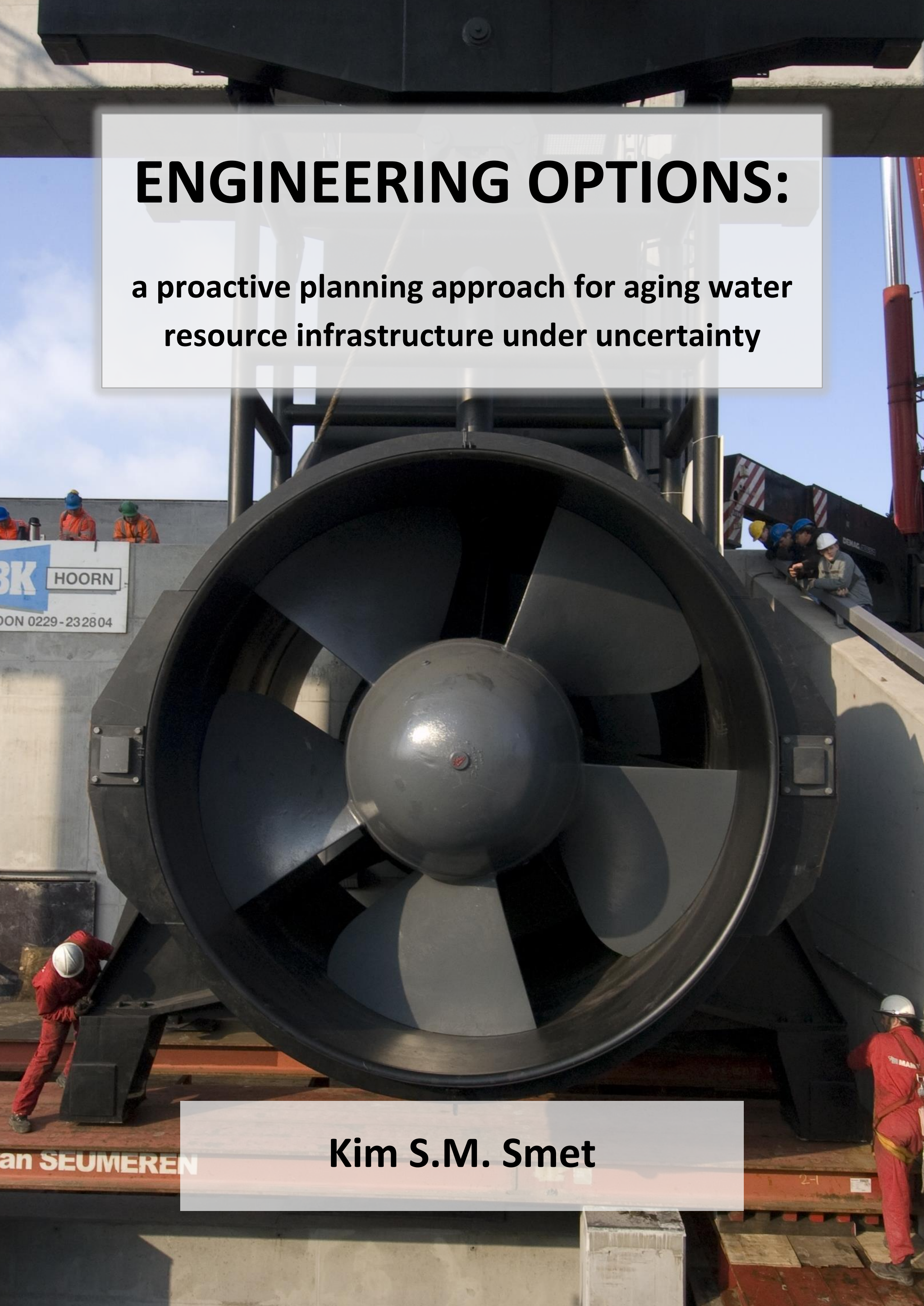
ENGINEERING OPTIONS:

a proactive planning approach for aging water resource infrastructure under uncertainty

Kim S.M. Smet



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Kim S.M. Smet

A dissertation presented by
Kim Sarah Maria Smet
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Abstract

This dissertation presents an innovative, value-enhancing approach for proactive replacement planning for aging water resource infrastructure given uncertain future conditions. This work addresses two shortcomings in the existing literature on long-term water infrastructure planning. First, existing approaches do not incorporate different drivers of investment within a single unified framework: they typically focus on infrastructural alterations driven either by changes in external operating conditions or by internal structural factors. Second, the majority of approaches developed to incorporate uncertainty within long-term planning are reactive towards uncertainty. The approach developed here advances the current state of research by accounting for different drivers of reinvestment, both changes in external conditions and structure-specific processes, and by taking a proactive rather than reactive stance toward uncertainty.

It draws upon two existing methodologies to develop an integrated long-term infrastructural planning framework. It uses Adaptation Tipping Points to generate a long-term planning timeline that incorporates diverse drivers of investment. It subsequently applies Engineering Options thinking to explore different courses of action taken at key moments in this timeline. Contrasting to the traditionally static approach to infrastructure design, designing the next generation of infrastructure so managers can update it incrementally is a promising method to safeguard the efficacy of current investments given uncertain future developments. Furthermore, the up-front inclusion of structural options within the physical system actively facilitates future adaptation, transforming the management of uncertainty in infrastructure planning from reactive to more proactive.

A two-part quantitative model underpins this conceptual approach. First, a simulation model generates future conditions consistent with diverse changes to the operating environment, allowing the development of a timeline of key intervention moments in the life of a structure. This feeds into an economic model, evaluating the lifetime performance of different possible infrastructural replacement strategies, making explicit the value of options and the flexibility they provide.

A proof of concept study demonstrates this approach: replacement planning for the multi-functional pumping station IJmuiden on the North Sea Canal in the Netherlands. The analysis models flexibility in design decisions, varying the size and specific options included in the proposed replacement structure. Results indicate that incremental adaptive designs and the incorporation of options can improve life-time economic performance, as compared to more traditional, “build it once and build it big” designs. However, the benefit from incorporating flexibility varies with structural functionality, future conditions considered, and the specific options examined. The approach demonstrated here is able to identify for which structural functions and under which conditions different replacement strategies are desirable.

HARVARD UNIVERSITY
Graduate School of Arts and Sciences

DISSERTATION ACCEPTANCE CERTIFICATE

The undersigned, appointed by the

Harvard John A. Paulson School of Engineering and Applied Sciences

have examined a dissertation entitled:

"Engineering Options: a proactive planning approach for aging water resource infrastructure under uncertainty"

presented by: Kim Sarah Maria Smet

candidate for the degree of Doctor of Philosophy and here by certify that it is worthy of acceptance.

Signature ______________________________

Typed name: Professor R. de Neufville

Signature ______________________________

Typed name: Professor M. McElroy

Signature ______________________________

Typed name: Professor M. van der Vlist

Signature ______________________________

Typed name: Professor P. Rogers

April 21, 2017

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In de jaren 20, tijdens het bekijken van de nieuwe Noordersluis aan IJmuiden, zei Minister Cornelis Lely tegen zijn ingenieurs:

"Maak hem maar een stuk groter, dan kan hij langer mee…"

*

Upon seeing the design of the newest shipping lock at IJmuiden in the 1920's, the Dutch Minister of Transport and Water Management, Cornelis Lely said to his engineers:

"Make it much bigger, that way it will last longer…"

*

Source: Joris Moes, (2001). *Noordzeekanaal 1876-2001.* Amsterdam Ports Association.

Almost a century later, this work explores whether this statement remains true in an era where we face unprecedented rates of change and an increasing awareness of the limitations of our knowledge.

Acknowledgements

An African proverb says "it takes a village to raise a child". The same could be said for successfully completing a PhD. Thank you to all those in my village:

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Finally, I dedicate this work to the late John Briscoe. It saddens me that he was never able to see the influence he had on my thinking. I hope he would have been proud.

1. Introduction

1.1 What is the problem currently being faced?

The need to reinvest in aging water resource infrastructure

For almost as long as humans have existed, we have been influencing and managing water resources. From early irrigation systems in ancient Mesopotamia, Egypt and China, to state of the art flood protection networks such as the present-day Delta Works in the Netherlands and the Mississippi River and Tributaries project in the United States, countries around the world have invested and continue to invest heavily in water resource infrastructure systems. Briscoe (2012 from Blackbourn, 2007) described the long-term development and evolution of such water resource systems as cycles of challenges and responses. As physical conditions change and societal preferences evolve, water-related challenges emerge; some form of response typically follows, shaped by diverse factors such as stakeholder needs, social priorities and the availability of technology and funding at the time; these interventions in turn change the state of the world and often form the basis of the next generation of future challenges. For instance, investment in municipal water supply infrastructure not only provides clean drinking water, but increased water use per capita typically follows this improved access to running water. This in turn means that sanitation and wastewater treatment grow more necessary and over time, further exploitation of additional water supply sources will become necessary. Similarly, construction of levees along a river provides not only flood protection, but contributes to future land subsidence which exacerbates flood risk, as sediment transported in the river can no longer build land in those areas of the watershed now protected by levees.

Concentrating on the more recent past, over the course of the last century, many developed countries around the world have invested heavily in infrastructural solutions to water management problems. What started as a piecemeal process of building one structure at a time ultimately produced extensive, complex and interlinked water infrastructure networks. While the focus in the previous century was first on building and then on operating and maintaining these systems, the newly emerging challenge is that of managing these aging infrastructure assets. This is the first time that on such a large scale the focus is shifting from new capital investment to reinvestment in existing systems, a transition coined as the "Dawn of the Replacement Era" (AWWA, 2001). The question of how best to approach the replacement/reinvestment process is becoming increasingly relevant.

As an example of the magnitude of the job at hand, Figure 1.1 gives an overview of the replacement task currently being faced in the Netherlands: it shows the number of hydraulic structures[1] approaching the end of their design life that will need to be replaced per decade over the course of the coming century. At an estimated average replacement cost of €33 million each (RWS, 2014), the upcoming investment is substantial and any gains in efficiency or cost reductions

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[1] The definition of a hydraulic structure varies somewhat between countries:

- In the United States, the United States Army Corps of Engineers (USACE) uses the definition "[h]ydraulic structures are anything that can be used to divert, restrict, stop or otherwise manage the natural flow of water" (USACE, no date). This definition includes locks and dams, pumping stations, sluices and storm surge barriers, among other structures.
- In the United Kingdom, May *et al.* (2002) define a hydraulic structure as "[a]ny structure used to control flows or any structure built in a position where it may affect or be affected by, flows." This usage of the term encompasses a broader set of structures than the definition described above, with additional structures such as bridges also included. (Standard texts published in the United Kingdom, such as Novak e*t al*. (2006) reinforce usage of the term in this way, explicitly including bridges when referring to hydraulic structures). This usage of the term "hydraulic structures" is consistent with the terminology "natte kunstwerken" used in the Netherlands, and the structures shown on Figure 1.1 are in line with this definition.

would be highly desirable. The situation in the Netherlands is by no means unique: according to the American Society of Civil Engineers 2017 report card for America's Infrastructure, water infrastructure within the United States receives a grade of C+ or lower (ASCE, 2017). Poor performance and unreliability due to the increasing age of these physical assets are largely responsible for this low grade.

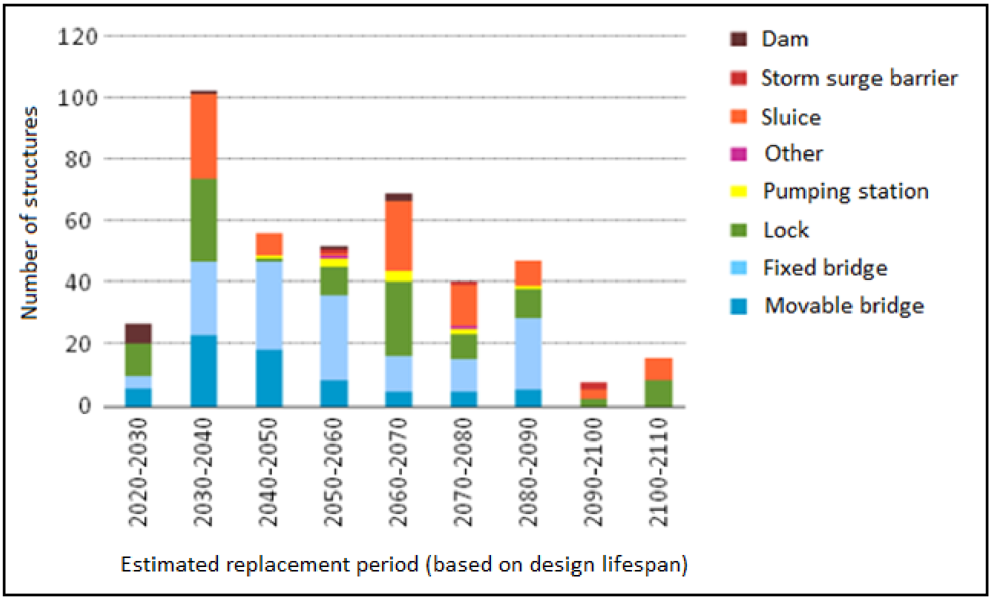


Figure 1.1: Estimated number of hydraulic structures in need of replacement in the Netherlands, during the course of the next century (Source: adapted from Rijkswaterstaat, Ministry of Infrastructure and Environment, 2012)

While no one can argue that investment in water resource systems has been without negative side-effects or long-term consequences (for instance on the environment or on under-represented stakeholder groups), the continued provision of water management services in the face of a myriad of challenges such as aging infrastructure, growing populations, urbanization and climate change impacts remains key. For instance, historic investments in flood protection have been some of the most successful civil works projects in history: according to the

Mississippi River Commission, $14 billion worth of flood protection infrastructure on the Mississippi River has accrued an estimated return on investment of 45 to 1 (MRC, 2014). Thus, the question of how to maintain continued functionality in the future is an important one.

To this end, this research specifically explores the question of **how we should systematically go about the process of infrastructure replacement and reinvestment when looking at extensive and complex water resource systems.** To keep the scope of this work manageable, this dissertation is limited to looking in detail at those water resource structures that primarily fulfil a flood management role[2]. The question of replacement planning is explored through the lens of hydraulic structures[3], an important and typically expensive component of wider flood management systems. However, the concepts presented and the novel planning approach developed here are, in principle, valid for water resource infrastructure more generally.

[2] Often structures can have a variety of different functions: for instance, a dam may have a primary function to store floodwaters and regulate high river flows, but can additionally serve as a water reservoir for municipal and agricultural use, as well as hydropower generation. While the structures considered in this research are typically multifunctional, they all principally fulfill some kind of flood management function.

[3] Many flood management systems integrate linear flood management structures such as dykes/levees and dunes, with point-location hydraulic structures, as introduced in Footnote 1. This research focuses on the replacement of hydraulic structures, explicitly excluding more extensive, linear flood management strategies that due to the characteristics of their earthen physical construction typically undergo continuous maintenance and improvement work rather than one well-defined replacement process. For recent work looking at investment in dykes/levees, see for instance, Brekelmans *et al.* (2012) and Zwaneveld and Verweij (2014).

Within this exploration of reinvestment in flood infrastructure systems, it is worth making a number of important scope delineations. First, the focus in this dissertation is on long-term strategic planning, over timeframes of several decades. This means that this work explicitly excludes consideration of the more short-term, day-to-day operational and mid-term tactical levels, as well as crisis-driven emergency planning and management. Second, effective flood risk reduction relies on a combination of many different measures, including hard engineering solutions (e.g. levees and hydraulic structures), soft watershed management strategies (e.g. zoning and building bylaws) and flood insurance[4], all supported by appropriate institutional governance arrangements. Given that the focus in this dissertation is on long-term strategic infrastructure replacement planning, hard flood management strategies, specifically hydraulic structures, take center stage. This is no way suggests that non-structural and other flood risk reduction measures are less important or should not be integrated into a comprehensive flood risk plan; these simply do not fall within the scope of the work presented here.

1.2 Why is the traditional planning approach considered inadequate for this task?

In the past, the planning and design of most water resource systems was based on a so-called “predict-then-act” framework (Hallegatte *et al*., 2012), where the primary focus was to identify an *optimal* course of action. First, a best estimate of the future was *predicted*, usually based on historically observed conditions, before subsequently *acting* in such a way as to optimize for this most-likely future

[4] All these different types of measures contribute to reducing the *flood risk.* Flood risk is generally defined as the probability of a flood of a certain magnitude occurring multiplied by the consequences of such a flood. Different flood risk reduction measures target different components of risk: structural measures typically reduce the probability of floodwater entering a populated area, while soft strategies such as zoning reduce the consequences when a flood event does occur.

scenario. Section 2.3 provides a more complete discussion of this traditional planning approach. Increasingly, there is growing consensus among those involved in water resources research and management that this traditional approach is no longer adequate for effectively planning the upcoming replacement work. Reasons for this shift include:

1. **The spectre of hydrological non-stationarity, and a shift from seeking optimal solutions to those able to function over a wider range of conditions**

   The planning and design of flood management systems has long been founded on the assumption that the relevant underlying natural systems can be adequately quantified by stationary processes and thus that history can give a meaningful indication of the future. This does not mean that there is no natural short-term variability in the system, but rather that processes vary between relatively well-defined static outer bounds of variability (Milly *et al.*, 2008).

   Substantial safety margins are typically used to address any residual uncertainty about future conditions that falls outside of the historic record. Increasing evidence has been put forth in recent years suggesting that human disturbances are fundamentally changing these natural processes (IPCC, 2013 and 2014) and that possible non-stationarity in these processes may lead to greater variability and uncertainty in future conditions. This means that we should no longer rely solely on historic records and past events to provide a meaningful indication of what to expect from the future.

   Within the context of replacing hydraulic structures within an existing flood management system, this means that we need to make design and investment decisions now about the next generation of flood infrastructure, despite not knowing with any confidence the conditions that these systems will need to withstand across their long useful lifetime (typically 80 to 100 years). In other words, the decisions made today must allow room for the system to withstand future conditions and remain functional over the better part of the next century. Driven by increasing awareness of the potentially vast impacts of uncertainty in the future, there has been a gradual transition in this field from searching for optimal solutions to identifying those that are variously described as being robust (e.g. Hashimoto *et al*., 1982; Lempert *et al*., 2003), resilient (e.g. Fiering, 1982; Gersonius, 2012), flexible (e.g. de Neufville and Scholtes, 2011) and/or adaptive (e.g. Woodward *et al*., 2014). This changing objective calls into question the adequacy of the existing planning approach and the decision support techniques it relies on.

2. Inherent differences between replacement and new construction projects

The question of replacement within an existing physical network is different from the initial construction and development process in a number of important ways. New projects are additions to the existing system, adding a desired functionality to address a specific problem identified by society. The underlying guiding question is first **if** we will do anything to address a specific problem, and then once the "if" has been established, then it becomes a question of **what** we should do. This is typically done with the help of a Cost Benefit Analysis. A Cost Benefit Analysis is an economic evaluation of different proposed project alternatives (e.g. do nothing; take small Action A; take large Action B) that translates all benefits and costs into monetary terms. The net benefit of each alternative is the difference between the costs and the benefits. Only those alternatives where the benefits exceed the costs are considered economically viable, and the most economically efficient alternative is the one with the highest net benefits. In other words, Cost Benefit Analysis first helps identify whether addressing a particular problem has more benefits to society than costs, and subsequently identifies the most economically efficient course of action that maximizes these net benefits. The timing of **when** such new construction is initiated is very flexible, depending strongly on political and budget cycles, as well as society's priorities and perception of the project's need.

Typical replacement work, by its very definition, need not necessarily result in an addition to the existing system, but rather a continued provision of previous functionality. The underlying question of **if** society should do something to address a particular historical problem has previously been answered when decision makers first decided to go ahead with the original project. When replacement is considered, the question of "if" remains relevant because external conditions and societal demands change over time, and functions may grow obsolete over time. Hence, when looking at replacement, the question of "if" needs to be revisited to ascertain whether the function provided by a structure needs to be maintained, changed or expanded into the future. If decision makers conclude that a certain function has not grown obsolete over time, then the central question is that of **what** we should do to maintain these functions most effectively and **when** we should do it. Possible alternatives of **what** to do are more constrained in form due to the physical characteristics of the existing infrastructure system dictating to some extent the spectrum of new strategies considered. While there is substantial flexibility in the exact timing of when in the lifetime of a structure replacement measures can be taken, in the limit, replacement work cannot be delayed indefinitely. As a structure approaches and passes its design life, the rate of outages and the risk of a catastrophic failure increase. In the context of replacement work, a Cost Effectiveness Analysis framework may be more suited to evaluating different replacement alternatives than a full Cost Benefit Analysis, as the focus lies on identifying which of the possible courses of action most efficiently fulfils a pre-defined functional performance level. Cost Effectiveness Analysis, also known as least-cost analysis, is an economic valuation method used to identify the lowest cost alternative for achieving a certain predefined set of objectives.

3. **A desire to do better than blindly replacing like with like, one structure at a time**

   Within some of the more proactive government planning agencies, there is emerging interest to explore whether the decision moment associated with the end of a structure's life and the need to reinvest can provide an infrequent and valuable opportunity to reassess the system as a whole. Early awareness of the large upcoming reinvestment allows room to consider or even create more novel and innovative planning strategies, as opposed to continuing with the status quo one-at-a-time type replacements. By allowing ample planning time and providing resources to look more broadly than the single structure that needs to be renewed, there is likely the opportunity to exploit desirable synergies or remove unnecessary redundancies and inefficiencies from the system. In other words, there is an emerging desire to do better than simply replacing like with like, one structure at a time.

The various reasons described above highlight the diverse shortcomings of the previous planning approach, and build a strong case for the need to develop a new and improved planning approach, pinpointing some of the limitations that any such new approach should seek to address.

1.3 What is the current state-of-the-art and what are its shortcomings?

The previous section described the limitations of the existing planning techniques and justified the need for a new and improved planning approach. A review of the existing literature (presented comprehensively in Chapter 2) provides a first indication of the work conducted so far in developing such a state-of-the-art planning approach. In brief, this review suggests that there are two primary areas where work related to the development of a new infrastructural planning approach is being conducted:

- The first area of relevance is the asset management and civil engineering literature. Here, the issues of aging assets and the upcoming era of replacement are approached from a largely technical design perspective. The emphasis within this field is on improving our understanding and ability to capture those factors that relate directly to the condition of the physical structure itself. This includes for instance improvements in the techniques used to predict the occurrence of the end of technical life of a structure. Section 2.2 provides detailed discussion of this portion of the literature.
- The second area of relevance focuses on the question of planning and decision making in times of uncertainty, with a particular focus on the potential impacts of climate change uncertainty. This conversation is emerging mainly from the decision making under uncertainty and climate adaptation literatures. These literatures emphasize external conditions and how these operating conditions enable (or prevent) a structure from fulfilling its intended design functionalities in the future. Section 2.3 provides detailed discussion of this literature.

As explained more fully in Section 2.4, there are two fundamental areas where this existing body of work leaves room for improvement:

- The two fields of inquiry introduced above have developed as two largely separate conversations. These two areas of research should not happen independently or in isolation: when exploring long-term reinvestment strategies for aging assets, both technical drivers of investment that are internal to the structure as well as impacts of broader external changes are relevant and should be combined into a more comprehensive approach for flood infrastructure planning under uncertainty. This dissertation serves as a first bridging of these two to-date separate areas of research and development.
- The second shortcoming relates to how these planning frameworks currently approach how to manage uncertainty. As discussed in Section 2.3, a diverse array of new planning approaches has emerged from the climate adaptation literature in recent years. All of these emerging approaches strive to facilitate a move away from the traditional quest to identify one optimum solution, towards approaches that instead emphasize the identification of strategies that continue to perform well under a multitude of possible futures, and/or can be easily adapted/upgraded as time goes on and uncertainty is resolved. This move from a predict-then-act to a manage-and-adapt paradigm is an important one and one that is garnering substantial research efforts (see e.g. Section 2.3). However, all of these emerging approaches remain fundamentally *reactive* to uncertainty: in all cases, while the likelihood that a planning strategy must be revisited and adapted in the future is increasingly acknowledged, the predominant attitude remains one of "wait-and-see". This dissertation seeks to make a first step in the direction of transforming the management of uncertainty in infrastructure planning from a reactive to a more proactive process. In this work, such a more proactive planning strategy is exemplified by incorporating options within the physical system, thus providing system managers with the up-front ability to actively transform the system and respond to possible future effects of uncertainty.

Thus, the proposed planning approach developed in this work offers two primary improvements over the current state-of-the-art. First, it offers a way to incorporate a more realistic spectrum of drivers of reinvestment (both those internal to the structure and the result of external changes). This is an improvement compared to the current fragmented approaches where internal, structural processes are treated separately from the impacts of external, broader changes in the operating environment. Second, it demonstrates how the proactive inclusion of sources of infrastructural flexibility within a planning approach can result in substantial benefits as compared to designing for robustness and over-dimensioning, which have been the long-standing tool of choice to cope with uncertainty within many engineering fields.

1.4 Statement of purpose and research questions

The purpose of this work is **to develop a systematic approach for effective proactive long-term planning and design for the replacement of flood management infrastructure, given uncertainty about future external conditions.** It builds this decision support framework by drawing on elements of two existing concepts (Adaptation Tipping Points, introduced in Section 3.1 and Engineering Options/flexibility in design, introduced in Section 3.2) to develop a single long-term infrastructural planning approach that is proactive to the possibility of future changes by incorporating flexibility within the physical system itself (described in Chapter 4). Thus within this over-arching objective, the following more specific research questions are examined:

1. This work identifies the separate treatment of structural and external drivers of infrastructure investment as a shortcoming of existing asset management practices. *What additional insights are obtained when infrastructure planning is conducted in a more integrated way that takes into account both internal*

structural drivers of investment as well as external processes causing changes in the operating environment?

2. Both in this work, and in the larger community of practitioners, it has so far been assumed that the creation of more adaptive infrastructure plans is desirable in flood management systems, as compared to traditional, fixed monolithic designs. *When looking specifically at flood management infrastructure, faced with diverse sources of uncertainty, can it be demonstrated that adaptive approaches do in fact offer economic benefits?*
3. This work identifies the reactive nature of adaptive water management as a shortcoming of existing water infrastructure planning approaches. *How do proactive adaptive approaches incorporating Engineering Options concepts perform compared to the more common reactive adaptive approaches?*
4. Flood management structures are typically multifunctional. *When looking at these kinds of complex multi-functional structures, how do we structure an analysis of sources of proactive flexibility? Is it possible to identify flexible design elements for each individual function? To what extent are the benefits derived from the inclusion of flexibility function specific?*
5. Technical systems do not exist in isolation: they are affected by a wide variety of social, economic, institutional and other factors. *What are possible barriers in these non-technical factors (e.g. financing/institutional/policy) that may complicate the more widespread utilization of the planning approach developed here?*

1.5 Research approach

This thesis comprises three main parts:

- The first portion justifies the need and provides background for a new-and-improved planning approach. This introduction provided in Chapter 1 is followed by a detailed literature review examining work done to date. Chapter 2 examines those portions of the literature that relate directly to the *problem* being addressed, namely: characteristics of flood management infrastructure planning, aging assets and the upcoming era of replacement and the incorporation of uncertainty into water resources infrastructure planning processes.

- Having highlighted the shortcomings of this existing body of work and delineating the research gap this dissertation seeks to fill, Chapter 3 moves away from defining the problem and looks towards the development of *a proposed solution* in the form of a new long-term infrastructural planning approach. This novel approach builds on two existing fields of research, namely Adaptation Tipping Points and Engineering Options, and within Chapter 3, both of these areas are introduced and their development to date is reviewed. The potential benefits of using these two techniques in conjunction with each other are also discussed. Chapter 4 subsequently describes how elements of these two existing techniques were incorporated into a new proactive planning approach for flood management under uncertainty.

  This new approach is made up of five main steps. The first two are introductory and involve defining and delineating the problem, as well as conducting a comprehensive analysis of the relevant sources of uncertainty. The existing body of work focusing on Adaptation Tipping Points informs the third step. Within this step, a timeline of different intervention moments is derived, highlighting when in the life of a structure changes must be made in order to maintain the functionality and technical soundness of the structure. A generic physical model that relates specific infrastructure design decisions to system performance indicators of interest to decision makers underlies this portion of the approach. The fourth step of the planning approach involves using the previously derived timeline to explore different possible replacement strategies. This portion of the approach is informed by options concepts, and is underlain by an economic evaluation model, able to quantify the relative long-term costs of maintaining a certain performance level by means of different infrastructure designs. These latter two steps in the approach form the quantitative core of this approach, and are linked by utilizing the occurrence of an Adaptation Tipping Point as an exercise or trigger point in a subsequent options analysis. Finally, the fifth step focuses on using the insights obtained to actually make and implement a decision. This general approach can be used to explore and evaluate the relative benefit of flexible infrastructure replacement strategies as compared to other more standard approaches.

- The third portion of this thesis demonstrates the applicability, strength and versatility of the proposed approach through a proof of concept demonstration. The demonstration (Chapter 5) focuses on application of the new planning approach as applied to the pumping station of IJmuiden on the North Sea Canal in the Netherlands. This application focuses on deriving proactive replacement strategies that allow us to evaluate the degree of flexibility that results from specific design decisions. This proof-of-concept demonstration is complemented by consideration of the practical, political, financial, social, institutional and other barriers that may complicate the adoption of this planning approach by real-world water and infrastructure management agencies (Chapter 6). Conclusions and reflections, as well as shortcomings of this approach and areas for further work are presented in Chapter 7.

Figure 1.2 serves as a roadmap of this dissertation. It reappears at the start of each chapter, as a reminder of where each individual section fits in to the bigger picture of this work.

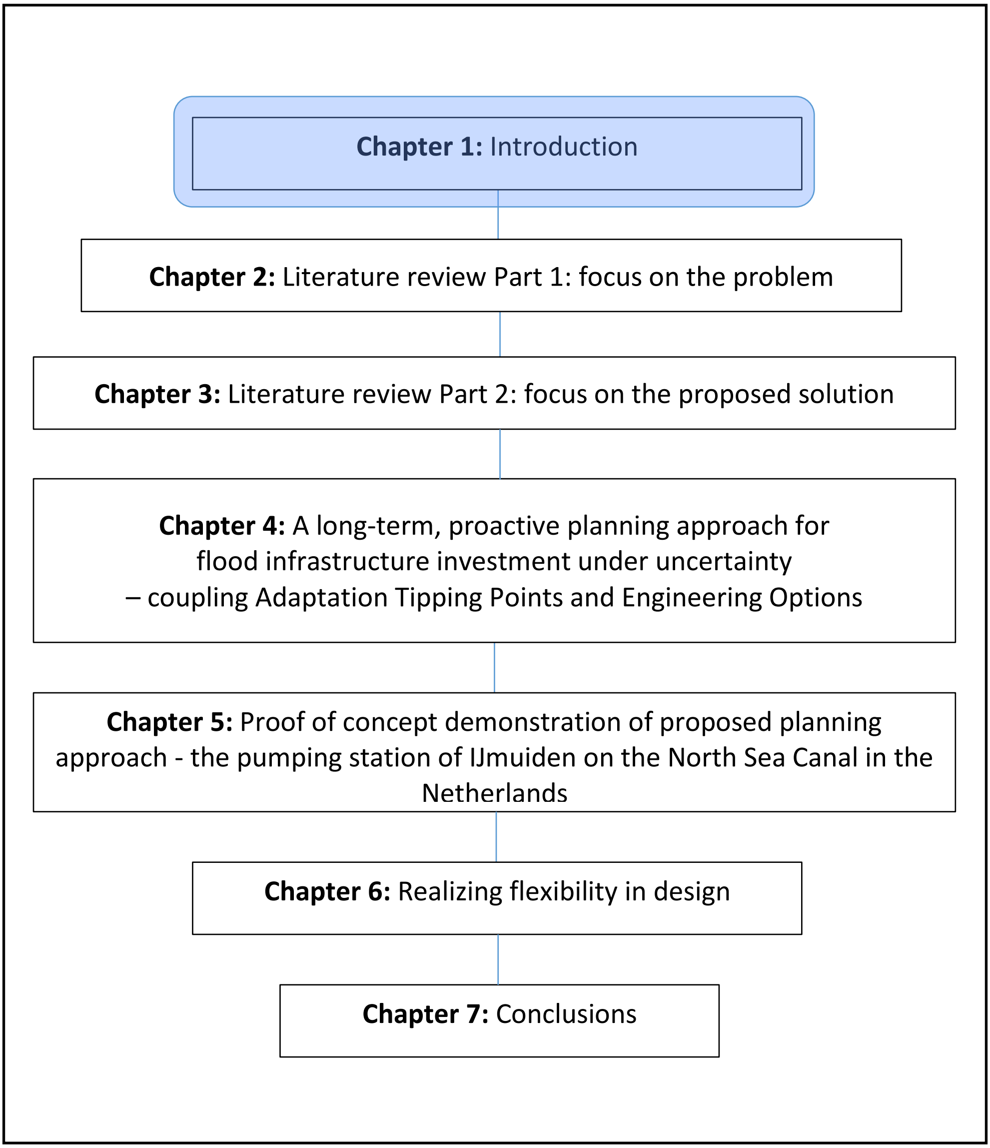
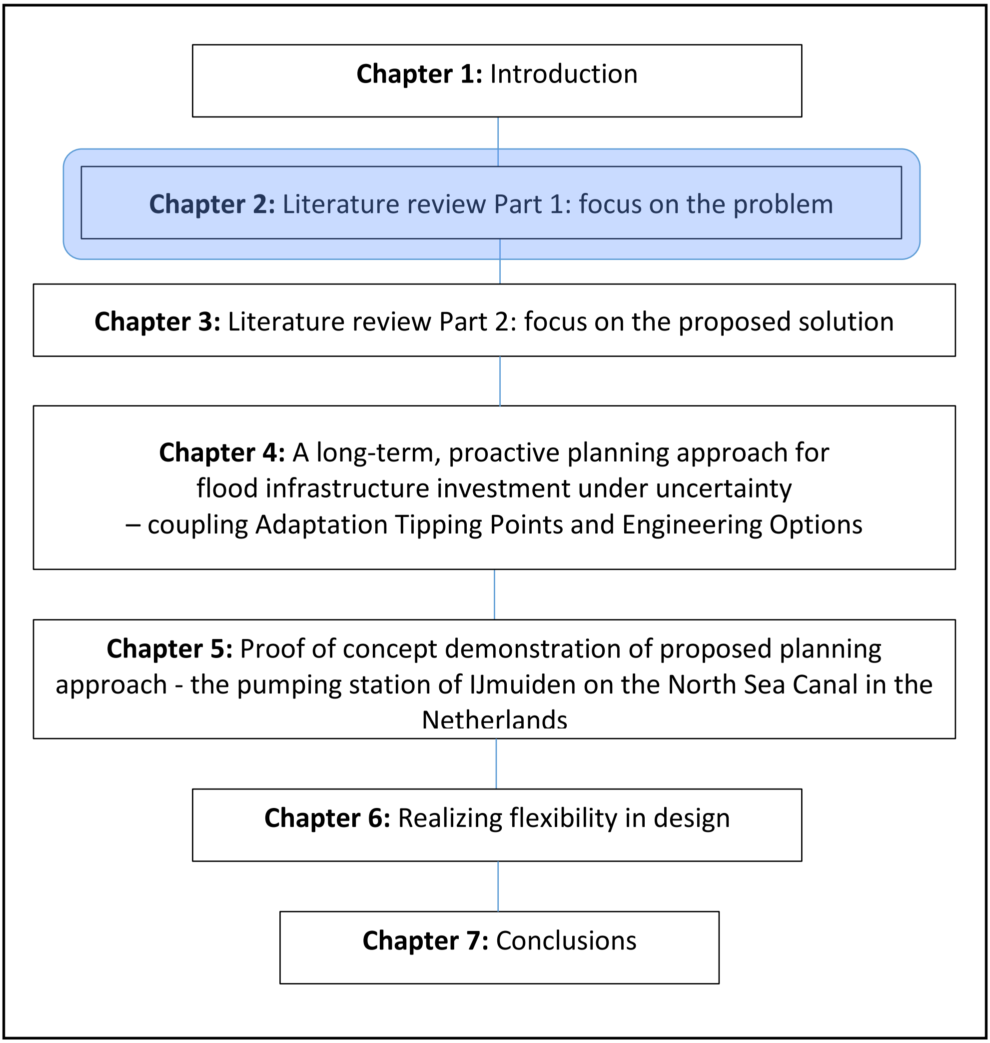
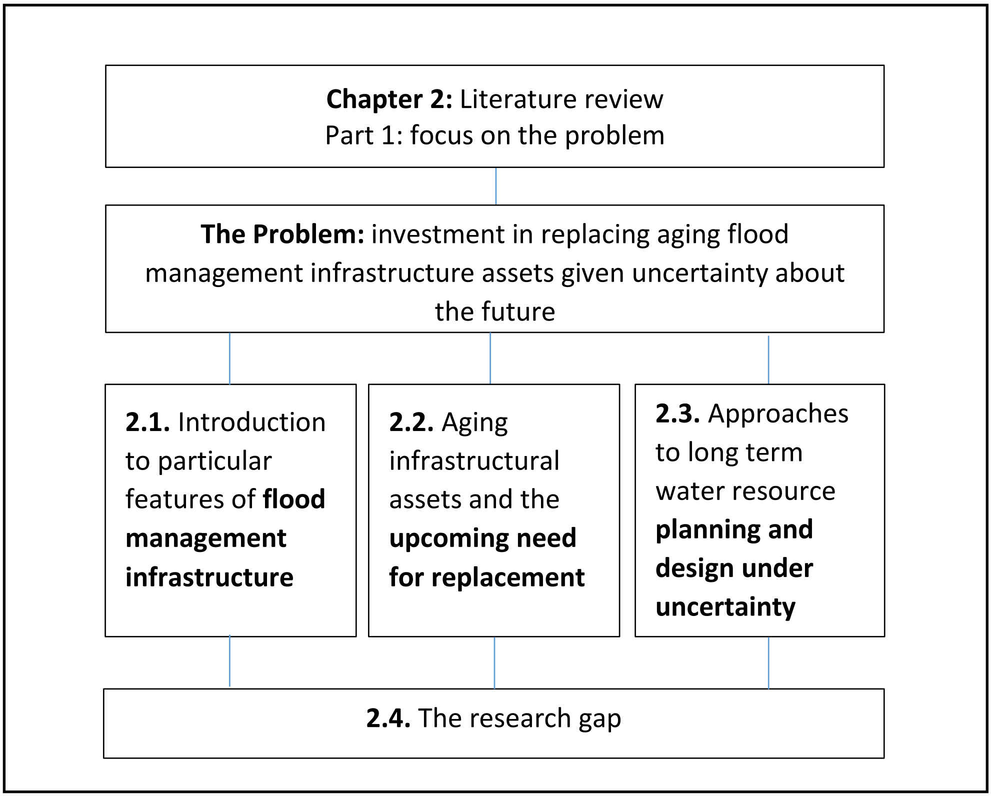


Figure 1.2: Roadmap of this dissertation

2. **Literature Review Part 1:** focus on the problem





Two separate conversations are currently occurring within the field of flood infrastructure planning, (which has a number of particular characteristics, as described in Section 2.1):

- The first focuses on the issue of aging assets and the upcoming era of replacement (introduced and discussed in Section 2.2). With topics such as improved degradation curves and end of service life predictions, this conversation is founded mainly in the asset management and civil engineering literature, with the focus being on drivers of reinvestment that are related to the condition of the physical structure itself.
- The second focuses on the question of water resource infrastructure planning in times of uncertainty, with a particular focus in recent decades on the

potential impacts of climate change uncertainty (introduced and discussed in Section 2.3). With questions such as the degree of sea level rise and incorporating this uncertainty into infrastructure planning, this conversation is emerging from both the climate adaptation literature and the decision making under uncertainty literature. The focus here is on drivers of infrastructural design and planning that are related to external conditions and how they enable or prevent a structure from fulfilling its intended design functionalities.

As presented in Section 2.4, this dissertation posits that these two conversations should not happen independently or in isolation: when exploring long-term investment strategies, both technical drivers of investment internal to the structure as well as impacts of broader external changes are relevant and should be combined into a more comprehensive approach for flood infrastructure planning under uncertainty. This dissertation serves as a first bridging of these two to-date separate areas of research and development. It does this by drawing on elements of two existing methodologies to develop a single long-term infrastructural planning framework.

2.1. Introduction to flood management infrastructure[5]

The following research question drives the work done in this dissertation: **given the particular features of flood management infrastructure, how do we systematically structure reinvestment in the replacement of these aging assets, given uncertainty about the future?** This brief introductory section highlights a number of particular features of flood management infrastructure, as they relate to the question of long-term planning and reinvestment in aging infrastructural

[5] Within this work, the focus is predominantly on *built* infrastructure and on the *technical* portions of engineering systems (as opposed to social infrastructure or the socio-institutional components of engineering systems).

systems. It also explores those societal developments and sources of uncertainty that are relevant at the long timescales explored in this work.

2.1.1 Characteristics of flood management infrastructure systems

Flood and water management infrastructure typically have long design lives (see Hallegatte, 2009 for examples). These structures are associated with high capital costs and traditionally, they have been difficult to change or reconfigure after their initial construction, meaning that there is substantial economic incentive to make the "right" decision from the outset. In this way, each structure is a multi-decade or even century long commitment to a decision made much earlier in time, a decision based on older insights and outdated predictions of the future. Because of this longevity, uncertainty in future conditions and future developments plays a big role. It is key to take possible developments and sources of uncertainty into account in the planning process. Such sources of change and uncertainty that are relevant over these long timescales are discussed in more detail in Section 2.1.2 below.

Furthermore, these long lifespans affect the economic evaluation of such water management structures: over project horizons of many decades, the effect of discounting is typically so dramatic that a relatively substantial portion of future benefits are reduced to zero in present day terms. This is not a problem unique to the water sector, affecting all long-lived projects; however, it does have the ability to complicate evaluation by altering the perceived value of different water resource investment plans.

Additionally, the construction of flood management infrastructure, as is the case with many large public structures, is typically associated with long lead times due to complex technical design and contracting requirements, as well as extensive and often lengthy stakeholder involvement. With lead times of a decade or more not unusual, any decisions about infrastructural investment cannot be left too late.

Finally, the flood management sector has historically been a relatively risk averse one, an unsurprising attribute given that the consequences of failure can potentially be catastrophic. Taking these potential losses together with long lead times, the result is a situation where a laid-back, wait-and-see approach could hypothetically have devastating impacts.

2.1.2 Sources of uncertainty relevant for flood management infrastructure planning

One of the features of flood management infrastructure introduced above is its long design life. Over the course of a century, relatively rapid processes of change, such as population growth and urbanization, can accumulate substantial degrees of change relative to the initial construction date. In addition, a timeframe approaching a century is long enough that even processes that evolve relatively slowly, such as climate change, need to be taken into account in the planning process.

Looking first at societal developments, changes such as urbanization, population growth and socio-economic development are key uncertain processes that affect long-term water resources planning. As of 2014, 54% of all people on earth live in urban areas (UN, 2015). In 1950, this was only 30%, and it is estimated that this proportion will grow to 66% by 2050 (UN, 2015). There are, of course, regional differences, with North America, Latin America and Europe having some of the most urbanized regions in the world, and Africa and Asia remaining generally more rural. Incorporating net rates of population growth into this projection, the world's urban population is expected to grow by 2.5 billion people by 2050 (UN, 2015). The bulk of this increase is expected to be concentrated in Asia (India and China) and Africa, with other parts of Asia and Europe seeing stagnant or declining populations. Thus, in the course of the typical lifetime of a water management structure, there is the potential for substantial changes in water resources planning needs. For instance, population growth typically drives increased municipal water demand. Urbanization and access to centralized water supplies can result in increased per capita water consumption. A greater collection of tangible assets and human lives in an area can increase the need for flood protection.

Shifting away from societal developments, gradual changes in natural processes are also important to consider in long-term water resources planning. A wide body of literature has explored the range of possible impacts resulting from anthropogenic climate change (e.g. IPCC, 2013 and 2014). Hallegatte (2009) ranked water and flood management infrastructure as two of the sectors most in need of effectively incorporating uncertainty in their long-term planning processes due to their long lifespans and their high exposure potential to negative impacts of uncertainty. The possibility of increased precipitation variability may call for storage reservoirs, drainage systems and municipal supply infrastructure that are able to cope with longer droughts as well as more intense rains. Sea level rise coupled with stronger storms will erode coastlines, calling for reassessment of coastal flood protection policies.

2.2. Aging infrastructural assets and the upcoming need for replacement

Within the field of flood management infrastructure planning, two relevant conversations are currently taking place. This section discusses the first of these research areas, where the focus is on issues of aging infrastructure networks and the upcoming era of replacement, as seen from an asset management/civil and structural engineering perspective. Within this research area, the emphasis is on the development of increasingly sophisticated quantitative models, ranging from models to improve predictions of end of life estimates of structures to models that optimize replacement schedules for components of a system. An overview of the existing body of literature is presented below, providing an indication of replacement-relevant research done to date, before identifying a number of shortcomings that this work seeks to address.

2.2.1 Then: a focus on the establishment and expansion of infrastructure systems

During much of the past century, the focus within now-developed countries was on developing the necessary infrastructure systems to support economic and population growth and raise standards of living. Government agencies responsible for civil works development in these countries, such as the Army Corps of Engineers in the United States and Rijkswaterstaat in the Netherlands, became largely synonymous with the development of large, technically sophisticated and complex infrastructure construction projects (see for example NRC, 2004 and 2012). As shown in Figure 2.1, construction of new infrastructure dominated Army Corps spending and activities for many decades.

Using terminology borrowed from a Large Technical System view of infrastructure (Hughes, 1987), Willems *et al*. (2015) describe how this initial *establishment* of water infrastructure systems was in most cases followed by a phase of rapid *expansion* and the subsequent *maturity* of the system. This evolution is accompanied by agencies such as the Army Corps and Rijkswaterstaat shifting from “construction centric organization[s], to [having more of] an operations and maintenance [focus]” (Hale *et al*., 2008). This trend is obvious when looking at Army Corps spending over the past century, as shown on Figure 2.1, with the Corps’ main “construction era” taking place between 1900 and 1969 (Frederick, 1992).

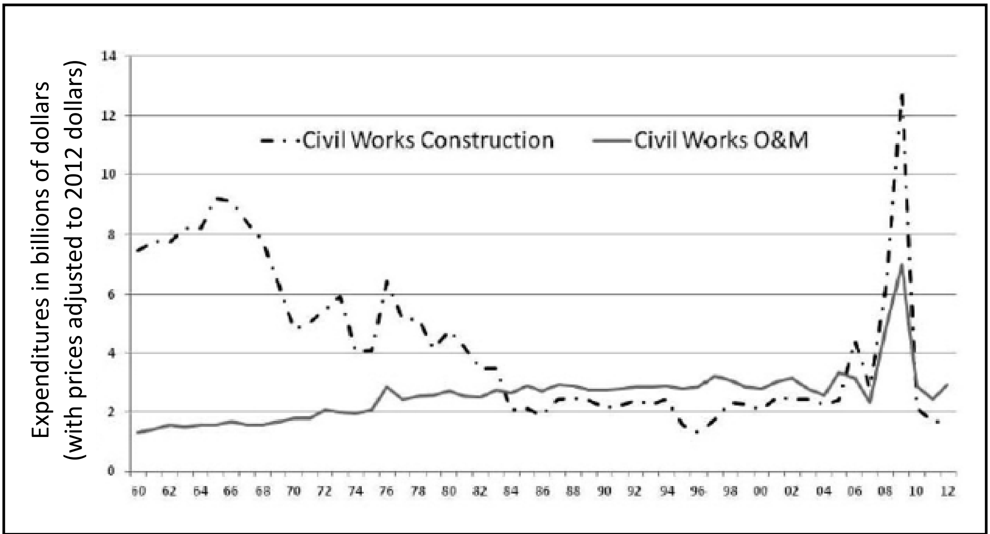


Figure 2.1: Trends in the Army Corps of Engineers’ annual appropriation of funds for new construction works as compared to operation and maintenance expenses (Source: adapted from National Research Council, 2012) - Note: the short-term peak in construction spending in 2009 was due to the American Recovery and Reinvestment Act, a stimulus measure following the financial crisis of 2007-8.

A report by the Organisation for Economic Co-Operation and Development (OECD) examining the needs of the infrastructure sector over the coming decades finds that “OECD countries [] will [continue to] be required to invest heavily to maintain, upgrade or replace existing (and often aging) infrastructures, and to preserve their international competitiveness” (OECD, 2007). This signals the transition from a mature system, to a phase of *renewal*, a phase that to date, engineers, water infrastructure managers and decision makers have little, if any, experience with. It is telling that, the asset management literature itself (see for instance Hale *et al*.,

2008) describe the field of asset management as centered on the tasks of investigating, developing, operating, maintaining and/or decommissioning assets, with replacement/renewal/reinvestment receiving no mention.

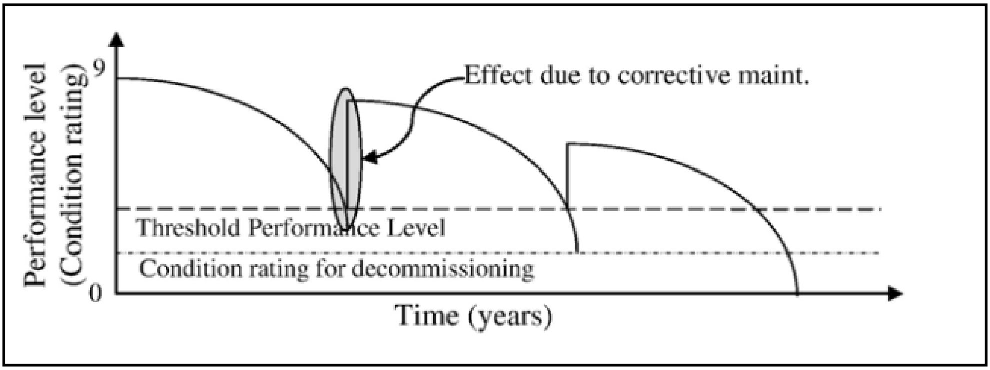
2.2.2 Now: renewal and the "Dawn of the Replacement Era"

As introduced above, large portions of the existing water infrastructure system present in developed countries today are entering a renewal phase, a transition coined by the American Water Works Association as "the Dawn of the Replacement Era" (AWWA, 2001). Acknowledging that the practical experience and hands-on asset management of the past decades have not provided many insights about infrastructural renewal, a review of the literature was conducted to explore if recent research provides any novel insights. This review indicates that to date, not much work has been done in this area.

At present, the most well-developed body of work that examines this replacement question in the water sector is focused specifically on the replacement of municipal drinking and wastewater infrastructure (see for instance AWWA, 2001; Dandy and Engelhardt, 2001; Kleiner *et al.*, 2009;McBean and Schuster, 2008; Moglia *et al.*, 2006; OECD, 2007; Pudney, 2010 and Stannard and Warmath, 2004). The concept of a so-called Nessie Curve emerged from this aging water utility asset management literature, as a tool to help plan for the upcoming reinvestment: it is a graphic forecast of the expected annual repair and replacement costs over a certain period of time, based on how existing assets deteriorate over the course of their lifetime.

To date, larger scale public flood management systems have to date received little to no attention in this body of research. A 2012 National Research Council report explores the question of aging infrastructure from the perspective of the Army Corps of Engineers and finds that “there exists no systematic process or guidelines for setting OMR [Operation, Maintenance and Rehabilitation] priorities”. The lagging of research focused on flood management infrastructural systems as compared to municipal water supply systems may not be surprising: water utilities serve a well-delineated, paying customer base, who expects consistent service levels irrespective of the age of the physical system or other technical challenges faced. This is in contrast to flood management systems: payment for this infrastructure does not come directly from a specific customer base, as it is usually in the form of tax revenue, and its benefits in the form of avoided flood damages are less obvious, more diffuse and often taken for granted.

A distinct but related small body of work focuses not on exploring network-scale replacement for a specific type of infrastructure system, but has a more detailed focus on improving our understanding of the physical processes associated with structural degradation and identifying when replacement becomes necessary for performance or economic reasons. Relevant examples include improved prediction of the end of service life of hydraulic structures (e.g. Kallen *et al*., 2013), novel deterioration models (e.g. Figure 2.2; Baik *et al*., 2006; Hong *et al*., 2007) and new insights about the impact of different maintenance regimes on replacement (e.g. Van Noortwijk and Frangopol, 2004). This body of work centers entirely on those drivers of reinvestment that are related to structural processes such as physical degradation.



<u>Figure 2.2: Sample infrastructure deterioration curve</u> (Source: Hong *et al*., 2007)

2.2.3 The future: getting to grips with replacement planning on a more strategic level

As demonstrated above, the question of how best to effectively structure the upcoming replacement and reinvestment task has to date not received substantial research efforts. The fundamental shortcoming of the work conducted to date is that it explores replacement planning in a very literal sense, as a continuation of the status quo: how do we most efficiently replace the existing system in its present form assuming a future much like the present? Fundamentally, this dissertation suggests that the question of what we replace existing structures with cannot be answered without addressing the question of how we plan to incorporate long-term uncertainty into the design process for the next generation of structures. Relevant sources of uncertainty can include climate change, population growth and socio-economic development. Focusing on climate change in particular, work by Rayner (2010) would appear to support this proposition when he states "incorporation of climate change into asset management design has so far been limited, with the vast majority of new infrastructure continuing to be designed against established codes or [] history-based asset-specific environmental criteria". Thus, there is a need for this asset management question to be elevated to a higher, strategic level, such that questions of designing for long-term uncertainty and a re-evaluation of the current system come into play. As described by Hanak *et al*. (2011), “replacement of aging infrastructure sometimes provides opportunities to modernize and update for both contemporary and anticipated conditions” and the current processes do not capture this.

As described more fully in Section 2.4, it is suggested in this work that this could be done by linking existing asset management practices that focus only on processes related to the physical structure itself with approaches from the fields of decision making under uncertainty/climate adaptation (described in Section 2.3). Neumann (2009) previously suggested this coupling for infrastructure in general, as did Meyer *et al*. (2010) for application to transportation infrastructure systems. It is proposed that this provides a valuable first step towards becoming better equipped to answer the question of replacement in such a way that adequately considers future uncertainties. As described by Daigger (2009), the opportunity to reinvest in aging infrastructure may present a timely and valuable opportunity to rethink our current *modus operandi* and incorporate new planning paradigms into water management.

2.3. Incorporating uncertainty into long-term water resources planning and design

As introduced previously, the question of making decisions under uncertainty is a second relevant focus area within flood infrastructure planning. Currently, water infrastructure managers, strategic planners and decision makers find themselves grappling with the question of how best to incorporate uncertainty into long-term planning procedures. The focus within this field is on the development of novel decision support tools that sustain effective decision making given the potentially large and varied impacts of uncertainty. This conversation is emerging mainly from the decision making under uncertainty and the climate adaptation literature. This portion of the literature is discussed in more detail below, identifying first how uncertainty has traditionally been incorporated in water resource infrastructure planning processes. This traditional approach is then contrasted to the current planning landscape, where uncertainties associated with a number of different natural and human-driven processes are increasingly complicating the planning process. Subsequently, an overview of the current state-of-the-art is provided, describing a number of newly emerging techniques that seek to improve our ability to incorporate uncertainty into decision support analysis and water resource planning tools. Finally, this leads into a discussion of the shortcomings of the current state-of-the-art.

2.3.1 Then: predict-then-act and the search for 'optimal' solutions

Historically, the planning and design of many water resource systems has been based on what has been increasingly characterized as a "predict-then-act"[6] framework (Hallegatte *et al*., 2012; Lempert *et al*., 2003). This approach integrates economic concepts of rational decision making with techniques to capture uncertainty, with the ultimate objective to identify a single, static *optimal* solution:

- ***Predict* a best-estimate of the future**

  Within water resources planning, the first step has historically been to compile the best available quantitative information describing possible future conditions, with a focus on reducing uncertainties. This step typically culminates in the creation of a single prediction of the future, which is used to

[6] While this thesis uses the currently popular "predict-then-act" terminology consistent with Hallegatte *et al*. (2012), a number of different terminologies have been used to describe this historic approach used in water resources planning, including a "predictive/optimization" method (Gersonius *et al*., 2010) or a "command-and-control approach" (Pahl-Wostl *et al*., 2007).

identify parameters and structural requirements in the subsequent design and engineering work. This prediction typically either ignores uncertainty entirely (i.e. a single deterministic prediction), or when a range of futures is considered, a single best-estimate prediction is often defined, that is intended to be representative of the most likely future. Even in cases where different scenarios of the future are explicitly included in the planning process, it is not uncommon for the question of “which scenario to choose” to emerge from planners and decision makers. (In the US, until as recently as 2013 when revisions were made, this was even formalized within the national Economics and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (WRC, 1983) which required that different project alternatives be evaluated against *the most likely future conditions*[7]. These former Principles and Guidelines were similar in content to the guidance traditionally used by most industrialized countries as well as several international lending agencies (Frederick, 2002).)

- ***Act*, optimizing for this most-likely future scenario**

  Thus, having identified the future one wishes to design for, the second step typically involves identifying the best course(s) of action given the specific features of the predicted future. Whether this is explicitly done using formal optimization methods, or using expert judgement and past experience, the aim here is to identify those actions that would be optimal if the future turns out as expected.

[7] Pages 46 through 48 of Armah *et al*. (2009) provide a good overview of how the 1983 Principles and Guidelines capture uncertainty and the shortcomings of this approach.

Within this predict-then-act framework, some form of the precautionary principle is often used as a catchall way to take any unforeseen impacts of uncertainty into account. Within systems engineering, this is typically done in the form of safety factors, margins of error, redundancy and over-dimensioning of structures. Textbox 1 presents a closer look at how this generic predict-then-act framework is applied specifically to flood management infrastructure planning.

In summary then, the traditional approach to incorporating uncertainty in infrastructure planning can be characterized as one centered around safety factors and margins of safety, a passive approach driven by a "build it once and build it big" mentality.

Textbox 1: A closer look at applying a predict-then-act approach to flood management infrastructure planning

- **What do we *predict* future flood magnitudes will be?**

Within flood management planning , this first step has two components and is often iterative: first, the desired flood protection level that the physical system is to offer is selected, before then predicting the specific physical flood characteristics (e.g. peak discharge amounts; flood stages) associated with this pre-defined flood standard.

The process of identifying the desired flood protection level has historically been conducted in a number of different ways. At its most elementary, this simply involves choosing a relatively *ad hoc* allowable flooding frequency, as deemed both socially and politically acceptable. In the US, for instance, guidelines issued in Executive Order 11296 in 1972 set the 100-year flood as the default flood standard applicable to most federal flood management projects (Robinson, 2004). This means that, on average, only once every 100 years should a flood occur that is of a large enough magnitude that the constructed flood defense system will be unable to discharge it successfully. A second, more involved method of identifying the desired protection level uses formal optimization, often utilizing some kind of Cost Benefit Analysis framework, to identify first if providing flood protection offers more benefits than costs and if so, what level of protection maximizes net benefits.

Textbox 1 continued: A closer look at applying a predict-then-act approach to flood management infrastructure planning

The first example of this kind of economic optimization for flood protection was used in the Netherlands by van Dantzig (1956), following the country's devastating 1953 flood, and has subsequently been improved and modified many times, with Kind (2014) as a good example of the current state-of-the-art techniques.

The second step, where physical characteristics associated with the chosen flood protection standard are identified, is typically informed by flood frequency analysis. Historically, future flood heights associated with a certain return period were estimated directly from the highest water level on record (Hoekstra and De Kok, 2008). Over time, this method has evolved into a probabilistic approach whereby historic peak water flows are used to populate stationary probability distributions, showing the frequency at which flows of a certain magnitude and thus floods of a certain height have occurred in the past and are thus expected to occur in the future. These empirical frequency analysis methods fall short when estimating the magnitude of rare and thus likely never yet recorded flood events, and are thus augmented using stochastic physical models. Here, diverse physical conditions are simulated to explore the size of rare flood events too large (and thus too infrequent) to have occurred in recorded history – for instance, predicting the magnitude of the 1 in 10,000 year flood event despite only having 200 years of recorded flood data. While a number of different variations of this approach are used (such as for instance, the concept of the Project Design Flood developed on the Mississippi River, which models maximum probable floods based on possible meteorological conditions (MRC, 2008)), all of these methods fundamentally rely on the use of historic data, whether it is in the form of past flood heights or past meteorological conditions generating record precipitation events. Note that this direct reliance on historic events becomes troublesome if the future is no longer treated as consistent with the past, as is the case in a non-stationary climate.

- ***Act,* sizing the system so as to be able to withstand the identified future flood characteristics**

  Having identified the desired flood protection level and the associated water levels, water resource engineers subsequently derive the associated infrastructural design characteristics, identifying for instance the required levee dimensions to be able to withstand the identified design flood characteristics. In the case of levees, possible impacts of uncertainty in the analysis are taken into account by augmenting the design height using a robustness factor or a so-called freeboard allowance (Stakhiv, 2010).

2.3.2 Now: greater awareness of uncertainty and the quest for more adaptive solutions

The continued viability of the traditional predict-then-act approach to infrastructure planning, with its quest to reduce uncertainties, search for optimal solutions and preference for over-dimensioning as the preferred strategy to manage remaining impacts of uncertainty, has been increasingly called into question in recent decades (e.g. Olsen *et al*., 2010; Pahl-Wostl *et al*., 2009). A number of concurrent processes and insights have driven this gradual mounting awareness of the need for a new planning paradigm to meet the changing needs of the future.

First, if optimizing for a single future, there is the risk that if future conditions emerge as being different than expected, the theoretically optimal solution ends up being at best, sub-optimal and at worst, a failure. McInerney *et al*. (2012) describe this situation as "dancing on the tip of a needle". Together, Miller and Lessard (2001) and de Neufville and Scholtes (2011) provide extensive evidence for the proposition that "the forecast is always wrong", which by extension fundamentally undermines the value of an optimal solution designed for any such incorrect forecast.

Secondly, there is increasing awareness and agreement that non-stationarity and changes in the global climate are having substantial impacts on the natural environment (e.g. IPCC, 2013 and 2014; Matalas, 1997; Milly *et al*., 2008)[8]. Most of

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8 The work by Milly *et al*. (2008) titled "Stationarity is Dead" created substantial discussion in the water resource field regarding the question of non-stationarity in hydrologic conditions. For instance, Matalas (2012) responded by stating that the cutoff between a stationary past and a non-stationary future is an artificial and inaccurate one. He makes the case that there has long been evidence available to hydrologists and water managers that

the water infrastructure in existence today was designed under the assumption that the historic record provides an adequate picture of future conditions. The increasing awareness that the past may no longer be a good indicator of the future creates doubt as to continued efficacy of current planning approaches and the adequacy of over-dimensioning as a strategy of coping with uncertain future conditions. Within the water resource sector specifically, work by Fiering (1982) and Rogers and Fiering (1986) surprisingly concluded that a substantial portion of projects in existence at that time had functioned effectively under a substantially wider range of operating conditions than they were ever designed for, due to the inclusion of large safety factors. However, this analysis has not been repeated in recent years with time series data that increasingly shows the emerging impacts of climate change. Furthermore, Stakhiv (2010) has stated that the gradual shift towards more holistic and sustainable water resource planning that includes fulfilling more objectives and meeting more requirements (i.e. a move towards Integrated Water Resource Management (IWRM)), has in fact limited the degrees of freedom that water resource engineers have to plan systems with large degrees of redundancy or margins of safety. Hashimoto *et al*. (1982) describe the result as 'brittle solutions'.

Finally, government infrastructure spending budgets are facing growing pressure by the impacts of the financial crisis and competing spending priorities (e.g. a 2004

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hydrologic flows contain both predictable stationary components (e.g. short-term auto-regressive persistence as well as long-term "Hurst" persistence) as well as non-stationary stochastic components. Webb and White (2010) assert that water resource experts have always implicitly known that hydrologic processes were non-stationarity. However, for many decades, stationarity was a necessary simplifying assumption given the short available data record and computational limitations. Regardless of these stationarity versus non-stationarity discussions, all these authors agree nonetheless that current planning paradigms will need to be revisited and updated for the changing demands and conditions of the future.

report by the National Research Council outlines some of the budget and financing issues increasingly faced by the US Army Corps of Engineers). While relying on increasingly large structures may continue to be technically feasible in the future, the high capital costs associated with this so-called “bunker mentality” incentivizes the search for an alternative way to cope with uncertainty.

Against this evolving backdrop, there is increasing support within the literature for a shift away from identifying an optimal solution and towards identifying solutions that can remain largely functional over a wider variety of future conditions (e.g. Adger *et al*., 2005; Carmichael, 2015; de Neufville and Scholtes, 2011; Dessai and Hulme, 2007; DiFrancesco and Tullos, 2014a and 2014b; Gersonius *et al*., 2010; Gersonius *et al*., 2011, Gersonius *et al*., 2013, Gersonius *et al*., 2015; Groves and Lempert, 2007; Lempert *et al*., 2003; Lempert and Groves, 2010; Linquiti and Vonortas, 2012; Pahl-Wostl *et al*., 2007; Rogers and Fiering, 1986; Stakhiv, 2010 and Woodward *et al*., 2014). A more detailed look at these references indicates that there are some semantic differences in this body of work, which Textbox 2 examines in more detail.

Textbox 2: Reconciling terminology I

The literature presented so far in Section 2.3.2 demonstrates a shift in the objective of planning decision support approaches from seeking a single optimal solution to searching for solutions that are able to cope adequately with a variety of conditions. However, differences in terminology may lead one to believe that individual factions of this literature are in fact calling for different things. This textbox seeks to reconcile different terminologies.

- **From optimality to … robustness**

Some portion of the literature (e.g. Dessai and Hulme, 2007; Groves and Lempert, 2007; Lempert *et al*., 2003; Lempert and Groves, 2010) advocate for a transition away from *optimality* (i.e. the right design) and towards *robustness* (i.e. a safe design). Here, robustness is used in an Operations Research sense, and is treated as an alternative for optimality, in the sense that an optimal solution is only optimal for a particular set of future conditions, whereas a robust solution performs adequately over a wide range of futures.

- **From optimality to … adaptability**

However, others within this same literature refer to this as a transition away from *optimality* and towards *adaptability*: "[t]he goal of management should be to increase the adaptive capacity to learn from and better cope with uncertain developments, rather than to try to find optimum solutions" (Pahl-Wostl *et al*., 2009).

Nontheless, both the optimal/robust and optimal/adaptive dichotomy are in agreement that a high level change in the *objective* of what quantitative decision support tools should do is necessary: whereas before, they were typically designed to identify an optimal solution, now increasingly they are called upon to identify robust/adaptive solutions that can cope with a wider range of conditions.

Parallel with this shift in design objective from optimality to being able to function adequately under many possible futures, one observes a change in how the ability to cope with possible impacts of uncertainty is incorporated in the design of infrastructural systems. In the past, safety factors and margins of safety were the default approach. However, as described earlier, the adequacy of relying on over-dimensioning as the sole coping mechanism for dealing with possible impacts of uncertainty is increasingly being called into question. Gradually, the focus is moving towards designing physical systems that can be changed and reconfigured over time, if and when external developments suggest such adaptation becomes necessary. Again, there are semantic issues at play here, with different groups of researchers using different terms to describe this desired characteristic of being able to incrementally make changes over time. Textbox 3 examines this in more detail.

Textbox 3: Reconciling terminology II

The existing literature presents a number of different strategies by which to the ability to cope with possible impacts of uncertainty is incorporated into the planning and design of infrastructural systems. Again, a number of different terminologies exist, and this textbox seeks to compile these different approaches, and to the extent possible, reconcile the different terminologies.

- **Then: coping with uncertainty through structural robustness**

In the past, structural robustness in the form of safety factors, margins of safety and over-dimensioning were typically used as a catch-all precautionary approach to uncertainty. Walker *et al*. (2013) term this *static* robustness. A statically robust structure has the necessary dimensions and physical strength to enable it to withstand passively disturbances of uncertain magnitude, with no need for external intervention. Note the differences between robustness used in this engineering, structural context and robustness used in Textbox 2 in an Operations Research context.

- **Now: coping with uncertainty through dynamic robustness/flexibility**

Today, one observes a move towards systems that cope with uncertainty by being incrementally changed and updated over time, as external conditions change. This has been variously described as increasing the *dynamic robustness* (e.g. Walker *et al*., 2013) or *flexibility* (e .g. DiFrancesco and Tullos, 2014b; Gersonius *et al*., 2011, Gersonius *et al*., 2013, Gersonius *et al*., 2015; Linquiti and Vonortas, 2012) of the system. Dynamic robustness involves an element of *active intervention* implied that is not present in the traditional definition of static robustness. The distinction here is that the physical system is not itself necessarily capable of passively withstanding external change due to its large size and strong construction, but rather that the system is managed in such a way that changes are made when necessary, resulting in a system that is also, by definition, robust to external changes. Thus, dynamic robustness incorporates aspects of actively changing a physical system in response to observed external changes. Flexibility similarly involves making design decisions that enable future adaptation and revisiting of past decisions.

In summary, fundamentally, the research community is in agreement that a shift from planning an optimal solution for one future to planning for solutions able to cope under multiple futures is a necessary and advisable transition. In addition, there is widespread agreement that designing long-term infrastructure systems in such a way as to increase our ability to revisit decisions and make adjustments as uncertainty is resolved over time is a promising strategy to face the demands of a highly uncertain future: “adaptive management may be the most effective way of dealing with future climate impacts under the current evaluation procedures and high degree of uncertainty” (Stakhiv and Pietrowsky, 2009). This transition from a predict-then-act approach, where robustness in engineered structures is the predominant technique to cope with uncertainty, to a more managed-adaptive approach, where learning and active intervention are more centrally utilized to handle uncertainty is illustrated conceptually in Table 2.1 and on Figure 2.3.

<u>Table 2.1: Differentiating the changing paradigms of planning under uncertainty</u>

	Then: Predict-then-act[9] Predict-and-provide[10] Static-robust[11] Predict-and-optimize[12]	**Now:** Managed-adaptive[13] Monitor-and-adapt[14]
Overall desired objective for infrastructure planning	Identifying optimal solutions	Identifying solutions that remain functional over a wider variety of future conditions
Primary strategy to cope with uncertainty	A precautionary approach, relying on safety margins and over-dimensioning	An incremental approach, designing systems that can be changed and reconfigured over time, if and when needed
Infrastructure management style	Relatively static	More iterative and dynamic

[9] E.g. see Lempert *et al*. (2003) and Hallegatte *et al*. (2012).

[10] E.g. see Wilby and Dessai (2010) and Hall and Murphy (2012).

[11] E.g. see Gersonius *et al*. (2011).

[12] E.g. see Stainforth (2010).

[13] E.g. see Gersonius *et al*. (2011).

[14] E.g. see Walker *et al*. (2013).

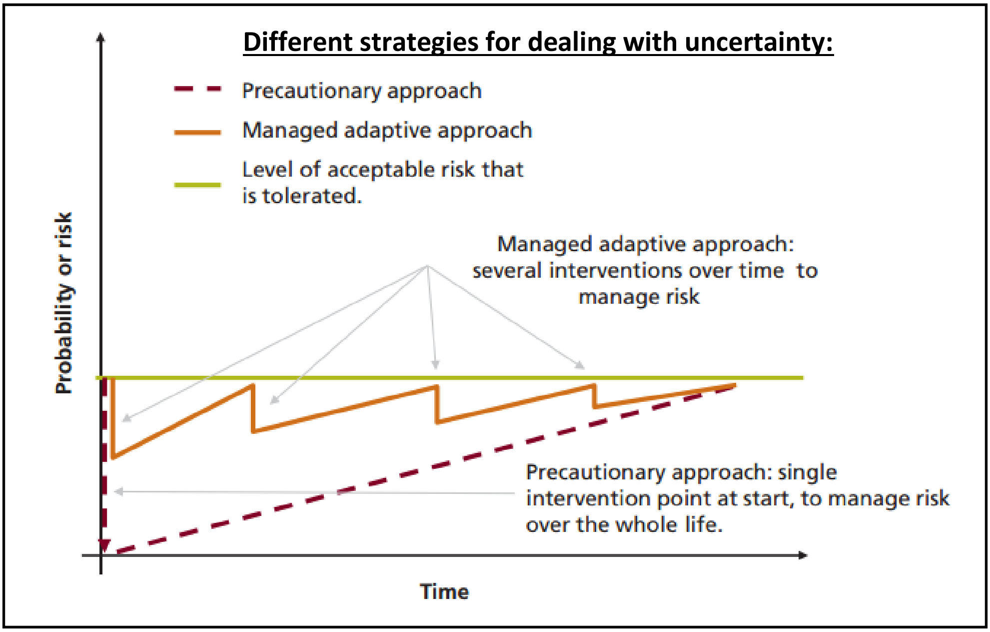


Figure 2.3: Contrasting the traditional predict-then-act approach to long-term planning with the emerging managed-adaptive approach (Source: adapted from HMGovernment and DEFRA, 2009)

However, what there is apparently little consensus on at present is a common and unified use of and hierarchy for relevant terminology[15]. While Textbox 2 and 3 provided an overview of the broad array of terminologies used in the literature, this paragraph defines how relevant terms are used within *this* work.

- *Adaptability* is used as a general description of a new generation of planning approaches that move away from a single, static optimum solution and search for ways to allow adjustments over time.
- *Robustness* is used in the traditional engineering sense, indicating a passive approach to uncertainty that relies on large dimensions and physical strength. It is treated as equivalent to *static robustness.*

[15] Work by Galloway (2011) makes a similar observation about the water sector at large.

- *Flexibility* is used as an alternative approach to robustness for coping with uncertainty. It is treated as equivalent to *dynamic robustness.*

Thus, within this work, adaptability to multiple futures is treated as the high-level objective, with different combinations of robustness and flexibility[16] utilized as the specific ways of achieving this.

Having defined how key terminology is used in this work, this next section (Table 2.2) highlights a number of specific conceptual approaches. These approaches emerged from the transition to a more adaptive planning paradigm, and attempt to operationalize the practical application of this new, more adaptive way of approaching water resources planning. Table 2.2 provides a simple overview of the approaches directly relevant to the questions posed in this work, ordered roughly chronologically. All of these techniques have their roots in *classic decision analysis* and *traditional scenario planning methods.* Decision analysis methods use quantitative probabilistic information to explore risk and evaluate the performance of different alternatives to identify a preferred course of action. In contrast, scenario-planning methods rely on participatory exploration of diverse conceivable "alternative worlds", to explore which courses of action perform well/poorly in which futures. Within Table 2.2, a distinction has been made between those *risk-based approaches* (shaded in dark blue), which utilize probability distributions to characterize uncertainties and *robustness approaches (*shaded in light blue), which

[16] There have been some initial attempts to develop a conceptual topology of the different possible types of flexibility: see for instance DiFrancesco and Tullos (2014b) and Anvarifar *et al*. (2016). As explored more fully and defined in Section 3.2.1, this dissertation is limited to looking at flexibility as it is derived from smart managerial and infrastructural design decisions (in the form of options) that afford infrastructure managers the right but not the obligation to change the course of an infrastructural investment project in the face of uncertainty.

reject the use of probabilistic information on the grounds that we are simply unable to reliably assign probabilities to those uncertainties of interest (Van der Pol *et al*., 2015[17]). This overview does not form a conclusive classification, nor does it do justice to the level of connectivity and co-evolution of these techniques.

[17] While van der Pol *et al.* (2015) characterize these as *risk-based* versus *robustness* approaches, Baecher (2009) talks about *scenario* approaches versus *probabilistic* approaches. Furthermore, Woodward (2012) characterize these same two categories as decision making *under risk* versus *under uncertainty* (this naming system draws on the 3-tier Knightian classification system, in which decisions can be made under certainty, risk or uncertainty (Knight, 1921)). Clearly, as of yet, no one widely accepted set of terminology has emerged from the literature to describe these two families of approaches.

Table 2.2: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty[18]

Engineering Options theory	Engineering Options theory is a quantitative planning technique that emphasizes the value obtained from the inclusion of flexibility in investment and infrastructure planning decisions. Engineering Options is an offshoot of an existing body of work, that of Real Options. As described in Section 2.4, the novel planning approach developed in this dissertation centrally builds on the concept of Engineering Options. Thus, given its central relevance to this work, a more thorough and comprehensive discussion of Options, Real Options, Engineering Options and the associated literature is provided in Section 3.2, with this reference to options included here for completeness sake only.
Information Gap Decision Theory (Info-gap theory)	Information-Gap Decision Theory (often shortened to Info-gap Theory) was developed by Ben-Haim over the course of the latter two decades of the 1900's. It was first applied to assays of materials (Ben-Haim, 1985) and the reliability of mechanical systems (Ben-Haim and Elishakoff, 1990 and Ben-Haim, 1996) before being developed into a more generally applicable framework for making decisions under uncertainty (Ben-Haim, 1999 and 2001). It is an analytic decision support framework that acknowledges that there is a discrepancy between the information we currently have and the information we need to know in order to make good design decisions: the information gap. It emerged as a way to become less reliant on probability distributions when dealing with uncertainty, given that the derivation and validation of these distributions is often not trivial. The traditional infrastructural design process first sees the derivation of expected future conditions, which are then used by the designer to create a system that can confidently meet the necessary performance requirements.

[18] Other less developed techniques such as backcasting and the threshold scenario approach are mentioned here for completeness sake, but are not discussed any further because they remain relatively under-developed, receiving little to no continued research or application efforts. Backcasting involves envisioning a desirable future and then planning backwards to take the necessary steps to ensure this future is realized (Robinson, 1990). The threshold-scenario framework suggests coupling qualitative threshold risk assessment with quantitative scenario risk assessment (Freas, 2008).

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Information Gap Decision Theory (continued)	Instead, Information Gap Decision Theory restructures this traditional design process by examining two decision functions. The first, called the robustness function, asks what degree of error in assumptions, models, data, parameters, input etc. the chosen design could handle before becoming unable to meet the necessary performance levels. By exploring this question for a number of candidate designs, decision makers are able to prioritize those designs that perform well over a diverse range of futures over those that only perform well under a very narrow range of future conditions. The second, the opportuneness function, focuses instead on possible upsides of uncertainty by asking what degree of error results in outcomes that are more positive than expected. Here, logically, designs that result in a large performance gain for only a small error are prioritized over designs that may have the same large performance gain, but at a larger error. The theoretical background upon which Information Gap Decision Theory is founded is conceptually similar to the work done on near-optimality in the 1980's by members of the Harvard Water Program (e.g. Harrington and Gidley, 1985). They describe how the focus of water resource planning models should not only be on seeking optimal designs, but also on identifying the shape of the near-optimal region19, thus generating several optimal or nearly optimal solutions that can be considered by decision makers.

[19] Harrington and Gidley (1985) use the analogy of topography to illustrate the concept of the near-optimal region: "if the topography is flat, then one can wander far from the peak in latitude and longitude without sacrificing much elevation. Conversely, if the topography is steep, nearness to peak elevation requires nearness to the peak latitude and longitude"

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Information Gap Decision Theory (continued)

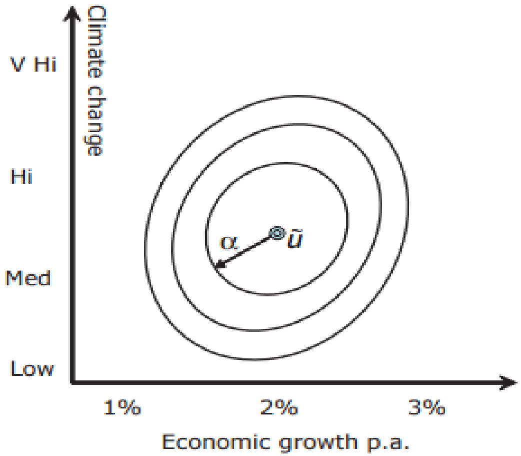


Figure 2.4: Illustration of a sample Info-Gap analysis
(Source: adapted from Hall and Solomatine, 2008)

These results show an info-gap analysis focused on two sources of uncertainty, namely socio-economic growth and climate change impacts. $\tilde{u}$ represents the decision given the best estimate of uncertain future conditions, and α indicates the magnitude of uncertainty being incrementally explored.

Overall then, Info-Gap starts at the best estimate of the future and then incrementally evaluates how the chosen design performs as future conditions depart further and further from the best estimate. Conceptually, this is illustrated on Figure 2.4. However, Info-Gap has been criticized (e.g. EA and DEFRA, 2009; Sniedovich, 2007 and 2010), with the main shortcoming of the approach described as "they adopt a single description of the future and assume alternative futures become increasingly unlikely as they diverge from his initial description. The method therefore assumes that the most likely future system state is known *a priori*" (EA and DEFRA, 2009). Thus the primary concern is that the entire analysis of the robustness of a design decision is dependent on the starting best estimate decision, which could at best be a local optimum and at worst, substantially wrong.

Since its development, Information Gap Decision Theory has been applied to a number of water resources applications, with Hipel and Ben-Haim (1999) using it to explore the impacts of hydrologic uncertainty, while Korteling *et al.* (2012) and Woods *et al.* (2011) look at water supply planning

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Information Gap Decision Theory (continued)	in the UK. Manning *et al*. (2009) use Info-Gap as a form of sensitivity analysis within a larger analysis of urban water supply. Hall and Harvey (2009) and Hine and Hall (2010) examine the impact of inundation model uncertainty on flood management decisions taken in the UK.
Robust Decision Making (RDM)	Robust Decision Making was developed at the RAND corporation over the course of the early 2000's (Lempert *et al*., 2003; Lempert *et al*., 2006; Groves and Lempert, 2007; Bryant and Lempert, 2010). It is an analytic framework aimed at identifying courses of action that perform well under a variety of uncertain futures. It emerged from a desire to conduct effective decision support and policy analysis without having to rely on probabilistic predictions of the future. It does this by reversing the traditional predict-then-act planning process: instead of predicting one/a few likely future scenarios and designing an optimal response for these conditions, a large and diverse ensemble of future conditions is created through scenario discovery and these are subsequently used to explore how different courses of action perform under different future conditions. In this way, those courses of action that perform well under all or most future conditions can be identified and tradeoffs can be made explicit.

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Robust Decision Making (continued)	Conceptually, Robust Decision Making builds upon elements drawn from Robust Optimization (e.g. using Laplace's principle of insufficient reason20 (Laplace, 1902), Wald's Maximin criteria21 (Wald, 1945) or Maximin Regret22 (Savage, 1951)). In addition, it builds on early work on a Robust Decision Making framework by Rosenhead (e.g. Rosenhead et al., 1972; Rosenhead, 1989 and 1990) and Assumption Based Planning (Dewar, 1993). However, whereas Robust Optimization typically seeks to find an optimal solution, Robust Decision Making is a satisficing method, whereby the aim is not to find one optimum, but a selection of solutions that satisfy a specified set of user-defined requirements. This set of solutions can then be further examined and narrowed by stakeholders and decision makers focusing on other evaluative criteria that were likely not captured in the quantitative modeling.

[20] Laplace's principle of insufficient reason (renamed The Principle of Indifference by Keynes in 1921) states that if no information about the probabilities of different future scenarios is available, it is reasonable to assume that each scenario is equally likely and is thus assigned equal probability. The extension to this is that decisions are made by calculating the expected outcome under each future scenario and selecting the course of action associated with the best-expected outcome (i.e. implicitly assuming a uniform probability distribution).

[21] Rawls (1971) described it very well when he said: "The maximin rule tells us to rank alternatives by their worst possible outcomes: we are to adopt the alternative the worst outcome of which is superior to the worst outcome of the others." This focus on the worst-case results in more conservative outcomes than if using the principle of insufficient reason.

[22] Regret is the difference between the optimal course of action that would have been chosen if perfect information about the future was available and the actual outcome given the reality of uncertain future conditions i.e. it measures a deviation from optimality. Thus the maximin regret rule tells us to rank alternatives by their worst possible regret (i.e. the largest deviation from the best decision in a given scenario), and then adopt the course of action for which the worst case regret is still better than the worst case regret for all the other alternatives. This criterion is less conservative that the traditional maximin approach because instead of considering the worst-case outcome, it focuses on the difference between outcomes as compared to the optimal decision.

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Robust Decision Making (continued)	Since its development, Robust Decision Making has been applied to a handful of water resource management (mainly urban water supply) problems by Dessai and Hulme (2007); Groves and Bloom (2013); Groves and Lempert (2007); Groves et al. (2015); Kasprzyk *et al*. (2013) and Lempert and Groves (2010). It has been actively explored by a number of water utilities, particularly in the Western United States (see WUCA (2015) for an overview). A version of Robust Decision Making has been developed by the Army Corps of Engineers and applied to climate adaptation planning for the Great Lakes (International Lake Ontario-St. Lawrence River Study Board, 2006; International Upper Great Lakes Study Board, 2009). However, similar to the findings presented in Section 2.2, the flood management sector appears to lag behind, as aside from work by Fischbach (2010) which looks at the use of non-structural flood defense measures in New Orleans, there is little evidence of any studies having been carried out where Robust Decision Making is applied explicitly to flood management questions.
Climate Informed Decision Analysis (CIDA) / **Decision Scaling**	Climate informed decision analysis, or decision scaling, is a decision support framework that incorporates climate risk assessment techniques with iterative risk management to seek decisions that perform well under many futures. Centrally, it does this by first seeking those future climate conditions that would negatively affect a particular project and then exploring how likely it is that these particular conditions will actually occur in the future. The core approach was developed in Brown (2010a, 2013), Brown *et al*. (2011) and Brown *et al*. (2012). It relies on a climate independent vulnerability analysis or stress test (Brown and Wilby, 2012), which first identifies the most vulnerable aspects of an existing or planned physical system. These identified vulnerabilities then define which specific scenarios are of most interest and should be revisited in detail to explore different possible risk management strategies. Only at this final stage do specific climate scenarios come into play. This means that the substantial uncertainty associated with different climate change scenarios and their relative probabilities enters the analysis much later, which reduces the propagation of these uncertainties throughout subsequent steps of the analysis. In addition, as the stress test is a distinct and to some extent, stand-alone, component of the analysis, it can be easily repeated in the future when new information or new model output becomes available.

Table 2.2 continued: Overview of the current “best available” conceptual approaches used for water resources planning under uncertainty

Decision Scaling (continued)	The stress test component of decision scaling is conceptually similar to work done by Prudhomme et al. (2010) on the so-called scenario-neutral approach. This approach also incorporates a sensitivity test to identify the impacts of diverse future conditions on a number of possible courses of action. However, this approach is less well-developed than decision scaling as it does not provide decision makers with a strategy to include the results of this vulnerability assessment in a systematic evaluative framework by which to compare different alternatives and weigh tradeoffs. A research team comprised of mainly water resource experts developed decision scaling. Hence, it is perhaps unsurprising that of the techniques presented in this table, it was developed for and has been most consistently applied to water resource management problems. For example, Brown (2010a) looks at the Niger Basin, Brown et al. (2011), and Moody and Brown (2012, 2013) look at water management of the Upper Great Lakes region, Brown et al. (2012) apply it to urban water supply and Ray and Brown (2015) explore run-of-river hydropower projects. At present, there is little evidence of any studies where decision scaling is applied explicitly to flood management applications. In addition to a growing number of applications, as summarized above, this approach has seen continued methodological development in recent years: by coupling decision scaling with decision trees, Ray and Brown (2015) have developed decision scaling into a more comprehensive water resources climate risk management framework for the World Bank; work by Poff *et al.* (2015) developed so-called eco-engineering decision scaling, which expands decision scaling to explicitly tradeoff engineering and ecological performance metrics. In terms of practical implementation, the Alliance for Global Water Adaptation (AGWA) together with the World Bank have explored the use of decision scaling for use in developing countries (Garcia *et al.*, 2014). Furthermore, at present, the US Army Corps of Engineers in co-operation with Rijkswaterstaat are exploring to what extent elements of decision scaling could be incorporated in their own respective planning guidance (G. Mendoza, personal communication, November 2015). A first draft of such a new methodology, referred to as Climate Risk Informed Decision Analysis (CRIDA), is presented in Gilroy *et al.* (in preparation) and sees decision scaling coupled with adaptation pathways.

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Decision pathways/ adaptation pathways/ roadmaps	Simultaneous with the development of decision scaling, introduced above, Dutch water researchers were developing the concept of adaptation pathways or decision pathways as a tool for long-term planning and decision making under uncertainty (Kwadijk et al, 2010; Haasnoot *et al*., 2011; Haasnoot *et al*., 2012; Haasnoot, 2013). It is a decision support framework that emerged in response to a government request to develop a planning approach that is less dependent on changing climate scenarios when making long-term national plans. Adaptation pathways focus on explicitly mapping out a different possible ways of continuing to meet desired societal objectives, identifying what degree of external change results in certain strategies becoming inadequate. Climate scenarios are superimposed on these decision pathways to explore the relative timing of different actions. Depending on which climate conditions end up being realized, actions can be completed earlier or later in time, or decision makers can switch to an entirely different decision path if future conditions warrant it. This approach centrally acknowledges that there are many possible routes to achieving a desired outcome and by producing such a decision map initially, lock-ins can be avoided and future decisions can be better anticipated. Figure 2.5 presents a sample decision pathway. In this sample problem, four possible adaptation actions (Actions A through D) have been identified. Any of these four actions could be implemented now; however, this may not be necessary yet. The concept of an Adaptation Tipping Point indicates the first moment in time when the current management system is unable to meet the necessary performance objectives and thus additional actions are necessary. Given the current policy, Figure 2.5 indicates that such an Adaptation Tipping Point will occur around Year 4. At this Adaptation Tipping Point, one of the four different actions can be chosen, with each action having different associated costs, benefits and a length of time over which it remains effective. For instance, Actions A and D remains effective up to the end of the project horizon over all future scenarios, whereas the effectiveness of Action B is shorter, necessitating further actions at the subsequent Adaptation Tipping Point, at around Year 8. The tradeoff between cost and effective lifetime of an action is made more explicit through constructing these decision pathways. The planning approach developed in this dissertation centrally builds on the concept of an Adaptation Tipping Point. Thus, given its central relevance to this work, a more thorough and comprehensive discussion of Adaptation Tipping Points and the associated literature is provided in Section 3.1.

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Adaptation pathways (continued)

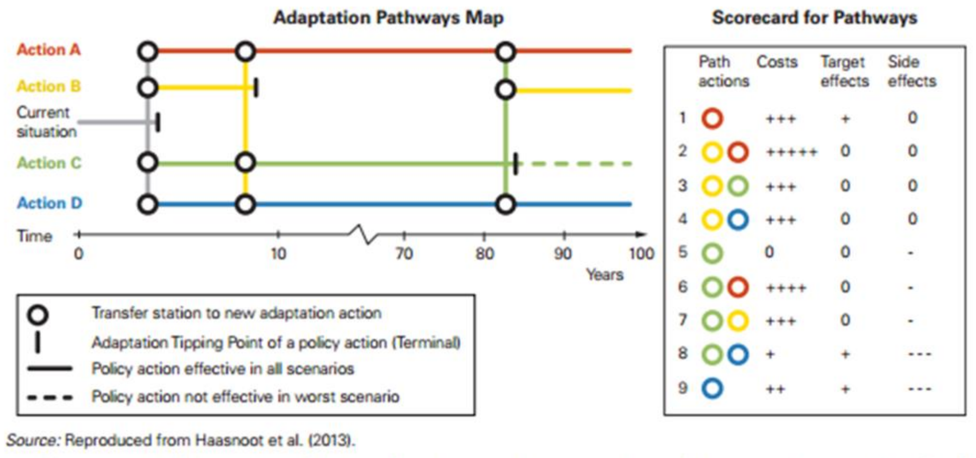


Figure 2.5: Illustration of a decision pathway (Source: adapted from Haasnoot *et al*., 2013)

Similar to decision scaling, adaptation pathways emerged directly from a water resources management question and thus it is not surprising that the vast majority of applications conducted to date have been to water resource management problems. For such a recently developed approach, it has seen substantial use in practice, with the Dutch Delta Program (van Rhee, 2012) incorporating pathways into its new policy of so-called Adaptive Delta Management, the Environment Agency (2012) in the United Kingdom constructing decision pathways for the Thames Estuary 2100 project, and other studies for New York City (Rosenzweig et al., 2011; Rosenzweig and Solecki, 2014) and New Zealand (Lawrence and Manning,

Table 2.2 continued: Overview of the current "best available" conceptual approaches used for water resources planning under uncertainty

Adaptation pathways (continued)	2012) considering a similar approach. In addition to this growing number of applications, this approach has seen continued methodological development in recent years: by coupling adaptation pathways with elements of adaptive policy making (Walker *et al.*, 2001), Kwakkel and Haasnoot (2012), Kwakkel *et al*. (2012) and Haasnoot *et al*. (2013) have developed a new approach to policy making, called Dynamic Adaptive Policy Pathways; simultaneously, Gersonius *et al*. (2012) included pathways within adaptation mainstreaming efforts.

Anyone familiar with the history of water resource planning may observe and wonder why *adaptive planning/management* is not explicitly examined as a distinct approach within Table 2.2. The concept of adaptive management first emerged as a high level-planning paradigm within the water resources sector in the latter portion of the 1900s, in response to the inadequacy of existing water management frameworks in responding to uncertainty, coping with unexpected changes, new insights as well as changing societal priorities (NRC, 2004). Despite extensive research efforts and widespread support of the theory of adaptive management (including inclusion in the revised Principles and Guidelines for Federal Investments in Water Resources (CEQ, 2013), which govern all national water resource projects in the US), its practical implementation remains somewhat limited and hampered by a diverse array of factors (see Brown, 2010b; Stakhiv, 2010; USDOI, 2012 for examples). "Adaptive management does not represent an end in itself, but rather a means to more effective decisions" (NRC, 2004) and for this reason adaptive management was not explicitly included in Table 2.2: it is suggested that the search for more adaptive approaches to water resources underlies all of the specific techniques presented in Table 2.2, with these approaches directly or indirectly attempting to operationalize this desired concept of adaptive planning.

At present, the degree of detailed, quantitative comparison of the different approaches remains very limited. Hall *et al*. (2012) and Roach *et al*. (2015) compared Information Gap Decision Theory with Robust Decision Making. Gersonius *et al*. (2015) compared Real Options Analysis with Adaptation Tipping Point Analysis, while Kwakkel *et al*. (2016) compared Robust Decision Making with Dynamic Adaptive Policy Pathways. Novel combinations of these methods remain rare: Matrosov *et al*. (2013) explore the benefits of coupling Information Gap Decision Theory with Robust Decision Making, while Gilroy *et al.* (in preparation) link Decision Scaling with Adaptation Pathways. There is certainly room for a more comprehensive comparison of the different approaches, as well as exploration into the possibility of combining elements of different approaches into a complementary whole.

2.3.3 The future: from reactive to more anticipatory responses to uncertainty?

Section 2.3.1 and 2.3.2 demonstrated that within the field of long-term infrastructural planning, one sees a move away from a command-and-control approach to planning for a single future, to considering a longer project horizon, with more possible futures and a more adaptive, feedback-driven approach to future planning and design decisions. This growing awareness that "[a]n increase in, and maintenance of, the flexibility and adaptive capacity of water management regimes should be a primary management goal" (Pahl-Wostl *et al.*, 2007) represents a substantial gain in the process of "future-proofing" existing planning and design processes. However, most importantly, this brief introduction to the state-of-the-art techniques attempting to operationalize the concept of adaptability demonstrates one crucial and pervasive shortcoming: as early as 1997, calls were made for a more proactive and anticipatory approach to infrastructure investment under climate change uncertainty in particular (Smith, 1997), however most of the adaptive approaches being considered to date (e.g. see those in Table 2.2) rely on a fundamentally "wait-and-see" mindset in their treatment of uncertainty. Matalas (1997) makes the case that "the strategy of wait-and-see i.e. delaying the making of important, expensive and essentially irreversible capital investments, could serve water managers well in coping with the uncertainties regarding climate change". However, this work suggests that when it comes to the specific case of large, aging infrastructural assets approaching the end of their service life, such as those discussed here, a passive "wait-and-see" approach can be risky due to their long construction lead times and dramatic consequences of failure. While admittedly, an adaptive approach does rely on the observation of changes in conditions and the experiencing of negative impacts before initiating changes to the system, this work takes the position that more can be done to anticipate these changes *ex ante*, than simply passively waiting and monitoring for signs that intervention is necessary.

It must be acknowledged that some of the approaches described above have made small first steps away from this "wait-and-see" approach to adaptation in the direction of more anticipatory adaptation. For instance, within the decision pathway approach described above, different possible routes to reaching a desired end-point are explored. Through this consideration of various futures and various courses of action to safeguard certain functionality, it becomes clear which pathways lead to becoming trapped in undesirable situations and which present-day decisions reduce the chance of ending up in such a lock-in. This pathway thinking also helps illustrate which possible courses of action may be worth keeping open now because they may prove to be valuable in the future.

However, within this work, it is posited that a greater degree of anticipation of possible future adaptation is possible and that this can be operationalized through the incorporation of physical options within physical infrastructure itself. Carmichael (2015) has described this as *designed-in adaptability*, versus *non-designed-in adaptability*: "With designed-in adaptability, the asset is deliberately designed *ab initio* with the view that adaptation will likely (but not necessarily) take place in the future. The alternative is to not include adaptability features, that is, the adaptability-ignored case, where the asset is deliberately designed initially without express adaptability features, but still may be capable of being adapted in some way, perhaps fortuitously, in the future." Thus, this thesis identifies the prevailing "wait-and-see" approach and its predominant reliance on non-designed-in-adaptability as a crucial research gap in the existing body of work. While "it is not possible to say, as a general comment, that [] designed-in adaptability is better or worse than fortuitous adaptation based on infrastructure designed independently of adaptability" (Carmichael, 2015), designed-in adaptability has resulted in substantial economic and performance improvements in other sectors (see the literature presented in Section 3.2) that the possibility of similar added value should be explored in this field too. Hence, as discussed more in Section 2.4, within this dissertation a long-term infrastructure planning and design approach is developed that explores whether a more proactive attitude to incorporating and managing uncertainty can add value.

2.4. The research gap

As introduced in Chapter 1, the central guiding question in this work is **given the particular features of flood management infrastructure, how do we effectively structure the reinvestment process to replace these aging assets, given the complications of uncertainty?** To this end, in the previous sections, a review of existing methods for reinvestment planning and incorporating uncertainty into long-term planning was conducted. As a result of this review, the identified research gap that this work seeks to address is two-fold:

- **Up to now, there has been no unified framework that allows long-term infrastructure planning to take into account both changes in external conditions as well as factors internal to the physical structure.** The literature looking at infrastructural replacement planning described in Section 2.2 focuses almost exclusively on those drivers of investment that are internal to a physical structure e.g. the need to conduct maintenance/renovation/ replacement due to structural degradation. On the other hand, that portion of the water resources planning literature that looks at how to make planning and design decisions under uncertainty described in Section 2.3 focuses exclusively on changes in the external environment as driving the need for investment e.g. when does sea level rise necessitate upgrading of existing structures. This separation ignores the reality of an existing stock of aging infrastructure, where both of these types of drivers of investment are important when conducting infrastructure investment planning. For instance, if analysis of recent sea levels suggest a structure should be heightened immediately in order to continue to provide the desired level of protection, it is relevant to the planning process to know whether the structure in question has 5 or 50 years left in its technical design lifespan. In other words, the singular focus on responding to structural deficiencies (previously shown on Figure 2.2) or to external changes (previously shown on Figure 2.3) should be treated in a more integrated manner (Figure 2.6).

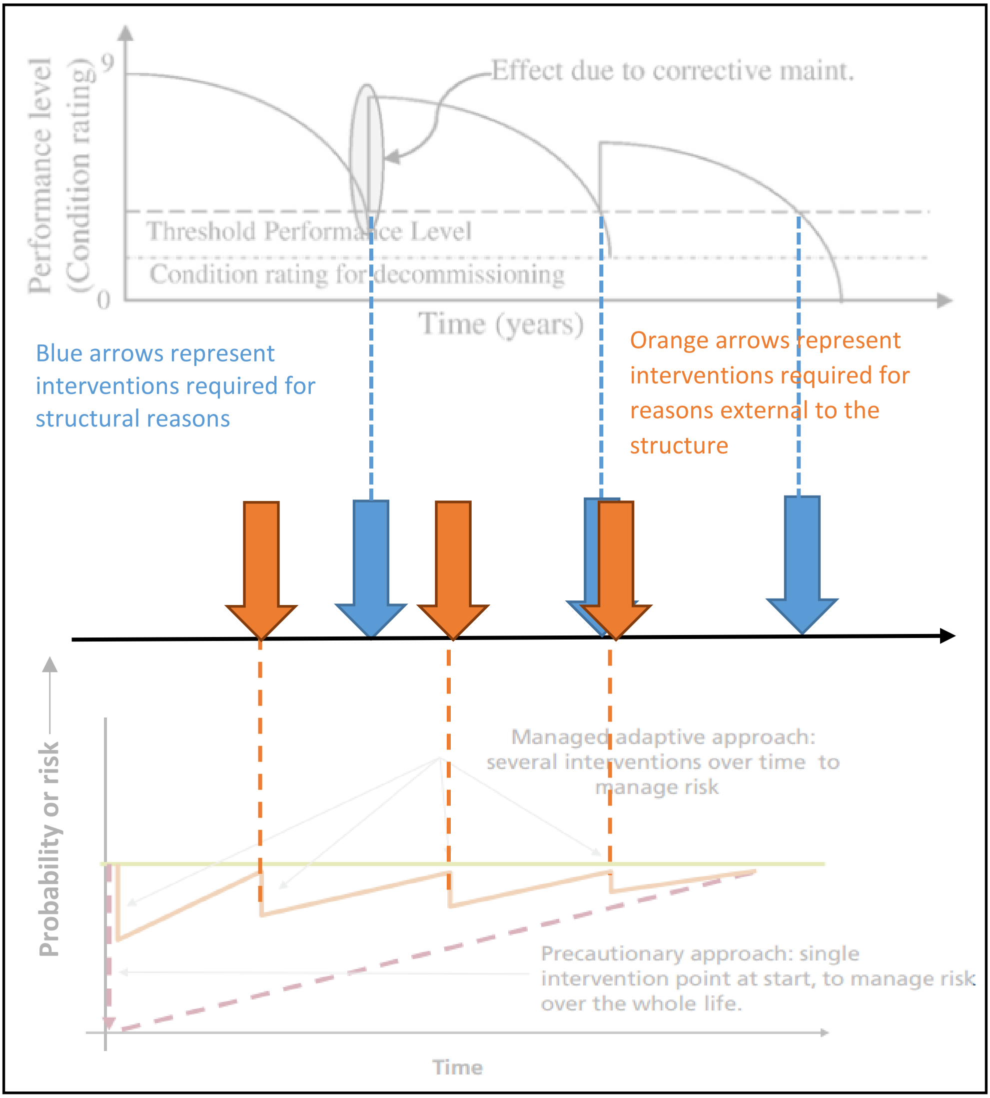
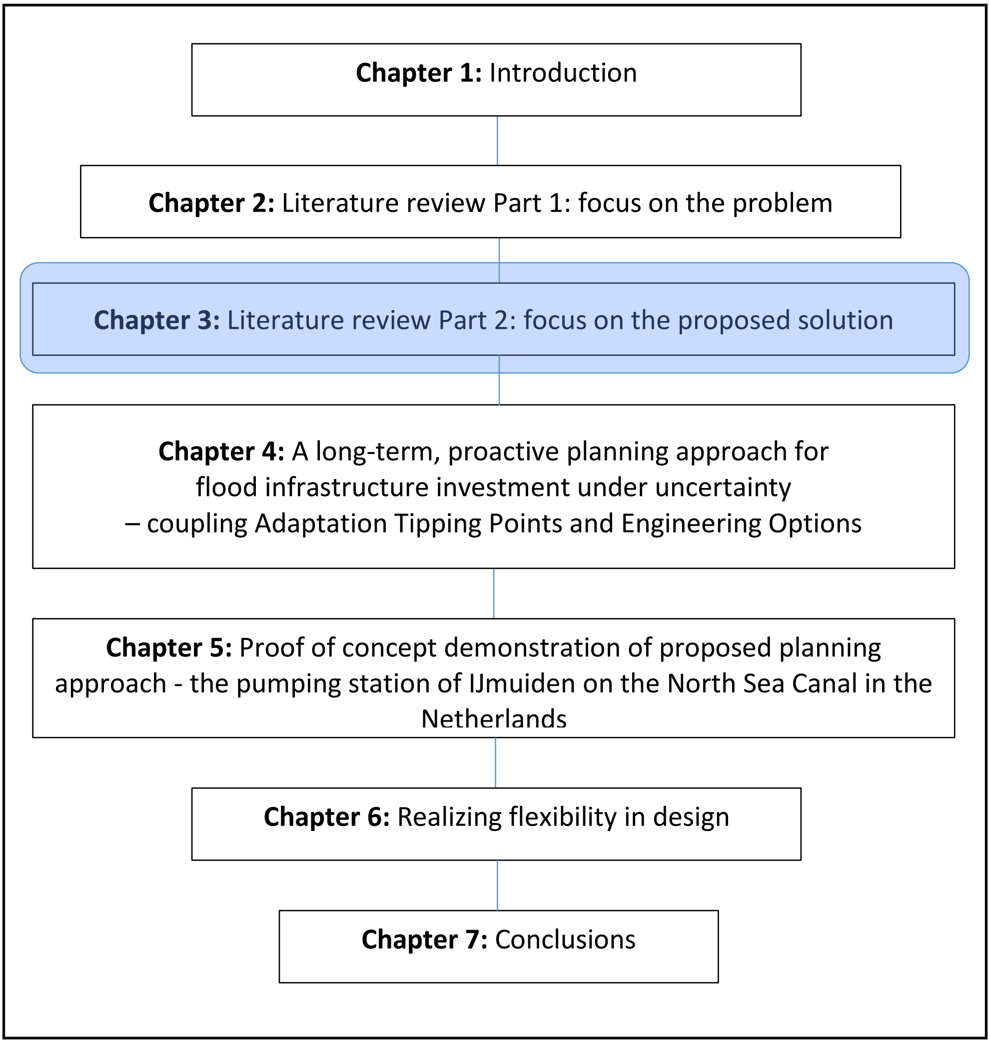


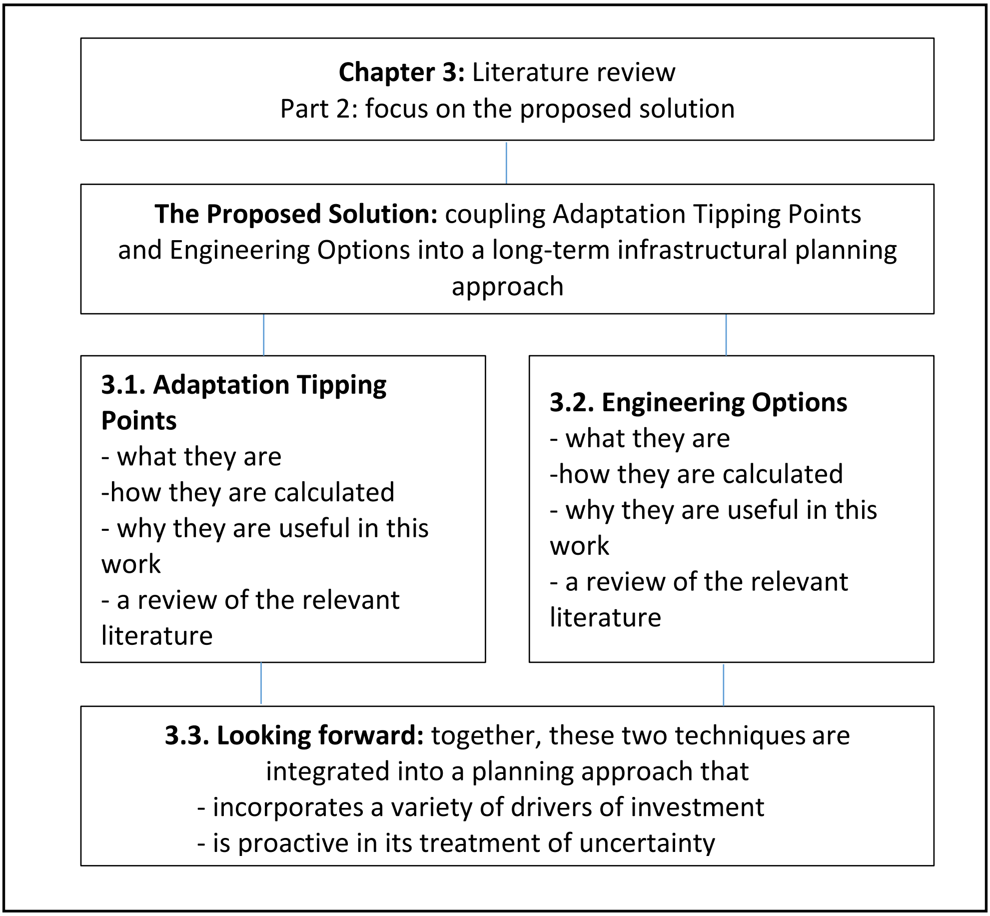
Figure 2.6: Integrated timeline of interventions taking into account different drivers of reinvestment (Source: adapted from Hong *et al.*, 2007 and HMGovernment and DEFRA, 2009)

- **To date, the majority of approaches developed to incorporate uncertainty in the long-term planning of water resources remain reactive, founded on a wait-and-see mindset towards uncertainty.** All of the methods that specifically focus on better coping with impacts of uncertainty remain fundamentally reactive to external change. While traditional strategies that rely predominantly on robustness and over-dimensioning as a method of coping with uncertainty are for the most part entirely unreactive by design, more recent adaptive strategies, described in Section 2.3, provide more opportunity to revisit a decision later on. However, they still see decision makers responding to uncertainty, rather than anticipating it. Given the long-lived nature of flood management structures and the high associated capital costs, there is room for an exploration of whether mechanisms to respond to uncertain developments could be incorporated within infrastructure planning and design in a more proactive way.

This said, the work presented in this dissertation develops a new planning approach that **takes into account different drivers of reinvestment**, namely changes in external conditions as well as structure-specific processes, and is **proactive rather than reactive** in how it deals with uncertainty. This new approach, described fully in Chapter 4, does this by drawing on elements of two existing methodologies, namely Adaptation Tipping Points and Engineering Options, to develop a single long-term infrastructural planning framework. Thus, before presenting the steps of this new integrated long-term planning approach in Chapter 4, Chapter 3 forms the second half of this literature review, introducing the conceptual background of Adaptation Tipping Points and Engineering Options and reviewing the existing literature in these two research areas.

3. **Literature Review Part 2:** focus on the proposed solution





The literature review in Chapter 2 identified two primary shortcomings of current long-term infrastructure planning approaches: first, there exists no unified framework that incorporates different drivers of reinvestment; second, existing methods are reactive, relying on a wait-and-see mindset to coping with uncertainty. Within this dissertation, these two existing methodologies are coupled into a new integrated planning framework to address these shortcomings. These two component techniques, presented in Chapter 3, are

- Adaptation Tipping Points (introduced and discussed in Section 3.1), a method of bottom-up adaptation planning, whereby performance thresholds are used to identify when external intervention is necessary in order for a system to keep functioning as required. Different types of Adaptation Tipping Points, focusing on structural factors as well as factors relating to the external operating environment, form a suitable means by which to incorporate different types of drivers of investment into a long-term planning framework.

- Engineering Options and flexibility in design (introduced and discussed in Section 3.2), are utilized to identify planning alternatives that are more anticipatory of possible impacts from future uncertainty, by incorporating the ability to adapt within the design of a structure itself.

These sections first conceptually introduce these two techniques, justify why they are well suited to the problem being explored in this work, and look at the existing body of literature where these approaches have been used so far. This leads directly into Chapter 4, which presents more complete details of this novel integrated planning approach.

3.1. Adaptation Tipping Points

The previous chapter concluded that different drivers of investment should not be considered in isolation as is currently done. It is important to consider drivers of investment both internal to a physical structure as well as relating to changes in external operating conditions in a unified way when exploring the long-term performance of an infrastructural system. The concept of an Adaptation Tipping Point is a useful means of integrating different types of decision moments into one long-term planning approach that takes into account uncertainty. To this end, Section 3.1.1 first introduces the notion of an Adaptation Tipping Point, which generically refers to a threshold beyond which a desired performance level can no longer be maintained. Section 3.1.2 provides a general overview of how to conduct an Adaptation Tipping Point analysis. Section 3.1.3 describes why, despite the relative simplicity of this concept, the use of Adaptation Tipping Points or a generic threshold measure can be a powerful addition to the long-term infrastructural planning process. Subsequently, Section 3.1.4 reviews the current literature. Ultimately, Section 3.1 builds the case for the inclusion of Adaptation Tipping Points within an infrastructural planning process as a valuable improvement over the current status quo in that it allows the inclusion of a multitude of different types of intervention moments.

3.1.1 An introduction to the concept of Adaptation Tipping Points

While the earliest concept of a tipping point originates in physics, describing the rapid change an object will undergo if it is perturbed in an unstable equilibrium, it has reappeared many times and in many different contexts over the last several decades (e.g. the triple point in chemistry; sociology: Grodzins, 1957; ecology: Scheffer *et al.*, 1993). More recently, consideration of tipping points has made a resurgence in the climate change research literature (see for instance Lindsay and Zhang (2005); McNeil and Matear (2008) and Nepstad *et al*. (2008)). In this field, they are also referred to as “large-scale singularities” (IPCC, 2007a). In all of these fields, the fundamental characteristic of the term “tipping point” is that a small external change can result in a fast-paced, dramatic shift in the state of an object.

Adaptation Tipping Points first emerged from the climate adaptation literature as an offshoot of this established notion of a climatic tipping point (Kwadijk *et al.*, 2010). While related, an Adaptation Tipping Point is distinct from a climatic tipping point as introduced above. An Adaptation Tipping Point focuses not on changes in physical processes such as a halting of the North Atlantic Meridional Overturning Circulation or the melting of the Antarctic ice sheet, but rather on the specific type of impacts that changes in these natural processes have on human developments.

Kwadijk *et al*. (2010) formally define Adaptation Tipping Points as "points [in time] where the magnitude of change due to climate change or sea level rise is such that the current management strategy[23], [chosen and implemented by decision makers in the past, to address a particular societal need or problem], will no longer be able to meet the [desired performance] objectives". Its essence lies in its role as a performance threshold that is used specifically within the realm of climate adaptation planning to indicate when the current socio-technical system first becomes inadequate due to changes in the external operating environment. Jeuken and te Linde (2011) subsequently revisited the distinction between these two related concepts, explaining that an Adaptation Tipping Point corresponds to a moment when it becomes necessary to revisit an existing management strategy. This moment does not necessarily coincide with a rapid and/or dramatic tipping point in the external natural biophysical system, but can occur at an earlier time because of gradual external changes incrementally affecting the efficacy of the current management strategy, resulting in conditions that are considered undesirable or unacceptable by society. Figure 3.1 conceptually illustrates this important distinction between climatic tipping points and Adaptation Tipping Points, with the most important differences summarized in Table 3.1.

[23]In this context, a management strategy is treated as a method of fulfilling certain functionalities required or desired by a particular society at a particular time. For instance, given an existing inland waterway system, it is conceivable that a policy of dredging is the current management strategy used to maintain the required channel depth for ship thoroughfare. Given the possibility that climate change impacts will result in more frequent low water levels in the future, different future management strategies to ensure the continued functionality of inland waterways could include, for example, more intensive dredging or transitioning to a shipping fleet of smaller boats (Haasnoot, 2013).

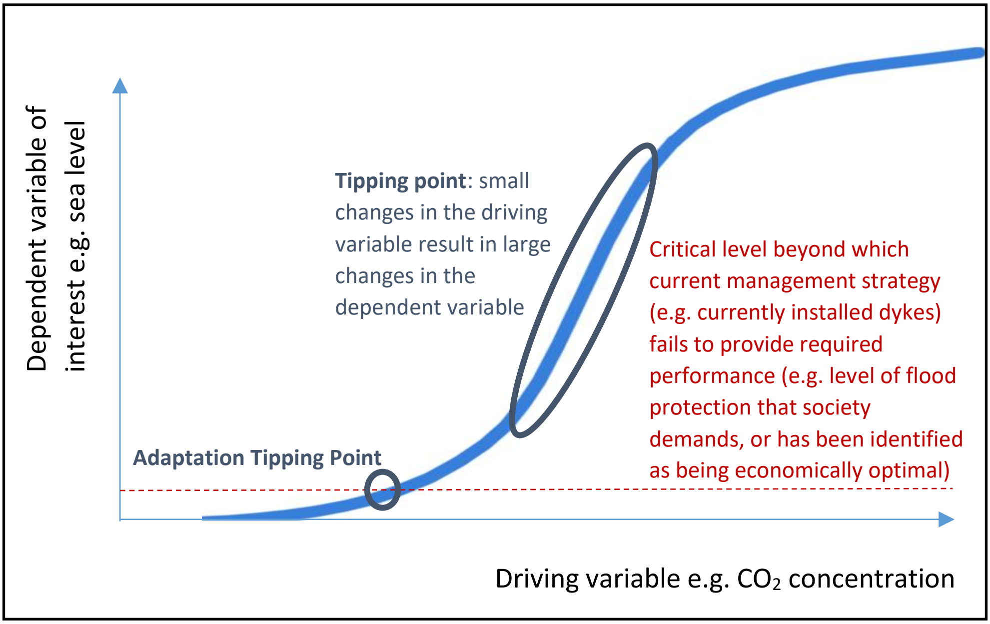


Figure 3.1: Conceptual difference between a tipping point and an Adaptation Tipping Point

Table 3.1: Summary of key differences between tipping points and Adaptation Tipping Points

Climatic tipping point (or large scale singularity)	*Adaptation* Tipping Point
Focus on changes in **external physical climatic processes** i.e. biophysical processes (as defined in Werners *et al*., 2013).	Focus on **impacts of external climatic changes on human processes** i.e. socio-political processes (as defined by Werners *et al*., 2013).
Physical laws define threshold beyond which a tipping point occurs. These thresholds are in many cases still unknown.	Society/decision makers define threshold beyond which an Adaptation Tipping Point occurs. Thresholds can be formally regulated (e.g. federally mandated flood defense levels), operationally adhered to despite no formal agreements or may be entirely unclear.
Concept formalized in **1950s**; first emerged in climate field in **2000s**.	Concept first developed in **2010s**; draws on elements of Assumption Based Planning, created in the **1980s**.

Fundamentally, the primary take-away point here is that, while related conceptually, tipping points focus on rapid, potentially irreversible changes in natural physical conditions, whereas Adaptation Tipping Points attempt to translate external changes more concretely into more tangible impacts that affect current human systems of importance. Thus, the notion of Adaptation Tipping Points was designed for very different purposes than the more traditional physical tipping points explored to date: Adaptation Tipping Points are intended to structure the socio-politically-centered conversation of infrastructure and adaptation planning, enabling continued provision of services given broad uncertainty about the extent of future climate change impacts.

Textbox 4: Reconciling terminology III

The argument has been made that the term "**Adaptation Tipping Point**" is a misnomer, because it does not describe a true **tipping point**. The critical component of the term tipping point as previously used in the literature implies that once a certain threshold is crossed, change can no longer be accurately predicted or halted. This is not necessarily applicable in the context of Adaptation Tipping Points, where the tipping point simply refers to the end of the usefulness of a current strategy (Werners *et al*., 2012). Werners *et al*. (2012) assert that instead of an Adaptation Tipping Point, a more appropriate and less confusing term would be an "**adaptation turning point**". Furthermore, a case could also be made for simply using the term "**adaptation threshold**" in this context. For a comprehensive discussion of the use of these terms in the current climate literature, see Werners *et al*. (2013). However, having acknowledged that there are some semantic and conceptual issues with this terminology, for the sake of consistency, the remainder of this work uses the term Adaptation Tipping Point, taking it to be consistent with the definition provided by Kwadijk *et al*. (2010), as provided earlier.

3.1.2 An introduction to Adaptation Tipping Point analysis

As first described by Kwadijk *et al*. (2010), and expanded by Gersonius (2012), the generic steps of identifying Adaptation Tipping Points are

- define the boundary of the physical system of interest
- identify the functions that the system fulfils
- for each function, identify relevant quantitative performance indicators, as well as the threshold performance level beyond which the system is no longer considered functional
- using diverse plausible climate scenarios, compute the increase in loading on the physical system
- estimate when this increased loading will first result in the required performance no longer being met.

As a demonstration, these steps are applied to a generic flood protection structure. The results of this simple demonstration are displayed in Figure 3.2. The boundary of the physical system of interest in this case is a coastal levee. Its primary function is flood protection for inland areas against high water levels on the ocean. A typical performance indicator for flood defense structures is the water level associated with the design flood return period. The threshold performance level beyond which the system is no longer considered functional is context and location specific. In this example, the coastal levee is required to withstand water heights that occur on average once in every 10,000 years, consistent with coastal flood protection standards in the Netherlands. Two different sea level rise scenarios (low and high), defined *ex ante*, are used to explore how different degrees of sea level rise affects the magnitude of the 1:10,000 flood event. Future scenario-specific 1:10,000 year water levels are shown in dashed red and orange lines on Figure 3.2. The two scenarios used here are linear future sea level rise scenarios, however any kind of user-defined scenario of interest could be used (e.g. exponential or stepped, non-continuous sea level rise). Finally, the current flood defense height of the levee is superimposed on the graph (shown in green on Figure 3.2), providing an indication of when and under which future conditions, the current structure becomes inadequate and hence an Adaptation Tipping Point is reached.

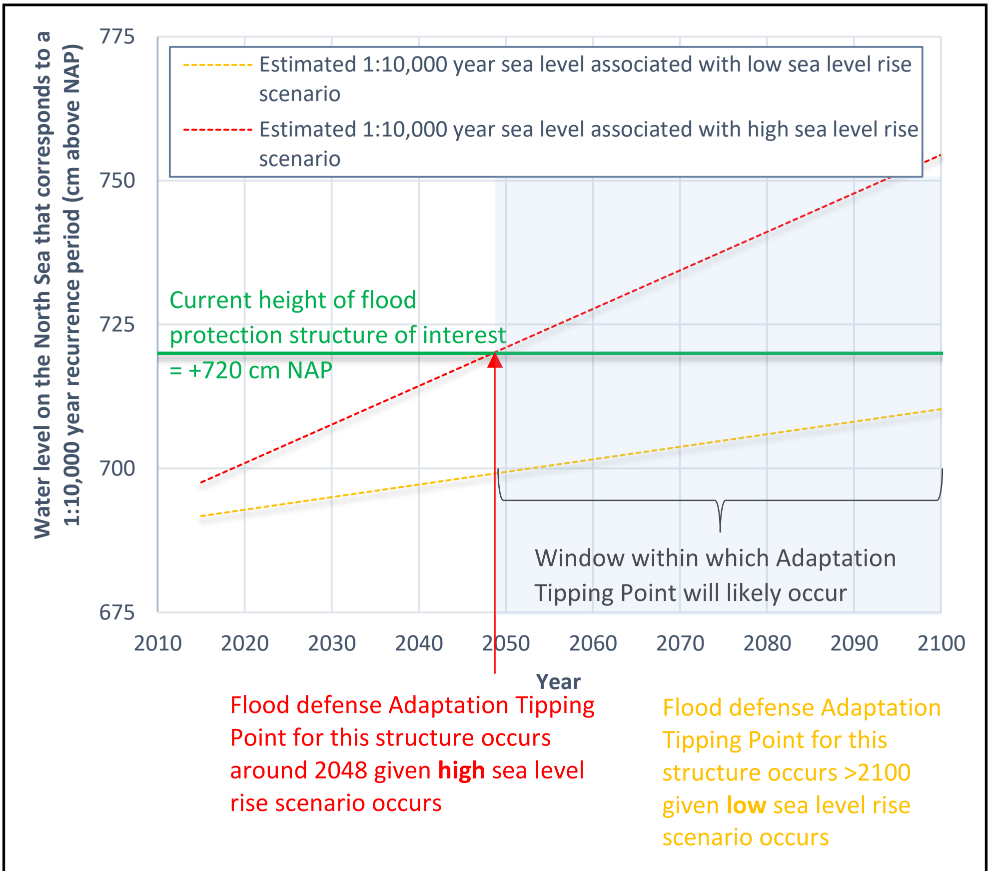


Figure 3.2: Demonstrating the occurrence of an Adaptation Tipping Point for a fictional flood defense structure

It should be apparent that computationally, this technique relies on translating an assortment of different individual future scenarios into indicators of interest, which are then superimposed on timelines to identify when one can first expect the failure of certain systems to meet necessary performance standards. Conceptually, this is no different from simply imposing a threshold of some kind and upon introduction of shocks or changes to a system, identifying when in time and under which conditions this threshold is exceeded. The key result to observe is the window of time that approximately delineates the earliest moment at which this particular structural system will no longer be adequate to meet societal demands. Obviously, the more extreme climate scenario examined is associated with the earliest occurrence of an Adaptation Tipping Point, with the most optimistic climate scenario associated with the furthest occurrence of an Adaptation Tipping Point. The objective of this technique is not to provide detailed predictions about whether this particular structure will no longer be adequate in 2048 as opposed to 2050. Rather, the intention is to be able to identify which functionalities of our existing system will be of concern first, how imminent this concern is (i.e. immediate or not for a few more decades) and under what conditions the existing system fails.

3.1.3 Why are Adaptation Tipping Points suited for this work?

To understand the particular strengths of the Adaptation Tipping Point approach, it is useful to look briefly at different classes of adaptation planning methodologies, highlighting how the specific shortcoming that Adaptation Tipping Points were designed to address. Within the early decades of climate change impacts assessment, most approaches developed were typically top-down, first deriving plausible climate change scenarios from downscaled global climate model output, before then attempting to predict the anticipated impacts to specific areas for each scenario and identifying necessary local adaptation measures to mitigate these impacts (IPCC, 2007b). This category of approaches has also been characterized as **cause-based approaches**[24], because they move forward along the cause-effect chain, starting at climatic processes (causes) and ending at impacts to sectors of interest (effects) (Gersonius, 2012). They fundamentally seek to answer the question "What if Scenario X occurs?" (Walker *et al.*, 2013). A crucial shortcoming of this class of approaches is the dependence of adaptation strategies on specifics

[24] Reeder and Ranger (2013) characterize these approaches as "**science-first**".

of climate scenarios, such that every time climate scenarios are adjusted or updated, so too all subsequent identification of impacts and possible responses change.

In reaction to this shortcoming that hampered the use of climate modeling output in furthering on-the-ground adaptation planning efforts[25], a second class of more bottom-up approaches emerged (Kwadijk *et al.*, 2010). By focusing first on the effects of external changes and identifying when these changes could first be anticipated to occur given different climate scenarios, so-called **effect-based approaches[26]** began to arise. As an effect-based method, the starting point of the Adaptation Tipping Point approach is centered on explicitly identifying what sectors of interest need to be able to do in order to be considered fully functional. Then, given different climate change scenarios and impacts, the moment when this functionality is no longer possible is identified, before exploring what measures can be taken to continue to safeguard this functionality in the future. This approach seeks to answer the question "*Under what conditions will the current plan no longer perform adequately?[27]*" (Walker *et al.*, 2013). Thus, when using Adaptation Tipping

[25] The specific event that initiated the eventual development of the Adaptation Tipping Approach was a request from the water management sector in the Netherlands, seeking guidance on how to update their long-term management plans given the imminent release of a new and improved set of country-specific climate scenarios (Kwadijk *et al.*, 2010). In particular, there was concern about the possibility of having to dramatically alter and overhaul their existing plans every time a set of new scenarios was released in the future.

[26] This group of approaches is also variously referred to as "**context-first**" or "**policy first**" (Reeder and Ranger, 2013).

[27] Conceptually, this Adaptation Tipping Point approach shows some similarities with a number of techniques previously discussed in Section 2.3:

- First, it has the same driving question as Assumption-Based Planning, a technique that was developed by the RAND Corporation in the 1980's (Dewar, 2002) and eventually contributed to the creation of Robust Decision Making. While conceptually seeking to points, the focus is on evaluating what the first sectors will be that are unable to meet their societally determined performance objectives and approximately when this will occur under different future scenarios. Crucially, there is never any attempt made to combine these scenarios using probability distributions, or chose only one scenario to design for.

There are a number of desirable strengths associated with utilizing this approach. As an effect-based approach, it starts from the very concrete and management-relevant departure point of identifying what exists already and what society demands that these existing systems are able to do. Thus, while computationally this technique is hardly revolutionary, its strength lies in its ability to link complex climate science with real world impacts and adaptation policies (Kwadijk *et al.*, 2010; Werners *et al.*, 2013). Through the relative simplicity of this concept, it provides an accessible framework by which to involve decision and policy makers (i.e. non-scientists) in conversations about uncertainty regarding climate change impacts and the need to adapt. Instead of the traditional focus on identifying one optimal adaptation strategy, made difficult by the many assumptions necessary and the need to assign probability distributions to climate scenarios, the strength of this approach is that it is largely exploratory. It allows decision makers to explore

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answer similar questions, the focus of these two methods is different however: Assumption-Based Planning was created as a technique by which to assess and increase the degree of adaptability of plans already in existence. By contrast, Adaptation Tipping Points focus explicitly on structuring the creation of new plans, with an emphasis on preventing lock-ins and enabling adaptation within the plan in the future.

- Adaptation Tipping Points also shows some conceptual similarity to the climate vulnerability analysis or stress test that forms the first step of Climate Informed Decision Analysis (Brown, 2010). However, while the stress test output feeds into an analysis that attempts to quantify how likely the bad scenarios are, Adaptation Tipping Points are typically developed into a series of decision pathways that provide decision makers with a suitable array of steps to take no matter how good or bad the future turns out to be.

different adaptation measures, taken at different times and in different sequences. This awareness that decisions and adaptation measures are flexible in time is important given that decisions today can directly affect available courses of action in the future. In addition, the general form of an Adaptation Tipping Point as a threshold is suitable as input for a variety of further quantitative or qualitative techniques (e.g. creation of adaptation pathways or economic evaluation of different actions taken at an Adaptation Tipping Point). It is proposed for these reasons that this Adaptation Tipping Point approach lends itself well to the creation of a long-term planning framework that links both asset management and climate adaptation work, as undertaken in this work.

3.1.4 A review of the existing Adaptation Tipping Point literature

A review of the existing literature shows a small, but rapidly growing body of published works focusing on Adaptation Tipping Points.

A review of the academic literature

Conducting a search of the existing academic literature shows that apart from the early work conducted by Kwadijk *et al*. (2010) and Jeuken and te Linde (2011), who first define the concept of an Adaptation Tipping Point, there has been little work looking at further developing or deepening the concept itself. The lack of further conceptual developments is likely attributable to the relative simplicity of the concept of what an Adaptation Tipping Point is and represents.

Since its development, Adaptation Tipping Point analysis has been progressively applied to a growing number of fields, including flood and water management problems (e.g. Haasnoot *et al.,* 2012; Kwadijk *et al*., 2010; van Slobbe *et al*., 2014), as well as to salmon conservation (Bolscher *et al*., 2013; van Slobbe *et al*., 2014), wine production and nature conservation (Werners *et al.,* 2012).

However, the most active field of research in this area at present has focused not on the further refinement of the concept of an Adaptation Tipping Point itself nor on its direct application in different sectors, but rather on its incorporation into more complete planning methodologies. For instance, as described more fully in Section 2.3, Adaptation Tipping Points have been developed into complete adaptation pathways (Haasnoot *et al*., 2011; Haasnoot *et al*., 2012; Haasnoot, 2013); they have been incorporated into a new policy making procedure called Dynamic Adaptive Policy Pathways (Haasnoot *et al*., 2013; Kwakkel and Haasnoot, 2012; Kwakkel *et al*., 2012) and as well as included in adaptation mainstreaming efforts e.g. (Gersonius *et al*., 2012).

Some things to notice in the academic literature

This next section provide a brief evaluation of the limited literature described above, highlighting in particular those observations most relevant to the approach developed later in this work.

- <u>Limited consideration of drivers of Adaptation Tipping Points beyond climate change</u>

A first important trend worth highlighting is the exclusive focus within the existing body of work on climate change as a driver of Adaptation Tipping Points. While this is not irrational given the development of Adaptation Tipping Points specifically in response to a need for more implementable climate adaptation strategies, Van der Vlist *et al*., (2015) argue that the concept of Adaptation Tipping Points is relevant to more drivers of reinvestment and policy change than climate change alone. While Van der Vlist *et al*. discuss other drivers of Adaptation Tipping points at a theoretical level, Van Vuren *et al*. (2015) provide a first demonstration of how these different types of Adaptation Tipping Points could be formalized in practice. Ahmed *et al*. (2015) offer support for the inclusion of other drivers of Adaptation Tipping Points, however they focus specifically on the developing country context. These isolated publications provide a springboard for the work conducted here, emphasizing the need to incorporate a more realistic and comprehensive set of drivers of reinvestment into a long-term reinvestment strategy, outside of climate change alone.

Shortcoming: To date, Adaptation Tipping Points have only considered climate change as a driver of declining performance. Within the context of aging infrastructure reinvestment planning, a broader range of drivers of investment should be considered, including drivers both internal and external to the structure.

- <u>The occurrence of an Adaptation Tipping Point provides no indication what to do in response</u>

A second point worth noting is that while an analysis of Adaptation Tipping Points provides valuable information about the relative vulnerability of different sectors to climate change, it does not provide any information about what we can or should do in response to the occurrence of an Adaptation Tipping Point. For instance, an analysis may show that drinking water infrastructure will reach an Adaptation Tipping Point much sooner than drainage infrastructure. However, the output of such an Adaptation Tipping Point analysis does not provide any explicit insights about what courses of action could be taken at that time, or how they compare. Thus, this output is somewhat limited in its usefulness and needs to be coupled with other established methods to generate possible responses.

Shortcoming: Adaptation Tipping Points do not provide any insights about what actions could/should be taken following the occurrence of such an Adaptation Tipping Point.

- <u>The lack of incorporation of Adaptation Tipping Points into quantitative evaluation frameworks</u>

This third and final observation is closely linked to the previous observation described above. It focuses on the absence to date of any kind of quantitative economic evaluation when utilizing Adaptation Tipping Points. So far, no attempts have been made to evaluate possible actions following an Adaptation Tipping Points using quantitative evaluation frameworks, such as Cost Benefit Analysis or options analysis (Ray and Brown, 2011). While Haasnoot *et al*. (2013) use a kind of qualitative score card to compare different courses of action that could be taken after an Adaptation Tipping Point occurs, they identify incorporation of Adaptation Tipping Points into a direct quantitative evaluation framework as an area for further research. Gersonius *et al*., 2015 do explore Adaptation Tipping Points in the context of Real Options, however, they treat them as alternative methods, conducting a comparison of their relative strengths and weaknesses, rather than treating them as complementary methods to be incorporated into a single planning framework as this work sets out to do.

Shortcoming: While Adaptation Tipping Points provide insights about the urgency of adaptation for different components of a system, they have yet to be integrated into any kind of quantitative evaluation framework that is able to compare different courses of action.

A review of the agency-specific grey literature

Exploring the existing grey literature, there appears to be a critical mass located in the Netherlands and the United Kingdom, where public agencies are actively incorporating Adaptation Tipping Points within planning efforts. The two most notable examples include

- **The Thames Estuary 2100 project** (Environment Agency, 2012), which sees the use of Adaptation Tipping Points (referred to as "key thresholds") to explore different strategies to manage increasing flood risk in the Thames Estuary and in London in particular, over the course of the next century. For further details, see Textbox 5.
- **The Dutch Delta Programme** (van Rhee, 2012) incorporates Adaptation Tipping Points as an explicit component of its new policy of so-called Adaptive Delta Management. For details, see Textbox 6.

From these two relatively high profile starting points, the central ideas of Adaptation Tipping Points appear to be slowly spreading outwards, as evidenced by studies being conducted in New York City (e.g. Rosenzweig et al., 2011; Rosenzweig and Solecki, 2014) and New Zealand (e.g. Lawrence and Manning, 2012). In summary, this notion of an Adaptation Tipping Point, despite being relatively new and still very much an area of active academic research, has already begun to garner significant implementation efforts.

Textbox 5: The Thames Estuary 2100 project

(Environment Agency, 2012)

The estuary of the River Thames has long been impacted by floods, of both tidal and fluvial origin. Defenses against high tides on the North Sea existed in the Thames Estuary as early as 1,500 years ago. Over the centuries, these have been incrementally improved, culminating in the construction of the Thames Barrier and a number of associated structures in the 1980's. To a large extent, the stimulus for the construction of the Thames Barrier was the occurrence of a major tidal flood in 1953. Across the English Channel, this same event spurred the creation of the Delta Programme in the Netherlands (- see Textbox 6).

Fast-forward three decades and at present, the Thames Estuary is protected by a physical system comprised of 330 km of floodwalls and embankments, 36 floodgates and more than 400 additional smaller structures. Given the increasing age of the existing structures and the large degree of uncertainty about future sea level rise, precipitation change and socio-economic development in the region, the Thames Estuary 2100 (TE2100) project was developed to explore how to continue to effectively manage flood risk in the region through to the end of the century.

A number of estuary-wide future courses of action were explored, including improving the existing flood risk reduction system, constructing tidal flood storage or developing a new barrier structure. These estuary-wide alternatives were complemented by a set of location-specific courses of action. Unique to the TE2100 plan is its explicit exploration of possible flood risk reduction actions at various time scales: short (first 25 years- investments of £1.5bn), medium (middle 15 years-investments of £1.8bn) and long-term (up to 2100- investments of £6-7bn). Courses of action are treated less as mutually exclusive alternatives, and more as a sequence of progressively more extreme (i.e. more effective, but more expensive) actions that may become necessary in the future depending on the degree of environmental and socio-economic change that materializes. In this way, no-regret actions such as floodplain management (e.g. no new development in vulnerable areas) and maintenance/improvement of existing defenses are implemented early on. These interventions are associated with a degree of external change beyond which they become unable to offer adequate protection (i.e. an Adaptation Tipping Point is reached). At such a time, further investments must be made (e.g. a new barrier structure, required after 2070). A monitoring system allows system managers to track, based on emerging data, when such far-term courses of action start to become necessary and if they need to be brought forward in time. By sequencing diverse actions over time, and using monitoring to adjust the otherwise flexible timing of implementation, the plan is effectively preparing for diverse future scenarios, rather than a single most-likely design scenario.

Textbox 6: The Dutch Delta Programme

The Netherlands has always been a country shaped by water, low-lying and flood-prone. The flood of 1953 killed around 2,000 people and served as a turning point. In response, the government created the Delta Commission, tasked with creating a plan to better protect the country against future flooding. On the basis of the commission's recommendations, between 1954 and 1997, €5bn was invested in a complex network of storm surge barriers, dams, sluices and dykes to protect the delta region of the country (together known as the Delta Works).

In 2005, the devastation of Hurricane Katrina on New Orleans served as a renewed wake-up call. Given the growing Dutch population, and the potential future impacts of sea level rise and climate change, how adequate would past flood risk reduction investments remain in the future? In 2007, the second Delta Commission was created, this time tasked with ensuring on-going flood protection and securing adequate access to freshwater, under altered future conditions. The recommendations drafted by this second commission and released in 2008 estimated an additional €100bn of investment would be needed through 2100 to achieve these goals. To operationalize this long-term vision, every year starting in 2010, a plan of work (the Delta Programme) has been released. This programme is allocated an average of €1.2bn annually, and so far there have been seven annual Delta Programmes.

A foundational tenet underlying all of the work encompassed by the Delta Programme is that of Adaptive Delta Management. In brief, Adaptive Delta Management explores possible actions over a long time horizon across diverse possible scenarios, but only those actions that are currently needed are actually implemented, with additional measures reserved for future execution, if/when required. This is seen as a strategy to balance future preparedness without over-investing too soon.

A concrete example of this can be found in the Delta Programme 2015 looking at future fresh water availability. Looking at freshwater availability in rivers and canals, under two future climate scenarios, it was concluded that under the more extreme scenario, water issues occur in 2050 even under average precipitation years. However, under the less extreme scenario, water issues only occur in 2050 during dry years. What investments should be made given the uncertain degree of scarcity? Adaptation pathways were developed for the region, phasing different possible response measures from short-term water conservation, to increasing water levels in reservoirs, to constructing additional storage upstream. Each of these interventions are associated with a degree of precipitation change beyond which they become ineffective without additional action (i.e. an Adaptation Tipping Point occurs). Exploring diverse alternatives up front, and phasing their eventual implementation based on the emergence of actual data allows an adaptive and appropriate response to future changes.

Some things to notice in the agency-specific grey literature

The above review of the grey literature demonstrates an interesting level of co-development and feedback between the academic and government realms in this specific field. While researchers continue to explore and develop these methods further, select government agencies have already made great strides to incorporate these ideas into more concrete adaptation strategies. Furthermore, development of these location-specific adaptation plans conducted outside of the traditional academic realm are garnering substantial academic attention (e.g. The Thames Estuary 2100 project – Jeuken and Reeder, 2011; Lavery and Donovan, 2005; McGahey and Sayers, 2008; Reeder and Ranger, 2013; Smith *et al*., 2011; and Wilby and Keenan, 2012). Within the ongoing development of Adaptation Tipping Points as a cause-based adaptation approach, it would appear that an environment of "learning by doing" predominates at the current time.

Overall, this review demonstrates that while Adaptation Tipping Points are still an area of emerging and active academic research, their uptake within more implementation-focused circles is already occurring. It is possible that this early uptake is largely due to the simple, easily communicable and fit-for-purpose nature of Adaptation Tipping Points. This work attempts to build on this growing interest in Adaptation Tipping Points by using them as a framework to introduce different drivers of change beyond climate change into an infrastructural reinvestment approach.

3.2 Engineering Options

Within the literature presented in Chapter 2, a substantial body of work was discussed that proposed that incorporating flexibility in the design of infrastructural systems may provide long-term practical and economic advantages over existing planning techniques, especially in light of climate change uncertainty. This dissertation suggests that by drawing on elements of Options Theory, it is possible to incorporate this concept of flexibility into an actionable planning framework and demonstrate the relative advantages of a more flexible approach. To this end, Section 3.2.1 first introduces Options Theory. Section 3.2.2 discusses options analysis, before Section 3.2.3 describes how this theory is relevant and why the concept of Engineering Options in particular is well suited to the problem this dissertation is exploring. Subsequently, given that this work proposes Options Theory as a technique that may have advantages over the current status quo, Section 3.2.4 presents a review of current literature to identify whether any work has already been done applying Options Theory to the problem of flood infrastructure investment under uncertainty. This section includes a review of any findings, as well as a discussion of how these findings are supportive of further research developments, possible shortcomings of work done so far and how the work presented later in this thesis is distinct from what has already been done.

3.2.1 An introduction to the concept of Engineering Options

The study of Engineering Options is a relatively new field, developed over the last decade. Its underlying concepts are genealogically linked to the more well established field of Real Options, which in turn grew out of financial options. In recent years, there has been a surge of references to options within the climate adaptation literature (see Section 2.3.4). A close look at this literature, coupled with anecdotal personal experience suggests that there is a fairly widespread lack of understanding of the differences between these related, but distinct fields. To explicitly highlight the unique features of Engineering Options, it is necessary to contrast the concept of Engineering Options to the other older, more widely referenced and commonly known types of options from which it evolved.

Emphasizing explicitly how they differ from each other requires a brief introduction to each, as shown in Figure 3.3 and explained below. Figure 3.3 depicts the progression of Options Theory over time, and shows that the initial ideas of financial options, formalized pre-1970, were subsequently incorporated into capital asset investment decisions through the field of Real Options in the late 1970s, which in turn was brought to bear on infrastructural design decisions, through the concept of Engineering Options, in the early 2000s.

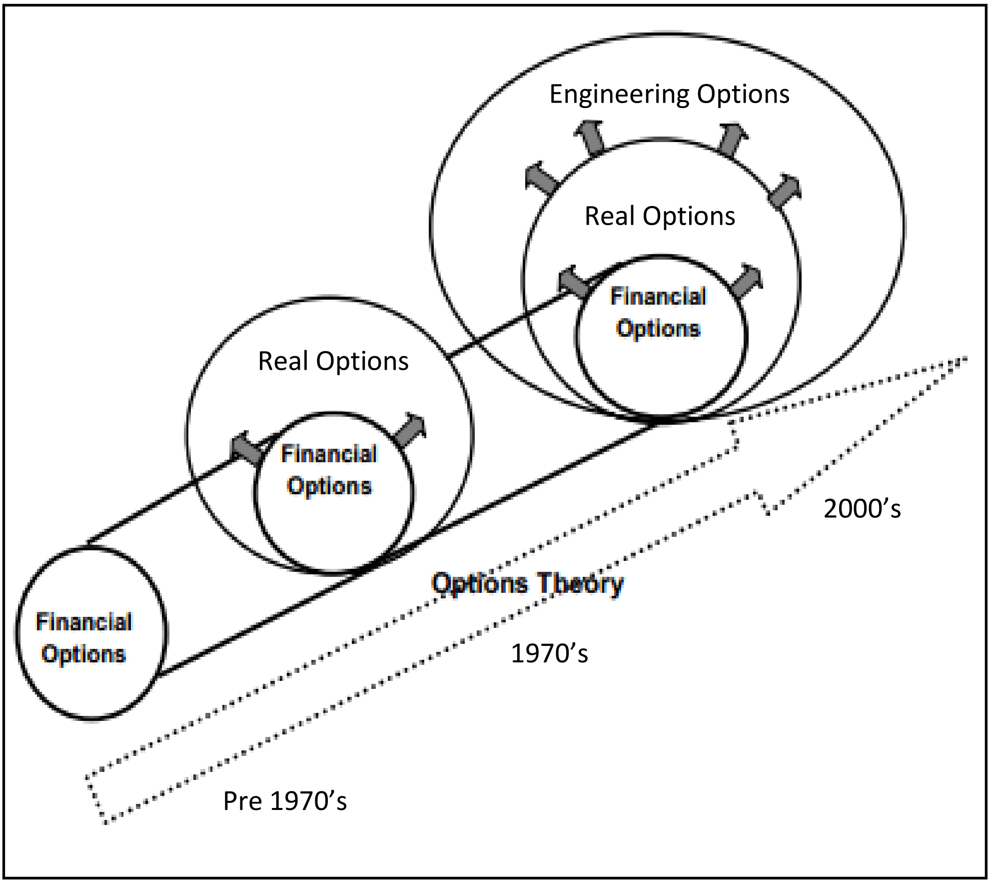


Figure 3.3: Development of Options Theory, illustrating the relationship between financial options, Real Options and Engineering Options (Source: adapted from Wang and de Neufville, 2005)

1. The birth of financial options – flexibility in stock market investments

While the first notion of an option can be traced back to the Ancient Greeks and their olive harvest (Siems, 1997), it first became formalized within financial circles in the form of an option on an underlying financial asset such as a stock. An option gives the holder the right to buy or sell a share in this asset, for instance a certain number of shares, for a previously set price at or before a predetermined time. The fundamental contribution of this concept is the realization that the ability to wait and observe uncertain external processes develop before taking decisive action has an implicit value, as Figure 3.4 shows conceptually. Thus, if the uncertain stock price increases over time, one still has the ability to benefit from buying stock at the earlier lower rate, whereas if the stock price drops, one can decide not to buy any stock at all and hence lose only the initial purchase price of the option. Clearly, if there is no uncertainty about a future outcome, there is no value in purchasing an option.

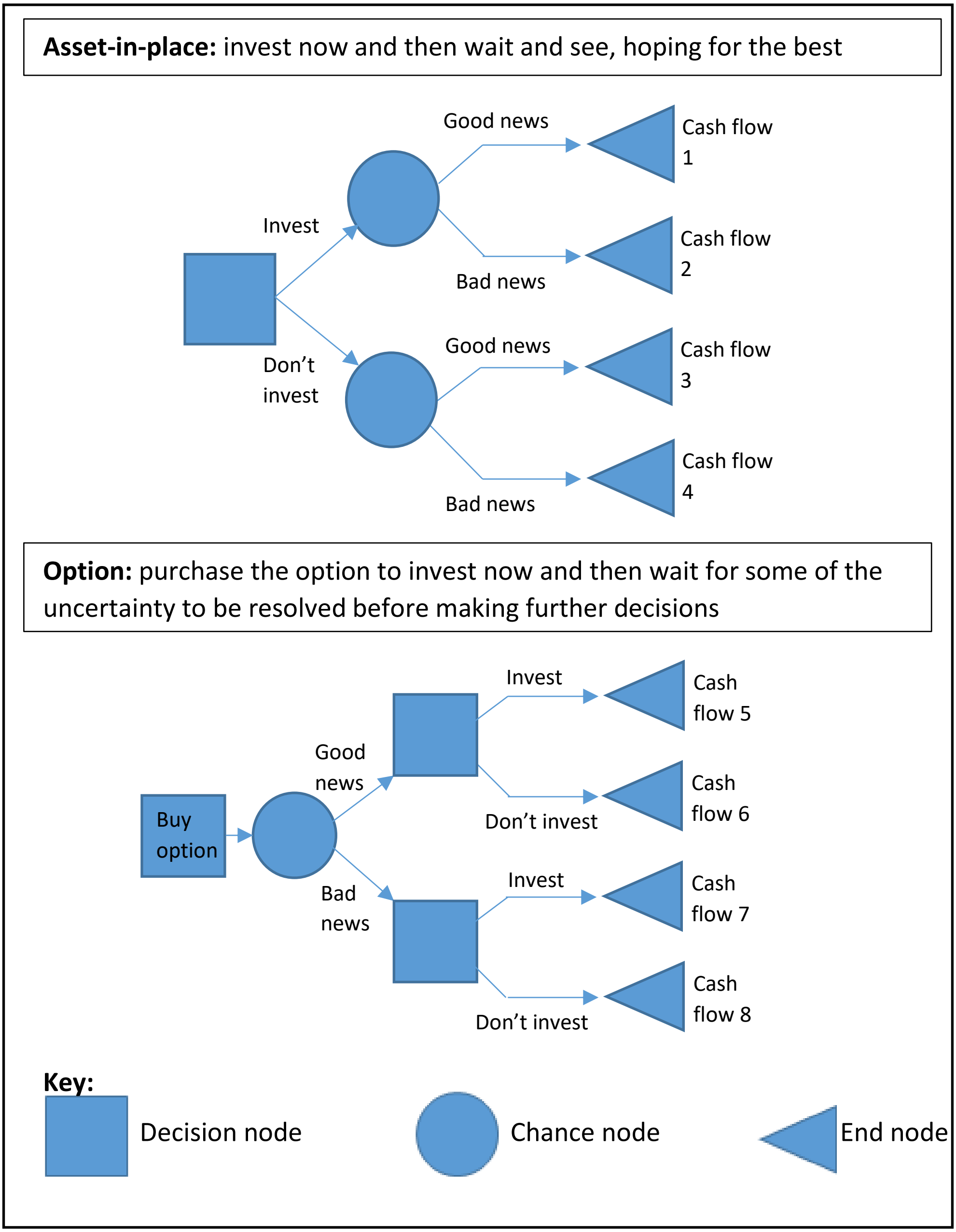


Figure 3.4: Decision trees illustrating a traditional asset-in place and an option on an asset (Source: adapted from Robinson and Kyng, 2003)

2. From financial options to Real Options – recognizing managerial flexibility

Building on these developments in the field of financial options, these same core ideas were extended from financial investment decisions that rely on financial instruments such as derivatives, to capital investment decisions that involve tangible physical assets. In 1977, Myers coined the term "Real Options[28]" to describe these "real" investments. A Real Option is defined as "the right but not the obligation to change a project in the face of uncertainty" (Trigeorgis, 1996).

The notion of a Real Option draws attention to the shortcomings of the traditional approach of exploring investment decisions as if they were fixed, static, now-or-never and all-or-nothing type decisions: e.g. invest in Plan A or not, where Plan A is treated as unvarying over time. This is not reflective of the true situation, where the management of assets is anything but static, and asset managers rarely just sit by and do nothing if past investment decisions prove to be less successful than initially envisioned. Instead, managers are able to revisit and review past investment decisions, making necessary adjustments in response to observed changes in uncertain external conditions. In other words, the exploration of an investment question should not be viewed as a take-it-or-leave-it set of alternatives: every project has embedded in it a

[28] Note that the words "**option**" and "**alternative**" are not interchangeable in the context of Real Options. Different investment *alternatives* may be to investment or not invest in a project. Within the "invest" alternative, there exists a multitude of different possible *options* that can be evaluated, such as delaying investment or phasing investments in time. Crucially, each of these options has an associated cost of keeping that option open as well as a cost of actually implementing that option. For instance, when phasing an investment, such as heightening a levee in the future, the cost of keeping that option open is the cost of purchasing more land than is currently necessary at the start, so as to leave room for widening of the levee base in order to support a height addition. The cost of implementing this option is obviously the cost of building the height addition on top of the existing levee.

multitude of different options that may be more or less economically attractive as compared to the static baseline Plan A. For instance, it is not just a question of comparing the alternatives of investing in plan A or not; one could also consider investing in Plan A now versus investing in Plan A later; or investing in a smaller version of Plan A. Fundamentally then, Real Options can be seen as equivalent to sources of managerial flexibility. Typical examples include the ability of a decision maker to acquire new assets, to expand, contract or abandon operations, to switch between different production lines, to invest in research and development, or to delay a decision while gathering additional information.

When framed in this way, it should be obvious that Real Options are in fact typically already present in most capital investment decisions. Thus, the development of Real Options did not so much change what asset managers were already doing, as it drew attention to this flexibility and provided a quantitative framework to take into account explicitly the added value of this flexibility in investment decisions (Dixit and Pindyck, 1994). Prior to this, these existing flexibilities were typically not included in the valuation estimates of different projects, meaning that more flexible project alternatives were relatively undervalued when compared to more traditional, less flexible alternatives.

3. From Real Options to Engineering Options – proactively seeking flexibility in the design of technical systems

As described above, within Real Options, the focus is primarily on highlighting and accounting for managerial flexibilities that are already available to asset managers. However, there is little explicit consideration of methods to expand actively the array of options available to system managers. Nor is any attention paid to technical considerations that may be central in exercising a specified Real Option: for instance, if managers decide to heighten a floodwall because sea level is rising faster than anticipated, does the existing floodwall design in fact allow for easy expansion? Would a different design have made expansion quicker and easier? Real Options theory has ignored details of the underlying physical asset, treating this technical system as a black box. However, from an engineering standpoint, when dealing with infrastructural assets, it is plausible that treating the technical system as a black box ignores potentially valuable sources of flexibility: what if one could relatively easily expand the pumping capacity of a pumping station if external conditions suggest such an expansion is necessary? Clearly, considering technical features of the physical system could provide additional elements of flexibility in the system, over and above the managerial flexibility already present. Recognizing this opportunity, the core ideas of Real Options were first applied to the design of infrastructure systems in the early 2000's (e.g. Ford *et al*., 2002; Ho and Liu, 2003; Zhao and Tseng, 2003 and Zhao *et al*., 2004), looking explicitly at searching for and incorporating flexibility into the physical design of a structure.

This distinction between traditional Real Options applied to managerial flexibility within capital investment decisions and options as applied specifically to the planning and design of infrastructure was first described by de Neufville in 2002. Wang and de Neufville (2005) first titled these as Real Options "on" systems and Real Options "in" systems respectively. However, this nomenclature using "on" and "in" has been met with widespread confusion and misuse. In an attempt to differentiate these more clearly, the distinction is now made between Real Options versus Engineering Options (R. de Neufville, personal communication, September 2016):

a) **A Real Option** is the right but not the obligation to change the course of an infrastructural investment project in the face of uncertainty, *treating the physical system as a black box and a fixed entity*. This ability to change a project is derived from external *managerial flexibility/options*.
b) **An Engineering Option** is the right but not the obligation to change the course of an infrastructural investment project in the face of uncertainty, where the ability to change a project comes from the interaction between both external *managerial flexibility/options and physical flexibility/options embedded within the technical design of the infrastructural system*.

Table 3.2 summarizes these primary conceptual differences, with the distinctions well illustrated by comparing two recent studies. A good example of a Real Options analysis can be found in Linquiti and Vonortas (2012). They evaluate the economic costs and benefits of heightening coastal flood defenses according to a pre-determined (i.e. inflexible) schedule as compared to heightening flood defenses according to a more flexible schedule that responds to actual external changes in sea level (i.e. the option to delay/bring forward investment). This is an application of Real Options, not Engineering Options, because while there is inclusion of different managerial options in time, there is no consideration of any physical options in the form of technical aspects of the problem e.g. which engineering design decisions would enable efficient heightening later on? In contrast, Woodward *et al*. (2014) conduct a comparable study, looking instead at Engineering Options. They too evaluate the costs and benefits of heightening a levee in response to climate change. They compare not just different heightening schedules (i.e. managerial options), but also different technical designs, some of which have physical options embedded in them e.g. a levee with an over-dimensioned base that can support a height addition later on. Consideration of this kind of structural option provides insights about sources of structural flexibility add value to the system as a whole.

Table 3.2: Summary of conceptual differences between Real Options and Engineering Options

Real Options (Real Options "on" a system)	**Engineering Options** (Real Options "in" a system/Flexibility in design)
Formalized in **1970's**	Developed in **2000's**
Focus on flexibility in **capital investment decisions** e.g. to heighten this existing levee now or later?	Focus on **infrastructural design and planning decisions** e.g. given the possible need to heighten this levee in the future, what physical options could I include in my initial design now?
Method highlights **existing** flexibility i.e. draws attention to actions that asset managers routinely perform, but were never before identified as sources of flexibility, nor included in valuation estimates	Method seeks new ways to **proactively build in flexibility** up-front i.e. explicitly seek out and evaluate which options to include in a design, given the many possible future developments
Primarily an **improved accounting system**, that captures the value of managerial flexibility	A **new design paradigm**
Treats **technical system as black box**	Explores **flexibility that can be built into the technical system itself**, hence cannot treat technical details as black box
Sources of flexibility derived mainly from **managerial options**	Sources of flexibility derived both from **managerial options as well as physical options**

The key take-away point from this introduction to Options Theory is that while related conceptually, each of these three types of options apply to different investment questions, focusing on assets with different characteristics, and as described below, must be evaluated using the appropriate valuation methods.

3.2.2 Introduction to options analysis

In general, options analysis focuses on quantifying the value of different options. The generic steps of conducting Engineering Options analysis, as developed by de Neufville *et al*. (2006) and Deng *et al*. (2013) are:

- build a baseline model and run preliminary deterministic analyses to help understand those system components that centrally influence performance
- conduct uncertainty analysis to identify and characterize those sources of uncertainty that most impact system performance
- incorporate the uncertain parameters into the baseline model and conduct Monte Carlo simulation to assess system performance under diverse futures
- generate candidate flexible design alternatives
- evaluate the flexible designs by conducting simulation using the previously developed model in combination with decision rules that trigger when an option should be exercised
- compare the performance of the traditional and flexible designs: the added value that comes from the incorporation of Engineering Options in the system can be estimated using Value of flexibility = Value $_{\text{flexible variant}}$ – Value $_{\text{traditional design}}$
- conduct sensitivity analysis

Just as Section 3.2.1 needed to introduce financial options and Real Options in order to differentiate them conclusively from Engineering Options, so too Textbox 7 describes why existing Real Options valuation techniques are not suited to Engineering Options analysis, providing the rationale for why the approach described above was developed.

Textbox 7: Why options and Real Options valuation methods do not apply to Engineering Options

A substantial literature has been dedicated to the development of options valuation methods for both financial options (e.g. Black and Scholes, 1973; Boyle, 1977; Cox *et al*., 1979; Merton, 1973 and Schwartz, 1977) and Real Options (e.g. Amram and Kulatilaka, 1999; Copeland and Antikarov, 2001; Dixit and Pindyck, 1994 and Trigeorgis, 1996). However, Wang and de Neufville (2004) explain that the existing options valuation methods are not suitable for evaluating different courses of action and valuing flexibility when looking at Engineering Options. There are a number of conceptual reasons for this.

- First, traditional options analysis seeks to determine an accurate monetary value for an option, thereby identifying the maximum that one should be willing to pay to purchase an option. In contrast, Engineering Options Analysis strives to compare different designs, identifying the best design and implementation strategy for a technical system. This means that a precise value is less important for Engineering Options Analysis, with more emphasis placed on the relative performance of different alternatives. Furthermore, Engineering Options need not be limited to monetary considerations, with other objectives such as reliability or the risk of failure being more important that cost alone.

- Furthermore, traditional options analysis operates in an environment where market uncertainty is the predominant source of uncertainty. Market uncertainty can typically be estimated with some degree of accuracy from existing data, quantifying for instance, the volatility of an asset. By contrast, Engineering Options analysis is influenced by a much wider range of uncertainties, including uncertainty in natural conditions, market developments and technological advances, all of which are much harder to quantify and characterize.

- Additionally, existing valuation techniques are simply not equipped to incorporate technical considerations. As introduced above, Real Options treat the physical system as a black box. The fundamental development of Engineering Options is that flexibility in the technical structure is also considered; hence, it is obvious that existing methodologies that do not consider these technical aspects are unsuitable for evaluating Engineering Options.

- Finally, financial options are path independent, meaning that the value of an option only depends on the current stock price, and not on historic changes in the stock price. However, development of physical systems is fundamentally path dependent: historic decisions and external factors have implicitly shaped the infrastructure present, which in turn affects the possible options going forward. Existing Real Options analysis techniques are unable to capture these path dependencies.

3.2.3 Why are Engineering Options suited for this work?

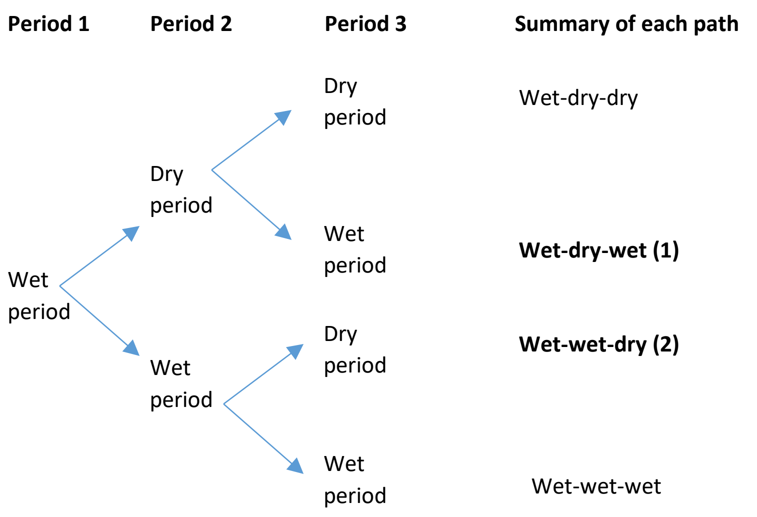
As previously introduced, this dissertation develops a novel flood management infrastructure planning approach, as explored through the lens of replacement planning for aging hydraulic structures. It does this by applying the core concepts of Engineering Options Theory to this question of long-term infrastructure planning under uncertainty. There are a number of reasons why an Engineering Options framework was selected for inclusion in the new approach developed here:

- An Engineering Options approach to infrastructure investment allows one to expand actively the decision space of possible alternatives under examination. It does this by explicitly seeking more flexible variants of traditional courses of action. Such sources of flexibility are crucial in designing a next generation of infrastructure that is adaptable to evolving future conditions.

- A key characteristic of Engineering Options that differentiates it from most other long-term planning techniques in use today is its proactive nature to coping with uncertainty. All the approaches previously presented in Section 2.3 are to some extent adaptive approaches as they acknowledge the ever-changing and uncertain future any decision faces. However, the Engineering Options approach is unique in that it squarely faces the question of balancing costs now versus possible benefits later, providing guidance as to which elements of an adaptive plan should be undertaken now. Hence, while most of the other approaches are proactive in their consideration of what we may need to do in the future, this method is able to answer the question of which proactive preparatory investments we should actively undertake in the present day.

- Flood management systems are complex technical systems, with many design variables. Thus, both managerial and physical options may exist, and it is likely that treating the physical system as a black box ignores important sources of flexibility that can be derived from the design of the physical structure itself.

- Structures within a flood management network exhibit significant path dependency. Different possible future replacement strategies are intrinsically dependent on past decisions, because the physical characteristics of the existing infrastructure system dictate to some extent the spectrum of new strategies that can be considered. For example, when looking at a physical flood management system, the ability of the system to manage different flood magnitudes in the future depend on the historic occurrence of floods in previous time periods, because the size and timing of historic floods may have resulted in changes being made to the physical system itself. For instance, if an extended very wet period was experienced previously, the flood management system may have been expanded physically to cope with these high flood magnitudes. In the subsequent dry period, the range of management decisions available to system managers is different than if the preceding period had been variably wet and dry and no system expansion had taken place. Fundamentally then, the feasible set of decisions and thus the value of different options depends on historic evolution of the system. Figure 3.5 demonstrates this.



The range of alternatives available after two wet periods (e.g. **(2)** on adjacent figure) are not necessarily the same as after a wet and a dry first and second period (e.g. **(1)** on adjacent diagram), as changes may have been made to the construction of the physical system after two particularly wet periods.

This means that the decision possibilities at each stage are dependent on the path taken to get to that stage. This means that

wet-dry-wet ≠ wet-wet-dry

Path (1) ≠ Path (2)

Figure 3.5: Decision tree illustrating path dependency

For these reasons, this Engineering Options approach lends itself well to inclusion within a long-term planning framework that integrates different drivers of investment and is proactive in its treatment of uncertainty.

3.2.4 A review of the existing options literature

A review of the existing literature shows thousands of published works focusing on Real Options. The vast majority of these publications focus on application areas where market uncertainty is of primary concern. The body of work looking at uncertainty in natural processes (e.g. climate change) is more recent and much smaller, with only a handful of applications looking specifically at flood management. Of these, an even smaller number incorporate technical considerations (i.e. Engineering Options), so as to provide any meaningful conclusions about design and planning questions. This demonstrates that the application of Engineering Options to planning questions in the flood sector is still very much in its infancy. While Real Options has become very much a buzzword, especially in climate adaptation circles, there are in fact very few publications to fall back on in terms of demonstrating a systematic and replicable procedure to apply Engineering Options to the specific features of flood management investment problems.

A review of the academic literature

Conducting a customary search[29] of the existing academic literature shows several thousand published works focusing on Real Options. This is not unexpected given that this field has been around since the 1970's. Early work by Myers in 1977 and subsequent methodological advances by among others Dixit and Pindyck (1994) and Trigeorgis (1996) are interspersed with increasing numbers of articles focusing on new applications, replicating the central concepts of Real Options in new contexts. From mining operations (e.g. Brennan and Schwartz, 1985) and petroleum projects (e.g. Steinar, 1988) to forestry management (e.g. Clarke and Reed, 1989) and renewable energy sources (e.g. Boomsma *et al.*, 2012), a large portion of applications focus on the fields of resource economics and environmental economics. As Figure 3.6 shows by summarizing the high-level findings of this review, Real Options related publications have consistently

[29] Searches were conducted using Web of Science.

exceeded the triple digit mark annually since the early 2000's, indicating continued research interest in adapting and applying these methods.

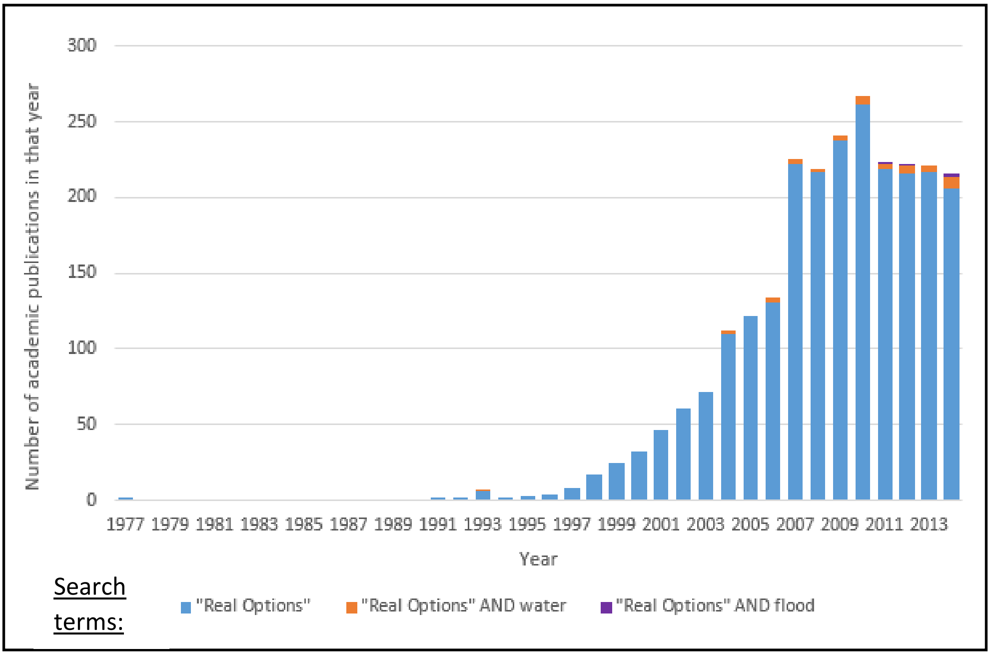


Figure 3.6: Summary of academic literature review- number of publications by year, focusing on specific Real Options[30] application areas

Looking specifically at water resource-centered applications, the first use of Real Options was conducted in 1993 by Michelsen and Young, who examined the benefits of using option contracts to transfer water from agricultural to urban areas during drought situations. Over time, much further work was conducted on the use of options in situations of water scarcity by Lund and Israel (1995), Jercich (1997), Howitt (1998), Gomez Ramos and Garrido (2004), Characklis *et al*. (2006), Brown

[30] When conducting these literature review searches, "Real Options" was one of the search terms used. The results shown in Figure 3.6 include both applications of Real "on" Options as well as Real "in" Options (i.e. Engineering Options). Closer examination of the results indicated that the vast majority of the publications presented in Figure 3.6 are applications of Real "on" Options, with only a handful of post-2000 studies incorporating both managerial flexibility and physical options.

and Carriquiry (2007), Kirsch, *et al*. (2009), Palmer and Characklis (2009) and Davidson *et al*., (2011). It is likely that this increased research activity was partially due to the impacts of a multi-year drought in California from 1987 to 1991 and the Millenium Drought experienced in Australia from 1995 to 2009. In the subsequent decades, the core options concepts were progressively expanded and applied to a variety of new water-specific application areas, including

- investment in water conserving irrigation technology (Carey and Zilberman, 2002; Seo *et al*., 2008; Heumesser *et al*., 2012)
- hydropower planning (Wang, 2005; Kjærland, 2007; Bockman *et al*., 2008; Martínez-Ceseña and Mutale, 2011; Ottoo, 2012; Baker *et al*., 2014)
- irrigation reservoir construction (e.g. Michailidis and Mattas, 2007; Michailidis *et al*., 2009a; Michailidis *et al*., 2009b)
- water trading markets (Cui and Schreider, 2009; Weber and Tomkins, 2010; Wheeler *et al*., 2011; Truong, 2014)
- water supply systems, both urban (Zhang and Babovic, 2009; Zhang and Babovic, 2012) and industrial (Suttinon and Nasu, 2010; Suttinon *et al*., 2012)
- urban water distribution systems (Huang *et al*., 2010; Marques *et al*., 2014a; Marques *et al*., 2014b, 2015a, 2015b and 2015c)
- urban drainage infrastructure (Gersonius *et al*., 2010, 2013 and 2015[31]; Eckhart, 2012; Deng *et al*., 2013; Park *et al*., 2014)

[31] One may observe the occurrence of terms such as "flooding system", "flood risk infrastructure" and "flood risk management" in the titles of these works by Gersonius *et al.* This may lead one to believe that these references are in fact misclassified and should have been presented in more detail in the subsequent section that explores the use of options in flooding applications. The flooding referred to in these works is restricted to urban flooding, with the analysis conducted focusing on the adequacy of urban drainage facilities such as sewers and underground conduits. While there is no denying that urban flooding due to insufficient capacity of the urban drainage system is a form of flooding, this work focuses on a larger, more regional scale of flooding. Instead of emphasizing high probability-low consequence events such as urban flooding, the focus here is on lower probability-higher

- reservoir management (e.g. Steinschneider and Brown, 2012)
- and river basin planning (Jeuland and Whittington, 2014)

It is unclear to what extent this research effort ultimately materialized into concrete changes in water resources planning approaches.

Within this relatively small body of work (as of 2015, the total number of academic publications focusing on applying options to water resource applications remains on the order of fifty – see Figure 3.6), specific consideration of flood management issues first emerged in 2010. As shown on Figure 3.6, there have only been a handful of flood-focused publications in total. As this sub-field is most directly relevant to this work, these publications are explored in some detail below, in contrast to the broad overview provided above. Accordingly, the paragraphs below provide a detailed exploration of all the existing academic publications to date in which any kind of options approach is taken to assess flood management investment questions. This section first provides a summary of these works, with a critical review and discussion of shortcomings provided in the next section below. This is the result of a systematic and comprehensive literature search and is presented as representative of the most advanced, and currently best available work looking at the application of options theory to flood management decision making under climate change uncertainty.

- The first attempts to apply options concepts to flooding problems originated, perhaps not surprisingly, from the Netherlands. While not referred to as options explicitly, Hoekstra and De Kok (2008) explore the economic performance of different dyke heightening strategies given uncertainty in

impact events, including coastal and river flooding. For this reason, the work presented by Gersonius *et al.* is considered less relevant within the context of this dissertation and no further detail is provided about these specific works.

future sea levels. In this work, they consider two different dyke investment strategies. The first is consistent with the approach currently used to size dykes in the Netherlands and is termed the probabilistic design. Predictions are made about the magnitude of flood events associated with a certain return period and dykes are sized to be able to withstand a flood event of this size. The second is called the self-learning dyke, which is representative of an older approach used before planners had sufficient modelling capabilities to conduct probabilistic analyses. This strategy involves dykes being incrementally raised to be always higher than the most recent high water level recorded. While this work is comparing the newer, widely used probabilistic approach to the self-learning design used in the past, the analysis conducted has strong parallels with options analysis. The results provide valuable insights about option value and flexibility, given that the self-learning dyke embodies managerial flexibility in the form of the option to invest at different moments in time, depending on external developments. They consistently find that the costs associated with the more flexible self-learning dyke are lower as compared to the less flexible approach which sees large dyke heightenings occurring at pre-specified times.

In a departure from their earlier referenced core work focused on urban drainage systems (i.e. Gersonius *et al*., 2010, 2013 and 2015), Gersonius *et al*. (2011) also examined levee/dyke raising strategies, where they compared levee/dyke raising to the alternative flood protection measure of sand nourishment of the Dutch coast. In their analysis, they treat sand nourishment as the more flexible strategy because sand can be added to the beach more easily, more frequently and in any size increment as compared to the less flexible heightening of a levee/dyke, which has historically been done infrequently, and in large increments. Again, they concluded that a more flexible strategy has lower net present costs overall when compared to a more traditional “build big and build once” approach.

Van der Pol *et al*. (2015) also reference options in the context of investment in adaptation measures for flood risk infrastructure. They present the beginnings of a conceptual framework that could be used to identify the value of learning in adaptation planning, and draw on options valuation techniques to do this. Given that this framework is a simple extension of a generic CBA and no further fleshing out or application of this framework is provided, this paper is mentioned here for completeness sake only but is not discussed any further here or in the more detailed review below.

- Almost simultaneously to these Dutch efforts, researchers in the United Kingdom were also applying options to flood management problems in the context of the Thames River Estuary. Woodward *et al*. (2010 and 2011) and Woodward *et al*. (2014) explore different levee/dyke-raising strategies, given uncertainty in future sea level rise. At present, this represents the only progressive research done in this field, as opposed to the other research efforts presented here which appears to be one-off explorations by the relevant researchers. Woodward *et al*. consider both managerial flexibility in the form of the option to delay investment in heightening the levee/dyke, as well as physical flexibility that comes from purchasing land adjacent to the levee/dyke, providing the option to easily heighten the dyke in the future. (Levee/dyke heightening requires widening of the base to maintain fixed height to width ratios for maximum dyke stability). They found that flexible strategies performed better than inflexible ones and in addition, that strategies which took into account both managerial and physical options performed better than those that only considered managerial flexibilities.

More recently, Hino and Hall (2017) conducted similar work in the context of floodplain management. They too explored fixed investments in levees versus options such a levee that can be heightened, or the purchasing of flood-prone land on which further development is foregone.

- Among United States-based researchers, there have been only two isolated attempts to examine options and flood infrastructure planning. The first is by Linquiti and Vonortas (2012), who examine different flood barrier heightening strategies in Bangladesh and Tanzania, considering uncertain sea level rise and uncertain future flood damages. They take into account managerial flexibility in the form of the option to delay investment. Contrasting slightly to the previously referenced findings by Gersonius *et al*. and Woodward *et al*., Linquiti and Vonortas found that flexibility added value in most, but not all, of the cases they examined. Fundamentally, this lower-than-expected economic performance of flexible course of action in some of their analyses was a side effect of the choice of discount rate. They conducted all of their analyses using two different discount rates (3% and 7%), in order to explore the sensitivity of results to the specific choice of discount rate. At the higher of the two discount rates, flexibility generally did not yield sufficient short-term benefits to offset additional up-front costs. These findings rightfully highlight that while flexibility does intuitively appear to be desirable, the computed value of flexibility can vary greatly depending on the specific parameters used, such as the discount rate. This issue is revisited later on in Chapter 4 and 5 of this dissertation.

  The second study is by Cunya *et al*. (2014), who explore investments in generic river flood control structures given uncertain river discharge volumes. They incorporate the option to delay investment, and provide a theoretical demonstration of their proposed technique using a hypothetical case study.

They found that delaying investment has value, up to a certain maximum number of years.

- Finally, there is one study from researchers based in Greece that apply options in the context of climate change-induced coastal flooding (Kontogianni *et al.*, 2013). They look at different moments of investing in coastal flood protection against sea level rise. Again, they take into account managerial flexibility in the form of the option to delay investment. Consistent with the majority of findings described above, they too found that flexibility to delay added value in all, of the cases they examined.

The central take-away point from this review so far, is that despite its relatively long history and diverse applications, the adaptation of options thinking in the form of Engineering Options to flood management and in particular, to flood management given uncertain impacts of climate change is still in its infancy, with only a handful of publications having attempted to explore this field. For ease of reference, these central publications and key aspects of the research they describe are summarized in Table 3.4 at the end of this section.

Some things to notice in the academic literature

The previous section presented a progressively more detailed look at the various sub-sections of the existing options literature. While this previous section was written to be comprehensive, objective and factual, this next section attempts to provide a critical review of the most relevant portions of this literature, highlighting a number of important trends, observations and shortcomings.

- <u>The predominance of Real Options and the relatively rare consideration of Engineering Options</u>

In the vast majority of publications shown on Figure 3.6, the focus is typically only on managerial options, with no attention paid in these works to technical options or questions of design (Engineering Options). This is not surprising given that chronologically speaking, Engineering Options is a much newer, less developed field compared to traditional Real Options.

Given that the first application of Real Options concepts to flood management (i.e. in 2010) post-dates the creation of the concept of Engineering Options (i.e. in 2005) one could perhaps expect that the existing body of flood-infrastructure-focused Real Options literature includes both managerial and physical options. However, looking more closely at the current state-of-the-art flood management applications presented in the previous section and in Table 3.4 below, the predominant focus remains on managerial options, with an almost universal emphasis placed on quantifying the value of delaying investment. The works of Gersonius *et al*. (2011), Linquiti and Vonortas (2012), Kontogianni *et al*. (2013) and Cunya *et al*. (2014) demonstrate this: they all use a Real Options framework to explore the added value that comes from being able to phase or delay investments in flood protection infrastructure in light of climate change uncertainty.

The single exception to this trend is the work of Woodward *et al*. (2010 and 2011) and Woodward *et al*. (2014). In addition to considering managerial flexibility in the form of the option to delay investment, they also consider physical options, specifically the flexibility that comes from purchasing land adjacent to a levee/dyke, as well as a levee/dyke design that has a larger than currently necessary base area. Both of these physical options facilitate easy levee/dyke heightening in the future, and this joint consideration of both managerial and technical design options makes this an application of Engineering Options. This work by Woodward *et al*. is thus unique within the flood infrastructure realm for its explicit integration of technical design choices and physical options with the more well established notion of managerial flexibility.

So why does it matter, that with the exception of this work by Woodward *et al*., physical options in the form of technical design considerations have so far been largely ignored in the field of flood infrastructure planning? Results presented in Woodward *et al*. (2014) demonstrate that investment strategies that took into account both managerial and physical options performed better than those that only considered managerial flexibilities. Thus, these findings suggest that ignoring physical options is ignoring likely valuable sources of flexibility "in" structures. In addition to these results, given the fact that most flood management systems are founded on a backbone of large-scale structural measures, it would simply appear logical to explore questions of smart infrastructure design when seeking to increase the degree of flexibility in these physical systems. Ray and Brown (2015) would appear to agree when they conclude that the type of options present in "most water resource engineering design problems are of the latter type" (i.e. options "in" the physical system).

Shortcoming: There has been very limited consideration of physical options in flood management planning so far, and what little work has considered these suggests that they can add additional value, over and above managerial options.

- <u>The progression from market uncertainty to natural uncertainty, and how that uncertainty is treated</u>

A second important trend to note here is that in the vast majority of publications examined, market uncertainty, often in the form of uncertain commodity prices, is the primary source of uncertainty taken into account in the respective analyses. This is perhaps easily explained given the roots of this methodology in finance and economics. In the majority of the water sector applications summarized above, this primary source of uncertainty typically takes the form of uncertain future water prices, uncertain future demand for water, uncertain crop yields resulting from irrigation, or uncertain electricity prices when selling hydropower. This kind of market uncertainty is relatively easily described and modeled using previous records of prices, and measures such as volatility and standard deviation.

However, when focusing on water resource applications, especially in the context of climate change and adaptation planning, by the very nature of the problem, uncertainty and increased variability in natural processes should take center stage. Thus, in applications of this kind it is difficult to justify focusing only on market uncertainty, entirely eliminating or ignoring all sources of uncertainty from natural processes. Hence, looking more closely at these publications, one can identify a gradual progression and increase in sophistication in the best-documented techniques used to incorporate natural uncertainty in the analysis. Note that this progression does not follow a clear chronological sequence where all publications past a certain date consider uncertainty in a certain way. Instead, while treatment of uncertainty remains varied, the most advanced individual studies demonstrating the most sophisticated incorporation of uncertainty have evolved over past decades:

Phase 1: Sources of natural uncertainty are simply ignored

The simplest way of dealing with sources of natural uncertainty, such as rainfall or sea level is to simply exclude them from any analysis. This has been done in a number of different ways. Kjærland (2007) and Baker *et al*. (2014), for instance, treat reservoir inflows as fully deterministic within a given season. Others factor them out of the analysis using assumptions. For instance, Michailidis and Mattas (2007) and Seo *et al*. (2008) eliminate uncertainty in rainfall by assuming that there are unlimited quantities of water available, such that water availability cannot be the limiting factor in the economic success of the irrigation schemes being examined. Suttinon and Nasu (2010) focus on water supply planning and eliminate uncertainty in rainfall by assuming that all supply sources together are enough to meet all future demand, and that it is just a question of which infrastructure to invest in to exploit which specific sources.

Phase 2: Natural uncertainty is included in the form of stationary probability distributions based on historic data

One level more sophisticated than simply ignoring hydrologic uncertainty, are those works that incorporate uncertainty in natural processes, using historic data as an indication of the range future values could conceivably take on. This has been done in a number of different ways in the existing literature, ranging from stochastic synthetic streamflow generation using past streamflow measurements by Michelsen and Young (1993) and Cunya *et al*. (2014) and sampling from historic precipitation datasets by Deng *et al*. (2013), to lognormal distributions of river flows by Wang (2005) and gamma distributions of water storage in a reservoir by Michailidis *et al*. (2009a and 2009b).

Phase 3: Attempts are made to capture the impacts of non-stationarity in natural processes

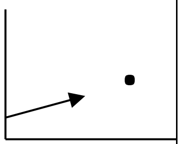
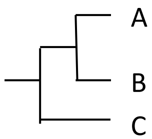
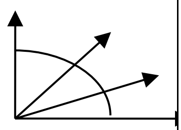
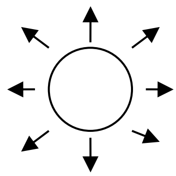
As discussions about climate change and the likelihood that climate change was creating non-stationarity in natural processes began to take center stage, treatment of uncertainty again showed a gradual transition. It was no longer sufficient to simply incorporate natural variability in the form of historic data or fixed probability distributions, researchers began to seek ways to incorporate long-term non-stationarity in their analyses of uncertainty. Linquiti and Vonortas (2012) treat future global sea level rise scenarios as being normally distributed. Gersonius *et al*. (2010), Gersonius *et al*. (2011), Gersonius *et al*. (2013), Gersonius *et al*. (2015),Woodward *et al*. (2010), Woodward *et al*. (2011) and Woodward *et al*. (2014) all put considerable effort into capturing stochastic variation as well as long-term trends in their scenarios of future rainfall intensity and sea level rise, and then treat all these scenarios as being part of a uniform distribution, with each having equal probability of occurrence.

Phase 4: Attempts are made to capture both the impacts of non-stationarity and the deeply uncertain nature of natural processes

Recent years have seen a growing body of work (e.g. Grubler and Nakicenovic, 2001; Kandlikar *et al*., 2005 and Hallegatte *et al*., 2012) that makes the case for climate change and its impacts to be treated as a source of deep uncertainty. By definition, deep uncertainty indicates that there is neither agreement about the magnitude of change nor the likelihood of different change scenarios occurring. This growing movement has resulted in substantial, albeit largely verbal, criticism of the assignment of probabilities to deeply uncertain conditions, such as future climate change scenarios. While most of the current state-of-the-art options flood applications (summarized in Table 3.4) do take non-stationarity and climate change into account, few have provided a satisfactory alternative to simply assigning fundamentally arbitrary probabilities to future scenarios. The exception to this is the work by Kontogianni *et al*. (2013) who utilize distinct scenarios for those parameters that are considered deeply uncertain, and conduct simulation of other uncertain parameters within each of these scenarios.

This review of the progression of how uncertainty is treated in the options literature to date shows distinct similarities with the classification of uncertainty proposed by Walker *et al*. (2003) and shown in Table 3.3 below. The bulk of the literature presented above dealt with Level 1 uncertainty, where natural processes were simply assumed to be deterministic and thus eliminated from further consideration. In the last five years, studies have begun to appear where natural uncertainty is treated probabilistically, consistent with Level 2 or 3 uncertainty. Further work remains to be done to explore how natural uncertainty can be adequately captured when we assume Level 4 applies and we are faced with so-called “unknown unknowns”.

<u>Table 3.3: A classification of progressive levels of uncertainty</u>
(Source: Walker *et al.*, 2003)

Determinism		**Level 1**	**Level 2**	**Level 3**	**Level 4 (Deep Uncertainty)**	Total ignorance
	Context	A clear enough future 	Alternate, trend-based futures 	A limited set of plausible futures 	Unknown future 	
	System Model	A single system model	A single system model with a probabilistic parameterization	Alternative system models, with different structures	Unknown system model; know we don’t know	
	System Outcomes	A point estimate and confidence interval for each outcome	Several sets of point estimates and confidence intervals for the outcomes, with a probability attached to each set	A known range of outcomes	Unknown outcomes; know we don’t know	
	Weights on outcomes	A single estimate of the weights	Several sets of weights, with a probability attached to each set	A known range of weights	Unknown weights; know we don’t know	

Shortcoming: So far, incorporation of climate change impacts into options analysis ignores the difficulties associated with assigning probabilities to future climate scenarios. Is it possible to incorporate deeply uncertain variables without known probability distributions within options analysis?

- <u>The limited scope of the current state-of-the-art flood management applications</u>

This third and final observation focuses on the scope of the current body of work that applies options techniques to flood management applications. Looking in more detail at the current state-of-the-art presented in Table 3.4 below, all of these publications to date focus on only one specific flood management infrastructural application area, namely flood barriers in the form of levees/dykes (e.g. Hoekstra and De Kok, 2008; Gersonius *et al*., 2011; Woodward *et al*., 2010 and 2011, Woodward *et al*., 2014; Linquiti and Vonortas, 2012). Results, as presented in Table 3.4, indicate that in most cases, a flexible approach does appear to out-perform more rigid traditional alternatives, which is promising for further research in this area. However, there are a number of reasons why it may be advisable to take these early positive results and focus on developing these ideas for application to flood management structures other than levees/dykes.

Firstly, levees/dykes consist of relatively uniform linear units, with these structures typically treated as having only one function, namely a flood management function. Within all of the previous work conducted, analyses were conducted by representing a levee system as a network of homogenous linear units, with the focus being primarily on making decisions at the network scale, identifying when and where to invest within the network. Acknowledging that levees/dykes do indeed form the backbone of many flood management systems in existence today, they are by no means representative of the diversity and complexity of all structural components of these systems. Reducing these networks to a simple series of levees ignores many other important components. Thus, for these findings to be of more practical relevance, it is necessary to explore their applicability when considering more technically complex, multi-functional structures. Hydraulic structures, typically located at the junction of different levees could be a sound next step. These are usually one-of-a-kind non-linear structures that are more technically complex and expensive than levees and often fulfill multiple functions such as shipping or irrigation, in addition to flood protection alone. Given that these structures are more technically complex, this may also provide more opportunity to identify a broader range of physical options within the structure to explore.

In addition, hydraulic structures are increasingly becoming an area of concern, because, as introduced in Chapter 1, the bulk of these structures are approaching the end of their useful life, and it will become critical in the coming decades to have an efficient method to structure the replacement/reinvestment process, especially given uncertainties from climate change. Thus, while it remains valuable to explore different adaptation strategies for the levee system already in existence today, the fact that levees undergo a continuous maintenance and renewal process, means that an important variable is not considered, namely the need to renovate/replace certain structures at the end of their useful life. Hence, in the face of an aging stock of structures, adapting existing work done on options to apply to hydraulic structures has the potential to provide valuable insights about how physical options focused on the fulfillment of one function can affect the overall functionality of a structure and how to incorporate flexibility when dealing with multi-functionality.

Shortcoming: So far, there has been very limited consideration of flood management structures other than levees/dykes. How do Engineering Options techniques perform when applied to other components of flood management

systems, especially those that have a more definite end of service life? E.g. more complex, multi-functional flood management structures such as hydraulic structures.

Table 3.4: Summary of published body of work that applies options techniques specifically to flood management problems

Authors	Application	Future uncertainty taken into account	Findings	Considers managerial flexibility? Which options?	Considers flexibility in technical system? Which options?	How is uncertainty taken into account?
Gersonius et al. (2011)	Dyke/levee raising versus sand suppletion along the coast of the Netherlands	Sea level rise	Cost was 6% lower for flexible alternative (sand suppletion) relative to robust alternative (large dyke/levee raising)	☑ Option to delay the addition of further sand to coastal protection dunes		Non-stationarity is taken into account; future sea level rise scenarios are treated as uniformly distributed (Phase 3, as defined above)
Woodward *et al*. (2010); Woodward *et al*. (2011); Woodward *et al*. (2014)	Raising dykes/ levees in the Thames Estuary in the United Kingdom	Sea level rise	NPV was higher for flexible strategy than for inflexible baseline; strategies that took into account both managerial and physical options performed better than those that only considered managerial flexibilities	☑ Option to delay investment	☑ Construct wider than necessary base or purchase land adjacent to dyke/levee, both providing the option to easily heighten dyke/levee in the future	Non-stationarity is taken into account; future sea level rise scenarios are treated as uniformly distributed (Phase 3, as defined above)

Table 3.4 (Continued): Summary of published body of work that applies options techniques specifically to flood management problems

Authors	Application	Future uncertainty taken into account	Findings	Considers managerial flexibility?	Considers flexibility in technical system?	How is uncertainty taken into account?
Linquiti and Vonortas (2012)	Different flood barrier heightening strategies in Bangladesh and Tanzania	Sea level rise; value of existing assets which determine flood damages	No general trend: flexible alternatives only outperform inflexible baseline in certain cases	☑ Option to delay investment		Non-stationarity is taken into account; future sea level rise scenarios are treated as normally distributed (Phase 3, as defined above)
Cunya et al. (2014)	Presents a generic framework to structure flood protection investment planning; no detailed application	River discharge volumes	Hypothetical case study application, hence no concrete results	☑ Option to delay investment		Non-stationarity is not taken into account; historic discharge data is used as representative of future discharge (Phase 2, as defined above)
Kontogianni *et al.*, 2013).	Different coastal flood defense strategies in Greece	Sea level rise; area of land inundated in the future; value of areas flooded	NPV was higher for flexible strategy than for inflexible baseline across all scenarios	☑ Option to delay investment		Non-stationarity is taken into account; future sea level rise scenarios are distinct with no probabilities assigned (Phase 4, as defined above)

A review of the agency-specific grey literature

Focusing on government and agency specific grey literature, there appear to be two peaks in the popularity of the options approach as applied to the water sector.

The first wave of interest started in the late 1990's, as evidenced by publications by the World Bank (e.g. Rios and Quiros, 1995; Holden and Thobani, 1996;), as well as government agencies (e.g. Hafi *et al*., 2006; McClintock, 2009) and the private sector (e.g. Beare and Szakiel, 2007; Borison and Hamm, 2008), particularly those in Australia. Consistent with academic publications during this time, these works focused on addressing issues of water scarcity, examining the role of options in facilitating water trading during droughts, investment in water conserving technologies and development additional supply sources. This early work is focused strictly on Real Options (in the form of options contracts allowing trading of water, as well as flexibility to phase investment in conservation and supply technologies). It appears to have culminated in the development of some fairly detailed and comprehensive water scarcity planning procedures, such as that of the Environment Agency in the United Kingdom (Baker *et al*., 2012).

A second wave of interest appears to have emerged in the last decade, driven specifically by discussions centered on how to create new and adapt existing urban areas and technical systems that are able to cope with a future altered by the impacts of climate change. This is demonstrated by a surge of references to options as applied to the water sector within the climate adaptation literature, particularly within grey literature from

- the World Bank (e.g. World Bank 2009, 2010 and 2011; Hallegatte *et al*., 2012; Scandizzo, 2012; Garcia *et al*., 2014; Kalra *et al*., 2014)
- Organisation for Economic Co-operation and Development (e.g. OECD, 2013)

- government agencies in the Netherlands (e.g. Bos and Zwaneveld, 2014; Schavemaker and Bakker, 2013; Van der Pol *et al*., 2016; van Rhee, 2011 and 2012) and in the United Kingdom (e.g. DEFRA, 2009; HMT and DEFRA, 2009[32])

Some things to notice in the agency-specific grey literature

While these growing numbers of references would suggest this is a fairly well developed area of thought, most of these works refer to options as a potentially valuable method for adaptation planning only, with very few detailed, systematic frameworks or applications available. In addition, there appears to be an emphasis only on the role of Real Options in enabling the delay or phasing of adaptation investments, with no explicit consideration of Engineering Options and the potential added value that could come from incorporating physical options within a structure itself. Thus, while a quick look at available publications may not suggest this, in contrast to the more mature applications of options to water scarcity planning, climate adaptation and flooding applications remain much less well developed.

Overall, the conclusion from this brief review of the grey literature is that options has become very much a buzzword in certain agencies and governments seeking to address climate adaptation planning. However, there are in fact very few publications to fall back on in terms of demonstrating a sufficiently well-developed,

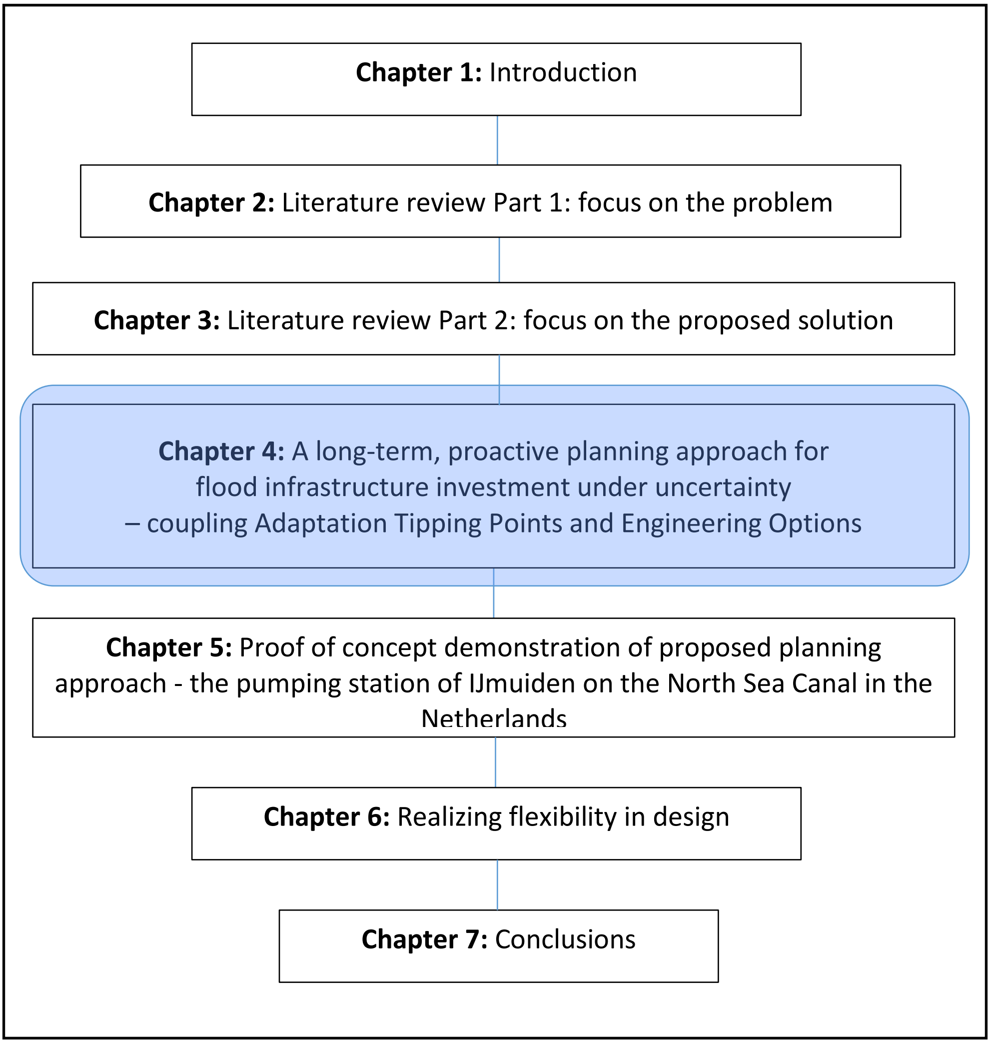
[32] In fact, Her Majesty's Treasury (HMT, the government's ministry of economics and finance) in the United Kingdom has gone so far as to recommend options analysis in a supplementary guidance to their Green Book. The Green Book describes government-issued guidelines that should be used for the economic evaluation and assessment of all government policies, programs and projects. In 2009, further guidance was produced regarding techniques to value climate adaptation projects. Options analysis is presented as a suitable framework to appropriately value flexibility when making adaptation decisions given uncertainty in climate change.

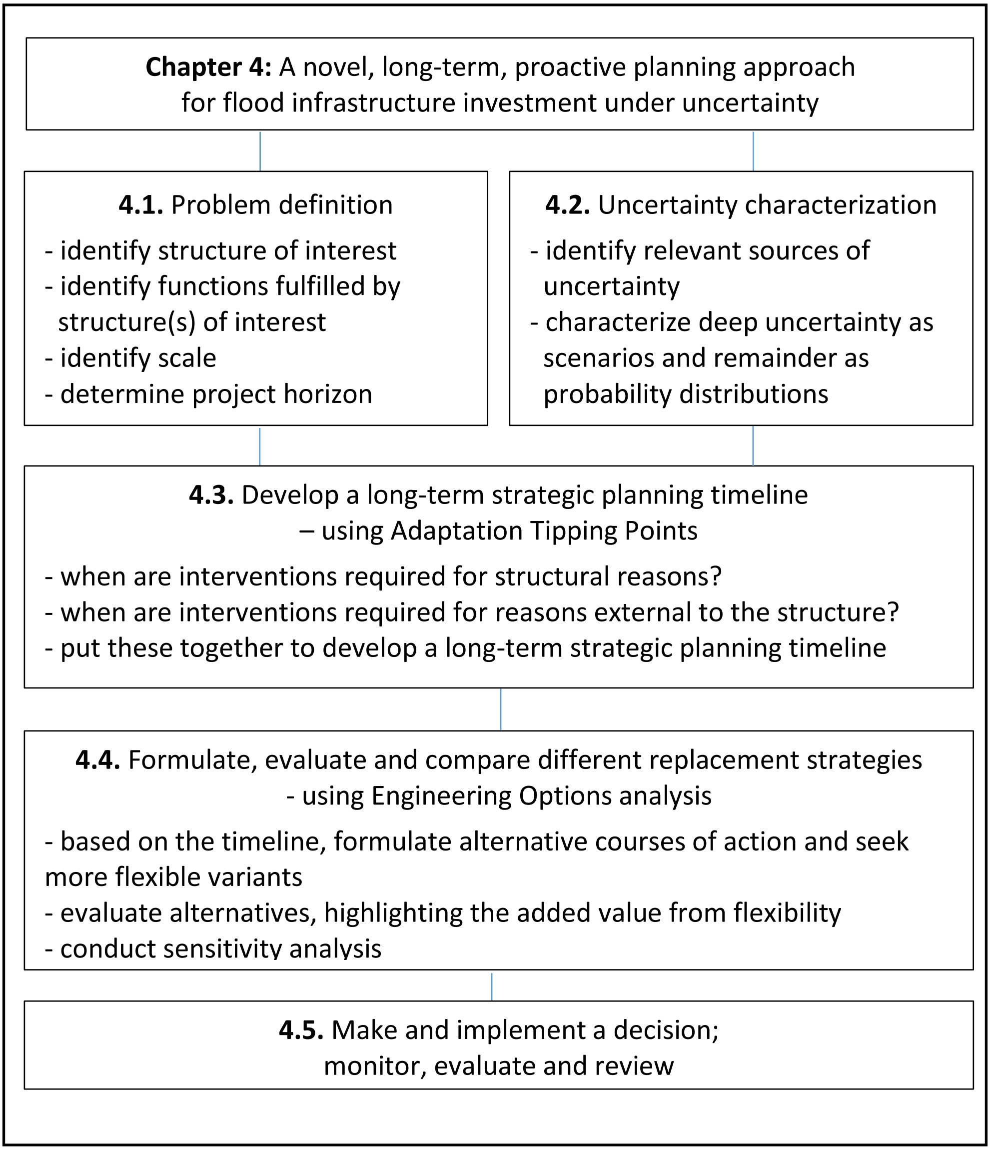
systematic and practically applicable planning procedure that can be used to apply Engineering Options to diverse, real-world flood management investment problems.

3.3 Looking forward: a proposed new integrated planning approach

Chapter 3 introduced two existing techniques, namely Adaptation Tipping Points and Engineering Options. These two approaches form the conceptual basis for the integrated planning approach that this work develops. As described in detail in Chapter 2, this planning approach seeks to address two fundamental and important shortcomings of existing infrastructure planning approaches. Specifically, Adaptation Tipping Points are used as the vehicle by which to incorporate different drivers of reinvention into one single planning framework, while Engineering Options provide a means to operationalize a more adaptive and anticipatory approach to long-term infrastructure planning. This long-term infrastructural planning approach is presented in depth in the following chapter, Chapter 4.

4. **Coupling Adaptation Tipping Points and Engineering Options:** A Novel, Long-term, Proactive Planning Approach for Flood Management Infrastructure Investment under Uncertainty





The previous two chapters presented a review of the existing literature as it relates to the central problem this work explores (Chapter 2) and to the proposed solution developed in this dissertation (Chapter 3). This chapter (Chapter 4) presents details of a novel, long-term, proactive planning approach for flood management infrastructure reinvestment under uncertainty. Novel because it offers the first integration of elements of two existing theories, namely Adaptation Tipping Points and Engineering Options. Long-term because it approaches capital investment decisions in the context of the entire infrastructural life-cycle, rather than simply looking for the strategy with the cheapest up-front costs. Proactive because it evaluates which structural design options that help prepare for possible future adaptation are worth investing in at the outset.

It is comprised of five main steps, with the first two serving a largely preparatory role. The first is a general problem definition step, identifying the structures of interest and their functionalities. Second, the relevant sources of uncertainty are analyzed. The third and fourth steps comprise the primary quantitative core of this planning approach. Rather than simply providing final analytical results at the end, the approach developed here presents results and insights after both Steps 3 and 4, with each offering distinct and important insights about a different aspect of long-term infrastructure planning. More specifically, in Step 3, long-term strategic planning timelines for the structure(s) of interest are derived by using Adaptation Tipping Point analysis. This identifies when structural degradation due to aging or changes in the external operating environment first result in the structure(s) becoming unable to fulfil its (their) performance requirements. Based on insights from this timeline, the fourth step involves formulating possible structural designs and replacement schedules, each with varying sources of flexibility as characterized by different options, and evaluating their performance under a multitude of future conditions. Finally, Step 5 considers the process of actually making a decision, implementing it and setting up an appropriate monitoring and review program.

This new planning approach offers two primary improvements over the current state-of-the-art:

- Through the use of Adaptation Tipping Points, it forms a unified framework that takes into account different drivers of reinvestment, including asset management drivers such as structural degradation, as well as external drivers, such as climate change or socio-economic growth
- By explicitly incorporating elements of flexibility within the design of infrastructure (i.e. Engineering Options), it moves away from the predominant reactive, wait-and-see nature of current infrastructure planning and towards a more proactive planning approach, that is more anticipatory of possible impacts from future uncertainty.

4.1 Step 1: Problem definition

The first step in the proposed infrastructural planning approach is a general problem definition step. This involves identifying the hydraulic structure(s) of interest, exploring the functionalities of these structures, defining the scale of the problem, and determining an appropriate project horizon. The components of this problem definition step are discussed in more detail below.

4.1.1 Structure of interest and its relevant background

Within the context of an aging stock of infrastructure in increasing need of replacement, the default unit of decision making has historically been that of a single hydraulic structure. While subsequent sections of the planning approach developed here will show that a broader, network view is advisable in certain situations, fundamentally, replacement works will be initiated structure by structure, as the need for some kind of intervention becomes obvious for different structures at different times. Thus, as a starting point it is necessary to identify the structural assets of interest, as well as explore the degree to which data, models and other relevant studies exist for these structures. Fundamentally, this step serves simply to become acquainted with the context of the problem.

4.1.2 Functions fulfilled by the structure(s) of interest

Throughout this work, the importance of infrastructure is framed through the lens of functionality. Following the adage of *form follows function,* a structure is constructed in order to fulfil functions that society desires. In other words, the physical characteristics of a structure are only seen as important in so far as they help fulfil a desired function. Thus, having identified the structure(s) of interest, the question of structure replacement is explored by focusing centrally on the continued ability of these structures to fulfil desired new or required existing functionalities. Hence, an exhaustive list of all the functionalities fulfilled by each structure and/or by the network as a whole must be compiled. This could be obtained through consultation with system managers and technical experts. However, given that functionalities evolve over time, involving stakeholders will provide confirmation that the functions for which a structure was designed are in fact the functions it continues to fulfill, or identify whether any functions have been overlooked. An illustrative example is that of a cascade of dams built on the Missouri River from the 1940’s to 1960’s: while originally tasked with joint navigation, flood protection and irrigation functions, they have additionally taken on an important recreational function for local residents.

4.1.3 Scale of the asset management question

When faced with the question of replacing an aging piece of infrastructure, an early practical consideration is one of scale: should the question of asset replacement be approached on a single structure level or is there room for a wider network view of the problem? In this work, the scale of the study is derived directly from the functionalities identified in Section 4.1.2. Figure 4.1 describes how consideration of functionality provides insights about the most appropriate scale of study. For each functionality, the extent to which continued provision of that function is location-bound is evaluated. For instance, the provision of coastal flood protection can only be done at the land-water interface. Thus, when the current structure becomes inadequate, there is no possibility to continue to fulfil this functionality in the future by making changes elsewhere in the network. Hence, a network level analysis is not required for functions that are location-specific. By contrast, when considering the replacement of a pumping station responsible for regional drainage, changes made elsewhere in the network, can influence the ability of the pumping station to continue to function as desired. Thus, for such structures, an analysis at the network level is more appropriate, including proximate structures that are hydrologically connected and fulfil the same function.

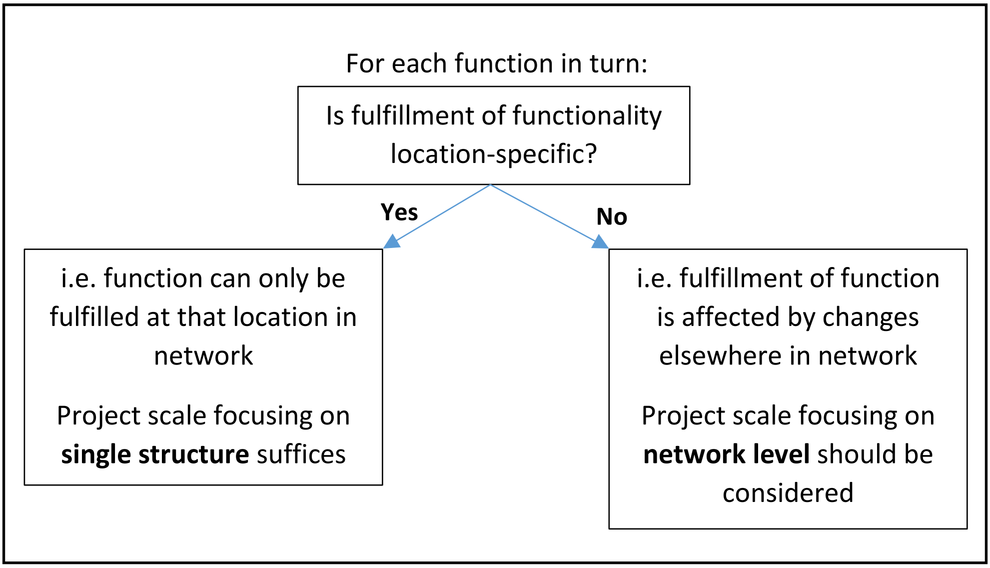


Figure 4.1: Schematic illustrating systematic approach to scale designation

So far, the designation of scale has been entirely driven by physical and functional characteristics of the system. However, in reality, the ultimate designation of scale will likely also be impacted by other more practical considerations such as timing, budget and the nature of the infrastructure manager. For instance, the single structure focus may be more suited to projects later on in the project planning process: if it has already been decided that a specific replacement project will proceed, there is likely neither time nor the necessary budget to zoom back out to the network scale to conduct a network-level analysis of what the best reinvestment strategy is. Furthermore, the focus on a single structure can also be driven by the nature of the stock of assets managed by a particular agency: local infrastructure managers may only have one or a few structures that they are in charge of, thus making a broader scale infeasible. In addition, a single structure focus can also be in response to the conclusion that some form of large intervention is needed at a specific structure, for instance because it was damaged during a flood event or because a structure is visibly displaying signs of advanced structural degradation. By contrast, a broader network scale, focusing on multiple structures is likely more suited to infrastructure investment programs (as opposed to specific projects) that are earlier in the planning process. This could be more easily done by national agencies that are in charge of planning for a large stock of assets (such as Rijkswaterstaat or the US Army Corps of Engineers), or who have the ability to forge collaboration and co-operation between different individual asset managers.

4.1.4 Determine an appropriate project horizon

The length of the project horizon is related to the specific types of structures being considered. The exact length of the project horizon (e.g. 80 vs 85 years) matters less; rather what is of primary importance is that the analysis captures a long enough period that the entire life cycle of a structure is included. Thus, if looking at structures that have an average design life of around 30 years, an initial, *ex ante* user-defined project horizon of 30-50 years is likely appropriate; if looking at longer lived structures that last 80 years for instance, an 80-100 year project horizon is better. While the initial project horizon is defined by the user, its length may be iteratively adjusted based on the predicted timing of Adaptation Tipping Points that emerge from the subsequent analysis described in Section 4.3. For instance, if all Adaptation Tipping Points of interest occur within the first 20 years of a 100-year project horizon, the analysis could consider shortening the project horizon, or explore ways to delay the occurrence of Adaptation Tipping Points.

These project horizons may appear long relative to those currently used in most infrastructure planning: this is consistent with a gradual shift in asset management from focusing only on capital expenditures towards whole life costing in asset management. (Whole life costing attempts to compare project alternatives on the basis of the total cost of ownership, thus preventing investment in a design that is cheap up front but with large hidden recurring costs throughout its lifetime.)

4.2 **Step 2:** Uncertainty characterization

As previously described in Section 2.3, uncertainty in water resources planning has historically been dealt with through the use of historic data sets in combination with wide margins of safety. Within this work, uncertainty takes on a central role and hence a separate portion of the planning approach developed here is dedicated to the characterization of those sources of uncertainty most likely to have an impact in the long-term infrastructural planning timeline. The sources and types of uncertainty defined here serve as a crucial input for the remainder of the analysis presented below, where the impact of uncertain drivers on the lifetime performance of the infrastructure system is analyzed. This step first identifies relevant sources of uncertainty, before classifying them into two separate types, each of which is quantified, modelled and captured in the analysis in a different way.

4.2.1 Determine relevant sources of uncertainty for each function

This step identifies those uncertain factors that influence design decisions and the lifetime performance of the infrastructure system in question. The identification of relevant sources of uncertainty can come from expert consultation, previous analyses, historic data records, or sensitivity tests. While diverse sources of uncertainty affect any given infrastructure project, early screening analyses or expert consultation should be used to focus on those uncertain factors that have the greatest impact on the performance of the asset.

As introduced in Table 3.3 (developed by Walker *et al.*, 2003) uncertainty can be classified into a number of different types, from those situations where there is uncertainty between well-defined alternatives with known likelihoods of occurrence to cases where neither the range of possible outcomes nor the associated probabilities are well characterized. When conducting long-term water resource planning, a number of these different types of uncertainty are typically relevant. For instance, day-to-day precipitation variability may be adequately described by stochastic variables informed by historic precipitation records, while long-term climate change induced increases in extreme precipitation remain much less clearly understood or quantified. Thus, the previously identified sources of uncertainty are characterized into two types, namely those that are considered deep uncertainties for which there is little consensus about the future likelihood of occurrence[33] and those uncertainties that can be modelled stochastically with some confidence. This approach of capturing deep uncertainty and "probabilistic uncertainty" by coupling scenarios with stochastic variables is a pragmatic way of coping with different relevant types of uncertainty. It has been used once before in the water resources planning research by Jeuland and Whittington (2013 and 2014).

4.2.2 For those sources of deep uncertainty, derive future scenarios

Those variables that are determined to be deeply uncertain are captured in the analysis through the use of scenarios. Scenarios are typically used as a qualitative tool to structure "what if" style discussions (e.g. scenario analysis, developed by the RAND corporation in the 1960's, was used by Shell during the 1970's Oil Crisis to explore the company's performance under different futures). Within the planning approach described here, scenarios are treated similarly: as distinct *ex ante* representations of the future, with no attempt made to assign probabilities to the different scenarios. Assigning relative likelihoods to scenarios is difficult, given that a set of scenarios is not typically designed in such a way as to comprehensively cover the feasible space of possible futures. This has important implications for determining the number of scenarios to develop and analyze. While more scenarios offer a more complete view of future possibilities, one needs to be wary of using large numbers of discrete scenarios: large numbers of scenarios complicate visual

[33] The impacts of climate change are a commonly mentioned source of so-called "deep uncertainty". However, the question of assigning probabilities to future climate change scenarios is a particularly controversial topic: while many argue that the state of science and uncertainty about emissions simply does not allow us to reliably derive probability distributions for future climate states, others counter by saying that the lack of assigned probabilities gives non-experts free reign to simply assign their own, less well-informed probability estimates. Some of the arguments for and against assigning probabilities to climate scenarios are presented in Grubler and Nakicenovic (2001), Pittock *et al*. (2001), Schneider (2001), Dessai and Hulme (2004) and Morgan and Keith (2008).

comparison of results and necessitate summary statistics (e.g. ENPV = $\frac{1}{N}\sum_{s=1}^{N} NPV_s$, where there are N scenarios, from 1…s, and NPV_s is the net present value associated with scenario s), which often implicitly places equal likelihood on each different scenarios. Typically, no fewer than two scenarios should be used, with any more than a handful of scenarios becoming cumbersome.

This limit on the number of scenarios in turn impacts the number of uncertain variables that can be considered. For instance, if X uncertain variables are determined to be relevant (e.g. Variables A, B and C), and n scenarios are developed for each (e.g. high and low), there are a total of n^x multi-variate scenarios to be explored (i.e. 8 multi-variate scenarios $\{A_{high}, B_{high}, C_{high}\}$, $\{A_{low}, B_{low}, C_{low}\}$, $\{A_{low}, B_{high}, C_{high}\}$, $\{A_{high}, B_{low}, C_{high}\}$, $\{A_{high}, B_{high}, C_{low}\}$, $\{A_{high}, B_{low}, C_{low}\}$, $\{A_{low}, B_{high}, C_{low}\}$, $\{A_{low}, B_{low}, C_{high}\}$), assuming independence between variables. Thus, this Curse of Dimensionality necessitates careful exploratory analyses to determine which uncertain variables are most influential on future infrastructural performance. However, where there is a substantial degree of correlation between variables, the Curse of Dimensionality is less of a concern. For instance, the proof of concept demonstration presented in Chapter 5 considers a number of different future sea level rise and precipitation change scenarios. These scenarios are highly correlated given that both variables are driven to some extent by the same physical and climatic processes (i.e. changes in temperature and atmospheric circulation). By looking across an appropriately diverse and plausible selection of scenarios one is able to get a qualitative sense of how the performance of different courses of action may vary across the feasible region of all possible futures.

Scenarios can be created using a number of existing scenario creation and discovery methods (e.g. Lempert *et al*., 2008; Ringland, 2014). Scenarios can be developed through expert consultation or obtained from previous research. Alternatively, existing scenarios already developed to facilitate policy and planning work in a particular location can also be used. (e.g. the Delta Scenarios were developed in the Netherlands for exactly such purposes). This scenario approach is most suitable for exploring the impact of gradual, incremental changes over a certain project horizon. The deeply uncertain variables likely to be of most relevance when exploring long-term infrastructure investment include future climatic conditions as well as socio-economic growth developments. Scenarios are unlikely to provide insights about so-called black swan events: impacts of a black swan event can only be explored in this way if these events are fathomable enough that they can be included in the user-defined scenarios.

The inclusion of such non-probabilistic scenarios in this planning approach does not resolve the fundamental question of how to cope with deep uncertainties. Rather, the exploration of different infrastructure strategies across a diverse range of future scenarios is simply a pragmatic way of gaining insights, while acknowledging that a deeply uncertain future can never be adequately known or anticipated.

4.2.3 Within each scenario, estimate probability distributions for remaining uncertainties

In the previous section, scenarios were introduced as a mechanism to capture and explore the impacts of deeply uncertain variables, without needing to assign probability distributions to future states of the world. Typically, when conducting quantitative scenario analyses using scenarios, the scenarios are treated as well-defined to the extent that no further uncertainties are considered within individual scenarios themselves (e.g. Li et al., 2015). This means that each individual scenario is treated as being fundamentally deterministic; we just don't know which scenario we are likely to end up in. However, this provides the flawed impression that given the defined conditions of a scenario, everything is known with certainty and no residual uncertainty remains. For instance, even if we know from the previously defined scenarios that sea level is anticipated to increase by 85 cm in one scenario, are we able to determine with sufficient certainty how this will impact future water level recurrence intervals? Even if we know that winter precipitation will decrease by 30% on average in one scenario, there remains substantial natural variability in the short-term precipitation experienced under this scenario. Within the approach developed in this work, while the definition of each scenario is deterministic, further attention is paid to the remaining sources of uncertainty within each individual scenario. Hence, while a well-defined scenario forms the starting point, our imperfect understanding of physical processes coupled with natural variability produce uncertainties that propagate even within a well-defined scenario. Given the central role that uncertainty plays in evaluating different infrastructure replacement strategies, more attention is paid in this work to the identification and quantification of uncertainty <u>within</u> each scenario than is traditionally the case when using scenarios. These remaining sources of uncertainty can be taken into account by using probability distributions or confidence intervals, typically based on historic data, which is perturbed in a variety of ways to capture altered future conditions.

The exact quantitative formulation of these stochastic variables depends on the nature of the study being conducted. As an example, when looking generally at water resource infrastructure planning, it is likely that precipitation is a recurring stochastic variable of interest. Precipitation is a very complex process, and it is important that any mathematical representation of a precipitation process retains statistical properties that are similar to real observed precipitation. This can be done in a number of different ways. Precipitation can be described as a variant of a stochastic auto-regressive variable of the general form

$P_t = c + \sum_{j=1}^{p} \alpha_j P_{t-j} + \varepsilon_t$ where

P_t is the precipitation at time t,

P_{t-j} is the precipitation j time-steps ago,

ε_t is a stochastic shock variable,

c and $\alpha_j \; \forall \; j \in \{1, \dots, p\}$ are parameters determined from historic precipitation datasets.

Makhnin and McAllister (2009) utilize such an autoregressive approach to precipitation modelling. Alternatively, many stochastic precipitation generators utilize a two-state Markov process to describe precipitation occurrence: a binary state variable, S_t^i, has a value of 1 if location i experiences precipitation at timestep t, or 0 if it is dry at timestep t. Such a Markov process is often coupled with a parametric model to determine the quantity of precipitation during a given time interval. This approach is demonstrated by for instance, Richardson (1981), Stern and Coe (1984), Wilks (1998) and Breinl *et al*. (2013). The take-away point here is that it is appropriate to quantify different uncertain variables in different ways, depending on the nature of the variable and the research done on its quantification to date. Where multiple possible methods do exist, the choice of which to use will likely be influenced by the experience and comfort level of the analyst with different approaches, the available data and computational limitations.

In summary, the second step of the general infrastructure planning approach developed here characterizes the existence of different sources of uncertainty and quantifies these different risks using probability distributions and stochastic generators nested within discrete, non-probabilistic scenarios. The use of diverse user-defined scenarios provides insights as to how uncertain drivers of change translate into impacts in the future. Despite not having reliable information about the probability of each individual scenario actually occurring, looking across all scenarios, one is able to piece together a snapshot of the range of possible impacts that could conceivably occur. Additionally, the use of probability distributions within each individual scenario provides complementary insights about the degree and impact of natural variability within each individual scenario.

4.3 Step 3: Explore the long-term strategic planning timeline for the structure

Having defined the scale of the infrastructural reinvestment question being explored, and characterized the relevant sources of uncertainty, the next step takes a closer look at the different processes that can influence the physical structure's long-term ability to continue to function as intended. This is done by building on the existing concept of Adaptation Tipping Points, as introduced Section 3.1.1. In its most general sense, consideration of Adaptation Tipping Points simply seeks to identify those thresholds and external conditions beyond which a physical system becomes unable to meet a desired societal function adequately. As explained below, this notion of performance thresholds is further refined and developed in this planning approach so as to capture different drivers of infrastructure investment, thereby allowing consideration of a number of different decision moments in the lifetime of an infrastructure system.

The literature review conducted in Section 3.1.4 identified the shortcoming that, to date, there has been very limited consideration of drivers of Adaptation Tipping Points beyond climate change. Van der Vlist *et al*. (2015) argue that this singular focus on climate change alone ignores that there are other relevant factors which may also drive the reinvestment and redesign of infrastructure systems. They make the case that not just changes in external environmental conditions, but also socio-economic and political factors can drive the occurrence of Adaptation Tipping Points. Furthermore, when applying the concept of Adaptation Tipping Points specifically to infrastructural systems, factors relating to the structure itself, such as aging and physical deterioration can also act as drivers of Adaptation Tipping Points.

Illustrating this, imagine a pumping station located in an urban area that has the primary function of maintaining the water level in the region. External climatic change can result in more intense rain events, occurring more frequently. An Adaptation Tipping Point occurs when the magnitude of change in precipitation patterns is substantial enough that the current pumping capacity is inadequate to maintain the required target water levels in the region. However, the current pumping station could also become functionally inadequate if a socio-political governance process determines that the service level of the pumping station must increase substantially (i.e a reduction in the frequency of allowable flooding events). Again, the pumping station with its current specifications is unable to adequately fulfil its pre-defined function. Alternatively, if an area in the region is transitioned from natural grassland to urban development with a greater proportion of pavement and thus producing more runoff, the additional discharge changes the ability of downstream structures to fulfil their intended functions. Finally, deterioration of the pumping station over time reduces its reliability and structural degradation can eventually result in the structure becoming unable to fulfil its function in a reliable, safe and cost-effective way. The take-away point here is that when considering the development of a long-term infrastructure plan, there are many drivers of reinvestment in addition to external climatic change that need to be considered.

Thus, within this work, the definition of an Adaptation Tipping Point provided earlier is expanded from

> "points [in time] where the magnitude of change due to **climate change or sea level rise** is such that the current management strategy, [chosen and implemented by decision makers in the past, to address a particular societal need or problem], will no longer be able to meet the [desired performance] objectives"

to

> "points in time where the magnitude of change due to **altered external environmental, socio-economic or political conditions, or deterioration of the physical structure** is such that the current management strategy, chosen and implemented by decision makers in the past, to address a particular societal need or problem, will no longer be able to meet the desired performance objectives"

These different drivers of change can be grouped into those where the function carried out by a structure, is affected by broader external changes, factors outside of the structure itself versus those where the functionality of the structure is impacted by processes relating predominantly to the physical structure itself. Thus, when examining flood management structures in the context of replacement planning, there are two important types of Adaptation Tipping Points, classified based on the type of factors that drive the occurrence of the Adaptation Tipping Point:

1. **Functional Adaptation Tipping Points**: points where the *magnitude or degree of external change* is such that the structure is no longer able to meet its functional performance objectives. This captures any kind of external change

that affects the ability of a structure to continue to function as intended, be it a natural or human-driven change.

2. **Technical Adaptation Tipping Points:** points where the *magnitude of physical deterioration* (i.e. internal change) of a structure is such that the structure is no longer able to meet its functional performance objectives.

The pumping station example introduced on the previous page, described how the structure could fail to meet performance standards in the future due to changes in its operating environment such as increased precipitation, increased runoff, or intensifying of the required performance levels. By the new definitions of Adaptation Tipping Points described above, these moments would correspond to Functional Adaptation Tipping Points, where external changes result in the pumping station becoming functionally inadequate. In contrast, a Technical Adaptation Tipping Point would occur when deterioration of the physical structure results in it being unable to fulfil its function.

To illustrate this extension of the existing theory of Adaptation Tipping Points, these two sub-types of Adaptation Tipping Points are illustrated conceptually for a generic hydraulic structure on Figure 4.2:

For any hydraulic structure of interest, assume the existence of a quantitative and measurable indicator of its ability to fulfil a function, P. P varies over time and is function specific i.e. performance is tracked as P_f^t $\forall\, f \in \{functionalities\}\ and\ \forall\, t \in \{project\ horizon\}$.

Each structure has at least two externally defined performance thresholds per function, namely

$P_{min\,req,\ f}$ = the minimum performance level the structure must fulfill for function f

$P_{max,\ f}$ = the maximum performance level the structure is physically designed to deliver for function f

For instance, in the case of a floodwall, $P_{min\,req}$ can be the required flood height that the structure must be able to withstand, while P_{max} is the currently installed flood defense height of the wall. The value of the minimum threshold can be federally mandated, determined through cost-benefit analyses or based on standard practice. The difference between these two thresholds is a measure of the margin of safety.

For every time period, t, in the future, one can envision two uncertain variables

$P^t_{desired,\ f}$ = the performance level demanded by users for function f at time t

= g (societal risk aversion; state of development; other factors)

$P^t_{received,\ f}$ = the performance level delivered by the structure for function f at time t

= h (structural factors; external conditions; other factors)

Three different outcomes may occur

1. **The structure functions as intended:**

   $P^t_{desired,\ f}$ is demanded by users, such that $P_{min\,req,\ f} \leq P^t_{desired,\ f} \leq P_{max,\ f}$

   Performance level $P_{min\,req,\ f} \leq P^t_{received,\ f} \leq P_{max,\ f}$ is achieved.

2. **A Technical Adaptation Tipping Point occurs:**

   $P^t_{desired,\ f}$ is demanded by users, such that $P_{min\,req,\ f} \leq P^t_{desired,\ f} \leq P_{max,\ f}$

   However, performance level $P^t_{received,\ f} < P_{min\,req,\ f}$ is achieved.

   Even through the structure is designed to provide at least performance level $P_{min\,req,\ f}$ it fails to deliver it when called upon for technical reasons, including aging, structural damage and degradation. This signals the occurrence of a Technical Adaptation Tipping Point.

3. **A Functional Adaptation Tipping Point occurs:**

   $P^t_{desired,\ f}$ is demanded by users, such that $P^t_{desired,\ f} > P_{max,\ f}$

   Instead, performance level $P^t_{received,\ f} \leq P^t_{desired,\ f}$ is achieved, where $P_{min\,req,\ f} \leq P^t_{received,\ f} \leq P_{max,\ f}$.

   While the structure may still be in technical working order, a lower than desired performance level is achieved, because performance demands outside of the design range are being requested, as driven by altered external operating conditions. This signals the occurrence of a Functional Adaptation Tipping Point.

Considered jointly, we are able to explore when structural degradation (i.e. the occurrence of a Technical Adaptation Tipping Point) and changes in the external operating environment (i.e. the occurrence of a Functional Adaptation Tipping Point) first result in the structure becoming unable to fulfil its performance requirements.

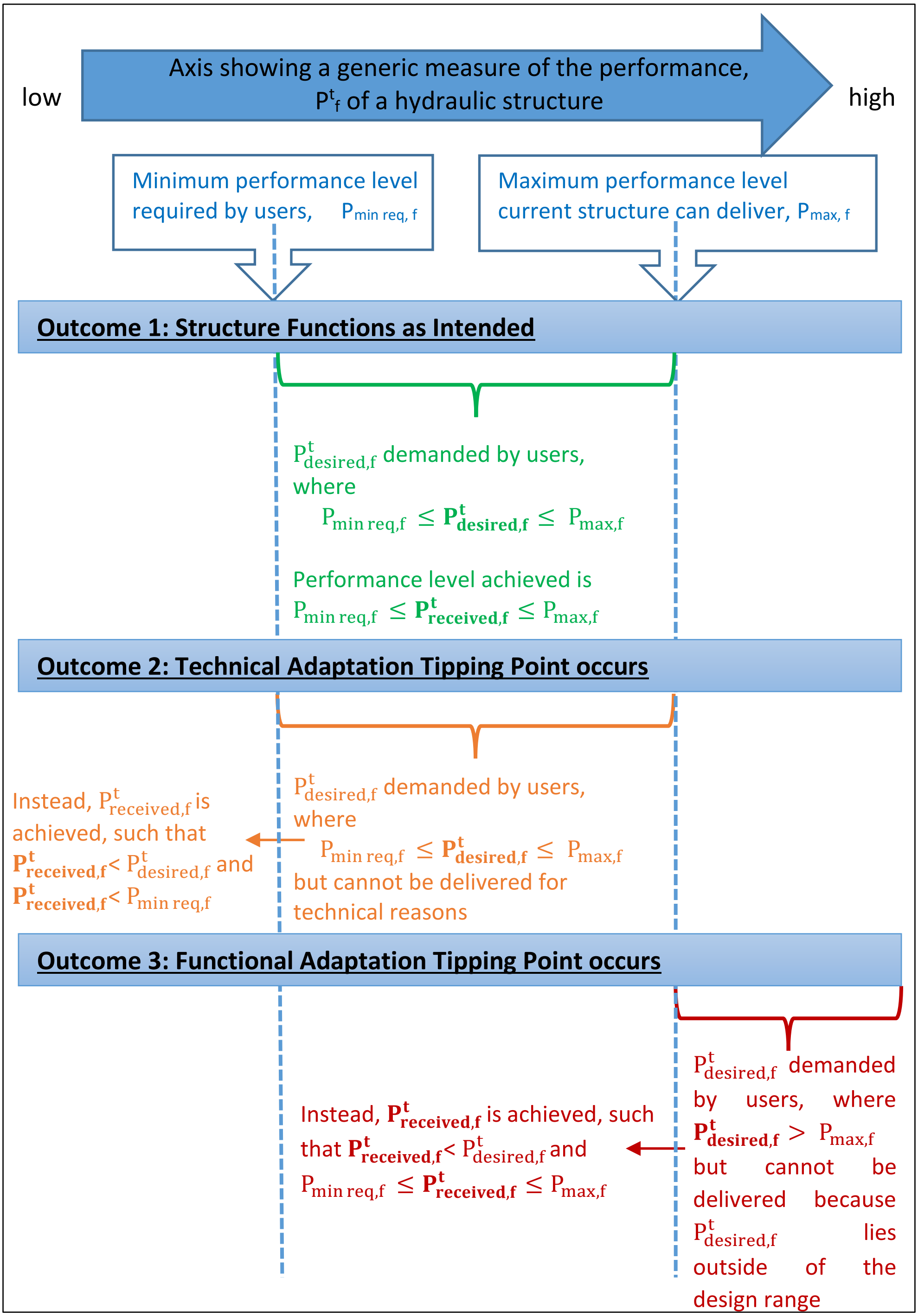


Figure 4.2: Schematic illustrating the concepts of Technical & Functional Adaptation Tipping Points

Notice that while these are categorized as two different classes of Adaptation Tipping Points[34], one single external change can in some situations affect the timing of both Technical and Functional Adaptation Tipping Points. For instance, increases in the magnitude and power of storms can speed up the occurrence of not just the timing at which a structure becomes unable to fulfil its intended function, such as withstanding a design flood of a certain magnitude, but the Technical Adaptation Tipping Point can occur earlier too because of increased wear and tear on the physical structure.

In different situations, these Adaptation Tipping Points can conceivably be caused by either incremental or sudden drivers of change. For instance, Functional Adaptation Tipping Points are driven by external changes, which can be incremental (e.g. climatic changes such as increases in sea level) or sudden (e.g. socio-economic changes such as the decision to change performance requirements). In contrast, Technical Adaptation Tipping Points are driven by physical deterioration of the structure, which can also be incremental (e.g. concrete rot or rusting) or sudden (e.g. structural undermining due to extreme weather events). Table 4.1 provides an overview of some of the different possible drivers of these two kinds of Adaptation Tipping Points. In general, the timing of those

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[34] Concepts analogous to the Technical and Functional Adaptation Tipping Points defined above, currently already exist in various subject-specific literature, under a variety of different terminologies:

- the Federal Highway Administration classifies the condition of bridges in the United States using the ratings "**structurally deficient**" and "**functionally obsolete**"
- within the discipline of civil engineering, structures can experience "**catastrophic failure**" or "**serviceability failure**"

While each of these terms differ slightly in their precise definition, and the specific threshold of when a structure is defined to reach one of these states can vary depending on specific details of the case at hand, the underlying conceptual basis of each of these pairs of terms is similar: when looking at a technical system, both internal physical characteristics as well as external societal demands affect the system's performance.

Adaptation Tipping Points driven by incremental processes that are gradual in nature can be modelled effectively as an Adaptation Tipping Point. However, it is not clear that more sudden unpredictable or inconceivable changes such as political decisions, extreme weather induced damages or black swan events can be sufficiently anticipated and modelled to be captured within this framework.

Table 4.1: Overview of the different types and some possible drivers of Adaptation Tipping Points, each with differing characteristics

Type of Adaptation Tipping Point	Driver	Nature of driver
Technical Adaptation Tipping Point	Normal structural deterioration	Gradual
	One-off structural deterioration resulting from extreme events	Sudden
Functional Adaptation Tipping Point	External climatic change	Typically gradual (could be relatively sudden in the case of a large scale singularity)
	External socio-economic change	Gradual
	Changes in societal priorities and preferences	Gradual
	External political decision to change performance objective	Sudden

Taken together, the timing of these different types of Adaptation Tipping Points is representative of moments in the lifetime of a structure where some sort of performance threshold is crossed and an intervention in the form of a capital expenditure may be warranted. By defining and considering these two different types of Adaptation Tipping Points, it is possible to incorporate both structural and external factors into developing a long-term strategic planning timeline for the structure of interest. The current consideration of only single drivers of investment, previously highlighted in Section 2.4, is one of the key shortcomings this novel planning approach seeks to address. The timeline produced by this step of the analysis provides insights about possible large-scale interventions that may become necessary over the course of an asset's lifetime to keep it functioning as intended. Thus, the overall objective of this step is to explore the long-term infrastructure prognosis under many possible futures, which in turn forms a basis for effective and proactive reinvestment and replacement planning. The individual components of this portion of the planning approach are presented in more detail below.

4.3.1 When are interventions required for structural reasons? – an analysis of Technical Adaptation Tipping Points

As defined above in Section 4.3, a Technical Adaptation Tipping Point is said to occur when *the magnitude of physical deterioration of a structure* is such that it is no longer able to fulfil the functions it was designed for. By design, Technical Adaptation Tipping Points serve as a gateway by which asset management considerations regarding the physical structure itself are introduced and included into this planning framework. Hydraulic structures are complex physical structures, and all their different components or sub-systems will deteriorate individually. Each of these deteriorated elements will differentially contribute to the continued ability of a structure to meet the relevant performance requirements. Deterioration of different elements will thus also warrant different responses: aging and unreliable pumps, for instance, may call for large-scale maintenance or possible replacement of the pumps; extensive deterioration of the structure's foundation, however may call for replacement of the whole structure. Clearly, a Technical Adaptation Tipping Point caused by routine deterioration of a structure can elicit a variety of possible managerial responses, from intensified inspection and maintenance, to repairs, replacement of components or complete structural replacement, depending on which specific element of the structure caused non-compliance with the performance requirement. Additionally, asset management is comprised of many overlapping lifecycles, from structural elements with very long lifetimes (e.g. the concrete housing of a structure), intermediate lifetimes (e.g. moving components), to short lifetimes (e.g. operational software). Given the focus of this study on long-term replacement planning for hydraulic structures, the emphasis in this work is on identifying those Technical Adaptation Tipping Points where deterioration is substantial enough that that a capital investment in the form of complete structural replacement is justified. Given the typically capital intensive nature of such interventions, they should not be seen in isolation from functional considerations such as capacity expansion for climate change adaptation purposes, or renovation of the structure to better serve a new function. However, while the focus in this work is on large-scale capital interventions, with further research efforts, future work could developed the approach introduced in this dissertation into a fully-fledged infrastructural planning and management framework that integrates all aspects of asset management (including more short-term, less capital intensive tasks) with broader external considerations.

Depending on the specific type of structure and the kind of data and models available, the occurrence of different Technical Adaptation Tipping Points could be estimated in a number of different ways, each of varying complexity. Most simply, an estimate of the time for an entire structure’s replacement could be based on its design life: adding the design life to its year of construction provides an approximate estimate of when replacement is expected to be necessary. A similar replacement estimate could be done for individual components of a structure, given that each component is usually associated with a specified design life. This most simple design life estimate can be supplemented with inspection and monitoring reports attesting to the actual condition of the structure at various times in its life as compared to the expected condition of a structure of similar age. For instance, Kallen *et al*. (2013) and Nicolai *et al*. (2014) do this in the form of a Bayesian update model whereby the theoretical design life of a structure (the prior) is sequentially improved on the basis of new conditional information in the form of inspection reports, knowing the structure's current age. Alternatively, discrete condition grades or quality scores can be used to track the condition of a structure as a whole or individual components over time. The assignment of individual scores to structures can be informed by visual inspections, or by expert opinion (e.g. EA, 2006; Kallen and van Noortwijk; 2005). These condition grades are often used in combination with deterioration curves to quantify the remaining useful life that a particular structure within a particular condition grade class has left, under different maintenance regimes (e.g. DEFRA and EA, 2009). Fault-tree analysis (developed by Watson in 1961) can provide additional information about the impact of different failure mechanisms on various sub-systems of a structure, which can be combined to provide estimates about failure rates for the structure as a whole. This approach has been most widely applied to bridge deterioration (e.g. Kallen *et al*., 2013; LeBeau and Wadia-Fascetti, 2000; Hong, 2007).

The intention here is not to provide an in-depth formulation of a comprehensive and novel deterioration model, but rather to provide an indication of where this kind of existing information and modelling tools already used by an asset management agency could slot into this new, more unified water resource infrastructure planning framework.

4.3.2 When are interventions required for reasons external to the structure? – an analysis of Functional Adaptation Tipping Points

As defined above in Section 4.3, a Functional Adaptation Tipping Point is said to occur when *the magnitude or degree of external change* is such that a structure is no longer able to meet its functional objectives. In other words, Functional Adaptation Tipping Points represent moments in time when interventions are necessary, because while still in adequate physical shape, a structure is no longer able to fulfil the functions that society and stakeholders desire. Examples of Functional Adaptation Tipping Points include the need for capacity expansion in response to altered external operating conditions (e.g. heightening of a flood wall due to increased sea levels) or addition of a function to a structure due to new societal desires and changing priorities (e.g. addition of a fish ladder to an existing structure to protect ecological habitat).

The data needs and modelling requirements to identify the occurrence of a Functional Adaptation Tipping Point differ depending on the nature of the problem being explored. In general, an exploration of Functional Adaptation Tipping Points is centered on the following steps, adapted from Deltares (2008), Kwadijk *et al*. (2010) and Gersonius *et al*. (2015):

1. **For each function, identify relevant quantitative performance indicators as well as the threshold performance level beyond which the system is no longer considered functional:**

   Delineation of the scale of the investigation as well as identification of the functions fulfilled by the physical system has already previously been completed during the problem definition steps described in Section 4.1. As previously introduced, this work incorporates a "policy first" approach to uncertainty, such that we are interested in identifying when current infrastructure is no longer able to function adequately given different possible rates of external change. (This is as opposed to a more traditional “science first” approach where uncertainties are quantified as accurately as possible and are incorporated into subsequent analyses in the form of a step-by-step growing cascade of uncertainties). Within this approach, functionality is central and thus efforts are necessary to explore what constitutes a structure being “functional”. The subsequent step is thus the identification of measurable and quantifiable performance indicators for the physical system. Subsequently, performance thresholds should be explored to provide an indication of the maximum allowable impacts that can be accepted before intervention is deemed necessary. In other words, *what level of performance must a structure or network continue to provide in order for it to be considered functioning and in compliance with society’s objectives?* These performance objectives are function-specific and hence should be identified and quantified for every function fulfilled by a given structure or system.

In some cases, identification of performance indicators and thresholds is a clear-cut and well-defined exercise. For instance, in the case of the Netherlands, the flood defense level provided by any structure is mandated by federal law in the Flood Defense Act (2009), with this protection level defined in terms of an annual exceedance probability. However, in many other cases, identification of a performance requirement is less clear-cut and is hence a more involved process. For instance, within the US, while a 1% exceedance probability is a commonly referenced flood defense standard, there is no single unified, enforceable performance requirement, requiring more in-depth, case-by-case consideration. In such cases where no single, clearly mandated performance objective is defined, the identification of these performance thresholds can be done in a number of ways. For instance, regional and local agreements such as water accords or operating guidelines can be consulted. Formal optimization could be undertaken in an effort to identify what a societally optimum performance level should comprise. Alternatively, stakeholder engagement with locals, users and experts can be conducted to determine what degree of change would be unacceptable to them and their respective uses of the water. Within such stakeholder discussions, it would be necessary not just to identify what degree of change would be unacceptable, but also discuss which of the possible performance indicators they feel is most in line with describing their needs. For instance, when talking about water releases from a structure for ecological reasons, is it enough to define total releases over a certain time period, or is the timing and distribution also of importance? When talking about urban flooding, is the number of flood events per year of most relevance, or is the duration of each event of greater relevance? This identification of not just the relevant performance objective but also an appropriate performance indicator is important for shaping the data and modelling needs of later steps in the planning process.

2. **Identify what degree of external change results in the current physical system being unable to meet these performance objectives:**

   Having identified the required performance thresholds, the next step is to explore the mechanisms by which external changes affect the physical system's ability to meet these performance objectives. This requires quantification of those variables that are responsible for determining the system's behavior and then determining how the system responds to changes in loading. For instance, when considering a reservoir's ability to adequately capture future flood flows, changes in precipitation and precipitation intensity are centrally relevant. In addition, changes in regional socio-economic development can impact local land-use which in turn alters the portion of precipitation that becomes runoff as well as the lag time between precipitation and inflow to the reservoir. The intention here is to link changes in external operating conditions, to infrastructure performance and finally to the measurable indicator of performance identified in the previous step. In this way, the impact of changing external conditions on measurable parameters of interest is made explicit. The condition whereby the degree of external change results in the current physical system being unable to meet the necessary performance objectives signals the occurrence of a Functional Adaptation Tipping Point for that particular function.

3. **Given different possible scenarios of future change, identify when in time external changes result in performance objectives no longer being met:** Finally, knowing the desired thresholds, and the mechanisms by which external changes affect the physical system's ability to meet these performance objectives, diverse scenarios of the future are mapped on to the previous results to identify when in time non-compliance with a performance objective first occurs. By projecting different scenarios of the future (as previously defined in Step 2), with different rates of future change on to the existing model of the physical system, *it is possible to explore which system functionalities are most immediately vulnerable and where action is needed the soonest*. By using a range of different scenarios of the future, one obtains a time window during which the performance of a system is expected to become inadequate. The size of this time window provides an indication of how strongly performance varies with external changes, with a wide window indicating substantial dependence on external change, and a narrow window indicating that uncertainty does not dramatically alter the timing of when the system first becomes inadequate. This ability to identify which functionalities are most at risk of future change helps identify long term planning priorities.

This process of assessing Functional Adaptation Tipping Points has some conceptual similarities with the so-called Climate Stress Test developed by Brown and Wilby (2012), a component of Decision Scaling, previously described in Section 2.3. The Climate Stress Test focuses on exploring which of an exhaustive set off possible futures results in the identified performance objectives no longer being met. Having assessed the vulnerability of a given plan, the remainder of the Decision Scaling process uses Global Climate Model output to estimate how likely it is that we end up in such a vulnerable situation in the future. However, within this work, some of the same general elements are used in a different way to achieve a different outcome for a different purpose. Just like the Climate Stress Test, this approach also starts with a bottom-up focus on identifying performance objectives. However, these performance objectives are then superimposed on the impacts of different climate scenarios to get a sense of the urgency of future functional upgrades. Unlike the Climate Stress Test, Adaptation Tipping Points can focus on a wider variety of uncertainties than climate change alone, including other factors such as socio-economic growth. Finally, the focus in the approach presented here is much more centrally on timing, and the question of when to invest in what.

4.3.3 Putting these together: a long-term strategic planning timeline

So far, Section 4.3 has described a generally applicable conceptual approach to identifying Technical Adaptation Tipping Points, which focus on internal structural processes, as well as Functional Adaptation Tipping Points, which focus on processes that affect the external operating environment of a structure. When combined, these results produce a long-term planning timeline that gives an overview of when structural interventions become necessary either for technical or functional reasons. Taken as a stand-alone end-product, such a long-term strategic planning timeline can serve as a useful thinking, discussion and planning tool, providing a sense of which elements of a system pose a more immediate management concern than others and when we can expect to have to take some sort of action. Timelines of this kind are already in use within Rijkswaterstaat, the Ministry of Infrastructure and the Environment in the Netherlands (see for example Van Vuren *et al*., 2015).

Figure 4.3 presents such long-term strategic planning timelines for a general structure, introduced here to demonstrate the kind of insights that the output of this step of the planning approach produces. The generic structure examined here fulfills and must continue to fulfil two functions, F1 and F2. The structure's ability to continue to fulfil these two functionalities is explored across three future scenarios, A, B and C. A Technical Adaptation Tipping Point is defined as occurring when the design life of the structure is reached.

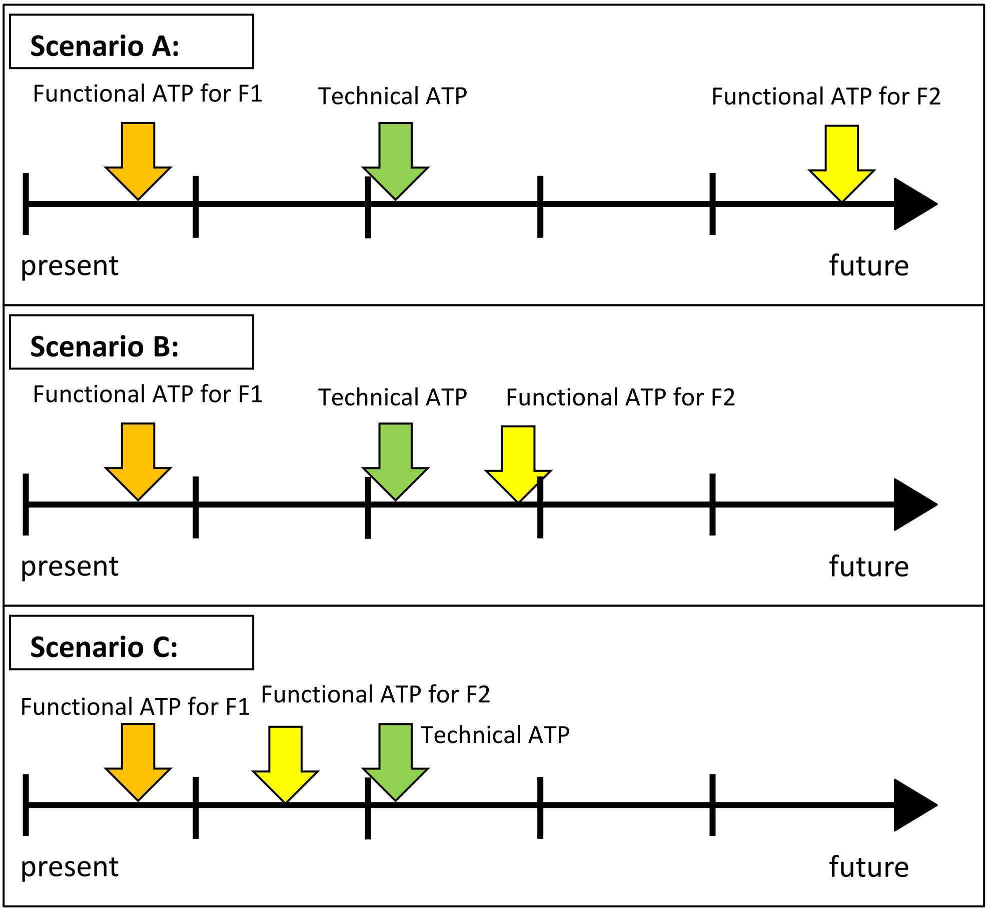


Figure 4.3: Sample results showing the occurrence of Technical and Functional Adaptation Tipping Points for a generic hydraulic structure across three different future scenarios – Imagine the structure presented here is a dewatering sluice located on a river channel at the land-ocean interface. The sluice fulfills two different functions: the first, F1, is its ability to discharge runoff waters from the river channel into the ocean; the second, F2, is its ability to withstand high water levels on the ocean, preventing flooding of inland areas. Under future Scenario A, the installed sluice capacity becomes limiting long before the structure reaches its design life, while the installed flood height remains adequate long after the design life has been passed. In other words, under Scenario A, the structure is under-designed with respect to F1 and dramatically over-designed with respect to F2. Scenario B is more extreme than Scenario A and shows that the structure is still under-designed with respect to F1 and only slightly over-designed with respect to F2. Under the most extreme of the three scenarios, Scenario C, the structure is under-designed with respect to both F1 and F2: both the installed sluice capacity and flood defense height become inadequate before the structure reaches its design life.

There are a number of aspects of these sample results that are worth highlighting to demonstrate the strengths of this particular approach when exploring infrastructure replacement. First, one should notice how the occurrence of a Functional or a Technical Adaptation Tipping Point implicitly calls for a different type of response. Conceptually, a Technical Adaptation Tipping Point occurs when elements of the structure, or the structure as a whole can no longer perform adequately due to their deteriorated physical state. Hence, at the occurrence of a Technical Adaptation Tipping Point, appropriate responses focus on the replacement or renewal of components of or the structure as a whole e.g. replacing a pump or renewing a floodwall. By comparison, a Functional Adaptation Tipping Point occurs when, despite the adequate technical state of the physical structure, it can no longer perform as required because the external operating conditions have changed. Appropriate responses thus focus on upgrading the capacity of the structure e.g. adding extra pumps or raising the height of a floodwall.

Furthermore, comparing the occurrence of Functional Adaptation Tipping Points across different scenario-specific results in Figure 4.3, allows one to identify how vulnerable a functionality is to future changes in external conditions. For instance, when looking at Function 1, one observes that across the three future scenarios examined, the timing of the occurrence of the Functional Adaptation Tipping Point (i.e. when external changes result in inadequate fulfillment of that function) varies only minimally. This demonstrates that when it comes to fulfilling Function 1, uncertainty about future conditions does not dramatically alter the prognosis of when capacity expansion will become necessary. In contrast, the timing of the occurrence of the Functional Adaptation Tipping Point for Function 2 varies substantially over the different scenarios: F2 is much more sensitive to the uncertainties captured in Scenario A, B and C than F1. Thus, when it comes to fulfilling Function 2, uncertain future conditions can substantially alter when capacity expansion is first necessary, and hence closer monitoring may be warranted.

Additionally, it is important to note here that the focus of the two-component Adaptation Tipping Point analysis described here is not on predicting with any high accuracy the timing of when structures first reach a threshold, signaling a technical or functional deficiency or on specifying an exact, static timeline of intervention moments that can be used for scheduling purposes. In other words, differentiating between an Adaptation Tipping Point predicted to occur in 2031 versus 2033 is not the focus. Rather, this analysis serves as a systematic way to tease apart the complexities associated with multi-functional structures, identifying which features of the structure are central in fulfilling a specified function, as well as providing a platform to explore how the relative sequencing and timing of Adaptation Tipping Points matters to the long-term planning process.

Finally, as alluded to above, it is important to consider the impact of different sequences of the different types of Adaptation Tipping Points. In those cases where a Functional Adaptation Tipping Point predates a technical one, it may be necessary to upgrade the capacity of a structure long before it becomes structurally deteriorated. One could see this as evidence of under-designing the structure, where there is a lack of capacity in the system relative to how long the structure can physically last. In those cases where a Technical Adaptation Tipping Point predates a functional one, a structure needs to be replaced due to wear and tear before it ever becomes functionally inadequate. This may suggest that the structure was over-designed relative to its design life. Conceptually speaking, the ideal situation would occur when all of the Technical and Functional Adaptation Tipping Points fall within a relatively narrow window of time, as shown in Figure 4.4.

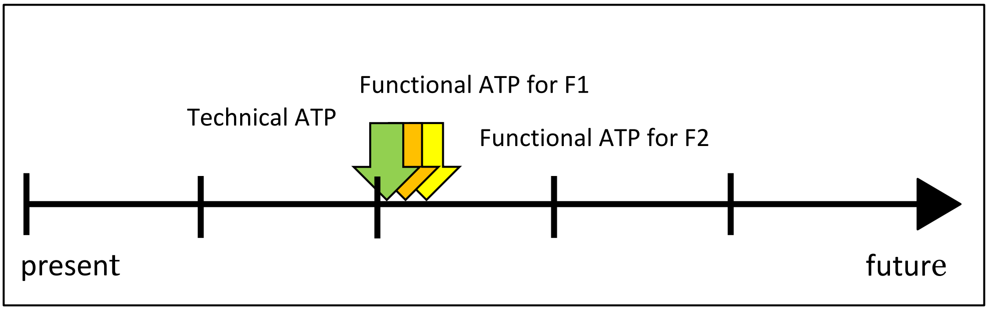


Figure 4.4: Sample results showing the ideal timing of Technical and Functional Adaptation Tipping Points for a generic hydraulic structure

This would mean that in the lifetime of the structure, large functional upgrades made necessary by external changes can be coupled with necessary replacement work required for technical reasons. However, given that the occurrence of each of these moments is dynamic and affected by a number of complex and evolving processes, it would appear more likely that these different moments requiring large-scale intervention will occur individually and spread out over the life of a structure. In fact, the proof of concept demonstration presented in Chapter 5 explores the occurrence of Adaptation Tipping Points for hydraulic structures in the Netherlands. Textbox 8 in Chapter 5 lends evidence to this supposition that Technical and Functional Adaptation Tipping Points are more frequently widely distributed throughout a structure's life rather than ideally clustered together.

One can envision two possible classes of responses to this discrepancy between the ideal situation where all Adaptation Tipping Points fall within a relatively narrow window of time and the true situation where Adaptation Tipping Points are widely dispersed in time. The first type of response would build on the traditional scientific desire to reduce uncertainty by making better, more accurate predictions so that structures could be designed in such a way as to remain functionally adequate for the entirety of their design life, but not too far beyond that. For reasons already discussed in Section 2.3.2 this strategy of reducing uncertainty is not considered any further within this work. A second response would accept the fact that the system and its external operating environment are highly dynamic and that multi-decade predictions will likely always miss the mark, and thus that structures should be designed in such a way that the need to revisit their structural configuration is actively acknowledged and pre-empted. This is the response that underlies the remainder of the planning approach developed within this work and justifies the need for more adaptable and flexible infrastructure design in the future.

In conclusion, so far, this use of Adaptation Tipping Points has developed a framework in which an awareness is created for the long-term inter-related nature of investment needs for both structural and functional reasons, fostering a more holistic whole life approach to infrastructure planning and replacement. The resulting long-term timelines serve as output in and of themselves, producing a number of insights, as discussed in detail above. However, while this use of Adaptation Tipping Points is able to identify approximately when intervention points occur, it provides no guidance in the exploration of what to do subsequent to the occurrence of an Adaptation Tipping Point. Thus, these planning timelines also serve as input for further analysis (presented in Section 4.4) where different possible courses of action in the form of diverse replacement strategies are formulated, evaluated and compared. Within this exploration of different replacement strategies, the focus is on including structural designs that acknowledge the likely need for future reconfiguration as uncertainty is resolved over time.

4.4 Step 4: Formulate, evaluate and compare different replacement strategies

So far, this approach has developed a long-term strategic timeline based on an Adaptation Tipping Point framework. This now serves as the input to explore how different possible actions taken at an Adaptation Tipping Point affect the occurrence of Adaptation Tipping Points in the future, as well as the lifetime investment costs of different courses of action. These two steps, namely the development of a long-term strategic planning timeline (Step 3) and the subsequent quantitative economic analysis of different possible courses of action (Step 4) are linked through the occurrence of an Adaptation Tipping Point: Adaptation Tipping Points form the basis of intervention moments in the timeline and serve as trigger moments in the analysis, indicating when changes are made to the structure.

4.4.1 Based on the timeline identified, formulate alternative courses of action and seek more flexible variants

This step seeks to compile a comprehensive list of alternative courses of action that could be chosen following the occurrence of different types of Adaptation Tipping Points. In general, these alternatives can be derived from previous studies, from local expert consultation or engagement with diverse stakeholders. The specific types of alternatives considered will be dependent on the scale of the project as previously identified in Section 4.1.3 i.e. courses of action focused on the single structure versus the network scale. Additionally, in most cases, the specific alternatives considered are context and location specific. Thus, given that this work is developing a general planning approach, applicable in general to water resources infrastructure replacement planning, it is not possible to provide a comprehensive discussion here of all the possible courses of action that could be considered. In the most general sense, courses of action could include alternatives such as replacing or renewing components of the structure, replacing or renewing the structure as a whole, adding capacity to the structure, adding a new functionality to the structure or making changes elsewhere in the system to eliminate the need for structural intervention at a particular structure. These are all well-established courses of action, typical to infrastructural asset management.

However, the real value added here comes from a strategic consideration of the need for adaptability in infrastructure. The literature review conducted in Chapter 2 identified as a shortcoming how existing infrastructure planning approaches are reactive to uncertainty, relying on a wait-and-see mindset to cope with uncertain impacts. Within the planning approach developed here, the notion of an Engineering Option or flexibility in the design of infrastructure is proposed as the primary effective tool by which to transition towards infrastructure designs that are more anticipatory and less reactive to possible impacts from future uncertainty. Options facilitate a more proactive approach to uncertainty by incorporating the ability to adapt within the design of a structure itself. Thus, the traditional generic alternatives already presented should be revisited with an eye on identifying possible opportunities to incorporate options within the design. One can imagine then that for each alternative there may additionally be one or many more flexible variants of that same alternative.

Consider for instance, the alternative of replacing a structure. One could easily envision a number of different variants, some adopting a more proactive stance on responding to future uncertainty. Consistent with the traditional approach to water resource planning, one can consider the base case replacement structure to be a *robust design*, designed with substantial enough safety margins to withstand any likely future. (This embodies the traditional engineering mindset, with an emphasis on over-dimensioning). Alternatively, building on insights derived from the Adaptation Tipping Point timelines presented in Section 4.3.3, one may chose to embrace a more adaptive approach, acknowledging that a robust structure may represent an over-investment and hence placing more emphasis on designing for the best-available current information and making changes as needed. This could be embodied by an *adaptive design,* that is sized for the best currently available knowledge of the future and will be adapted as needed as the future unfolds. (This embodies the wait-and-see mindset, and could hence also be called a reactive adaptive design). Finally, one could go one step further in preparing for the future by choosing to include an option within the initial structure: this *flexible design*, is sized only for the short-term, but incorporates options to easily adapt in the future. One could also term this a proactive adaptive design.

The generation of those most promising flexible variants is not obvious. de Neufville and Scholtes (2011) provide an overview of available methods (summarized in Table 4.2) by which those flexible variants most worthy of further consideration can be identified. Additionally, while by no means comprehensive, Table 4.3 compiles a list of possible sources of flexibility derived from the existing literature that can be used to seed the approaches presented in Table 4.2. Taken together, these tables provide insights as to how more adjustable or flexible variants of otherwise relatively standard infrastructural investment plan could be derived in practice.

Table 4.2: Possible approaches to identify flexible design variants

(Source: adapted from de Neufville and Scholtes, 2011)

Approaches to Identify Flexible Design Variants	Description
Expert consultation	The use of a simple conceptual model of the problem and facilitated out-of-the-box thinking by decision support analysts, designers and decision makers can be used to generate possible case-specific flexible design variants for further detailed analysis. Cardin *et al*. (2013) look in more detail at factors affecting the eventual success of such guided, collaborative design-generating consultation exercises.
Use of optimization-driven screening models	Screening models are simple representations of more complex models, which allow rapid completion of many thousands of model runs to screen a large feasible region of possible designs. Optimization identifies the design variants that are most desirable according to user-specified objectives, thereby populating a short-list of designs for further analysis.
Use of patterned search screening models	Patterned search systematically tries out and evaluates different user-defined designs, based on industry specific insights derived from conceptual models or previous comparable projects. There is no mathematical process that explicitly hunts for an optimum, rather, portions of the design space presumed to be desirable based on existing insights are systematically explored.

Table 4.3: Possible sources of flexibility in the design of water resource infrastructure systems

Possible Sources of Flexibility	Description
Phased investment	Conducting design and investment decisions in phases allows system managers to resolve some degree of uncertainty about future developments by monitoring and collecting additional data. E.g. increasing the height of levees every 20 years, when necessary, instead of designing a levee to withstand uncertain water levels 100 years from the present Such a phased approach may forego some economies of scale associated with a single large investment.
Modular design	The use of modular designs facilitates the addition of extra modules after initial construction. E.g. if all pump facilities in a certain management area are comprised of similar two-pump modules, there are efficiencies to be gained from learning rates associated with the consistent use of the same modules.
Option to expand	By building in the capacity to expand at a later date, infrastructure can be built smaller initially, reducing the up-front investment and enabling growth in response to favourable future conditions. E.g. The Ross Dam in Washington State was built with the option to expand the dam's height: "the dam was designed with a unique concrete waffle facing in order to accommodate future additions on the top of the first stage" (Simmons,1968).
Option to add additional functionality	By allowing for the addition of future functionalities to a structure, infrastructure will remain functional over a wider range of possible future developments. E.g. For instance, in the Netherlands, there is a gradual trend towards multifunctional levees, that offer not just a flood defense function, but are used as recreational areas and for parking, among other uses. The reservation of land adjacent to a levee can safeguard the flexibility to make functional changes in the future.

4.4.2 Evaluate alternatives, making explicit any added value from including proactive options – Engineering Options Analysis

Within this step, a quantitative comparison of the expected performance of the different possible replacement strategies is performed. The intention here is to provide insights about a number of different questions that are of interest to decision makers when weighing different possible courses of action, including

- How do the relative lifetime (economic) performance of the different alternatives compare?
- Which alternative performs best under which future conditions?
- Which functionalities are most dramatically impacted by uncertainties about future conditions?
- Are there any designs that perform well under all future conditions explored?

Exploration of questions such as these to support decision making is fairly standard in many existing decision support tools, such as quantitative decision analysis. However, where the approach developed here goes one step further is in its ability to quantify the added value that comes from crafting structures that proactively support future reconfiguration and capacity expansions. In other words, not only is the economic performance of different courses of action of interest to us, but so too is the comparison of different more and less flexible variants. Hence, the results of this comparative step can provide additional insights, such as

- How does the relative lifetime economic performance of flexible replacement designs that explicitly incorporate the ability to respond to different intervention moments compare to traditional, less flexible ones?

- Does flexibility through the inclusion of engineering options always add value, as compared to less flexible variants without options? If not, under which conditions does flexibility add value- i.e. when is the added up-front cost of incorporating an option outweighed by the expected future benefits?
- Is the value of flexibility function specific?
- How do different sources of uncertainty affect the value of flexibility?

Again, given the diversity of water resources applications this approach could be used for, the details of the particular modelling arrangement will vary on a case-by-case basis. However, in general, in order to conduct such a quantitative evaluation, two primary model components are necessary:

- **A physical performance module** that links changes in future operating conditions such as regional socio-economic growth or altered climate conditions to performance indicators of interest, such as water level return periods at a certain location. Some model of this kind is typically already required to conduct the analysis of functional Adaptation Tipping Point described in Step 3 in Section 4.3. However, a typical analysis of Adaptation Tipping Points focuses on the occurrence of the first ensuing set of Adaptation Tipping Points, identifying when a structure is first expected to be unable to perform as desired. i.e. given the characteristics of a current physical structure or management strategy, when will the degree of external change be such that it first becomes unable to perform as required? However, within the novel planning approach developed here, we are interested in not just the first set of ensuing Adaptation Tipping Points for a particular structure, but in the interplay between how actions taken at such an Adaptation Tipping Point affect the occurrence and timing of future Adaptation Tipping Points. Thus, it is not enough for this model component to simply indicate under what future conditions the current physical system becomes inadequate, but must also capture how different possible courses of action affect the performance of the system in the future. In other words, at an Adaptation Tipping Point, one could envision two possible courses of action, A and B, with A costing $x and B costing $y: the model developed must be able to provide insights about how long we expect action A to perform as desired as compared to B, under a wide range of future conditions.

- **An evaluation module** that is able to compare different courses of action on the basis of whichever metric(s) is (are) considered to be most suitable. A standard approach is to use an economic model to do this, which could be in the form of a Cost Benefit Analysis, some kind of multi-objective analysis, a Cost Effectiveness Analysis or a life cycle cost analysis.

Figure 4.5 shows the role of these two models within the overall analytic framework underlying the planning approach developed in this work.

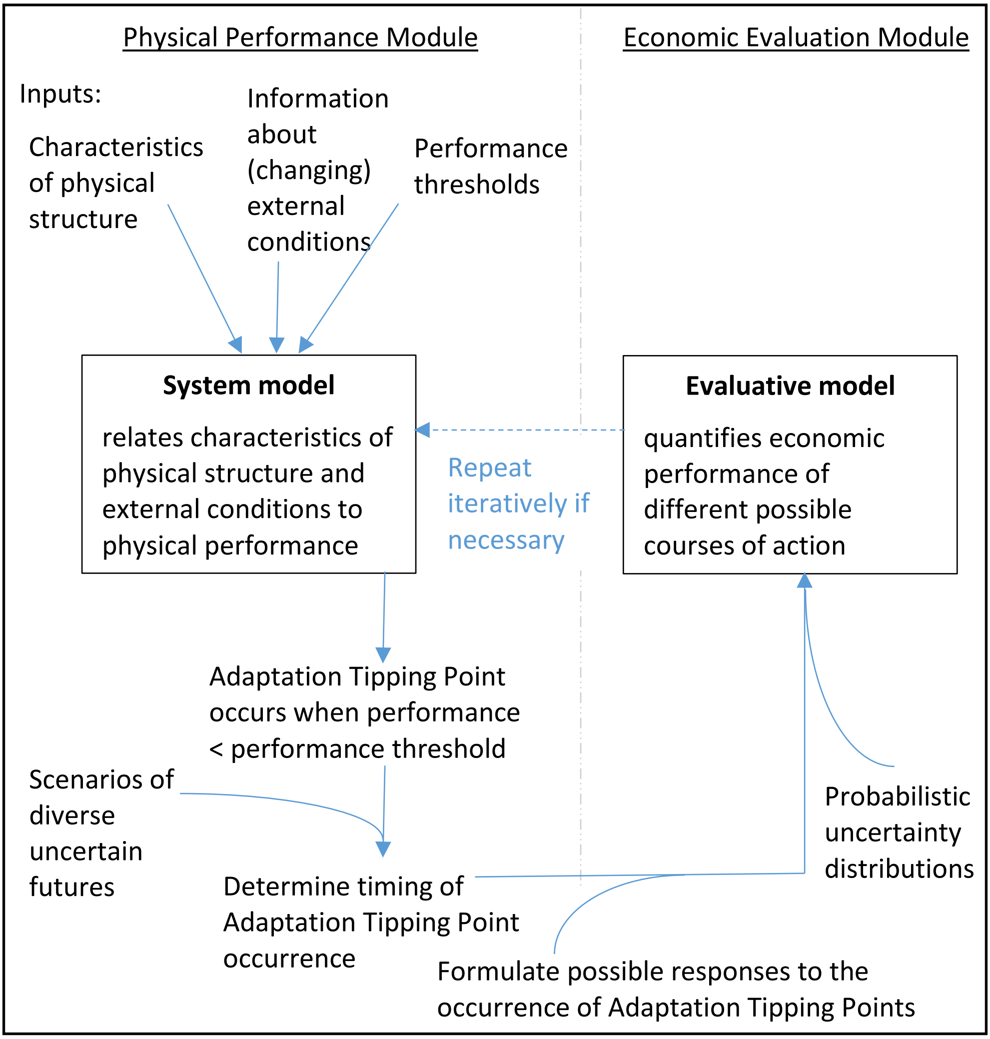


Figure 4.5: Conceptual overview of the components of the long-term infrastructural planning approach developed here

Having introduced the generic two-component model core above, a number of more specific additional modelling considerations are presented and discussed below.

The role of decision rules

Typically, within modelling formulations such as the one described above, some form of decision rule is used to indicate the conditions under which changes to the infrastructural system become necessary, and what actions are subsequently undertaken. A generic example of a decision rule could be in the form of an IF statement that triggers a specified action only when certain sets of conditions are met. For instance: IF performance of structure X during time interval t is less than a threshold minimum performance level, THEN structural intervention should be carried out in t+1, ELSE do nothing.

Revisiting the formulation of an Adaptation Tipping Point provided previously in Section 4.3 (i.e. $if\ P^{t}_{received,\ f} < P^{t}_{desired,\ f}$ then an Adaptation Tipping Point occurs), it should be obvious that the occurrence of such Adaptation Tipping Points is by definition equivalent to the IF portion of this generic decision rule (i.e. “IF performance of structure X during time interval t is less than a threshold acceptable performance level”). In other words, the occurrence of Adaptation Tipping Points has already implicitly incorporated two key elements necessary for the formulation of a decision rule, namely a quantitative measure of performance and a relevant threshold value. By going one step further and linking these previously determined Adaptation Tipping Points to specified courses of action that will be taken when an Adaptation Tipping Point does occur, one has all the necessary components to fully describe a decision rule.

Thus, Adaptation Tipping Points form the basis of decision rules and hence intervention moments in the timeline and serve as trigger moments in the economic analysis, indicating when changes should be made to a structure. In other words, the long-term strategic planning timeline developed in Section 4.3 and the subsequent quantitative economic analysis of different possible courses of action described in Section 4.4 are linked through the occurrence of an Adaptation Tipping Point, as captured within a decision rule.

The choice of optimization versus simulation

The generic two-component model described above can be formulated and run in a number of different ways.

One could envision setting it up as an optimization model, whereby within each scenario the alternative and variant with the lowest lifetime costs or highest lifetime ENPV are identified. Differing results across scenarios could be reduced to one suggested course of action by using Wald's Maximin criteria (Wald, 1945), Maximin Regret (Savage, 1951) or some other form of robust optimization. Optimization tools are often favoured in engineering applications because they are able to cope with large, multi-dimensional feasible regions, returning a single "optimum" solution, or a Pareto front of best possible multi-objective solutions.

However, work by Rogers and Fiering (1986) explored reasons why, at the time, the use of optimization remained relatively rare in practical water resources applications. They reached the conclusion that the indiscriminate search for a global optimum often produced models that did not reflect what decision makers cared about and necessitated substantial assumptions about constraints and parameter values. They pushed for greater consideration of near-optimal solutions and for simpler, more transparent models that generate more true insights into decision making and tradeoffs, rather than one single, neat "optimum". Almost three decades later, with computing power and capabilities now vastly improved, Jeuland and Whittington (2014) continue to express similar concerns:

> "We do not try to determine economic optimality across alternatives in a formal sense because we do not believe systems-optimization approaches are likely to be compelling to decision makers. This is because: (1) we find that no single alternative dominates others across a range of plausible future scenarios; and (2) we believe that neither decision makers nor planners are likely to be satisfied with optimal choices that follow from assignment of essentially arbitrary probabilities to future changes in hydrology and anticipated water demands. [] Indeed, it makes little sense to speak of optimal alternatives if optimality depends on what is assumed about a highly uncertain future."

In response, this work choses to utilize an exploratory, Monte Carlo simulation based approach to long-term infrastructure planning, as opposed to an optimization set-up. As explained above, there is no structural reason why the approach developed here could not be run as a formal optimization problem. Rather, the form of the results produced from a simulation-based approach is more useful within this work for the following reasons:

- The output of Monte Carlo simulation is in the form of complete probability distributions of different alternatives' performances, rather than the identification of a single optimum alternative. By explicitly tracking distributions of results, decision makers are able to observe economic trade-offs emerging from the results, as well as evaluate together with stakeholders what trade-off balance is most desirable. For instance, Figure 4.6 shows some generic cost modelling output. The purple alternative is associated with the lowest total cost and thus a generic cost minimization optimization formulation would produce this alternative as optimal. However, it may be of interest to a risk averse decision maker to know that there exists a sub-optimal red alternative, whose average total cost is only 5% higher than the purple alternative, but is associated with a substantially narrower range of outcomes than the purple alternative. By running this analysis as simulations, and presenting these results in this way, it is immediately visible how the different options perform in relative terms across an entire spectrum of uncertain futures. In addition, by presenting distributions of performances for all alternatives considered, it is easier for decision makers to qualitatively trade-off factors not directly incorporated into the modelling (e.g. social acceptability of different options) with factors that are captured directly by the modelling output (e.g. cost). So for instance, decision makers may decide to proceed with the red alternative on Figure 4.6 below, which despite being sub-optimal in terms of average performance, is associated with a narrow range of possible performances and has a much higher political or social acceptability associated with it than the optimal purple alternative.

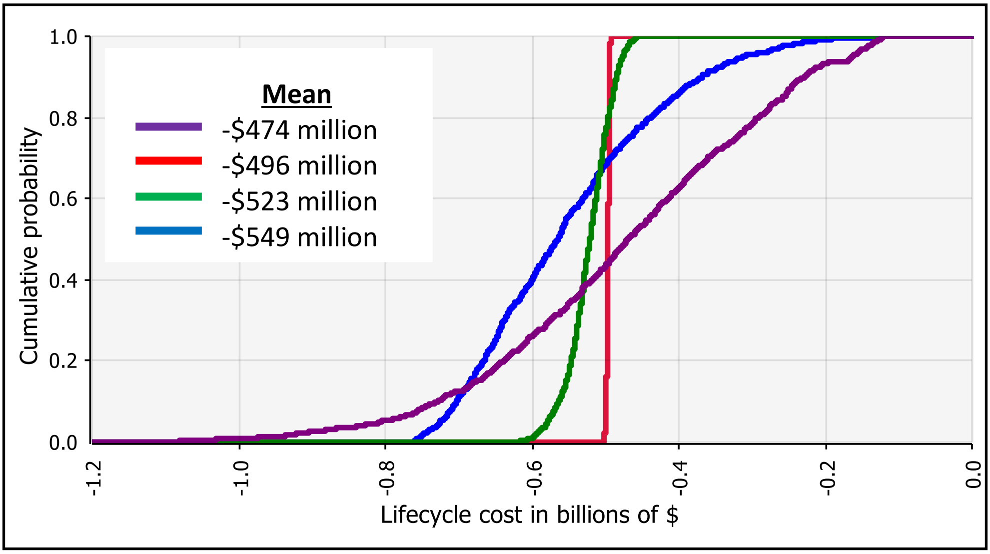


Figure 4.6: Sample results demonstrating how simulation may provide more useful output for decision makers than optimization

- Furthermore, simulation has the computational advantages that it can be used to model systems governed by unusual probability distributions, as well as variables like precipitation that are governed by complex functional forms.

Thus within this work and the proof of concept demonstration presented in Chapter 5, the two-part model core described above is run many times using Monte Carlo simulation to evaluate the physical and economic performance of different alternative courses of action over the duration of a specified project horizon, over many possible futures, within each specific scenario in turn. Given that one simulation explores one possible uncertain future state of the world, it is necessary to run a sufficient number of simulations to adequately sample all possible futures. For consistency, each alternative course of action as well as the different variants thereof should be exposed to the same set of simulated futures, so as to compare their relative performances across the same selection of future conditions. This is repeated for each distinct scenario in turn. As discussed in Section 4.2, this joint use of distinct scenarios with probabilistic uncertainties is a pragmatic way of acknowledging the existence of deeply uncertain variables, while still using some degree of quantitative, probabilistic analysis where relevant. However, a shortcoming of this simulation-based approach is its reliance on probability distributions: if every relevant variable in an analysis is considered to be deeply uncertain, Monte Carlo simulation is no longer possible.

Choice of economic performance metric

As in any economic analysis, there are a number of different performance metrics that can be used, including ENPV, Standard Deviation, minimum and maximum, Capital expenditures (CAPEX) and Operating expenditures (OPEX) or Value at Risk (VaR) and Value at Gain (VaG) (e.g. the 5^{th} and 95^{th} percentile of the cumulative NPV respectively). The exact choice of which of these to use depends to some extent on the particulars of the problem being explored. However, in all cases more than one single metric should be utilized. The reason for this was previously demonstrated on Figure 4.6, where consideration of the mean alone ignored the fact that the alternative with the best mean value was associated with the largest total range and standard deviation, potentially making it less desirable to a risk averse decision maker.

Estimating the cost of alternatives

When attempting to conduct a meaningful evaluation of the role of flexibility in the form of engineering options within a structure, it is important to use appropriate cost information. Specifically, it is crucial that the cost estimation methods used adequately capture relevant structural economies of scale and can be applied to non-traditional designs, such as a structure with a larger than usual foundation enabling a height addition, with extra pump bays enabling easy expansion of pumping capacity or with specialized hydropower turbines designed to work over a wider range of water heads that is typical. Fundamentally, economies of scale within the structure push the balance in the direction of building big and building once, whereas the resolution of uncertainty over time and the possibilities that are afforded by keeping options open push the balance in the direction of building more modestly and investing in sources of flexibility.

Lindsey and Walski (1982) identify three general ways of constructing engineering cost estimates:

- *The historical data approach*, where data analysis of completed projects provide insights about the cost of future projects
- *The parametric approach*, where the cost is estimated as a function of a small number of key design parameters that are known early in a project's development e.g. cost =f(pumping capacity)
- *The cost-element approach*, where the quantity of every item required is determined and then multiplied by per unit costs to obtain a total cost. The per unit price can itself be a function of the required quantity

As discussed further in the proof of concept demonstration presented in Chapter 5, currently, planning agencies typically use linear per unit parametric cost estimation methods to explore different infrastructural project alternatives- an approach that is unsuitable for this work because it does not adequately capture economies of scale. In addition, the reliance of the historical data approach on actual past projects, makes its usefulness for costing options unlikely. Thus, it is likely that the cost-element approach is the most promising one to pursue for cost estimation in this context. The absence of cost estimation methods that can adequately capture economies of scale and can be applied to non-traditional designs is a substantial hurdle that many agencies would have to overcome if they chose to adopt an approach such as the one developed here.

Discount rate considerations

The choice of discount rate is one of the most controversial inputs to any economic evaluation, especially when considering multi-generational issues such as climate change:

- Stern (2006) advocates for a value of around 0% when looking at long-term climate related questions;
- Nordhaus (2007) pushes for a rate of 3%, declining to 1% in 300 years;
- many government agencies continue to use values greater than 5%
    - for civil works projects, Rijkswaterstaat typically uses 5.5% (=2.5% risk free rate + 3% risk adjustment) when conducting cost-benefit analyses and 2.5% for life cycle cost analyses (Rienstra and Groot, 2012);
    - federal projects in the US typically apply a 7% discount rate (Department of the Army, 2012), with the exception of water resources projects managed by the US Army Corps of Engineers, for which the discount rate is recalculated annually (the rate was 3.125% in 2016) (CRS, 2016).

The economic research community remains actively involved in exploring this question of discounting. Varian (2006) conclude that "[t]here is no definitive answer to this question because it is inherently an ethical judgment." As such, this work does not attempt to offer any new insights about what the most suitable discount rate to use is, beyond reiterating the widely stated caution that it is wise to conduct thorough sensitivity analysis irrespective of the exact percentage value chosen.

In addition to the choice of discount rate, it is necessary to address briefly the question of risk. When considering two assets, one more and one less risky, a risk-averse investor will not treat them as equal. Typically, riskier investment are associated with the use of a higher discount rate than less risky investments. This higher discount rate is known as the risk-adjusted discount rate and is equal to the risk free rate plus some calculated risk premium. Within this work, this means that when comparing different alternative courses of action, as well as different more or less flexible variants, some may be riskier than others and thus warrant the use of a different discount rate. Within economic applications, a number of different procedures exist to compute the value of the risk premium and thus estimate the appropriate risk adjusted rate. However, these methods are based on a number of fundamental assumptions, including the existence of a market in which the objects being valued are openly traded. de Neufville and Scholtes (2011) and Cardin (2014) provide a more complete discussion of these issues and they ultimately reach the conclusion that these assumptions simply do not apply when talking about large-scale engineering systems. For instance, is there a clear market in place when talking about one-of-a-kind, large-scale engineering structures? Within the growing literature where engineering options are evaluated, the use of fixed discount rates is increasingly accepted (e.g. de Neufville and Scholtes, 2011 and Cardin *et al.*, 2015) and this same approach is taken here.

Interpreting results and how they are useful for decision makers

Finally, a short note regarding how to interpret the results obtained from this evaluative step. In general, the outcome of this step is in the form of a number of distinct, scenario-specific distributions of the economic performance of different alternative courses of action and different more or less flexible variants. Different insights are obtained by looking at results for each scenario in turn versus looking at results across all scenarios examined.

Firstly, within any given scenario, results are probabilistic, providing an indication of the distribution of possible outcomes within a future state of the world. Within individual scenarios, the performance of different courses of action can be directly compared on the basis of a number of different metrics, similar to how alternatives are compared in other standard economic analyses, such as cost-benefit analyses. Additionally, within individual scenarios, one can compare the performance of more or less flexible variants of a single course of action (e.g. baseline alternative = replace structure; more flexible variant = replace structure, embedding option to expand). In particular, given that this work emphasizes the role of flexibility in infrastructure planning, it is of interest to estimate the added value from the proactive inclusion of options. As discussed in detail in Section 3.2.1, while the study of options analysis has seen the development of a number of different techniques aimed at valuing options, they have limited relevance for valuing engineering options, given that the fundamental economic assumptions underlying these methods simply do not apply when looking at engineering structures. de Neufville *et al*. (2006) suggest that the value of added flexibility can be estimated by comparing the economic performance of a baseline "inflexible" course of action, with a more flexible variant of that same course of action:

$$\text{Value of flexibility} = \text{Value}_{\text{flexible variant}} - \text{Value}_{\text{baseline design}}$$

A value of flexibility <0 means the inclusion of an option costs more up-front than it ever delivers over the lifetime of the structure; a value of flexibility =0 means that the baseline alternative and flexible variants perform similarly, while a value of flexibility >0 means that incorporating flexibility into the system delivers more benefits than it costs.

By design, the development of alternatives described in Section 4.4.1 sought to create sets of alternatives coupled with more flexible variants of these same alternatives, which subsequently lends itself to this method of estimating the added value of flexibility. Thus, by comparing each scenario in turn, one is able to gain information about which alternatives perform better than others, and which options are worth investing in because they add value relative to the less flexible baseline design.

Moving on to look at results across scenarios, it is important to remember that scenarios as used here are not probabilistic in nature. They simply indicate diverse possible future states of the world. Visual inspection of results across scenarios can provide an indication of how and to what extent results vary across futures, without needing to assign likelihoods. These inter-scenario results can provide an indication of which sources of uncertainty have the biggest impact and can help identify courses of action that perform well across all future scenarios. These inter-scenario results could form the basis of further analyses, if desired. For instance, Jeuland and Whittington (2014) utilize Robust Decision Making at the end of their scenario-based analysis, to help select a course of action given that no single alternative dominates across all futures.

4.4.3 Sensitivity analysis

In order to give an indication of the robustness of the results obtained to uncertain parameter variations, thorough sensitivity analysis should be conducted to delineate the range of values that uncertain parameters can take on before resulting in a substantially altered conclusion. This step is exploring the steepness of the response curve to different inputs, and can be seen conceptually as exploring the nature of the "near-optimal" region. "Decision models should be used to generate several alternative optimal or nearly optimal solutions that can then be considered by decision makers in the light of relevant non-quantifiable criteria" (Harrington and Gidley, 1985). A commonly used approach to conducting sensitivity analysis involves varying each uncertain parameter, one-factor-at-a-time.

4.5 Step 5: Make and implement a decision; monitor, evaluate and review

Finally, the insights obtained from the Adaptation Tipping Point timeline and quantitative options analysis described above need to be translated into the making and implementing of a decision. The process of reaching a satisfactory decision is not discussed in detail here, given the preferential focus of this work on the development of a decision-support planning framework which produces supporting information on which to base a decision. Once decision makers have reached a decision, other implementation issues should be considered in more detail, including among others, financing and stakeholder engagement.

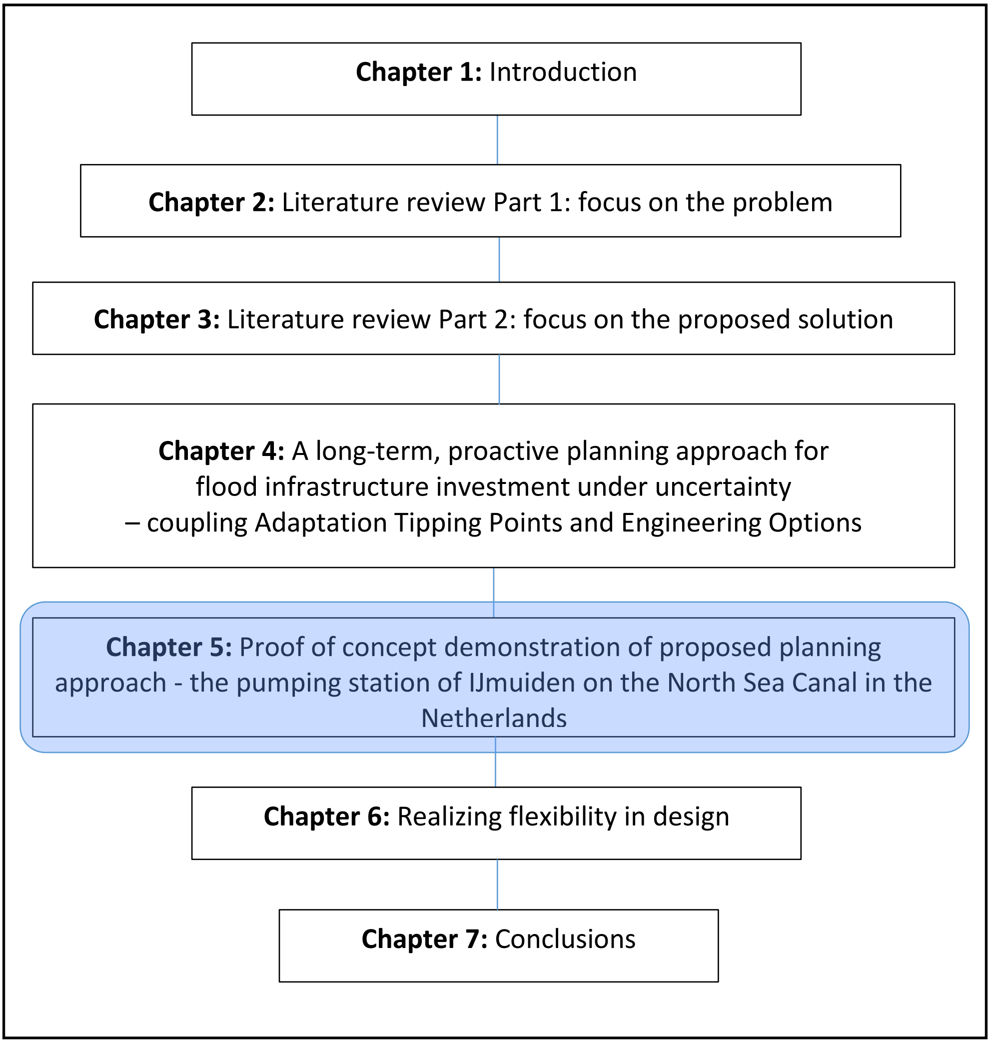
Given the more incremental and adaptive nature of the planning approach described here as compared to traditional approaches to infrastructure investment, it is important that a comprehensive monitoring plan is designed and implemented. It should be determined who is responsible for monitoring, which parameters are of most relevance to include in a monitoring plan, suitable monitoring intervals as well as who will finance ongoing monitoring. Updated insights gained from such a monitoring plan are key in informing when existing options should be exercised.

Finally, as described by Gilroy *et al.* (in preparation), it is important that any decision is also appropriately "institutionalized", meaning that it should be fully integrated into the existing regulatory, institutional and governance landscape. In some cases, this may mean making changes to existing procedures.

4.6 Looking forward: proof of concept demonstration of this new planning approach

Chapter 4 presented details of the new hybrid planning approach that this work develops. Specifically, Adaptation Tipping Points were used as the vehicle by which to incorporate different drivers of reinvestment into one single planning framework, while Engineering Options provided a means to operationalize a more adaptive and anticipatory approach to long-term infrastructure planning. Given the case-specific nature of most water resources problems, the novel infrastructural planning approach was presented here in general terms. To demonstrate these concepts in a more concrete and applied way, Chapter 5 presents a detailed proof of concept demonstration centered on the application of this new approach. The demonstration looks at the replacement of the IJmuiden pumping station on the North Sea Canal in the Netherlands.

5. A proof of concept demonstration: replacement planning for the pumping station of IJmuiden on the North Sea Canal in the Netherlands[35]



[35] This proof of concept study was developed during time spent as a visiting researcher at Rijkswaterstaat and Delft University of Technology in the Netherlands.

Chapter 5: A proof of concept demonstration of the proposed planning approach focusing on the structure scale

5.1. Problem definition

- identify structure of interest
- identify functions fulfilled by structure(s) of interest
- determine project horizon

5.2. Uncertainty analysis

- identify relevant sources of uncertainty
- characterize deep uncertainty as scenarios and remainder as probability distributions

5.3. Develop a long-term strategic planning timeline – using Adaptation Tipping Points

- when are interventions required for structural reasons?
- when are interventions required for reasons external to the structure?
- put these together to develop a long-term strategic planning timeline

5.4. Formulate, evaluate and compare different replacement strategies - using Engineering Options analysis

- based on the timeline, formulate alternative courses of action and seek more flexible variants
- evaluate alternatives, highlighting the added value from flexibility
- conduct sensitivity analysis

5.5. Developing a suitable cost model

5.6 Inland water regulation function
- Model formulation
- Results and conclusions

5.7 Flood defense function
- Model formulation
- Results and conclusions

5.8. Conclusions for IJmuiden

5.9. Reflections about the method as a whole

Chapter 4 presented the components of the long-term infrastructural planning approach developed in this work. This approach is illustrated here by systematically working through a real-world, contemporary proof of concept demonstration, namely the replacement of the pumping station at IJmuiden, located on the North Sea Canal in the Netherlands. The first portion of this proof of concept demonstration closely mirrors the structure of the general methodology described in Chapter 4: Section 5.1 introduces the case, identifying the structure of interest and its functionalities. Section 5.2 characterizes the relevant sources of uncertainty. Section 5.3 conducts an analysis of relevant Adaptation Tipping Points, constructs prognosis timelines and discusses relevant insights. Building on insights from this timeline, Section 5.4, generates possible replacement structural designs and evaluates their performance under a multitude of future conditions. The remainder of the chapter deviates from the general approach outlined in Chapter 4: Section 5.5 describes the novel cost model developed for this work; Section 5.6 and 5.7 provide the model formulation and results for each of the two structural functions in turn, with Section 5.8 and 5.9 offering conclusions and reflections respectively.

It must be stated here that the central intent of this work is not to identify and provide a detailed, well-substantiated preferred course of action for how to proceed in the reinvestment/replacement process for the pumping station of IJmuiden. Instead of a precise, actionable solution, the objective here is to provide a sample application of the proposed planning approach described in Chapter 4, highlighting strengths, new insights and areas where further work is required. Thus, where necessary, simplifications and assumptions are made to reduce complexity and fill data gaps, in order to demonstrate fully the novel planning approach central to this dissertation.

5.1 **Step 1:** Problem definition

As introduced in Chapter 4.1, the first step in the proposed infrastructural planning approach is a general problem definition step.

5.1.1 What is the structure of interest and its relevant background?

In the early 1800's the rapid growth and development of the city and port of Amsterdam were stalled by their reliance on a long and unreliable shipping channel that saw them having to traverse the swampy inland Southern Sea *en route* to world markets (shown in red on Figure 5.1).

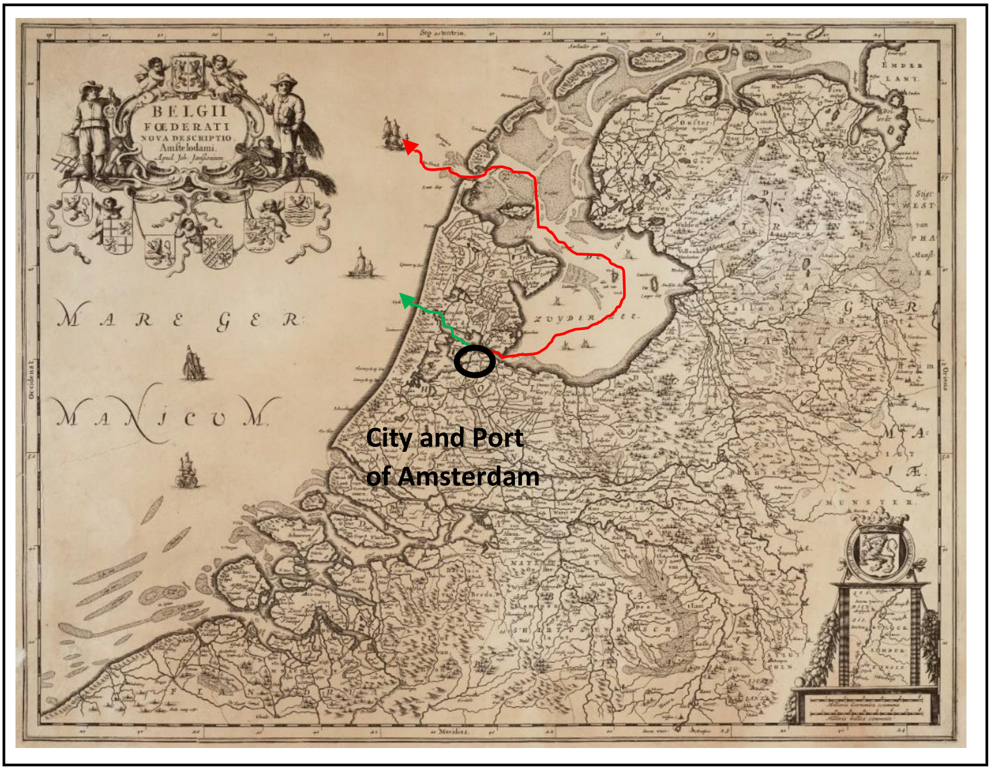


Figure 5.1: Map showing the historical Southern Sea shipping route (red) and the proposed North Sea Canal shipping route (green) (Source: adapted from Janssonius, 1658)

In 1865, construction of a canal, cutting through the narrowest stretch of land between Amsterdam and the North Sea was initiated (shown in green on Figure 5.1). Eleven years later, the North Sea Canal was complete, finally linking the North Sea directly to the city and port of Amsterdam. Many decades later, the North Sea Canal, was connected to the Amsterdam Rhine Canal, which links the city/port of Amsterdam to the Waal River and German trade markets to the southeast (see Figure 5.2). Today, the North Sea Canal and Amsterdam Rhine Canal (shortened from now on as the NS-AR Canal) are in open connection with each other and must thus be treated as one hydrological unit.

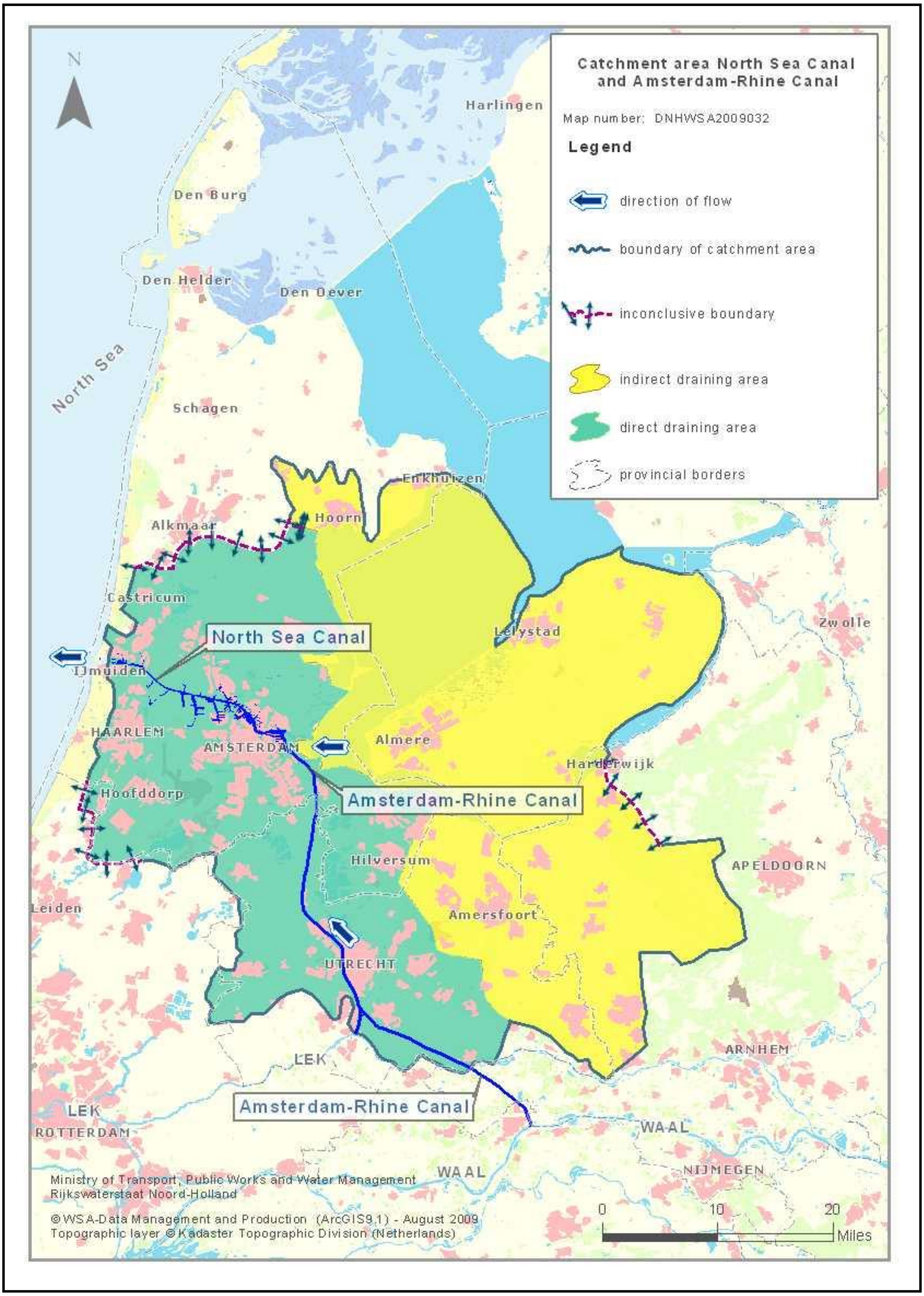


Figure 5.2: Map showing the location of the North Sea and Amsterdam-Rhine Canals (Source: Ministry of Transport, Public Works and Water Management, 2009)

Historically, the coast of the Netherlands was protected from high tide and storms on the North Sea by a wide swath of natural sand dunes running parallel to much of the coastline. During construction of the North Sea Canal, it was necessary to pierce this frontline component of the country's flood defense system in order to allow ships to enter and exit the canal. At this location, known as IJmuiden, a set of shipping locks were built, balancing the need for shipping access to the canal with the necessity to maintain appropriate defenses to keep sea-water out of the hinterland.

While the canals were first built to facilitate shipping, over time, increasing volumes of precipitation runoff were channeled from the city of Amsterdam and surrounding areas into the North Sea Canal. Gradually, the canal's role in inland water level management grew in importance as the canals form a key discharge route for the transport of precipitation runoff to the North Sea (the catchment areas from which precipitation runoff drains into the NS-AR Canal are shown on Figure 5.2). In order to better regulate the surface and groundwater levels in the area, a set of discharge sluices were built at IJmuiden in 1940, to increase the volume of water that could be released from the canal at any given time. These sluices can transmit volumes up to 500 m^3/second, but can only be used at times when the canal water level is higher than sea level, as water must flow out to the sea under gravity. During high tide, instead of discharging canal water to the North Sea, it was instead channeled into the inland freshwater lake, the Marker Lake to the North. However, by the 1970's, environmental concerns were growing about the release of brackish water from the canal into the freshwater environment of the inland Marker Lake. As more control over the water level in the canal was desired without relying on discharge to the Marker Lake, in 1975 a pumping station was constructed at IJmuiden, allowing water to be pumped out of the canal into the North Sea even when the sea level is higher than the canal water level.

With an initial pumping capacity of 160 m^3/second, which was expanded to 260 m^3/second in 2004, this pumping station is the largest in Europe and it plays an important role in water management regionally. With an intended design lifetime of approximately 80 years, the pumping station is expected to reach the end of its design life in the coming decades. This proof of concept demonstration focuses specifically on exploring different possible replacement strategies, as applied to the *pumping station of IJmuiden* and explicitly does not include the four existing and one under-construction shipping locks at IJmuiden, which are located in the vicinity of the pumping station.

5.1.2 What functions does the structure fulfil?

The pumping station fulfils a number of different functions, as shown in Table 5.1. However, this proof of concept demonstration limits itself to considering only two of IJmuiden's primary functions, namely the structure's role in *flood defense* and as a *regulator of inland water levels*. Two functions (as opposed to only one) were considered in this study because this multi-functionality is realistic and typical of complex water management cases. This explicit consideration of the multifunctional nature of structures is in contrast to previous work done by for instance Kwadijk *et al*. (2010), where the focus lies only on single functions, with no consideration of the multi-functional nature of infrastructure nor how the different functions interact with each other. While the remaining functions of IJmuiden could be incorporated into this study, two functions (as opposed to three or more) were chosen as no further methodological gains would be obtained by adding further functions to this analysis.

Table 5.1: Functions fulfilled by the pumping station of IJmuiden

Function	Further information
Flood defense	The structure serves as a barrier between the North Sea and inland areas, reducing the risk of flooding from high tide or storms on the North Sea.
Inland water level regulation	The structure enables the discharge of inland precipitation runoff to the North Sea. At present, approximately 69% of flows to the canal come from local precipitation, with remaining inflows either released purposefully from adjacent waterways to prevent saline intrusion or inadvertently as shipping traffic passes through locks (RWS-WNN, 2013). The inflows from precipitation runoff originate in a catchment area of approximately 2,300 km^2 in size (shown in green on Figure 5.2[36]). While there exist a number of outflow points, 95% of the water that accumulates in the canal is released to the North Sea via one single exit point, namely the IJmuiden sluice and pumping complex (RWS-WNN, 2013).
Water quality management	The structure separates the saline water of the North Sea and the fresher water in the canal, thus limiting the progression of saline intrusion further upstream. The bulk of the salt water in the canal originates from the shipping locks at IJmuiden. A constant minimum flow of water is maintained through the sluices/pumping station in an attempt to constantly flush out incoming saline water.
Ecological management	The structure facilitates the passage of fish through specialized fish ladders.

[36] Figure 5.2 separates the NS-AR Canal catchment area into a "direct draining area" shown in green and an "indirect draining area" shown in yellow. The green portion of the catchment represents those areas that always drain directly to the NS-AR Canal. In contrast, the yellow portion of the catchment represents additional surrounding areas that may drain to the NS-AR Canal indirectly via the Marker Lake. In times of extreme low water on the canal, water can be diverted from the inland freshwater Marker Lake into the canal so as to maintain the required water depth for shipping, and sustain minimum discharge rates at IJmuiden to prevent intrusion of salt water from the North Sea. Throughout this discussion of the inland water level management function of IJmuiden, the focus lies on situations of excess water and managing high water levels, with the impacts of reduced canal inflows and falling water levels not considered. Thus, while this indirect catchment area is shown for completeness on Figure 5.2, only the "full-time" catchment area in green is taken into account within the analyses presented here.

5.1.3 What is an appropriate project horizon?

Given that the intended design life of the pumping station at IJmuiden is approximately 80 years, within this proof of concept demonstration a time horizon of 85 years is used. As mentioned before, the exact length of the project horizon matters less, so long as the analysis covers the entire life-cycle of a structure, so as to be able to compare different replacement alternatives on the basis of total cost of ownership rather than initial capital costs alone.

5.2 Step 2: Uncertainty characterization

As previously described in the general planning framework in Chapter 4, characterization of those sources of uncertainty most likely to have an impact in the long-term infrastructural planning timeline is a crucial input for the remainder of the analysis presented here. In particular, different relevant sources of uncertainty are first identified, before classifying them into two separate types, namely those that are considered deep uncertainties for which there is no consensus about the future likelihood of occurrence and thus scenarios are used, and those uncertainties where probability distributions can be assigned with some confidence.

5.2.1 For each function, what are relevant sources of uncertainty?

Within this proof of concept demonstration, those sources of uncertainty with the largest potential impact on the long-term functionality of the pumping station at IJmuiden were determined through expert consultation. As shown in Table 5.2, these sources of uncertainty are function specific.

Table 5.2: Sources of uncertainty relevant for long-term planning for the pumping station of IJmuiden

Station Function	Source of uncertainty	Mechanisms by which uncertainty can have impact
Flood defense	Sea level rise	Affects the adequacy of the installed flood defense height.
Inland water level regulation	Sea level rise	Decreases the proportion of time that water discharges under gravity from the canal to the North Sea under gravity. In addition, when pumping is required, a higher sea level increases the pressure head and thus the hydraulic head between the canal surface and the sea surface, reducing the pumps discharge ability.
	Increases in precipitation intensity	Affects the volume of water entering the canal at any given time. Given limited storage in the canal, increased inflows may require expansion of existing discharge capacity.

Future socio-economic development in the region can also impact canal inflows and thus the ability of the pumping station to adequately regulate canal water levels. However, given that the catchment is already heavily urbanized, the impact of further development is not believed to be substantial, and hence this driver of uncertainty is not included in any of the subsequent analyses conducted here.

5.2.2 For those sources of deep uncertainty, derive future scenarios

Within this proof of concept demonstration, all uncertain climatic variables are treated as being deeply uncertain, namely sea level rise and precipitation. As described in Section 4.2.1, it is at present difficult to defend the assignment of probability distributions to deeply uncertainty variables, hence within this work, these are explored using scenarios. This case uses two sea level rise scenarios and four precipitation scenarios to inform its analyses over an 85-year project horizon, as presented later in Section 5.3 and 5.4. These scenarios, defined in Table 5.3, are by definition discrete and do not have probabilities assigned to them.

<u>Table 5.3: Definition of Scenarios, indicating amount of change by 2100, relative to 2015[37]</u>

Uncertain variable	Scenarios for 2100 relative to 2015			
Mean sea level	Low: +35 cm		High: +85 cm	
Mean precipitation	Low: Winter = +4.5% Summer = +1%	High: Winter = +12% Summer = -8%	Medium: Winter = +11% Summer = -4.5%	Extreme: Winter = +30% Summer = -23%

Note the correlation between these scenarios: while there are eight possible permutations of sea level rise and precipitation, there are in fact only four realistically possible joint sea level rise and precipitation scenarios, as shown by the columns above, namely (Sea level$_{low}$; Precipitation$_{low}$), (Sea level$_{low}$; Precipitation$_{high}$), (Sea level$_{high}$; Precipitation$_{medium}$) and (Sea level$_{high}$; Precipitation$_{extreme}$). Thus, for instance, the combination of (Sea level$_{low}$; Precipitation$_{low}$) is considered possible, but (Sea level$_{low}$; Precipitation$_{extreme}$) is not. This is caused by the physical mechanisms driving these models, such that for instance the relatively modest temperature change resulting in the Sea level$_{low}$ scenario is highly unlikely to produce the large changes in atmospheric circulation necessary to produce scenario Precipitation$_{extreme}$.

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[37] These scenarios draw upon country-specific climate scenarios developed by the Royal Netherlands Meteorological Institute (KNMI). They KNMI scenarios were created by taking existing general circulation model output, conducting high resolution nested regional climate model simulations and then finally downscaling the results and incorporating local observations, to apply specifically to the Netherlands. Details of the development of these local climate scenarios can be found in van den Hurk *et al*. (2006) who describe the initial development of the first set of Dutch climate scenarios in 2006, and KNMI (2012 and 2014) who describes changes and improvements incorporated in the 2014 climate scenarios. The sea level rise scenarios shown in Table 5.3 build on the 2006 KNMI scenarios while the precipitation scenarios are consistent with the 2014 KNMI scenarios.

By looking across all these scenarios, we can get a sense of how the performance of different courses of action varies across a spectrum of future scenarios, despite not having clear probabilistic information.

5.2.3 Within each scenario, estimate probability distributions for remaining uncertainties

Section 5.2.2 defined a number of scenarios describing possible future climatic conditions. As such these scenarios are deterministic and form the basis for an exploration of what would happen if each of these scenarios were to occur with certainty. However, as explained in Section 4.2.3, within each of the scenarios defined above, there remain additional residual sources of uncertainty. Thus, even within one single sea level rise or precipitation change scenario, the impacts of uncertainty and natural variability may be large. Within each of the scenarios defined above, the analysis included the following additional sources of uncertainty and natural variability as probabilistic variables:

- Uncertainty in the water heights associated with a particular flood return period,
- Natural variability in precipitation, and
- Uncertainty in the precipitation-canal inflow relationship.

These are described more fully in Section 5.5 below, where the specific model formulation is presented.

5.3 **Step 3:** Explore the long-term strategic planning timeline for the structure

Having defined the scale and nature of the infrastructural reinvestment question being explored in Section 5.1 and identified the main sources of uncertainty in

Section 5.2 above, the next step examines the different processes that influence the pumping station's long-term ability to continue to function as intended[38].

5.3.1 When are interventions required for structural reasons? – an analysis of Technical Adaptation Tipping Points

As defined in Section 4.3, a technical Adaptation Tipping Point is defined as occurring when the magnitude of physical deterioration of a structure is such that it is no longer able to fulfil the functions it was designed for. As described in Section 4.3.1, a number of specific techniques can be used to provide insights about the occurrence of such Technical Adaptation Tipping Points. This proof of concept demonstration, as a conceptual demonstration, uses the simplest of these estimation method, namely simply using the design life of a structure to estimate the moment when complete structural replacement is needed. There are many more sophisticated ways this can be done, and as such this is an area for future

[38] As previously indicated, this proof of concept demonstration was developed during time spent as a visiting researcher at Rijkswaterstaat and the Delft University of Technology in the Netherlands. Within Rijkswaterstaat, I was based out of a project named "Replacement of hydraulic structures" ("Vervangings Opgave Natte Kunstwerken" or VONK, in Dutch). From the perspective of Rijkswaterstaat, the objective was for me to explore the existing output from VONK and if possible use any appropriate elements of this output to conduct an economic evaluation of flexibility in the design of hydraulic structures using Engineering Options. This evaluation of flexibility is described fully in Section 5.4. However, the work presented in Section 5.4 builds on work done within VONK, in particular the so-called Sensitivity Test. Certain limited aspects of this work have been published in English (Kallen *et al.*, 2013; Bernardini *et al.*, 2014; Van Vuren *et al.*, 2015); other portions were published in Dutch (Nicolai *et al.*, 2014; Rijkswaterstaat, 2014); but in general there is no unified, appropriately detailed, case-specific description of the relevant material that formed the input for my subsequent analysis. Hence, this section and its associated appendices attempt to bring together the most central, relevant portions of the VONK output and explain their use within this proof of concept study and the broader planning approach developed in this dissertation. This is done all the while acknowledging that the results presented in Section 5.3.1 and 5.3.2 were initially conducted by Rijkswaterstaat and were remodeled and expanded here for descriptive purposes and to serve as input for my further analyses (e.g. those in Section 5.4).

improvement of this proof of concept demonstration. However, here the emphasis lies on demonstrating how the different components of this planning approach work together and the insights they provide.

Thus, given a construction year in 1975, and a design life of 80 years, a Technical Adaptation Tipping Point is estimated to occur around 2055. This is treated as representative of the moment in time when replacement of a structure first becomes necessary for structural reasons. Conceptually, the occurrence of a Technical Adaptation Tipping Point corresponds to the moment when, despite the structure being high enough to theoretically prevent sea water from entering and despite having enough installed pumping capacity to theoretically manage the inland water level, the structure is physically unable to meet the flood defense and water level regulation performance requirements due to its age and physical deterioration.

5.3.2 When are interventions required for reasons external to the structure? – an analysis of Functional Adaptation Tipping Points

As defined in Section 4.3, a Functional Adaptation Tipping Point is defined as occurring when the magnitude or degree of external change is such that a structure is no longer able to meet the level of functionality that users demand. These drivers of external change can be climatic, socio-economic or political in nature. In this section, the occurrence of functional Adaptation Tipping Points driven by only the impacts of gradual environmental change is examined. As the occurrence of Functional Adaptation Tipping Points is defined by function-specific performance objectives and governed by different physical processes, analysis of these Adaptation Tipping Points is conducted separately for the two functions of interest fulfilled by IJmuiden. Application of the general steps of the procedure for identifying Functional Adaptation Tipping Points (described in Section 4.3.2) and the subsequent results are summarized in Tables 5.4 and 5.5.

Table 5.4: Overview of the analysis to determine Adaptation Tipping Points for the *water level regulation function* of IJmuiden

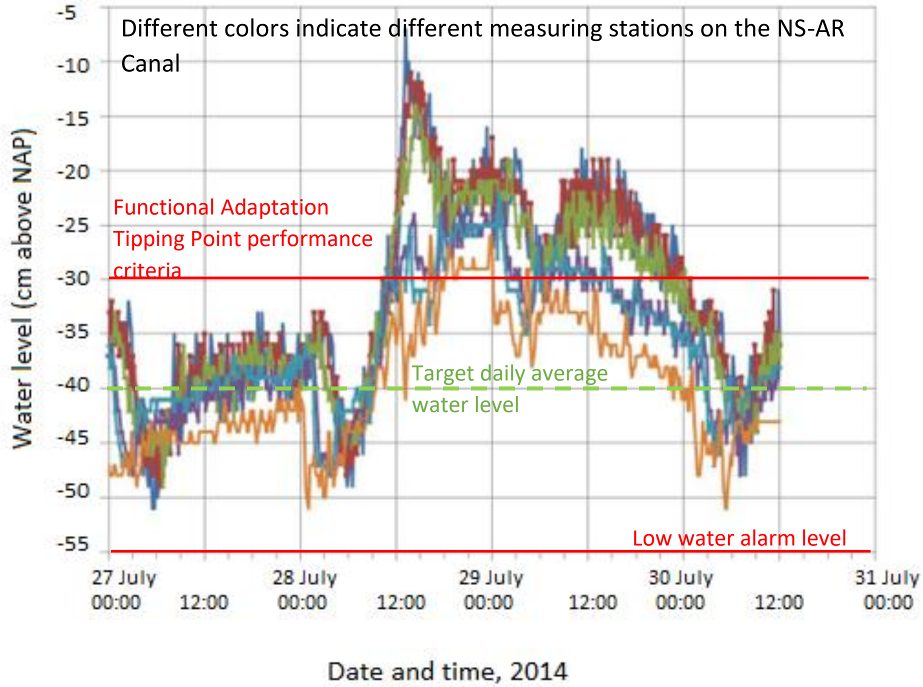
1. For each function, identify relevant quantitative performance indicators as well as the threshold performance level beyond which the system is no longer considered functional: Specifically, what are the maximum allowable water levels on the canal? How frequently can they be exceeded?
While clear, federally mandated performance requirements exist for structures in the Netherlands that have a flood defense function, these are much less well defined for the management of inland water levels. The 2013 Water Accord for the NS-AR Canal (Beuse, 2013), specifies a target daily average water level on the NS-AR Canal of -0.40 m NAP, with an acceptable range from -0.30 m to -0.55 m NAP. A water level of -0.30 m NAP or higher is considered an alarm threshold, and thus, in this work, compliance with the threshold water level of -0.3 m NAP is treated as the performance objective for this Adaptation Tipping Point analysis[39].
2. Identify what degree of external change results in the current physical system being unable to meet these performance objectives: Specifically, is the pumping station currently able to maintain the necessary water levels on the canal? Through what mechanisms do changed water levels in the future affect the structure's ability to regulate water levels on the canal?
First, recent historic water level data is explored to provide an indication of the extent to which the structure is currently able to fulfill the required performance

[39] This threshold level is only one of a number of performance objectives that emerged from a review of past studies and water agreements. These alternative objectives are discussed more fully in Section 5.6.3.

Table 5.4 (continued): Overview of the analysis to determine Adaptation Tipping Points for the *water level regulation function* of IJmuiden

objective. The most recent high water event occurred in July 2014, and according to the performance threshold defined above, a Functional Adaptation Tipping Point for the inland water management function of IJmuiden has already occurred prior to the present day: as shown in Figure 5.3, even under present-day operating conditions, the current structure is unable to maintain the necessary water levels on the canal. IJmuiden's continued ability to effectively manage water levels on the canal is primarily related to its ability to effectively discharge flow volumes during unusually wet periods of time. This in turn relates to the capacity to store or transport water through the system. The ability to change the storage capacity of the canal and densely populated surrounding areas is treated as negligible, thus the ability to adequately manage the canal water level in the future is related to the total discharge capacity installed in the sluices and pumping station. Given that rising sea levels will gradually reduce the proportion of the time when free flow discharge can occur under gravity, the *installed pumping capacity of the pumping station* will be critical in maintaining inland water levels given increased inflows and reduced opportunities to sluice water out. Thus, whenever the target water level on the canal is exceeded, the installed pumping capacity at IJmuiden is considered inadequate and a Functional Adaptation Tipping Point for the water level management function of IJmuiden is reached.

<u>Table 5.4 (continued): Overview of the analysis to determine Adaptation Tipping Points for the *water level regulation function* of IJmuiden</u>



<u>Figure 5.3: Water levels experienced on the NS-AR Canal during high water event of July 2014</u> (Source: adapted from Bottema, M., 2014)

3. Given different possible scenarios of future change, identify when in time external changes result in performance objectives no longer being met: Specifically, how are future changes in sea level and precipitation expected to affect water levels on the canal? When does the pumping station have insufficient discharge capacity to maintain the required water levels on the canal?
Having explored the present situation, the final step in an Adaptation Tipping Point analysis typically involves an exploration of future conditions and how vulnerable the function of interest is to external changes. However, as Figure 5.3 indicates, the installed discharge capacity at IJmuiden is even at present insufficient to ensure the water levels on the canal are maintained in accordance with the desired performance objectives. If expansion of the structure can already be considered in the present day, adding future changes such as sea level rise (which reduces the proportion of the time the sluices can be used) and increasing precipitation intensity (which will increase inflows to the canal) are expected to only make this need more pressing.

Table 5.5: Overview of the analysis to determine Functional Adaptation Tipping Points for the *flood defense function* of IJmuiden

1. For each function, identify relevant quantitative performance indicators as well as the threshold performance level beyond which the system is no longer considered functional: Specifically, what is the flood protection level to be provided by the structures at IJmuiden?
In the Netherlands, the flood defense level provided by any structure is mandated by federal law (the Flood Defense Act, 2009). IJmuiden is a part of the coastal dune protection system, which is required to protect against water levels on the North Sea that are exceeded on average once every 10,000 years.
2. Identify what degree of external change results in the current physical system being unable to meet these performance objectives: Specifically, is the pumping station currently fulfilling the necessary flood defense objective? Through what mechanisms do changed external conditions in the future affect the structure's ability to continue to meet the 1:10,000 year protection requirement?

First, the water level associated with a 1:10,000 year recurrence period is computed for present day conditions using the widely-used Hydra-K model, developed by Rijkswaterstaat. Figure 5.4 shows the current flood frequency curves for water levels on the North Sea at IJmuiden.

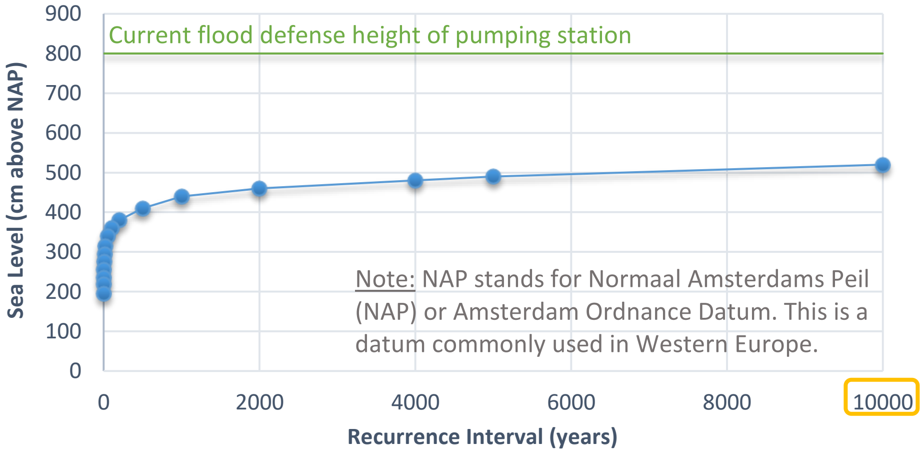


Figure 5.4: Water level-frequency curves for the North Sea at IJmuiden Buitenhaven, 2006 (Source: data is from Ministerie van Verkeer en Waterstaat, 2007)

Table 5.5 (continued): Overview of the analysis to determine Functional Adaptation Tipping Points for the *flood defense function* of IJmuiden

A number of different failure mechanisms can result in a hydraulic structure providing inadequate flood protection due to gradually increasing water levels, including overtopping the structure, seepage under the structure and structural instability resulting in tipping of the structure as a whole. Each of these failure mechanisms is driven by inadequacies in different structural variables: for instance, when looking at overtopping, the primary structural variable that is inadequate is the height of the structure, while for seepage, the depth of installed sheet pile is defining. Within this work, it is assumed that the primary failure mechanism by which the pumping station becomes unable to meet the 1:10,000 year protection requirement in the future is through overtopping by increasing water levels in combination with wave action on the North Sea. Thus, when looking at the flood defense function of IJmuiden, the continued fulfillment of this function is related to the *structure's height:* whenever the installed height of the structure at IJmuiden is lower than the best estimate of the 1:10,000 year water level at that time, a Functional Adaptation Tipping Point for the flood defense function of IJmuiden is reached and some sort of action to re-comply with this required performance level should be considered. Taking flood defense height as the indicator, a Functional Adaptation Tipping Point has not yet been reached for the pumping station: as shown on Figure 5.4, the current height of the structure is not yet exceeded by the 1:10,000 year water level.
3. Given different possible scenarios of future change, identify when in time external changes result **in performance objectives no longer being met:** Specifically, how are future changes in sea level expected to affect the water level on the North Sea that occurs, on average, once every 10,000 years? When is the pumping station no longer high enough to provide protection against the future 1:10,000 year water level?
Having explored the present situation, it is subsequently necessary to determine how the water level associated with this mandated 10,000 year return period is expected to change in the future. This is done using the sea level rise scenarios previously defined in Table 5.3: a low and high sea level rise scenario are considered, that assume respective increases in water levels on the North Sea of 35 and 85 cm by 2100. Insights about the effects that changing climatic conditions will have on water and flood management in the Netherlands are

Table 5.5 (continued): Overview of the analysis to determine Functional Adaptation Tipping Points for the *flood defense function* of IJmuiden

explored using the state-of-the-art Delta Model[40], developed by Deltares and Rijkswaterstaat. The water level associated with the 1:10,000 year return period has been computed for each of the two sea level rise scenarios defined, for several reference years (2015, 2050 and 2100) using this Delta Model, with the output shown in Figure 5.5. Data was linearly interpolated for all years in between model output years (i.e. 2015, 2050 and 2100) and a supplement was added to the model output to account for wave impacts not captured in the model. The historically calculated 1:10,000 year water levels (shown in grey) are included on Figure 5.5 as relative reference points. The final step to determine the imminence of a functional Adaptation Tipping Point occurring involves comparing the unchanging height of the pumping station at IJmuiden to the gradually increasing 1:10,000 year water level computed. This is done on Figure 5.5 and it is easily determined that under both sea level rise scenarios considered, the pumping station is expected to have sufficient installed height to afford the required 1:10,000 year protection level until after the end of the project horizon in 2100. This demonstrates that the occurrence of a functional Adaptation Tipping Point for the flood defense function and the subsequent need to heighten these flood defenses is not considered a short- term concern. These results also identify just how robust the current dimensions of the pumping station are when it comes to providing flood protection from the North Sea.

[40] The Delta Model is an integrated model that links a number of standalone models developed over the last decades to help support policy decisions relating to the long-term management of water resources in the Netherlands. It draws first on an integrated country-wide model system (NHI) that can simulate large-scale processes such as changing climatic conditions, differing water distribution and availability, altered demand for water, as well as explore the impacts of different management decisions. The output of this typically feeds into a 1-D or 2-D hydrodynamic surface water model (Sobek model) to calculate the subsequent impacts of these external factors on the water level, discharge and flow rates of surface water bodies. This in turn serves as input into a number of different possible effect modules, used to explore in more detail the impact of these expected changes on specific water management sectors such as navigation (BIVAS model), agriculture (AGRICOM), ecology (DEMNAT and HABITAT), among others. Further information about the Delta Model can be found in Prinsen *et al*. (2014) and Slomp *et al*. (2014).

Table 5.5 (continued): Overview of the analysis to determine Functional Adaptation Tipping Points for the *flood defense function* of IJmuiden

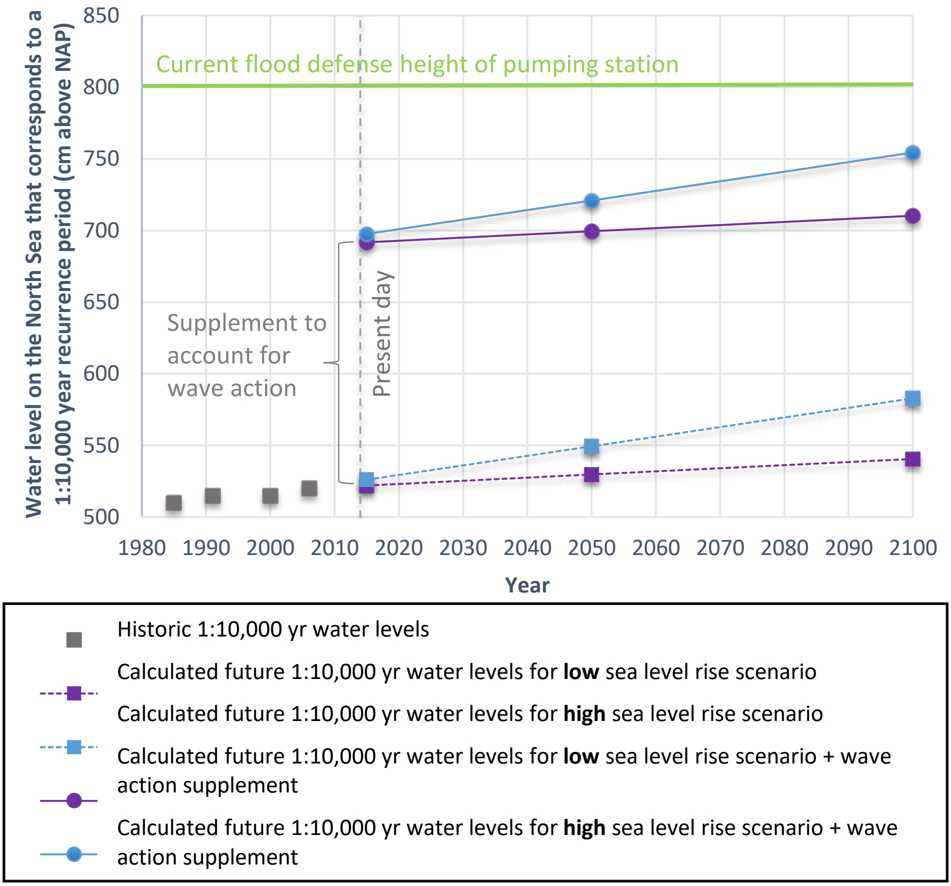


Figure 5.5: Future scenario-specific water levels on the North Sea at IJmuiden, corresponding to 1:10,000 year return period (Source: data from WTI, 2001 and 2006 and Deltamodel, 2014)

One observes conceptual differences between how Functional Adaptation Tipping Points are determined for these two different functions: while historic data suffices for determining that a Functional Adaptation Tipping Point has been reached for the inland water level regulation function, the flood defense function requires the use of statistical models in combination with the scenarios defined in Table 5.3. There are two primary reasons for these apparent differences in approach:

1. **The nature of the performance requirements for these two functionalities:** The performance requirement for the flood defense function is defined in the form of a water level associated with a certain recurrence period, 10,000 years in this case. As we do not possess 10,000 years worth of historic water level data, the estimation of the 10,000 year water level is a statistical extrapolation of a more short-term dataset. (Typical flood frequency analyses fit available data to a Log-Pearson Type III distribution). Implicit in this performance requirement is a residual risk and a possibility of failure than has been deemed acceptable i.e. water levels greater than the 10,000 year water level, while rare, can occur. In contrast, the performance level for the inland water regulation function is much more black-and-white: a functional Adaptation Tipping Point is defined as occurring after the first exceedance of a water level of -30 cm NAP on the canal, which can be trivially determined by comparing historic data/future model simulations to this threshold. A more involved statistical approach would be required and a very different picture could emerge if the performance objective for water levels on the canal was defined both in terms of water levels, as well as allowable exceedance frequencies.

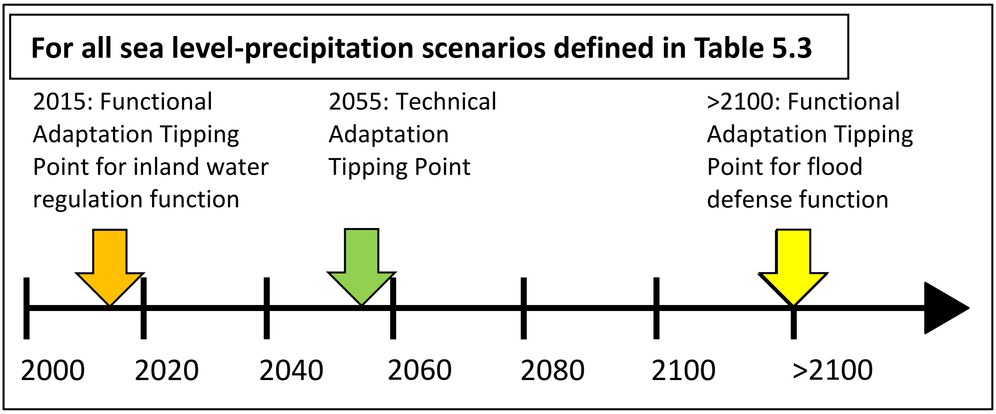
2. **The occurrence of a Functional Adaptation Tipping point now versus in the future:** In assessing the occurrence of a Functional Adaptation Tipping Point, the adequacy of a structure is first evaluated under present conditions, before using scenarios to explore the adequacy of the structure under diverse futures. If a structure is found to perform inadequately under present day conditions (e.g. as evaluated using existing data), there is no need to proceed to scenario analysis: inadequate under present day conditions will certainly remain

inadequate under more extreme future conditions. By contrast, if a structure presently meets the performance requirements, scenarios must be invoked to explore how much longer the structure remains functional and how imminent non-compliance may be. This explains why the analysis of the Functional Adaptation Tipping Point for the inland water regulation does not proceed to using future scenarios (i.e. Adaptation Tipping Point has already occurred), while the flood defense analysis does (i.e. structure is currently functional, so when in the future will the Adaptation Tipping Point occur?).

5.3.3 Putting these together: a long-term strategic planning timeline for IJmuiden

So far in Section 5.3, the intent has been to set up the necessary analyses to identify the occurrence of moments in the lifetime of a hydraulic structure where some sort of structural condition or societally-defined performance threshold is reached and action is warranted. This proof of concept demonstration has focused specifically on exploring two different types of Adaptation Tipping Points that are relevant in the long-term planning horizon, namely Technical Adaptation Tipping Points that identify when the impacts of *internal deterioration* of a structure first result in non-compliance with performance requirements and Functional Adaptation Tipping Points that capture when the impacts of *external change* first result in non-compliance with defined performance requirements. Here, these individual results are brought together to develop a long-term strategic planning timeline and explore the insights this provides. Figure 5.6 summarizes the results obtained for the Adaptation Tipping Point analyses conducted above for the pumping station at

IJmuiden[41]. The results are presented on a timeline from 2015 to 2100, in line with the 85-year project horizon used in this work.



<u>Figure 5.6: Timing of the estimated occurrence of Technical and Functional Adaptation Tipping Points for the pumping station at IJmuiden</u> – Notice that these results are entirely scenario independent. i.e. these results remain the same for all four scenarios analyzed, namely (Sea level$_{low}$; Precipitation$_{low}$), (Sea level$_{low}$; Precipitation$_{high}$), (Sea level$_{high}$; Precipitation$_{medium}$) and (Sea level$_{high}$; Precipitation$_{extreme}$). This is not a general conclusion, but rather an artefact of the form of the results obtained in this specific proof of concept demonstration: across all sea level rise and precipitation scenarios, the Functional Adaptation Tipping Point for the water level management function occurs immediately and any occurrence in the present day is by definition scenario independent. Furthermore, the Functional Adaptation Tipping Point for flood defense occurs beyond the end of the project horizon for all climate scenarios, which within this 85 year project horizon also translates to being scenario independent. Thus, this scenario independence occurs for different reasons in each case.

One observes that the different Adaptation Tipping Points occur as distinct intervention moments across the 85-year planning horizon. The Functional Adaptation Tipping Point for the water level regulation function occurs immediately, which indicates that even at present, there is insufficient pumping

[41] A similar conceptual timeline for the pumping station of IJmuiden has previously been reported in Rijkswaterstaat (2014) (Dutch) and in Van Vuren *et al*. (2015) (English). These studies use the computed timelines to develop adaptation pathways for the future. The work presented here is different but complementary in that it uses the same starting point to subsequently conduct an analysis of flexibility using Engineering Options.

capacity installed to maintain the desired water levels on the canal. This is followed by the Technical Adaptation Tipping Point in a few decades, which is an indication that the structure is so deteriorated that its replacement is required at that time. Finally, the Functional Adaptation Tipping Point for flood defense is estimated to occur beyond the end of the project horizon of 2100, which indicates that across all sea level rise scenarios examined, the current flood defense height of the pumping station remains adequate to provide the necessary flood protection. Together, this indicates that the most imminent concern is the necessary expansion of the structure's ability to regulate water levels on the canal, rather than the physical degradation of the structure.

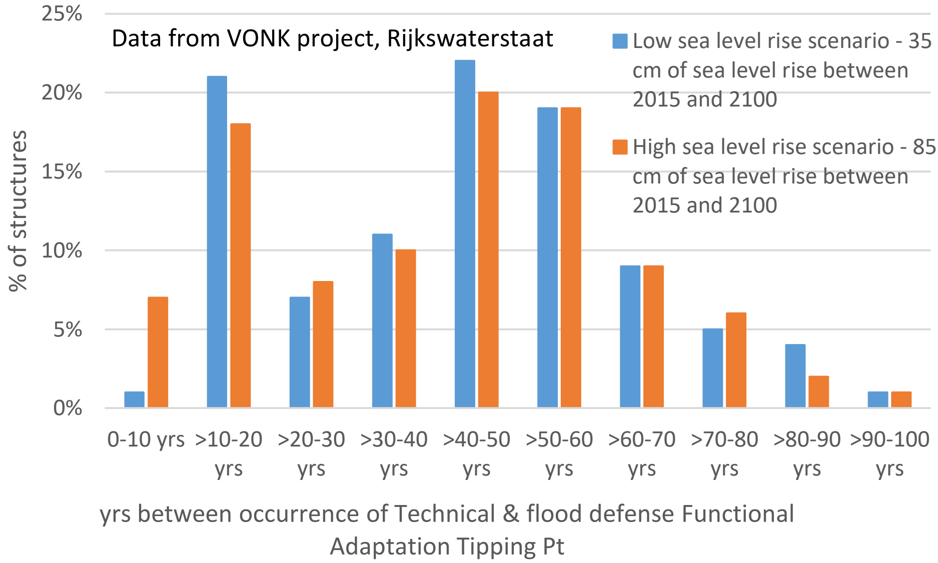
The observation that these different types of Adaptation Tipping Points are spread out across the structure's life has a number of important implications. The sequence of Adaptation Tipping Points shown on Figure 5.6 suggests that the current structure is under-dimensioned when it comes to the water level regulation function: the structure's ability to regulate inland water levels is inadequate a number of years before the structure reaches the end of its design life. This means that work to augment the installed pumping capacity becomes necessary even though the existing structure remains in technical working order. On the other hand, the results suggest that the current structure is over-dimensioned when it comes to the flood defense function: the structure's design life is reached long before the structure becomes unable to withstand the required flood heights. This over-dimensioning for the flood defense function is likely at least partially intentional, a side-effect of societal risk aversion to flood damages. However, this result nonetheless calls into question the value of designing a flood defense with such substantial robustness margins, such that before these safety margins are ever truly necessary, the structure must be replaced anyway because it has reached the end of its design life.

As previously shown on Figure 4.4, from a conceptual perspective, the ideal situation would occur when all of the technical and functional Adaptation Tipping Points fall within a relatively narrow window of time, indicating minimal over- and under-designing of the structure. So is the pumping station of IJmuiden the exception or the norm in terms of these widely ranging Adaptation Tipping Points, being simultaneously over- and under-designed for different functions? An exploration of Adaptation Tipping Points for additional hydraulic structures in the Netherlands (presented in Textbox 8) demonstrates that in 67% of structures examined, there was more than a 30 year gap between the occurrence of the Technical and flood defense Functional Adaptation Tipping Points, suggesting that Technical and Functional Adaptation Tipping Points are more frequently widely distributed throughout a structure's life rather than ideally clustered together. Admittedly, the results shown in Textbox 8 estimate the occurrence of Technical Adaptation Tipping points simply by looking at the intended design life of a structure, leaving room for a more sophisticated, inspection-based study to validate these initial findings. Nonetheless, these results change the tone of the question of infrastructure replacement somewhat: this proof of concept demonstration was approached from the perspective of exploring how replacement planning should be conducted, yet through this analysis, it has grown increasingly clear that replacement due to aging may not be the most pressing concern, as compared to the need for functional upgrades to existing structures. Clearly, when looking at long-term infrastructure planning, replacement for structural deterioration reasons cannot be treated as independent from other functional considerations that affect the structure's lifetime performance.

So how could system managers and decision makers respond to these insights? In general, this dissertation has hypothesized that system managers should seek to design structures in such a way that the need to revisit their structural configuration is actively acknowledged and pre-empted. In this work, this is operationalized in the form of strategic design decisions in the form of options. Section 5.4 explores this hypothesis as it applies specifically to the pumping station of IJmuiden.

Textbox 8: The disparate timing of Adaptation Tipping Points – the case of hydraulic structures in the Netherlands

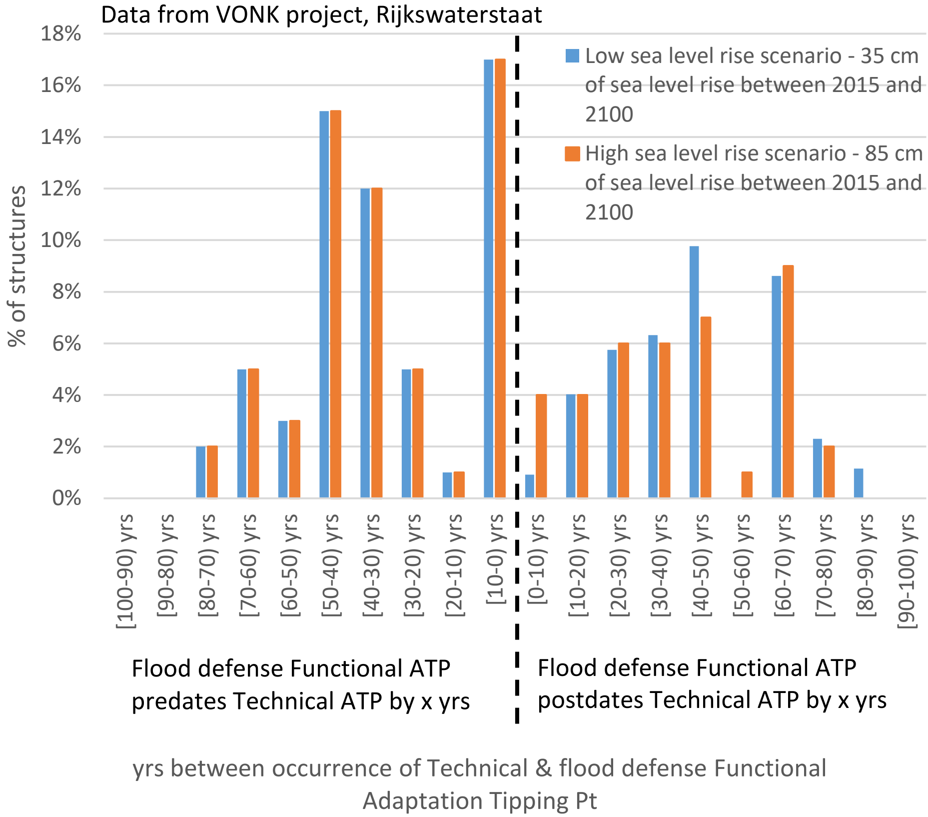
Under the auspices of the VONK project, Rijkswaterstaat (the Ministry of Infrastructure and the Environment in the Netherlands) has begun to explore Technical and Functional Adaptation Tipping Points for the 654 hydraulic structures they manage. Focusing only on those that fulfill a flood defense function (174 structures), it was found that in 67% of cases, there was more than a 30-year gap between the occurrence of the Technical (estimated using the intended design life) and flood defense Functional Adaptation Tipping Points:



From the perspective of Rijkswaterstaat as decision makers and infrastructure managers, it is important to know whether these disparately occurring Adaptation Tipping Points suggest under-designing of structures (i.e. Functional Adaptation Tipping Point is reached before structural design life) or over-investment (i.e. structural design life is reached before structure's full functionality is ever utilized). It would be

Textbox 8 continued: The disparate timing of Adaptation Tipping Points – the case of hydraulic structures in the Netherlands

reasonable to presume that the large disparity between the flood defense Functional Adaptation Tipping Point and the Technical Adaptation Tipping Point could be caused by a risk-averse tendency to err on the side of caution and over-dimension flood defense structures. Further analysis of the available data for these same structures shows that in fact 60% of structures are under-designed (i.e. flood defense Functional Adaptation Tipping Point is expected to occur before structural design life is reached). This suggests that work to upgrade these structures may be required, an important insight for any infrastructure manager.



5.4 **Step 4:** Formulate, evaluate and compare different replacement strategies

5.4.1 Based on the timeline identified, formulate alternative courses of action and seek more flexible variants

The analyses presented in Section 5.3 looked in detail at the aging pumping station of IJmuiden and briefly at the existing stock of water management structures in the Netherlands. By looking at both technical and functional considerations of such aging infrastructure, the results so far have demonstrated that instead of one single, clear-cut replacement moment, there occur multiple moments in the lifetime of a structure where capital interventions and structural or functional upgrades may become necessary. Conceptually, this calls into question the success of the status quo engineering approach, which focuses on designing a structure intended to remain functionally adequate until at least the end of its design life.

Based on these insights, this case investigates a number of different proposed replacement designs for the pumping station of IJmuiden under the uncertain conditions described above. As discussed in Table 4.2, different methods exist to generate possible courses of action: in this particular proof of concept demonstration, the different design alternatives were the result of expert consultation. Table 6 schematically displays these design alternatives. Each of them maintains the same minimum, function-specific level of service throughout the entire planning horizon, as previously defined in Tables 5.4 and 5.5 respectively: for flood defense, IJmuiden should continue to protect against North Sea levels exceeded on average once every 10,000 years; for the regulation of inland water level, this study used service levels consistent with the 2013 North Sea Canal Water Accord (Beuse, 2013).

The differentiation between the design alternatives lies in the choice of initial structural design and how further capacity is added over time. The proof of concept demonstration examined three possibilities:

- *Fixed Robust design,* consistent with the traditional predict-then-act approach to water resource planning. The structure provides at least the minimum level of service throughout its design life, with a safety margin added to account for any residual uncertainties. It embodies the traditional engineering mindset, emphasizing over-dimensioning and taking advantage of any economies of scale. (Figure 5.7, column a)

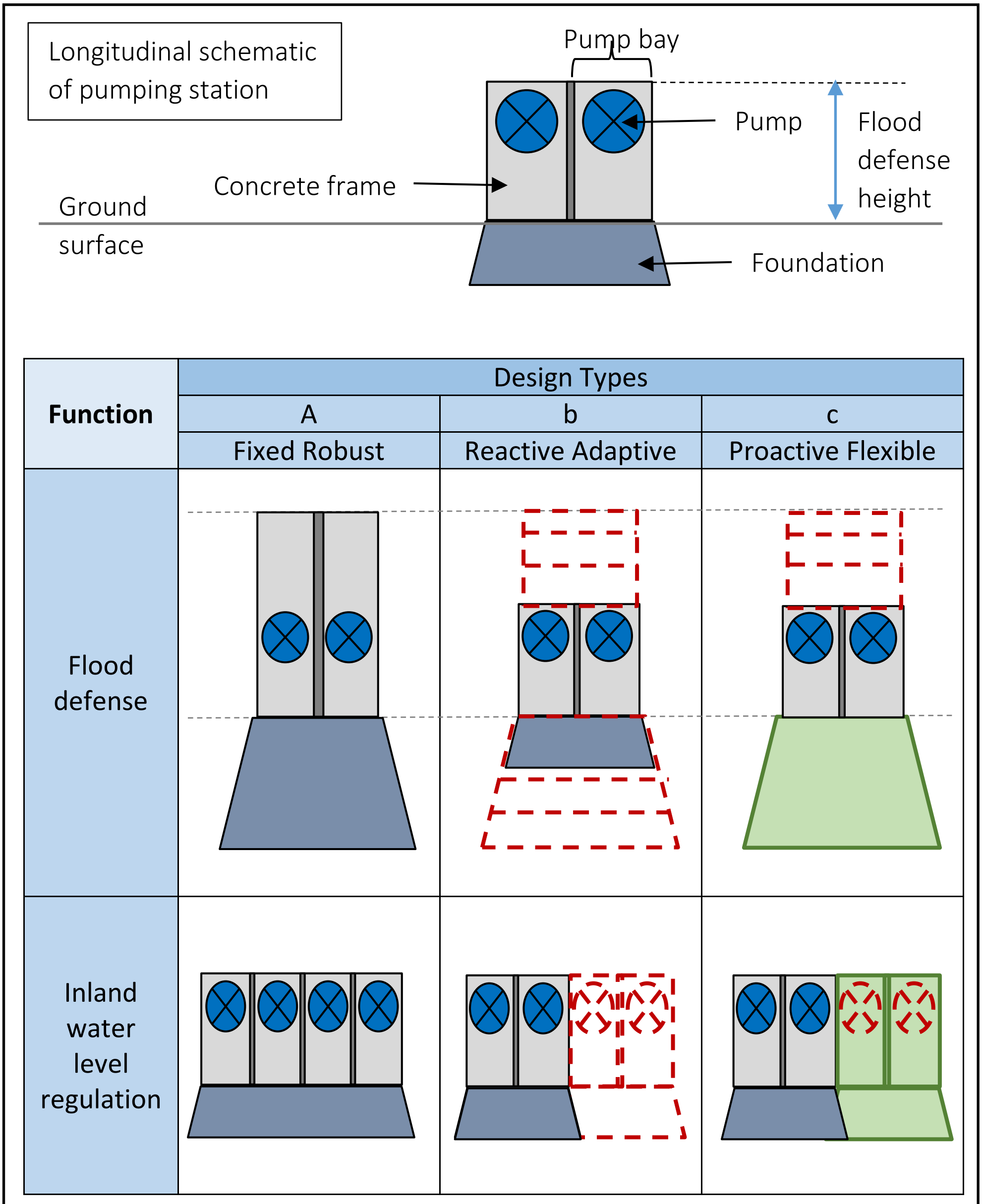
- *Reactive Adaptive design*, which acknowledges that a fixed structure may represent an over-investment and hence emphasizes designing for the best-available current information and making changes as needed as the future unfolds. (Figure 5.7, column b). Designers size adaptive designs for the short-term, but make no explicit preparations to facilitate possible future adaptations.

- *Proactive Flexible design,* which goes a step further than reactive adaptive design in that it prepares for the future by choosing to include options within the initial structure. (Figure 5.7, column c). Designers size flexible designs for the short-term, but proactively incorporate options that enable easy adaptation in the future.

The proactive flexible design considers two function-specific options:

- The option to expand the flood defense function includes a larger-than-currently necessary foundation for the structure: this facilitates height additions as needed.
- The option to expand the function to regulate the level of inland water includes additional pump bays in the concrete frame: these enable easy installation of additional pumps if/when necessary. Steel gates seal off these additional bays until such time that managers install additional pumps.

Within this proof of concept demonstration, the factor that drives necessary modifications to the structure is the need to provide a continued level of service in spite of evolving external operating conditions, with capacity expanded whenever the required service level can no longer be maintained.



Red shows possible future expansions
Green indicates a structural option, proactively enabling future expansion

Figure 5.7: Design alternatives considered

5.4.2 Evaluate alternatives, making explicit any added value from including proactive options - Engineering Options analysis

Within this step, a quantitative, economic comparison of the expected performance of the different possible replacement strategies is conducted, with a particular interest in identifying whether the proactive inclusion of options improves the structure's long-term performance. The core of the quantitative analysis couples a physical and an economic module. The:

- *Physical performance module* links changes in future operating conditions (specifically higher sea level and increased precipitation) to performance indicators of interest (namely water levels associated with specified return periods). It generates many simulations of future environmental conditions, consistent with the different sea level rise and precipitation change scenarios (defined in Table 5.3). This module both indicates under what future conditions the current physical system becomes inadequate, and captures how different possible courses of action affect the future performance of the system. Capacity is expanded whenever the required service level can no longer be maintained, with appropriate decision rules used to operationalize this expansion. There is a different module for each of the two functions this case examined, with the formulation of each described in detail in Section 5.5.

- *Economic evaluation module* uses the simulations of the physical system as input to compare the previously identified candidate courses of action (see Figure 5.6) based on whichever metrics are considered most suitable. While any standard form of economic evaluation could be suitable, this proof of concept demonstration used a Cost Effectiveness Analysis. Cost Effectiveness Analysis (also known as a least-cost analysis) is used to identify the lowest cost way to fulfill a set of *ex ante* user-defined objectives, thereby assuming that direct benefits are the same across all alternatives considered[42]. This is well-suited to the framework developed here, because the previously conducted Adaptation Tipping Points analysis is built on the identification of societally defined performance objectives. The analysis compares the different structural designs based on total cost of ownership, including possible later expansion costs in addition to initial capital costs. Rijkswaterstaat typically applies a discount rate of 5.5%, consistent with the 2.5% risk-free rate and a 3% risk premium, when evaluating costs in capital investment projects. However, the proof of concept demonstration explores the impact of a range of other discount rates. The Cost Effectiveness Analysis used Monte Carlo simulation to evaluate 1000 different versions of the future for each of the different scenarios, computing the costs of maintaining a certain pre-defined performance level over the specified project horizon.

The output is in the form of a scenario-specific distribution of life cycle costs for different possible structural designs, over many possible futures. The coupled physical performance–economic model used to conduct this analysis is function specific, with its formulation dependent on the specifics of the function being explored. Thus, the detailed model formulations and associated results and insights are presented for each function in turn in Sections 5.6 (inland water level regulation function) and 5.7 (flood defense function respectively. But first, Section 5.5 addresses the issue of estimating costs for non-traditional structural designs

[42] A shortcoming of this approach is that the benefits of providing a performance level over and above the objective are not considered. For instance, the fixed robust design may offer flood protection against the 1:15,000 year water level at the start of the project horizon, reducing to 1:10,000 year protection at the end of the project horizon. The benefits from this incremental degree of additional protection provided during these early years are not included in this work.

incorporating options such as those explored in this proof of concept demonstration (Figure 5.7).

5.5 Developing a suitable cost model

A reliable quantitative comparison of the performance of the different possible structural designs requires the use of appropriate cost information. As introduced in Section 4.4.2, it is important that cost information is obtained from an estimation method that takes into account relevant economies of scale and can be applied to non-traditional designs.

5.5.1 Exploring the cost estimate tools currently used by Rijkswaterstaat

As a first step in deriving the costs necessary for this research, the cost estimation methods currently used by Rijkswaterstaat were explored. The capital costs of pumping stations are primarily dependent on two design parameters, namely pumping capacity and pumping head. Walski (2012) conducted an analysis of different cost formulas and concluded that capacity has a much greater effect on cost than head does. In line with this, Rijkswaterstaat currently conducts capital planning for pumping stations using capacity-specific rule-of-thumb figures (Table 5.6), treating cost ≈ f(capacity).

<u>Table 5.6: Cost estimates currently used by Rijkswaterstaat to budget pumping station capital costs</u>

Source: Cees van der Werff, Cost Specialist, RWS

Pumping station capacity (m^3/sec)	**Estimated total project costs (2015 €)** - includes material expenses, labor, engineering, site preparation and tax
0.01 – 0.03 (10 – 100 m^3/hr)	217,529
0.03 – 0.14 (100 – 500 m^3/hr)	774,947
0.14 – 0.28 (500 – 1,000 m^3/hr)	1,468,320
0.28 – 4.17 (1,000 - 1,500 m^3/hr)	2,324,841

Walski (2012) have showed that pumping stations demonstrate sizeable economies of scale, hence these rule-of-thumb derived costs were used to compute per-unit-costs to see to what extent economies of scale are captured. As shown by the green line on Figure 5.8, the current estimation method does exhibit fairly substantial economies of scale, with the per unit cost of a pumping station of 0.01 – 0.03 m^3/sec more than double the cost of a much larger structure of 0.28 – 4.17 m^3/sec.

Despite the dangers of conducting any further analysis given only four data points, a non-linear least squares regression of the functional form **cost = a capacity^b** (as used by Walski (2012)) was attempted (results are shown in grey on Figure 5.8). a and b are coefficients, with $b \leq 1$, a measure of the economies of scale. A value of b equal to 1 indicates no economies of scale and thus means multiple smaller structures cost the same as one larger one, whereas a lower value of b indicates increasing economies of scale, driving one toward large, one-off capital projects. Using the best-fit coefficients from this regression (a=5x10^6 and b=0.75), a cost estimate for replacing IJmuiden (capacity = 260 m^3/second) of 320 million Euro was derived. Subsequent expert consultation produced a replacement value for IJmuiden (replacing the structure like with like, with no upgrades to the structure's functionality other than designing and constructing according to today's requirements and techniques) of approximately 180.5 million Euro, a value just over half of the model estimate.

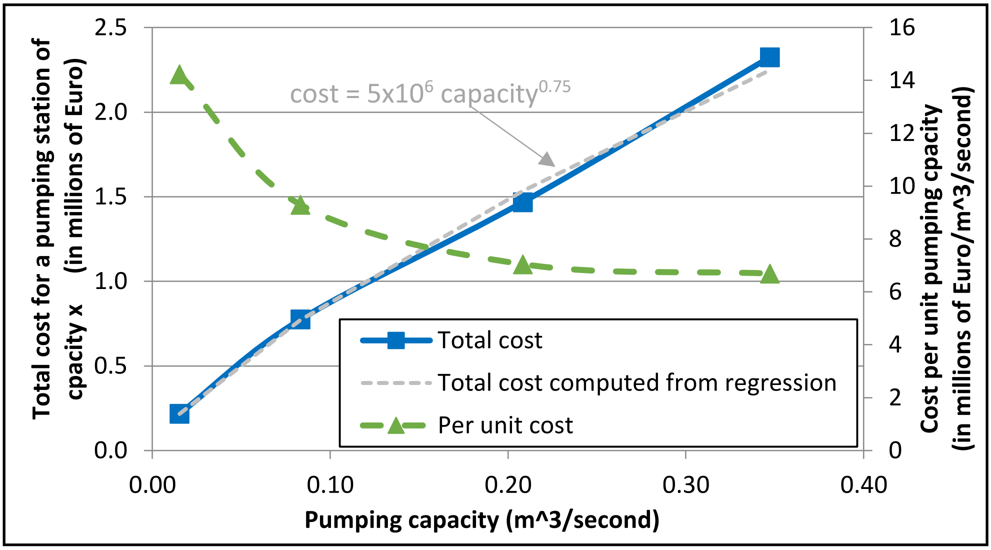


Figure 5.8: Exploring the economies of scale for the current pumping station cost estimate method

Why does the currently utilized cost model fall short when applied to IJmuiden? The pumping station of IJmuiden is the largest in Europe, and with its current capacity of 260 m^3/second, it is almost two orders of magnitude larger than the pumping stations currently captured by the estimates shown in Table 5.6 and Figure 5.8. These estimates may be useful for the many small and intermediate pumps managed and operated by Rijkswaterstaat, but these results demonstrate their lack of applicability to this single, large outlier.

In addition, even if the current model was improved by populating it with cost data and rules-of-thumb more relevant to large pumping stations, there is no clear way to extend this parametric cost estimation model to be applicable to non-traditional designs, such as those explored in this work. Thus, a new fit-for-purpose cost model was developed in this work, and is described below.

5.5.2 Creation of a new cost estimation tool, suitable for non-traditional designs

Section 5.5.1 attempted to expand a simple existing cost estimation method to include larger magnitude pumping stations. Having identified the limitations of this *parametric approach* where the cost is modelled as a function of a single key design parameter, this section develops a more in-depth cost estimation model using the so-called *cost-element approach w*here the quantity of each component item is determined before multiplying these quantities by the per unit cost. This approach allows easy manipulation of individual structural elements to produce cost estimates for structures including options that are not typically included in traditional estimation techniques. This cost-element model is summarized in Table 5.7, with the model user interface appended to this dissertation as Appendix A. It draws on design parameters obtained from as-built drawings from the pumping station's initial construction in 1975, supplemented with photographic and GIS measurements where necessary; recent monitoring reports; information obtained from the current managers of the pumping station; reports completed when IJmuiden was expanded in 2004; interviews and cost estimates obtained from the contractors and suppliers involved with the 2004 expansion, as well as expert consultation. While the specific dimensions, parameters and per unit costs utilized in this model are obviously case and location specific, the general form of the model as shown in Table 5.7 could be updated and used in a variety of other contexts, assuming the existence of appropriate data with which to update the model.

Table 5.7: Overview of components of cost element model

<table>
<tr><td colspan="2">User-defined variable</td></tr>
<tr><td colspan="2">Desired pump capacity (m³/sec)</td></tr>
<tr><td colspan="2">Desired flood protection height (m+ NAP)</td></tr>
<tr><td>Intermediate variables</td><td>Intermediate output</td></tr>
<tr><td>Dimensions of excavation</td><td>Volume to be excavated x price per unit = Cost of excavation</td></tr>
<tr><td>Dimensions of temporary levee required around construction site</td><td>Volume of levee to be constructed x per unit price = Cost of levee construction</td></tr>
<tr><td>Sheetpile for seepage prevention under structure</td><td>Area of sheetpile to be installed x per unit price = Cost of seepage prevention</td></tr>
<tr><td>Dimensions of concrete structure</td><td>Volume of concrete to be poured x per unit price = Cost of civil construction</td></tr>
<tr><td>Pumps, gates, debris screens, one-way flow valves and related electro-technical components</td><td>= Cost of pump installation</td></tr>
<tr><td>Dredging of adjacent channels</td><td>Volume to be dredged x per unit price = Cost of dredging</td></tr>
<tr><td>Operator’s building</td><td>= Cost of building</td></tr>
<tr><td colspan="2">Output</td></tr>
<tr><td colspan="2">Direct material costs (millions of Euro)</td></tr>
<tr><td colspan="2">Total capital project costs = Direct material costs x supplement factor[43]</td></tr>
</table>

[43] The supplement term that is used to estimate total project costs from direct material costs of a capital investment project is a geometric factor that attempts to capture project variables such as site preparation costs, engineering, labour, project management and implementation, reserve fund, and any applicable taxes. Within Rijkswaterstaat it is standard practice to use a value of 2.4 for this supplemental factor. Conceptually what this suggests is that there are no economies of scale involved with the non-material aspects of a capital investment project i.e. that a project of $10 million will require ten times as much management, preparation, labor etc. as a project of $1 million. This assumption can be questioned, and could be addressed by using variable values for this supplemental factor. This is an area for future research.

5.5.3 Assessing the performance of this new cost estimation model

So how does this new model fare with regards to capturing relevant economies of scale and its ability to price non-traditional designs? Does the model produce estimates that expand on, but remain in line with conventional engineering insights?

Capturing Economies of Scale

Economies of scale were explored by conducting several runs of the cost model, first holding the flood defense height constant (at 8m +New Amsterdam Datum (NAP)) and varying the desired pump capacity and then holding the pump capacity constant (at 300 m^3/second) and varying the flood defense height. This isolated the effect of each of these design variables on the total project cost. Figures 5.9 and 5.10 show the results. Notice that the vertical axis on the left shows total structure cost and is scaled differently to the vertical axis on the right that shows per unit cost. The vertical axes on Figures 5.9 and 5.10 were deliberately set to the same scale in order to highlight the different cost behavior of these two design parameters.

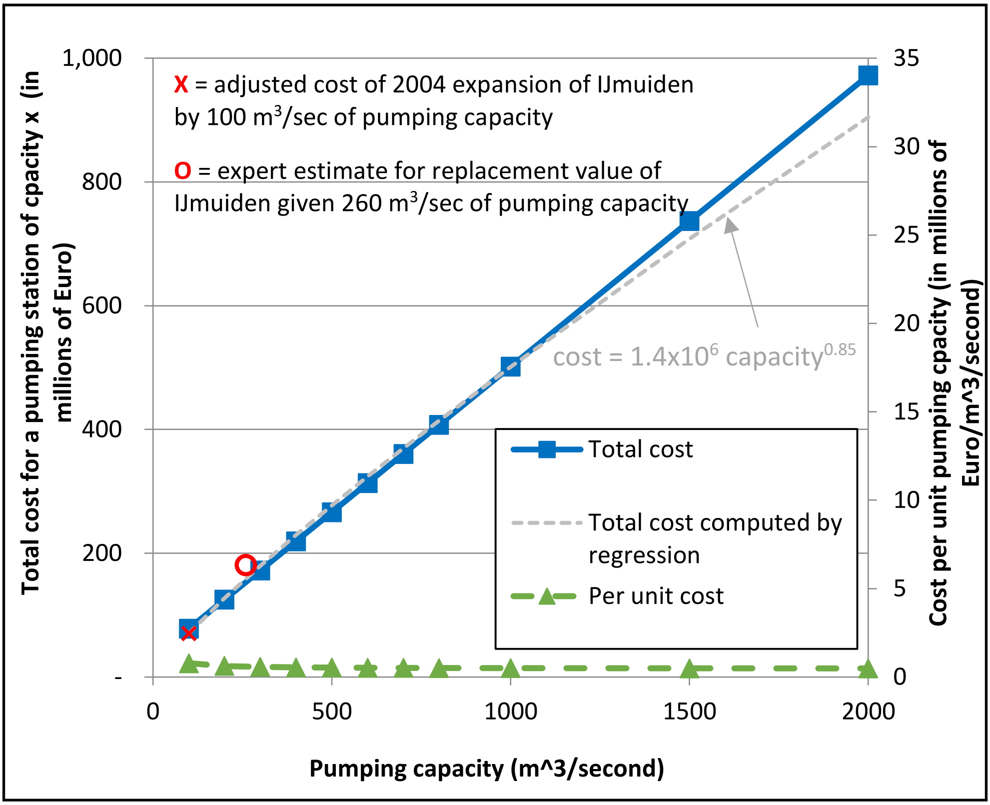


Figure 5.9: Isolating the impact of changing pumping capacity on total cost - To explore how this new cost-element model performs as compared with independent point estimates available to date, the two only existing data points are superimposed on Figure 5.9. The first is the final cost of the 2004 expansion of IJmuiden: an additional 100 m^3/second of pumping capacity was added to the existing structure at a cost of 54 million Euro. This addition was treated as equivalent to the construction of a separate pumping station of capacity 100 m^3/second, costs were adjusted to 2015 and plotted as a red **X**. The second is the independent expert estimate for the present day cost of replacing the current pumping station: a new pumping station of 260 m^3/second pumping capacity was predicted to cost 180.5 million Euro in 2015 (shown as a red **O**). In both cases, the cost estimate obtained from the model is within 10% of the true cost/expert prediction. While a much larger validation data set would provide more confidence in this model's predictive abilities, such a data set simply does not exist at this time.

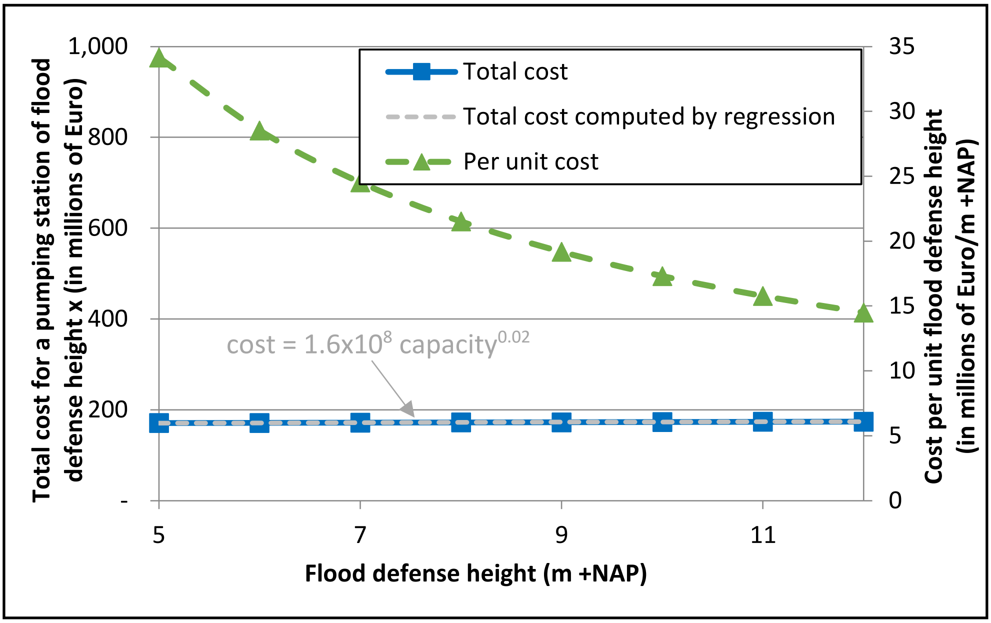


Figure 5.10: Isolating the impact of changing flood defense height on total cost

One observes that both for increasing pump capacity and flood defense height, the *total* project cost (blue line on Figures 5.9 and 5.10) increases approximately linearly. However, for this type of large pumping station, increasing pump capacity has a much more dramatic impact on capital cost than increasing flood defense height: a doubling in pumping capacity is associated with a cost increase two orders of magnitude larger (~100's of millions of Euros) than the cost increase associated with a doubling of the flood defense height (~millions of Euros). This suggests that when looking at pumping capacity, the bulk of the associated costs are in the form of variable costs, whereas for flood defense, there is a more substantial fixed cost, with less significant variable costs.

As expected, looking at the *per unit costs* (green line on Figures 5.9 and 5.10), both design variables exhibit some degree of economy of scale, with both the pumping capacity and flood defense height associated with decreasing per unit costs as the total size of the structure increases. As before, the total cost data was fitted to the functional form **cost = a capacity^b** (grey line on Figures 5.9 and 5.10), where b is a measure of the economies of scale. The best-fit coefficients produce the following relationships: cost = $1.4x10^6$ (pumping capacity$^{0.85}$), holding flood height constant and cost = $1.6x10^8$ (pumping capacity$^{0.02}$), holding pumping capacity constant. One observes that the value of b is much lower for the flood height design parameter than for pumping capacity, meaning that flood height exhibits more significant economies of scale than pumping capacity.

Conceptually speaking, these findings are consistent with existing structural insights which to some extent validates the approach underlying this cost model: in a flood defense hydraulic structure, the bulk of the costs are driven by below-ground elements, such as the size of the work excavation and the foundation. This represents a large fixed cost, with the actual above-ground height of the structure a relatively much smaller variable cost. Once building a structure of this kind, whether one builds it to say, 4 or 5 m height has relatively little impact on the final cost. In the case of pumping capacity, the reverse is true: the pumps themselves are such a large, variable cost, that the fixed cost associated with the pump housing is relatively small in comparison. Taken together, the large fixed costs and greater economies of scale of the flood defense height design parameter will make a structure with high flood defense heights relatively more economically appealing, nudging the designer and decision maker towards structural over-dimensioning. Conversely, the large variable costs and slight economies of scale of the pumping capacity design parameter make a structure with more capacity than strictly necessary less economically appealing.

Ability to Price Non-Traditional Designs with Options

By design, this cost element model disaggregates a structure into its key design components, allowing users to input the specific design parameters for non-traditional designs such as a pumping station with ten pump bays, but only six pumps installed. However, it remains difficult to assess the accuracy of the model estimates when it comes to these atypical designs: little to no literature exists on this subject and few previous structures of this kind have previously been completed for which cost data is available. While the cost model presented here was developed in collaboration with cost experts at Rijkswaterstaat, the validation and further improvement of this model component remains an area for future work. Notwithstanding, this best available cost model was used to generate the cost estimates (shown in Tables 5.6 and 5.10) that serve as input to the analysis described below, for each function in turn.

5.6 Inland Water Level Regulation Function

5.6.1 Physical-Economic Model Formulation

As introduced in Section 5.3.2 and presented on Figure 5.3, a cursory data analysis exercise indicates the recent occurrence of a functional Adaptation Tipping Point for the inland water level management function, suggesting that the existing structure is in need of expansion in order to continue to be able to adequately fulfil its water level management function under altered external operating conditions. However, we are interested in not just a one-time functional Adaptation Tipping Point for IJmuiden's water level management role, but in different possible future functional Adaptation Tipping Point given different interventions. Thus, it is necessary to model the external environment and infrastructural system in such a way that captures the feedbacks present in the system: increasing precipitation and runoff may drive capacity expansion of the pumping station, but the very act of expanding the pumping capacity alters the water level on the canal, which is the performance indicator of interest here.

The model formulation used relies on several different elements, starting with multiple simulations of future precipitation consistent with the precipitation scenarios previously defined in Table 5.3. These precipitation time series serve as input to a rainfall-runoff model, which determines the magnitude of canal inflows at any given time. A simple mass balance model of the NS-AR Canal in turn determines when the target water level is exceeded, given different abilities to discharge water from the canal to the North Sea via IJmuiden, which is indicative of the moment when a functional Adaptation Tipping Point occurs. The general model formulation is described in Table 5.13 below, with more complete, case-specific details presented in Appendix B. The eventual output provides an indication of the moment when a functional Adaptation Tipping Point occurs, and how different interventions in the infrastructural system affect the occurrence of future Adaptation Tipping Points. Conceptually, the occurrence of an Adaptation Tipping Point serves as a trigger moment, indicating when changes are made to the existing structure. Observe that the individual physical-economic model components are linked through the variable e_t^s, the capacity expansions required in any given year, in a specified scenario. This formulation is run for every replacement strategy, within every scenario, for 1,000 simulations each.

Table 5.8: Coupled Physical-Economic Model Formulation

Physical Performance Module: When do Adaptation Tipping Points occur?	
$Q_t^s = r_t + t\Delta^s + u_t$ for $\forall\ t \in [1, T],\ s \in \{scenarios\}$	Describes uncertain changing precipitation over time, as defined by scenario s
$\frac{dh_t^s}{dT} = \frac{Q_t^s - O_t^s}{A}$ for $\forall\ t \in [1, T],\ s \in \{scenarios\}$	Mass balance of the canal, that tracks changing water levels, balancing uncertain inflows and outflows as defined by scenario s
$i_t^s = \max(h_t^s - L_t^s; 0)$ for $\forall\ t \in [1, T],\ s \in \{scenarios\}$	Identifies when the installed pumping capacity becomes inadequate: i.e. water level management functional Adaptation Tipping Point occurs when $h_t^s \leq L_t^s$ or when $L_t^s - h_t^s \geq 0)$
$e_t^s = \lceil i_t^s;\ e^{min} \rceil$ for $\forall\ t \in [1, T],\ s \in \{scenarios\}$	Rounds off the capacity deficiency experienced to a multiple of the minimum allowable capacity expansion
$P_t^s = P_1 + \sum_1^t e_t^s$ for $\forall\ t \in [2, T],\ s \in \{scenarios\}$	Keeps track of total pumping capacity installed at time t in scenario s
Inputs	
r_t	= daily precipitation, consistent with present day climate, as generated by stochastic precipitation generator
Δ^s for $\forall\ s \in \{scenarios\}$	= annual change in average precipitation, as defined in scenario s
u_t	= natural variability in daily precipitation, sampled for time t
T	= number of years in project horizon
A	= surface area of canal
L_t^s	= maximum acceptable water level on canal
e^{min}	= minimum allowable pumping capacity expansion
O_t^s	= outflow rate from canal
Independent Variable	
T	= time, in years
Calculated Variables	

Table 5.8 (continued): Coupled Physical-Economic Model Formulation

Q_t^s	= uncertain daily canal inflows at time t in scenario s	
h_t^s	= water level in canal at time t in scenario s	
P_t^s	= installed pumping capacity of structure at year t in scenario s	
i_t^s	= outflow capacity by which present structure is inadequate in year t in scenario s	
e_t^s	*= magnitude of height expansion to be undertaken at end of year t in scenario s*	
Economic Performance Module: **How do different responses to an Adaptation Tipping Point compare?**		
$C^{lifetime} = C^{capital} + \frac{1}{(1+r)^t}\sum_t^T C_t^{O\&M} + \frac{1}{(1+r)^t}\sum_t^T C_t^{expand}$		Computes lifetime costs of maintaining a certain performance level over the entire project horizon T
$C_t^{expand} = C^{fixed} + C^{variable} e_t^s$ for $\forall\ t \in [1, T],\ s \in \{scenarios\}$		Computes cost associated with capacity expansions of varying sizes
Inputs		
$C^{capital}$	= initial capital costs	
r	= discount rate	
$C_t^{O\&M}$	= annual operation and maintenance costs; is a function of the capacity installed at that time (P_t)	
C^{fixed}	= fixed cost associated with capacity expansion	
$C^{variable}$	= variable per unit cost of capacity expansion	
Variables		
$C^{lifetime}$	= lifetime costs of maintaining a specified performance level	
C_t^{expand}	= cost of addition	
e_t^s	*= magnitude of capacity expansion to be undertaken at end of year t in scenario s*	

5.6.2 Modelling Inputs

The analysis utilized the following specific parameters and inputs:

Table 5.9: Sources of Uncertainty Captured in the Analysis

Class of Uncertainty	Source	Details
Deep uncertainty	Sea level rise	2 sea level rise scenarios explored, as previously defined in Table 5.3: $scenarios = \{high; low\}$ $W_1 = 6.95\ m + NAP$ Scenario-specific annual increases in 1:10,000 water level, as derived by Deltamodel: $\Delta^{high} = 0.0070\ m/year$ and $\Delta^{low} = 0.0018\ m/year$
	Changes in precipitation patterns	4 precipitation scenarios explored, as previously defined in Table 5.3: $scenarios = \{low; medium; high; extreme\}$
Probabilistic uncertainty	Natural variability in daily precipitation	Natural variability is captured by using multiple runs of a synthetic precipitation generator, as described more fully in Appendix B.2.2.
	Uncertainty in precipitation-canal inflow relationship	Residuals from the fitted precipitation-canal inflow model are found to follow a 5 time-step moving average process, as described more fully in Appendix B.2.1.

Table 5.10: Specific Design Parameters for Replacement Alternatives

	Design parameters	
Design alternative	**Flood defense height**	**Pumping capacity**
Fixed Robust design	Held fixed at 9 m +NAP	$P_t^s = 450$ m³/second[44] for $\forall\ t \in [1, T],\ s \in \{scenarios\}$
Reactive Adaptive design		$P_1^s = 250$ m³/second for $\forall\ s\ \{scenarios\}$; minimum increment for capacity expansion, $e^{min} =$ 50 m³/second
Proactive Flexible design		$P_1^s = 250$ m³/second for $\forall\ s\ \{scenarios\}$, *with extra pump bays installed in concrete structure to allow expansion to 450 m³/second; extra bays are sealed with steel gates till extra capacity is required;* minimum increment for capacity expansion, $e^{min} =$ 50 m³/second

[44] The robust pumping capacity of 450m³/second was obtained by estimating the pumping capacity needed to stay compliant with the performance standards in 2100 if the most extreme of the four scenarios defined in Table 5.3 came to pass i.e. a simple worst case analysis.

Table 5.11: Costs Associated with the Different Design Alternatives being Considered

	Costs (in millions of 2015 Euro)		
Design alternative	**Capital costs** $(C^{capital})$[45]	**Expansion costs** (C_t^{expand})[46]	**Annual operation & maintenance costs** $(C_t^{O\&M})$[47]
Fixed Robust design	242.6	n/a	3.6
Reactive Adaptive design	146.2	49.9 for an addition of 50 m^3/second	0.006515 P_t where P_t = pumping capacity installed at time t
Proactive Flexible design	172.6	17.5 for an addition of 50 m^3/second	0.006515 P_t where P_t = pumping capacity installed at time t

5.6.3 Results and Discussion

To maintain the required water levels on the North Sea Canal throughout the project horizon we explore three alternative replacement strategies:

- *Fixed Robust design*, which establishes now the maximum pumping capacity that might eventually be needed;
- *Reactive Adaptive design*, which builds what is needed now, and will upgrade the installed pumping capacity as dictated by emerging future conditions; and

[45] Capital costs are obtained from the cost model described in Section 5.5.2.

[46] Expansion costs are obtained from the cost model described in Section 5.5.2.

[47] Personal communication with Giel Klanker on 27 November 2014 indicated that annual operation and maintenance expenditures go almost entirely to pump servicing and maintenance, and are thus centrally determined by the installed pumping capacity, with the flood defense role playing only a minimal role. At present, a planning estimate of 6,515 Euro/m^3/second of pumping capacity is used by Rijkswaterstaat, and this same value is used throughout this work.

- *Proactive Flexible design*, which creates a pumping station with the maximum number of pump bays that might be needed, but defers purchasing and installing the pumps until actually necessitated by external developments, and thus saves on immediate costs.

The reactive adaptive design represents the current state-of-the-art when it comes to water resources infrastructure planning: it acknowledges that while an incremental strategy may be a prudent one given large uncertainty about future developments, smart proactive investment in options have the potential to facilitate such expansion work that may become necessary later on.

Figure 5.11 shows the relative lifetime economic performance of these three alternatives, for the two most extreme scenario from Table 5.3 (i.e. low precipitation-low sea level and extreme precipitation-high sea level scenario), using discount rates of 0 and 5.5%. The results are presented in the form of a cumulative probability distribution of life cycle costs, also known as a VARG (Value At Risk/Gain) or Target Curve. Among different alternatives considered, a stochastically dominant alternative is the desirable outcome: this implies that across 100% of simulation runs and across all scenarios explored, one alternative performs better (i.e. lower life cycle costs) than the others.

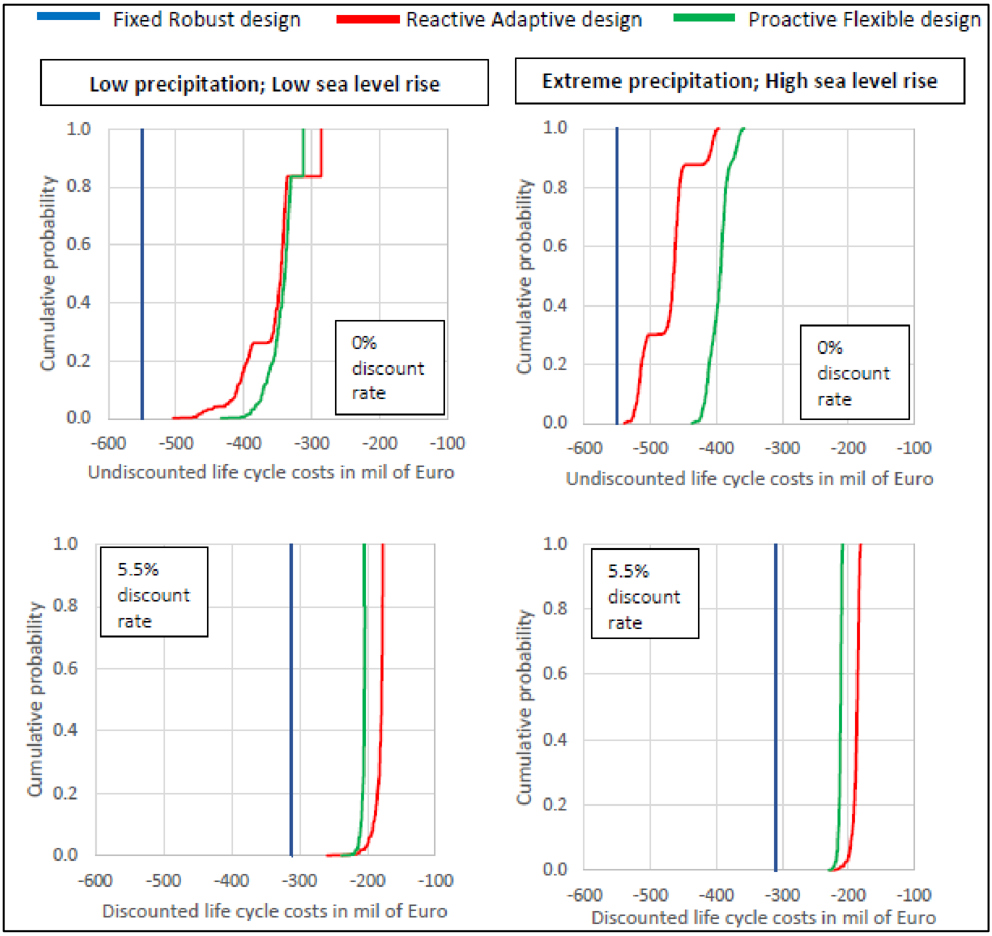


Figure 5.11: Lifetime economic performance of design alternatives for regulating inland water level, for two sea level rise-precipitation scenarios, at discount rates of 0 and 5.5%

For the water level regulation function in this case, both the reactive adaptive and proactive flexible designs always perform better than the robust fixed design, across both scenarios and discount rates shown in Figure 5.11. The results for other two intermediate scenarios are not appreciably different from those in Figure 5.11. This demonstrates that for the water level management function, incremental adaptive and flexible designs can offer substantial gains as compared to the traditional fixed approach.

The form of these results is driven to some extent by the particular cost break-down for construction of a pumping station of this kind, as well as the impact of discounting and the timing of necessary expansion work. When looking at the water level management function of a structure, installation of the pumps themselves is associated with relatively low economies of scale, as well as having relatively high recurring maintenance costs per unit of capacity installed. Thus, the monolithic, fixed robust design not only faces a large, undiscounted capital cost at the start, but it requires annual maintenance of pumps that are perhaps, not yet needed. Both of the incremental approaches are substantially cheaper because they delay investment in pumps and pump maintenance until external conditions demonstrate it is necessary.

So far, it is clear that the two incremental approaches outperform the robust fixed design. So, which of these two incremental approaches is better? Table 5.12 and Table 5.13 provide insights on this, showing the relative lifetime economic performance of the same three design alternatives, using a number of different performance criteria including average lifetime cost, 5th and 95th percentile cost, range, standard deviation and initial investment.

Table 5.12: Multi-Criteria Summary Table Lifetime costs (in millions of 2015 Euro, discounted at 0%) - the bolded values indicate which design performs best for each criterion in turn

Design alternative	Fixed Robust	Reactive Adaptive	Proactive Flexible	Best design
Low precipitation; Low sea level rise scenario				
5th percentile	550.8	286.3	312.7	Reactive Adaptive
Mean	550.8	353.5	342.9	Proactive Flexible
95th percentile	550.8	422.8	380.0	Proactive Flexible
Range	0	218.4	121.2	Fixed Robust
Standard deviation	0	43.2	20.2	Fixed Robust
Initial capital expenditure	242.6	146.2	172.6	Reactive Adaptive
Extreme precipitation; High sea level rise scenario				
5th percentile	550.8	405.6	367.2	Proactive Flexible
Mean	550.8	472.2	395.6	Proactive Flexible
95th percentile	550.8	523.7	420.5	Proactive Flexible
Range	0	144.4	79.6	Fixed Robust
Standard deviation	0	34.7	15.2	Fixed Robust
Initial capital expenditure	242.6	146.2	172.6	Reactive Adaptive

Table 5.13: Multi-Criteria Summary Table Lifetime costs (in millions of 2015 Euro, discounted at 5.5%) - the bolded values indicate which design performs best for each criterion in turn

Design alternative	Fixed Robust	Reactive Adaptive	Proactive Flexible	Best design
Low precipitation; Low sea level rise scenario				
5th percentile	310.6	177.1	203.5	Reactive Adaptive
Mean	310.6	182.2	205.6	Reactive Adaptive
95th percentile	310.6	198.5	212.4	Reactive Adaptive
Range	0	82.2	34.7	Fixed Robust
Standard deviation	0	7.6	3.2	Fixed Robust
Initial capital expenditure	242.6	146.2	172.6	Reactive Adaptive
Extreme precipitation; High sea level rise scenario				
5th percentile	310.6	182.0	205.5	Reactive Adaptive
Mean	310.6	187.5	207.8	Reactive Adaptive
95th percentile	310.6	198.0	212.2	Reactive Adaptive
Range	0	46.8	19.7	Fixed Robust
Standard deviation	0	5.6	2.4	Fixed Robust
Initial capital expenditure	242.6	146.2	172.6	Reactive Adaptive

When there is no discounting of future costs (i.e. a 0% discount rate), the Proactive Flexible design generally outperforms the Reactive Adaptive design. Furthermore, in the riskiest two scenarios examined (i.e. those associated with high sea level rise), the Proactive Flexible design dominates stochastically over the Reactive Adaptive design in delivering lower costs. In the two less risky scenarios (i.e. those associated with low sea level rise), the Proactive Flexible design delivers lower costs on average and more reliably than the Reactive Adaptive Design. As shown on Figure 5.11, the Proactive design leads to higher costs than the Reactive Adaptive design in about 15% of simulations, but still costs less about 25% of the time. Looking across scenarios, the Proactive Flexible design grows more valuable the riskier the future scenario: the greater the number of expansions required over the course of the project horizon, the better the flexible design that enables relatively cheap expansions. This is in explicit contrast to the more short-sighted Reactive Adaptive design that implicitly gambles on few, if any, expansions ever becoming necessary. This observation is consistent with the established knowledge that the value of options grows as the degree of uncertainty about the future increases.

When future costs are discounted over the long-project horizon, this reduces the advantage of the Proactive Flexible design. In this case, the discount rate of 5.5% negates the disadvantage of expensive future adaptations, making the Reactive Adaptive design the dominant solution across all scenarios explored.

Figure 5.12 explores the results across all four precipitation-sea level rise scenarios, by looking at the number of capacity expansions the adaptive designs undergo under each scenario. The two scenarios associated with low sea level rise track each other closely, experiencing anywhere between 0 and 3 capacity expansions by 2100. For the two scenarios associated with high sea level rise, this range increases to between 2 and 4 expansions by 2100. The degree of similarity between the two low and the two high sea level rise scenarios is interesting: it suggests that of the two sources of uncertainty examined, sea level rise and its impact on pumping has greater impact on life cycle cost than more intense precipitation and increased canal inflows. The practical implication of this is that system analysts should preferentially place more emphasis on refining future sea level estimates, rather than those for precipitation.

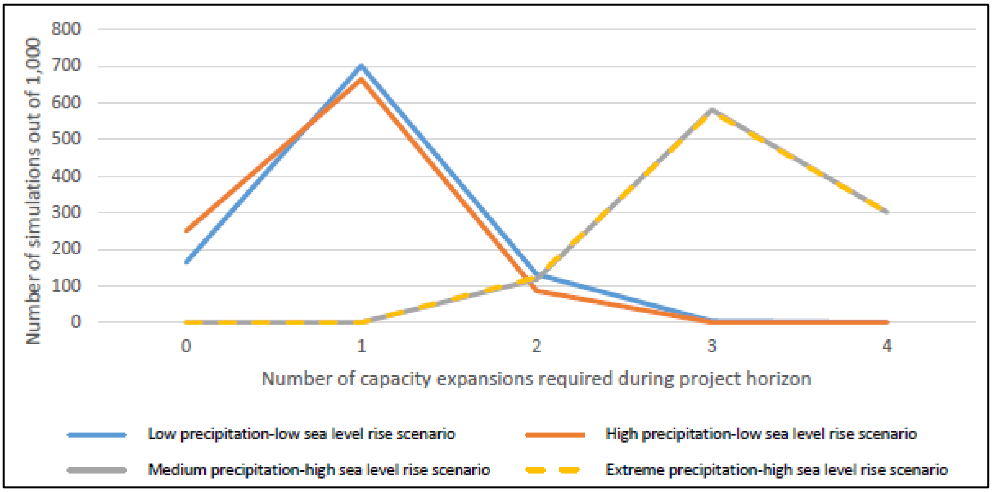


Figure 5.12: Number of times pumping capacity was added to the structure during project horizon for an adaptive strategy, as compared across four future scenarios

Having identified that different scenarios are associated with different numbers of expected capacity expansions, Figure 5.13 examines the distribution of the occurrence of these expansions, focusing on when the first capacity expansion becomes necessary. These results are important because they demonstrate that, in the first 30 years of the project horizon, a relatively small number of simulations suggest expansion will be necessary. However, after the first 30 years, the different scenarios diverge noticeably and rapidly. In terms of long-term strategic infrastructure planning, this kind of insight would be helpful to identify a window of time in which the focus can remain on monitoring and observation and a point in time beyond which rapid change is expected and decisive action is crucial.

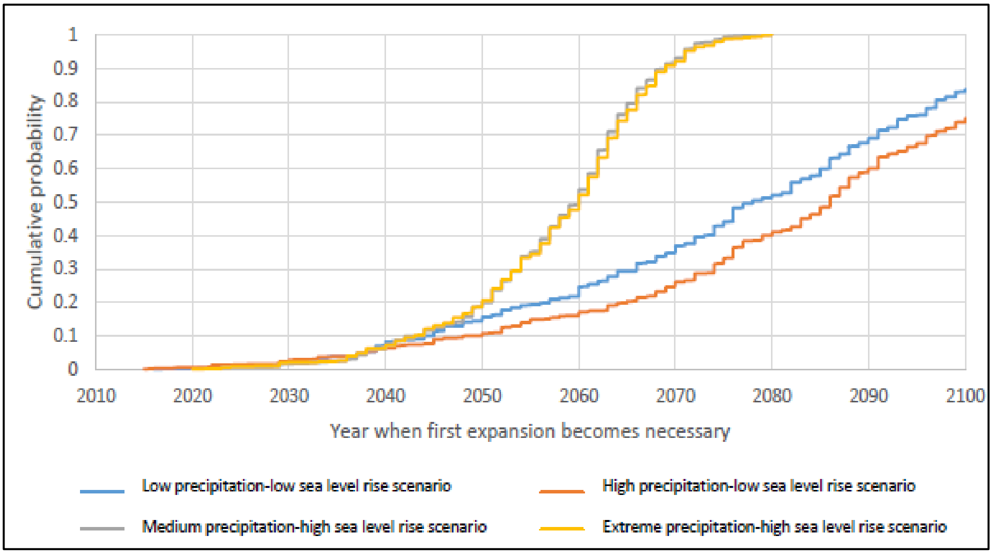


Figure 5.13: Distribution of the timing of the first necessary capacity expansion across four future scenarios

5.6.4 Sensitivity Analysis

The analysis described above was repeated for a series of different discount rates, as this can dramatically alter results, especially over long project horizons such as those used here. Specifically, the impact of using 0, 2, 4 and 5.5% discount rates on the economic performance of the different alternatives is compared in Figure 5.14 and 5.15. For ease of presentation, the analysis is spread across two figures: Figure 5.14 focuses on the two low sea level rise scenarios, namely low precipitation-low sea level rise (shown on the left) and high precipitation-low sea level rise (shown on the right); Figure 5.15 presents the two high sea level rise scenarios, medium precipitation-high sea level rise (shown on the left) and extreme precipitation-high sea level rise (shown on the right).

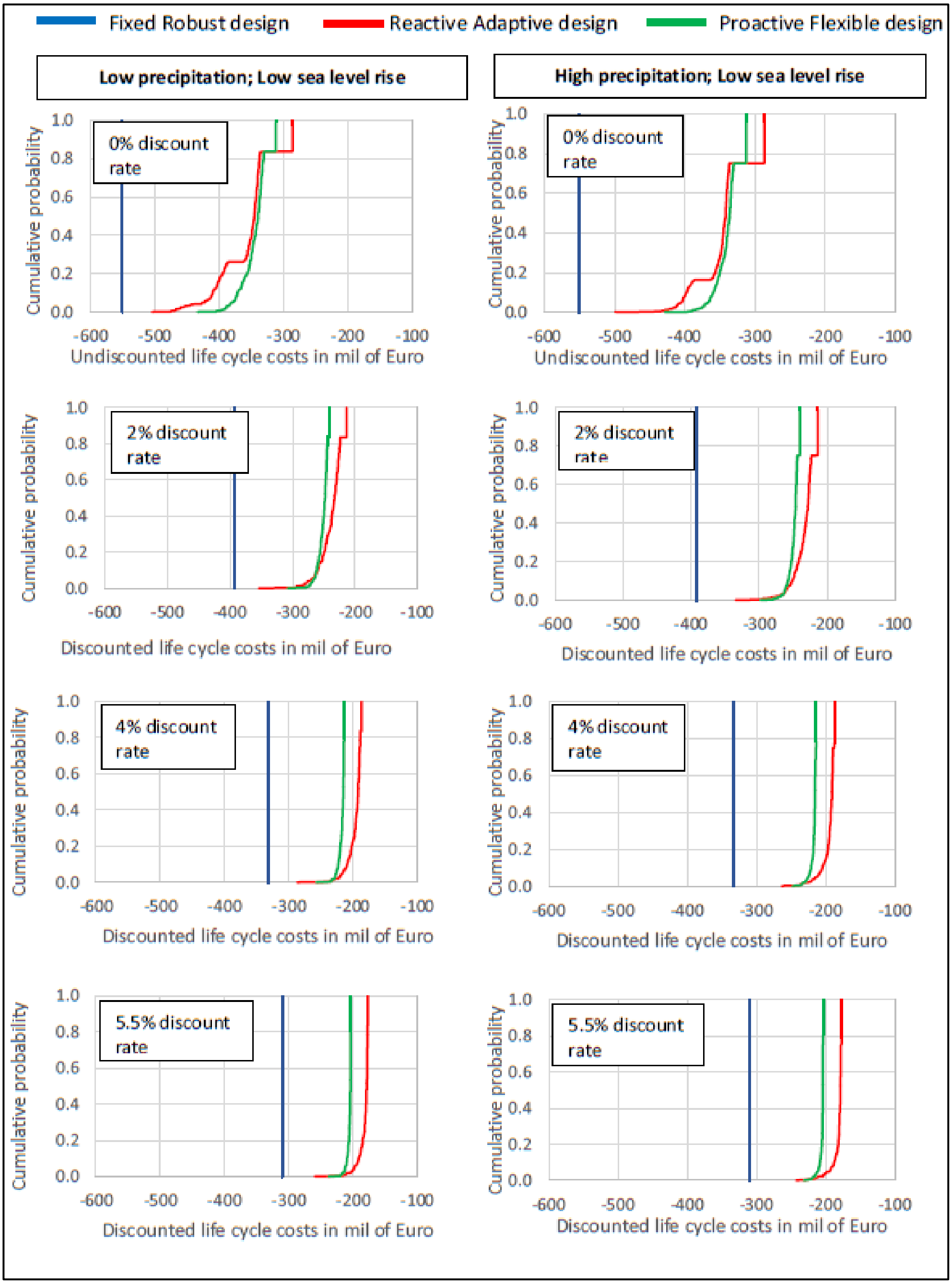


Figure 5.14: Lifetime economic performance of different replacement strategies, varying discount rate

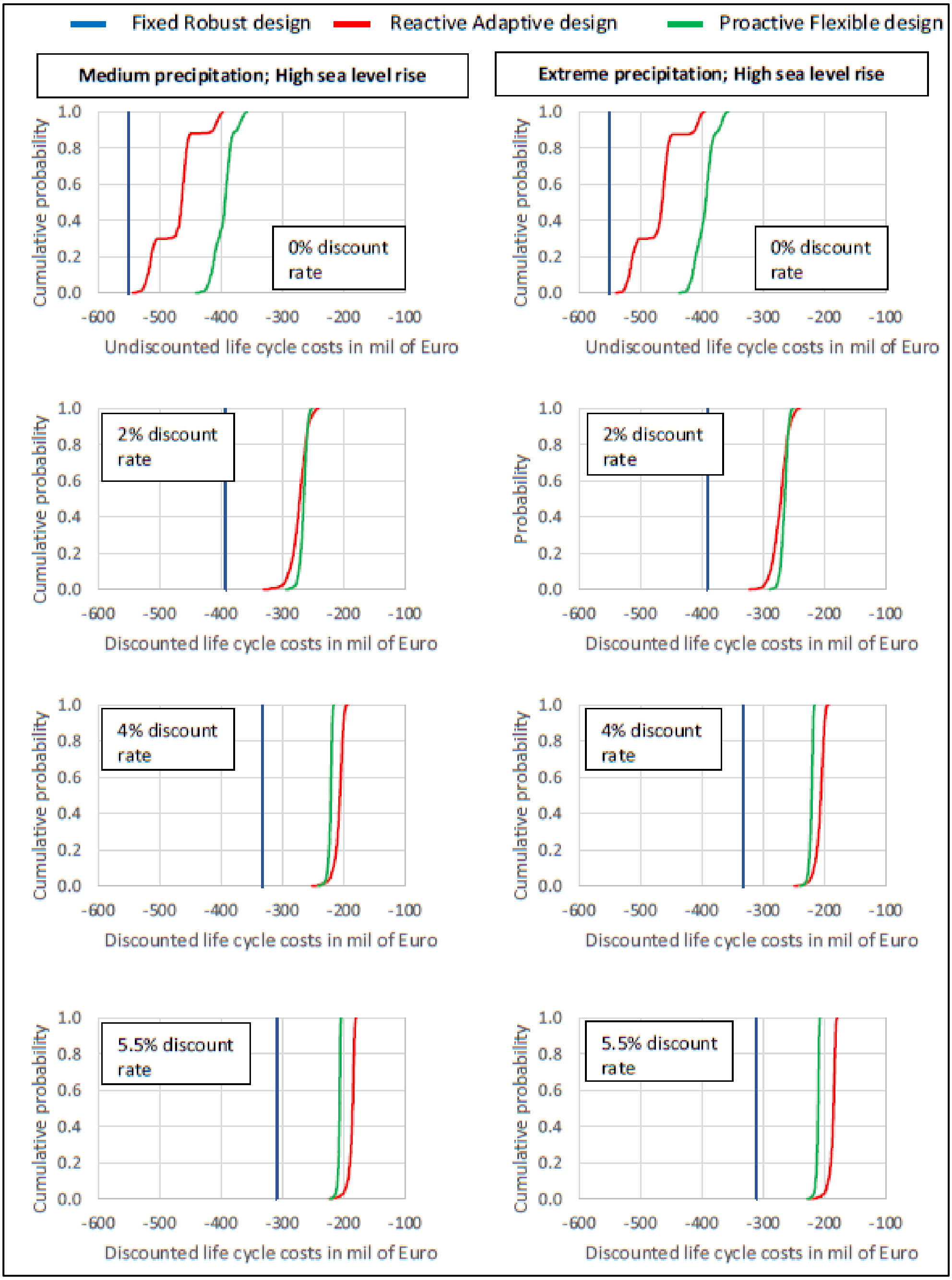


Figure 5.15: Lifetime economic performance of different replacement strategies, varying discount rate

For obvious reasons, as the discount rate increases, the costs calculated decrease across all simulations, scenarios and alternatives. One also observes that as the discount rate increases, the cost curves become increasingly smooth, with the undiscounted results following a less continuous, more step-wise shape than the others. In the undiscounted case, the results of the 1,000 simulations become approximately grouped into groups where a total of one capacity expansion is needed, two expansions are needed etc. As there is no cost difference between an expansion in year 1 or year 50, the step-wise shape simply mirrors the number of expansions that are necessary across the different simulations, with some small smoothing due to the capacity specific maintenance costs. Discounting has a smoothing effect on these results because it differentiates between not only the number of height expansions that are necessary, but also the exact year in which they take place: the further into the future an expansion occurs, the lower the associated cost.

One observes that differing degrees of discounting affects the relative ranking of the different design strategies. As increasing discounting is conducted, the Reactive Adaptive strategy typically dominates over the other two designs due to its low up-front cost and potentially large, but severely discounted future costs. The less discounting is conducted, the more the Proactive Flexible design dominates.

Similarly, under less extreme futures, the Reactive Adaptive design performs well. In contrast, the more extreme the future scenario and thus the greater the number of expansions required over the course of the project horizon, the more the Proactive Flexible strategy begins to dominate. The reason behind this is that the Proactive Flexible strategy is explicitly designed to allow relatively cheap expansions, as opposed to the Reactive Adaptive structure which gambles on not many expansions being necessary.

This sensitivity analysis demonstrates that in this case, the Proactive Flexible design grows in appeal the lower the discount rate used and the greater the uncertainty about the future is. These results suggest that even though discounting is routinely used in economic analyses, a brief look at the undiscounted values may provide insights that are otherwise obscured by the impacts of discounting. In addition, these results demonstrate that in this case, the choice of discount rate changes not only the exact lifecycle costs obtained but also the relative desirability of the different replacement strategies.

5.6.5 Conclusions

In conclusion, in this case, based on minimizing life cycle cost alone (previously explained and justified in Section 5.4.2), there is no single stochastically dominant strategy for maintaining the required water levels on the North Sea Canal over the next 85 years. However, across all scenarios and discount rates, the two adaptive designs outperform the traditional fixed design, which is a valuable insight. The relative economic performance of these two different adaptive alternatives varies across scenarios and discount rates: the Reactive Adaptive design is favored in less extreme scenarios and at high discount rates; while the Proactive Flexible design grows increasingly dominant in more extreme scenarios under low or no discounting. While the results suggest that an incremental adaptive approach is always favorable, the ultimate choice of whether to include a proactive structural option or not depends on the decision maker's perception of the degree of risk. Decision makers who perceive future climate risk as being less than currently assumed, would prefer the Reactive Adaptive strategy, which performs best if sea level and precipitation increase less than expected. These decision makers favor the low up-front costs of the Reactive Adaptive design and gamble on few, if any, height expansions ever becoming necessary through the life of the structure. In contrast, decision makers who perceive climate risk as being potentially larger than currently assumed would prioritize the Proactive Flexible strategy, because it is designed to continue to perform adequately if sea level and/or precipitation increase more than expected.

This analysis has indicated that for this function, the inclusion of flexibility in the form of additional pump bays does improve the average life cycle cost as compared to the existing robust strategy. Compared to the incremental approach without an option, the primary value of including this structural option is as a form of insurance policy: an additional up-front cost provides protection from a future worst-case outcome.

5.7 Flood Defense Function

5.7.1 Physical-Economic Model Formulation

For the previous inland water level management function described in Section 5.6, the act of expanding pumping capacity altered the water level on the canal, representing a feedback loop that had to be captured in the modelling formulation. By contrast, for the flood defense function, the linking of external changes in sea level to user-imposed interventions and subsequent impacts on performance is relatively simple because the physical system simply responds to external changes without itself affecting the operating environment. In other words, increasing the flood defense height of the pumping station can protect against increasing sea level but the act of increasing the structural height in no way affects the 1:10,000 year water level.

Table 5.14 presents the coupled physical-economic modeling formulation used to evaluate the different replacement strategies detailed in Section 5.4.1. Again, the two individual model components are linked through the variable e_t^s, the height expansions required in any given year, in a specified scenario. Conceptually, the occurrence of an Adaptation Tipping Point serves as a trigger moment, indicating when changes are made to the existing structure. This formulation is run for each of the three different replacement strategies, in every scenario, for 1,000 simulations each. This analysis generates distributions of life cycle costs for each design, highlighting the performance of each design over a variety of futures.

Table 5.14: Coupled Physical-Economic Model Formulation

Physical Performance Module: When do Adaptation Tipping Points occur?	
$W_t^s = W_1 + \Delta^s t + u_t^s$ for $\forall\ t \in [2, T],\ s \in \{scenarios\}$	Describes uncertain changing 1:10,000 year water level over time, as defined by scenario s
$i_t^s = \max(W_t^s - h_t^s; 0)$ for $\forall\ t \in [1, T],\ s \in \{scenarios\}$	Identifies those time periods in which the installed flood height becomes inadequate: i.e. flood defense functional Adaptation Tipping Point occurs when $h_t^s \leq W_t^s$ or when $W_t^s - h_t^s \geq 0$
$e_t^s = \lceil i_t^s;\ e^{min} \rceil$ for $\forall\ t \in [1, T],\ s \in \{scenarios\}$	Rounds off the height deficiency experienced at any time to a multiple of the minimum allowable height expansion
$h_t^s = h_1 + \sum_1^t e_t^s$ for $\forall\ t \in [2, T],\ s \in \{scenarios\}$	Keeps track of total height installed at time t in scenario s
Inputs	
W_1	= 1:10,000 year water level at the start of the project horizon (t=1)
Δ^s for $\forall\ s \in \{scenarios\}$	= annual change in 1:10,000 year water level, as defined in scenario s
u_t^s	= uncertainty associated with 1:10,000 water level computed for time t and scenario s
T	= number of years in project horizon
e^{min}	= minimum height expansion
h_1	= initially installed flood defense height of structure
Independent Variable	

Table 5.14 (continued): Coupled Physical-Economic Model Formulation

T	= time, in years
Calculated Variables	
W_t^s	= uncertain 1:10,000 year water level at time t in scenario s
h_t^s	= flood defense height of structure at year t in scenario s
i_t^s	= height by which current structure is inadequate in year t in scenario s
e_t^s	*= magnitude of height expansion to be undertaken at end of year t in scenario s*
Economic Performance Module: How do different responses to an Adaptation Tipping Point compare?	
$C^{lifetime} = C^{capital} + \frac{1}{(1+r)^t}\sum_t^T C_t^{O\&M} + \frac{1}{(1+r)^t}\sum_t^T C_t^{expand}$	Computes lifetime costs of maintaining a certain performance level over the entire project horizon T
$C_t^{expand} = C^{fixed} + C^{variable} e_t^s$ for $\forall\, t \in [1, T],\ s \in \{scenarios\}$	Computes cost associated with capacity expansions of varying sizes
Inputs	
$C^{capital}$	= initial capital costs
r	= discount rate
$C_t^{O\&M}$	= annual operation and maintenance costs
C^{fixed}	= fixed cost associated with capacity expansion
$C^{variable}$	= variable per unit cost of capacity expansion
Variables	
$C^{lifetime}$	= lifetime costs of maintaining a specified performance level
C_t^{expand}	= cost of height addition
e_t^s	*= size of height expansion undertaken at end of year t in scenario s*

5.7.2 Modelling Inputs

The analysis utilized the following specific parameters and inputs:

Table 5.15: Sources of Uncertainty Captured in Analysis

Class of Uncertainty	Source	Details
Deep uncertainty	Sea level rise	2 sea level rise scenarios explored, as previously defined in Table 5.3: $scenarios = \{high; low\}$ $W_1 = 6.95\, m + NAP$ Scenario-specific annual increases in 1:10,000 water level, as derived by Deltamodel: $\Delta^{high} = 0.0070\, m/year$ and $\Delta^{low} = 0.0018\, m/year$
Probabilistic uncertainty	Uncertainty in determining water levels associated with the 1:10,000 year recurrence period	Geerse and Wojciechowska (2014) previously derived statistically-based uncertainty bounds for the water levels associated with different recurrence intervals for different locations along the Dutch coast. These confidence intervals ($u_t^s \sim Weibull(\lambda = 1.736, k = 1.542)$) are carried forward into the analysis below as representative of the uncertainty in future estimates of the 1:10,000 year water level. In order to prevent erratic simulation values from year to year, all years in one single simulation are drawn from the same percentile within the envelope of uncertainty defined above.

Table 5.16: Specific Design Parameters for Replacement Alternatives

	Design parameters	
Design alternative	**Flood defense height (h_t^s)**	**Pumping capacity**
Fixed Robust design	$h_t^s = 12$ m +NAP for $\forall\ t \in [1, T],\ s \in \{scenarios\}$	Held fixed at 300 m^3/sec
Reactive Adaptive design	$h_1^s = 7.5$ m +NAP[48] for $\forall\ s\ \{scenarios\}$; minimum increment for height addition, $e^{min} = 1$ m	
Proactive Flexible design	$h_1^s = 7.5$ m +NAP for $\forall\ s\ \{scenarios\}$ *with foundation sized to allow multiple height additions later,* up to a maximum height of 12m +NAP; minimum increment for height addition, $e^{min} = 1$ m	

Table 5.17: Costs Associated with the Different Design Alternatives Considered

	Costs (in millions of 2015 Euro)		
Design alternative	**Capital costs ($C^{capital}$)[49]**	**Expansion costs (C_t^{expand})[50]**	**Annual operation & maintenance costs ($C_t^{O\&M}$)[51]**
Fixed Robust design	180.7	n/a	1.95
Reactive Adaptive design	165.5	Variable depending on height expansion	1.95
Proactive Flexible design	178.7	Variable depending on height expansion	1.95

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48 The flood defense height to be installed in both of the adaptive strategies is obtained by estimating the 1:10,000 year water level in 10 years and adding a free-board allowance of 50 cm to obtain a structural height of +7.5 m NAP.

49 Capital costs are obtained from the cost model described in Section 5.5.2.

50 Expansion costs are obtained from the cost model described in Section 5.5.2.

51 Annual operation and maintenance costs ≈ 6,515 Euro/m^3/second of pumping capacity (Personal communication with Giel Klanker, Rijkswaterstaat on 27 November 2014).

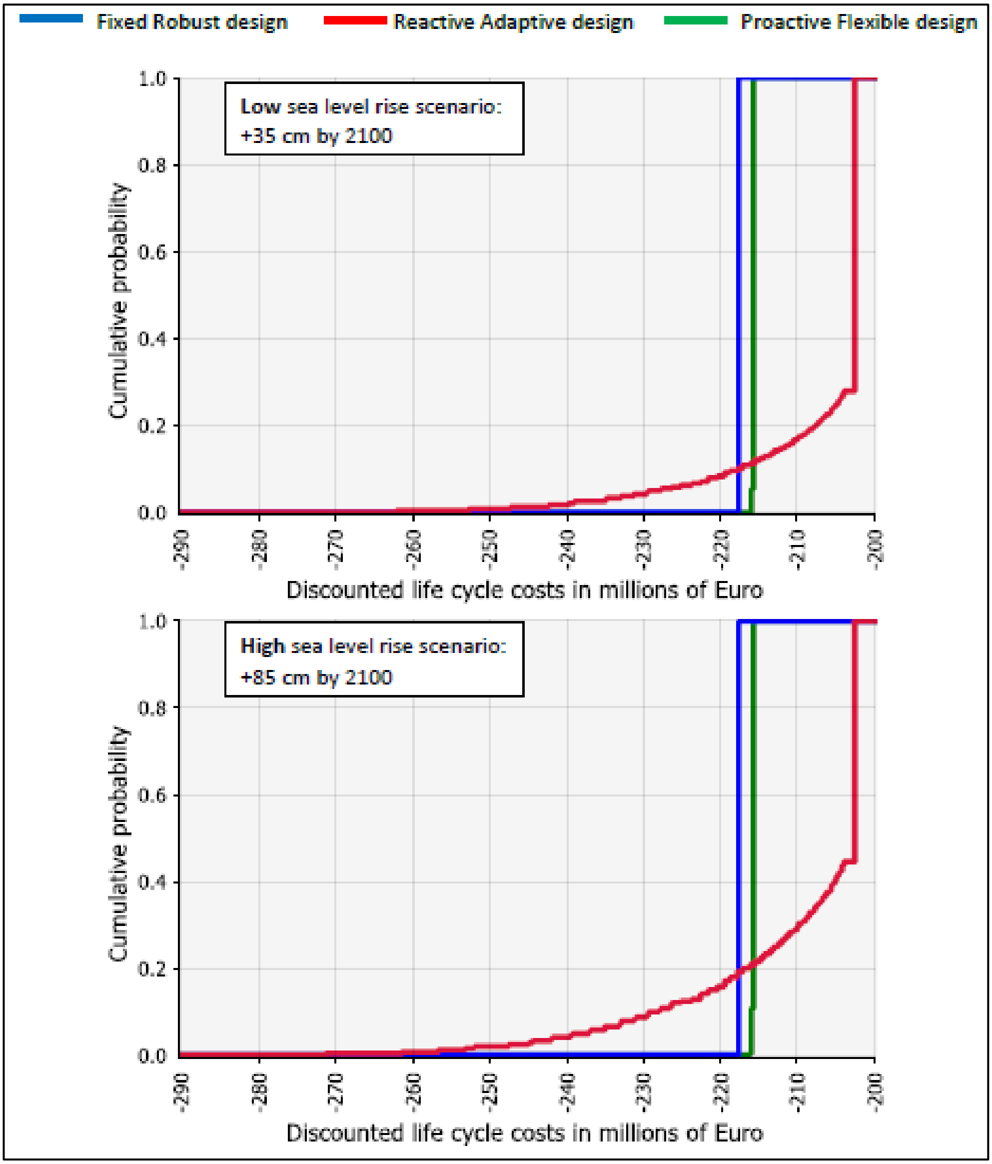
5.7.3 Results and Discussion

To maintain the required 1:10,000 year flood protection throughout the 85-year project horizon we explore the performance of three alternative replacement strategies:

- *Fixed Robust design*, which establishes now the maximum flood defense height that might eventually be needed;
- *Reactive Adaptive design*, which builds what is needed now, and will upgrade the flood defense height as dictated by emerging future conditions; and
- *Proactive Flexible design*, which creates the foundation on which to build the maximum flood defense height that might be needed in the future, but defers raising the height until actually necessitated by external developments, and thus saves on immediate costs.

Figure 5.16 shows the relative lifetime economic performance of these three different structural designs, using the standard 5.5% discount rate for the two different sea level rise scenarios explored in this analysis. Again, results are in the form of a cumulative probability distribution of life cycle costs.

The Fixed Robust strategy is associated with life cycle costs of approximately 217.7 million Euro across all simulations and scenarios. This result is deterministic because of this model's focus on life cycle costs alone (as opposed to both costs and benefits) where, by design, the structure is sized to be large enough for any future developments across all possible futures and hence does not need to be expanded over its lifetime. The Reactive Adaptive strategy involves average life cycle costs that are approximately 5% lower than those of the Fixed Robust structure, however, this adaptive strategy has much large possible range of outcomes, from 202.5 to 290.0 million Euros in the worst case. Finally, the Proactive Adaptive strategy is associated with life cycle costs that are approximately 1% less than those of the Fixed Robust strategy, with the Proactive Adaptive strategy slightly outperforming the Fixed Robust strategy across all futures examined. Furthermore, the Proactive Adaptive strategy has a much narrower range of outcomes than the Reactive Adaptive strategy.



<u>**Figure 5.16: Lifetime economic performance of three design alternatives for flood defense, across two sea level rise scenarios, at a discount rate of 5.5%**</u>

These results is primarily driven by the particular cost break-down for construction of a structure of this kind, as previously observed in Section 5.5.3, when building the cost model. During initial construction, the dimensions of the foundation and other below ground structural components are central determinants of the capital cost. The Fixed Robust and Proactive Adaptive structures both provide for the same eventual flood defense height, are thus associated with the same below-ground foundation dimensions and hence show very similar life time costs. (The 1% cost reduction of the Proactive Flexible design relative to the robust design is primarily the result of being able to discount costs deferred into the future, as in absolute terms, an incrementally-built structure does cost more in this case than one constructed all at once.) By contrast, the Reactive Adaptive structure commits initially to a lower height and thus a smaller foundation. While it is substantially cheaper to build initially, it may lead to substantial (all be they discounted) future costs when a height addition and thus reconfiguration of the foundation are deemed necessary.

Table 5.18 is complementary to the cumulative probability distributions shown in Figure 5.16, showing the relative lifetime economic performance of the same alternatives, using a number of different performance criteria. By examining these multiple performance criteria (Table 5.18), decision makers can explicitly decide whether they most value minimum average cost (i.e. chose the Reactive Adaptive design) or will accept a higher average cost in order to reduce the possible range of outcomes and provide more certainty with regard to future performance (i.e. chose the Fixed Robust or Proactive Flexible designs). This narrowing of the range of outcomes is an explicit and desirable characteristic of the inclusion of a structural option: a small investment at the outset helps system managers be better prepared for a wider range of possible futures.

Table 5.18: Multi-Criteria Summary Table Lifetime costs (in millions of 2015 Euro, discounted at 5.5%) - the bolded values indicate which design performs best for each criterion in turn

Design alternative	Fixed Robust	Reactive Adaptive	Proactive Flexible	Best design
Low sea level rise scenario				
5th percentile	217.7	202.5	215.7	Reactive Adaptive
Mean	217.7	206.6	215.7	Reactive Adaptive
95th percentile	217.7	228.0	215.9	Proactive Flexible
Range	0	75.3	0.5	Fixed Robust
Standard deviation	0	9.5	0.06	Fixed Robust
Initial capital expenditure	180.7	165.5	178.7	Reactive Adaptive
High sea level rise scenario				
5th percentile	217.7	202.5	215.7	Reactive Adaptive
Mean	217.7	209.9	215.8	Reactive Adaptive
95th percentile	217.7	239.0	215.9	Proactive Flexible
Range	0	77.9	0.5	Fixed Robust
Standard deviation	0	12.7	0.08	Fixed Robust
Initial capital expenditure	180.7	165.5	178.7	Reactive Adaptive

Comparing the results across both sea level rise scenarios, the relative life cycle costs of the different strategies surprisingly remain largely the same across the two scenarios. The Fixed Robust strategies have equal costs in both scenarios as we are preparing for a predefined worst case. In the case of the Reactive Adaptive strategy, the low sea level rise scenario is associated with average total costs that are 1.5% lower than the high sea level rise scenarios. This is consistent with fewer structural heightenings being needed as sea level rises more gradually than in the high scenario. In the case of the Proactive Adaptive strategy, the high sea level rise is also associated with a higher proportion of simulations where expansion is necessary. This can be seen more clearly in Figure 5.17, which provides a close-up of a portion of Figure 5.16, to better display the shape of the cost curve for the Proactive Flexible strategy. Looking at Figure 5.16 once more, the Reactive Adaptive strategy has the best cost performance in about 90% of the low scenarios simulations and 80% of the high scenario simulations, with the Proactive Flexible strategy performing best in the remainder of simulations. This suggests that the more extreme the future turns out to be, the better the Proactive Flexible design performs.

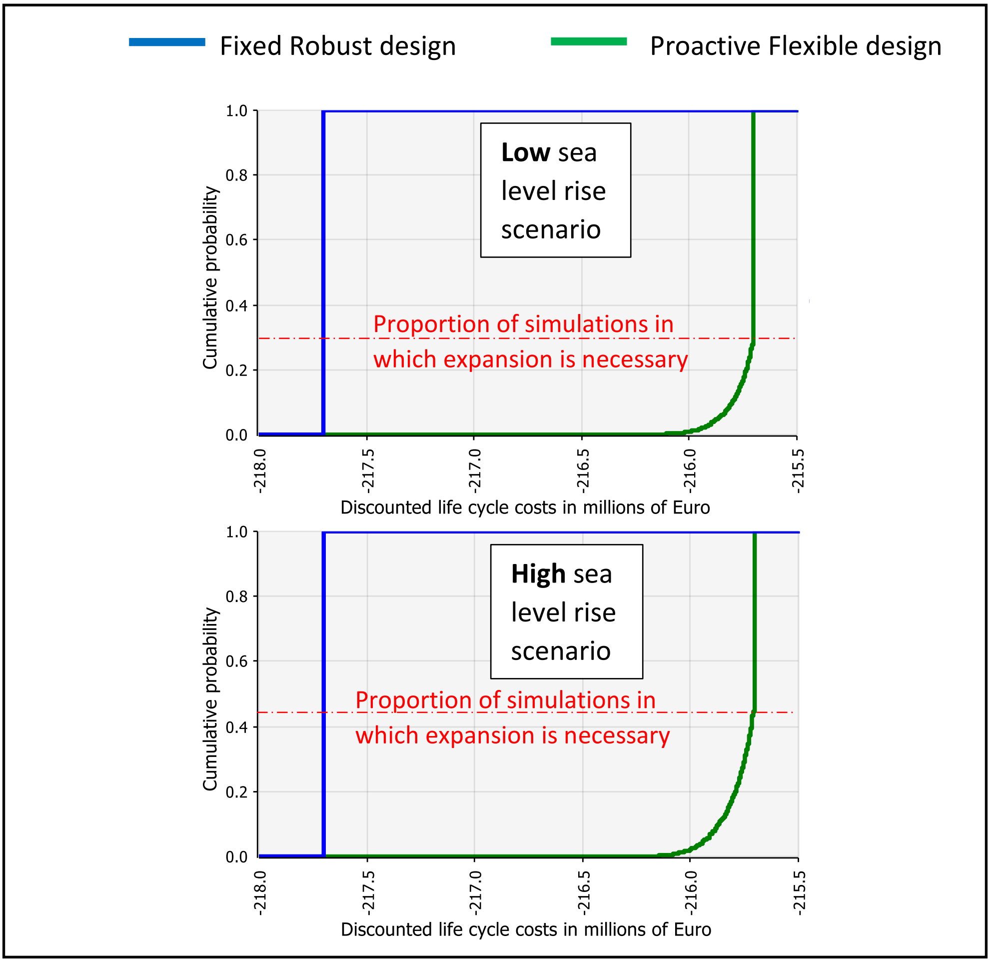


Figure 5.17: Close-up of the lifetime economic performance of the robust and proactive flexible strategies, for two sea level rise scenarios, at a discount rate of 5.5%

The similarity of the results obtained across the different sea level rise scenarios appears to demonstrate that uncertainty in future sea level rise is a relatively lesser determinant of life cycle costs. This could again be a result of the specific cost breakdown for this structure: when building a structure anyway, the fixed costs for flood defense structures are so high, that relatively small differences in the design height of the structure make only a minimal difference in the total life cycle costs. Additionally, it may also suggest that statistical uncertainty in determining the 1:10,000 year water levels is in fact much more influential for life cycle costs than the degree of sea level rise itself. This minimal impact that uncertainty in future sea level has, once the need for any kind of flood defense structure has been determined, is surprising given that sea level rise is often discussed as a critical source of uncertainty for investment and design of future flood protection infrastructure.

5.7.4 Sensitivity Analysis

This analysis was repeated for a series of different discount rates (0, 2, 4 and 5.5%) as shown on Figure 5.18. On some of the graphs shown, the green curves showing the Proactive Flexible strategy is not clearly visible because it is largely overlain by the blue curve representing the Fixed Robust strategy. This demonstrates that for some discount rates, these alternatives are associated with comparable costs.

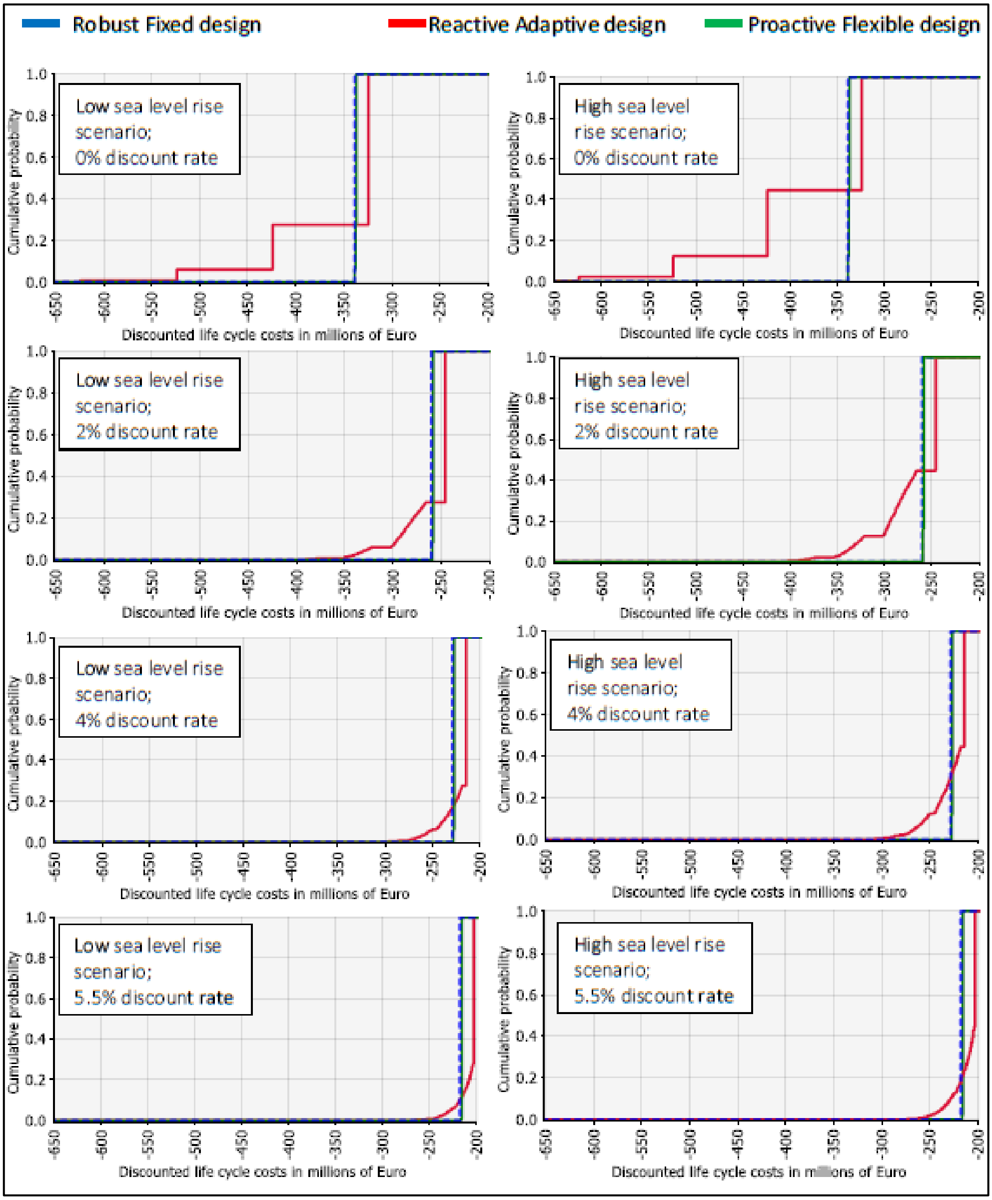


Figure 5.18: Lifetime economic performance of different design alternatives, across two sea-level rise scenarios, for different discount rates

One observes that across all discount rates, the relative economic performance of the different alternatives stays the same, with the Proactive Flexible strategy costing less, on average, than the Fixed Robust strategy, and the Reactive Adaptive strategy in turn spanning a wide range of life cycle costs depending on the exact future conditions. This demonstrates that while the choice of discount rate does change the exact lifecycle costs obtained, the relative desirability of the different replacement strategies is not affected by the exact discount rate chosen. This is in contrast to the inland water level management function (explored in Section 5.6) where the relative economic performance of the different alternatives changed across discount rates, meaning that discounting affected the ranking of the different design strategies.

For obvious reasons, as the discount rate increases, the costs calculated decrease across all simulations, scenarios and alternatives. One also observes that as the discount rate increases, the cost curves become increasingly smoothed, with the undiscounted results following a sharper, step-wise shape than the others. In the undiscounted case, the results of the 1,000 simulations become grouped into groups where a total of one capacity is needed, two expansions are needed etc. As there is no cost difference between an expansion in year 1 or year 50, the step-wise shape simply mirrors the number of expansions that are necessary across the different simulations. Discounting has a smoothing effect on these results because it differentiates between not only the number of height expansions that are necessary, but also the exact year in which they take place: the further into the future an expansion occurs, the lower the associated cost.

5.7.5 Conclusions

In conclusion, in this case, based on minimizing life cycle cost alone, there is no single stochastically dominant strategy for maintaining the required 1:10,000 year flood protection level over the next 85 years. However, across all scenarios and discount rates, the relative economic performance of the different alternatives stays the same. Thus, the ultimate choice of alternative will depend on the decision maker's perception of the degree of risk: decision makers who perceive future climate risk as being less than currently assumed, would prefer the reactive adaptive strategy, which performs best if sea level increases less than expected. These decision makers favor the low up-front costs of the Reactive Adaptive design and assume that no height expansions will ever become necessary through the life of the structure. In contrast, decision makers who perceive climate risk as being potentially larger than currently assumed would prioritize the Proactive Flexible strategy, because it is designed to continue to perform adequately if sea level increases more than expected. This analysis has indicated that for this function, the inclusion of flexibility in the form of a larger foundation does not improve the average lifecycle cost as compared to the existing Fixed Robust and Reactive Adaptive strategies; rather, the primary value of including this structural option is the narrowing of the range of potential outcomes, especially when compared with the Reactive Adaptive design. Thus, the ultimate choice of which strategy to select depends on a number of factors including the risk aversion of the decision maker, the length of their planning horizon and any other local tradeoffs to be made.

5.8 Conclusions for IJmuiden

This proof of concept demonstration explored replacement planning for a complex structure that fulfills a number of different functions. For IJmuiden, the initial analysis of Adaptation Tipping points demonstrated that moments when large-scale interventions become necessary due to structural degradation or external changes in operating conditions are widely spread out throughout the life of the structure. From the perspective of an asset manager, having functional and technical Adaptation Tipping Points in close succession would be more efficient, with this observed disparate timing intuitively suggesting the value in exploring an adaptive and incremental approach to infrastructure planning. Building on this, an Engineering Options analysis was conducted, comparing the traditional, robust fixed approach to infrastructure planning with two more adaptive approaches, one reactive and one proactive to uncertainty through the inclusion of an option as an insurance policy.

In the case of the inland water level regulation function, it is reasonable to conclude from the Engineering Options analysis that

- The incremental adaptive designs (both reactive and proactive) outperform the fixed design;
- The Proactive Flexible design dominates the Reactive Adaptive design in riskier futures, and when lower discount rates are applied, while the Reactive Adaptive design performs better in less risky futures;
- The preferred choice between adaptive designs depends on the decision maker's belief about the future and their willingness to bear high-cost worst-case outcomes.

In the case of the flood defense function, it might be reasonable in this case to conclude that:

- The cost-reduction benefits of the Reactive Adaptive design do not justify its risks;
- There is little to choose from between the Robust Fixed and Proactive Flexible designs, with comparable lifetime costs;
- So the preferred policy might be to adopt the Robust Fixed design and be done with it.

By coupling Adaptation Tipping Points with an Engineering Options approach, we have the tools to structure an analysis of such complex, multi-functional systems, first creating infrastructure prognosis timelines for aging structures and subsequently quantitatively evaluate the performance of different possible alternative courses of action, exploring which functionalities could benefit from a flexible approach and which conditions maximize these benefits.

Importantly, these case-specific results indicate that when planning a structure's replacement, it need not be the case that the structure as a whole should be designed to be either robust, adaptive or flexible; rather, individual function-specific components may call for different design approaches. The pumping station at IJmuiden demonstrates this, calling for robustness when designing flood defense elements of the structure and for flexibility when designing pumping elements of the structure.

It is worth mentioning here that within this proof of concept demonstration, there is no direct competition between design elements for each of the two functions: the structure's flood defense abilities are driven primarily by foundation size and structure height, whereas its inland water level regulation abilities are driven largely by the installed pumping capacity. There is no obvious tradeoff necessary between these two sets of design decisions. However, it is likely that in other, more complex structures fulfilling more or different functions, the situation may arise that different functions require tradeoffs to be made. In these situations, the same methodology applied above can still be used, first exploring each function at a time; however, an additional final step would be required, whereby the tradeoffs are made explicit and a satisfactory compromise is identified. This could be done through formal multi-objective optimization, searching for Pareto efficient solutions. This could be driven by socially determined priorities: for instance, in the

Netherlands, a federal priority use list for water exists ("*verdringingsreeks*"), which sees resources going first to flood safety, then to drinking water and energy needs, and finally to navigation, farming, industry and recreation. Identifying and coping with such tradeoffs is an area that should be explored further in future applications of this approach.

5.9 Reflections about the method as a whole

The final section of this chapter takes a step back from the specifics of the IJmuiden proof of concept demonstration, and attempts to reflect and evaluate on the method as a whole.

First and foremost, the demonstration has shown that the novel, long-term, proactive planning approach for water infrastructure investment under uncertainty developed in this work is practically and computationally tractable. It has shown that there is a difference between a proactive replacement strategy versus the traditional alternatives of robust fixed or reactive adaptive approaches. The application of Engineering Options techniques does enable us to quantitatively evaluate the differences between these different planning mindsets. These initial results are however based on imperfect data, in particular a lack of reliable cost data. The promising nature of these initial results suggests that it is worth investing further into producing better cost data and additionally improving this planning approach. In addition to these brief evaluations, a few more detailed reflections are presented below.

5.9.1 This method's reliance on well-defined performance levels

The planning approach developed in this work uses the concept of an Adaptation Tipping Point as a signal that some sort of intervention is required in the existing infrastructure network, which are then subsequently treated as triggers in a quantitative exploration of different possible responses. A shortcoming of this approach's reliance on such Adaptation Tipping Points is their need for well-defined performance standards: it is only possible to estimate when an Adaptation Tipping Point occurs if a clearly defined performance standard or functional objective exists. The existence of such quantified performance objectives varies widely, both geographically and between different structures fulfilling different functions.

For instance, in the proof of concept demonstration described above, the flood defense performance objective was clearly defined by federal law. However, for water level management, performance requirements are much less well defined. In the analysis above, a water level of -0.30 m NAP or higher is treated as the performance objective for this Adaptation Tipping Point analysis, consistent with The 2013 Water Accord for the NS-AR Canal (Beuse, 2013). However, this threshold level is only one of a number of performance objectives that emerged from a review of past studies and water agreements (see Table 5.19). In such a situation, which is the correct threshold to use? Who decides this? A lack of well-defined objectives can be problematic when using this integrated Adaptation Tipping Points-Engineering Options planning approach to explore different ways of maintaining a certain desired performance level.

Table 5.19: Performance objectives governing maximum water levels on the NS-AR Canal

Performance Objective	Source
Maximum water level = -0.30 m NAP	2013 Water Accord for the NS-Ar Canal (Beuse, 2013); Delta Program, 2015 (Rijkswaterstaat, 2014)
According to the regional canal managers, the water level at which negative impacts start being felt is around -0.14 m NAP	Personal communication, Thijs Jansen, 30 October 2014
Maximum water level = 0 m NAP Probability of exceedance must not be greater than 1/100 per year	Expansion of pumping capacity on the North Sea-Amsterdan Rhine Canal (Brouwer *et al*., 2000)
Maximum water level = +0.15 m NAP Probability of exceedance must not be greater than 1/1,000 per year	Memo: wave overtopping at IJmuiden and storage potential on the NS-AR Canal (Meijerink, 2014)
Maximum water level = +0.20 m NAP Probability of exceedance must not be greater than 1/100 per year	Life Cycle Cost Analysis for Pumping Station IJmuiden (van der Wiel *et al*., 2013)

However, this shortcoming can also be seen as an exploratory tool to provide insights about the impact of different possible thresholds: instead of starting with a fixed performance level and seeing how much it will cost to achieve this, the same model sequence can be used to explore what the lifetime costs are for different performance levels. This was done briefly for a number of different water level thresholds on the canal, as summarized in Table 5.19. Figure 5.19 shows how many expansions are expected under the extreme precipitation-high sea level scenario, when applying five different performance thresholds.

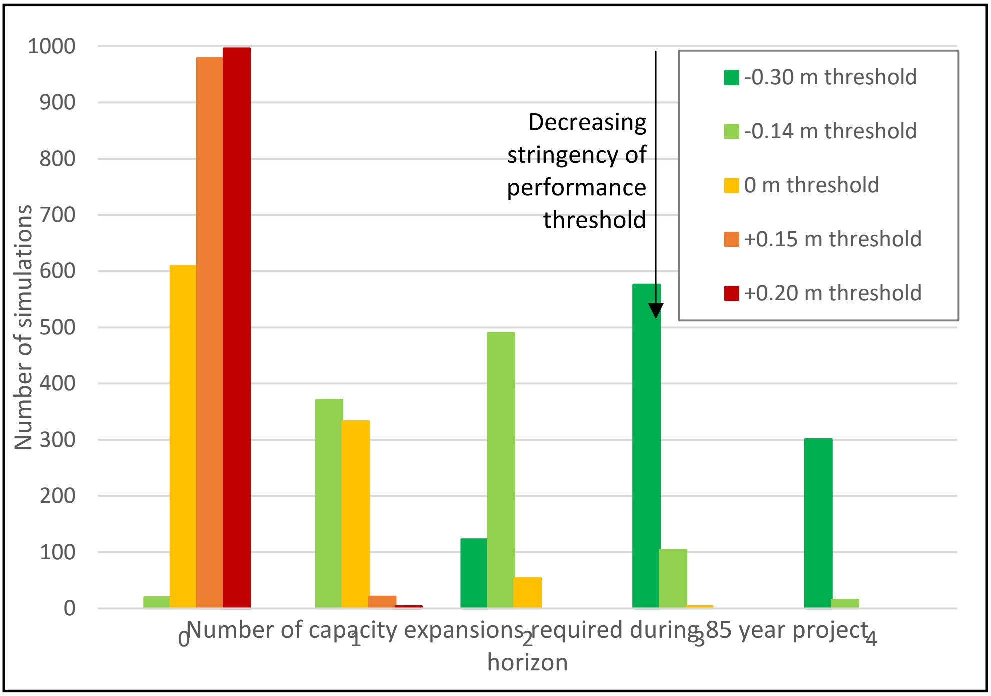


Figure 5.19: Number of expansions required for the adaptive replacement strategy, for the extreme precipitation- high sea level scenario, varying the acceptable maximum water level

As expected, the different maximum allowable water level thresholds are associated with very different numbers of necessary capacity expansions over the course of the project horizon, which in turn translates to very different life cycle costs. Logically, as the performance threshold becomes less stringent, the number of required expansions decreases. If the water level threshold was relaxed to +0.15 m NAP or higher, it is likely that no capacity expansions would be required prior to 2100. Obviously the decision to raise water levels cannot be made based on this information alone as there are certainly other indirect societal costs associated with a higher water level on the canal. From the results presented earlier, we know that the proactive adaptive strategy becoming incrementally less attractive the fewer expansions are required, and thus the proactive adaptive strategy is expected to become less attractive the more relaxed the water level threshold becomes.

These results demonstrate **that while the long-term planning approach developed here does rely on well-defined performance thresholds to identify Adaptation Tipping Points, in situations where these do not exist, the same modelling set-up can be easily used to explore the impact of choosing different performance thresholds.** Thus, this planning approach can not only provide insights about strategic infrastructure planning, but in reverse, can inform the setting of the objectives that these infrastructure systems must comply with.

5.9.2 The degree to which Adaptation Tipping Points are used as signals for action by decision makers

The approach presented in this work uses the concept of an Adaptation Tipping Point as a signal that an intervention is required. Section 5.8.1 discussed how this necessitates the existence of a well-defined threshold, and how the same sequences of models can be used in reverse to explore the lifetime costs associated with different possible performance thresholds, if one does not exist. In this section, the focus remains on Adaptation Tipping Points, but rather on their congruence (or lack thereof) with the external signals actually used by decision makers to make infrastructural investment decisions.

Within this proof of concept demonstration, when looking at the inland water level management as described in Section 5.3.2, it was discovered that even at present, the installed pumping capacity is insufficient to maintain the desired water levels on the canal. The occurrence of such an Adaptation Tipping Point in the present is interesting in that it allows a comparison of what the theoretical quantitative output says we should be concerned about right now and what issues policy and decision makers are in fact engaging with in the present day. There is at present no capacity expansion being considered for IJmuiden. Nor is there any sentiment of being on borrowed time on this issue, or that a crisis is approaching. This discrepancy suggests that, despite early attempts by Rijkwaterstaat to use Adaptation Tipping Points within their long-term planning process, as of yet, the signals actually used by decision makers to make decisions about capacity expansions are not in line with those used in this analysis. This suggests a rift between the analytical decision support methods developed and used here and the actual decision making process. The interplay between quantitative engineering analysis and decision making within the wider context of an existing political and institutional arena is long-winded and complex, and hence the discrepancy observed is likely unsurprising. However, a brief investigation using data analysis and expert consultation was conducted to explore whether any insights can be gained about what the signals are that are actually used by decision makers to indicate that a capacity expansion may be becoming necessary.

First, using 10 minute canal water level data from 1996 to the present day, all high water events on the canal were identified, using all of the different high water thresholds presented earlier in Table 5.19. These results are shown on Figure 5.20: of the five different thresholds referenced in existing documents and summarized in Table 5.19, only the two most stringent ones were ever violated during the period of record. Expert consultation indicated that the process of capacity expansion was initiated by the single high water event of magnitude greater than -0.14 m NAP that occurred in 1998. By 1999 the decision to expand had been finalized and the second event greater than -0.14 m NAP in 2002 occurred when the expansion was already underway. Taken together, this would suggest that when looking only at canal water levels, the signal actively noticed by decision makers is that of exceedances of the -0.14 m NAP threshold.

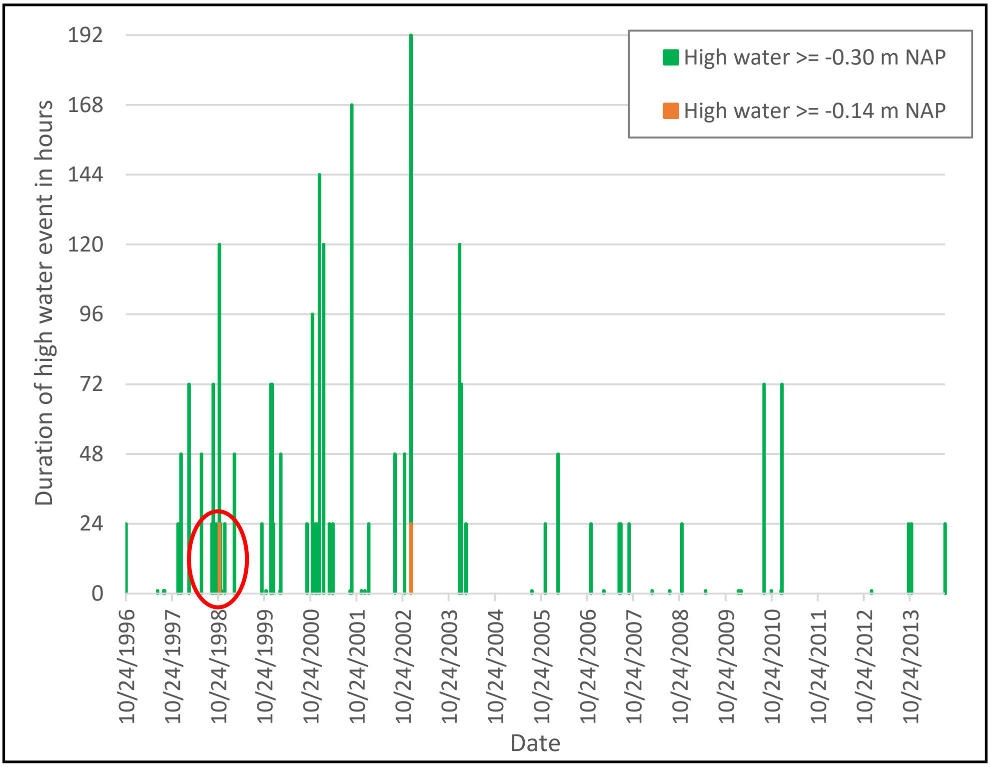


Figure 5.20: High water events on the NS-AR Canal between 1996 and 2016

The reason this is an important insight is that so far in the approach developed here, Adaptation Tipping Points have been treated to some extent as an exogenous input to the quantitative exploration of different structural replacement strategies. In other words, the occurrence of an Adaptation Tipping point is governed simply by an externally selected performance threshold. This result suggests **that there is much to be gained from treating this Adaptation Tipping Point threshold less as a fixed, exogenous input and more as an iterative exploration of the degree of consistency or discrepancy between the values used by quantitative decision support modelers and those used by other people elsewhere in the decision**

process. In other words, this same planning approach that uses Adaptation Tipping Point thresholds as a simple exogenous input can also be used to make more explicit the implicit signals that decision makers use.

5.9.3 The move from robust to adaptive designs is not a silver-bullet solution

As documented extensively in Section 2.3, the traditional approach to the design of water resources infrastructure has been one centered on a predict-then-act approach, with substantial emphasis placed on over-dimensioning and the use of safety margins to account for the uncertainties. More recently however, there are substantial portions of the emerging water resource management and climate adaptation literature that have begun to call for more adaptive solutions in light of substantial future uncertainties.

However, what the results presented on Figures 5.14, 5.15 and 5.18 suggest is that **adaptive solutions should not be seen as a silver bullet to every infrastructure investment problem, with the relative efficacy of an adaptive strategy as compared to the historic robust approach needing to be evaluated on a case-by-case basis, exploring each individual function fulfilled by a given structure**. In particular, when it comes to the flood defense function (shown on Figure 5.18), a short-sighted adaptive solution that simply designs for the short-term and does not prepare for the longer term is substantially worse than the status quo approach of robust over-dimensioning in situations where external changes occur more rapidly than expected.

Furthermore, when looking at typical multi-functional water management structures, it is likely that **an effective long-term infrastructure investment plan should combine both elements that are adaptive and elements that are robust,**

rather than treating them as mutually exclusive design strategies, as is often done in the existing literature. The method developed and demonstrated in this work is valuable in that it is able to identify those infrastructural elements where these different design strategies would be most effective i.e. which functions and which structural components should be designed for robustness and which are more effective if approached in an adaptive way. Within this proof of concept demonstration, results appear to suggest that when focusing on the inland water level management function, an adaptive design is a sensible choice, whereas for the flood defense function, a number of different strategies could be justified, depending on the degree of risk aversion and short-sightedness of the decision maker. Hence, a single structure could be optimally designed to contain robust and adaptive components.

5.9.4 All adaptive strategies are not created equal: reactive adaptive strategies perform substantially differently from proactive adaptive strategies

Section 5.8.3 discussed that adaptive strategies do have the potential to offer performance benefits as compared to the traditional, monolithic approach to infrastructure design. Typically, however, such an adaptive strategy still sees decision makers responding to uncertainty, rather than making sensible, early preparations for it. In this proof of concept demonstration, a more proactive adaptive strategy is explored, operationalized through physical options embedded into the structure itself, which facilitate making future changes in response to updated information and observations. The results presented on Figures 5.14, 5.15 and 5.18 demonstrate that **there is a potentially substantial difference in the life cycle costs of a more commonplace adaptive strategy that is treated as short-sighted and reactive, and one that actively and proactively acknowledges future**

adaptations by embedding the flexibility to make changes. In other words, **not all adaptive strategies are created equal.** An effective adaptive solution should not be equated to a wait-and-see solution: while the delaying of investments by taking only short term actions now does have theoretical cost reductions due to the impact of discounting over time, these may be more than offset later by the added cost of recovering from a previous short-sighted decision.

Looking more closely at the results presented in Figures 5.14, 5.15 and 5.18, the proactive strategy is not always dominant over the reactive strategy, with the relative economic performance of these two different design strategies being function-specific and scenario specific. In general, **a proactive design grows in desirability the more uncertain and extreme the future is, the lower the economies of scale at play and the lower the discount rate used.** However, the proactive design outperforms the reactive design across all variables for one important performance criterion: **across all variables, the proactive flexible strategy is associated with a narrower range of outcomes than the reactive adaptive strategy.** In particular, **the proactive flexible design eliminates the high costs associated with a worst-case outcome**. Thus, the inclusion of an option and the flexibility this offers is in effect performing like a kind of insurance policy: a premium up-front helps prevent a very bad outcome in the future. Thus, when evaluating different courses of action, a narrow total cost range should be prioritized more than looking at the average cost alone, especially when dealing with vastly uncertain futures.

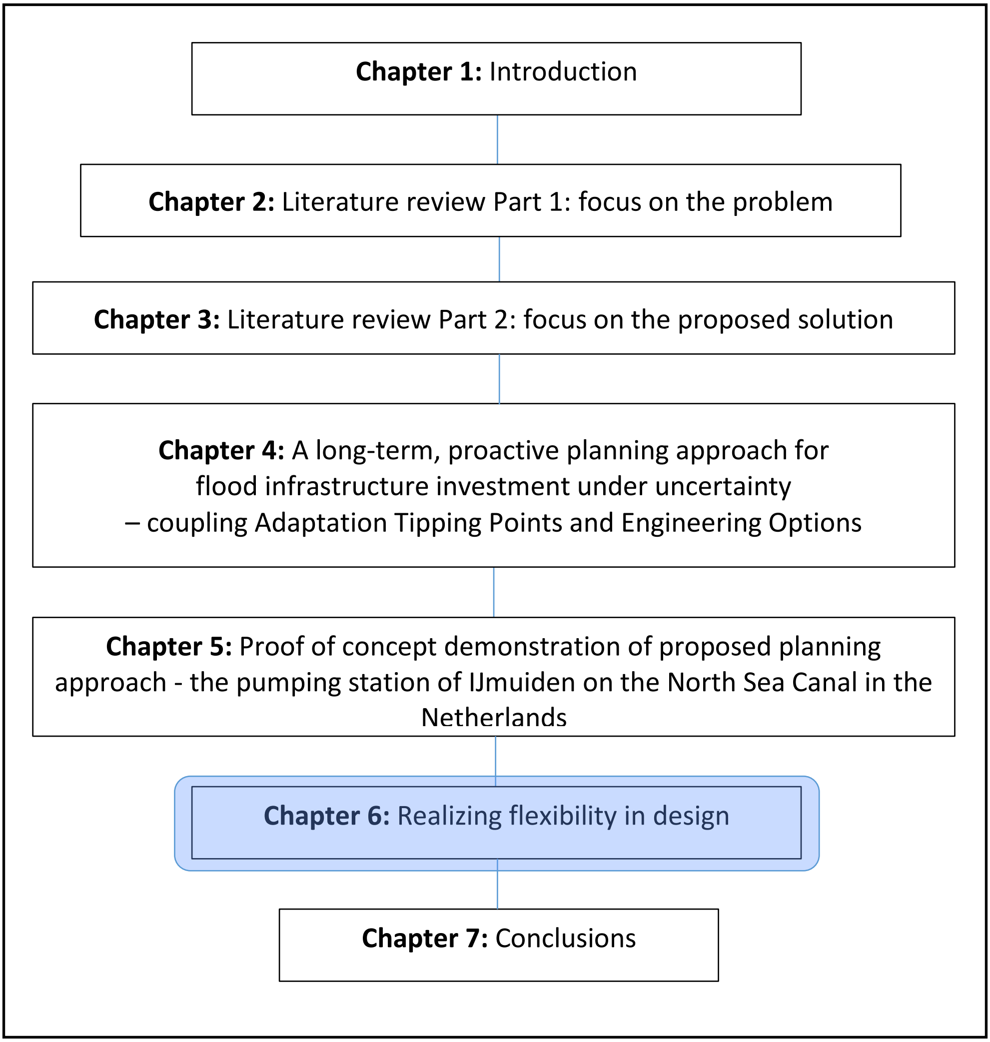
5.9.5 Discount rates in the context of infrastructure replacement

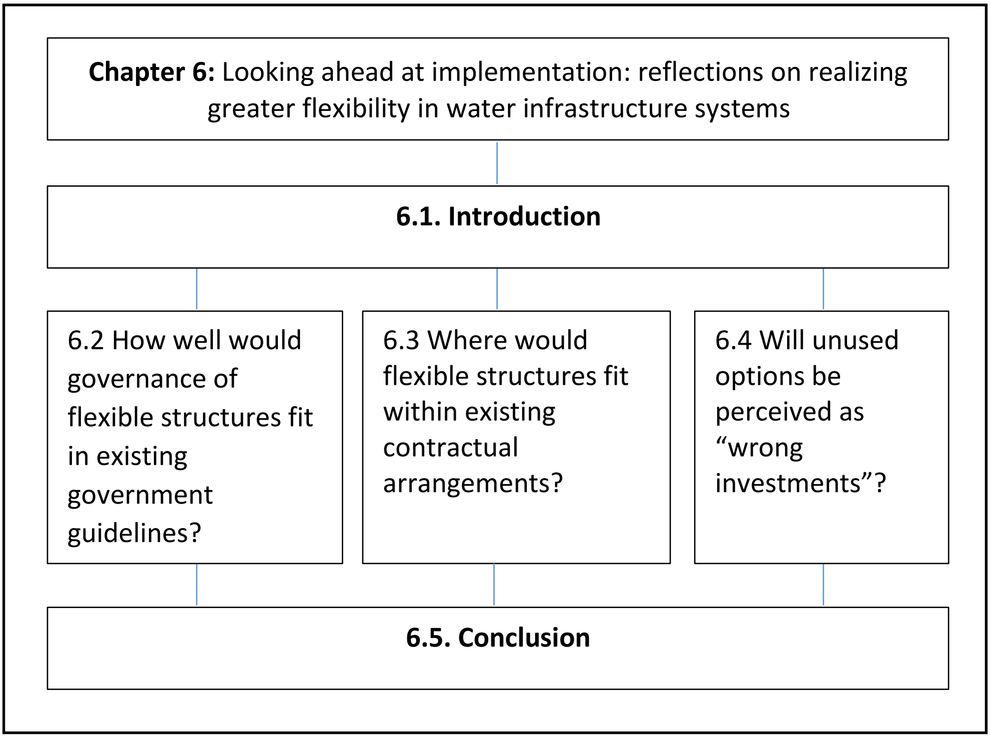
The Engineering Options analyses described in Sections 5.6.4 and 5.7.4 present results for a series of different discount rates, specifically 0, 2, 4 and 5.5%. In many government agencies involved in infrastructure investment, the discount rate is fixed: Rijkswaterstaat uses a rate of 5.5%, while the US Army Corps of Engineers uses a 3.125% discount rate for water resources projects. So why invest any time in exploring the impact of different discount rates if the ultimate end user has a predetermined rate anyway?

During the development of this proof of concept demonstration, the question emerged as to **whether replacement infrastructure projects should in fact be evaluated using the same discount rate as new infrastructure projects?** For instance, the 5.5% discount rate used by Rijkswaterstaat for all capital investment projects is comprised of a 2.5% risk-free rate plus an additional 3% risk premium. When constructing a new shipping lock for instance, there is uncertainty about future shipping traffic, with no past data able to provide insights because a lock has never existed at that location. If computed appropriately, this 3% risk premium should balance these financial risks of the project as a whole. However, in the case of replacement, this is less uncertainty regarding how much shipping traffic will materialize because a lock has been in operation there for many decades. Would it not be reasonable then to adopt a lower (or no) risk premium when it comes to replacement projects as compared to new construction?

The reason this is important in the context of this work is because different design strategies are favored by different discount rates: higher discount rates favor short-term, adaptive designs, whereas lower discount rates favor proactive flexible designs. Thus, if there is a case to be made that the discount rates previously used by government agencies for new capital investments should be revised down in the current replacement era, then proactive flexible structures may grow in their economic appeal. However, extreme caution should be exercised when proposing differential discount rates for different projects: through discount rate manipulation, virtually any course of action can be made to look like “the winner”, regardless of its true merits or shortcomings.

6. **Looking ahead at implementation:** reflections on realizing greater flexibility in water infrastructure systems





Chapter 5 served as a demonstration and proof-of-concept of the planning approach developed in this dissertation, examining the replacement of the pumping station at IJmuiden, located on the North Sea Canal in the Netherlands. This chapter, Chapter 6, is complementary to the IJmuiden proof of concept demonstration, reflecting on possible contextual considerations that may hinder the practical application and implementation of the new planning approach developed in this dissertation. Section 6.1 provides a brief introduction describing the objectives of this chapter. Sections 6.2 through 6.4 reflect on a number of factors affecting implementation that emerged from the IJmuiden proof of concept demonstration, and Section 6.5 provides some concluding remarks.

6.1 Introduction

This dissertation has developed a long-term planning approach for the design of flood management infrastructure that is proactive in its treatment of uncertainty by incorporating flexibility in the form of Engineering Options. The focus in this dissertation has been on articulating how the technical, modelling and engineering components of such an approach fit together and what kind of new insights they offer compared to the status quo. However, infrastructure investment and long-term water resource planning do not occur in isolation, with an array of other contextual factors (e.g. governance structures, financing, stakeholder engagement, data management) affecting the practical application of any new approach and its ultimate execution and success. Unsurprisingly, different water governance models abound in the literature: for instance, Hattingh *et al*. (2007) propose a three-pronged model of natural resources governance, comprised of government, society and science/engineering components, while the OECD's principles for water governance are centered on effectiveness, efficiency and trust & engagement (OECD, 2015).

Rather than trying to use one of these water resource governance models to structure this discussion, the materials presented here stem directly out of the IJmuiden study (Chapter 5), and are presented as a number of reflections. These are not the result of a systematic study of the steps required to implement new planning strategies; rather they emerged as issues and sticking points through the course of conducting, disseminating and refining this proof of concept demonstration. These reflections focus on this issue of contextual considerations that may enable or repress the possible implementation of a more proactive and flexible approach such as the one developed here. The intent of this chapter is contemplative, drawing attention to relevant factors that emerged from the proof of concept demonstration, lying outside of the direct realm of technical infrastructure planning and engineering. These observations are explored and placed within the context of any relevant existing literature. Each of the reflections discussed below warrant further detailed analysis and a closer study of what could be done to minimize the impact of these potential barriers to implementation. While such detailed analysis falls outside the scope of this dissertation, this chapter serves as an acknowledgement that physical systems do not exist in a vacuum and acts as a bridge to future research in other disciplines that is crucial to the successful continuance of the approach developed in this work.

6.2 How well would flexible structures fit within existing governance practices?

Through the development of the IJmuiden proof of concept demonstration (Chapter 5), the question emerged repeatedly from within Rijkswaterstaat as to **where an incremental, flexible infrastructure design incorporating a structural option would fit within existing infrastructure planning procedures?** As the executive branch of the Dutch Ministry of Infrastructure and the Environment, Rijkswaterstaat is responsible for public water management projects in the Netherlands. However, their existing planning guidelines do not offer clear provisions for the management and governance of new, proactively flexible structures, such as those developed in this work.

Over the last decade, there has been a concerted effort by Rijkswaterstaat to update past infrastructure governance processes to incorporate an increasing emphasis on infrastructure replacement, renovation and maintenance as opposed to new construction alone. To this end, at present, water infrastructure projects can fall into one of the following categories, each associated with their own work processes and funding mechanisms:

1. **Multi-year Infrastructure, Spatial Planning and Transport (MIRT)**[52] **Program**

   This program contains individual capital infrastructure investment projects as well as a sub-program focusing on the replacement and renovation of existing structures[53]. The boundary between new capital investment and renovation projects is not well-defined: if an existing deteriorated structure is entirely razed and replaced with a newer version of the same structure, does that count as new investment or renovation? Similarly, what if virtually every component of an existing structure is upgraded, thereby essentially creating a new structure with expanded functionality? The boundary between new capital investment projects and renovation projects has been somewhat arbitrarily defined, with any construction project costing more than €112.5-225 million[54] being removed from the replacement program and designated as an individual capital investment project (Ministry of Infrastructure and the Environment, 2012).

2. **SLA projects**[55]

   The focus here is on operation and maintenance of existing infrastructure systems in order to ensure that they continue to provide certain desired levels of functionality.

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[52] MIRT stands for *Meerjarenprogramma Infrastructuur, Ruimte en Transport*.

[53] This replacement sub-programme is titled V&R, which stands for *Vervanging en Renovatie*.

[54] The exact threshold value between new capital investment projects versus projects encompassed by the renovation program is location specific.

[55] SLA stands for Service Level Agreements.

The federal contributions to all of the different types of infrastructure projects under these two categories are funded from the so-called *Infrastructuurfonds*, a national infrastructure fund into which the federal government assigns money every year, with a planning horizon of 14 years into the future. When allocating money to this infrastructure fund, capital infrastructure projects are one sub-category of funding, while renovation, renewal, operation and maintenance are lumped as a second funding category. Individual capital infrastructure projects receive specific budget allocations as individual line items in the annual budget, whereas replacement and renovation, and operation and maintenance receive funding as programs as a whole, rather than specific needs being allocated particular amounts of money. Not only is each of these different project categories associated with separate funding sources, but also different sequences of steps in the implementation process. Long-term budget allocation and decision making about upcoming infrastructure planning tasks occur separately within these different infrastructure categories, with no formalized overarching mechanisms in place to ensure that decisions made in one category are well-aligned with plans in another.

So while Rijkswaterstaat has invested substantial effort into creating new and updated governance guidelines that reflect the changing priorities over the last decades (from new investment to re-investment), it is not obvious that these guidelines are necessarily equipped to seamlessly cope with a non-traditional, intentionally incremental, flexible infrastructure portfolio. When envisioning planning of and investment in such a flexible project, initial construction would likely be classified as a new capital investment project under the MIRT program. However which funding stream is responsible for the initial added cost of including an option in the design, given that this added cost is already preparing for a possible later structural expansion/upgrade? Furthermore, when the time for expansion arrives, likely many decades after initial construction, would this project then be classified as renovation? Or as a continuation of the initial capital investment? How difficult is it for different phases of an infrastructure project to be switched between the different planning and financing tracks introduced above? How should the exercising of an option in an infrastructure project (e.g. capacity expansion in the case of IJmuiden) be managed differently from the initial project investment given that it is effectively a continuation of a project initiated years earlier? How could the money necessary for such an expansion be reserved within the federal budget, despite not knowing if and when such an expansion may become necessary? Could a fund be set up into which annual investments are deposited specifically for long-term adaptation of existing infrastructure network- perhaps the Highway Trust Fund in the United States could serve as an example? Among those managing the infrastructure system, how can we ensure that awareness of the existence of options is maintained and not lost over time? Thus, if we look at moving towards a guidance system that encourages flexibility as a tool to cope with future uncertainty, especially in light of aging structures, what further changes will have to be made to the existing institutional framework?

As a point of comparison, this Dutch context is briefly contrasted with water infrastructure guidance in the United States, as experienced by the US Army Corps of Engineers. Similar to Rijkswaterstaat, during much of the past century, the Army Corps of Engineers' water management focus was on developing water infrastructure systems. The Corps drew guidance for their water resource management responsibilities from the Economics and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies (WRC, 1983), as well as from relevant executive orders, and executive branch and agency directives (Armah *et al.*, 2009). As an agency where new infrastructure investment dominated spending and activities for many decades (National

Research Council, 2012), it is no surprise that these Principles and Guidelines focused primarily on new capital investment projects, as shaped by the natural and economic conditions and social priorities of the previous decades. Examining these 1983 Principles and Guidelines, a 2012 National Research Council report found that "there exists no systematic process or guidelines for setting OMR [Operation, Maintenance and Rehabilitation] priorities", indicating the difficulty the Corps was experiencing in shifting from a "construction centric organization, to [having more of] an operations and maintenance [focus]" (Hale *et al*., 2008). Other shortcomings of the 1983 Principles and Guidelines include how to operationalize the notion of adaptive management (National Research Council, 2004). In response to a mandate from Congress (WRDA, 2007), an updated set of Principles and Requirements for Federal Investments in Water Resources was released in 2013, addressing these shortcomings. Thus, in both the Dutch and US water management context, existing guidance has been updated in the last decade to be better prepared for project types other than the traditional focus on new capital investment projects. However, once again, it remains to be seen how management of a flexible structure would fit in to these existing procedures.

Conceptually speaking, what is being described here is a demonstration of previous work by Finger *et al*. (2005) and Willems *et al*. (2015): they make the case that for a complex technical system to function as intended, there must be a substantial degree of coherence/congruence between the technical and physical portions of the system and the underlying institutional and governance arrangements. Said another way, "all water management solutions are provisional" (Briscoe, 2012 from Blackbourn, 2007): not only does a technical solution to a water management problem often beget the next generation of water management challenges[56], so too the institutions and guidelines that govern these solutions are provisional in that their effectiveness diminishes as the problems being addressed evolve and contextual factors change over time.

By means of a case study, Willems *et al*. (2015) demonstrate that there is often a considerable lag time between changes in the technical and governance portions of a system, caused by a variety of factors that hinder the rapid transformation of an existing governance system. In other words, while governance arrangements must evolve with the changes in the physical system, these kinds of institutional changes are typically slow and lag behind the needs of the physical system itself. Herder *et al*. (2011) have described this as a lock-in: “organisations acquire a certain routine, [] dependent on the historical path the organisation has taken.” Thus, if it is determined desirable to move towards a system that accepts and encourages flexibility in infrastructure design as a method to cope with future uncertainty, the existing governance arrangements will need to be revisited in order to assess their continued suitability in light of changing needs and conditions.

In conclusion, the IJmuiden proof of concept demonstration raised the concern that existing government guidance may need to be re-evaluated and adjusted in order to craft governance structures and guidance that can explicitly cope with the particular needs of a flexible infrastructure system. A look at existing research in this area has validated this reflection, providing evidence that institutions and governance arrangements are typically on a delay with the changing needs of the technical components of any system. As such, further case-specific research and

[56] See for example Niebling *et al*. (2014) for an exploration of such challenge-response cycles on the Lower Mississippi River.

efforts will be required to effectively and purposefully adapt existing governance arrangements to the point where flexibility is routinely considered and effectively incorporated into infrastructure planning decisions.

6.3 Where would flexible structures fit within existing contractual arrangements?

Through the development of the IJmuiden proof of concept study (Chapter 5), a tension emerged between the different time scales involved in infrastructure financing. In recent decades, public infrastructure projects in the Netherlands have increasingly being financed as collaborations with the private sector, in public-private partnerships (PPPs)[57]. **A flexible infrastructure design takes a long-term view, assuming conditions will change over time and building in the ability to respond to these changes– how are the different possible PPP contractual arrangements more or less well-equipped to capture the needs of such a proactive and intentionally incremental infrastructure system?**

Different types of PPP contracts delineate what the relevant responsibilities, roles, costs and benefits of the public and private actors are. An overview of the different common PPP types is provided in Figure 6.1. Within Rijkswaterstaat, the predominant type of contract that has traditionally been used to tender new infrastructure construction projects is a five-year Design-Construct contract (shown as Design-Build in Figure 6.1, highlighted in blue). The contract holder is responsible for designing and constructing a structure that meets the design specifications of

[57] As a point of contrast, interest in PPPs continues to grow in the United States. However, their use remains restricted in the water sector (Congressional Research Service, 2016), for among other reasons, “a long-standing bias in favor of public control of infrastructure that is financed by taxpayers and ratepayers and managed by [] elected representatives” (Gabriel and Devlin, 2015).

the client, Rijkswaterstaat in this case, before turning it back over to the client for long-term operation and maintenance. The government typically arranges financing of the project, with Rijkswaterstaat responsible for paying the consultant or consortium of consultants who hold the contract for the completed product.

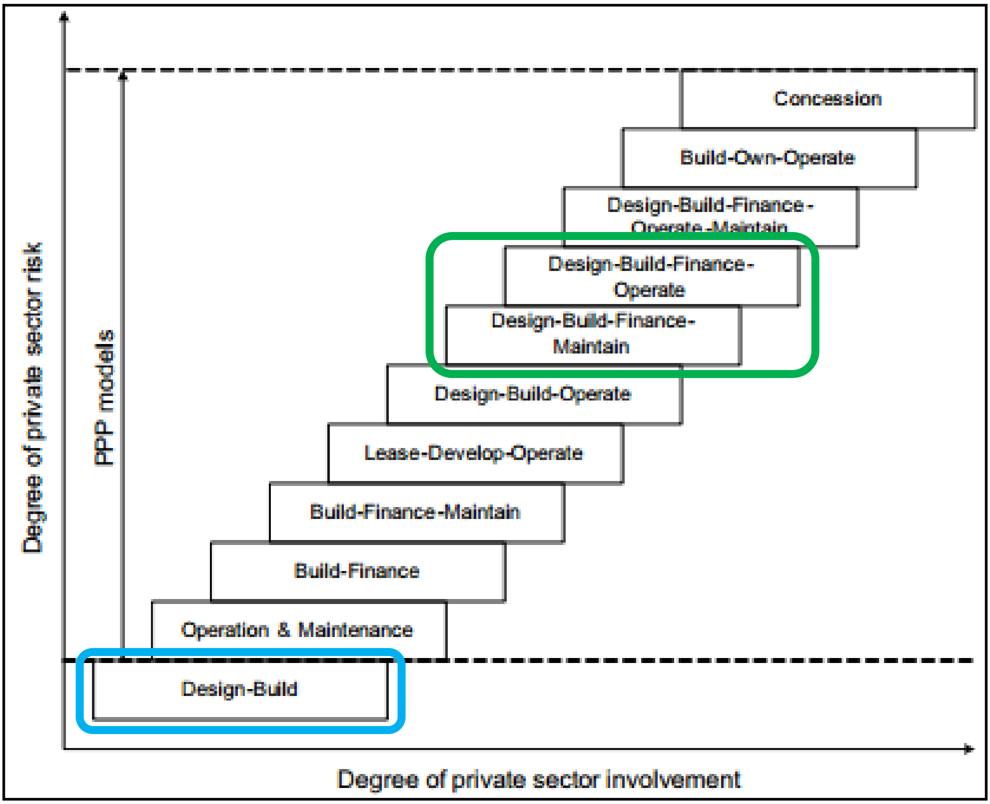


Figure 6.1: Types of Public-Private Partnerships (Source: Altamirano, 2010, adapted from the Canadian Council for Public Private Partnerships)

Starting in 1999, there has been a concerted effort by Rijkswaterstaat to explore other contract types, with a strong push to use so-called Design-Build-Finance-Maintain (DBFM) and Design-Build-Finance-Maintain-Operate (DBFMO) contracts more frequently (highlighted in green in Figure 6.1 above). This shift came at a time when one of the neo-liberal government's political priorities was to reduce the size of the government by reducing the amount of technical work done in-house and instead, relocating more projects to private market entities. The hope was that market-driven competition and increasing the role of private partners would allow more room for technologically innovative solutions, which would subsequently reduce costs and improve the efficiency of such projects as compared to the more traditional and more rigidly defined Design-Construct model. In addition to allocating more responsibility to the private partner, DBFM contracts are also associated with much longer timeframes that the typical five-year Design-Construct contract, with DBFM contracts typically spanning multiple decades.

One of the first examples of such a DBFM contract applied to a water infrastructure project in the Netherlands occurred in August 2015, when such a contract was awarded to the OpenIJ consortium for the construction of a new shipping lock at IJmuiden. Under this 26 year contract, the consortium is responsible for designing the new lock, obtaining financing, completing construction including any changes needed to the surrounding areas to create a construction site, as well as conducting operation and maintenance of the lock and channel until 2041 (Van Oord, 2015).

While the move from Design-Construct to DBFM contracts in the Netherlands was done for reasons unrelated to flexibility in design, this new contract structure may in fact have the advantageous side-effect of supporting the inclusion of flexibility in design. At the heart of flexibility in infrastructure design lies the trade-off between the added up-front cost of including an option versus the possibility of increased benefits (or decreased costs) in the future. It should be clear that such a long-term planning approach relying on flexibility only makes sense if the added costs at the start and the added benefits later accrue to the same party: under a Design-Construct contract, a private partner is unlikely to be willing to invest more in the initial construction of a structure, as they know that they will no longer be in charge when the long-term cost savings are realized many decades in the future.

The ability to revisit and update decisions in the future may not be in line with the short-term nature of many of the infrastructure contracts used today. By contrast, if the same entity is responsible for the functionality of a structure for a number of decades, initial design decisions will be viewed in a more long-term fashion, as the same player remains responsible for continued operation even as the future evolves. Of course, this assumes that the private partner/consortium remains fiscally sound and in business over these long timeframes. Barring regulation to the contrary, a short-term contract may encourage those infrastructure designs associated with the lowest initial capital costs, which implicitly dis-incentivizes the inclusion of options in infrastructure. Thus, in order for flexibility in infrastructure design to make economic sense, the timescale of infrastructure contracts needs to match the timescale over which uncertain impacts accrue, on the order of a few decades. Within the Netherlands, this shift towards contract structures that place more of the risk burden on the private partner occurred simultaneously with (or because of) a transition from focusing on lowest capital cost designs to taking more of a long-term life cycle perspective[58]. Thus, it is realistic that a multi-decade contract like a DBFM will differentially facilitate inclusion of flexible elements in the form of options than would be the case if a shorter-term Design-Construct contract were used.

AlMisnad *et al*. (2016) have explored this issue of the impact of contracts on flexibility in more detail, as applied to the municipal water supply sector. They conclude that the form of the contract does impact infrastructure design choices, and has the ability to either steer decision makers towards or away from a more flexible infrastructure planning approach. Research by for example, Roosjen (2013)

[58] In 2012, Rijkswaterstaat released guidance describing when and how life cycle cost analyses should be conducted in infrastructure investment projects (Schavemaker, 2012).

and Demirel *et al*. (2015) explored to what extent the so-called *change procedures* included in PPP contracts provide an effective mechanism by which to update and keep contracts relevant given changing needs and external conditions.

However, despite Rijkswaterstaat's resolute move towards longer-term DBFM contracts, there are other counter-factors at work that continue to incentivize the use of short-term, more traditionally used contract forms. The construction of the shipping lock at IJmuiden described above is part of a pilot program, *Het Sluizenprogramma*, designed to test the use of DBFM contracts in practice. This pilot program initially encompassed six water infrastructure construction projects. However, one project has already been relegated back to a Design-Construct contract form in order to be able to get maximum European Union subsidy[59] assistance (Ministry of Infrastructure and Environment, 2015). Clearly, there are a myriad of inter-related factors that influence the choice of contractual arrangements.

In conclusion, the IJmuiden case raised the question of the impact that different contract forms may have on encouraging or confounding the implementation of flexibility in design. Research in other fields has confirmed that contracts do impact the ultimate choice of design, and hence further research is warranted to explore how the choice and duration of a PPP contract affect the employment of proactive flexibility in our water resource infrastructure systems.

[59] Specifically, this project qualified for the Trans-European Network Transport (TEN-T) subsidy.

6.4 Will options that are never exercised be perceived as “wrong investments”?

This dissertation developed a proactive way of better anticipating and responding to uncertainty in long-term infrastructure planning and design, by searching for Engineering Options that enable easy changes or upgrades to be made to an infrastructural system in the future. These kinds of options are typically associated with an added capital cost up-front, relative to a design without such an option. Despite thorough quantitative analyses prior to investing in an option, it remains possible that uncertain future conditions may evolve in such a way as to never require the option to be exercised. The development of the IJmuiden proof of concept demonstration (Chapter 5) ran concurrently with a number of other studies within Rijkswaterstaat and the CPB Netherlands Bureau for Economic Policy Analysis exploring the use of options in infrastructure planning (e.g. Bos and Zwaneveld, 2014). One of these study proposals called for a review of recent infrastructure projects for which existing economic evaluations were available and an exploration of whether consideration of flexibility could have resulted in any new insights or altered conclusions (Van der Pol *et al.*, 2016). It was made clear from senior levels of Rijkswaterstaat to those proposing the study that it was unacceptable to report any kind of findings that were politically sensitive and/or that called into question previous infrastructure investment decisions. Furthermore, cases where the decision making process was still ongoing were off-limits in case the study produced results counter to previous conclusions. To this end, the reflection presented in this section is focused on **the social unacceptability to governments for being perceived as having have made “wrong” investment decisions, for instance in the form of engineering options that are never fully exercised**.

As discussed in the proof of concept demonstration presented in Chapter 5, the inclusion of flexibility in the form of options comes at a cost. This additional cost of flexibility must be balanced against the likelihood of any resulting benefits in the future, and logically, only those options where the up-front cost is more than offset by the expected future benefits or cost reductions should be considered as desirable design strategies. This trade-off between the additional costs to keep options open now versus the potential of added benefits later is typical of this kind of flexibility in the form of options. It should be obvious that the value of investing in such an option is dependent on the degree of uncertainty one has about the future (Brosch, 2008): the more uncertain the future, the more investment in an option becomes desirable. Furthermore, such options are asymmetric in nature (Trigeorgis, 1996): if the passage of time reveals that it is never necessary to expand the pumping capacity of IJmuiden, then at that time, the option ends up becoming worthless because decision makers unnecessarily invested in a larger than ever necessary concrete pump housing. This option to expand only adds value as compared to a design without the option to expand when the option is actually exercised and the cost savings associated with the option-assisted expansion are realized. Thus, even though a thorough and well-substantiated economic analysis may conclude that investment in a particular source of flexibility is worth it, the possibility always exists that we end up in a future where exercising the option does not turn out to be necessary. This is simply the nature of a stochastic world. However, this may appear to the public who are ultimately also the taxpayers and voters, that the decision makers wasted resources on unnecessary infrastructure investments and that this money should have instead been invested elsewhere. It is difficult to communicate to the general public that despite the fact that an option may never be utilized as future uncertainty becomes resolved, the added up-front option cost remains worth it given the flexibility to respond to uncertain development that an option provides. Furthermore, a flexible planning approach may see certain parts of the decision to invest left open until some time in the future. “In a political context, this flexibility can be [mis-]understood by adversaries as failure to make choices or fear of making choices” (Herder *et al*., 2011). In the past, this kind of investment in flexibility in the form of infrastructural options has been likened to the purchase of life or fire insurance: so long as the premium is reasonable, most rational consumers are very happy to pay a small fee to lessen the chances of bad outcomes in the future (de Neufville, 2003). Similarly, as a society, we find no fault with architects who include fire escapes in buildings or designers who include airbags in vehicles: in these instances, it is widely accepted that the cost of these features is worth the rare tragedy they may prevent. Perhaps similar analogies could be helpful in communicating to and educating the public about the possible value of including options within our water resource infrastructure systems.

This observed sensitivity of government agencies to being seen as making wrong or seemingly wasted infrastructure investments has been previously described in the literature. van de Riet (2008) concluded that decision makers are afraid that the revisiting of earlier decisions may be viewed as a sign of earlier failure. Herder *et al*. (2011) explored a different facet of this public perception issue by examining past European mega-projects. They observed that mega projects are typically politically sensitive and have a tendency to run far over budget, factors which appear to further reduce politicians’ willingness to deviate from the tried-and-tested status quo approach to infrastructure investment.

Additionally, in a colourful example, Belgian investigative journalist Jean-Claude Defossé released a book titled “*Le Petit Guide des grands travaux inutiles”* (The Little Guide to useless infrastructure works) (1990). It documents infrastructure projects in Belgium that were never completed, or whose utility was called into question. These same themes were revisited over the course of the following decades by a number of other journalists and authors, including Douglas De Coninck and Samy Hosni. Figure 6.2 displays one example of a past infrastructure project that has been classified as a *travail inutile*: when the A17 highway in Belgium was being developed, a number of motorway bridges over railway tracks were necessary as part of the project. Despite the fact that it was not yet clear whether certain branches of the highway were necessarily required, all the necessary bridge components were completed as a bulk project. Later on, it became apparent that a number of portions of the highway would not be necessary and thus would not be completed, thus leaving these completed bridges stranded. It is unclear to what extent the decision to build these bridges up-front was based upon an economic analysis that explicitly calculated the value from including such options. However, regardless of whether such an analysis was conducted, the future evolved in such a way that the option was never exercised and thus its value expired. Even if the flexibility provided by this decision was deemed worth it at the time, how can this kind of complex logic be explained to the broader public? As the references introduced above suggest, such projects appear to be overwhelmingly seen by the public as the wrong decision and a sign of government incompetence. Given that the desire to be re-elected taints many if not all public sector decision makers, it is not unreasonable to assume that these decision makers may not embrace an infrastructure investment strategy that could be seen as routinely opening them up to such criticisms from the public.

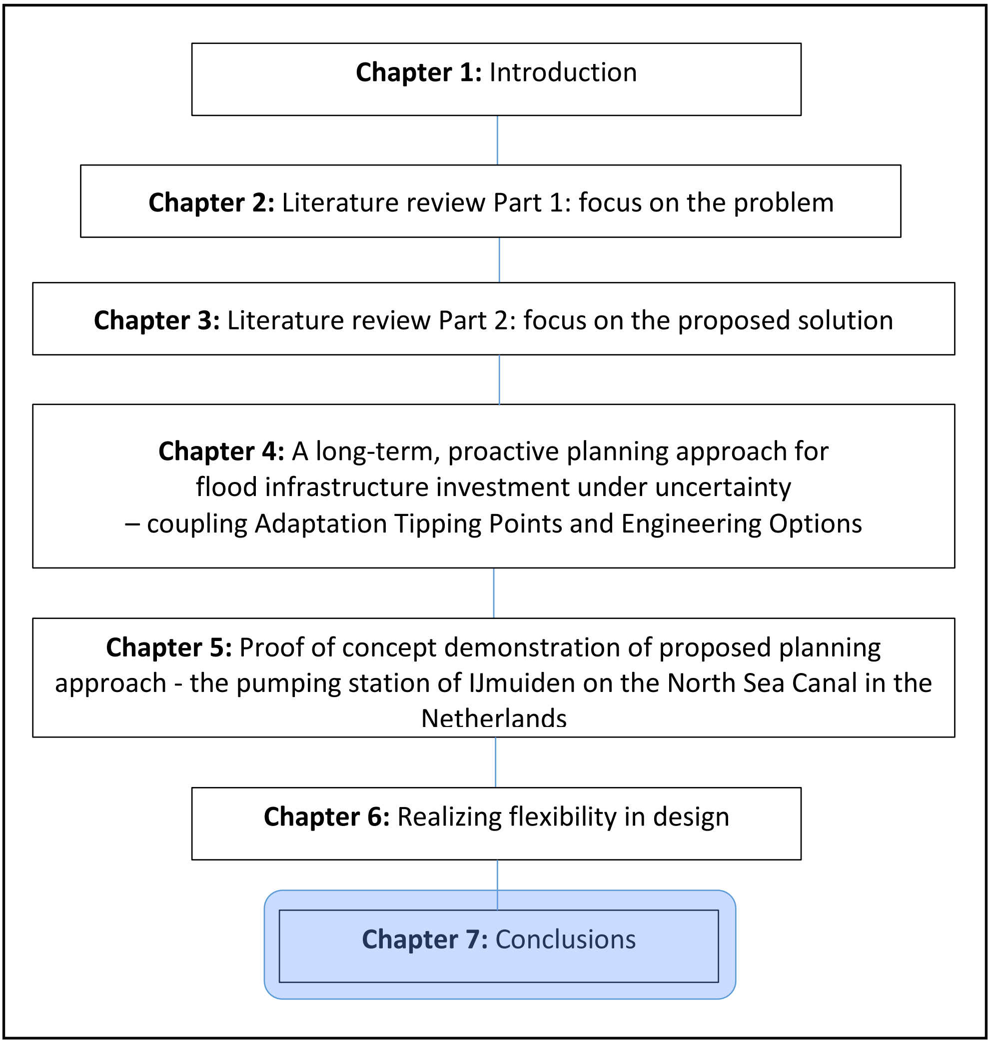
<u>Figure 6.2: A motorway bridge over the Ostend-Bruges railway on a stretch of the A17 highway that was never completed</u> (Source: Wikimedia Commons, 2008)

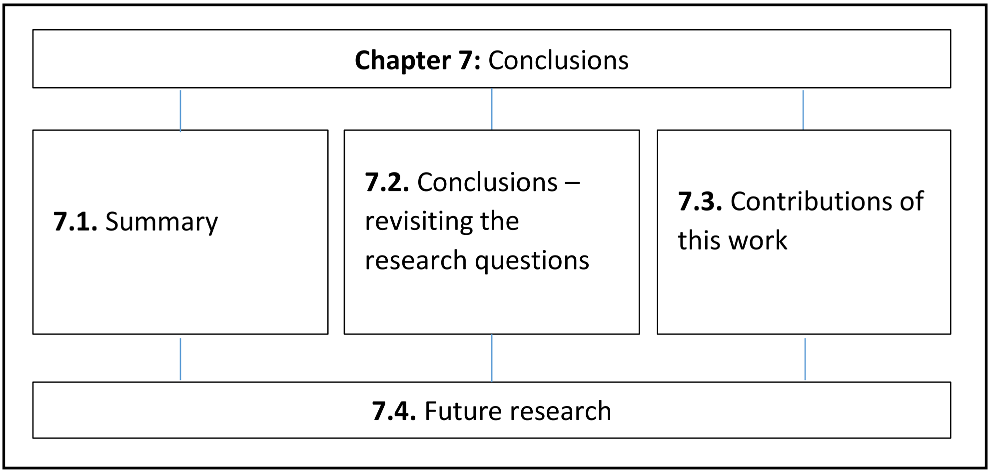
In summary, it is inherent in a flexible infrastructure design that decision making will be phased and open-ended and that there remains the possibility that an option may never be exercised. The political and public perception ramifications of these characteristics of flexible design may form substantial barriers for government buy-in to a new planning approach centered on the use of options as a way of coping with future uncertainty. Research regarding public perception of such investments and the communicating of the concepts of flexibility to the public is needed.

6.5 Conclusion

This chapter has demonstrated that in order to achieve benefits from the inclusion of flexibility in infrastructure systems, infrastructure managers, engineers, designers and contract negotiators need to consider more than just the technical aspects of the problem. They need to recognize that other far-reaching factors also impact the ultimate success of a new planning approach. It matters whether institutional and governance guidance is up-to-date with the needs of today's ever-changing society and physical system. It matters what form the contract describing the roles and responsibilities of the different public and private partners takes. It matters when the taxpayers and voters see projects as being useless and a waste of money. In addition, an array of other factors not discussed here, such as a focus on short-term cost minimization versus whole life-cycle costing, as well as differing country-specific public attitudes to investment in flood protection, all matter. All of these stray far from the areas of expertise of a traditional water resource engineer. However, the success of any of the work a water resource engineer does depends so profoundly on these broad interdisciplinary factors that they simply cannot be ignored.

7. Conclusions





This chapter concludes the research presented in this dissertation. Section 7.1 first offers a summary of the work done. Section 7.2 presents conclusions and new insights gained, by revisiting the research purpose and research questions previously defined in Chapter 1. Section 7.3 subsequently discusses the contributions of this work, with Section 7.4 offering a few recommendations for future work.

7.1 Summary

This dissertation explored the question of replacement of aging water management infrastructure. As introduced in Chapter 1, infrastructure investment is inherently a capital intensive, slow-moving and complex process. Water resource structures are typically long-lasting with design lifespans up to a century. The long-term planning of such infrastructure is complicated by the impacts of uncertainty (e.g. climate change uncertainty, uncertainty in socio-economic development, inherent variability of natural processes), as gradually accrued changes over such long time frames can be substantial.

The literature review described in Chapter 2 explored current methods used to inform infrastructure investment, planning and replacement under uncertainty. These methods were drawn from several relevant portions of the literature, including asset management and civil engineering, as well as climate adaptation and decision making under uncertainty. Two fundamental shortcomings of existing approaches emerged, as related to the specific needs of water resource infrastructure replacement planning:

- First, existing infrastructure planning approaches focused either on technical drivers of investment internal to the structure (e.g. degradation of different structural components), or on external changes to the operating environment (e.g. impacts of climate change or regional socio-economic development), never both. This separation is to some extent historically determined: prior to initial construction, infrastructure designers place much emphasis on developing a structure able to function under the anticipated external operating conditions that the structure will face throughout its life; once in existence, asset managers look more inwardly, focusing on the operation and maintenance of the structure itself. However, both drivers of investment become important when considering the replacement and re-design of an existing aging system: interventions may be necessary for either structural degradation reasons or due to reduced functionality driven by altered external operating conditions.
- The second shortcoming relates to how existing planning frameworks manage uncertainty. Within water resources management, there has been a gradual shift towards so called adaptive water management to cope with uncertainty: room is created in the physical and institutional system to revisit past decisions and make changes based on new information and improved knowledge. While such an adaptive approach to water resources

poses a promising way of coping with the impacts of uncertainty, it remains fundamentally *reactive* to uncertainty: the likelihood that a planning strategy must be revisited and adapted in the future is acknowledged but the predominant attitude remains one of “monitor-and-see”.

Chapters 3 and 4 described in detail how a new approach to water resource infrastructure replacement planning was developed to address these two shortcomings:

- First, the theory of Adaptation Tipping Points was expanded and used as a way to incorporate a more realistic spectrum of drivers of reinvestment (both those internal to the structure and those resulting from external changes) within long-term replacement planning. This integrated approach is an improvement compared to current fragmented approaches where internal, structural processes are treated separately from the impacts of external, broader changes in the operating environment.
- Second, the concept of Engineering Options was used as a way to operationalize the emerging adaptive paradigm and transform the management of uncertainty from a reactive to a more proactive process. The development and inclusion of Engineering Options exemplify a more proactive strategy to cope with uncertainty through smart design decisions taken at the outset, thereby providing system managers with the up-front ability to actively transform the system and respond to possible future changes.

This novel proactive planning approach for water resource infrastructure investment under uncertainty was subsequently demonstrated through a proof-of-concept study (Chapter 5). This proof of concept demonstration explored replacement planning for the pumping station of IJmuiden on the North Sea Canal in the Netherlands.

Finally, Chapter 6 was complementary to the IJmuiden study, reflecting on possible contextual considerations that may hinder the practical application and implementation of the new planning approach developed in this dissertation.

7.2 Conclusions – revisiting the research questions

As stated in Chapter 1, the purpose of this work was **to develop a systematic approach for effective proactive long-term planning and design for the replacement of flood management infrastructure, given uncertainty about future external conditions**. This high-level objective was concretized by identifying a number of more specific research questions. This section presents the main conclusions and take-away points of this work by revisiting these research questions first formulated in Section 1.4:

Research Question 1: This work identifies the separate treatment of structural and external drivers of infrastructure investment as a shortcoming of existing asset management practices. *What additional insights are obtained when infrastructure planning is conducted in a more integrated way that takes into account both internal structural drivers of investment as well as external processes causing changes in the operating environment?*

The concept of Adaptation Tipping Points was used to include structural and external operating considerations into a single integrated planning approach. By differentiating and analyzing different types of Adaptation Tipping points, the proof of concept demonstration presented in Chapter 5 showed that moments when large-scale interventions become necessary due to structural degradation or external changes in operating conditions are widely spread out throughout the life of the structure. The implication of considering structural and external factors together demonstrated that aging infrastructure may require investment sooner than their design lifespan would suggest due to reduced functionality driven by external change.

Research Question 2: Both in this work, and in the larger community of practitioners, it has so far been assumed that the creation of more adaptive infrastructure plans is desirable in flood management systems, as compared to traditional, fixed monolithic designs. *When looking specifically at flood management infrastructure, faced with diverse sources of uncertainty, can it be demonstrated that adaptive approaches do in fact offer economic benefits?*

Adaptive infrastructure designs can offer economic benefits as compared to traditional fixed designs, however they need not. As demonstrated in Chapter 5, the relative performance of adaptive designs is function specific. In the case of the inland water level regulation function of the pumping station, an incremental adaptive design outperforms the fixed design across all futures examined. However, in the case of the flood defense function, an incremental adaptive approach is associated with lower costs on average, but substantially higher costs in extreme cases. The implication of this is that the recent trend towards adaptive solutions should not be seen as a silver bullet to every uncertain infrastructure investment problem. Adaptive solutions are favoured over static ones in cases where there are low structural economies of scale and large degrees of uncertainty.

Research Question 3: This work identifies the reactive nature of adaptive water management as a shortcoming of existing water infrastructure planning approaches. *How do proactive* *adaptive approaches incorporating Engineering Options concepts perform compared to the more common reactive adaptive approaches?*

Proactive adaptive designs can offer economic benefits as compared to reactive adaptive designs, however they need not. Returning once more to the proof of concept demonstration in Chapter 5, results showed that for the inland water level regulation function, the proactive adaptive design dominates the reactive adaptive design in riskier futures, and when lower discount rates are applied, while the Reactive Adaptive design performs better in less risky futures. In the case of the flood defense function, the proactive adaptive design has a higher average cost but much narrow range of outcomes than the reactive adaptive design. Ultimately, the preferred choice between adaptive designs depends on the decision maker's belief about the future and their willingness to bear high-cost worst-case outcomes. Again, the implication of this is that proactive adaptive solutions cannot be seen as a universal approach to every uncertain infrastructure investment problem. Rather, the analysis of any infrastructural design problem should explore not just robust and reactive adaptive solutions, but also proactive adaptive strategies, because each offers particular benefits in particular situations. Thus, this new proactive adaptive strategy to infrastructure planning is one additional infrastructure design strategy that should be included in infrastructure planners' toolkits, one that offers an effective way to protect against worst case outcomes.

Research Question 4: Flood management structures are typically multifunctional. *When looking at these kinds of complex multi-functional structures, how do we structure an analysis of sources of proactive flexibility? Is it possible to identify flexible design elements for each individual* *function? To what extent are the benefits derived from the inclusion of flexibility function specific?*

After identifying the functionalities fulfilled by a structure or system, the analysis of Adaptation Tipping Points and Engineering Options allows the teasing apart of those design elements that relate to each function individually. As previously indicated in Research Questions 2 and 3 above, the results were found to be function specific, with the pumping station at IJmuiden calling for static robustness when designing flood defense elements of the structure and for proactive flexibility when designing pumping elements of the structure. The implication of this is that when planning a structure's replacement, it need not be the case that the structure as a whole should be designed to be either robust, adaptive or proactively flexible; rather, individual function-specific components call for different design approaches. Different components of a structure or system may be better suited to adaptive or fixed approaches, depending on their specific cost functions.

Research Question 5: Technical systems do not exist in isolation: they are affected by a wide variety of social, economic, institutional and other factors. *What are possible barriers in these non-technical factors (e.g. financing/institutional/policy) that may complicate the more widespread utilization of the planning approach developed here?*

As discussed in Chapter 6, current governance practices, contractual arrangements and the public perceptions of options that are never exercised could serve, among other factors, as potential hindrances to the practical implementation of this approach.

In conclusion, by coupling Adaptation Tipping Points with an Engineering Options approach, **this dissertation has developed tools to structure an analysis of**

complex, multi-functional systems, first creating infrastructure prognosis timelines for aging structures and subsequently identifying and quantitatively evaluating the performance of different possible alternative courses of action, exploring which functionalities could benefit from a proactive approach and which conditions maximize these benefits.

7.3 Contributions of this work

The primary research contributions of this new approach to water resource infrastructure replacement planning under uncertainty relate directly to two fundamental shortcomings previously identified in the existing literature:

- First, this work integrates a spectrum of drivers of reinvestment (both those internal to the structure and those resulting from external changes) into a single long-term replacement planning approach, as compared to current approaches that treat internal, structural processes in isolation from the impacts of external, broader changes in the operating environment.
- Second, it operationalizes a planning approach that is proactive rather than reactive in its management of uncertainty.

Furthermore, this work offers a number of more particular contributions, related to several noteworthy limitations that emerged from the literature review in Chapter 3. Hence, at a more operational level, the approach developed in this work also offers the following contributions, continuing to advance the state of the art in the Adaptation Tipping Point and Engineering Options literature:

- **Expanded the application of Adaptation Tipping Points beyond consideration of climate change alone:**

To date, the body of work on Adaptation Tipping Points only considers climate change as a driver of declining infrastructural performance. Within the context of aging infrastructure reinvestment planning, it is necessary to consider a broader range of drivers of investment. By defining different types of Adaptation Tipping Points, this work demonstrates that the existing theory of Adaptation Tipping Points can be expanded to be able to include diverse other processes including structural degradation, socio-economic development in addition to climate change.

- **Integrated Adaptation Tipping Points within a quantitative evaluative framework to identify and evaluate possible subsequent actions:**
  Solely identifying Adaptation Tipping Points does not provide any insights about what actions could/should be taken following the occurrence of such an Adaptation Tipping Point. To explore possible responses, previous work has seen the development of Adaptation Tipping Points into so-called adaptation pathways (see Section 3.1.4). While these pathways provide insights about the urgency of adaptation for different components of a system, they do not easily allow any kind of quantitative evaluation by which to compare different courses of action. A novel contribution of this work is the integration of Adaptation Tipping Points with Engineering Options. This allows not just the identification of crucial intervention moments in the life of a structure, but formulation and systematic quantitative comparison of diverse possible courses of action, highlighting the added value derived from the inclusion of flexibility in the system.

- **Explicitly considered Engineering Options as applied specifically to flood management infrastructure planning:**

Where options theory has previously been applied to the field of flood management planning, to date, the vast majority of existing work has focused only on managerial options (e.g. delaying or phasing investment), with little attention paid to technical options or questions of design (i.e. Engineering Options). This work has made explicit the role that structural options can play in long-term flood infrastructure design and has demonstrated that technical options embedded in the physical design can add additional value, over and above managerial options alone.

- **Expand existing flood management options applications beyond levees/dykes to more complex, multi-functional flood management structures:**
  The limited body of work that has explored options theory in the context of flood management has solely been focused on linear structures such as levees/dykes. To date, there has been no consideration of how options concepts perform when applied to other components of flood management systems, especially those that have a more definite end of service life, are structurally more complex or serve multiple functions. This work focused on multi-functional hydraulic structures, demonstrating how options concepts can be applied to a more diverse group of flood management structures.

- **Incorporated deeply uncertain variables within Engineering Options analysis:**
  So far, incorporation of climate change impacts into Engineering Options analysis has largely ignored the difficulties associated with assigning probabilities to future climate scenarios. Recent years have seen a strengthening of the case for treating climate change and its impacts as a source of deep uncertainty, where, by definition, there is no agreement about the likelihood of different future scenarios occurring. Most of the current state-

of-the-art options flood applications do take non-stationarity and possible climate change impacts into account, however few have provided a satisfactory alternative to simply assigning fundamentally arbitrary probabilities to future scenarios. This work couples probabilistic information, as typically used in options analysis, with discrete scenarios, to explore the performance of diverse possible courses of action over many deeply uncertain futures of which the probabilities are unknown. This demonstrated that a lack of probabilistic information need not prevent the application of an options-based approach.

7.4 Proposed future work

As is typically the case with research, one research question begets another. The following are a few proposed areas of work related to this dissertation that warrant additional future research:

- **Expanding the approach developed here to include other sources of flexibility:** The novel approach to proactive long-term water infrastructure replacement developed in this work focuses on Engineering Options as a source of flexibility in infrastructure systems. Engineering Options, as used in this work are structural in nature and within this dissertation, the focus has been on demonstrating the approach's applicability at the scale of a single hydraulic structure and its components (e.g. see the proof-of-concept demonstration presented in Chapter 5). However, one could envision scaling up this approach to explore replacement strategies at a larger network scale. Scaling up of this approach allows the inclusion of others sources of possible system flexibility such as redundancy in discharge routes, increased storage capacity upstream in addition to structural options that enable later adaptation. Further research is needed to explore how the value of different possible sources of flexibility compare: How does the value of different sources of flexibility change depending on the scale of the problem being analyzed? E.g. within a single structure versus within a corridor versus within an entire network. At what scale does this approach offer the greatest benefits relative to the status quo planning approach? As we increase the scale of the physical system included in the analysis, at what point does the problem become computationally intractable?

- **How do flexibility in time and space relate to each other:** The existing options literature has looked mainly at flexibility in time e.g. replace IJmuiden now versus delay replacement. This is perhaps not unexpected given that Real Options stem from Financial Options, in which the primary questions being examined is **what** to do and **when** to do it. Within the infrastructure sector, there is room to consider not just flexibility in time, but also flexibility in space e.g. treating a second pumping station as an option in the system that can help IJmuiden fulfil its water level management function in times of high canal flows (i.e. **what** to do, **when** to do it and **where** to do it). Are these intrinsically different types of flexibility?
- **Coupling this approach with an existing asset management strategy:** Within this work, asset management considerations are coupled with changes in external operating conditions through the use of Adaptation Tipping Points. In the proof-of-concept demonstration provided in Chapter 5, estimated design life is used as a simple way to capture the anticipated structural replacement date within the analysis. However, there is no conceptual reason why more sophisticated asset management information could not be included within this framework. Future research should demonstrate how a detailed asset management plan could be incorporated within a proactive replacement strategy.

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Appendix A: Cost module user interface

Table A.1: Overview of cost module user interface

Cost estimation model for pumping station IJmuiden		by Kim Smet and Cees van der Werff		Prices in 2015 Euro	
User Inputs					
Desired pump capacity	m3	300			
Flood defense height of structure	m+ NAP	8.0			
Model Output					
Direct material costs		71,723,862.63			
Adjustment factor to incorporate site preparation, engineering, labour, tax		2.4			
Total capital costs	€	172,137,270			
Price per m3/sec pump capacity	€	573,790.90			
Total capital costs, in million Euro, rounded off to the nearest million	€	172.1			
Dimensions of new structure					
Capacity per pump	m3/sec	50.0			
Pump diameter	m	8.00			
Horizontal dimensions of pump housing					
Number of pump bays	#	6.0			
Number of walls between bays, each 1 m thick	#	5.0			
Number of outside walls, each 1 m thick	#	2.0			
Length of pump housing	m	55.0			
Width of pump housing, assumed to be constant	m	60.0			
Vertical dimensions of pump housing					
Depth of foundation	m NAP	-9.3			
Total height of structure	m	17.3			
Height of surface	m NAP	4.0			
Excavation					
Length of base, plus 10 m workspace on each end	m	75			
Width of base, plus 10 m workspace on each end	m	80			
Depth to excavate	m	13.3			
Width to height ratio of excavation walls		2			
Addition to length and width for sloped walls		26.5	**Cost of excavation**		
Volume to excavate	m3	143,229.2	€/m3	5.0 €	716,145.9
Temporary levee around work excavation					
Width to height ratio of levee		2.0			
Required width of top of levee	m	5.0			
Height of levee (= to required flood defense height)	m NAP	8.0			
Height of levee to be constructed above surface	m	4.0			

Width of levee base	m	21.0				
Cross-sectional area of levee	m2	52.0				
Length of levee along long edge of excavation	m	149.0				
Length of levee along short edge of excavation	m	154.0	**Cost of temporary levee**			
Total volume of levee to be built	m3	31,512.0	€/m3	10.0	€	315,120.0
Sheetpile						
Number under structure	#	3				
Length	m	55.0				
Depth	m	10	**Cost of sheetpile**			
Quantity of sheetpile required	m2	1,650.0	€/m2	150.0	€	247,500.0
Number adjacent to structure (2 per side)	#	4				
Length	m	20.0				
Depth	m	10				
Quantity of sheetpile required	m2	800.0	€/m2	150.0	€	120,000.0
Civil construction						
Length of floor	m	55.0				
Width of flood	m	60.0				
Thickness of floor	m	1.5	**Cost of concrete**			
Quantity of concrete required	m3	4,950.0	€/m3	120.0	€	594,000.0
Formwork - outside edge	m2	345.0	€/m2	60.0	€	20,700.0
Formwork - inner to connect to pump bay walls	m2	247.5	€/m2	60.0	€	14,850.0
Amount of steel reinforcement for concrete	kg/m3	120.0	**Cost of reinforcement**			
Quantity of reinforcement required	kg	594,000.0	€/kg	1.0	€	594,000.0
Number of lengthwise walls	#	2				
Length of each lengthwise wall	m	55.0				
Height of each lengthwise wall	m	17.3				
Thickness of each lengthwise wall	m	1.0				
Concrete reduction for pump openings	m3	603.2	**Cost of concrete**			
Quantity of concrete required	m3	1,294.3	€/m3	120.0	€	155,317.7
Formwork	m2	3,795.0	€/m2	50.0	€	189,750.0
Amount of steel reinforcement for concrete	kg/m3	140.0	**Cost of reinforcement**			
Quantity of reinforcement required	kg	181,204.0	€/kg	1.0	€	181,204.0
Number of widthwise walls (at edge of structure and between pump bays)	#	7				
Length of each widthwise wall	m	60.0				
Height of each widthwise wall	m	17.3				
Thickness of each widthwise wall	m	1.0	**Cost of concrete**			
Quantity of concrete required	m3	7,245.0	€/m3	120.0	€	869,400.0
Formwork	m2	14,490.0	€/m2	50.0	€	724,500.0
Amount of steel reinforcement for concrete	kg/m3	140.0	**Cost of reinforcement**			
Quantity of reinforcement required	kg	1,014,300.0	€/kg	1.0	€	1,014,300.0
Length of roof	m	55.0				
Width of roof	m	60.0				
Thickness of roof	m	1.0	**Cost of concrete**			
Quantity of concrete required	m3	3,300.0	€/m3	120.0	€	396,000.0
Formwork - roof slab	m2	3300.0	€/m2	40.0	€	132,000.0
Formwork - outside edge	m2	230.0	€/m2	60.0	€	13,800.0
Formwork - inner to connect to pump bay walls	m2	165.0	€/m2	60.0	€	9,900.0
Amount of steel reinforcement for concrete	kg/m3	120.0	**Cost of reinforcement**			
Quantity of reinforcement required	kg	396,000.0	€/kg	1.0	€	396,000.0
Pumps			**Pump costs**			
Pumps	#	6	€/ea	3,600,000.0	€	21,600,000.0

Cooling system	#	6	€/ea	970,000.0	€	5,820,000.0
Transformer	#	6	€/ea	320,000.0	€	1,920,000.0
Transport	#	6	€/ea	160,000.0	€	960,000.0
Installation	#	6	€/ea	1,250,000.0	€	7,500,000.0
Placement of electrical connection	#	6	€/ea	200,000.0	€	1,200,000.0
Crane for pump repair	#	10	€/ea	210,000.0	€	2,100,000.0
Debris screen	#	6	€/ea	160,000.0	€	960,000.0
Pump gates (2 per pump)	#	12	€/ea	900,000.00	€	10,800,000.00
One way valve (1 per pump)	#	6	€/ea	420,000.0	€	2,520,000.0
Dredging of waterway adjacent to pumping station						
Depth of dredging		13.3				
Width of upstream water body	m	100.0				
Distance away from pumping station to dredge	m	500.0				
Width of downstream water body		191				
Distance away from pumping station to dredge	m	500.0	**Dredging costs**			
Volume to dredge	m3	1,927,875.0	€/m3	5.0	€	9,639,375.0
Operators building	#	1	€/ea	300,000.0	€	300,000.0

Appendix B: Physical performance module for water level management

As discussed in Section 5.7.1, it is not enough to know that even at present, the pumping station at IJmuiden has insufficient capacity to adequately fulfil its water level management function, as defined by a set performance threshold. We are interested not just in a one-time Functional Adaptation Tipping Point for IJmuiden's water level management role, but in exploring how the occurrence of future functional Adaptation Tipping Points varies given different possible interventions. In order to do this, it is necessary to model the external environment and infrastructural system in such a way that the effects of user-imposed changes to the infrastructure, such as adding pumping capacity, can be estimated. This model formulation is comprised of a number of different steps, summarized in Figure B.1, the output of which ultimately provides an indication of the moment when a Functional Adaptation Tipping Point occurs, and how different changes in the infrastructural system affect the timing of these Adaptation Tipping Points. Details of these different model components are presented within this appendix.

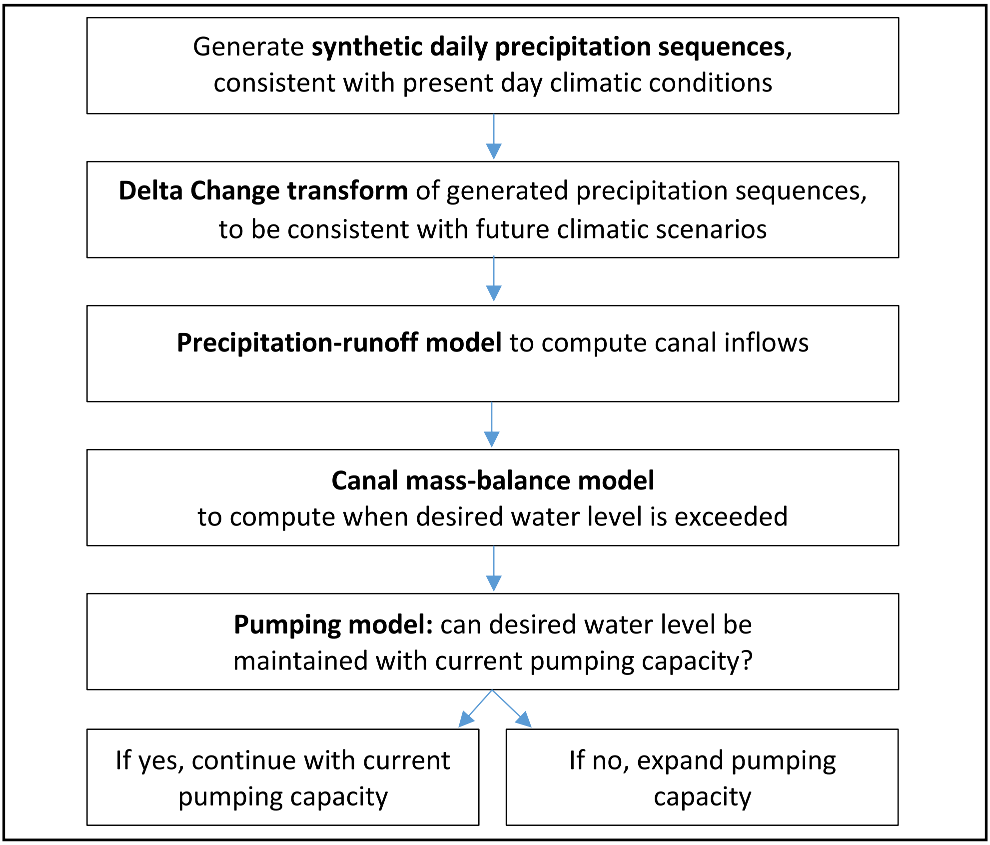


Figure B.1: Overview of the different modelling components used for the inland water level management function

B.1 Mass balance of canal

The core component of modelling the physical performance of the inland water level management function of IJmuiden is in the form of a mass balance model. The comparison of inflows to and outflows from the NS-AR Canal allows water levels to be tracked over time and under varying external precipitation and sea-level conditions, making it clear when the performance objective for water level management on the canal (in the form of a maximum water level) can no longer be met. In the short-term, such a mass balance can help determine exactly when water should be discharged from the canal to the North Sea via IJmuiden, and over longer timeframes such as in this work, it is used to identify the moment when water levels on the canal exceed the performance threshold, thus signaling the occurrence of a functional Adaptation Tipping Point.

The mass balance model utilizes the following general formulation to track the water level over time:

$$\frac{dh_t^s}{dT} = \frac{Q_t^s - O_t^s}{A}$$

where $\frac{dh_t^s}{dT}$ = change in water level over time period of length T (m/day)

Q_t^s = total inflow to canal during day t in season s (m^3/day)

O_t^s = total outflow through IJmuiden during day t (m^3/day)

A = surface area of canal system (m^2)

The occurrence of $h_t > L_t^s$ where L_t^s is the predetermined maximum allowable water level is taken as a signal that the installed pumping capacity has become inadequate, that a Functional Adaptation Tipping Point has occurred and that capacity expansion should be considered.

Given the explorative nature of this work and the need to run many thousands of simulations over many decade time sequences, the simplest possible mass-balance model is used here to demonstrate the approach developed in this work while introducing only a minimum number of case specific details. To this end, a number of simplifying assumptions are made. The NS-AR Canal is treated as a single rectangular reservoir, of known depth and surface area. Inflows to the canal are assumed to distribute uniformly over the entire canal, with no height gradients created between different portions of the canal. This also ignores the impacts of wind in raising water levels at one side of the canal system. Similarly, when sluicing or pumping water out of the canal into the North Sea, it is assumed that the water level across the entire canal adjusts instantaneously in response to outflows. It is assumed that the only exist point is at IJmuiden, which ignores the existence of a number of relatively small (<5% of total outflows) alternative outflow points. In addition, the time interval, T used throughout this work is equal to one day. For operational purposes, a unit of time of a day is not a sensible one as it is too long to be able to make accurate decisions about when to sluice versus when to pump in relation to changing water levels and tidal cycles. However, when looking at a long-term strategic planning timescale which is the focus in this work, a day was considered an adequate compromise, balancing short-term detailed considerations with the need to explore multi-decade project horizons.

The remainder of Appendix B takes a closer look at the two central inputs to this mass balance, namely Q_t^s, inflows to the canal and O_t^s, outflows from the canal. Section B.2 focuses on generating canal inflows representative of diverse future precipitation scenarios, while Section B.3 derives a formulation for outflows under different possible precipitation and sea level rise scenarios.

B.2 Modeling inflows to the NS-AR Canal

B.2.1 Characterizing the primary drivers of inflows to the NS-AR Canal

Examining the existing Decision Support System for the NS-AR Canal

The majority of inflows (69%) to the NS-AR Canal are from precipitation runoff from the surrounding catchment, with the remainder originating from industrial releases, salinity management and releases from shipping locks. At present, Rijkswaterstaat manages real-time control of water levels and pumping rates on the NS-AR Canal using a decision support system incrementally developed by Vermeulen and Versteeg (1999), Vreugdenhil and Vermeulen (2001), Kooremans (2002), Beuse *et al*. (2004), Schobben (2005), Goedbloed (2006, 2008) and Vierstra (2011). A central component of this decision support system is an empirically derived model that relates precipitation to total canal inflow, which is in turn equated to the total volume to be discharged at IJmuiden (Goedbloed, 2006 and 2008). This model is informed by physical processes, where inflows are divided into two portions: a variable, time dependent component derived from precipitation and a fixed, time independent component derived from other sources such as industrial releases and shipping:

$$Q_t^s = \mathrm{C}^s \left[\sum_{\mathrm{i}=0}^{\mathrm{n}} a_i^s \, \mathrm{P}_{\mathrm{t-i}}\right] + Q_{base}^s$$

where Q_t^s = total inflow to canal during day t in season s (m^3/day)

C^s = conversion constant in season s (m^3/mm). C^s captures three elements: the area of catchment that experiences precipitation during a given precipitation event (m^2); the proportion of precipitation that is channeled to canal as runoff, as opposed to infiltration or evaporation (unitless); and a unit conversion constant (m/mm)

n = number of days of past precipitation that affect current inflow

a_i^s = relative contribution of precipitation on day t-i to inflows experienced on day t in season s, where $\sum_{\mathrm{i=0}}^{\mathrm{n}} a_i^s$ = 1 (unitless) for $\forall\, s$, and $\forall\, a_i \geq 0$

$P_{t\text{-}i}$ = daily precipitation on day t (mm/day)

Q_{base}^s = constant inflows to canal from other sources in season s (i.e. industrial releases, water to prevent saline intrusion and releases from shipping locks) (m^3/day)

At present, the rainfall-runoff module of the decision support system is run using 20 days-worth of historic data as recorded at 10 minute intervals, separated into four different seasons and using differentially weighted precipitation data as measured at three different weather stations in the catchment area. In validation analyses conducted to date, the modelled and observed canal inflows have Pearson product-moment correlation coefficients (or R^2 values) ranging from 0.28 to 0.83 (Vierstra, 2011).

Simplifying the existing Decision Support System

This analysis requires that many thousands of runs of the precipitation-runoff model are simulated, over a time frame of multiple decades, with this only one step within a further modelling sequence. To keep the computational requirements manageable, a number of simplifying assumptions were explored for this existing precipitation-runoff formulation, with their impact on model performance evaluated each in turn. Ultimately, a number of simplifications were made to the existing precipitation-runoff model:

- Daily precipitation data was used instead of the 10 minute or hourly data used in the current decision support model. This simplification is considered acceptable given that the existing model is focused on detailed operational concerns, whereas the work presented here focuses instead on more long-term strategic questions.
- The number of days of past precipitation included in the model was reduced from 20 to 8 days: calculation of the adjusted R^2 value[60] suggests n=12 days

[60] A common problem with using the Pearson product-moment correlation coefficient or R^2 value to assess model fit is that the addition of new variables to a regression model is almost always associated with a better fit and thus an increase in R^2, whether this newly added variable makes physical sense or not. Hence, to prevent overfitting of the model, the question arises as to how many variables make physical sense to include in the regression.

provides the best fit between computed and observed inflow data, without overfitting the model. However, precipitation more than 8 days ago typically contributes less than 5% to the total measured inflows, which makes the reduction to 8 days of past precipitation data a reasonable one.

- The number of seasons was reduced from 4 to 2, namely winter and summer only.
- The number of precipitation input locations was reduced from 3 to 1, using only De Bilt weather station. This makes the assumption that the precipitation measured at or predicted for De Bilt weather station is representative for the entire catchment area.

This simplified precipitation-runoff model was calibrated using daily precipitation and canal inflow data for 2012, with the results presented in Table B.1. From Table B.1 one observes a number of seasonal differences in local hydrological processes. First, the value of C^s is substantially higher in winter, indicating that a greater proportion of the basin experiences precipitation during an event and with more of that precipitation entering the canal in winter than in summer. This is likely the result of differing seasonal precipitation characteristics: summer rainfall occurs in more localized, distinct events, allowing drying of the soil between precipitation events which results in a greater proportion of a precipitation event infiltrating the sub-surface, rather than be channeled as runoff to the canal. In winter, precipitation events are more widespread and last longer, which can result in the infiltration-runoff balance shifting to produce a greater proportion of runoff. In addition, Q^s_{base} demonstrates there is a higher constant inflow during the winter as compared to the summer.

An adjusted R^2 measure addresses this by correcting the original R^2 value for the relevant degrees of freedom:

$$R^2_{adj} = 1 - \frac{(1 - R^2)(N - 1)}{(N - k)}$$

where N is the sample size and k is the number of variables. These adjusted values increase in magnitude only when a new variable improves the model fit more than would have been expected based purely on chance, and decreases when a new variable improves the model fit less than expected by chance.

Table B.1: Best fit precipitation-canal inflow parameters obtained from linear least squares regression for n=8

Parameter	**Summer value** (for April 1st to September 30st)	**Winter value** (October 1st to March 31st)
C^s = conversion constant (m^3/mm)	604,154	1,222,974
a_i^s = relative contribution of precipitation on day t-i to inflows experienced on day t	a_0 = 0.31 a_1 = 0.13 a_2 = 0.07 a_3 = 0.11 a_4 = 0.12 a_5 = 0.16 a_6 = 0.06 a_7 = 0.03 Sum = 1	a_0 = 0.31 a_1 = 0.21 a_2 = 0.15 a_3 = 0.09 a_4 = 0.02 a_5 = 0.05 a_6 = 0.07 a_7 = 0.09 Sum = 1
Q_{base}^s = constant inflows to canal from other sources (m^3/day)	4,716,401	5,127,801

The simplified precipitation-runoff model is applied to daily precipitation data for 2012, with the results summarized in Figures B.2 and B.3. Figure B.2 provides a visual indication of the overall goodness of the fit of this model form. From Figure B.3 one observes that agreement between the observed and predicted values produced by this simplified model generally remains high, with most points lying along a straight line. An R^2 value of 0.7 is computed, which is still in the same range as the original precipitation-runoff model.

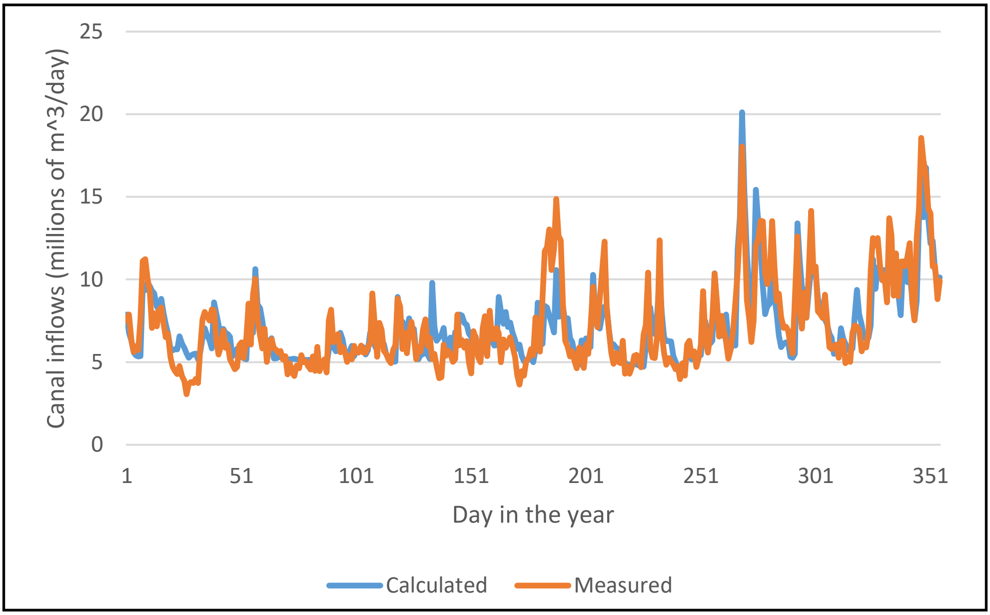


Figure B.2: Comparison of measured and calculated daily canal inflows for 2012

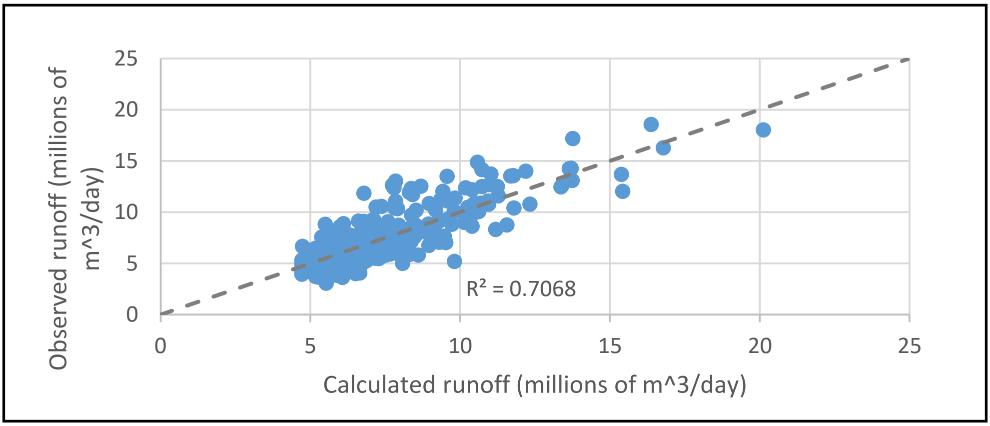


Figure B.3: Model validation- assessing goodness of linear fit

Quantifying the residuals

An R^2 value close to 1 is not enough to conclude the adequacy of a model functional form: in addition, a good model fit should display residuals that are approximately normally distributed, have a mean of zero and constant variance. The residuals should also show no significant degree of correlation or memory: if residuals do demonstrate patterns, this behaviour could be included in the model formulation rather than being described as a random process. The ideal residual is in the form of an entirely random white noise process, indicating that all patterns present in the data have been captured by the model formulation. The results of the model validation conducted are summarized in Figures B.4 to B.7.

Figure B.4 plots the residuals as they occur across the calendar year. The distribution of results does not demonstrate a clear seasonal pattern in the remaining residuals. There appears to be some correlation among residuals, with high residuals occasionally clustered with other high residuals, and low residuals occasionally grouped with other low residuals. This possible correlation between residuals is explored further in Figure B.7.

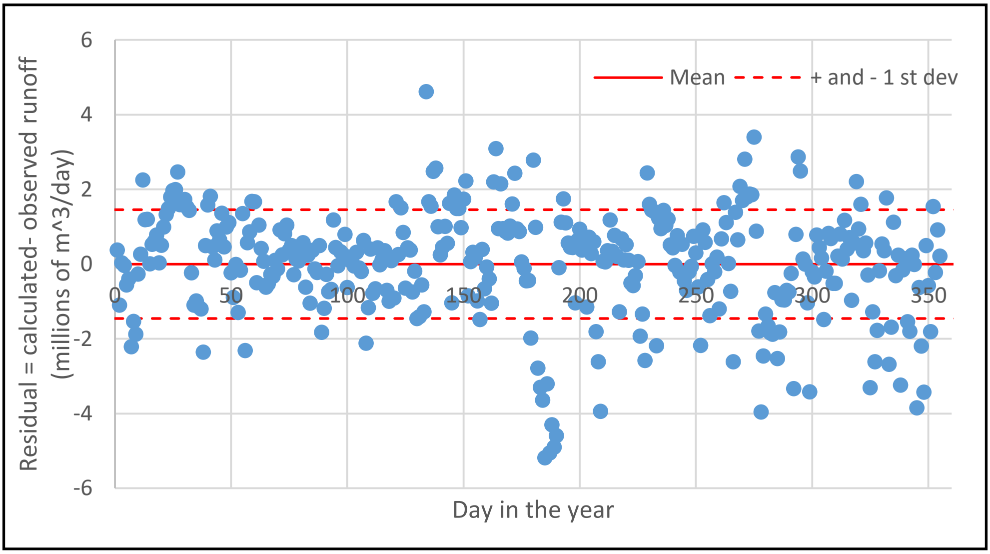


Figure B.4: Model validation- assessing occurrence of residuals

Figure B.5 indicates that the residuals have a mean of approximately zero, with a variance that appears constant and does not vary dramatically with the size of the prediction. The residuals also appear symmetrical in that the model appears to randomly equally over- and under-estimate inflows.

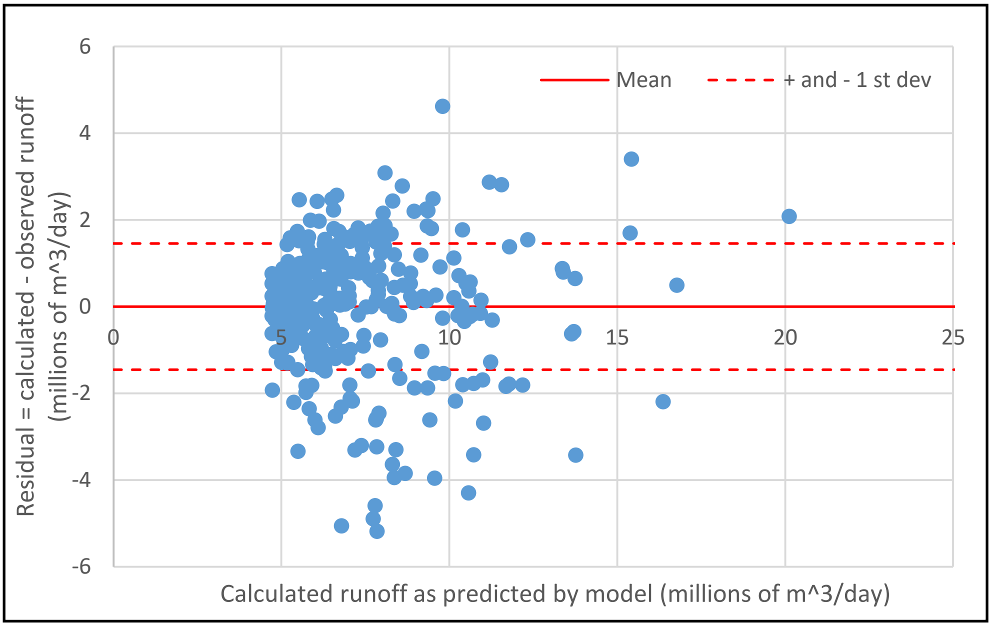


Figure B.5: Model validation- assessing residual variance across data

Figure B.6 shows that the residuals, displayed in blue, fairly closely represent a normal distribution, as shown in red.

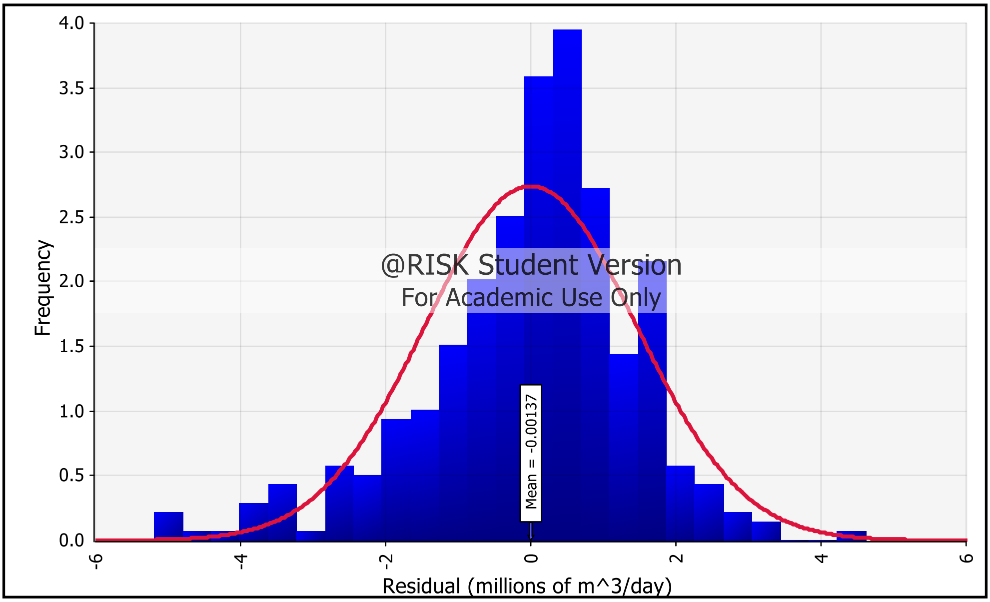
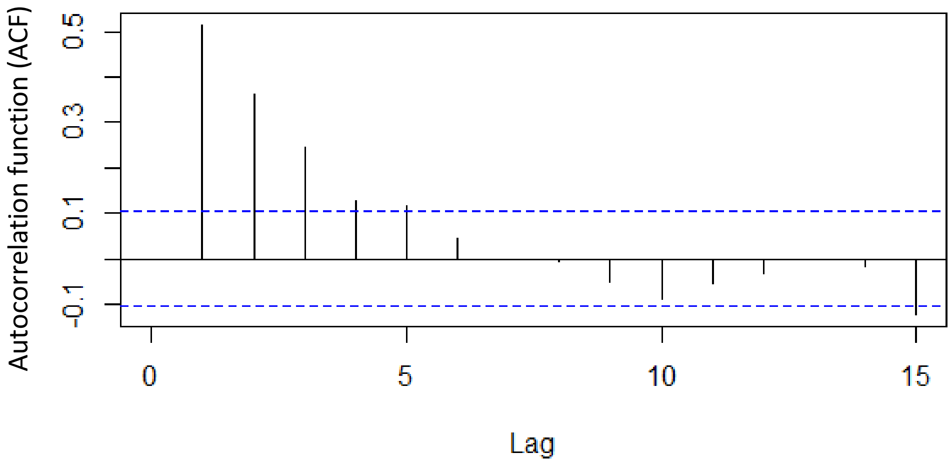


Figure B.6: Model validation- assessing distribution of residuals

Finally, Figure B.7 further explores the possible correlations identified in Figure B.4 by deriving the autocorrelation function between the residual sequence and the lagged residual sequence. The blue lines on Figure B.7 indicate 95% confidence bounds, with autocorrelation values outside of these bounds treated as statistically significant and those within the blue lines treated as statistically insignificant and equivalent to white noise. For this model formulation, the computed autocorrelation values show significant correlation for lags 1 through 5. This indicates that if an unusually high or low residual occurs at t=0, the residuals for 5 time steps afterwards are also expected to be higher/lower than average. The autocorrelation function does not appear to decrease exponentially, suggesting that an autoregressive process may not be the best fit to capture the memory in the residuals. Instead, a 5 time-step moving average process is derived to quantify the memory in the residuals. The residual distribution $r_t \sim \mathcal{N}(-0.001, 2.12 * 10^{12})$ (derived in Figure B.6 above) and the moving average (MA5) process $u_t = r_t + \theta_1 r_{t-1} + \theta_2 r_{t-2} + \theta_3 r_{t-3} + \theta_4 r_{t-4} + \theta_5 r_{t-5}$ governing the residuals (derived in Figure B.7) are together carried forward into the remainder of the analysis presented here to simulate the uncertainty associated with the calculation of canal inflows from local precipitation.



Number of lags	1	2	3	4	5	6	7	8
ACF	0.51*	0.36*	0.25*	0.13*	0.11*	0.04	-0.01	-0.04
Number of lags	9	10	11	12	13	14	15	
ACF	-0.05	-0.09	-0.05	-0.03	-0.01	-0.02	-0.11	

* indicates ACF is statistically significant

Figure B.7: Model validation- assessing any correlation between residuals

B.2.2 Generating precipitation sequences representative of future scenarios

Having confirmed the extent to which precipitation drives canal inflows, and having identified a tractable functional relationship linking precipitation and canal inflow, simulations of future precipitation are generated to explore canal inflows under changing external conditions. This is done in two steps, as described below.

Generate precipitation sequences consistent with present conditions

Within the Netherlands, a rainfall generator has previously been developed specifically for the Rhine River Basin (Beersma and Buishand, 1997, 1999a, 1999b; Wójcik *et al*., 2000; Beersma, 2002, 2011; Schmeits *et al*., 2014). This generator uses daily historic precipitation data as input, and through detrending and resampling, is able to produce many different daily precipitation sequences that are consistent with present day conditions, while retaining the relevant annual cycles, seasonal behaviour and auto-regressive characteristics of precipitation in these areas. However, no such generator exists specifically for the NS-AR Canal or for De Bilt, the weather station of interest located centrally within the canal catchment. Thus, precipitation sequences that were previously produced by the KNMI for the Rhine River catchment were transformed to be representative of De Bilt using passive simulation[61]. This means that the existing, internally consistent precipitation series for the Rhine are adjusted and standardized based on the historic precipitation records observed at De Bilt. The eventual output of this step is in the form of 100 separate 100-year long daily synthetic precipitation time series for De Bilt weather station that are consistent with present day conditions. A relatively large number of synthetic precipitation sequences are generated in order to capture the impacts of natural variability in precipitation, in addition to the impacts of long-term climate change as described below.

As a brief validation check, the mean and standard deviation of the synthetic and observed precipitation series were compared: the mean of the synthetically generated precipitation sequences is within 5% of the mean historic data record, with the standard deviation of the synthetic and observed precipitation sequences within 1% of each other. Figure B.8 displays one sample synthetic precipitation sequence.

[61] Thanks to Jules Beersma and the KNMI for providing 50,000 year synthetic precipitation sequences for the Rhine River.

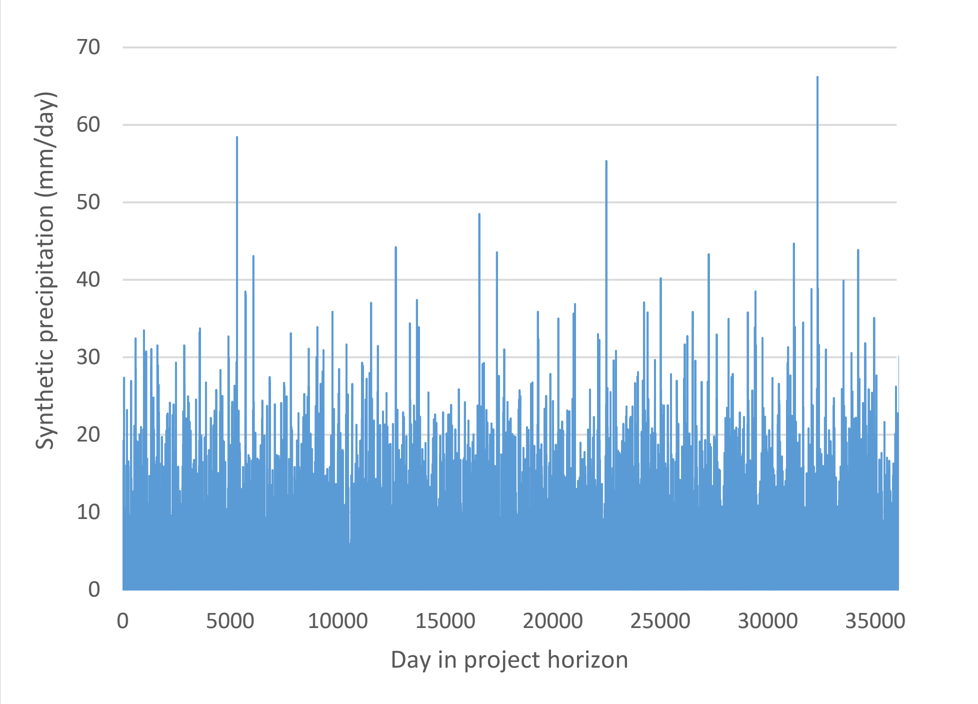


Figure B.8: Sample synthetic precipitation sequence

Transform generated sequences to be representative of future scenarios - the Delta Change method

The long-term trend-free synthetic precipitation records derived above are subsequently fed into a transformation tool in order to create precipitation time series that correspond to different future climate change scenarios, as previously defined in Table 5.3 in Section 5.2. This transformation to future time series of climate-change-altered precipitation was conducted using the *perturbation* or *delta (δ) change method*: historic precipitation data is transformed to be representative of future precipitation, as guided by the output of general or regional climate models[62]. This method is based on the idea that the future can be

[62] The use of historic datasets in this way is a technique that emerged in recent years as an alternative to using downscaled output of climate models. Often climate model output was not at an appropriate level of detail for subsequent hydrologic modelling (Bergström et al., 2001), or it contained substantial systematic biases (Varis et al. 2004), making it difficult to directly use in follow-up effect modelling studies looking to explore in more detail the impacts of these climatic changes at a smaller scale. The so-called *perturbation method*, or the *change factor* or *delta (δ) change approach* emerged as a pragmatic alternative: it

seen as a perturbation of the past, and that the size and type of perturbation can be informed by climate modelling efforts. The precipitation sequences derived above were transformed to be consistent with future conditions under different scenarios using the KNMI's time series transformation tool. A description of this tool can be found in Bakker and Bessembinder (2012). The output of this step is 100 separate 100-year long daily synthetic precipitation time series for De Bilt weather station that are transformed to be consistent with four different future scenarios.

B.2.3 Translating precipitation time series to canal inflow time series[63]

In Section B.2.1, the form of the precipitation-canal inflow relationship was identified, using the general formulation Q_t^s = C^s $[\sum_{\mathrm{i}=0}^{\mathrm{n}} a_i^s \, \mathrm{P}_{\mathrm{t-i}}] + Q_{base}^s$. This formulation is subsequently used to deterministically transform the synthetic daily precipitation time series (P_t) obtained in Section B.2.2 into daily canal inflow totals (Q_t^s). Each of the 100 synthetic precipitation scenarios are transformed into the four different precipitation scenarios examined. For every day in the sequence, uncertainty in the precipitation-canal inflow relationship is captured by randomly

---

involves taking the findings of these general or regional climate modelling efforts and using them to transform a de-trended historic data set. For instance, climate modelling results may indicate that given a certain climate scenario, rainfall in a region will increase by x% on average, with extreme events increasing in magnitude by y% and occurring z% as often as during the historic reference period; these change factors are then used to produce a time series indicative of what rainfall could be experienced given this particular climate scenario. Sample applications of this technique can be found in Lenderink et al. (2007), Te Linde *et al*. (2010), Jackson *et al*. (2011) and van Pelt *et al*. (2012).

A primary advantage of downscaling methods over the delta change approach, as cited by Lenderink *et al*. (2007) and Te Linde *et al*. (2010), is that downscaling allows the incorporation of geographical differences in the subsequent effect modeling. However, in this work, focusing on a relatively small homogenous study area, geographic considerations are considered less important and thus the relative simplicity and transparency of the delta change method is chosen.

[63] In reality, the vast majority of inflows to the NS-AR Canal are in the form of pumped inflows, as the adjacent catchment areas have a lower elevation that the canal itself. This means that the maximum inflow to the canal can simply be determined by adding up the individual pumping capacities of these areas i.e. inflows =f(precipitation) only when inflows ≤ total installed pumping capacity. The assumption in this work is that given the possibility of increased precipitation in the future, the inflow pumping capacities are incrementally increased over time so as to allow the discharge of equal proportions of the total precipitation to the canal.

drawing a residual value from the distribution shown in Figure B.6 ($r_t \sim \mathcal{N}(-0.001, 2.12 * 10^{12})$), incorporating it into the MA(5) process shown in Figure B.8 ($u_t = r_t + \theta_1 r_{t-1} + \theta_2 r_{t-2} + \theta_3 r_{t-3} + \theta_4 r_{t-4} + \theta_5 r_{t-5}$) and adding this autocorrelated residual to the calculated inflow. This assumes that the random variability observed in the precipitation-inflow relationship today will remain the same in the future, under a number of altered climate scenarios. This simulation of precipitation-inflow uncertainty is repeated 10 times for every precipitation scenario. The eventual output is 1,000 simulations of 100 year time series of future canal inflows, given conditions consistent with four different climate change scenario each in turn.

B.3 Modeling outflows from the NS-AR Canal

When computing canal inflows, as described in Section B.2 above, four different future precipitation scenarios were used to explore the impacts of a spectrum of possible futures. When looking at outflows, there is a confluence between not just altered precipitation patterns in the future, but also increased sea levels affecting the releases of water from the low-lying NS-AR Canal to the North Sea. This relationship between inland and external water levels, outflow and sluice/pumping rate is relatively complex, with each depending on a range of different variables including the head difference between the two bodies of water, tidal cycles, relative water densities, pump efficiency and the type of pump installed, among others. This level of detail is beyond the scope of this proof of concept study, hence this works develops a simple formulation to estimate how future conditions will impact the ability to sluice/pump water and when additional capacity may be required.

B.3.1 Sluicing – free outflows under gravity

At present, approximately two thirds of the outflow at IJmuiden occurs as free flow under gravity through the sluice, while around one third of the total outflow is pumped discharge. Outflows are preferentially sluiced by gravity at low tide, with the pumps only used when further discharge is required. As of 2000, the average duration of a single sluice event is around 3 hours and 50 minutes (RWS, 2000). As sea levels rise in the future, the proportion of time that the water level on the North Sea is lower than that on the canal will decrease, thus reducing the length of sluicing events, reducing the amount of water that can be released by sluicing and subsequently increasing reliance on pumps. A formulation to estimate decreasing sluice discharge in the future was previously developed by van der Wiel *et al*. (2013) and this formulation forms the basis of the work presented in this section.

IJmuiden is exposed to a semidiurnal tide cycle, which means it experiences two high and two low tides approximately every day. Throughout this work, it is assumed that the length of one single tide cycle is exactly 12 hours, resulting in two complete high and two complete low tides per day. Sluicing is assumed to be able to occur until such time as the water level in the canal and North Sea are equal[64]. Consistent with the work done by van der Wiel *et al*. (2013), the average daily tidal cycle is used as a starting point to estimate the impact of changes in future sea level, with the average daily tidal cycle assumed to have water levels that follow a sinusoidal progression, as shown in Figure B.9. One observes that at present, on average, free discharge of water under gravity is possible for 3.75 hours every tidal cycle.

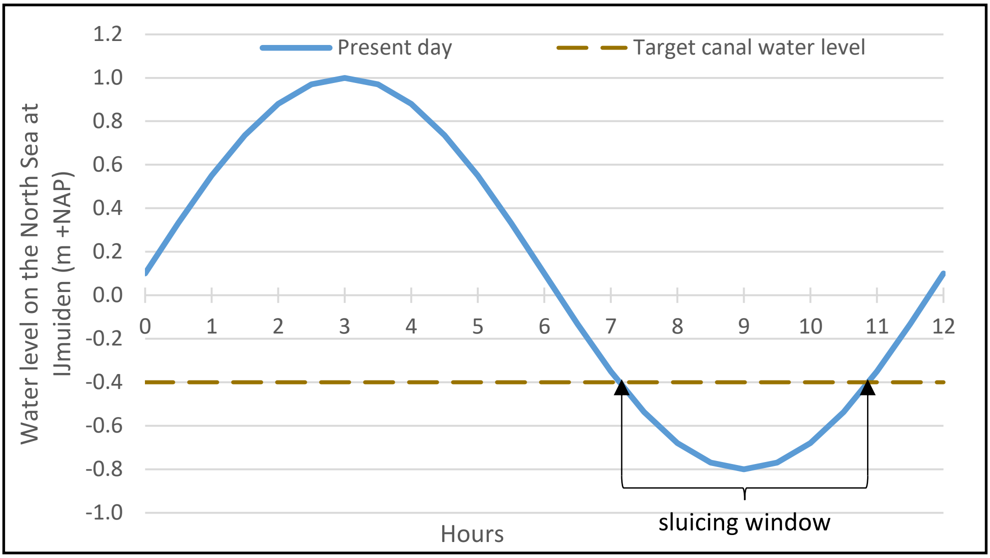


Figure B.9: Average semidiurnal tide cycle representative of present conditions at IJmuiden

Having estimated current average tidal conditions, long-term scenario specific sea level rise as previously defined in in Table 5.3 in Section 5.2. are superimposed on the present day to explore how changes in sea level are expected to affect the length of time that water can be sluiced as well as the head difference and the total volume discharged. It is worth highlighting that in addition to the average daily tidal sequence, only long-term sea level rise is captured in this analysis, with intermediate cycles such as the occurrence of spring or neap tides not considered.

[64] In fact, it is no longer possible to sluice water when the canal water level is less than 12 cm higher than the sea level, due to the differing densities of freshwater in the canal and salt water in the North Sea.

The impacts of different rates of sea level rise are shown in Figures B.10 and B.11. The dotted line shown on Figure B.10 pinpoints the first year where sea level rise is expected to prevent any sluicing from occurring because the entire tidal cycle will result in water levels higher than those on the canal.

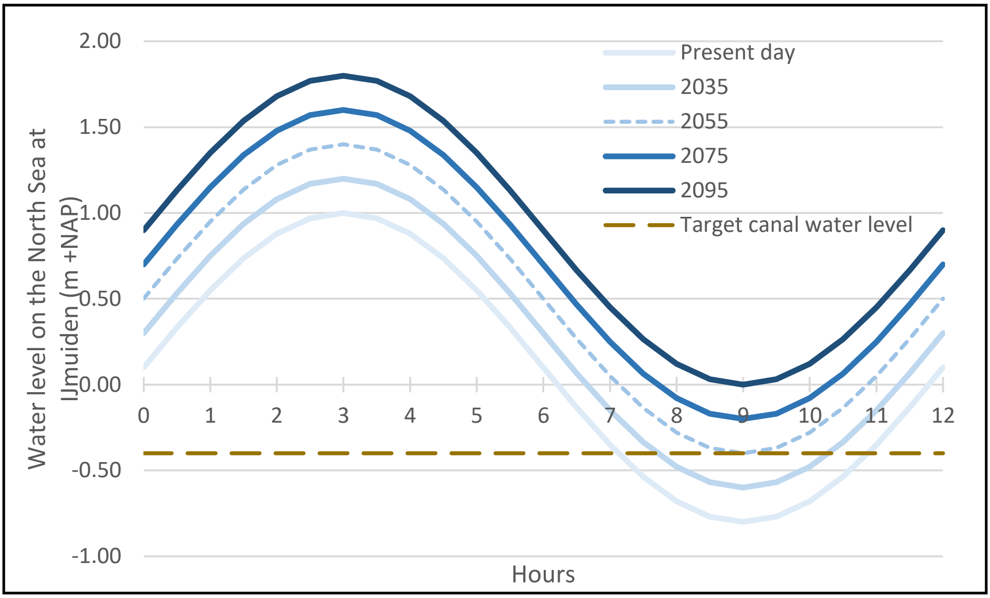


Figure B.10: Average semidiurnal tide cycle representative of future conditions under the high sea level rise scenario at IJmuiden

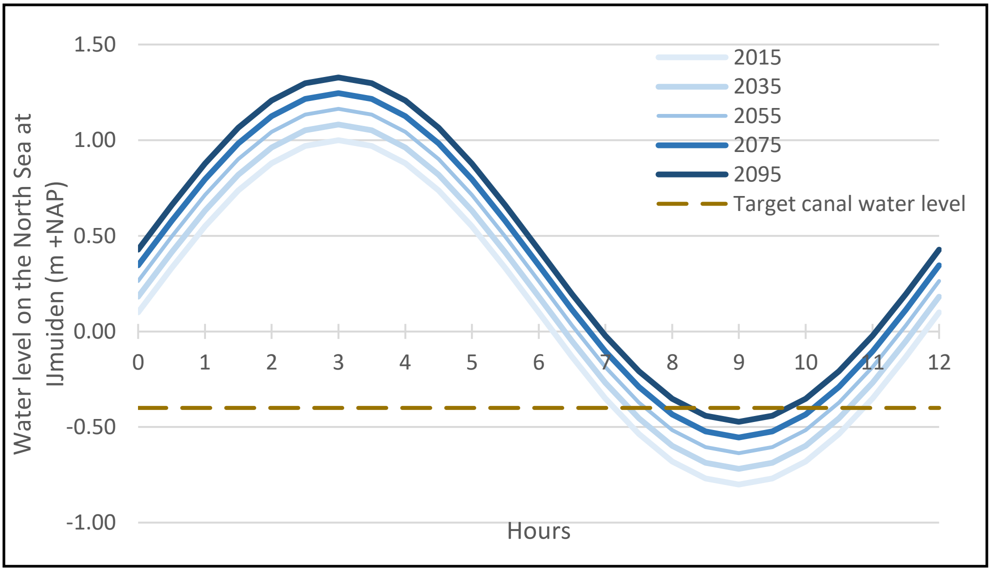
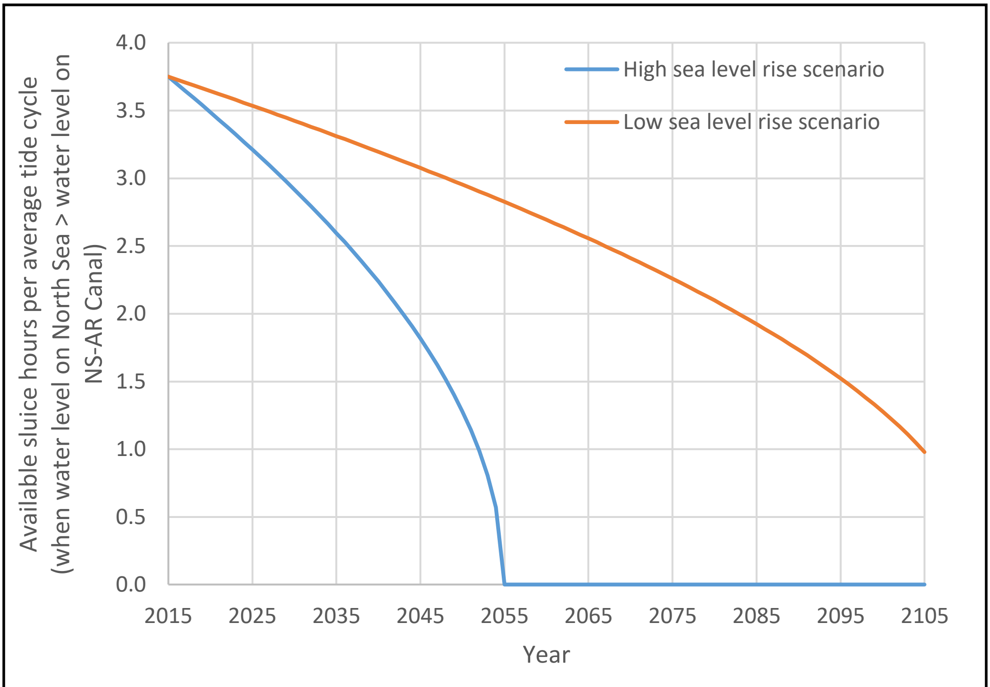


Figure B.11: Average semidiurnal tide cycle representative of future conditions under the low sea level rise scenario at IJmuiden

From these scenario-specific future tidal cycles, the average length of time per tidal cycle that water can be released from the NS-AR Canal under gravity is calculated. The results are shown in Figure B.12. One observes that in the high sea level rise scenario, as soon as 2055, it is possible that on average there will be 0 hours per tidal cycle that water can be released from the NS-AR Canal under gravity. By contrast, under the low sea level rise scenario, some sluicing appears to remain possible until beyond 2100.



<u>**Figure B.12: Average number of hours per tidal cycle that sluicing will be possible at IJmuiden under different future sea level rise scenarios**</u>

Knowing how the sluice time interval changes in the future, the total discharge volume during a sluice event in the future can be estimated using the general equation for discharge through an orifice in m^3/second is $Q_t = a\sqrt{g\Delta h}$ where a = constant that captures factors including the cross-sectional area of the opening and a coefficient of discharge (in m^2), g = acceleration due to gravity (9.8 m/sec^2) and Δh = the head difference between the two water bodies (in m). Q_t represents an instantaneous rate of discharge and to compute the total volume released during a sluice event, integration of Q_t from the start to end of the sluice event is required:

$$
\begin{aligned}
V_{total} \qquad &= \int_{t_{start}}^{t_{end}} Q_t \ dt \\
&= \int_{t_{start}}^{t_{end}} a\sqrt{g\Delta h_t}\, dt \\
&= \int_{t_{start}}^{t_{end}} a\sqrt{g(h_t^{canal} - h_t^{sea})}\ dt \\
&= \int_{t_{start}}^{t_{end}} a\sqrt{g(h_t^{canal} - (b\sin(t) + c))}\ dt
\end{aligned}
$$

where V_{total} = total volume released during a sluice event of duration $t_{end} - t_{start}$ (m^3)

$t_{start} = time\ at\ which\ sluicing\ starts$ i.e. $h_t^{canal} \geq\ h_t^{sea}$

$t_{end} = time\ at\ which\ sluicing\ ends$ i.e. $h_t^{canal} <\ h_t^{sea}$

Q_t = discharge (m^3/sec)

a = constant that captures factors including the cross-sectional area of the opening and a coefficient of discharge (m^2)

g = acceleration due to gravity (9.8 m/sec^2)

Δh_t = the head difference between the two water bodies at time t (m) = $h_t^{canal} - h_t^{sea}$

h_t^{canal}= head on canal at time t (m)
h_t^{sea} = head on North Sea at time t (m)

b and c = constants related to the amplitude and vertical shift of the sinusoidal tides

The solution to this integral is estimated numerically, with the results presented on Figure B.13. The results suggest that the combined impact of decreasing Δh and decreasing the length of time over which sluicing can occur results in an approximately linear decrease in the total discharge volume over time. This estimate of the relationship between the total free flow discharge volume and the date in the future is carried forward into the remainder of the modelling to provide an indication of the extent to which the sluices will continue to contribute to water outflow from the canal.

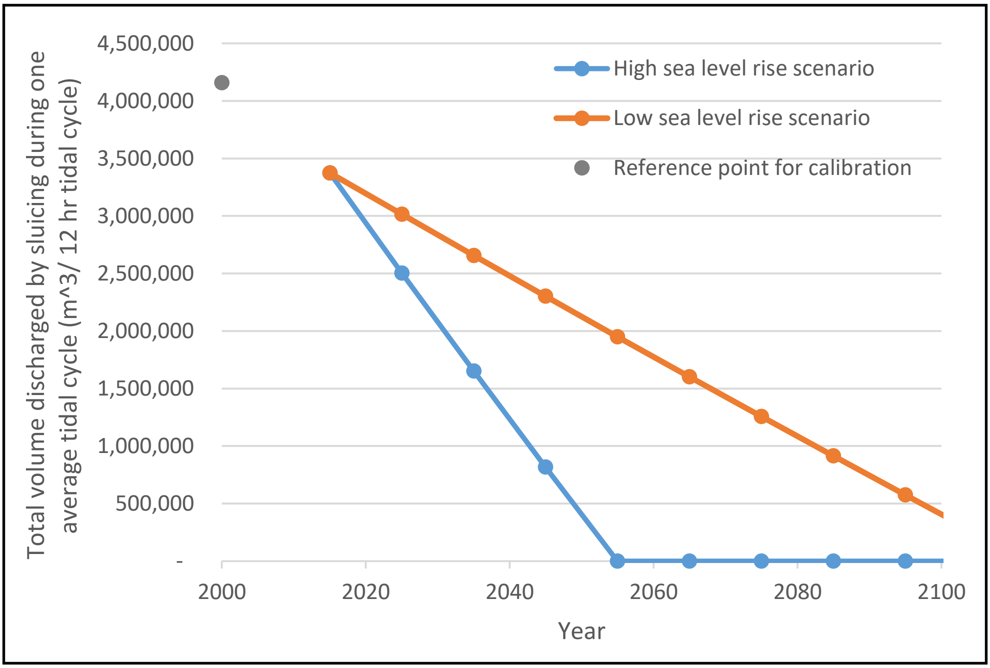


Figure B.13: Total volume of water released per average sluice event at IJmuiden under different future sea level rise scenarios

B.3.2 Pumped outflows

As introduced above, the long-term impact of increased canal inflows and rising sea levels are expected to result in less water being released from the canal under gravity and a greater reliance on pumping water out to the North Sea. However, increased sea level and the resulting increased head differences between the canal and the sea also impact the ability of the current pumps to discharge water. The higher the head, the lower the achievable pumping rate, as shown on Figure B.14. This pump performance curve is used to estimate how future pumped discharge rates will diminish with increasing water levels on the North Sea. This implicitly makes the assumption that all six pumps that are currently in use are of the same type and follow the same performance curve[65]. In addition, it is assumed that any

[65] In reality, there are two different types of pumps installed in the pumping station: four of the pumps date back to the original structure's construction in 1975 and were manufactured by Stork, while two newer Nijhuis pumps were added in 2004.

future pumps added will be of a similar capacity and type as those currently installed, and will thus deliver similar performance levels.

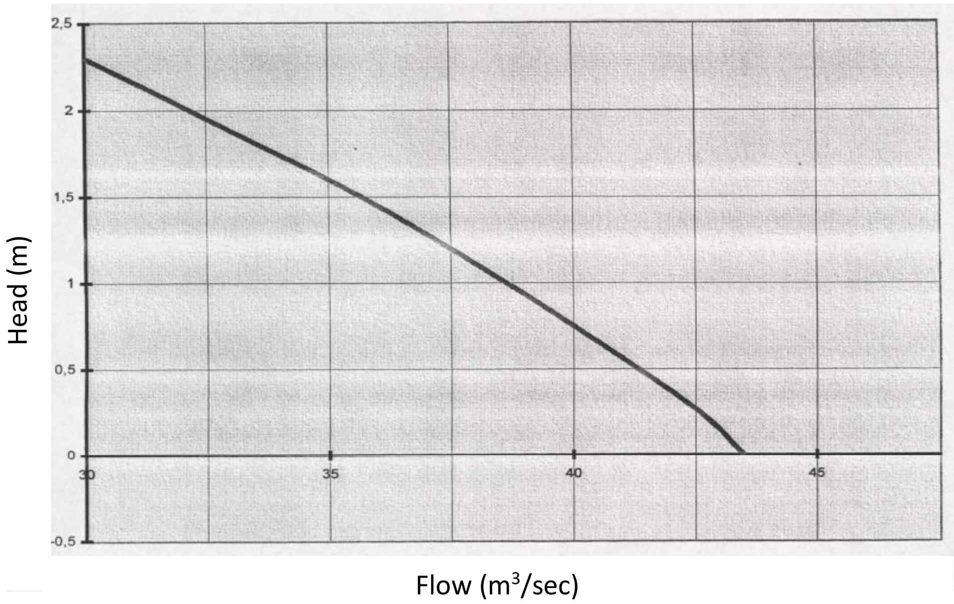


Figure B.14: Pump performance curve representative of the existing Stork pumps at IJmuiden (Source: adapted from Rijkswaterstaat West-Nederland Noord and Utrecht, Ministry of Infrastructure and Environment, 2000)

This pump performance curve was coupled with the average future scenario-specific tidal cycles shown in Figures B.10 and B.11 to estimate how future changes in the relative head are expected to impact achievable pumping rates and thus the total discharge that can be removed from the canal per tidal cycle. The output was subsequently calibrated observed historic pumping data from days that experienced unusually high tidal water levels and were thus taken as being representative of the average scenario a certain number of years in the future. The output of this analysis is in the form of scenario-specific discharge curves that estimate how the total pumped discharge per tidal cycle will decline in the future, and how the addition of new pumps will augment this. Capacity expansion is assumed to occur in units of 50 m^3/second. This is shown in Figure B.15. This estimate of the relationship between the total pumped discharge volume and the date in the future is carried forward into the remainder of the modelling to provide an indication of the extent to which the pumping capacity installed at any given time will continue to be adequate to manage water outflow from the canal.

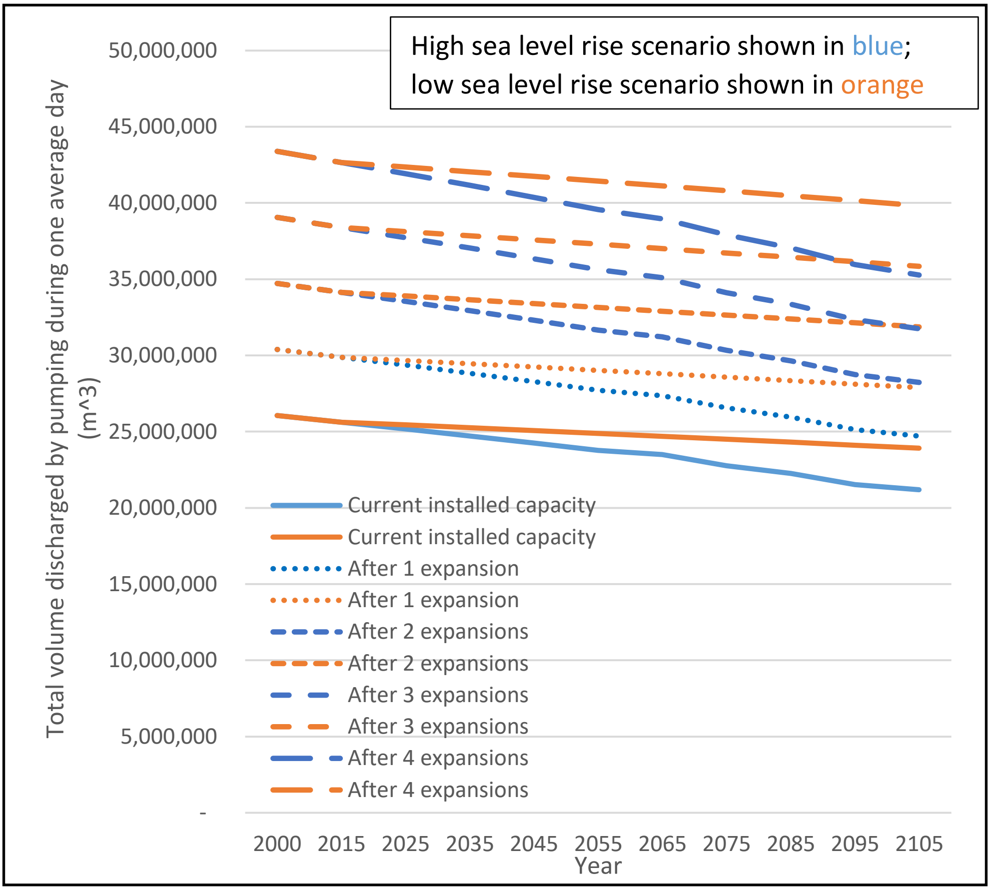


Figure B.15: Total volume of water released by pumping at IJmuiden during an average day under different future sea level rise scenarios

B.4 Putting it all together

The previous sections have described a generally applicable mass balance, an inflow formulation and a quantification of outflows. The final step requires that these individual components be linked in such a way as to provide insights when and under what conditions the desired water level on the canal will be exceeded in the future.

To link inflows, outflows, the general mass balance and water levels, a simple optimization model was initially developed that indicated when water should be released from the canal in order to maintain a water level between the maximum and minimum acceptable levels at all times. However, this optimization formulation was not compatible with the 1,000's of deterministic inflow sequences generated above: the results demonstrated that over long periods of time, minimum water levels were maintained simply to accommodate a future high inflow. While this kind of drawdown of water levels in preparation of a flood is realistic over a time-frame of a few days, it is conceptually incorrect to assume that the canal will always be kept at minimum levels to prepare for a high water event that may happen years or decades into the future. Improving these results would have required a move towards further, short-term operational considerations which is not the goal of this work.

Instead, a simple heuristic-type formulation was developed, whereby each day is treated as an independent time unit. The inflows generated in Section B.2 are in the form of daily totals and it is assumed that this volume of water instantaneously flows into the canal at 00:00 hours every day, with the water level at the target water level of -0.40m NAP at this time. The outflows described in Section B.3 occur either by sluicing and/or pumping over the course of the next 24 hours and if at 24:00 hours, the water level remains greater than the maximum allowable water level, this is taken as a signal that capacity expansion is necessary. This assumes that outflows at IJmuiden are instantaneously followed by corresponding drops in the canal water level along its entire length.

Thus, in conclusion, this sequence of different model components is ultimately focused on exploring the impact of changing precipitation on canal inflows, and how this affects water levels in the canal, providing an indication of when an expansion of the pumping capacity at IJmuiden becomes necessary. As described in Section 5.7.2, the physical model described in detail here is coupled with an economic module that allows the exploration of the physical and economic performance of different possible replacement designs and replacement strategies.

B.5 A note on assumptions

As introduced above, this series of model components make a number of simplifying assumptions that are worth highlighting:

- Canal inflows originate only from variable precipitation runoff and a seasonally constant component derived from other sources such as industrial releases and shipping. We assume that the proportions of these sources of inflow are constant over time. In addition, the model formulation used assumes no inflows from groundwater via baseflow.

- The model formulation used ignores the role of alternative outflow points from the canal. This is considered reasonable, because together all the alternative outflow points from the NS-AR Canal account for less than 5% of the total canal outflows (RWS-WNN, 2013). This model formulation also does not account for possible measures used in times of extreme high water e.g. requiring that the surrounding sub-catchments store and hold their runoff until the high water level on the canal has dropped back down to acceptable levels.

- The use of daily precipitation data provides fine enough temporal resolution to model peaks in canal inflows and water levels.

- The precipitation measured at or predicted for De Bilt weather station is representative for the entire catchment area.

- The degree of random variability in the precipitation-inflow relationship remains the same in the future under a variety of different climate scenarios

- Inflows to the canal are distributed uniformly over the entire canal, with no height gradients created between different portions of the canal. Canal water levels are not affected by wind or other local conditions. When sluicing or pumping water out of the canal into the North Sea, it is assumed that the water level across the entire canal adjusts instantaneously in response to outflows.

- One tidal period is equated to exactly 24 hours, as opposed to 24 hrs and 50 minutes. It is assumed that the switch from sluicing to pumping water occurs when the water levels in the North Sea and the canal are equal. In fact, it is no longer possible to sluice water when the canal water level is less than 12 cm higher than the sea level, due to the differing densities of freshwater in the canal and salt water in the North Sea. In addition to the average daily tidal sequence, only long-term sea level rise is captured in this analysis, with intermediate cycles such as the occurrence of spring or neap tides not considered.

- The assumption is made that all six pumps that are currently in use are of the same type and follow the same performance curve. In addition, it is assumed that any future pumps added will be of a similar capacity and type as those currently installed, and will thus deliver similar performance levels.

Put together, these are some fairly dramatic simplifications. These assumptions were made as the primary objective of this work is not to provide a well-substantiated recommendation of what to build at IJmuiden, but rather to demonstrate a new, more generally applicable long-term planning approach. The intent of this section was not to replace sophisticated models that accurately make predictions about canal inflows and water levels. Rather, it was as a demonstration of the critical elements required for a model to be able to not just identify when a water level management Adaptation Tipping Point occurs, but then subsequently give an indication of when future Adaptation Tipping Points will be reached given different possible changes made to the physical system. Thus all of these assumptions are areas where further work could be done should a more detailed and ultimately actionable output be desired.