DEALING WITH AGING OF HYDRAULIC INFRASTRUCTURE: AN APPROACH FOR REDESIGN WATER INFRASTRUCTURE NETWORKS

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ABSTRACT

For centuries, engineers around the world have focused on regulating water systems in order to facilitate a number of important societal functions. This resulted in extensive, interlinked water infrastructure networks that provide protection against flooding, sufficient freshwater supply and a thriving navigation network. Due to either technical wear and/or malfunctioning, or by changing functional requirements resulting from climate change and/or societal developments, hydraulic structures reach the end of their lifetime, making replacement or renovation necessary. The fact that hydraulic structures operate in a complex water network, fulfilling many functions and involving many stakeholders, makes the redesign of these infrastructural assets a complex task. This paper introduces an approach to help define long term reinvestment strategies for the replacement or renovation of hydraulic structures within existing water infrastructure networks. The framework presented is based on the principles of 'Adaptive Delta Management', developing flexible strategies using the concepts of adaptation tipping points in combination with adaptation pathways. The potential of this approach is illustrated with a case study in the Netherlands, namely the Discharge Sluice and Pumping Station IJmuiden.

Keywords: hydraulic structures, infrastructure networks, renovation, replacement, redesigning, adaptation tipping points, adaptation pathways

1. INTRODUCTION

Around the world, water systems have been heavily trained for a variety of purposes, including flood protection, safe and efficient navigation, and the provision of sufficient quantities of clean freshwater, among others. Training works can consist of sluices, weirs, storm surge barriers, pumping stations, locks and bridges, among others. Today, this has resulted in extensive, interlinked water infrastructure networks that comprise large numbers of multifunctional hydraulic structures.

The complex water infrastructure network in the Netherlands is a good example. The Netherlands divides its different water networks in (1) a main water system, (2) regional water systems, and municipal water systems. The main water system is comprised of approximately 650 large-scale, nationally managed hydraulic structures. While the oldest structure within this network dates back to 1853, the majority of these hydraulic structures were constructed in the period between 1920 and 1960. With a design lifetime of 80 to 100 years, a large number of these hydraulic structures in the Netherlands are nearing the end of their lifetime in the coming decades. The end of their lifetime is defined as that moment when it is no longer economically efficient to maintain these structures or when they can no longer fulfil their functional requirements. The occurrence of the end of a structure's lifetime makes replacement or renovation necessary. The fact that hydraulic structures operate in a complex network (comprised of both main and regional water systems) with many functions and stakeholders, makes the redesign of these infrastructural assets a complex task. On the other hand, the replacement of a key hydraulic structure offers stakeholders a valuable opportunity to re-think the water system as a whole by adding or subtracting functionality to structures.

However, aging of hydraulic structures is not the only reason for reconsidering the design of the water infrastructure network. In 2010 the Dutch government launched the national Delta programme. "The Delta programme addresses challenges resulting from climate change and socio-economic developments. The aim of the Delta programme is to protect the Netherlands against flooding and to ensure an adequate freshwater supply, today and in the future. Within the Delta programme, so-called Delta strategies are developed. Short and long term (up to the year 2050 and 2100) strategies for flood risk management and freshwater supply in the Netherlands are developed based on a scenario approach. A number of hydraulic structures play an important role in these strategies. This leads to a strong connection between the Delta programme and the replacement strategy of the infrastructure" (Bernardini *et al*., 2014).

Within the national Delta programme an approach called 'Adaptive Delta Management' (ADM) has been developed to deal with the uncertainties involved in such very long term strategies and to connect long term goals to short term decisions and measures (Van Rhee, 2012). The planning principles of ADM requires sequencing a set (or more than one set) of possible actions and measures through time, to respond in a flexible manner to uncertain developments over time, allowing room to respond to new opportunities and insights. Key elements in this ADM approach are:

- Looking for flexible sets of policies and measures and seeing the future in terms of 'adaption pathways', instead of identifying fixed sets of measures to reach a pre-defined end goal.
- Connecting short term decisions and measures in the water system with long term developments and goals.
- Reducing the chance of under- or overinvestment in water infrastructure by valuing flexibility in adaptation pathways.
- Connecting investment agenda's from public and private stakeholders to create synergy in long term policies.

In this paper we focus on the designing of a flexible strategy, as it relates to the replacement and renovation of hydraulic structures. This is done by coupling two different existing methodologies: **adaptation tipping points** are used in the development of **adaptation pathways**, which together allow exploration of different possible replacement/renovation strategies.

Adaptation tipping points were first defined by Kwadijk *et al*. (2010) as "points where the magnitude of change due to climate change or sea level rise is such that the current management strategy will no longer be able to meet the objectives"[1]. This basic concept was subsequently applied specifically to hydraulic structures by Van der Vlist *et al*. (2015). They suggest that there are a variety of drivers in addition to the impacts of climate change that have the ability to influence the occurrence of adaptation tipping points when looking at hydraulic structures. For instance, in addition to changes in external environmental conditions, socio-economic and political factors, the aging and physical deterioration of the structure can also drive the occurrence of adaptation tipping points. These concepts have been operationalized by Kallen *et al*. (2014), who developed a method to determine the timing of different kinds of adaptation tipping points in the life of a hydraulic structure.

The notion of adaptation pathways has its early roots in the planning and decision making literature, drawing on the use of decision trees and aspects of the Strategic Choice Approach (e.g. Faludi and Van der Valk, 1994). When designing a water management strategy for an unknown future, uncertainty has typically been taken into account by modelling future conditions using probability distributions and accounting for this uncertainty in the design, or by using a selection of possible future scenarios and using these scenarios to optimise the design (Voortman *et al*. 2013). However, both of these methods assume an *ex ante* fixed final situation. Within the context of climate change adaptation, adaptation pathways emerged in the last decade as a method to help visualize the process of planning for an uncertain future. Critically, it does not assume a fixed end point, but instead presents a step-by-step method of dealing with future uncertainties, allowing decision makers the flexibility to respond to uncertain developments over time. Adaptation pathways were first demonstrated using the Thames River barrier as an example (Reeder and Ranger, 2011), and have subsequently been described in more detail by Van Rhee (2012) and Haasnoot *et al*. (2013).

This paper presents the development of an integrated framework, coupling adaptation tipping point analysis with the designing of adaptation pathways, in order to develop adaptive strategies for the replacement and renovation of hydraulic structures (see also Bernardini et al., 2014). This framework is illustrated using the Discharge Sluice and Pumping Station IJmuiden in the western part of the Netherlands to demonstrate how estimates of the remaining useful life of hydraulic structures can be used to develop replacement/renovation strategies. The novel contribution of this paper is threefold. Firstly, the improved integration of long term strategies for short time decisions about the replacement and renovation of hydraulic structures and the ADM approach, secondly the elaboration of using the assessed end of lifetime of a hydraulic structure as adaptation tipping points and thirdly the application of this approach in a case study to illustrate the potential.

This paper is organized as follows. Section 2 starts with an introduction of the proposed integrated framework for redesign of the water infrastructure networks. Section 3 introduces the case study, giving a description of the water infrastructure network of the North Sea Canal (NSC) and the Amsterdam-Rhine Canal (ARC) in the Netherlands and the role that the Discharge Sluice and Pumping Station of IJmuiden play in this system. Section 3 presents also the results of the case study, with final conclusions and recommendations provided in Section 4.

2. APPROACH

As introduced above, in this paper a method has been developed to cope with the challenges of making infrastructural design and investment decisions given the constraints of the existing infrastructure network and uncertainty about future conditions. This method integrates the use of adaptation tipping points in the form of end of life forecasts for each structure, with an exploration of possible redesign strategies of the water infrastructure network, in the form of different adaptation pathways. Specifically, this approach consists of the following steps:

[1] Note the explicit differences between the term "tipping point" as previously used in the field of climate science (e.g. Lindsay and Zhang, 2005 and McNeil and Matear, 2008) and the more recent term "adaptation tipping point". The fundamental characteristic of a "tipping point" is that small external changes can result in a fast-paced, dramatic shift in the state of an object, such that the new end state cannot be predicted with confidence. An adaptation tipping point is a related, but distinct concept, which corresponds to the moment when it becomes necessary to revisit an existing management strategy; this moment does not necessarily coincide with a tipping point in the external natural physical system, but can occur at a different time as a result of gradual external changes incrementally affecting the efficacy of the management strategy.

1. Description of the current water infrastructure network and the stakeholders involved;
2. Description of current and future functionality of the hydraulic structures in the water infrastructure network;
3. Estimation of the remaining useful life of hydraulic structures using adaptation tipping point analysis;
4. Identification of possible courses of action for the replacement and renovation of specific hydraulic structures;
5. Identification of strategies for the redesign of the water infrastructure network;
6. Development of adaptation pathways.

A more detailed description of each of these components is provided below.

2.1 Description of the current water infrastructure network and the stakeholders involved

For a good understanding of the complexity of the renovation or replacement task, a proper description of the water infrastructure network is required, including information about the functional services provided by the network, the hydraulic structures that are part of this network and the stakeholders that are involved.

2.2 Description of current and future functionality of the hydraulic structures in the water infrastructure network

The importance and contribution of specific individual hydraulic structures in fulfilling societally desired functions of the wider infrastructure network, such as flood protection, navigation and provision of freshwater, should be made explicit. It is important not only to come to grips with the role of hydraulic structures within the current water infrastructure network, but also to take into account probable future developments and the service demands of future generations. The required future functionality of hydraulic structures should therefore be defined as best as possible, taking into account uncertainty in climate change and socio-economic developments, as well as in future use. The most widely used approach for this is to create scenario's, such as the Delta scenario's developed in the Dutch Delta programme and used in this paper (Delta programme, 2012).

2.3 Estimation of the remaining useful life of hydraulic structures using adaptation tipping point analysis

Given the relatively old age of the current stock of hydraulic structures in the Netherlands and the high cost of replacing each structure, from the perspective of the decision maker, there is the need to have a clear prognosis about the timing of replacement work in order to budget the necessary funds and planning capacity for these projects. This forecasting can be done by estimating the remaining service life of individual hydraulic structures, which can be assessed in a number of different ways.

At its simplest, an indication of when a structure must be replaced can be derived by taking the design lifetime of a structure as its replacement age. Using generic information such as the year of construction and the design lifetime (80 or 100 years), an estimation of the end of a structure's lifetime can be obtained by adding the design life to the year of construction. This 'basic' approach enables a rapid assessment of the remaining useful life of a hydraulic structure. However, it dramatically simplifies reality and pays little attention to the fact that, in reality, the age at which a hydraulic structure needs to be replaced is highly uncertain. The following are examples of processes that could affect the remaining service life of a hydraulic structure (Benardini *et al*., 2014):

- More or less extensive use of the structure, resulting in faster or slower deterioration, both of which directly affect the remaining useful life;
- Climate change and socio-economic developments, resulting in a structure no longer meeting its functional requirements;
- Multi-functionality of a structure, making a structure reach its end of service at different times for different functions.

Kallen et al. (2014) present a more sophisticated methodology to determine end of life estimates for hydraulic structures that accounts for uncertainty. This method distinguishes between functional and technical end of lifetime estimates: functional end of life occurs when a structure is no longer able to fulfil its functional objectives due to *external changes* such as sea level rise or changes in the level of service required by users of the system; technical end of life occurs when a structure is no longer able to meet its functional objectives due to the magnitude of *physical deterioration* it has undergone. The output of this method is in the form of time windows: a lower and upper bound on the end of the technical and functional life of a hydraulic structure. Taken together, the timing of these different types of end of life estimates can be treated as adaptation tipping points, providing useful information about when a system change could be made: distinct moments in the long-term asset management timeline at which some sort of action is necessary to maintain the desired functionality of the system. These adaptation tipping points are a necessary input to the process of developing adaptation pathways, as described in Section 2.5 below.

2.4 Identification of possible courses of action for the replacement and renovation of hydraulic structures

We note the explicit differences between options and/or courses of action and strategies, i.e. many individual actions can be taken together as a replacement strategy (see section 2.6). In order to determine which actions and measures are possible in the replacement and renovation of hydraulic structures to let the water system function according to probable future requirements, a proper understanding of the functioning of the system is needed. This includes knowledge on the main- and regional water network, the key hydraulic structures within these networks and how they interact.

One way to identify possible courses of action is going through each function of the system in turn in collaboration with the main stakeholders to find opportunities in the system for meeting probable future requirements of this function. Possible courses of action could also be identified by considering the various functions in a more integrated holistic manner. System analysis (using model simulations) and brainstorm sessions with engineers, managers and other stakeholders can help identifying possible courses of action.

2.5 Identification of strategies for the redesign of the water infrastructure network

Having coupled the end of life predictions of hydraulic structures with different possible actions, overarching strategies for the replacement and renovation of hydraulic structures can be identified. Combining the end of life predictions of hydraulic structures with a functional analysis of a given water system and insights in probable future developments and uncertainties, the replacement of hydraulic structures (i.e. future tipping points) can lead to a set of possible strategies, to achieve the future desired objectives for the system. Adaptation tipping points indicate when action is needed, possible strategies must indicate which combination of measures are possible and desirable. This relationship between the replacement and renovation of hydraulic structures, the functioning of water system as a whole and the (desired) objectives of a water management strategy are the key elements of the integrated framework developed in this paper.

2.6 Development of adaptation pathways

As introduced earlier, within the context of ADM, adaptation pathways are suggested as a method to help deal with future uncertainties in decision making in a flexible and incremental way. Having identified a wide variety of different possible courses of action in the previous step, these pathways are constructed by exploring different possible combinations of actions and external interventions in a stepwise way over time, transitioning towards a variety of possible final states of a system. The transition from one pathway to another is determined by the occurrence of adaptation tipping points, as previously determined in Section 2.3 above. With this step-by-step approach it is possible to identify no-regret decisions that are worth pursuing no matter what the future entails, avoid lock-in situations and respond in a flexible manner to uncertainties and possible unforeseen developments over time. Such pathways show which courses of action are possible and determine where the opportunities are for aligning short-term measures with long-term goals. It provides insight into those strategies where it is possible to speed up or slow the sequence of actions, in response to the speed of future developments (Van Rhee, 2012).

In the exploration of different strategies and adaptation pathways, two aspects are worth highlighting. First, as described above, any single hydraulic structure has a number of different adaptation tipping points, namely one that relates to its internal physical degradation (the technical end of life) and one that relates to it being unable to fulfil the function (or functions) it is intended to (the functional end of life). Given that many structures fulfill multiple functions, one single structure can thus experience multiple end of functional life moments. Having a clear overview of the timing of these different moments for all the different structures in a network allows the exploration of system synergies. For instance, if a structure is determined to be unable to fulfill a particular function at a certain time, can this adaptation tipping point be pushed back in time by making changes elsewhere in the system, thus delaying the need for large-scale renovation or replacement? Secondly, when considering different strategies using adaptation pathways, the individual replacement/renovation moment provides an opportunity to link work on one particular structure with the wider network or regional development vision.

3. CASE STUDY: THE DISCHARGE SLUICE AND PUMPING STATION IJMUIDEN

We demonstrate this methodology using the case study of the Discharge Sluice and Pumping Station IJmuiden in the north western part of the Netherlands. The framework presented above is used to define strategies to cope with the nearing end of life of these hydraulic structures.

3.1 Description of the current water infrastructure network and the stakeholders involved

We start with a description of the study area and the Discharge Sluice and Pumping Station IJmuiden. Complex IJmuiden is located at the boundary between the North Sea and the North Sea Canal (NSC). Figure 1 illustrates the location of the study area, including the Discharge Sluice and Pumping Station IJmuiden. The Discharge Sluice and Pumping Station IJmuiden fulfill various functions, i.e. flood protection, water management in the western Netherlands (pumping and discharging water), water quality (fresh and salt water separation), fish passage, etc. In this case study, we focus only on those functions of Complex IJmuiden that relate to (extremely) wet conditions, namely its flood protection function and its inland water management function.

- Flood protection function of IJmuiden

Together with the shipping locks at IJmuiden and the connecting embankments, the Discharge Sluice and Pumping Station IJmuiden form part of the Netherland's primary flood defense against the waters of the North Sea. These structures provide protection against water levels on the North Sea that are exceeded on average only once every 10,000 years.

- Inland water level management function of IJmuiden

The Discharge Sluice and the Pumping Station IJmuiden play an important role in the water management of the north western part of the Netherlands, controlling the water levels and flow rates in the NSC and the Amsterdam Rhine Canal (ARC). A catchment area of 8.900 km^2 discharges excess water into these two canals via regional water systems, or/and extract water from these canals for use in the adjacent regional water systems (e.g. for agriculture, nature, drinking water). The water level of the canal is also important in preserving the moisture conditions of nearby peat dikes and buildings with wooden foundations (such as in the historic centre of Amsterdam) and to prevent peat oxidation. If peat flood defense embankments lose too much moisture, the resulting decrease in the embankment's weight reduces its ability to hold back water. This can lead to failure of the peat embankment, which leads to flooding. Additionally, at decreased groundwater levels peat could oxidize irreversibly, resulting in more rapid subsidence and increased CO_2 emissions. The Discharge Sluice and Pumping Station IJmuiden are by far the largest contributor (± 95%) to the regulation of the water levels and water flows of the NSC, the ARC and the city waters of Amsterdam.

The Discharge Sluice IJmuiden date back to 1940 and allows water from the NSC to enter the North Sea under free flow. The sluice consists of seven discharge passages. Water discharge under free flow is only possible during low tide at sea, which typically amounts to a maximum of several hours of sluicing per day. The sluice has a total discharge capacity of 500 m^3/s. The capacity could increase up to 700 m^3/s, when there is a sufficiently large difference between the water level on the NSC and the North Sea.

The Pumping Station IJmuiden consists of six pumps. Four of these pumps along with the structure were constructed in 1975, while the other two pumps were added in 2005. The total discharge capacity is 260 m^3/s. If water cannot be discharged to the North Sea as a consequence of high tide, and the water levels on the NSC/ARC are unacceptably high, the pumping station is used to control the water levels in the NSC/ARC. In theory, system operators strive to discharge about two-third of the water via the discharge sluice, and a third via the pumping station. However, in practice, this is closer to a 50%-50% distribution.

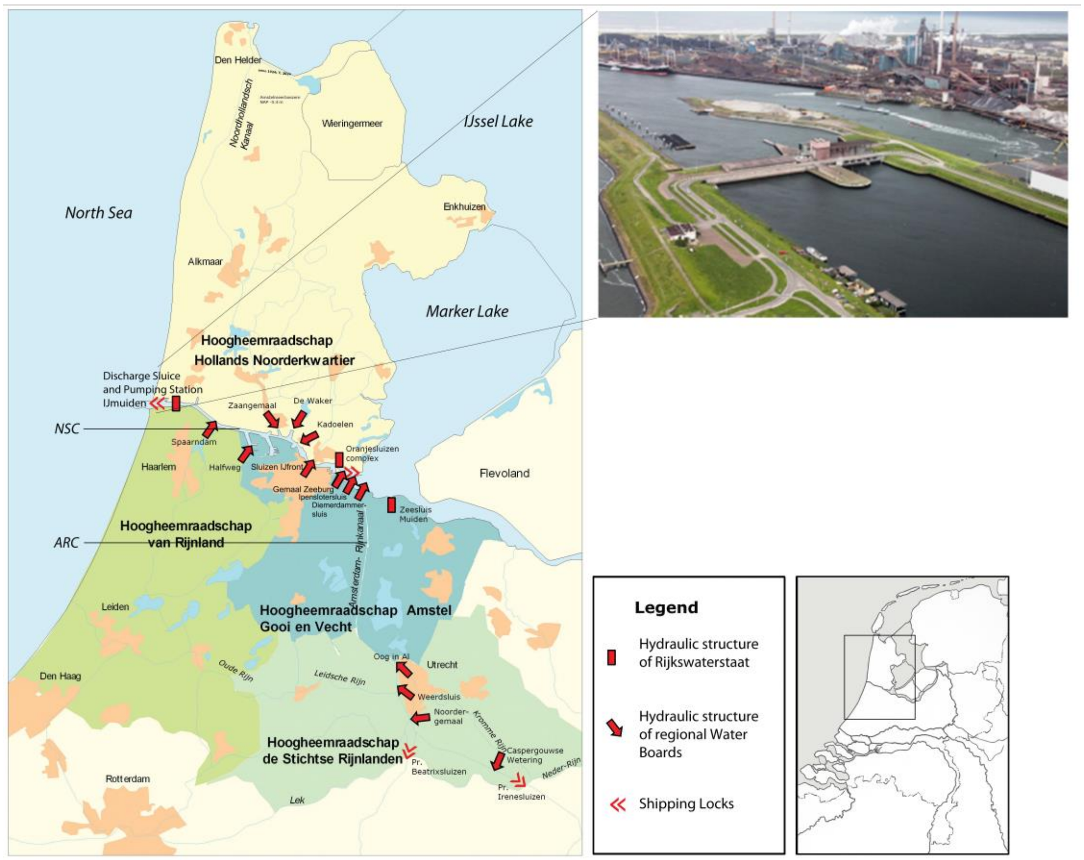

Figure 1. Study area: the North Sea Canal and the Amsterdam-Rhine Canal in the Netherlands, and the hydraulic structures in (1) the main water network and (2) the regional water systems.

Four regional water boards are involved as stakeholders (see Fig. 1): Water Board[2] Hollands Noorderkwartier (beige), Water Board Van Rijnland (green), Water Board Amstel Gooi and Vecht (blue) and Water Board De Stichtse Rijnlanden (light green). In addition, the national Ministry of Infrastructure and the Environment, Rijkswaterstaat and the municipality of Amsterdam are involved.

Furthermore, the Dutch Delta programme is also involved in the development of strategies for flood risk management and fresh water supply in this part of the Netherlands. Hence, they are also a relevant stakeholder that should be included in the process of defining possible strategies.

3.2 Description of current and future functionality of the hydraulic structures in the water infrastructure network

The Discharge Sluice and Pumping Station IJmuiden play an important role in the water management of this part of the Netherlands. Hence, the structures of Complex IJmuiden should therefore be analyzed in conjunction with the related subsystems, namely the NSC, the ARC and the surrounding regional water systems. This section discusses the functionality of the hydraulic structures within the water infrastructure network in more detail.

[2] Waterboard in Dutch : Hoogheemraadschap

Figure 2 shows hydraulic structures in either the main water infrastructure network or the regional water system of the study area. The figure indicates that there are a variety of different alternate water discharge routes, namely via:

- hydraulic structures that withdraw water **from** the NSC/ARC and discharge it to the North Sea or Marker Lake;
- hydraulic structures that discharge water from the adjacent regional water systems **to** the NSC/ARC;
- hydraulic structures at **other** locations in the adjacent main water infrastructure network or the regional water system. These structures enable the discharge of excess water via alternative routes, by-passing the NSC/ARC. These alternate routes include discharge via the Wadden Sea, via the IJssel Lake, via the Marker Lake and/or North Sea.

The orange arrows in Figure 2 indicate the position and sluice capacity of those hydraulic structures that allow the discharge of free-flowing water under gravity out of the NSC/ARC. The total sluice capacity out of the NSC/ARC is 570-770 m^3/s. The dark green arrows indicate the position and capacity of pumping stations that are able to pump water out of the NSC/ARC, with a total capacity of 317 m^3/s. The blue arrows show the most important groups of hydraulic structures that discharge water from the adjacent regional water systems into the NSC/ARC, with a total capacity of 360 m^3/s. The light green arrows indicate other hydraulic structures located elsewhere in the study area.

Figure 2. Overview of the discharge capacity of hydraulic structures discharging water (1) from the NSC/ARC to the North Sea or Marker Lake (a) under free flow (orange arrows) and (b) using pumps (dark green arrows), (2) from the adjacent regional water systems to the NSC/ARC (blue arrows), and (3) at other locations elsewhere in the water system (light green arrows).

Future climate change and socio-economic developments, their impact on the functional requirements of hydraulic structures and the measures required to cope with climate change and socio-economic developments, will influence the functioning of the Discharge Sluice and Pumping Station IJmuiden and thus affect how long it remains able to effectively manage water levels on the NSC/ARC and in the surrounding areas. This means that the moment when a hydraulic structure in the NSC/ARC water system reaches its end of life depends on several external factors. The purpose of this case study is to explore how the continued functioning of these hydraulic structures will be affected by these developments in the future and how actions to extend the end of life of a structure can influence the end of life of other structures in the system.

For instance, sea level rise and (more severe and more frequent) extreme precipitation events induced by climate change will affect the functioning of the Discharge Sluice and Pumping Station IJmuiden. The Discharge Sluice and Pumping Station IJmuiden will have to withstand larger hydraulic loads as a consequence of sea level rise. Due to sea level rise, discharging water from the NSC/ARC to the North Sea via the discharge sluices may not always be possible. More and more often, the pumping station will need to be used to control the water levels on the NSC/ARC. In addition, the maximum head of the pumps will be reached more often than in the current situation, which will result in reduced pumping capacity. Taken together with a higher probability of more extreme precipitation events, this will result in more frequent and longer lasting high water levels on the NSC/ARC, with the probability of flooding increasing as a consequence.

The following uncertain future developments should be taken into account while identifying courses of action and developing adaptation pathways:

- The speed and impact of climate change (sea level rise and frequency and magnitude of heavy rainfall);
- Socio-economic changes (economic growth, changes in ground use);
- Changing requirements by law and social needs;
- Changing requirements due to developments elsewhere in the water network.

3.3 Estimation of the remaining useful life of hydraulic structures using adaptation tipping point analysis

We demonstrate here how information about the end of life of hydraulic structures and the importance of hydraulic structures in the water infrastructure network can be used to identify possible courses of action to incorporate in adaptation pathways. When looking at the water management function, the discharge capacity of a hydraulic structure (see Section 3.2) is an indicator of the relative importance of that structure within the wider infrastructural network.

As introduced in Section 2.3, estimates of the end of life moments for any hydraulic structure can be derived using the so-called 'basic' method, which simply adds the design life to the initial construction year of a structure (Bernardini *et al.*, 2014). The Discharge Sluice IJmuiden was constructed in 1940 and has a design lifetime of 100 years. This results in an end of lifetime prediction of 2040. The Pumping Station IJmuiden dates back to 1975 and has a design lifetime of 80 years, thus, by this method, it will reach its end of lifetime in 2055. By the same logic, end of lifetime predictions were derived for every other hydraulic structure that is hydrologically connected to the NSC/ARC, with Figure 3 providing a chronologic sequence as well as a geographic representation of these estimates.

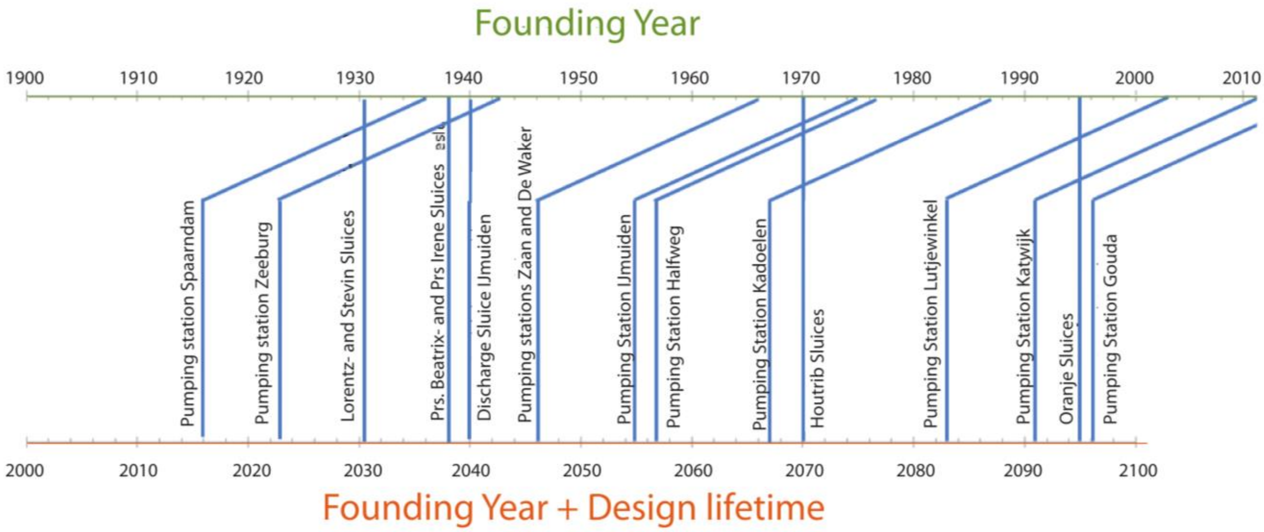

Figure 3. End of life predictions for hydraulic structure that are within the NSC/ARC network, as computed from the 'basic' method which utilizes founding year and design lifetime. Upper panel: a chronologic sequence of the resulting end of life predictions. Lower panel: a geographic representation.

The advanced method of Kallen *et al*. (2014) was subsequently applied to determine the functional and technical end of lifetime of the Discharge Sluice and Pumping Station IJmuiden, producing a timeframe for each end of life estimate.

Figure 4 provides an overview of the end of life predictions obtained for the Discharge Sluice and Pumping Station IJmuiden, based on both the basic method relying on founding year and design lifetime, as well as the adaptation tipping point analyses developed by Kallen *et al*. (2014).

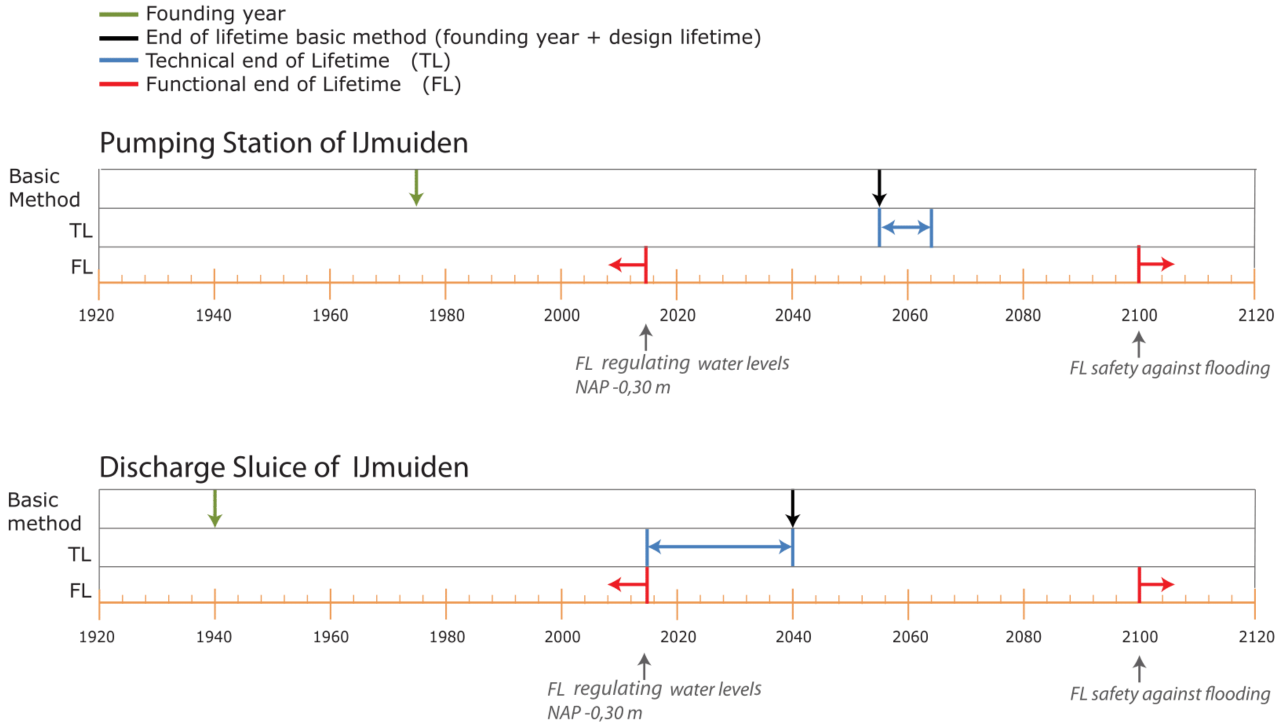

Figure 4. Forecasts of the end of life predictions for the Discharge Sluice and Pumping Station IJmuiden based on (1) founding year and design lifetime (black lines), (2) functional end of lifetime analyses (red lines) and (3) technical end of lifetime analyses (blue lines). The grey line gives the founding year.

3.4 Identification of possible courses of action for the replacement and renovation of specific hydraulic structures

In Section 3.3 the chronologic end of life sequence of hydraulic structures and their functionality in the water system NSC/ARC is presented. In this section we will focus on the possible courses of action that could be taken within the NSC/ARC system. The transformation from the courses of action identified here to complete adaptation pathways is described in Section 3.5.

To continue to meet the required inland water level management performance objectives during increasingly more extreme wet conditions, a number of actions in the primary and regional water systems can be taken. Information about the hydraulic functioning of the entire water system, the key hydraulic structures (their remaining end of life, and their characteristics) and predictions about probable future developments (the Delta scenario's), are used as a basis to define possible courses of action. Possible courses of action were identified in collaboration with the key water management stakeholders active within the NSC/ARC region. A number of possible courses of action are listed below. Note that this is not an exhaustive list.

The following possible courses of action were identified that help safeguard the continued effective management of water levels on the NSC/ARC in the future (see Figure 5):

1. *Expansion of the pumping capacity of the Pumping Station IJmuiden or replacement and reconstruction of the entire complex*.
   By expanding the discharge capacity of the Discharge Sluice and Pumping Station IJmuiden its functional end of lifetime and that of other structures in the NSC/ARC region could be expanded.
2. *Temporary storage of water in the Marker Lake during periods of extreme high water*.
   By temporarily storing water in the Marker Lake, the required peak discharge capacity of Discharge Sluice and Pumping Station IJmuiden could be lower. Complex IJmuiden and other structures in the NSC/ARC region will reach its functional end of life of the water level management function later in time.
3. *Discharge water from the regional water systems to the Marker Lake and IJssel Lake, instead of to the NSC/ARC.*
   By creating an alternative discharge route for water from the regional water systems that usually release water to the NSC/ARC, we can extend the functional end of lifetime of all discharging hydraulic structures of the NSC/ARC region.
4. *Discharge water from the region to the river Lek, instead of to the NSC/ARC.*
   By creating an alternative discharge route for water from the NSC/ARC catchment region we can extend the functional end of lifetime of all discharging hydraulic structures in the NSC/ARC region.
5. *Discharge more water through alternative regional discharge options by optimizing the existing regional discharge routes.*
   By utilizing existing alternative regional discharge options, more flexibility is introduced in the system and the discharge of excess water to the NSC/ARC can be reduced. This will extend the functional end of life of Discharge Sluice and Pumping Station IJmuiden and other structures in the NSC/ARC region.
6. *Expansion of the discharge capacity of alternative regional discharge options by expanding hydraulic discharge structures or constructing new ones.*

By expanding alternative regional discharge options, more flexibility is introduced in the system and the discharge of excess water to the NSC/ARC can be reduced. This will extend the functional end of life of Discharge Sluice and Pumping Station IJmuiden.

7. *Temporary storage of water within the regional water systems by expanding regional storage capacity, thus reducing peak discharge from regional to NSC/ARC*.
   By reducing peak discharge capacity from regional to NSC/ARC water system, the required peak discharge capacity of Discharge Sluice and Pumping Station IJmuiden could be lower. Complex IJmuiden and other structures in the NSC/ARC region will reach its functional end of life later in time.

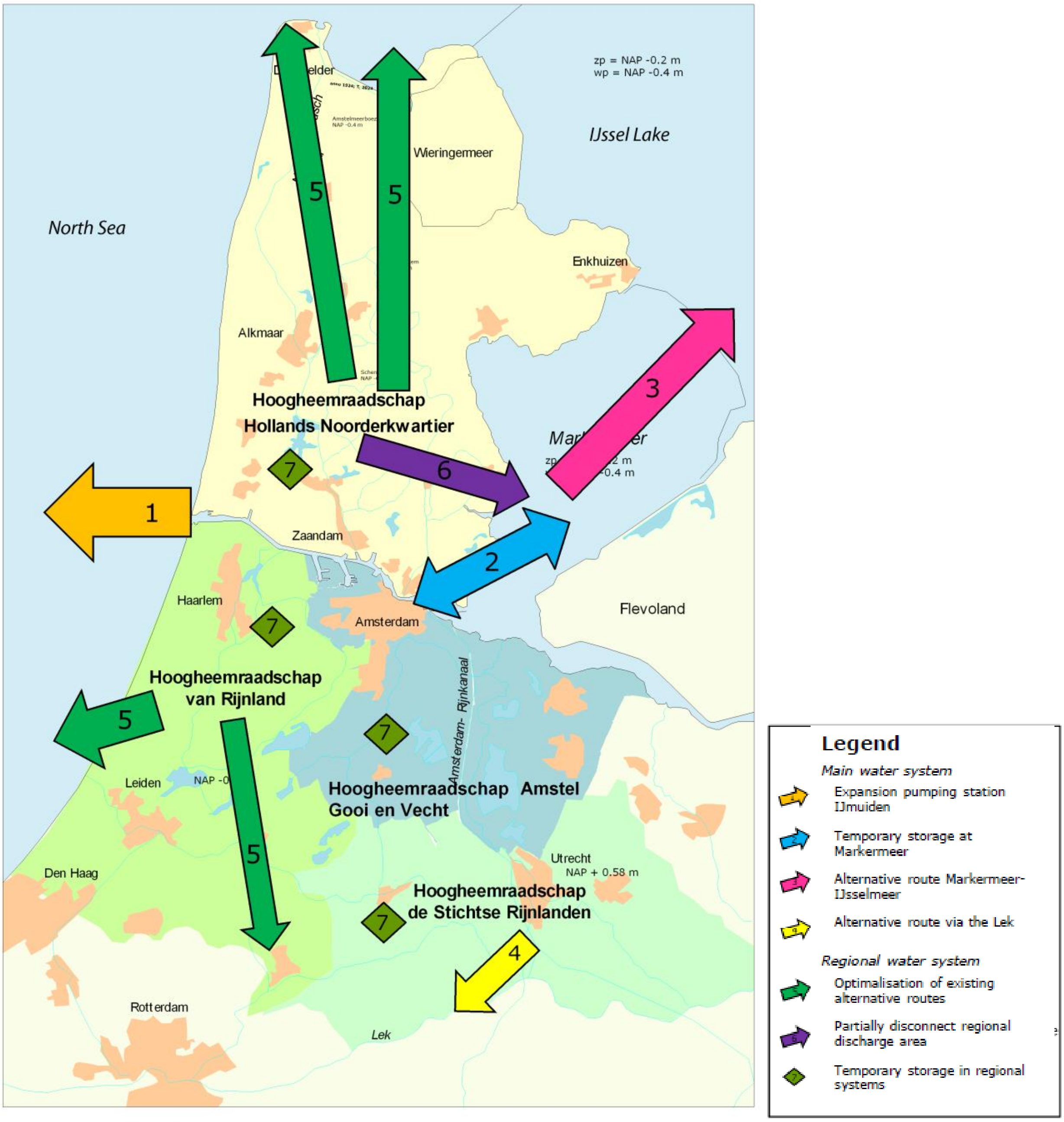

Figure 5. Map of possible courses of actions in the main- and regional water systems.

3.5 Identification of strategies for the redesign of the water infrastructure network & development of adaptation pathways

Sections 3.3 and 3.4 have shown how functional and technical end of life of a hydraulic structure can be determined and which aspects are important to take into account, in order to set up adaptation pathways. Together with information about future stakeholder's goals, this is input for the identification of strategies for the redesign of the water infrastructure network and development of adaptation pathways. In this section we cover both steps 5 and 6 of our approach (see section 2.5 and 2.6) together since in the process followed during this case these steps have been executed hand in hand.

Technical and functional end of life of hydraulic structures in the regional- and main water system identify the approximate timing of future adaptation tipping points, indicating a transition along an adaptation pathway. Therefore the timeline of end of life of the hydraulic structures in the NSC/ARC-system, which shows in which sequence structures will reach their end of life, provides starting points for setting up different adaptation pathways (see Figure 6).

At each adaptation tipping point, a number of choices can be made: (1) improve maintenance and operations to extend the end of life of the structure, (2) replace the structure with the same functionality, (3) replace the structure with extended functionality, or (4) intervene at another hydraulic structure, which could extend the functional end-of life of the structure. This choice should be made in an integral way, considering the functionality of the whole water system and reviewing the cost effectiveness of each option.

In the case of IJmuiden a first possible (fictional) adaptation pathway was compiled together with regional stakeholders. This pathway is developed from the perspective of Discharge Sluice and Pumping Station IJmuiden, given the end of life of its surrounding hydraulic structures. The pathway is shown in Figure 6.

The pathway shows the first, no-regret step: namely optimization of existing regional water management operations to postpone large investments (waiting till more information is available) or accepting a decreased performance. When this strategy can no longer provide the required performance of the system due to climate change and other external developments a new strategy is needed.

In collaboration with the key water management stakeholders two possible future strategies have been identified (1) a strategy following the adaptation path 'taking measures in the main water system' and (2) a strategy following the adaptation path 'taking measures in the regional water system'.

The first strategy boils down to advancing the replacement of Discharge Sluice and Pumping Station IJmuiden, including an extension of its capacity. Remaining future choices are additional measures in the regional water system and elsewhere in the main water system.

The second strategy follows the idea that when a regional pumping station or discharge sluice reaches its end of life, it will be replaced by a pumping station with extra capacity. Subsequently the peak discharge from the regional water system to the NSC/ARC system will be reduced, and thus the required discharge capacity of Complex IJmuiden could be lower and the functional end of life time of the water management function will be later in time. This implies that a large investment for the replacement of Complex IJmuiden could be postponed. On mid-term further interventions in the regional water system or in the main water system (Pumping station IJmuiden, Discharge Sluice Oranjesluizen, Discharge Sluice Beatrixsluizen reach end of life) are required. An essential principle of ADM is that the choices for these next steps can be made when more information is available by keeping the options open.

4. CONCLUSIONS AND RECOMMENDATIONS

A large number of hydraulic structures in The Netherlands are nearing their end of lifetime in the coming decades, making replacement or renovation necessary. The fact that hydraulic structures operate in complex water networks (both main and regional water system) with many functions and stakeholders, makes the redesign of the infrastructural assets a complex task.

This paper focused on the replacement of hydraulic structures in this complex field, according to the principles of Adaptive Delta Management. We have shown that replacement of a hydraulic structure should be done taking into account uncertain future demands and possible future water management strategies for the whole water system in which it operates. This requires understanding of the functioning of a hydraulic structure in relation to the surrounding hydraulic structures and required (future) functionality and performance. This is made possible by using a flexible, integrated, step-by-step framework.

The framework integrates the forecasts of replacements / renovation of hydraulic structures with the process of possible functional redesign of the main- and regional water system, according to estimated future requirements. By integrating both approaches, we conclude that the technical and functional end-of-life of hydraulic structures in a water system can serve as valuable adaptation tipping points in the application of Adaptive Delta Management in the construction of adaptation pathways.

Two aspects of our framework are worth highlighting when it comes to defining long term reinvestment strategies for the replacement or renovation of hydraulic structures within existing water infrastructure networks. They both follow from the relationship between the replacement and renovation of hydraulic structures, the functioning of water system as a whole (consisting often of many hydraulic structures) and the required objectives of possible future water management strategies. This is therefore one of the key elements of the integrated framework developed in this paper.

1. Any single hydraulic structure has a number of different adaptation tipping points (technical end of life and often multiple functional adaptation tipping points). If a structure is determined to be unable to fulfill a particular function at a certain time, this adaptation tipping point may be pushed back in time by making changes elsewhere in the system, thus delaying the need for large-scale renovation or replacement.
2. When considering different strategies using adaptation pathways, the individual replacement/renovation moment of a key hydraulic structure provides stakeholders a valuable opportunity to re-think the water system as a whole by adding or subtracting functionality to structures and in this way implement new water management strategies attaining the required objectives.

These conclusions have been demonstrated in the case study Discharge Sluice and Pumping Station of IJmuiden.

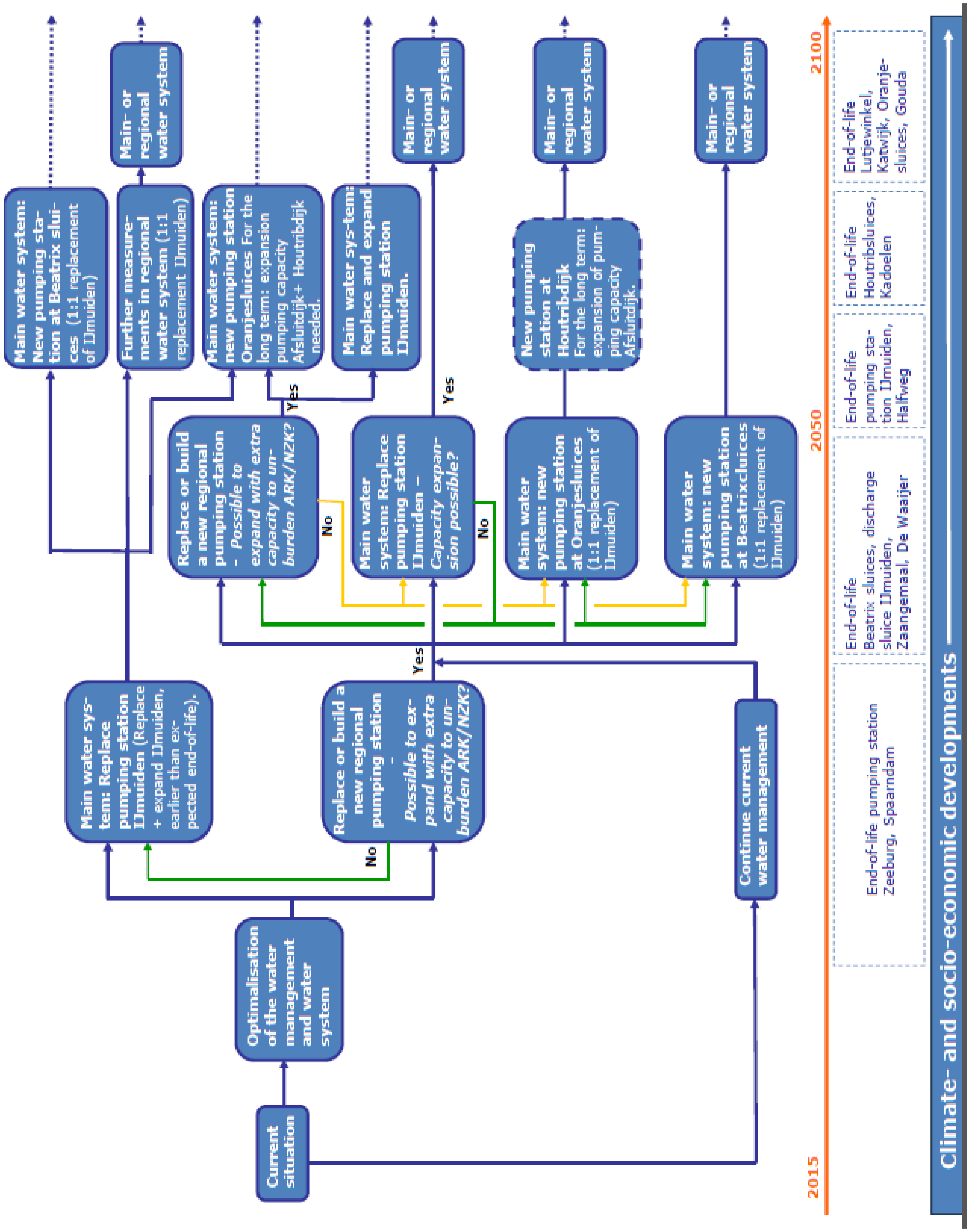

Figure 6. Overview of a possible (fictional) adaptation pathway for the Discharge Sluice and Pumping Station of IJmuiden, based on end of life (founding year + design lifetime) of the hydraulic structures in the water system of the NSC/ARC.

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REFERENCES

Bernardini, P., Van Vuren, S., Van der Wiel, W.D., Wolters, M., Roovers, G. and Tosserams, M. (2014). Integrative framework for long term reinvestment planning for the replacement of hydraulic structures. *PIANC World Congress San Francisco*, USA, 2014.

Delta Programme 2012 (2011). Delta Programme 2012 Acting today, preparing for tomorrow, The Netherlands

Delta Programme 2015 (2014). Background article: Vervangingsopgave Natte Kunstwerken. Meerwaarde van de Gevoeligheidstest Natte Kunstwerken voor Adaptief Deltamanagement (in Dutch), The Netherlands.

Faludi, A. and A. Van der Valk (1994). *Rule and Order Dutch Planning Doctrine in the Twentieth Century*. ISBN 0-7923-2619-9. Kluwer academic Publisher.

Haasnoot, M., Kwakkel, J.H., Walker, W.E. and ter Maat, J. (2013). Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*. 23(2):485-498.

Kallen, M.J., Nicolai, R.P., Van der Wiel, W.D., Willems, A., Van den Dungen, E.L.E. and Klatter, L. (2014). Functional and technical end-of-service estimates for hydraulic structures. Conference proceedings of the 22nd European Safety and Reliability in Amsterdam, The Netherlands *Safety, Reliability and Risk Analysis: Beyond the Horizon*. Eds. Steenbergen et al., Taylor & Francis Group, London, ISBN 978-1-138-00123-7, 679-685.

Kwadijk, J.C.J., Haasnoot, M., Mulder, J.P.M., Hoogvliet, M.M.C., Jeuken, A.B.M., Krogt, R.A.A., Oostrom, N.G.C., Schelfhout, H.A., Van Velzen, E.H., Van Waveren, H. and De Wit, M.J.M. (2010). Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdisciplinary Reviews: Climate Change* 1(5), 729-740.

Lindsay, R. W., & Zhang, J. (2005). The thinning of Arctic sea ice, 1988-2003: Have we passed a tipping point? *Journal of Climate*. 18(22): 4879-4894.

McNeil, B. I., & Matear, R. J. (2008). Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO2. *Proceedings of the National Academy of Sciences*. 105(48): 18860-18864.

Reeder, T. and Ranger, N. (2011). How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project. World Resources Report.

Van der Vlist, M. J., Ligthart, S.S.H. and Zandvoort, M. (accepted for publication). The replacement of hydraulic structures in light of tipping points. *Journal of Water and Climate Change*.

Van Rhee, G. (2012). Handreiking Adaptief Deltamanagement (in Dutch), the Netherlands

Voortman, H.G. and Van der Kolk, H. (2013). Adaptive design as an answer to climate uncertainty. Conference proceedings of the 22nd European Safety and Reliability in Amsterdam, The Netherlands *Safety, Reliability and Risk Analysis: Beyond the Horizon*. Eds. Steenbergen et al., Taylor & Francis Group, London, ISBN 978-1-138-00123-7.

[3] VervangingsOpgave Natte Kunstwerken (VONK) is a Dutch project about developing a Replacement Strategy for the Hydraulic Structures owned by the Ministry of Infrastructure and Environment.