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Assessing the functional end of life of critical hydraulic structures in The Netherlands

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ABSTRACT: Next decades, many hydraulic structures in the Netherlands will reach their end of life. Timely mitigation requires accurate estimates of the end of life. This appears however hard since many external drivers and multiple functions may lead in many plausible combinations to insufficient technical or functional performance. As a consequence, a complete integrated assessment is rather labour intensive and time consuming. This study shows a quick-scan of the end of life of five storm surge barriers and three other critical hydraulic structures in the Netherlands. The quick-scan reveals that sea-level rise is the major driver for the end of life of most coastal hydraulic structures since it impacts both the free discharge capacity and the flood protection function. Yet, the strategy to adapt the river delta to climate change may be even more important. Future developments are however such uncertain that the life time assessments may prove especially useful for the exploration of adaptive asset management strategies and to a lesser extent as an accurate planning tool.

1 INTRODUCTION

The Netherlands are currently preparing for a major replacement and renovation of large parts of their aging infrastructure as many objects are approaching their technical or economic end of life.

The planning and management of this massive replacement task ideally builds on accurate estimates of the end-of-life. For hydraulic structures, the decision to replace may also be triggered by changes in requirements or loadings as a result of socio-economic developments and/or climate change (Klatter et al. 2019, Breedeveld & Kramer 2019). In those cases, it is the (perceived) insufficient functional performance that determines the end of life.

Critical hydraulic structures typically bear multiple functions such as protecting against flooding, facilitating navigation and enabling the discharge of rivers and precipitation. The performance of these functions might be affected by divergent external drivers. End of life assessments therefore require a systematic approach that ensures that all pathways that might lead to the end of life are assessed (Vader et al. in press, Van Baaren et al. 2019).

Recently, Vader et al. (in press) proposed a four step 'top-down' approach for the systematic assessment of the end of life of storm surge barriers in order to identify the dominant pathways. First, clear and unambiguous definitions of the different life span concepts (technical, economical

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and functional) should be set to avoid confusion in the subsequent steps. Second, a functional analysis and physical decomposition are performed. Third, the relevant external drivers and their impacts on the technical state and the different functions are listed. And fourth, the most important external drivers and pathways that may lead to the end of life are identified.

The usefulness of the framework is convincingly demonstrated by means of a case study with the oldest storm surge barrier in the Netherlands, the Hollandsche IJssel barrier (HIJK). Yet, the framework is rather labour intensive and a full assessment of all Dutch storm surge barriers and other critical hydraulic structures may require considerable time. Therefore, this paper presents a quick-scan in order to explore to what extent end of life assessments of different hydraulic structures reveal common pathways to the end of life that deserve more attention. The quick-scan assesses the end of life of five storm surge barriers, a discharge sluice, a flood gate and a pumping station by loosely applying the framework of Vader et al. (in press).

2 METHOD

In this study we adopt the same life time concepts as defined by Vader et al. (in press).

- The technical life is 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.
- The functional life is 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.
- The economic life is the time period over which the costs of owning and operating an asset are still lower than the costs of equivalent alternatives.

Since this quick-scan mainly focusses on the functional end of life, the system analysis is restricted to a functional analysis (see section 3). Furthermore, explicit performance requirements are not determined as the purpose of this assessment is only to identify the most threatened functions and the major drivers that may cause insufficient functional performance. Instead, it is assumed that the structures more or less comply with the current requirements and can be adjusted for small changes in requirements or loads.

The analyzed physical drivers are based on Vader et al. (in press) complemented by a recent, first interpretation of the Sixth Assessment Report of the IPCC (2021) for the Netherlands by the Royal Netherlands Meteorological Institute (KNMI, 2021). For the socio-economic developments this study uses the four principle adaptation strategies to sea-level rise as recently presented by the Dutch Delta Program (Van Alphen 2022, Haasnoot & Diermanse 2022).

3 SYSTEM ANALYSIS OF HYDRAULIC STRUCTURES

In this study we assess the end of life of five storm surge barriers, one major discharge sluice, a flood gate and a pumping station (Table 1 and Figure 1). Storm surge barriers are partly movable barriers that only close at extreme storm surges to keep the water levels behind within acceptable/safe limits and such to protect the hinterland against flooding (Mooyaart & Jonkman, 2017). The Netherlands count five storm surge barriers that were constructed between 1954 and 2002. The Hollandsche IJssel barrier (HIJK), the Eastern Scheldt barrier (OSK), Maeslant barrier (MK) and the Hartel barrier (HK) protect the southwestern delta against extreme storm surges from the North sea and the Ramspol barrier (RK) protects an area in the eastern part of the Netherlands against surges from Lake IJssel.

The Haringvliet sluices (HV) also play an important role in the flood protection of the Southwestern delta. At low tide, they enable the free discharge of the Rhine and Meuse rivers into the North Sea, while they prevent the water of the North Sea to flow back during high tide.

Floodgate Ravenswaaij (FGR), is a 80m wide vertical lift gate in between the Lek (one of the Rhine branches in the Netherlands) and a reach of the Amsterdam-Rijn Canal. Like storm

Table 1. Main characteristics of the assessed hydraulic structures.

Structure name (abbreviation)	Type	Gate/pump type	Design life
Hollandsche IJssel barrier (HIJK)	Storm surge barrier	Double lift gate (80m)	1958-2058
Haringvliet sluices (HV)	Discharge sluices	17 Tainter gates (56.5m)	1971-2071
Eastern Scheldt barrier (OSK)	Storm surge barrier	62 lift gates (42m)	1986-2136
Maeslant barrier (MK)	Storm surge barrier	2 floating sector gates (360m)	1997-2097
Hartel barrier (HK	Storm surge barrier	2 lift gates (98m, 48m)	1997-2097
Ramspol barrier (RK)	Storm surge barrier	3 inflatable rubber gates (80m)	2002-
Floodgate Ravenswaaij (FGR)	Flood gate	Lift gate (80m)	1978-2078
Pump-weir complex IJmuiden (PWIJ)	Pump	4 Stork pumps (40m3/s)	1975-2025
		2 Nijhuis pumps (50m3/s)	2004-2054
	Weir	7 movable weirs	2040-

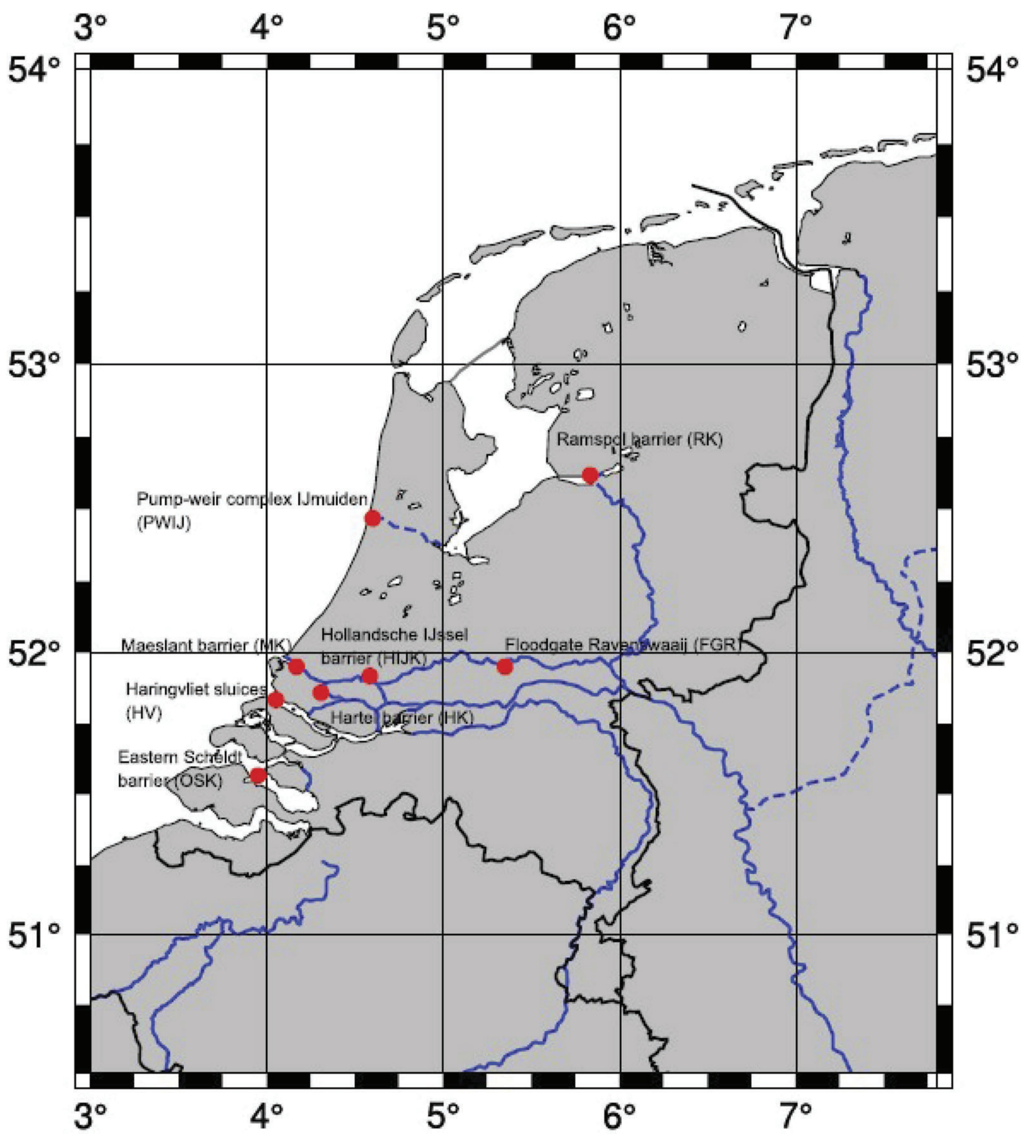

Figure 1. Overview of the assessed hydraulic structures.

surge barriers, the floodgate is open under normal conditions and only closes in case of extreme river water levels to protect the hinterland from flooding.

The main function of Pump-weir complex IJmuiden (PWIJ) is to manage the water level and quality in the North Sea Canal and Amsterdam-Rijn Canal. The complex separates the canal system from the North Sea, discharges precipitation and excessive water from the surrounding polders and regulates the salt intrusion.

Besides the water management functions, the assessed structures all bear several other functions (Table 2). Navigation is facilitated at or near all structures. The Hollandsche IJssel barrier, Floodgate Ravenswaaij and the Hartel barrier allow free passage under normal conditions and by means of adjacent navigation locks when closed. The Maeslant barrer and the Ramspol barrier only allow free passage of ships under normal condition and at Pumping-weir complex IJmuiden, the Haringvliet sluices and the Eastern Scheldt barrier ships can only pass through nearby navigation locks. Furthermore, the structures have ecological, monumental/iconic and road functions.

Table 2. Main functions of assessed hydraulic structures.

Function*	HIJK	FGR	HV	GSIJ	OSK	MK	HK	RK
Retain extreme water levels	x	x	x		x	x	x	x
Facilitate navigation	x	x				x	x	x
Provide discharge capacity for polders	x	x	x	x				x
Allow (natural) river discharge			x					x
Provide fresh water	x							
Prevent salt intrusion	x		x	x				
Allow tidal flow	x		x		x			
Provide corridor for fish migration			x		x			x
Provide road connection	x	x	x		x			
Provide iconic/monumental value	x		x		x	x		

* Functions of adjacent and nearby navigation locks are not taken into account

4 FIRST ORDER EFFECTS PHYSICAL DRIVERS

Analysis of the identified functions leads to the same short-list of potentially relevant physical drivers (Table 3.) as found by Vader et al. (in press). This seems logical as the assessed structures are located in nearby and comparable areas and together only serve two additional functions with respect to the Hollandsche IJssel barrier (allow natural river discharge and provide corridor for fish migration).

Careful analysis reveals that sea level rise is *the* dominant driver for changes in the functional performance of the assessed hydraulic structures. Sea level rise will directly increase the exceedance probability of critical levels. It is estimated that a rise of 50-75 cm will increase the exceedance probabilities roughly with a factor 10 and a rise of 100-150 cm with a factor 100 (e.g. Haasnoot et al. 2020). Without adaptation, this has a direct impact on the required reliability (operational, structural and height) and on the number of closures (and consequently on the hindrance for navigation).

Moreover, sea level rise will substantially decrease the capacity and time window for free discharge because the levels at low tide will also rise. For pumping-weir complex IJmuiden it is for instance estimated that 30 cm sea level rise might reduce the free discharge capacity by 90%, which needs to be compensated by sufficient pumping capacity (Van Gijzen & Bakker 2023). For the Haringvliet sluices it will be way more challenging to replace the free discharge capacity by pumps as it needs to discharge the rivers Rhine and Meuse.

Next to sea level rise, precipitation and drought deserve some attention. Precipitation extremes are expected to increase substantially, but this especially concerns local, relatively

Table 3. Identified potentially physical drivers.

Driver	General consequence
Temperature	Extreme temperatures can temporarily reduce the operational reliability. The impact on the hydraulic performance is considered minor since extreme temperatures do typically not occur in stormy conditons.
Precipitation	Increased precipitation extremes may result in higher pump volumes from polders.
Land subsidence	Lowering of the crest height of dikes. Foreseen subsidence is however small compared to projected sea level rise.
Sea level rise	Increase in exceedance probability of critical water levels. Higher number of storm closures. Decrease in free discharge capacity.
High river discharges	Higher volumes to be discharged
Low river discharges	Reduction of (navigation) depth and fresh water availability
	Salt intrusion
Drought	Dike instability
	Increase in fresh water demand
CO_2 concentration	no impact on requirements, use or loads
Wind	minor changes in wind regime expected (KNMI 2021)

short term precipitation (KNMI 2021). Increases in larger scale, multi-day events that are more determinant for the necessary discharge capacity will be more moderate. Also more frequent droughts may urge for substantial system adaptations and potentially increase the importance of the fresh water retention function of the Haringvliet sluices and the Pump-weir complex IJmuiden. However, the direct impacts of sea level rise on the functional performance may be several orders of magnitude and will dwarf the potential effects of the other physical drivers.

5 EFFECTS OF SYSTEM ADAPTATION TO CLIMATE CHANGE

Next to physical drivers, socio-economic developments can seriously affect the functional performance of a hydraulic structure. In the decades to come, the functional performance is likely to be dominated by the chosen strategy to adapt to sea level rise.

Recently, the Dutch Delta Program presented four principal adaptive strategies to (accelerated) sea level rise (Van Alphen 2022, Haasnoot & Diermanse 2022). The first strategy 'Protect-open' basically is a continuation of the current policy. First and second line flood defenses will be strengthened in line with the changing hydraulic loads while maintaining an open connection with the sea. The second strategy 'Protect-closed' focusses on the strengthening of the first line of defense and will close the connection with the sea to prevent higher levels and salinization of the inland water bodies. This strategy will however require enormous pump capacity to drain the rivers Rhine and Meuse (see also section 4). The third strategy 'Advance' advocates to extend the present coastline seawards to be able to build more robust flood defenses and create new land and water storage. The fourth strategy 'Accommodate' proposes to accept changes and prepare for the 'living with water' concept and/or retreat.

The studies argue that the current policy 'Protect-open' may be continued up to 1m sea level rise, maybe 2m if the closure levels of the storm surge barriers are heightened. This may, however, require substantial adaptation or even replacement of the current storm surge barriers. For instance, the Maeslant barrier was originally designed for only 25cm sea level rise during its entire design life time and the Maeslant barrier is currently already struggling to meet the strict requirements for the operational reliability and the gradually shrinking time window for maintenance.

In 2014, a group of six experienced Dutch engineers led by Frank Spaargaren proposed to replace the Maeslant barrier by a closed dam with navigation locks, watering sluices and a pumping station in order to anticipate the sea level rise induced challenges (e.g. Dokter et al. 2016). This potential first step towards 'Protect-closed' would imply the end of life of the Maeslant barrier, but also substantially impact the remaining life of other hydraulic structures. The Hollandsche IJssel barrier, for instance, is located behind the Maeslant barrier. The replacement of the Maeslant barrier by a closed dam would significantly reduce the impact of sea level rise which could imply the elongation of the functional life. Yet, severe reduction of the extreme water levels could also nullify the flood protection function which would imply the economic end of life. On the other hand, heightening of the target water levels in the southwestern Delta in order to longer benefit from free discharge would immediately increase the functional relevance of the Hollandsche IJssel barrier again.

In contrast to a closed dam, the sea level rise induced challenges of the Maeslant barrier could also be tackled by 'Advancing'. A recent study of Mooyaart et al. (in review) suggests that a second sea ward storm surge barrier could be cost effective at sea level rise beyond 0.45m. This second, redundant barrier would actually elongate rather than end the remaining life of the Maeslant barrier.

It is clear, that every step in the system adaptation can have enormous impact on the remaining functional and economic life of hydraulic structures. It is however impossible to predict which adaptation step will be implemented first as this is a political decision. This means that accurate functional end of life estimates are actually impossible for more than several decades ahead.

6 CONCLUSIONS

The quick-scan presented in this paper suggests that sea-level rise is *the* determinant factor for the functional end of life of coastal hydraulic structures. It is not expected that a more thorough assessment will identify other physical drivers as the potential effect of sea level rise can be several orders of magnitude larger.

The large uncertainties in future sea-level rise projections also make the functional end of life estimates intrinsically uncertain. Maybe more important are the uncertainties in the exact adaptation pathway to sea level rise (and maybe drought). Many plausible adaptation options exist. Yet, which adaptation option is implemented when is a political choice and the impact on the functional and economic end of life really depends on the implementation details.

Accurate estimates of the functional end of life for more than several decades ahead are not possible under rapidly, but uncertain changing circumstances. Nevertheless, functional end of life assessments may prove very useful for the exploration of detailed adaptation pathways.

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