Adaptive design alternatives

Adaptive design alternatives are created a little differently. The long-term goal should be specified, for example 'staying safer than the 1:100 safety norm'. Then adaptation pathways are constructed, in which the interventions can be placed to adhere to that long-term goal. Some measures may already be necessary, for example creating the closing provision to separate north and south, in the case of HD Louwes. Other, such as expanding the capacity are not yet needed and can be done later.
The choice can be made to place several succeeding non-adaptive alternatives in pathways, which is also a perfectly fine approach to reach the long-term goal. This refers to the *what*, *where* and *when* of interventions (Busscher et al., 2014). Additional to a broad view on those aspects of adaptive thinking, inherently adaptive alternatives are a good fit for a pumping station. for HD Louwes, these flexible alternatives are design alternative 4 and 5 in which the pumping station itself can be modified in the future if needed.

With adaptive design alternatives, you don't need to pick one specific scenario that you build your pumping station for. You still need to decide which scenarios you want to anticipate on, though. If the consequences of these scenarios are known, as well as the current situation, then you can create the design alternatives so they can adapt to any of the scenarios if needed. Of course you will still be limited by your budget, but adaptive design alternatives require often a smaller initial investment. The life cycle cost estimation later in the framework help to keep track on the costs of adaptation. Under different scenarios, it becomes clear when the tipping points for expansion are likely to happen and how the design alternatives will eventually look under each scenario.

7.3. Evaluate the influence of the design alternatives on the interdependencies

After creating the set of design alternatives, you need to be able to compare them before reaching a decision on which one is the most preferred to implement. Deciding this can rely on many factors, but this research focused on what would be the preferred design alternative based on the alternatives' influence on interdependence. Parallel to the interdependence, this research has given an indication of the life cycle costs in its net present value for the alternatives. This will be further discussed in section 7.4. The three interdependencies are judged on their influence on the factors that emerged during the scoring sessions. These factors are listed in the framework under each interdependence. They are listed as part of the interdependence because it is not known what their reciprocal importance is. This research has shown that these factors need to be taken into account, but it is still unknown whether some factors should have a heavier vote than others. Right now the eventual score is an expert judgement of the influence of the factors. The next paragraphs will discuss each interdependence and their factors, and the last step of repeating the process step for all considered scenarios.

7.3.1. Sequential interdependence

Sequential interdependence is concerned with what happens downstream of the pumping station, in the following infrastructure in the sequence. If you replace the current pumping station with the new one, how will that influence the infrastructure downstream? Does this intervention expedite the moment at which the downstream infrastructure needs to be renewed, or does it postpone that moment? Three factors have emerged that are of importance to sequential interdependence.

1. **Influence on downstream water barriers**
   Downstream of the pumping station, water barriers can be present. These can be along the river or channel, or in the case of the HD Louwes along a lake. How high are they, and how high should they be with the added amount of water that comes from the new pumping station? And with changing the location of the pumping station, what kind of influence does that have?

2. **Influence on next piece(s) of infrastructure in the sequence**
   The next piece(s) of infrastructure are not the water barriers, but the next pieces of infrastructure that actively do something with the water. This could be another pumping station, a weir or a sluice for example. In the case of the HD Louwes there is only one piece of infrastructure left, the discharge sluices, after which lies the sea. With the added capacity of the new pumping station, is the next piece of infrastructure capable of handling the extra water? Otherwise the design alternative might keep its own hinterland safe but cause extra problems downstream. If a discharge sluice towards the sea is the final piece of infrastructure in the sequence, then sea-level rise should be considered as well since that narrows the window for discharging water.

3. **Influence on bottleneck situations**
   Bottleneck situations are locations where the waterway is too narrow to properly let all water pass, and congestion happens. For the HD Louwes this is the narrow Hunsingo sluice which would cause problems for design alternative 1 and 2. To evaluate this factor, one should have a clear overview of what items are present in the waterways and how a new pumping station with more capacity influences possible bottleneck situations. Does it make it worse or better? The location of the intervention plays an important role in this factor.

7.3.2. Balance interdependence

Balance interdependence refers to the flowing of the waterways in the hinterland of the pumping station. From the previous piece of infrastructure in the sequence, the water should flow neatly towards the pumping station that is being renewed. This is not always the case, as seen with the HD Louwes. Interventions can solve imbalances in the system, if they are present. The following factors are of importance for balance in the water system when renewing a pumping station:

1. **Influence on water supply towards the design alternative**
   If you place a new pumping station, are the waterways equipped in a right way that the water flows towards the pumping station? A pumping station with a high capacity creates a draught of water, and it can be that the waterways towards the pumping station are too narrow to accommodate this draught. If this is the case, then you either need to broaden the waterways, or you have no benefit of the higher capacity.

2. **Influence on water balance in hinterland**
   How was the water balance in the hinterland, and how does that change with the placement of the new pumping station, with in the case of the HD Louwes the additional closing provision in the river between the northern and southern part of the bosom? Also look further ahead. You may solve an imbalance that is present by separating two water systems, but then you should also consider the water balance in the new system that you have created. Are there any problems there? Does the capacity or the location of the design alternatives change any of those issues?

7.3.3. Environmental interdependence

Environmental interdependence refers to the management of the water level in the hinterland of the pumping station. This water level is maintained for several environmental purposes such as ecology or agriculture. Renewing a pumping station changes the manner of grip that you have on that water level, which can increase or decrease. This grip is dependent on three factors.

1. **Influence on water level manageability in case of excess of water**
   This factor refers to removing water out of the polder, the core business of a pumping station. In

this regard, a high capacity can be seen as always better than a low capacity. This is because a pumping station does not always have to run at full capacity, it can adjust its power according to the needed capacity of the moment. With a high capacity, you are ready for any excess of water coming your way. This may not be as efficient in terms of other aspects such as costs, but for this factor it applies that a high capacity is always better.

2. **Influence on water level manageability in case of shortage of water**
   This factor refers to letting water back in during periods of drought. These periods are expected to happen more often, in any of the climate scenarios. Letting water back in is not necessarily something that a pumping station is able to do. This can be done through sluice gates if the water level is the same on both sides of the pumping station, through a flowback provision if the water level downstream is higher than the water level upstream, or through backward pumping if the water level downstream is lower than the water level upstream. Here the same principle applies that a high capacity is better than a low capacity.

3. **Ability to cope with future water level management changes**
   The way that the water level can be managed is heavily dependent on the decisions that are made about the water level on both sides of the pumping station. Choices can be made to maintain a higher or lower water level for a multitude of reasons. The pumping station's grip on the water level depends on the capability to cope with those changing decisions. However, it's impossible to tell what those decisions will be for the next hundred years.
   Basically there are three options for the future: the water level is the same on both sides; the water level is higher downstream; the water level is higher upstream. The score of the design alternatives for this factor depends on how the alternative scores on the above two factors under these three scenarios.

7.3.4. Repeat for all scenarios

When all the factors are considered, then the influence of the design alternatives in the interdependencies is known. In this research, the experts have considered the design alternatives once, and they took the future into account. If one has the possibility to calculate all the scenarios however, then for each scenario the influence of the design alternatives on interdependence can be assessed. If the course of a scenario is known, then the moment at which an adaptation of the flexible alternatives is needed can be known. For the lifetime of the alternatives under each scenario the influence of the alternatives on interdependence can be determined, giving a complete overview. The same goes for the non-adaptive alternatives, but their design stays the same. They do function differently under different climate scenarios.

7.3.5. Scoring overview

Once the influence of the design alternatives on interdependence has been assessed for all alternatives and scenarios, you have an overview of the scores of all alternatives. This overview presents the information that is needed to identify the design alternative that performs the best with respect to its influence on interdependence.

7.4. Evaluate life cycle costs

Next to evaluating the influence of the design alternatives on interdependence, an indication for the costs is also a good thing to have. This provides you with an argument for the implementation of certain interventions. One might think that adaptive alternatives are inherently more expensive, but the previous chapter has shown that this not true, adaptive alternatives can turn out to be cheaper. At the same time you cannot say that flexible alternatives are always cheaper, so to have an indication of the costs is good to have and to compare the alternatives.

7.4.1. Life cycle costs factors

Such life cycle costs can be made as detailed as the user of this framework would like. This research has aimed on its indicative power rather than the full details, and has used the three factors that need to be included at least in such a calculation, using the net present value.

1. **Investment costs and lifetime of components**
   If you have determined which components should be taken into account in the calculation of the costs, then their investment costs and lifetime duration should be determined. With non-adaptive alternatives, all investments are done beforehand and at the end of the lifetime of the component. Adaptive alternatives can postpone certain investment costs, while other investments are higher to proactively build the flexibility into the design.

2. **Yearly maintenance costs of components**
   Each component has yearly maintenance costs that have to be spent each year until the component is being replaced by a new one.

3. **Moment and costs of expansion**
   For the scenario that you are analyzing, there are certain tipping points where the adaptive alternatives need to be expanded, or where even the non-adaptive alternatives do not function sufficiently enough anymore. The years where this is the case, extra costs need to be made. For the adaptive alternatives these costs are easier to know (the costs for one extra pump are easy to find) but for a non-adaptive alternative it is important to find out what the investment costs are when they are not good enough anymore. Does the entire pumping station have to be renewed? Or can they in some way be expanded too? Knowing this helps in creating a trustworthy costs comparison.

7.4.2. Repeat for all scenarios

Just as the evaluation of the influence of the design alternatives on interdependence, do the life cycle costs of the design alternatives differ per scenario. Under some scenarios expansion may not be needed or limited, and in some cases much expansion is needed. That is why the costs calculations need to be repeated for all scenarios that are being considered.

7.4.3. Costs overview

When the life cycle costs have been calculated for the design alternatives for all scenarios, you have an overview of the costs. This overview presents the information that is needed to determine which design alternative is economically the best option.

7.5. Outcome of the framework

The outcome of the framework is the preferred design alternative with respect to interdependence. For the interdependence there is a scoring overview of the results, as well as for the cost calculation. The results of this overview are free to be interpreted by the decision-maker. One could choose to pick the alternative with the best influence on interdependence as the preferred alternative, irrespective of the costs. Or a performance/ costs ratio can be constructed to see which one performs the best for the least amount of money. This interpretation is up to the decision-maker. The presented framework provides the way to arrive at this consideration.
When the preferred design alternative with respect to interdependence is known, the process can continue. It is likely that other factors such as public acceptance are also being considered to arrive at an overall preferred design alternative. When that has been selected, one can progress to the actual development of the pumping station.

8 Conclusion and discussion

In this chapter the conclusion and discussion of the research are presented. In the conclusion the main research question is answered. Furthermore, it will be discussed what the main contributions of this research are in scientific perspective, as well as in a practical perspective. The discussion will discuss the limitations of the research, and recommendations for further research will be given.

8.1. Conclusion

8.1.1. Answer to the main research question

The main research question was: *To which extent does incorporating climate change uncertainty and interdependence influence decision-making for the renewal of hydraulic infrastructure?*

This main research question can be answered as follows: Incorporating interdependence and climate change uncertainty influences the decision-making process in such a way that flexible and adaptive alternatives are becoming more preferable than static design alternatives. This goes for both interdependence and climate change uncertainty.

Incorporating this further influences the decision-making process in the sense that interdependence of design alternatives that is implicitly thought of beforehand are now made explicit, and it shows the differences between the design alternatives for those interdependencies. Where previous methods may think of some interdependence when creating the design alternatives and later solely look at the isolated alternatives for a decision of a preferred design alternative, does this method show that there can still be differences between those design alternatives and that those differences impact which design alternative is most likely to perform best.

One can incorporate interdependence by dividing interdependence of infrastructure into categories of interdependencies, and finding factors that are distinctive for those categories and which shape the outcome of the influence of those categories. The design alternatives that have been created can be evaluated with those distinctive factors. When the influence of the design alternatives on the interdependencies is known for all considered scenarios, and an indication of the costs is given through the life cycle costs for all scenarios, then a preferred design alternative can be selected by a decision-maker. Since the presented framework is a decision-support framework instead of a decision-making framework, it does not make a choice. It presents the decision-maker with information based on which he or she can confidently and arguably decide.

The framework can be considered an adaptive framework for two reasons. The first reason is the fact that with the creation of the (adaptive and non-adaptive) design alternatives and their evaluation under several scenarios, the alternatives are prepared to deal with uncertainty for the long-term, and one can proactively create pathways of adaptation for several futures.

The second reason is that the framework itself has adaptive properties. The scenarios with which the influence of the design alternatives on interdependence is assessed can be interchanged for other scenarios. Also, the factors that are distinctive for the interdependencies can be altered or removed, or new factors can be added. The listed factors are considered to be important ones for all projects of pumping station renewal, but if further research finds new insights regarding these factors they can be altered.

The preferred design alternative that is a consequence of the method that is presented, is not necessarily the overall preferred design alternative. Besides interdependence do other factors such as a support base in the population play a role as well. The preferred design alternative with respect to interdependence needs to be evaluated in light of those other terms as well, before it can be considered as an overall preferred design alternative.

In the beginning of the research the question was raised under which circumstances the choice of preferred design alternative would differ from the current preferred design alternative. The adaptive design alternatives start to be better suited when the level of uncertainty becomes higher. This makes sense since you do not need an adaptive design alternative if you already know what is going to happen. If the future is uncertain, then the need for flexible solutions is higher so the operator can adapt to the evolution of the climate and the water system.

8.1.2. Scientific contributions

The research gap that was identified at the beginning of the research was that decision-support frameworks that are available in the literature consider the hydraulic infrastructure that is to be renewed as an isolated piece, when comparing between design alternatives. The fact that the different design alternatives can have a different effect on the water system in which the hydraulic infrastructure operates, is not yet a part of the decision-making process.
The method presented in this research provides a supplement to the decision-support frameworks that are available to decide on the preferred design alternative. The hydraulic infrastructure that is to be renewed is no longer treated as an isolated piece, but their functioning within the water system is explicitly evaluated.
Placing this research in the perspective of science regarding the renewal of hydraulic infrastructure, this research provides a way to not only look at the isolated asset when thinking of how to renew it, but also to look at the water system it operates in. The difference between design alternatives in terms of their differing effect on the water system can be evaluated and incorporated into the process of deciding on a preferred design alternative.

The factors that are identified to determine the score for an interdependence, are not new concepts. In the interviews, it became clear that they have already been considerations based on which the old preferred design alternative (alternative 3 in this research) has been shaped. Some considerations were more explicit, some more implicit, and some were thought of in the beginning but deemed too uncertain to consider. This research explicitly states these considerations as factors that shape the outcome of the score of the interdependence. Doing this would cause the users of this framework to think about whether this is the case for their design alternatives, and what the consequence is for the water system that they work in. If the results of the interdependencies are quite negative, the users of the framework may be better off to go back to the drawing board and alter their design alternatives.

Next to interdependence does this framework provide a handle to make decisions that face long-term uncertainty. For the renewal of a pumping station you need to look a hundred years into the future, which is surrounded by many uncertainties. This framework helps in grasping the uncertainties and anticipating on their possible outcomes.
Placing this research in the context of scientific research regarding adaptive planning or policymaking, this research does not provide substantial additions to the body of knowledge that is there. It is however another illustration of the added value that adaptive designing and thinking can have in light of long-term uncertainty. The fact that this research focused on interdependence does in light of adaptivity theory not matter that much, the influence of climate change on the outcome of interdependence is just part of long-term uncertainty.

8.1.3. Practical contributions

An advantage of this method is the fact that adaptive and non-adaptive design alternatives can be compared with each other. This is not a new contribution to science but it does help in weighing options.

A non-adaptive alternative will not change under different scenarios, unless the scenario assumes a steep climate change where the capacity of the alternative is not enough anymore and its functional end-of-life will be reached prematurely. If it doesn't change it may still have different influences on interdependence, according to a different scenario. Adaptive alternatives can have different configurations under different climate scenarios. Their influence on interdependence changes accordingly. This method can evaluate each alternative independently and compare them as equals. It is very well possible that sometimes a non-adaptive design alternative performs better, in a not so complex situation for example.

This method shows that design alternatives that contain an intrinsic flexibility with regard to their capacity, are capable of dealing with long-term uncertainty with regard to climate change, have a better influence on the interdependencies, and can possibly save money as well, compared to non-adaptive design alternatives since purchase and maintenance costs can be postponed.

The indication of the life cycle costs that has been performed in this research further provides an argument to not immediately write off adaptive design alternatives because they cost more money initially (the Engineering Options alternative) or because they ask for relatively large construction works in the case of capacity expansion (the Modular alternative). The cost of preparing for flexibility is still far lower than expanding a non-adaptive alternative. Furthermore, if for the Modular alternative constructions need to be done, that will happen once every few decades so there is not that many nuisance as a consequence for the nearby surroundings. Depending on the scenario and the underlying assumptions, up to 13% of costs can be saved when comparing the current preferred design alternative with the adaptive alternatives.
Here it must be noted that this cost reduction will likely not be achieved in the first projects where adaptive design alternatives are applied. Intrinsically adaptive design alternatives are not yet applied that much, and the presented alternatives in this research are on a conceptual level, not ready yet to immediately implement. This means that first knowledge needs to be gained about the correct engineering of such adaptivity and the fitting of such alternatives into the water system. This will cost time and money, which means that at first such projects will not immediately lead to the projected cost reductions. Though this does show the potential cost reductions in the future.

Building a pumping station in a changing climate may no longer ask for a single, once in a (technical) lifetime investment that will last a hundred years. Preparing for different futures and taking smaller steps along the way helps in staying in sync with climate change and to keep maintaining the safety norms.

8.2. Discussion

In the discussion, the limitations of the research are discussed and recommendations will be made for future research.

8.2.1. Limitations of the research

This section will reflect on the limitations of the research, where the methodology could have been different or ways to improve the findings.

The first limitation is the one that was already mentioned in the methodology chapter itself, being the qualitative judgement of the influence of the design alternatives on interdependence rather than qualitative. The reason for that choice has been substantiated already, being that calculating all scenarios and all influences in a hydrologic water system model was too complex for this research. The 'repeat for all scenarios' part of the final framework in Chapter 6 has not been done in this research. That should however be done in a quantitative calculation, which is why it was inserted into the framework. The influence of the design alternatives on interdependence is judged by experts, whose judgement is valid too. First the responses of the experts were needed to find out which factors form the basis of the interdependencies. Those factors that have been found would serve as parameters in a quantitative model. There might arise some differences however in the results of the qualitative and the quantitative method, while they are likely to resonate for the largest part.

The second limitation is that this research has not tried to discover all interdependencies that are present in this system. Three general water management phenomena are assumed to be the most prominent three, and the research has focused on finding out how to assess those, rather than digging up every little interdependence that may be there, such as fish migration across the water system. While the three interdependencies that are used in this research are considered the most important, it could be that other interdependencies that could also play a meaningful role in the water system are overlooked in this analysis.

The third limitation of the research is that there is no knowledge yet about the relative importance of the factors that influence the outcome of the interdependence. For example, for sequential interdependence the influence of the design alternative on bottleneck situations might be more important than the influence of the design alternative on the regional water barriers downstream. At the moment these factors are considered as equals.
The same goes for the relative importance of the interdependencies themselves. Sequential interdependence could perhaps be more important than balance interdependence, but that is not known yet.

8.2.2. Recommendations for future research

Following the conclusions of the research and the limitations of the research, several recommendations for future research will be made in this section in order to enhance the knowledge about incorporating interdependence into decision-making.

The first recommendation for future research is the evaluation of the framework. It can be evaluated in terms of whether this framework is generalizable to use on projects of the renewal of pumping stations. It could also be evaluated whether this framework is applicable to other hydraulic infrastructure renewal in a broader sense. So perhaps for weirs or sluices or other hydraulic infrastructure.

The second recommendation for future research is that the evaluation of the influence of the design alternatives on interdependence can be done quantitatively instead of qualitatively. The factors that make up the interdependencies are the parameters according to which the model can be made. Furthermore, the relative importance of the factors and the interdependence can be researched and put into the model as well. This could be done in a relatively similar way as Beta's in RUM-MNL models.

The third recommendation for future research is to research whether this framework could also be applied to other water systems than a polder system. Perhaps this framework could also be useful in for example river basins and the infrastructure that is present in that basin. Perhaps it needs alterations first before it can be used in other water systems.

The final recommendation may be more of a philosophical one. It can be good to determine what exactly makes up a preferred design alternative. Even if rational thinking and analyses may find that the Engineering Options alternative is the preferred design alternative, the old preferred design alternative may still be the most desirable alternative to implement.
The reason for this is that water authority Noorderzijlvest has spent a lot of time and effort into creating a solution that is widely accepted within the local community, by combining projects and keeping in sync with the wishes of the stakeholders. Furthermore, the project was awarded the 'Duurzame Parel' status for their implementation of sustainability into the project. For the Engineering Options alternative this is not yet known.
So, additional to the performance and costs of the Engineering Options alternative, the approval of the community is also very important to determine whether or not this project of hydraulic infrastructure renewal could be a success. The way to measure success is up for debate.

A

Scientific research paper

A.1. Abstract

In order to keep the hydraulic infrastructure system in the Netherlands from deteriorating, large investments will have to be done in the near future. Decision-support frameworks help in making the right investment decisions for infrastructure that is intended to stand for a hundred years. Such a long lifetime brings forth a high level of uncertainty, regarding climate change as well as its impact on interdependence. So far, most of the adaptive decision-support frameworks do look at climate change uncertainty, but do not consider interdependence as a distinctive factor between design alternatives. This research presents a first impulse to incorporate climate change uncertainty and interdependence into the decision-making process. Under the scope of a case study, the renewal of a pumping station, relevant interdependencies are identified. Next to the original design alternatives, new design alternatives are created based on the theory of Adaptivity, Engineering Options and Modularity. The influence of the alternatives on the interdependencies is assessed, and their life cycle costs are calculated. The findings are presented in a proposal for a decision-support framework. This research shows that incorporating interdependence and climate change uncertainty makes inherently flexible design alternatives more desirable than static design alternatives. For the identified interdependencies, the adaptive design alternatives have a more positive effect. Also, the costs of the adaptive design alternatives are continuously lower than the static design alternatives.

A.2. Introduction

Infrastructures age. In the Netherlands, a large portion of the hydraulic infrastructure (such as weirs and pumping stations) has been built between the 1920's and the 1960's (Willems et al., 2016). When this infrastructure is built, the common technical lifetime of this infrastructure is between 80-100 years. This indicates that in the coming years, a large part of the hydraulic infrastructure will reach the end of its technical lifetime and will need to be renewed. The research institute TNO (2021) confirms this in in a prognosis of the status of Dutch civil infrastructure.

When the technical or functional lifetime of hydraulic infrastructure has come to an end, the decision has to be made on what to do with that piece of infrastructure. When infrastructure needs to be renewed it presents a 'once in a lifetime opportunity' to try to restructure the the system so that it meets new goals (Vuren et al., 2015).

In creating the design alternatives and subsequently in deciding between them, there are factors that complicate the process. When a hydraulic structure is built, it is desired that it functions as intended for its complete technical lifetime. As said, a common technical lifetime is 80-100 years. This can be considered as long-term, which brings a high level of uncertainty into play about its functioning in the future (Pot et al., 2018). The precise impact of climate change is unknown, future technologies can make the current technology redundant, and socioeconomic changes can have an impact on the demand towards infrastructure (Haasnoot et al., 2013).

To support decision-making regarding hydraulic infrastructure in light of long-term uncertainty, several researchers recommend the application of the theory of adaptivity to the planning of infrastructure renewal (e.g. Busscher et al., 2014; Hui et al., 2018).

Another factor that complicates the process of hydraulic infrastructure renewal, is the matter of interdependence. In an infrastructure system, one piece affects the larger whole (Brown, 2014). This is especially the case for hydraulic infrastructure. The interdependencies of hydraulic infrastructure work in two ways: functional interdependence where a structure influences other infrastructures; and interdependence of a structure with its surroundings such as ecology.

So far, there is not yet a way to take interdependence into account when deciding between design alternatives, and to analyse how this might influence the decision on the preferred design alternative. The available decision-support frameworks treat the renewal of a hydraulic structure as if it's an isolated piece of infrastructure, without influence from and on the environment in which it operates.
This article aims to contribute to the incorporation of interdependence and climate change uncertainty into the decision-making process. It explores how interdependence could be incorporated and to which extent this influences the choice of the preferred design alternative. This will be done in light of a case study, being the renewal of the pumping station H.D. Louwes in Zoutkamp.
The main research question that is answered is the following: *To which extent does incorporating climate change uncertainty and interdependence influence decision-making for the renewal of hydraulic infrastructure?*

This paper is structured as follows: the used methods and the case in which they have been used will first be elaborated on in section A.3. Then, the possible ways to deal with long-term uncertainty when designing hydraulic infrastructure will be discussed. section A.5 is about the decision-support frameworks that are already present in literature. After this chapter the case will be described, and following on the description of the case the relevant interdependencies will be identified. New design alternatives will be created in section A.7 and the assessment of the design alternatives in light of the interdependencies and climate change uncertainty will be discussed in the Results chapter. Finally, the Conlcusion will answer the main research question and presents the contributions of this research, while the Discussion will discuss the limitations of the research and propose future research directions.

A.3. Methods

A literature review will be done to answer two sub research questions: *What are possible ways to deal with long-term uncertainty in designing hydraulic infrastructure?*; and *What is available in literature regarding decision-support frameworks for the renewal of hydraulic infrastructure?*
The first sub research question will be supplemented with an expert interview, because of the limited availability of relevant literature. The interviewee is a teacher at the department of Hydraulic Engineering at the TU Delft and is specialized in multi-functional water barriers.

The case that has been used to perform this research is the pumping station H.D. Louwes in Zoutkamp, in the north of the Netherlands. It is the responsibility of regional water authority Noorderzijlvest and it is in need of renewal. The cause for renewal is the fact that there is an imbalance in the polder that the H.D. Louwes keeps dry, together with pumping station the Waterwolf. This imbalance has water flowing south, where the Waterwolf is partly doing the H.D. Louwes's job in pumping water from the polder into the Lauwersmeer, after which the water will be discharged into the Wadden Sea. This can cause problems elsewehere in the polder system during heavy rain. Figure A.1 shows the river that is responsible for this imbalance.
To solve this problem, a provision will be built in the problematic river that can be closed during situations of high water. This will separate the water system into two water systems that each have their own responsible pumping station. For the H.D. Louwes to be able to keep its own water system dry, it needs to be renewed.

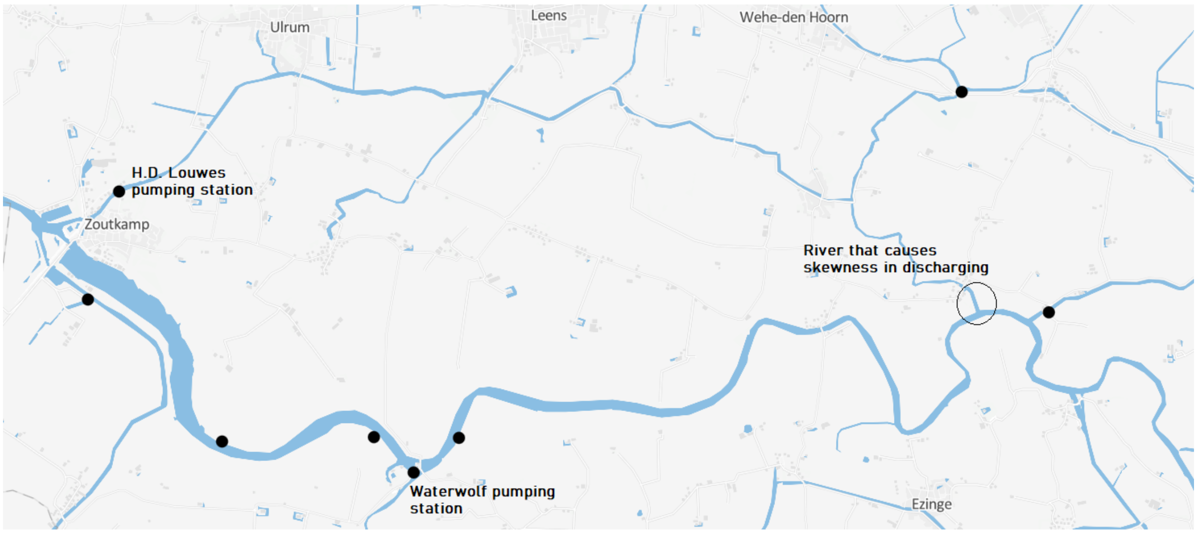


Figure A.1: The imbalance that is the cause for the renewal of the H.D. Louwes

In this case study, documents have been analysed, interviews have been conducted, and the life cycle costs of design alternatives have been calculated.

In order to incorporate interdependence into the decision-making process, first the relevant interdependence that plays a role needs to be identified. These interdependencies are collected through various sources. They do not present new phenomena, since they are water management issues that have been present since there is water to be managed. They are however new as an interdependence, which is why they will be assigned new names in this research. The identification of the interdepence is done through literature analysis, document analysis and interviews with parties closely involved with the case.

Then new design alternatives will be created. These new design alternatives are created based on the findings of the first two sub-questions, and they should be able to deal with climate change uncertainty. The new design alternatives are analysed alongside the already existing design alternatives when incorporating interdependence to see if there is a difference in the outcome.

For the analysis of the old and new design alternatives, expert sessions have been organized. For each of the identified interdependencies the expert assigned scores to the design alternatives. The scores correspond to a negative of a positive influence of the design alternative on the interdependence, according to a five-point scale. (– to ++). These results are synthesised in the end and a preferred design alternative with respect to interdependence is the result.

The life cycle costs of the old and new design alternatives have been analysed, to see whether the new design alternatives are economically competitive with the old design alternatives. These costs are calculated based on the investment costs, yearly maintenance costs and lifetime of the components that make up a pumping station.

When the costs have also been calculated, it can be determined by the decision-maker what the preferred design alternative should be. The impact of incorporating climate change uncertainty and interdependence into the decision-making process is assessed. Furthermore a decision-support framework is proposed that takes these two aspects into account.

A.4. Possible ways to deal with long-term uncertainty in designing hydraulic infrastructure

Following from the literature review and the supplementing interview, there are two theorems that could deal with long-term uncertainty when designing hydraulic infrastructure: Engineering Options and Modularity.

A.4.1. Engineering Options

A possibility to be able to adapt to unforeseen changes in the future when designing and implementing hydraulic infrastructure is to make use of Options theory. The concept of financial options has been used and modified to serve (hydraulic) infrastructure renewal tasks. This is the so-called Real Options theory, which later has been modified again into Engineering Options (Smet, 2017).
Real Options has originated from financial stock options. An option gives the holder the right to buy or sell a share for a previously set price at or before a predetermined moment in time. This concept of financial options has been modified to 'real' options, which encompasses 'real world' investments, such as investments in infrastructure projects. Trigeorgis (1996) defines RO as "the right but not the obligation to change a project in the face of uncertainty".
While this does create a more flexible environment for investment decisions for (hydraulic) infrastructure projects, the focus of RO is on managerial and strategic thinking. 'Real In Options' (RIO) analyses are the application of RO to infrastructure (re)development projects, where the options relate to the technical characteristics of a system (de Neufville, 2004). RIO has been used to quantify the added value of building flexibility into infrastructure systems. This way it can be found out which of the flexibilities are worth their added additional cost to the construction cost of the project.
While RIO presents a way to assess the value of built in flexibilities in hydraulic infrastructure, it is mainly concerned with urban infrastructure (Gersonius et al., 2013). In an urban drainage system there are many small parts that can be quite easily replaced. When looking at a single piece of hydraulic infrastructure, it can be more difficult. A pumping station needs to have a certain minimum capacity, and accounting for future uncertainty most likely results in simply oversizing the facility. This is not a very cost-effective solution.

Evolving from Real in Options, Engineering Options is coined to illustrate Options theory in light of the Engineering of the separate structures, instead of the system (Smet, 2017). This is similar to 'flexibility in design' (Chester & Allenby, 2019). In a proactive way, the technical components that a structure needs to have aree thought in advance when considering long-term uncertainty. An example is a pumping station with additional pumping bays but with only some of those pumping bays have been made operational with a pump. In the future a pump could be added if extra capacity is needed.

A.4.2. Modularity

Hydraulic infrastructure in the Netherlands is custom built. While this has its advantages, it comes at the expense of flexibility. Chester and Allenby (2019) argue that successful infrastructure in the twentyfirst century needs to be agile and flexible. Modularity and economy of numbers in infrastructure design can provide the flexibility that is desired when creating Engineering Options (Dahlgren et al., 2013). This flexibility could also be custom made, but standardized and mass-produced modules are likely to be cheaper. For a pumping station, a module could be a prefabricated pumping bay, including a pump. There are some conditions that need to be met before modularity becomes preferable over the traditional approach. These include a skilled labor force and a skilled management team (Wuni & Shen, 2019). These skills need to be taught to people that will be the ones to work with the modules. Furthermore, a complete supply-chain of modular infrastructure needs to be present before it gets economically competitive. This requires political decisions on long-term investments to set such a development into motion.

A.5. Decision-support frameworks for the renewal of hydraulic infrastructure

In literature, the research that has been conducted to decision-support for the renewal of hydraulic infrastructure is divided into three categories: *When* does hydraulic infrastructure need to be renewed, *What* are the possible types of intervention and *how* do you decide between the options?

Determining the moment of hydraulic infrastructure renewal is done with the use of an Adaptation Tipping Point (Kwadijk et al., 2010). When a tipping point is reached, the infrastructure does not function as desired anymore and something has to be done. The three factors that cause a tipping point to be passed are structural deterioration, biophysical change and socio-economic change (van der Vlist et al., 2015). Knowing when an adaptation tipping point will occur in the future is valuable knowledge, so methods have been created to try and estimate that moment (Kallen et al., 2013; van Vuren et al., 2017).

When an adaptation tipping point is established, the decision will have to be made on what the best options for renewal are. The problem with infrastructure that is meant to last a hundred years is that there is a lot of uncertainty about the future. How will the climate change? Will this pumping station still have enuogh capacity by then? Or does it have a too high capacity? Furthermore, interdependence is present in the water system. The uncertainty regarding climate change also enlarges the uncertainty around the effect of the interventions on interdependence.
In the spatial planning domain, the proposed mechanism to cope with uncertainty is the theory of adaptivity (e.g. Gupta et al., 2016; Rauws and De Roo, 2016). Adaptive policymaking is setting a long-term goal after which short-term steps are taken to continuously reach that goal. An adaptive policy would include a systematic method to monitor the environment and to gather information. The moment for adaptation can be determined by signposts that signal when an indicator passes a threshold (Raso et al., 2019). The short-term actions can differentiate in the *type* of intervention, the *location* of intervention and the *moment* of intervention (Busscher et al., 2014). Presenting these steps in Adaptive Policy Pathways provides insight into the several paths of options that a decision-maker has (Haasnoot et al., 2013; Bernardini et al., 2014; Restemeyer et al., 2017). The moment that an Engineering Option is added is also one of these short-term actions. The location is predetermined, as well as the type of intervention. The moment of adding this Option can vary.

With the theory of adaptivity, several different alternatives for hydraulic infrastructure renewal can be specified. The next question is how to decide on which alternative is the best. For this goal, several decision-support frameworks have been constructed (e.g. Pot, 2019; Haasnoot et al., 2020; Gersonius et al., 2013). In order to assess whether or not an alternative is better than the other for its complete lifetime, an estimation of the future situation needs to be made. Constructing scenarios is the best option to prepare for several likely futures. Then, the costs that are associated with a pathway can be determined under different scenarios. Brown et al. (2020) present a similar approach but base the outcome of the framework on utility instead of costs. Pot (2019) just specifies a set of criteria that need to be adhered.
The uncertainty regarding interdependence was discussed in the above paragraph. The issue with the present decision-support frameworks in literature is that they do not regard interdependence as a factor that makes one alternative better than the other. They treat a piece of infrastructure as an isolated piece and then its performance and costs are assessed. Vuren et al. (2015) are the only ones that look at the influence of an intervention on the functional lifetime of other infrastructures in the system, be it only a positive or negative influence. This research presents an assessment of interdependence on more levels.

A.6. Identifying interdependence

In this research, interdependence is split out into categories. This has been done within the scope of the case study, the renewal of pumping station H.D. Louwes in Zoutkamp. Through document analysis and open interviews that provided context of the system, three main interdependencies have been identified identified. These are sequential interdependence, balance interdependence and environmental interdependence. These interdependencies are not new, they are quite general water system management indicators. They have however not yet been used to differentiate between design alternatives.

Sequential interdependence is the influence of a piece of infrastructure on downstream pieces of infrastructure in the chain of structures. This could be any such as water barriers, sluices or other pumping stations.
In the case of the H.D. Louwes, the downstream infrastructures are the regional water barriers around the Lauwersmeer, the monumental Hunsingo sluice, and the Clevering discharge sluices that discharge the water from the Electra polder into the Wadden Sea.

Balance interdependence is the influence of a piece of infrastructure on the balance of water flow in the system. Does all water flow towards the pumping station, and how does this design alternative change that?
In the case of H.D. Louwes, this interdependence was the cause for intervention. As said, an imbalance in the system causes problems elsewhere in the system because the Waterwolf partly does the H.D. Louwes' job. The question is whether there are still imbalances in the new situation, and how the design alternatives influence that. This interdependence is illustrative for the growing importance of interdependence. This imbalance has been here forever, but in light of climate change it is becoming a problem.

Environmental interdependence is the influence of infrastructure on the manageability of the water levels in the water system. Different water levels are preferable for different types of land such as nature and agriculture. A pumping station maintains those preferred water levels. Here the question of drought also comes into play. A pumping station's core business is pumping water away, but what if there are periods of severe drought?
In the case of the H.D. Louwes the largest part of the polder has a water level of -0.93m NAP. The Lauwersmeer, which is where the H.D. Louwes pumps its water towards, has the same level. During normal circumstances these two areas regulate themselves. If somewhere the area is more dry then water will flow there. However, there are several developments going that might end this self-regulation, for example the Rietproef where a higher water level at the Lauwersmeer is maintained. such developments have an influence on the water levels. The question is how the design alternatives are able to cope with such changes.

A.7. New design alternatives

A.7.1. Old design alternatives

For the renewal of the H.D. Louwes, three design alternatives have originally been created by water authority Noorderzijlvest and their advisors. Their specifications can be seen in Table A.1, a schematic visualization in Figure A.2, Figure A.3 and Figure A.4. Original alternative 3 is the preferred design alternative by Noorderzijlvest, because it combines several issues such as the restoration of the Hunsingo sluice. All design alternatives, original and new, contain a closing provision in the river that is the cause for the imbalance in the water system. Without that provision, the norms are already not adhered to.

Table A.1: Overview of the specifications of the original design alternatives

Design alternative	**1**	**2**	**3**
Location	Old location	Old location	Southwest of the Hunsingo sluice
Sluice type	Weir sluice	Navigation lock	Navigation lock
Initial capacity (m^3/ minute)	1600	1600	1600
Capacity expandable to	Not expandable	Not expandable	Not expandable
Freshwater flowback option	Through opened navigation lock	Through opened navigation lock	Through opened navigation lock

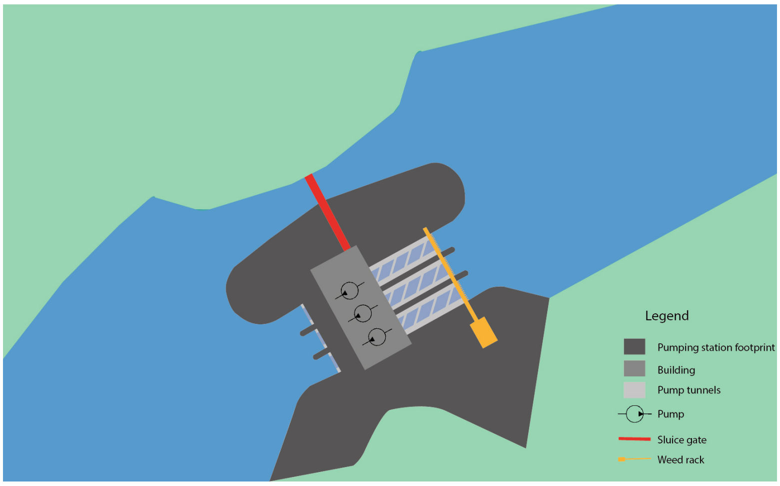


Figure A.2: Schematic visualization of original alternative 1

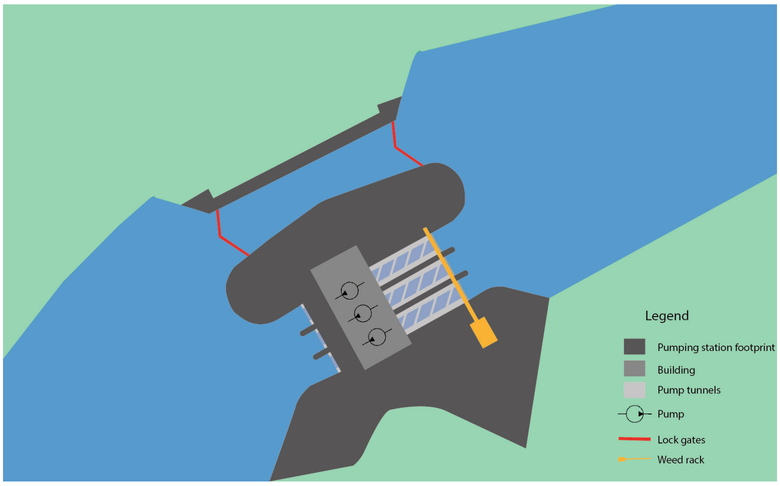


Figure A.3: Schematic visualization of original alternative 2

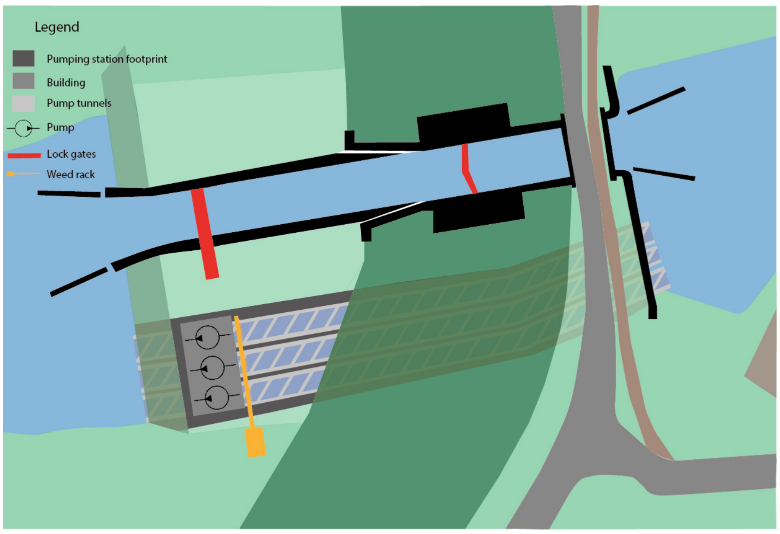


Figure A.4: Schematic visualization of original alternative 3

A.7.2. New design alternatives

For the analysis, three additional design alternatives have been created. Two of those are based on the concepts found in literature that can incorporate flexibility and adaptivity into the design of hydraulic structures and the management of the water system, as discussed in section A.4 and section A.5. These concepts are Engineering Options and Modularity. According to literature, should these new alternatives be better suitable to cope with climate change uncertainty than the original design alternatives. The analyses in the next chapter will determine if this is also the case for interdependence. The third new design alternative, the Big alternative, is created to see what happens if you build everything at once, an all-inclusive pumping station with a high capacity. How does it compare? The specifications of the new design alternative can be seen in Table A.2, a shcematic visuzalization in Figure A.5, Figure A.6 and Figure A.7.

Table A.2: Overview of the specifications the new design alternatives

Design alternative	**Engineering Options**	**Modular**	**Big**
Location	Southwest of the Hunsingo sluice	Southwest of the Hunsingo sluice	Southwest of the Hunsingo sluice
Sluice type	Navigation lock	Navigation lock	Navigation lock
Initial capacity (m^3/ minute)	1066	1066	2132
Capacity expandable to	2132	2132	Not expandable
Freshwater flowback option	Backward pump	Through opened navigation lock	Backward pump

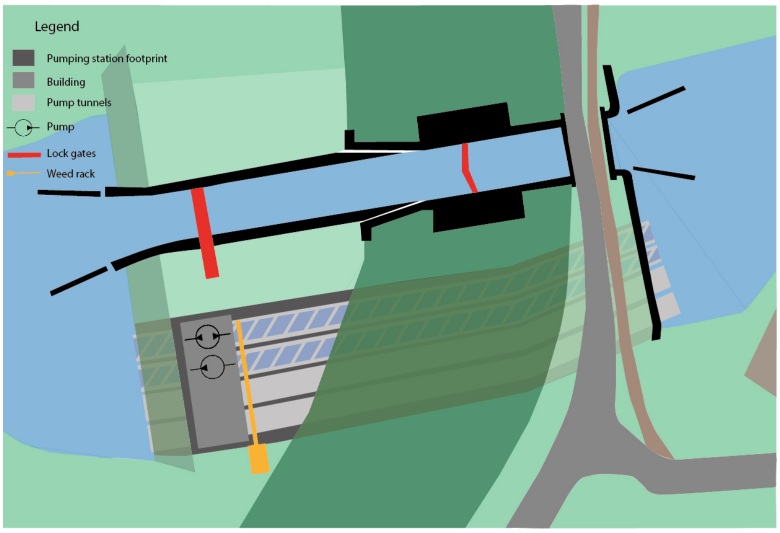


Figure A.5: Schematic visualization of the Engineering Options alternative

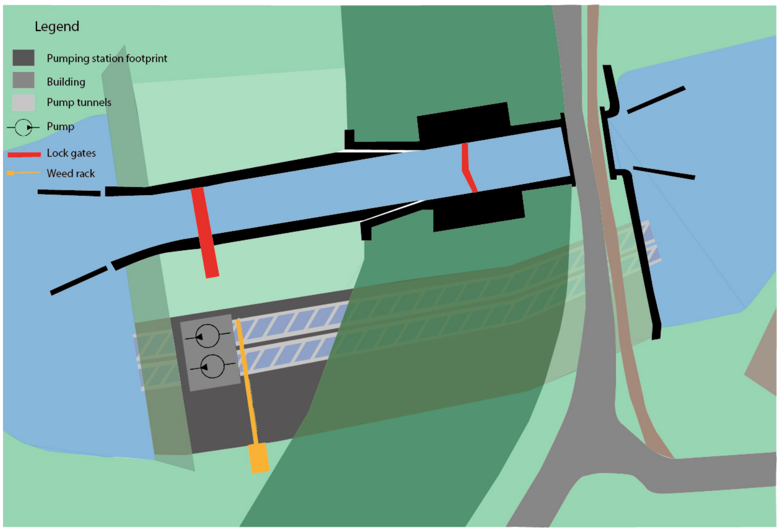


Figure A.6: Schematic visualization of the Modular alternative

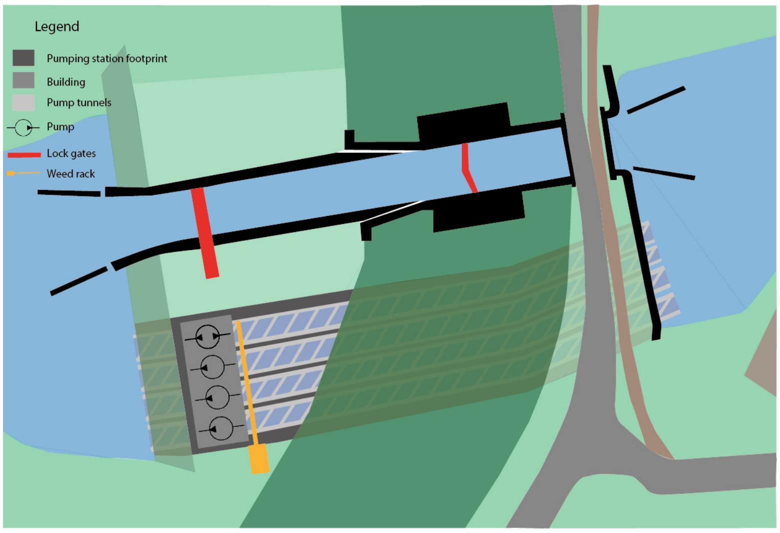


Figure A.7: Schematic visualization of the Big alternative

The Engineering Options alternative has a built in a proactive flexibility to expand the capacity if needed. A building that can accommodate 4 pumps will be built, as well as 4 pumping bays. However, only in 2 of the pumping bays will an actual pump be built. This way, there is sufficient capacity for the years in the near future to adhere to the safety norms. If climate change develops in such a way that more capacity is needed, an extra pump can easily be installed. Its initial capacity is 1066 m^3/minute, which can be expanded to 2132 m^3/minute. Additionally, the monumental sluice is renovated into a navigation lock, and a backward pump is installed as well to help combat drought.

The Modular alternative is based on modularity. First an oversized foundation is built, which can accommodate future expansions. In the initial situation 2 pumping modules, consisting of a pumping bay and pump, will be built. The initial capacity is 1066 m^3/minute, which can as well be expanded to 2132 m^3/minute. If the capacity in the future is not sufficient anymore, first measures in the water system will be explored, such as water retaining areas. If such measures are no longer enough or are more expensive than capacity expansion, then the capacity of the pumping station can be expanded by installing an additional module. No backward pump is installed yet. This can be an extra module to install if water needs to be pumped back. Additionally, the monumental sluice is renovated into a navigation lock.

The Big alternative is used as comparison. What if you ’build it once and build it big’? How would the influence on interdependence and costs compare to the original alternatives, and the adaptive alternatives? It has a capacity of 2132 m^3/minute which cannot be expanded. There is a backward pump present, and the monumental sluice will be renovated into a navigation lock.

A.8. Results

A.8.1. Influence of the design alternatives on interdependence

Through expert sessions, the influence of all 6 design alternatives on the 3 categories of interdependence has been assessed. Scores have been assigned to indicate a positive or negative value of the alternative on the interdependence, and the reasons for those scores were explained. This way, the factors that make up an interdependence are identified. These factors will later be presented in the proposed decision-support framework.

For Sequential interdependence, three factors arose as distinctive for this category. The first one is the influence on water barriers downstream.
In the town of Zoutkamp, where the H.D. Louwes lies next to, regional water barriers around the Lauwersmeer go through the town, where the streets function as water barriers. These barriers need to be heightened, which would case problems. Relocating the pumping station and using the former sea dike as new regional water barrier makes sure that those barriers do not need to be heightened anymore, which is a positive effect for the relocated design alternatives.
The second factor is the influence on next piece(s) of infrastructure in the sequence. The next piece of infrastructure in the sequence that handles the water are the Clevering discharge sluices. These have such a high capacity that the effect of the design alternatives on these sluices is negligible. However, due to sea-level rise the window of discharge is getting smaller, which makes that the Lauwersmeer should hold more water, for which its barriers need to be high enough.
The third factor is the influence on bottleneck situations. If the pumping station would be built on the same location as the current pumping station, then the monumental Hunsingo sluice would cause a bottleneck through which not all pumped up water can freely flow towards the Lauwersmeer. This would cause problems, which is a negative effect for original alternative 1 and 2, and a positive effect for the other design alternatives.

For Balance interdependence, two factors were found. The first one in the influence of the design alternatives on the water supply towards the design alternative. If you place a new pumping station, are the waterways equipped in a right way that the water flows towards the pumping station? A pumping station with a high capacity creates a draught of water, and it can be that the waterways towards the pumping station are too narrow to accommodate this draught. If this is the case, then you either need to broaden the waterways, or you have no benefit of the higher capacity.
The second is the influence on the water balance in the water system. Since all design alternatives include the closing provision in the river that caused the skewness, all design alternatives have a positive effect on this part of balance interdependence. However, this separation creates a new water system, that the H.D. Louwes is responsible for. How is the water balance in this new system? None of the respondents actually knew.

For Environmental, three factors came out of the scoring sessions. The first one is the influence on water level manageability in the case of an excess of water. This refers to pumping excess water away which is the core business of a pumping station. In this factor, a higher capacity is better. That is why the Big alternative scores high, as well as the Engineering Options and Modular alternative since their capacity can be expanded.
The second factor is the influence on water level manageability in the case of a shortage of water. Here water needs to go back into the system to maintain water levels. The alternatives with a backward pump score high, the alternatives where water flows through the opened lock and can’t be influenced score less high.
Both the above mentioned factors depend on the policy decisions on water levels. Maybe the water level is lower in than in the Electra polder in the future, or maybe higher for several different reasons.

The third factor mentions this, as it is the ability to cope with future water level management changes. Here the adaptive design alternatives have an advantage, as well as the Big alternative since it is so big that those changes do not really matter.

The scoring synthesis of the design alternatives with respect to interdependence can be seen in Figure A.8. The Engineering Options alternative has turned out to be the new preferred design alternative when looking at interdependence. Original alternative 3, the Modular alternative and the Big alternative share a second place.

Total	Sequential	Balance	Environmental	Average
1	-1,75	+0,5	-0,75	-0,67
2	-1,5	+0,5	-0,25	-0,42
3	+1	+1,25	+1	+1,08
Engineering Options	+1	+1	+2	+1,33
Modular	+0,75	+1	+1,5	+1,08
Big	+0,5	+1	+1,75	+1,08

Figure A.8: Influence of the design alternatives on interdependence

A.8.2. Life cycle costs of the design alternatives

Next the life cycle costs of the design alternatives have been calculated, to see how they financially compare to each other. These costs have been calculated for the components that make up the pumping station for the pumping station's technical lifetime, which is 100 years. These components are listed in Table A.3.
Three scenarios are assumed for climate change: Low, Middle and High. Each has a different rise in the needed capacity. As the needed capacity increases, a tipping point is reached when the needed capacity exceeds the current capacity. The adaptive alternatives can use their built-in flexibility to increase capacity. The non-adaptive original alternatives, with their fixed three pumps need to build a new pumping station if extra capacity is needed. The scenarios can be seen in Figure A.9.

Table A.3: Costs and lifetime of the different components of the pumping station

Component	**Investment costs (€)**	**Yearly maintenance costs (€)**	**Lifetime (years)**
Pump incl. drive	400,000	2,500	30/60
Hatch	40,000	50	60
Valve	50,000	50	60
E-installation	1,500,000	500	30
PLC (hard- and sofware)	50,000	250	15
Hydraulic unit	150,000	500	30
Civil construction below ground	2,500,000	0	100
Civil construction above ground	500,000	800	100

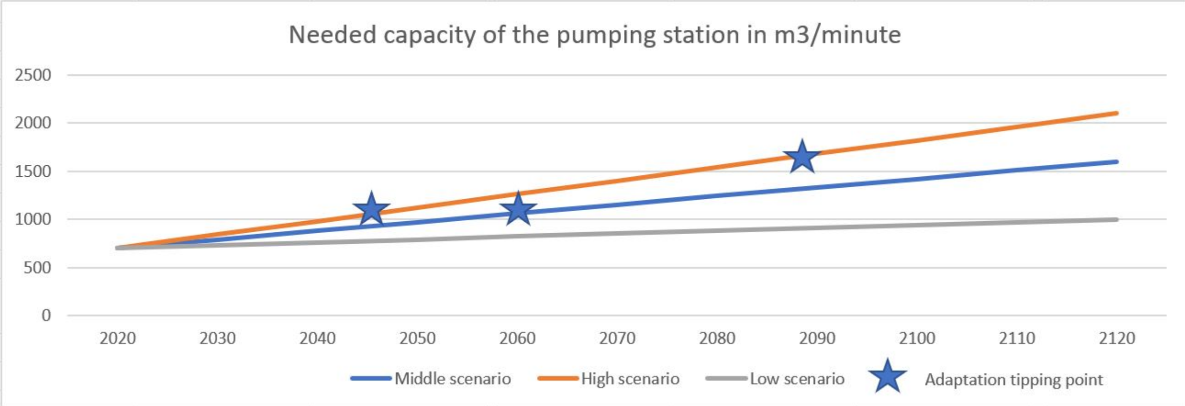


Figure A.9: The climate scenarios and their adaptation tipping points across time

Table A.4 shows the results of the life cycle costs calculations. In all scenarios, the Engineering Options and Modular alternative cost less money than the original design alternatives. In the Low and Middle scenarios this is due to maintenance and investment costs for pumping capacity that is not (yet) necessary that are saved in the adaptive alternatives. In the High scenario do the original alternatives have to be replaced with a new pumping station, where the Engineering Options and Modular alternatives still have adaptive room to grow with an additional third and fourth pump.
The Big alternative is everywhere more expensive than the two adaptive alternatives. In the Low and Middle scenario it is also more expensive than the original design alternatives. In the High scenario its 'better safe than sorry' attitude pays off, since it becomes a cheaper alternative than the originals which have to be rebuilt. However, it is still more expensive than the Engineering Options and Modular alternative since you need to pay a lot of maintenance costs yearly, for a long period of time where you do not yet need the high capacity.

Table A.4: Overview of the life cycle costs of the different alternatives

Alternative	Low	Middle	High
1	€16,5 million	€16,5 million	€19,8 million
2	€16,5 million	€16,5 million	€19,8 million
3	€16,5 million	€16,5 million	€19,8 million
Engineering Options	€15,0 million	€16,0 million	€17,0 million
Modular	€14,4 million	€15,9 million	€17,4 million
Big	€19,0 million	€19,0 million	€19,0 million

A.8.3. Proposal of a decision-support framework that incorporates interdependence and climate change uncertainty

From the results of the case study, a decision-support framework is proposed that incorporates interdependence and climate change uncertainty into the decision-making process, but that at the same time makes sure that the costs do not get out of hand. This framework can be seen in Figure A.10 The framework is a conceptual representation of the research process that has been conducted in this research. The steps that have been taken, and the factors that have been found to influence the outcome of those steps are integrated into the framework. The purpose of this framework is to also be applicable to other projects of pumping station renewal.

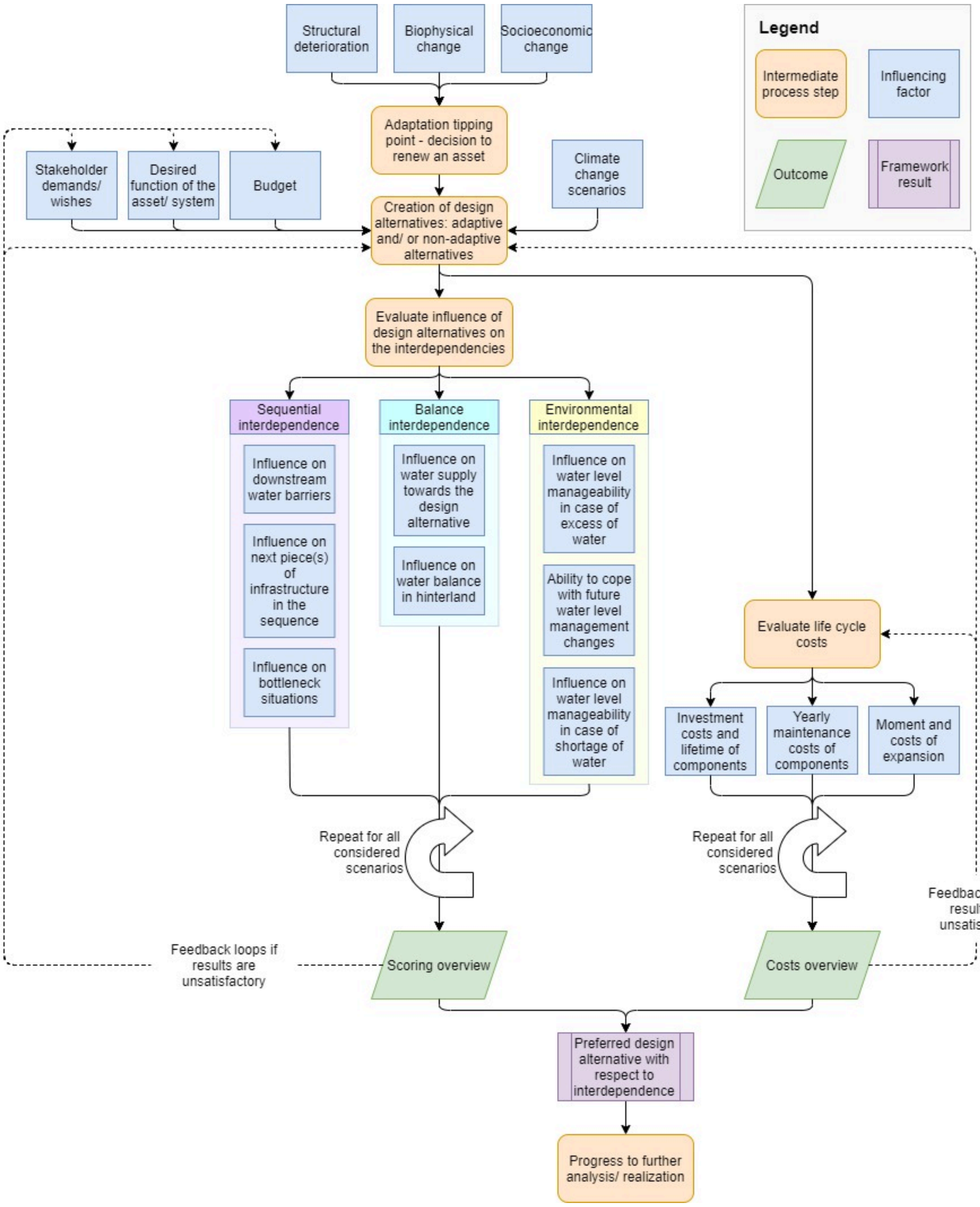


Figure A.10: The framework (own production)

A.9. Conclusion and discussion

A.9.1. Conclusion

The main research question of this research was: *To which extent does incorporating climate change uncertainty and interdependence influence decision-making for the renewal of hydraulic infrastructure?* Incorporating interdependence and climate change uncertainty influences decision making in such a way that flexible and adaptive design alternatives are becoming more preferable than static design alternatives. This goes for both interdependence and climate change uncertainty. Furthermore incorporating interdependence takes aspects of the design process that were thought of implicitly beforehand and makes them explicit, which means they are less likely to be overlooked in other projects.
Interdependence can be split up into categories of relevant interdependencies. The factors that make

up the interdependencies determine the success of a design alternative. When the influence of the design alternatives on interdependence is assessed under all climate scenarios, and the life cycle costs are calculated, then a preferred design alternative can be chosen. The presented framework supports decisions, so the final choice still lays with the decision-maker. The actual preferred design alternative can be chosen on other criteria as well.

This research presents a way to not just look at the isolated piece of infrastructure anymore. This research shows that the design alternatives function in a different way within the water system and that this different functioning has consequences for the water system.

In this decision-support framework, adaptive and non-adaptive design alternatives can be compared. This is an advantage because being adaptive is not always the best option, for example in situations with low uncertainty. It is important to consider both, go through the assessment process and see which design alternative comes out on top. The indication of life cycle costs helps in this regard, to make sure that the design alternatives do not exceed heavily in costs.

Building a pumping station in a changing climate may no longer ask for a single, once in a (technical) lifetime investment that will last a hundred years. Preparing for different futures and taking smaller steps along the way helps staying in sync with climate change and to keep maintaining the safety norms.

A.9.2. Discussion

This research has chosen to assess the influence of the design alternatives on interdependence with the use of expert scoring sessions. This has been done for practical reasons. It may however be wise to conduct this same research, and to translate the interdependence into a water system model and quantitatively calculate the influence on interdependence. This does require a very large model that incorporates the behaviour of the water, under different climate change scenarios, for several design alternatives.

Furthermore, this research has assumed the three mentioned interdependencies to be the only ones to consider in the assessment. This does not mean that there are no more interdependencies. A recommendation for further research is therefore to look at the interdependencies. Are these really the most important ones? How do they relate to each other in terms of relative importance? The same goes for the factors that make up an interdependence. Are there more factors? And how is their relative importance, compared to each other? These are interesting avenues to explore.

The last recommendation is to evaluate the proposed framework. It will be interesting to see how it performs when applied to other projects of pumping station renewal. Perhaps it could be used for other hydraulic infrastructure renewal as well. Also, this framework with its interdependence is aimed at a polder system. The matter of Balance interdependence will matter less in a water system in the hills, where there is always a height difference. Research could show which alterations this framework might need to also be applicable to other water systems.

B

Interview Guide Mark Voorendt

Inleidende vragen

Wie ben je en wat doe je.

Vragen over het onderwerp
Wat is de huidige manier om er zeker van te zijn dat een gemaal goed functioneert/ voldoende capaciteit heeft?
Groot bouwen?

Kijkend naar de toekomst, dan is de mate van klimaatverandering nog omgeven met onzekerheid, wat betreft de snelheid en de impact ervan. Hoe wordt er omgegaan met onzekerheid over de toekomst bij het bouwen van gemalen?
Nog groter bouwen?

Wat voor manieren zijn er om 'flexibel civil engineering' te bedrijven?
Wat komt daarbij kijken? Is daar extra kennis voor nodig, of kost het gewoon meer?

In de literatuur wordt er gesproken over Real Options of Engineering Options, is dat iets wat veel wordt toegepast?

Zou modulair bouwen een uitkomst kunnen zijn? Dmv het bijplaatsen van modules indien nodig de capaciteit verhogen?
Zou dit snel geïmplementeerd kunnen worden?

Een gemaal heeft als primaire eigenschap het afvoeren van overtollig water. Zou een gemaal in tijden van droogte ook bij kunnen dragen aan het aanvoeren van water?
Moet er dan simpelweg voor gezorgd worden dat er naar beide kanten gepompt moet worden?
Hebben alle gemalen een mogelijkheid om water terug te laten stromen? Bijv. een inlaat? Of moet die speciaal gebouwd worden?

C Scoring Sessions

C.1. Powerpoint used in the scoring sessions

HD Louwes

Beoordeling alternatieven
MSc thesis Erik Hadders

TAUW TUDelft

Verloop interview

1. Introductie onderzoek
2. Het doel van dit interview
3. Uitleg over onderlinge afhankelijkheden en de manier van scoren
4. De alternatieven
5. Scoren van de alternatieven
6. Einde

Introductie onderzoek

- Vervangingsopgave verouderde natte infrastructuur
- Gevolgen van klimaatverandering
- Hoe kies je wat je het beste kunt doen?
- Onzekerheid
- Naast de eigen werking van het gemaal, opereert een gemaal in een water systeem
- Hoe kun je daar rekening mee houden bij de vervangingsopgave van een gemaal, zodat je niet elders problemen veroorzaakt door het probleem slechts met een lokale blik op te lossen?
- Hoe kan dat in een besluitvormingsmodel worden gevangen?

Het doel van dit interview

- Een gemaal heeft naast de kwestie van doelbereik, ook invloed op het grotere watersysteem – bijv beheersbaarheid van waterpeil in de boezem, wat weer ecologische danwel agrarische gevolgen heeft
- Oorspronkelijke idee was het kwantitatief doorrekenen van deze alternatieven voor het hele watersysteem, bleek te complex voor een Msc-scriptieperiode
- Daarom kwalitatief scoren van alternatieven dmv experts.

Onderlinge afhankelijkheden (interdependence) en manier van scoren

- Sequential interdependence (geschakelde afhankelijkheid)

Kan de aanwezige infrastructuur benedenstrooms de vergrote hoeveelheid afgevoerd water aan? Versnelt de nieuwbouw van het gemaal het functionele levenseinde van die infrastructuur?

In Electra: De Cleveringsluizen hebben een enorme capaciteit. Het probleem zit hem in de mogelijke momenten voor spuien. Door o.a. zeespiegelstijging worden die periodes kleiner. Het Lauwersmeer moet in staat zijn om water vast te kunnen houden op momenten dat er niet gespuid kan worden. Als die bergingscapaciteit te weinig blijkt, is er de keuze om pompcapaciteit aan de Cleveringsluizen te geven, danwel de regionale keringen verhogen.

Manier van scoren: Beantwoord de onderstaande vraag met een score van - - naar + +:

"Wat is de invloed van dit alternatief op het moment dat er aanpassingen moeten worden gedaan aan de inrichting van het Lauwersmeer of de Cleveringsluizen?"

Als dat moment wordt versneld, dan is dat een negatieve invloed. Als dat moment wordt vertraagd, is dat een positieve invloed.

Onderlinge afhankelijkheden (interdependence) en manier van scoren

- Balance interdependence (waterbalans)

Pompt ieder gemaal water weg uit het beheersgebied waarvoor het is gebouwd? Hoe verandert het nieuwe gemaal deze balans?

In Electra: Deze afhankelijkheid is de aanleiding geweest voor het afsluiten van de Kromme Raken en de daarbij behorende capaciteitsuitbreiding van de HD Louwes. Zijn daarmee alle problemen opgelost? Stroomt al het water linea recta van naar de HD Louwes? Of zijn er nog andere stroomrichtingen die voor problemen kunnen zorgen?

Manier van scoren: beantwoord de onderstaande vraag met een score van - - naar + +:

"Wat is de invloed van dit alternatief op de balans in het watersysteem?"

Onderlinge afhankelijkheden (interdependence) en manier van scoren

- Environmental interdependence (peilbeheersbaarheid)

Hoe is de grip op het waterpeil in de Electraboezem? Wordt met de huidige ingreep het beheersen van het waterpeil (in de zomer en in de winter) eenvoudiger of lastiger?

In Electra: Het waterpeil is grotendeels -0,93 NAP, het Lauwersmeer heeft hetzelfde peil. In de winter is peilbeheer het drooghouden van het land dmv water wegpompen bij een overschot. In de zomer is zoetwater nodig om verzilting tegen te gaan en om de gewassen en de natuur voldoende water te geven. Zoetwater in de zomer komt momenteel voornamelijk uit het IJsselmeer en wordt via het zomercircuit verspreid over de boezem.

Manier van scoren: beantwoord de onderstaande vraag met een score van - - naar + +:

"Wat is de invloed van dit alternatief op de beheersbaarheid van het waterpeil in de Electraboezem?"

De alternatieven

- Alternatief 1

Locatie	Zelfde plek als huidige gemaal
Capaciteit	1600 m3/min
Type sluis	Keersluis
Zoetwateraanvoer uit Lauwersmeer	Via sluis

N.B. Alle 6 alternatieven gaan gepaard met de afsluitvoorziening in de Kromme Raken

De alternatieven

- Alternatief 2

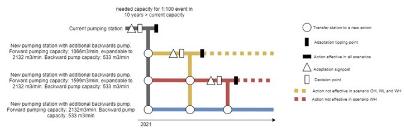
Locatie	Zelfde plek als huidige gemaal
Capaciteit	1600 m3/min
Type sluis	Schutsluis
Zoetwateraanvoer uit Lauwersmeer	Via sluis

De alternatieven

- Alternatief 3

Locatie	Ten westen van de Hunsingosluis
Capaciteit	1600 m3/min
Type sluis	Schutsluis
Zoetwateraanvoer uit Lauwersmeer	Via sluis

De alternatieven

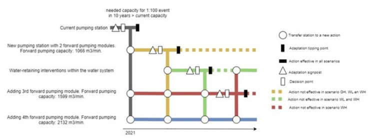


- Alternatief 4

Locatie	Ten westen van de Hunsingosluis
Capaciteit	1000 m3/min, uitbreidbaar naar 2100 m3/min
Type sluis	Schutsluis
Zoetwateraanvoer uit Lauwersmeer	Via pomp

- Opmerking: In dit alternatief wordt een gemaal gebouwd met 4 pompkanalen. In slechts 2 daarvan wordt een pomp geïnstalleerd. Aan de hand van monitoring van de voorspellingen kan gesignaleerd worden dat de verwachte neerslagpatronen de 1:100 norm in de boezem over 10 jaar overschrijden. Vervolgens kan een extra pomp worden geïnstalleerd.

De alternatieven



- Alternatief 5

Locatie	Ten westen van de Hunsingosluis en elders in de Electraboezem
Capaciteit	1000 m3/min, uitbreidbaar tot 2100 m3/min
Type sluis	Schutsluis
Zoetwateraanvoer uit Lauwersmeer	Via sluis, mogelijkheid tot plaatsing pomp of inlaat

- Opmerking: De fundering wordt zodanig gedimensioneerd dat een gemaal van 2100 m3/min er kan functioneren. Er worden twee 'modules' geplaatst: Een pompkanaal inclusief pomp. Wanneer door monitoring van de voorspellingen extra capaciteit benodigd blijkt, wordt er eerst gekeken naar watersysteemoplossingen in de boezem (bijv. extra waterberging). Zodra dat niet meer genoeg is of niet meer economisch voordelig is kan er worden besloten tot het plaatsen van een extra module.

De alternatieven

- Alternatief 6

Locatie	Ten westen van de Hunsingosluis
Capaciteit	2100 m3/min
Type sluis	Schutsluis
Zoetwateraanvoer uit Lauwersmeer	Via pomp

- Opmerking: Dit alternatief dient voornamelijk ter vergelijking. Wat zijn de verschillen als je het wel in één keer het groots aanpakt? Dit alternatief wordt ook gebruikt als vergelijking wat betreft de kosten

Scores van de alternatieven

1. Geschakelde afhankelijkheid

"Wat is de invloed van dit alternatief op het moment dat er aanpassingen gedaan moeten worden aan de inrichting van het Lauwersmeer of de Cleveringsluizen?"

Wordt dit moment versneld (- -) of uitgesteld (+ +)?

Alternatief	Score
1 (Oude plek + keersluis)	
2 (Oude plek + schutsluis)	
3 (VKA)	
4 (Opties tot plaatsen extra pompen)	
5 (Modulair gemaal)	
6 (Grootste gemaal)	

Effect	Score
Negatief	- -
Licht negatief	-
Neutraal	0
Licht positief	+
Positief	+ +

Scores van de alternatieven

2. Waterbalans

"Wat is de invloed van dit alternatief op de balans in het watersysteem?"

Stroomt water weg uit het beheersgebied van de HD Louwes (- -) of stroomt al het water netjes naar HD Louwes toe (+ +)?

Alternatief	Score
1 (Oude plek + keersluis)	
2 (Oude plek + schutsluis)	
3 (VKA)	
4 (Opties tot plaatsen extra pompen)	
5 (Modulair gemaal)	
6 (Grootste gemaal)	

Effect	Score
Negatief	- -
Licht negatief	-
Neutraal	0
Licht positief	+
Positief	+ +

Scores van de alternatieven

3. Peilbeheersbaarheid

"Wat is de invloed van dit alternatief op de beheersbaarheid van het waterpeil in de Electraboezem?" (denk ook aan water inlaten)

Wordt de beheersbaarheid minder (- -) of beter (+ +)?

N.b. als de mate van beheersing gelijk blijft terwijl de neerslag onvoorspelbaarder en intenser wordt, is de beheersbaarheid dus minder.

Alternatief	Score
1 (Oude plek + keersluis)	
2 (Oude plek + schutsluis)	
3 (VKA)	
4 (Opties tot plaatsen extra pompen)	
5 (Modulair gemaal)	
6 (Grootste gemaal)	

Effect	Score
Negatief	- -
Licht negatief	-
Neutraal	0
Licht positief	+
Positief	+ +

Eindoverzicht

	Sequential	Balance	Environmental
1			
2			
3			
4			
5			
6			

C.2. Score overview of the experts

Respondent 1	Sequential	Balance	Environmental
1	- -	-	- -
2	-	-	0
3	+ +	+	+
Engineering Options	+	+	+ +
Modular	0	+	+
Big	+	+	+ +

Respondent 2	Sequential	Balance	Environmental
1	- -	+	0
2	- -	+	-
3	-	+	+
Engineering Options	0	+	+ +
Modular	0	+	+
Big	-	+	+ +

Respondent 3	Sequential	Balance	Environmental
1	- -	+	0
2	- -	+	+
3	+	+	+
Engineering Options	+	+	+ +
Modular	+	+	+ +
Big	+	+	+ +

Respondent 4	Sequential	Balance	Environmental
1	-	+	-
2	-	+	-
3	+ +	+ +	+
Engineering Options	+ +	+	+ +
Modular	+ +	+	+ +
Big	+	+	+

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