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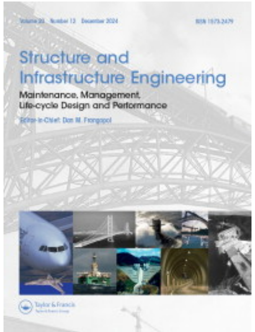

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A framework for assessing the remaining life of storm surge barriers

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ABSTRACT

Over the course of the last century, storm surge barriers have been built in several countries and proven to be successful in preventing flooding. However, the operation, reliability, and remaining life of these structures have come under increased pressure due to changing demands, intensified utilisation, and climate change. Yet, there is relatively little known about how these factors affect the remaining life of storm surge barriers. To address this issue, a framework is presented to assess the impacts of external drivers on the remaining life in a systematic manner. The framework considers both the technical state and functional performance and uses scenarios to evaluate the impact of external drivers. The application of the framework is demonstrated for the Hollandsche IJssel barrier (the Netherlands). The results indicate that sea level rise (SLR) is the dominant physical driver. Even in moderate SLR scenarios, the lifespan of the barrier may end in the 2040s if the functional performance with respect to flood protection and navigation cannot be improved. Ultimately, the study demonstrates how the remaining life of storm surge barriers could be assessed systematically and the impact of external drivers on the remaining life could be evaluated.

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1. Introduction

Storm surge barriers are fully or partly movable barriers that can be closed temporarily to reduce or limit the rise of water levels in the basin behind the barrier and thereby protecting the hinterland against flooding (Mooyaart & Jonkman, 2017). To date, eighteen storm surge barriers have been built worldwide, of which five in the Netherlands. These barriers are vital for the protection of the low-lying coastal region of the Netherlands. However, changing societal demands, economic developments, and climate change, especially sea level rise (SLR), are starting to affect the operation, maintenance, and remaining life of these barriers. In addition, more frequent closure of storm surge barriers will result in increased hindrance to shipping and put the existing ecosystems behind the barriers under pressure. This means that asset managers, such as Rijkswaterstaat, the executive body of the Dutch Ministry of Infrastructure and Water Management, will not only be confronted with very large replacement and renovation challenges, but may also have to reconsider current flood protection strategies. Therefore, it is vital to gain a better understanding of how external drivers, such as climate change and socio-economic changes, impact the remaining life of storm surge barriers.

The end of life of an infrastructure asset can be prompted by technical aspects, such as structural deterioration, inadequate functioning, or economic considerations. Accordingly, three types of lifespans can be identified: technical, functional, and economic life. Researchers and asset managers employ slightly divergent definitions for these concepts, see for example, Hermans (1999), Hertogh et al. (2018), and Wilkinson et al. (2014). This study adopts the following definitions:

- Technical life: the time period over which an asset is able to fulfil its functions according to the original requirements before it must be replaced due to deterioration of non-replaceable components or the use of outdated technologies.
- Functional life: the time period during which an asset complies with the functional requirements, such as the exceedance frequency of the critical water level or the acceptable number of closures. Societal developments, changes in physical conditions, or new functional requirements could mark the end of the functional life.
- Economic life: the time period over which the costs of owning and operating an asset are still lower than the costs of equivalent alternatives.

According to these definitions, the technical life is only related to the deterioration and ageing of structural components, the functional life involves the functional performance and associated requirements of an asset, and the economic life is determined by comparing the life cycle cost of the asset with the life cycle cost of alternatives. Replacement of a storm

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surge barrier on economic grounds is considered unlikely as the operational costs are very low compared to the investment costs. The technical and functional life will therefore likely determine the overall remaining life of storm surge barriers.

Relevant literature on the lifespan of assets has been primarily focused on assessing the technical life of assets, i.e. deterioration of structures. Rijkswaterstaat, for example, developed a method to generate statistical estimates of the remaining technical life of groups of similar structures (Kallen et al., 2014; Nicolai & Klatter, 2015). However, the results of this method are insufficiently accurate to be applied to individual assets. Moreover, the statistical analysis is not suitable for the analysis of storm surge barriers due to the fact that storm surge barriers are not present in large numbers. Other researchers suggest physical models or stochastic models to study deterioration processes (Gaal, 2004; Heutink et al., 2004; Nicolai et al., 2007). Instead of estimating the technical life, these studies tend to focus more on improving maintenance strategies, such that the technical life can be extended.

The functional life has only been considered in recent years as changing demands and changes in the spatial environment cause functional aspects, such as the performance in terms of flood protection, to become more relevant (Klatter et al., 2019). Breedeveld and Kramer (2019) have made a first step towards a method to assess the functional life of hydraulic structures by providing a framework and an overview of the existing models that could be used in the assessment of the functional life. But more research is required to identify appropriate models and their added value, the uncertainties in different parts of the method, and how these uncertainties affect the estimated functional life (Breedeveld & Kramer, 2019). Studies that looked at the functional performance of storm surge barriers were mostly concerned with evaluating the impact of SLR on the functional performance with respect to flood protection (Op ’t Landt, 2018; Von Meijenfeldt et al., 2017; Welsink, 2013). Other functions of the storm surge barrier have been studied to a limited extent and from a global or systems perspective only (Von Meijenfeldt et al., 2017).

There is limited literature on the impact of external drivers on infrastructure assets. The few studies known to the authors mostly address the impacts of climate change on infrastructure assets. For instance, Schwartz (2010) and Rowan et al. (2013) presented overviews of the potential impacts of climate change on infrastructure, Kumar and Imam (2013) assessed the impacts of climate change induced atmospheric changes on built infrastructure, and Mondoro et al. (2018) discussed the challenges climate change poses to coastal bridges. Although these studies mainly analyse the impacts on bridges and other transportation infrastructure, the identified impacts, e.g. extreme temperatures or precipitation, may apply to storm surge barriers as well. However, the relevance and magnitude of certain impacts will likely be different. In addition, these studies focus on the impacts of climate change on the technical state of infrastructure and less on the functional performance.

Overall, a comprehensive method to identify how and to what extent external drivers, such as climate change, impact the remaining life of storm surge barriers is lacking. The goal of this paper is to address this knowledge gap and develop a method to identify the dominant factors and related uncertainties impacting the remaining life of storm surge barriers, with a focus on both the technical as well as functional lifespan. First, the proposed framework is introduced in Section 2. Next, the Hollandsche IJssel barrier is used to demonstrate the application of the framework (Section 3). In the fourth section, the results of the framework application are used to establish quantitative estimates of the storm surge barrier’s remaining life. The article concludes with a discussion of the proposed method and conclusions (Section 5).

2. Framework

There are numerous pathways how a storm surge barrier may reach its end of life (EOL). When estimating the remaining life, it is key to assess all these different ways. In order to do this in a systematic way, a framework to assess how external drivers may affect the remaining life is introduced (Figure 1).

2.1. Conceptual framework

The framework distinguishes two types of external drivers that could lead to the end of life of storm surge barriers (bottom row): societal developments and physical drivers. Societal developments consist of policy changes and socio-economic developments. The physical drivers include climate change related drivers, e.g. SLR and other physical drivers such as land subsidence and atmospheric composition. Societal developments could impact the functional performance, but also (functional) requirements. More economic growth, for example, could result in stricter requirements with respect to flood protection. The physical drivers could affect the functional performance and requirements as well as the deterioration processes of structural components. The required functional performance levels could also have an impact on the deterioration process. For example, if the water level at which the barrier must close is raised, the barrier has to be closed less frequently, positively impacting the deterioration process of closure elements. At a certain moment inadequate functional performance or severe deterioration could result in either the functional, economic or technical end of life. And either one of these could induce the end of life of the barrier.

2.2. Step-by-step approach

For the application of the framework, a top-down approach is proposed as shown on the left in Figure 1. This approach consists of the following main steps:

1. Establish lifespan definitions:
   Different definitions of the lifespan exist among research and asset managers depending on the scientific discipline or context. For example, a distinction between the functional or economic lifespan is not always made (PIANC,

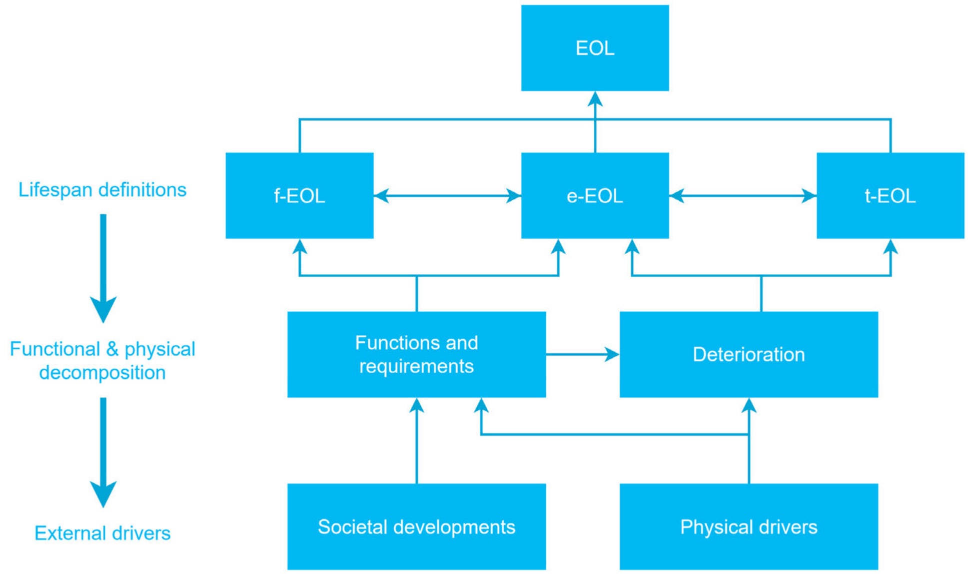

Figure 1. Flow chart of the framework for assessing the remaining life of storm surge barriers. f-EOL: end of functional life; e-EOL: end of economic life; t-EOL: end of technical life.

2008; Van Veelen, 2016). Therefore, the analysis should start with clear definitions of the different lifespans in order to avoid any confusion or misconception about what is meant when referring to these types of lifespans.

2. Perform functional analysis and physical decomposition:
The functional analysis is intended to obtain an overview of the functions of the storm surge barrier and establish the requirements to support the assessment of the impact of external drivers. The physical decomposition should be carried out for the assessment of the technical life. By decomposing the structure into different structural components, the dominant deterioration mechanisms and external drivers impacting these deterioration mechanisms can be identified.
3. List the relevant external drivers and their potential impacts:
The overview of functions and their requirements for the storm surge barrier, and the dominant deterioration mechanisms of its structural components, that follow from the previous step enables one to examine how a specific external factor/driver impacts the storm surge barrier's remaining life. For each function, one should analyse what external drivers could impact the functional performance and how these drivers could do so. A similar analysis should be performed to identify the external drivers that affect the deterioration of structural components. This is a qualitative step that aims to obtain a complete overview of all potentially relevant external drivers and their impacts.
4. Identify most important external drivers:
Once all relevant external drivers are listed, their impacts can be evaluated to identify the most important/dominant ones. Climate change scenarios and, if available, socio-economic scenarios form the basis of this evaluation. The scenarios should include a wide range of possible future situations to ensure the robustness of the analysis. A quantitative analysis is not always necessary. For some effects of external drivers, the evaluation can be done qualitatively based on information obtained from other studies. (Semi-)quantitative assessments are only required when qualitative judgements provide insufficient information for the evaluation of the effects. The results of this step can be presented in tables that summarise the impacts of the drivers on the functions or main structural components. These tables allow for composing a shortlist of the dominant external drivers that should be assessed more elaborately.

The main advantage of using the 'top-down' approach described by the four steps above is that it provides proper guidance to systematically identify the external drivers that could impact the functional or technical life of the storm surge barrier. If one starts by listing all possible external drivers, important interactions or functions may be overlooked and the evaluation of the impacts becomes more challenging as the functions and relevant deterioration mechanisms are identified at a later stage. Reasoning from the functions and dominant deterioration mechanisms of the storm surge barrier, as the 'top-down' approach proposes, provides more guidance for the evaluation of the impacts of external drivers.

3. Application to a case study

3.1. The Hollandsche IJssel barrier

The Hollandsche IJssel barrier was used to demonstrate the application of the framework. This storm surge barrier is located in the south western part of the Netherlands. The construction of the storm surge barrier was completed in 1958, making it the oldest storm surge barrier in the Netherlands. The envisioned lifespan of the barrier at the time of construction was 100 years. Replacement or major renovations of the storm surge barrier are therefore anticipated in the early second half of the 21st century. However, planning and implementing a new strategy or structure takes roughly 20–40 years (Haasnoot et al., 2020; Hallegatte, 2009), which makes it particularly relevant to obtain better insight into the remaining life of this storm surge barrier. Below an example is given of how the remaining life of the Hollandsche IJssel barrier can be assessed following the steps described in Section 2. Note that step 1 of the approach is omitted as definitions of the types of lifespans were already given in the introduction of this paper.

3.2. Step 2: perform functional analysis and physical decomposition

The functions of the Hollandsche IJssel barrier are visualised in Figure 2. First, the barrier closes off the tidal part of the Hollandsche IJssel, thereby reducing the extreme water levels in the hinterland (flood protection). Next, the Hollandsche IJssel is an important shipping route between the Port of Rotterdam and inland terminals (navigation), and provides storage capacity for and discharge of water from surrounding polder areas in periods of abundant rainfall (water management). The fact that the Hollandsche IJssel is a tidal river influences the water quality and creates a particular ecosystem. Therefore, preserving the tidal regime is considered a fourth function. Finally, the storm surge barrier complex provides a road connection between the areas on both sides of the river.

From a structural point of view, the storm surge barrier consists of a number of different components of which the deterioration processes impact the remaining technical life. These components can roughly be divided into three groups: fixed structures, movable parts, and electrical installations. This subdivision follows from the typical lifespan of the components and the relevant deterioration mechanisms. Fixed structures include the concrete towers, foundation, lock heads, etc. These components typically have a design lifespan of 100 years. Examples of movable components are the lifting gates and drive mechanisms of the gates. The lifespan of moveable components is typically 50 years. The category electrical installations include hardware such as the control system and communication systems as well as software. These components generally require replacement within 5, 10 or 30 years. An overview of the major components of the storm surge barrier is given in Figure 3 (see Vader 2021 for a more detailed description of these components).

The components shown in Figure 3 are subject to various deterioration processes. For example, the fixed concrete structures are prone to deterioration through sulphate attack, alkali-aggregate reactions, and corrosion of the reinforcement. The most important deterioration processes of the fixed structures are the ones related to reinforcement corrosion: carbonation and chloride ingress. The steel gates mainly suffer from corrosion. The impact of fatigue is limited due to the infrequent usage of the gates. The other movable parts, the gate drive mechanisms, are sensitive to wear and fatigue. The electrical installations are susceptible to regular wear and tear and obsolescence. Hence, these components generally have to be replaced within eight to fifteen years, but this will not lead to the end of life of the storm surge barrier as a whole.

3.3. Step 3: list the relevant external drivers and their potential impacts

Based on the identified functions and dominant deterioration mechanisms, the external drivers and their potential impacts were analysed. Besides the overview of functions and deterioration mechanisms, scenarios with the projected changes in external drivers, such as climate change scenarios, give insight into relevant external drivers. As an example, the flood protection function is considered. The performance is governed by the local water levels and the characteristics of the flood defences. Hence, factors such as SLR, river discharge (high and low), precipitation, and land subsidence are identified as relevant ones. Regarding the deterioration of the concrete structures, relevant drivers are identified as changes in temperature, precipitation, and CO_2 concentration since variations in these variables impact the carbonation induced

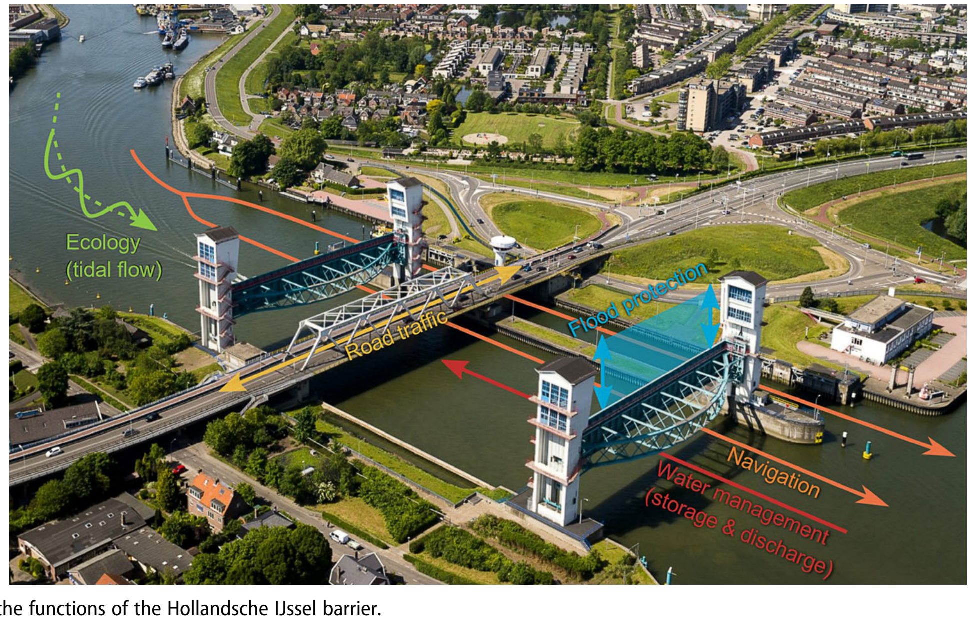

Figure 2. Overview of the functions of the Hollandsche IJssel barrier.

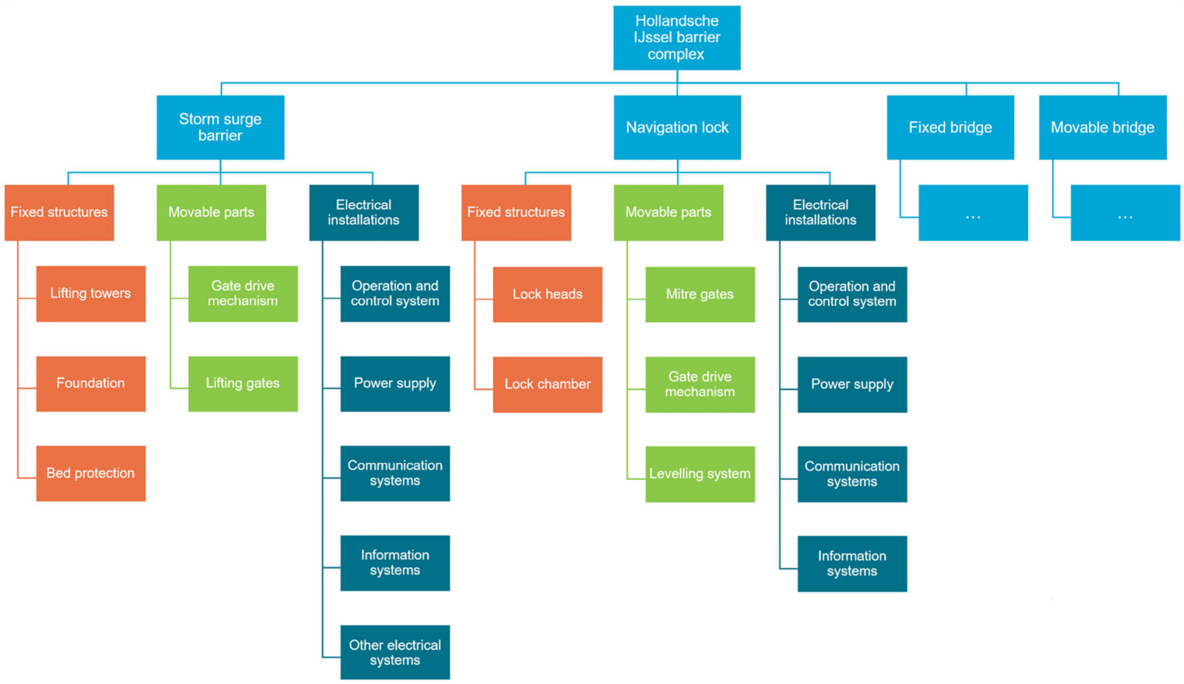

Figure 3. Physical decomposition of the Hollandsche IJssel barrier.

reinforcement corrosion. In a similar manner, external drivers are identified for the other functions and deterioration mechanisms of the storm surge barrier. The list of relevant external drivers is given in the first column of Table 1. The coloured cells indicate that the specific driver affects the function, italic text indicates that the impact is limited or accounted for in the design, and bold text indicates that the impact may lead to early end of life and cannot easily be dismissed.

3.4. Step 4: identify most important external drivers

For the semi-quantitative assessment of the drivers, this study uses the KNMI'14 climate change scenarios (Van den Hurk et al., 2014) to evaluate the impacts of climate change related drivers. The socio-economic scenarios developed by the Bureau for Economic Policy Analysis (Centraal Planbureau, CPB) and the Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving, PBL) (Wolters et al., 2018) were used to evaluate the impacts of socio-economic changes. To give an indication of the magnitude of changes in the climate change scenarios, the scenarios cover a range from 1.3 °C to 3.7 °C increase in mean temperature, 4.5–30% increase in winter precipitation, and 0–23% decrease in summer precipitation by 2085. The socio-economic scenarios project changes in population ranging from a decrease by 1 million (to 16 million) to an increase by 2 million (to 19 million), and an economic growth of 1–2% per year. These changes are projected for 2050.

How every driver can affect the remaining life of the storm surge barrier was assessed using the scheme in Figure 1. For instance, as a consequence of SLR, critical levels are more frequently exceeded and closures are more often needed. The more frequent occurrence of extremes directly impacts the safety level. The higher closure frequency, on the other hand, may negatively impact the performance of several functions such as navigation, water management and ecology and may accelerate deterioration. In some cases, the impact of a driver is such that it may lead to early end of life. An overview of the assessed impacts of all drivers is provided in Table 1 for the three most affected functions: flood protection, navigation, and water management. The table shows that these functions, together with ecology, are predominantly affected by SLR (a full overview is available in supporting information Appendix A).

The impact on the deterioration seems limited (see supporting information Appendix A). The technical end of life of movable parts and electrical installations generally implies the replacement of the specific parts, but not the end of life of the barrier as a whole. The deterioration processes, like carbonation and chloride ingress, that may affect the technical state of the non-replaceable components, i.e. fixed, concrete structures, can be controlled by regular inspection and adequate maintenance. As a consequence, the deterioration processes of the movable parts are mainly relevant for the maintenance costs. The cumulative and increasing maintenance costs will by far not exceed the replacement costs of the barrier as a whole and will not lead to an early end of the economic life of the storm surge barrier. For this reason, the functional life is considered dominant and assessed to quantify the remaining life of the Hollandsche IJssel barrier.

4. Quantitative evaluation

The framework in Figure 1 only provides a structured approach to identify the dominant external drivers that affect the remaining life of the storm surge barrier. The results of such an analysis provide valuable information for

Table 1. Overview of the impacts of drivers on the three most affected functions of the Hollandsche IJssel barrier.

Driver	Flood protection	Navigation	Water management
Physical drivers			
Temperature			
Precipitation	*Higher water levels due to increase in river discharges*		*Frequency of a pumping stop may be increased by a more frequent or increased discharge of water from the polders*
Land subsidence	*Higher flooding probability as a result of lower dike heights*		*Lower dike heights may prompt adjustments of the water level at which pumping is stopped or the frequency of a pumping stop may increase as more water has to be discharged from the polders*
Sea level rise	**Increase in the probability of extreme water levels**	**More closures lead to more hindrance to shipping**	**Increase in the probability of reaching the critical water level at which pumping has to stop**
High river discharges	*Limited effect on the probability of extreme water levels*		
Low river discharges		*Lower water levels affect the navigability, but this is unrelated to the functioning of the storm surge barrier*	
Drought	*Stability of the dikes could become an issue, but storm surge barrier is not part of any strategy against droughts*		*Salt intrusion could worsen or freshwater supply could become an issue, but the storm surge barrier is not part of any strategy against droughts*
CO_2 concentration		*Limited impact*	
Wind			
Societal developments			
Changes in the Water Act		*Limited impact*	
Population growth			
Economic growth			

a quantitative evaluation of the remaining life as only the most important drivers need to be considered. The next step is then to quantify the remaining life given the impacts of these drivers. However, this step is not necessarily the same for all storm surge barriers since different functions, technical aspects, or external drivers may turn out to be governing for each storm surge barrier. The actual quantification of the remaining life is thus case-specific. Nevertheless, the following sections will demonstrate how the remaining functional life is obtained from analysing SLR with respect to closure frequency and reliability requirements. Such an analysis is transferable to storm surge barriers worldwide where flood protection and navigation are impacted by SLR.

In the case of the Hollandsche IJssel barrier, functional aspects and the effects of SLR on these aspects were found to be governing after application of the framework. Therefore, suitable methods to assess the impact of SLR on the functional performance of the Hollandsche IJssel barrier are presented below. The main focus of this quantitative evaluation lies on the functions flood protection and navigation. The other functions of the storm surge barrier were not assessed in the quantitative analysis for a number of reasons. The functional performance with respect to road traffic is dealt with separately in other studies in which modifications to the bridge are also considered, see Gemeente Rotterdam et al. (2020). This functional requirement for transport will not determine the storm surge barrier's end of life. The performance regarding water management is expected not to be a decisive factor for the remaining life as the changes in performance are relatively small and there are alternatives to cope with future increases in discharge demand, e.g. diversion to other watercourses or installation of pumping systems.

4.1. Assessment of the flood protection function

The functional performance with respect to flood protection was evaluated by comparing the extreme water levels behind the Hollandsche IJssel barrier with a critical water level. This critical water level should not be exceeded to limit the loads on the dikes along the Hollandsche IJssel. For this study, the critical water level was assumed to be the water level above which the dikes along the Hollandsche IJssel may fail. The functional performance of the Hollandsche IJssel barrier must be such that the exceedance probability of this water level is less than 1/30,000 per year. Based on the water level statistics in front of the storm surge barrier and the non-closure probability of the barrier, the exceedance probabilities of the water levels behind the barrier, and thus the critical water level, can be determined using the open-source, probabilistic model Hydra-NL.[1] The resulting critical water levels corresponding to a non-closure probability of 1/200 and 1/1000 per closure are NAP +3.04 m and NAP +2.90 m, respectively (NAP = Dutch Ordnance Datum, which approximately corresponds to mean sea level). These critical water levels are further referred to as assessment water levels to avoid any confusion with other critical water levels.

The extreme water levels behind the storm surge barrier for the future situation with SLR were calculated using a simplified representation of the probabilistic model Hydra-NL. The reason being that wind speed and sea water level are coupled in the model for small waterways such as the Hollandsche IJssel. This coupling reduces the computational efforts and is valid as a higher wind set-up is generally correlated with higher wind speed. But when SLR is added, this coupling results in higher wind speeds in the model, which could cause unrealistically high surges and corresponding water levels. This issue can be resolved by performing additional hydrodynamic simulations with a specified amount of SLR. However, when one wishes to evaluate the functional performance for a range of SLR values, as is the case in this study, this approach becomes infeasible as new hydrodynamic simulations are required for each SLR value to model the effects of SLR on the water levels. Hence, the following fundamental relationship between the exceedance probability of water levels behind the storm surge barrier and the exceedance probability of water levels in front of the barrier, where this coupling is not present in the model, was adopted to calculate the extreme water levels behind the barrier:

$$P_{\mathrm{bb}}(h) = P_{\mathrm{nc}} \cdot P_{\mathrm{fb}}(h) \tag{1}$$

where $P_{\mathrm{bb}}(h)$ is the exceedance probability per year of water levels behind the storm surge barrier, P_{nc} is the non-closure probability per closure of the storm surge barrier, and $P_{\mathrm{fb}}(h)$ is the exceedance probability per year of water levels in front of the storm surge barrier. The validity of Equation (1) was assessed by comparing the resulting extreme water levels with extreme water levels obtained from Hydra-NL for which additional hydrodynamic simulations with a limited number of SLR values were performed. This analysis revealed that Equation (1) approximates the extreme water levels behind the storm surge barrier reasonably well for return periods that are relevant to flood protection (>10,000 years) (Vader, 2021).

The overall approach for the assessment of the flood protection function comprises the following steps: (i) derive the extreme water levels in front of the storm surge barrier for various SLR values using Hydra-NL, (ii) approximate the extreme water levels behind the barrier by means of Equation (1), and (iii) determine the critical SLR values for which the assessment water levels are exceeded. This final step is illustrated in Figure 4. The figure shows the water levels behind the Hollandsche IJssel barrier with a probability of exceedance of 1/30,000 per year for various non-closure probabilities of the barrier as a function of SLR. The coloured lines with different line styles indicate the non-closure probability of the storm surge barrier that was used to derive these water levels. These water levels are compared with the earlier derived assessment water levels (dashed thin horizontal lines) to estimate critical SLR values, i.e. SLR values for which the functional performance in terms of flood protection becomes inadequate (coloured vertical lines).

An implicit assumption of the approach is that the functional performance is just acceptable for the non-closure probability that is used to derive the assessment water level. This assumption is however justified as extensive reinforcements of the dikes behind the Hollandsche IJssel barrier are currently required to comply with the prescribed safety levels. It also means that any amount of SLR would result in the exceedance of the assessment water level. This can also be seen in Figure 4 where the coloured lines of the non-closure probabilities 1/200 and 1/1000 per closure cross the horizontal lines of the assessment levels corresponding to the same non-closure probabilities at 0 cm SLR. Since these crossings of the assessment water levels are meaningless for the remaining functional life, they are not included in the figure with coloured vertical lines.

Note that failure due to non-closure is not the only failure mechanisms that determines the performance of a flood defence. According to the Dutch standards and guidelines ('t Hart et al., 2018), there are four main failure mechanisms of hydraulic structures: overtopping, piping, structural failure due to lack of strength or stability, and failure due to non-closure. However, a review of the impact of SLR on these failure mechanisms showed that the mechanism failure due to non-closure is the only relevant failure mechanism for the end-of-life assessment of the Hollandsche IJssel barrier. Failure due to overtopping, piping, or insufficient structural strength would only become relevant for 1 m SLR or more due to the presence of a more seaward storm surge barrier, the Maeslant barrier (Vader, 2021).

4.2. Assessment of the navigation function

For the navigation function, the performance of the storm surge barrier was considered insufficient when a critical water level is exceeded too often (number of closures per year) or for too long (unavailability). Two critical water levels were used, the current closure level of the storm surge barrier (NAP +2.10 m) and the closure level of the navigation lock adjacent to the barrier (NAP +2.50 m). Both levels were used in the evaluation of the unavailability of the waterway to make a distinction between partial unavailability, a situation in which the lock can still be used by vessels, and complete unavailability of the waterway. For the number of closures, only the closure level of the barrier (NAP +2.10 m) was used since this critical level represents any hindrance to shipping.

There are no specific performance requirements for navigation, e.g. an acceptable number of closures or total duration of closures. In this study, an average of nine closures per year was considered acceptable. This number is the total of the storm and test closures in the current situation, and it was used because it is currently considered acceptable. Regarding unavailability, a maximum of 175 hours (2% unavailability per year) was considered acceptable for both partial and total unavailability. This unavailability requirement is based on the 98% (of the operational hours) availability requirement for primary navigation locks in the Netherlands (Willems et al., 2018).

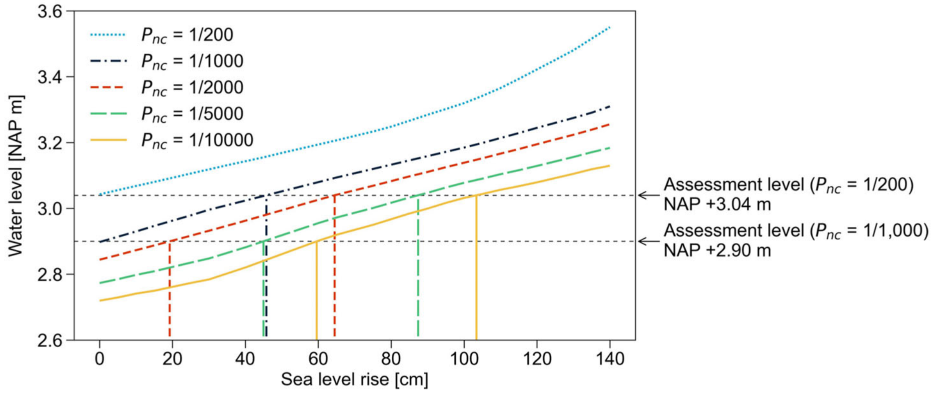

Figure 4. Comparison of the water levels behind the Hollandsche IJssel barrier with a probability of exceedance of 1/30,000 per year—depicted as a function of SLR for various non-closure probabilities—with the assessment water levels.

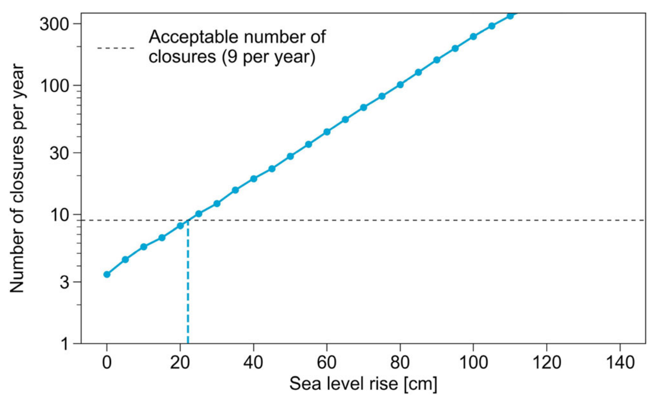

Figure 5. Annual number of closures of the Hollandsche IJssel barrier as a function of SLR.

Water level measurements at the Hollandsche IJssel barrier were used to estimate the current performance with respect to navigation. The water level measurements are publicly available at the website Waterinfo of Rijkswaterstaat (Rijkswaterstaat, n.d.). By counting the number of exceedances of the closure level of the barrier (NAP +2.10 m), the annual number of closures was approximated (Figure 5). The durations of these exceedances in the dataset were used to estimate the annual duration of the closures, i.e. unavailability of the waterway (Figure 6). In case that the time in between two subsequent closure events is less than 6 hours the closure events were combined and treated as a single event. This additional check ensures that the results correspond better to the reality in which the barrier will remain closed if the next moment of closure is expected to be within a few hours after the previous event. An additional 2 hours were added to each closure event to account for the time between the start or end of a closure operation and the waterway being available for traffic again. SLR was included by adding 0.8 m to the measurements per 1.0 m SLR. The factor 0.8 is the result of the more inland location of the Hollandsche IJssel barrier. This factor was derived from an analysis of the water levels at the storm surge barrier for various SLR values with Hydra-NL (Vader, 2021).

Figures 5 and 6 illustrate that the functional performance in terms of navigation is governed by the number of closures. The acceptable number of nine closures per year is reached for a SLR of about 20–25 cm, whereas the critical limit for unavailability is reached after 61 cm or 111 cm of SLR, depending on the critical water level (NAP +2.10 m or NAP +2.50 m). However, these findings do not yet answer the question of remaining life. In the next sections, it is demonstrated how these results can be combined with SLR projections to obtain estimates of the remaining life.

4.3. Probabilistic SLR scenarios

The results from Sections 4.1 and 4.2 were combined with probabilistic SLR projections in order to determine probabilistic estimates of the residual life. These projections include a bandwidth that characterises the 5% and 95% values of the SLR in a certain year. The first projection that was used to estimate the remaining life of the Hollandsche IJssel barrier is the SLR projection for the W scenario of the KNMI'14 climate change scenarios issued by the Royal Netherlands Meteorological Institute (KNMI) (Van den Hurk et al., 2014). This projection was selected since it is one of the scenarios used in the Dutch Delta Programme, a national programme of the Dutch government in which strategies and plans are developed to protect the Netherlands from flooding, ensure a sufficient supply of fresh water, and achieve a climate-proof and water-resilient Netherlands by 2050 (Deltaprogramma, 2020). The projections of KNMI'14 climate change scenarios are based on the global IPCC scenarios of the fifth assessment report (AR5), which are considered unsuitable for long-term decision making or risk management since they only represent a limited part of the uncertainty (66% probability or more) (Bakker, 2015; Hinkel et al., 2015, 2019). Moreover, recent SLR projections (Bamber et al., 2019; Kopp et al., 2017; Le Bars et al., 2017) suggest that the projections of the KNMI'14 climate change scenarios are rather overconfident (Bakker et al., 2017).

In the light of these observations, a more recent SLR projection was also included. In this SLR projection, the ice sheet projections for the H scenario of Bamber et al. (2019) are incorporated. Contributions of other components such as ocean thermal expansion, glaciers, and land-water storage were obtained from Kopp et al. (2014). This projection was considered as the study by Bamber et al. (2019) sought to incorporate the current state of scientific knowledge on the contribution of the ice sheets, which is one of the key uncertainties in SLR projections (Bamber et al., 2019; Garner et al., 2018; Horton et al., 2018; IPCC, 2019; Jevrejeva et al., 2019). The differences between the SLR projections for the W scenario of KNMI'14 (Van den Hurk et al., 2014) and the H scenario of Bamber et al. (2019) are substantial (Figure 7). The SLR projection based on Bamber et al. (2019) has a significantly wider 90% probability range and higher upper bound SLR. For the KNMI'14 projection, the upper value (95th percentile) in 2100 is about 1 m, whereas the SLR could be more than 2 m in 2100 for the projection based on Bamber et al. (2019).

4.4. From SLR projections to remaining life estimates

As SLR is the dominant factor for the remaining life of the Hollandsche IJssel barrier, the probability distribution of the remaining life can be derived directly from the distributions of the two SLR scenarios. For example, if the 90th percentile of x, which is the critical amount of SLR, is reached in year y, then there is a 10% probability that the actual SLR will be greater than x in year y, and thus there is a 10% probability that the structure's end of life is reached earlier than year y given that x implies the end of life of the structure. In other words, the inverse of the cumulative distribution function of the remaining life equals the cumulative distribution function for a specific amount of SLR. This procedure to derive estimates of the remaining life is demonstrated in Figure 8. As soon as the SLR exceeds the critical amount of SLR, the storm surge barrier's end of life is reached. By determining the year in which the critical SLR value is exceed for each percentile of the SLR projection, the probability distribution of the remaining life can be obtained. In the example in Figure 8, the critical SLR value is 50 cm. The figure shows that the median value of the end-of-life estimate is about 2065 with a 90% probability range of 2050–2090. Based on the approach illustrated in Figure 8, the remaining life estimates of the Hollandsche IJssel barrier can be obtained by combining the required performance levels for the considered functions expressed as critical amounts of SLR with the two SLR projections described in the previous section.

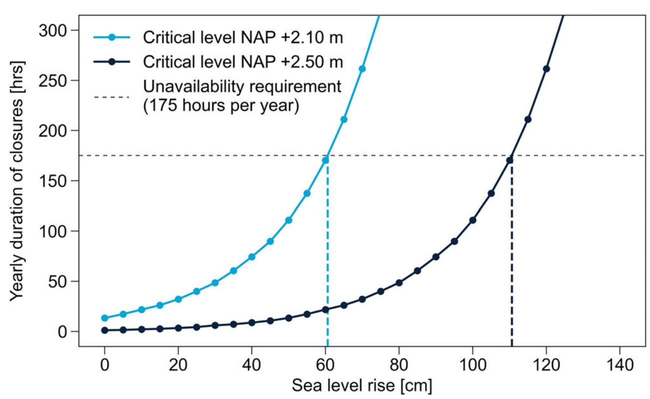

Figure 6. Annual unavailability of the waterway as a function of SLR. Water level NAP +2.10 m corresponds to the situation in which vessels have to resort to the navigation lock next to the storm surge barrier to pass the barrier complex. At a water level of NAP +2.50 m, the navigation lock also becomes inaccessible to vessels.

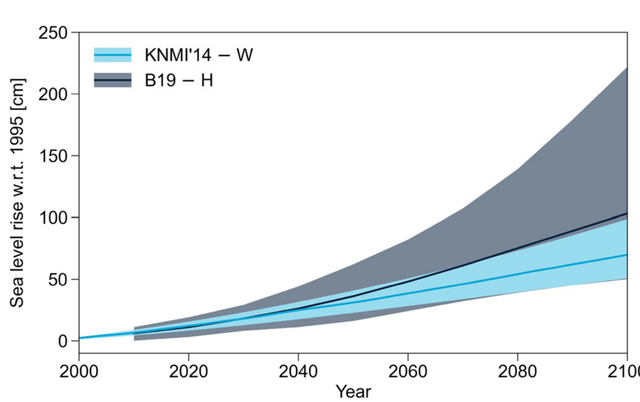

Figure 7. Projections of SLR along the Dutch coast for the W scenario of KNMI'14 and the H scenario of Bamber et al. (2019). Lines represent the median values, and the bandwidth depicts the 5th–95th percentile range of the projections.

4.5. Resulting estimates of the remaining life

The 90% probability ranges (horizontal bars) and median values (circles) of the remaining life estimates of the Hollandsche IJssel barrier are shown in Figures 9 and 10 for the two considered SLR projections. The resulting estimates for the different criteria are indicated by means of solid, dashed and dash-dotted lines. The figures show that the storm surge barrier's remaining life is shortest for the assessment level NAP +2.90 m and a non-closure probability of 1/2000 per closure. Based on the median values, the end of life of the storm surge barrier may be reached in the 2040s in case this assessment level and non-closure probability are used for the evaluation of the flood protection function. Around the same time, the number of closures will exceed the most stringent requirement of nine closures a year for the navigation function. The unavailability of the

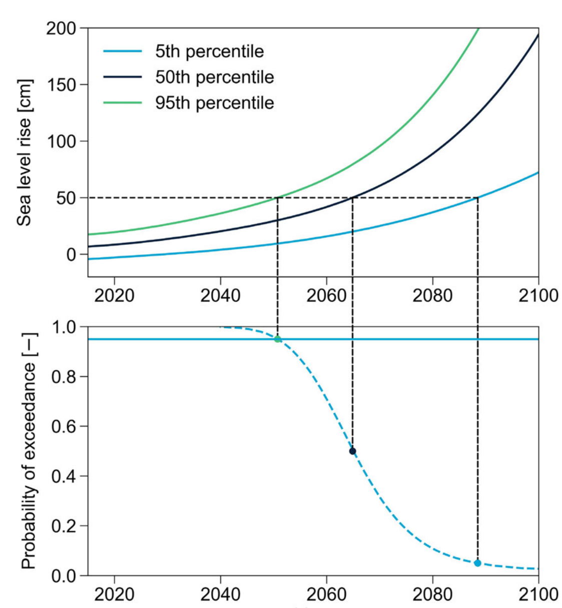

Figure 8. Depiction of the approach to derive the probability distribution of the remaining life of the storm surge barrier from an arbitrary SLR projection.

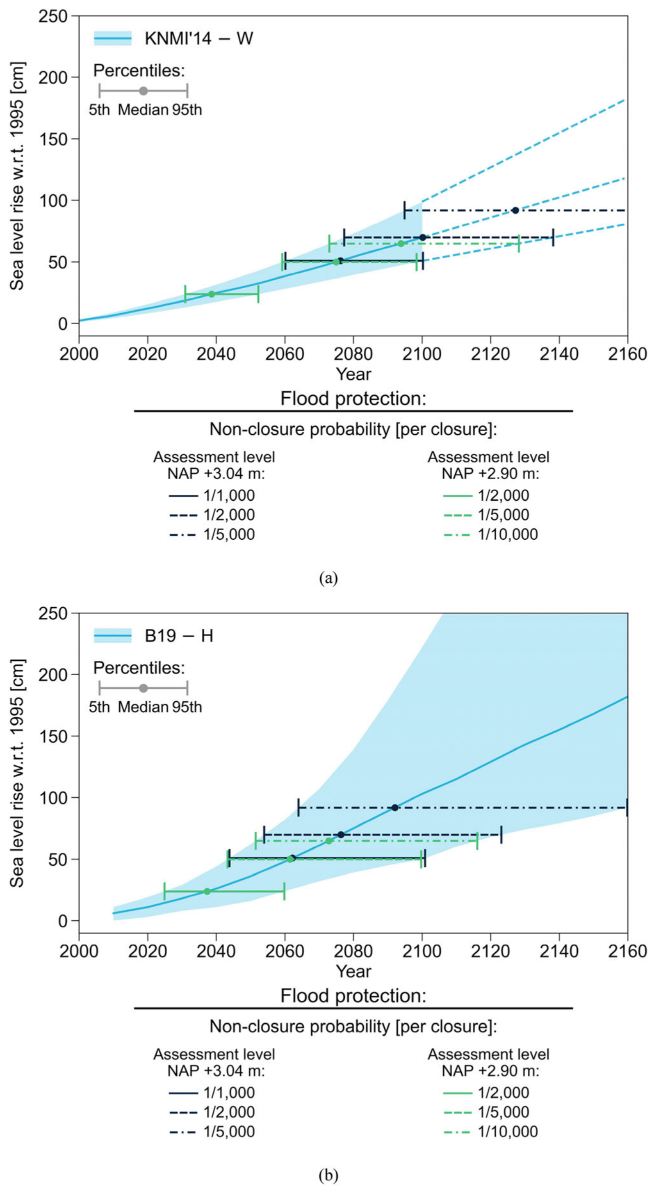

Figure 9. Estimates of the end of life of the Hollandsche IJssel barrier with respect to flood protection for: (a) the W scenario of KNMI'14 and (b) the H scenario of Bamber et al. (2019). The end-of-life estimates for the various requirements are indicated by solid, dashed, and dash-dotted lines.

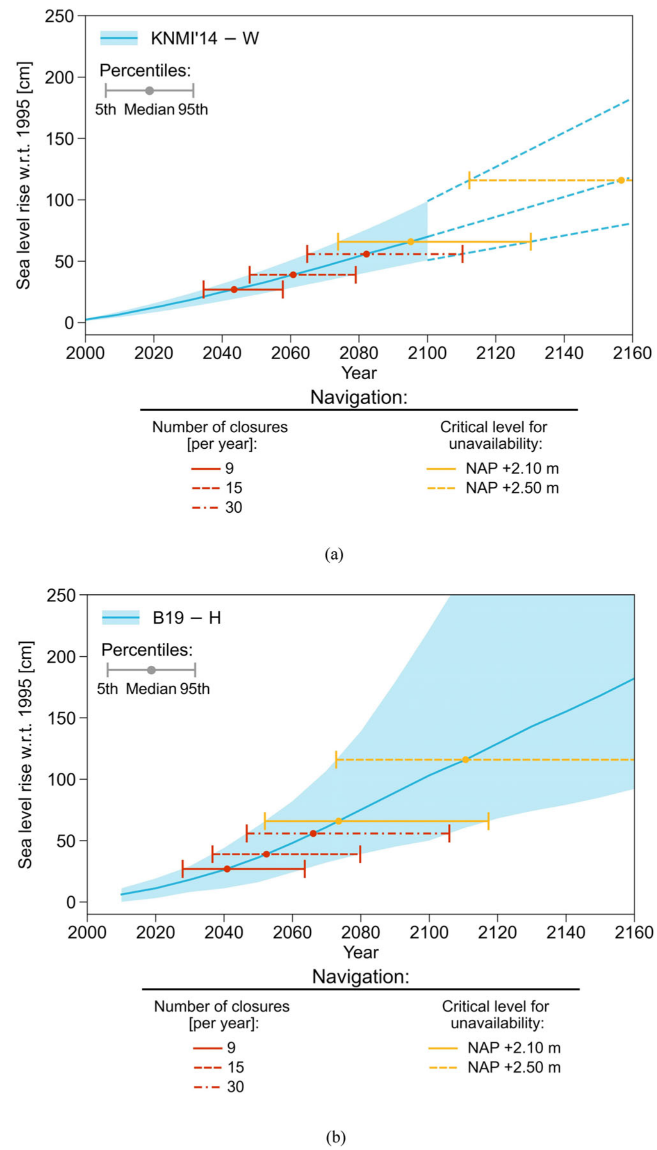

Figure 10. Estimates of the end of life of the Hollandsche IJssel barrier with respect to navigation for: (a) the W scenario of KNMI'14 and (b) the H scenario of Bamber et al. (2019). The end-of-life estimates for the various requirements are indicated by solid, dashed, and dash-dotted lines.

waterway is the least critical aspect since the unavailability requirement only starts to be exceeded in the second half of the 21st century.

The large uncertainty in the end-of-life estimates of the storm surge barrier in Figures 9 and 10 is related to the uncertainty in the SLR projections. This is especially the case for the estimates for the SLR projection based on Bamber et al. (2019). In the most extreme cases, the 90% probability range of the estimates can span more than 100 years. This large range is mostly the result of the extreme upper bound values (95th percentile), which are less relevant because they correspond to situations with low probability and minor consequences. The lower bound values and median values are more meaningful from a risk management perspective as they provide information about the probability of having a remaining life shorter than anticipated.

By including the estimates for less stringent requirements for the functional performance, the figures also give an idea of how the estimated remaining life of the Hollandsche IJssel barrier could be extended. For instance, reducing the non-closure probability of the storm surge barrier will reduce the failure probability, i.e. exceedance of the assessment water level, and thus extend the remaining life with respect to flood protection. For navigation, accepting more closures per year could potentially be an effective measure to extend the lifespan. The results suggest that reducing the non-closure probability and increasing the acceptable number of closures by a factor two could lead to extensions in the order of 10–20 years.

4.6. Implications of the case study results

The results of this case study provide relevant information for infrastructure replacement and renovation programmes, but also SLR adaptation programmes that are, amongst others, concerned with the tenability and resilience of existing infrastructure assets. The results indicate that the probability that the Hollandsche IJssel barrier will reach its end of life in the 2040s is substantial, provided that the non-closure probability of the barrier cannot be reduced and more hindrance to shipping cannot be accepted. This would mean that replacement or renovation would be required earlier than the anticipated timeframe of 2050–2100 that is mentioned in the Delta Programme for the region of the Hollandsche IJssel. In the Delta Programme, it is stated that the non-closure probability is planned to be reduced from 1/200 to 1/1000 by 2030.

However, greater reductions may be required to maintain the current storm surge barrier for a longer period. According to the results of this study, a probability of 1/2000 or even 1/10,000 may be required. Besides flood protection, the navigation function could also play an important role in shortening the lifespan of the storm surge barrier. Alternatives to the storm surge barrier may have to be implemented, or at least explored, earlier than anticipated if the closure level of the barrier cannot be raised or more hindrance to shipping is considered unacceptable. The results indicate that the most stringent criteria for the navigation function could be exceeded within about 20 years (median value).

5. Discussion

Given the myriad of uncertainties surrounding the lifespan of storm surge barriers, it is key to develop a systematic approach for assessing the impacts of external drivers on their remaining life and identify the dominant drivers. Research on assessing the remaining life of storm surge barriers is underrepresented. The current research adds to the body of knowledge by introducing a framework which supports the complex assessment and quantification of external drivers that affect the remaining life of storm surge barriers in a systematic way. The approach allows one to identify the most important external drivers affecting the functional performance or deterioration of components, making a subsequent quantitative estimation of the remaining life of storm surge barriers more manageable. The current research also adds a systematic approach to assess the remaining life for the functions flood protection and navigation under probabilistic SLR projections.

The proposed framework is generally applicable to storm surge barriers. However, the dominance of the drivers that affect the remaining life should be investigated for each barrier. The case presented in this research primarily dealt with the effects of SLR on the functions flood protection and navigation. The remaining lives of storm surge barriers in general are also expected to be sensitive to SLR. As such, the approach to the quantification of the remaining life is transferable to other storm surge barriers, but this does not exclude the investigation of other drivers. For the Maeslant barrier, for example, high river discharges for a sustained period of time may become an issue since the structure is not built to withstand large negative water level differences, i.e. low outer water level and high water levels in the basin.

Despite the large flexibility in the use of the framework, there are several important conditions to be met for an effective and useful application of the framework. First, a lack of assessment criteria or service level requirements to evaluate the impact of drivers, such as SLR, on the storm surge barrier's performance and its remaining life. In the case presented in this study, it was found that, especially for functional aspects, performance requirements are lacking. For instance, limits to the hindrance to shipping or disruption of the tidal regime have not been defined. To enhance the usefulness of this kind of analyses, well-defined requirements or limiting criteria are required. Second, scenarios describing the external drivers and their development over time are a key element of the evaluation stage of the framework. Climate change scenarios to assess the impact of physical drivers are generally available, but socio-economic scenarios or policy-related scenarios are often missing. These types of scenarios should be developed if one wishes to draw more solid conclusions regarding the effects of societal developments on the lifespan of storm surge barriers.

6. Conclusions

In conclusion, the results of this case study show that functional aspects are governing for the remaining life of the Hollandsche IJssel barrier and that SLR is the main (physical) driver potentially leading to a reduction of the functional life. Even in moderate SLR scenarios, the end of life could be reached within 20 years due to a reduced performance in terms of flood protection and navigation. However, earlier than anticipated replacement of the barrier is not entirely inevitable. By improving the closure reliability and accepting more hindrance to shipping (by more frequent closures), the functional life of the storm surge barrier could be extended by up to several decades.

The findings suggest that it is worthwhile to intensify research on especially the functional life of storm surge barriers. In addition, limiting criteria and requirements for the functional performance, e.g. criteria or requirements related to shipping or ecology, should be established to better evaluate the performance and thereby remaining life of storm surge barriers. Further application and testing of the approach would be beneficial in that respect, but also help in producing improvements to the framework. One such improvement could be, for instance, the development of a standard list of external drivers that should at least be considered in the analysis of the remaining life of storm surge barriers. In this way, the possibility of overlooking important effects can be reduced. A similar philosophy lies behind the requirement of considering at least several standard failure mechanisms in the Dutch 'WBI' (Safety Assessment Tool for the primary water defences).

Disclosure statement

No potential conflict of interest was reported by the authors.

Note

1. Hydra-NL is an open-source model that is frequently applied to derive hydraulic boundary conditions, including extreme water levels, for flood defences in the Netherlands (Ministerie van Infrastructuur en Milieu, 2016).

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