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Determining the future functional requirements of a pumping-weir station with the help of data-analysis

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ABSTRACT: The pumping-weir complex at IJmuiden plays an important role in the drainage of excess water in the Western Netherlands. Multiple pumps need replacing as 4 out of 6 pumps near their end-of-life term. The optimal replacement strategy critically hinges on the future required pumping capacity. Yet, currently available models are not suited to assess the effect of sea level rise or extremer precipitation events as they ignore certain complexities of the water system. Preliminary data analysis in this paper showed the sensitivities of the system. The required pumping capacity is sensitive to the ability of free discharging during extreme water events. Yet, it is less susceptible to extremer precipitation events. Further research will aim at including more of the water system's complexity in the model. Due to the node-like structure and high availability of data, a neural network modelling approach will probably be suitable.

1 INTRODUCTION

The pumping-weir complex located at IJmuiden functions as a separator between the complex water system of the Amsterdam Rhine Channel - North Sea Channel and the North Sea. Most pumping stations are found in sewage systems or in prevention against urban floods due to heavy rainfall. Yet, not often are they found at the end of a channel system with over 200 access points such as weirs, sluices and local pumps.

The water system situated in the Western Netherlands has been the result of efforts over the last centuries to protect the land from the sea and facilitate navigation at the same time. The result is a channel from the Rhine, via Amsterdam to IJmuiden (North Sea), into which the surrounding low-lying polders excess water (Figure 1). The channel from Amsterdam to IJmuiden was officially opened in 1876, with locks separating the channel from the North Sea. In 1940 the weirs were constructed, through which excess water was discharged and they are still part of the complex today. By 1975 four pumps were added to the complex, to be able to closer regulate the channel's water level and to be able to discharge the water to the North Sea during high tide. Two extra pumps were added in 2004 to increase the discharge capacity. By now, the 4 oldest pumps in the complex are nearing their technical end-of-lifetime and need to be replaced.

The new pumps will need to meet their functional requirements for at least 30 years into the future. Therefore the predicted sea level rise along the Dutch coast plays an important role in determining those future functional requirements. For as the sea level rises, the window for regular discharging through the weirs will get shortened and more volumes will need to be disposed of by means of pumping

Additionally, the extreme rainfall events are expected to get more intense (KNMI, 2014). In terms of precipitation a distinction can be made between the area precipitation and peak rainfall. The area precipitation is expected to increase by 2.5-5.5 % depending on the scenario, which will lead to a similar increase of volumes that will need to be pumped out of the ARC-NSC system. Earlier research has concluded that the current pump capacity will suffice to process this increase

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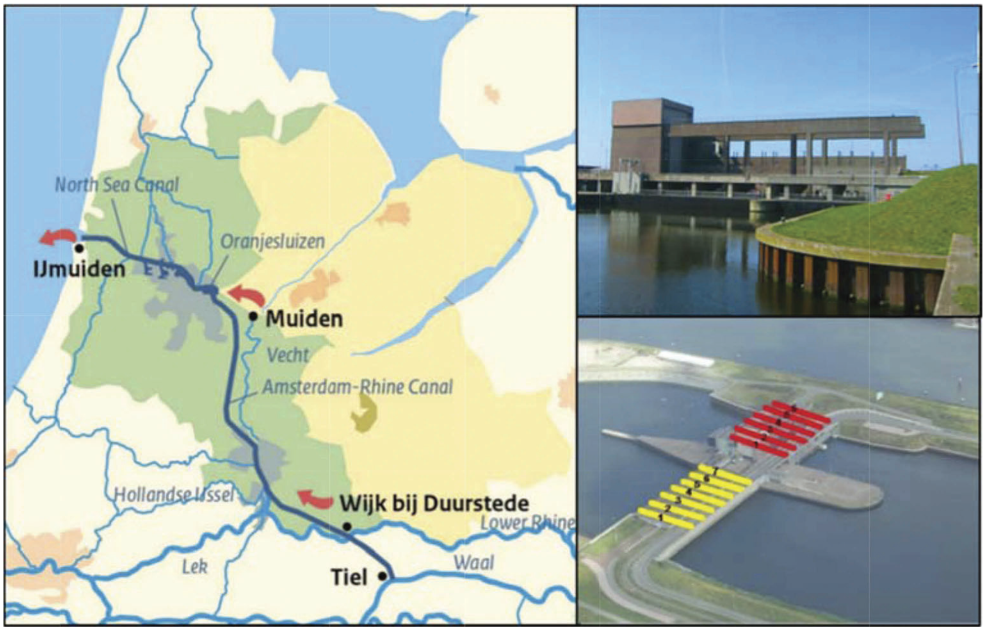

Figure 1. Left) System overview of the NSC-ARC (in dark blue). The catchment area is pictured in green (direct) and yellow (indirect), adapted from (Rijkswaterstaat, 2019). Top right) Pumping-weir complex at IJmuiden (NGS, 2022). Bottom right) Location of the 6 pumps (red) and 7 weirs (yellow).

as the volumes are averaged out over time (van Veen, 2022). Yet, an increase in extreme peak rainfall events might require extra pump capacity in the future. Therefore new functional requirements need to be determined for the pumps. Due to the complex nature of the system, the more traditional methods of designing a pumping station are likely not feasible in this case.

The most important questions for the pump set-up are: How much pump capacity will be required, how often will it be required and with what reliability during its proposed lifetime? These questions are difficult to answer at this moment, as the current available models are not suitable to estimate the required future capacity. A long sequence of historical operational data of the pumps is available at Rijkswaterstaat. Presumably, a lot can be learned from the historical data, which can help estimating the future requirements of the pumps.

This paper shows that historical data analysis can indeed provide various useful insights, which helps estimating the future required pump capacity. Additionally, the sensitivities of the system can be identified based on the conducted data analysis. Following this new information, new methods will be suggested to improve the estimation of the required pump capacity for the pump-weir complex in future studies.

Due to the difficult acquisition of data, the outcomes in this paper are preliminary results. Therefore, the goal of this paper is not to provide precise and direct answers on the required pump capacity and reliability. It is the goal to showcase the complexity of the system, show the sensitivities and propose subsequent steps that can be taken to determine the required capacity.

2 SYSTEM OVERVIEW

The water system North Sea Channel - Amsterdam Rhine Channel (NSC-ARC) fulfils an important role in navigation and draining the surrounding low-lying areas of excess water, thereby it prevents flooding events in the Western Netherlands. The water level in the system is highly regulated as all incoming water sources except for precipitation are regulated by pumping stations, sluices or weirs. The system provides drainage of an area of approximately

2300 km^2 (Rijkswaterstaat, 2020), which includes highly developed regions surrounding Amsterdam and Utrecht (Figure 1). The target water level is NAP[1] -0.40 m for the entire channel system, but the margins for variations are small. An increase of 10 cm can lead to importunity in the low-lying surrounding polders, a decrease of 10 cm can harm navigation by going below the required navigation depth. The 'alarm' water level of NAP -0.30 m was only exceeded for 10 days in the last 10 years and the water level of NAP -0.20 m was never reached . Numerous smaller pumping stations excess water into the water system, with a maximum combined discharge of 360 m^3/s. Yet, the largest and most important pumping station is located at IJmuiden, which discharges all water to the North Sea.

The North Sea Channel - Amsterdam Rhine Channel guides the excess water of the surrounding regions (Figure 1) towards IJmuiden like a funnel, where the largest portion of water exits the system through the pumping-weir complex to the North Sea. The pumping station has 3 main functions: 1) Regulating the daily water level (max NAP -0.30/min NAP -0.55), 2) Prevention of extreme water levels, 3) Salt/freshwater regulation.

The pumping station at IJmuiden consists of 6 pumps and 7 weirs with each different discharge capacities (Table 1). At this moment about 50\% of the water is discharged through the weirs and 50\% is pumped out of the system (Vermeulen et al., 2021). Discharging through weirs is always preferred as this requires no energy, except for lowering the weir doors. The pumps 1-4 were constructed in 1975 and need replacement in the near future.

Table 1. Characteristics of the pumps and weirs.

	capacity	unit	operational head	unit	quantity	since
Pumps 1-4	40	m^3/s	0 – 2.3	m	4	1975
Pumps 5-6	50	m^3/s	-0.2 – 2.7	m	2	2004
Weirs	72	m^3/s	-0.12 and lower	m	7	1940
Total pumps	260	m^3/s				
Total weirs*	500	m^3/s				

* The preferred flow rate under normal circumstances is 300 m^3/s. Under extreme circumstances 700 m^3/s is possible but undesirable.
** Head difference between sea and channel when the pumps can operate.

3 DATA COLLECTION & METHOD

3.1 *Data collection*

Operational pump data of the time period 1984-2018 was obtained from Rijkswaterstaat where the data quality is internally assessed. The following variables are entered manually: date, start time of operation [HH:MM], end time of operation [HH:MM], discharged volume [m^3] and the number of activated pumps. The discharge of the pumps is determined based on measurements with pressure sensors, but their accuracy is uncertain as additional information could not be obtained at this point in time.

To analyse the relation between pumped volumes and the historical data of surrounding stations was obtained from the KNMI (Royal Dutch Meteorological Institute) (KNMI, 2022a). The data is collected at the so called precipitation stations where the daily sum of precipitation is measured. It concerns the precipitation from 08:00 UTC on the previous day to 08:00 UTC at the mentioned date. The quality of that data is guaranteed by the internal control service of the KNMI. There is no data available on the freely-discharged volumes via the weirs for the 1984-2018 period. Data will likely be obtained in a later stage, when it will be incorporated in the analysis.

[1] NAP = Dutch Ordnance Datum, which approximately corresponds to mean sea level

3.2 *Analysing the outgoing discharge volumes during extreme events*

First, a trend-analysis was conducted by analysing the annual daily maxima and averages. After that, the general characteristics of the usage of the pump will be determined. To assess the required outgoing discharge capacity, a simple water balance is assumed (Figure 2).

In section 4 the return period of daily pumped volumes during extreme events will be determined based on historical data. The current free-discharged volume (Q_{weirs}) is assumed to be equal to the pumped volume (Q_{pumps}) (Vermeulen et al., 2021).

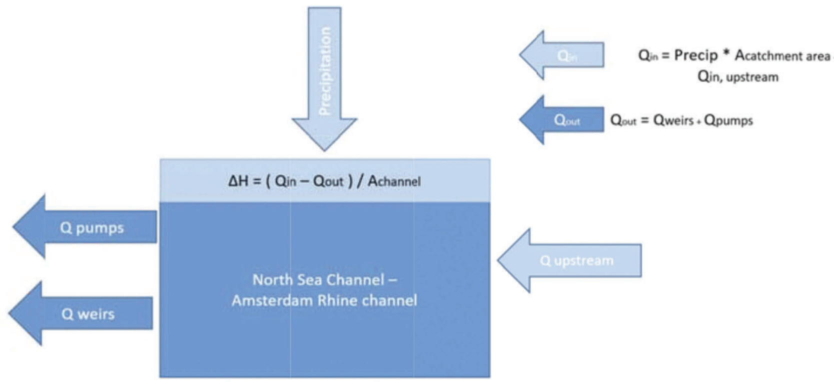

Figure 2. Conceptual scheme of the simplified water balance of the water system.

3.3 *Assessment of the future requirements*

The future Q_{in} is assumed to increase as the precipitation increases. Additionally, the distribution between Q_{weirs} and Q_{pumps} will likely change as the window for free-discharging is reduced due to sea level rise. Therefore, the required Q_{pumps} would increase with sea level rise. An estimation of the required pump capacity during future extreme events is made by adding the lost capacity of Q_{weirs} to the required Q_{pumps}. Possible future rainfall sequences were generated with the KNMI Transformator (Bakker, 2015) to assess the effect of more extreme rainfall events on the required Q_{pumps}. The newly calculated return periods will provide an indication if the more extreme rainfall events requires more pump capacity.

4 ANALYSIS OF HISTORICAL DATA

Historical pump data is available from1984, which allows for analysing long-term trends. Both the annual average daily volume per year and the annual maximum daily volume were calculated and have been depicted in Figure 3. The daily maximum shows a clear jump since 2004, which coincides with the installation of 2 extra pumps. Therefore the historical sequence will be divided in two different periods for further analysis: 1984-2003 when 4 pumps were available and 2004-2018 when 6 pumps were available.

The pumps have been activated about +/- 30 \% of the time since 1991. Figure 3 shows that most of the time only 1 or 2 pumps are activated, so the pumps are mainly used to regulate the daily variations to maintain the target water level of NAP -0.40 m. The older pumps are operated at full capacity (40 m^3/s), but a varying discharge amount can be used at the 2 newer pumps (max. 50 m^3/s). If 5-6 pumps are activated, it can indicate that the pumps are used to prevent extreme water levels in the channel, with a maximum capacity of 260 m^3/s. This is the case for 3.8 \% of the time. However, the 'alarm' water level of NAP -0.30 m was only exceeded for 10 days in the last 10 years and the critical water level of NAP -0.20 m was never reached. Insufficient data is available to identify so called pump-stops due to high tide, while it was required due to high water levels in the channel.

The return periods of daily pumped volumes during extreme events are shown in Figure 4 do not include Q_{weirs}. Different analyses were conducted for a 1-day sum, multi-day sum, weekly sum and a monthly sum. In all sub-plots the pumped volumes seems to approach its maximum asymptotically as the return period increases, which can be explained by the finite

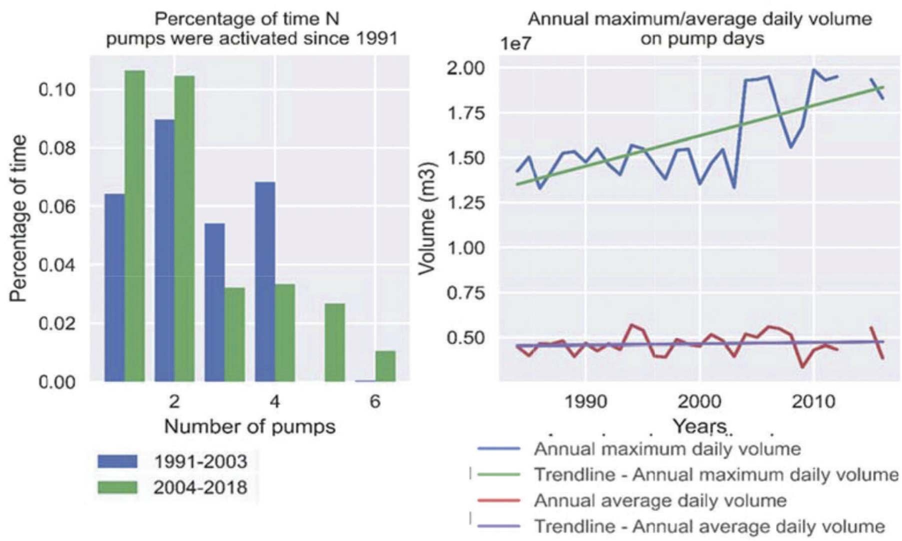

Figure 3. Left) An overview of the usage of the pumps. A distinction is made between the time periods 1991-2003 and 2004-2018. Right) The daily maximum pumped volume each year in blue and the yearly averaged daily pumped volume. The data from 2013, 2014, 2017 and 2018 was excluded from the analysis due to large gaps in the data sequence.

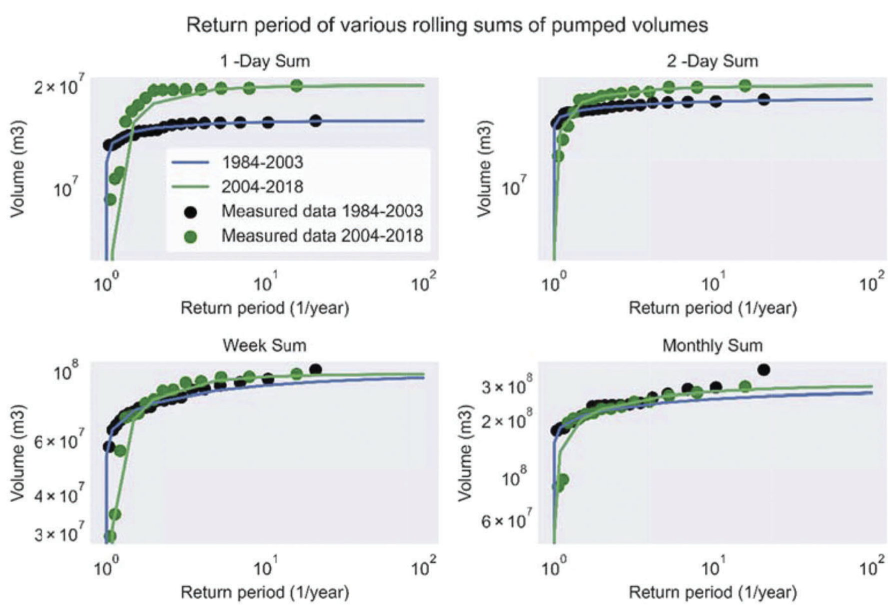

Figure 4. Depiction of the return period of the daily pumped volumes (Q_{pumps}). The total sequence was divided into the period of 1984-2003 when there were two pumps in the complex and 2004-2018 when two extra pumps were added. These volumes do not include Q_{weirs}.

capacity of the pumps. Higher extremes are found in the 1-day sum. Yet, the 2-day sum subplot shows a reduced difference between the extremes. This indicates that not all 6 pumps were required during 2 consecutive days. This difference decreases even further when the weekly sum and the monthly sum are concerned.

5 FUTURE EXPECTATIONS

5.1 *Reduction of free-discharge as a result of sea level rise*

For the ARC-NSC system we are interested in the absolute sea level rise, as a fixed target water level is maintained and the surrounding dikes can be heightened (Vermeulen et al., 2021). In this paper the following quantities of absolute sea level rise will be considered, it is yet uncertain when these will occur: 10 cm, 30 cm and 80 cm SLR.

Currently, the distribution of discharging through pumps and weirs is approximately 50 \%/50\%. The reduction of free-discharging capacity (Q_{weirs}) due to sea level rise was determined by (Vermeulen et al., 2021) and can be found in Table 2. To approximate the required pumpng capacity in the future (Q_{pumps}), the reduction of Q_{weirs} will be added to Q_{pumps}, keeping Q_{out} constant. Simultaneously the effect of 2 possible mitigation measures will be assessed: 1) increasing the target water level from NAP -0.40 m to NAP -0.20 m, 2) introducing an extra pump (50 m^3/s). Figure 4 (right) shows the new return periods of pumped volumes for several amounts of SLR. The current maximum daily pumping capacity is indicated in yellow, which is exceeded for every scenario. If an extra pump is added the maximum daily capacity will increase, which is depicted in the dashed blue line. In that cases, the maximum daily capacity is exceeded with 80cm SLR. In Figure 4 (right) the target level is increased to NAP -0.20 m, which will result a lower reduction of free-discharging capacity. This results in different return periods than the left, especially for 0.30 cm SLR.

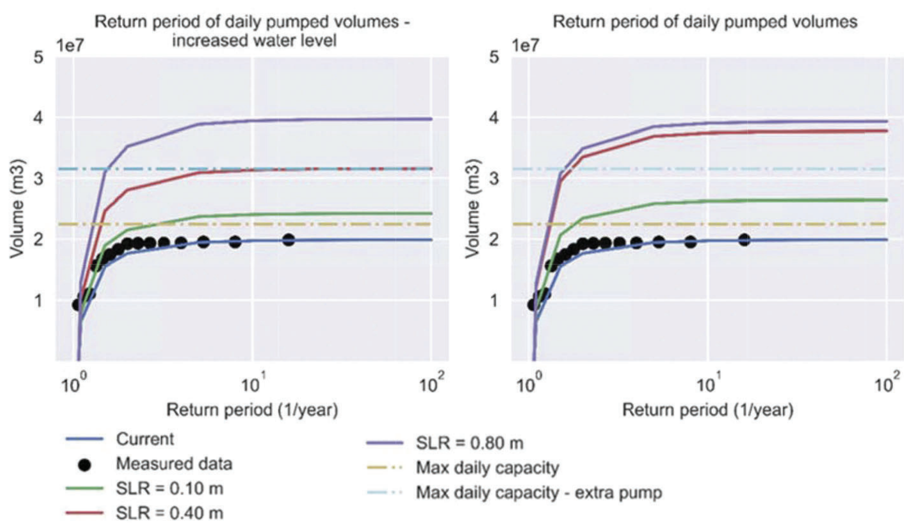

Figure 5. Return period of the daily pumped volumes of the historical data (black) which was fitted in blue with the generalized extreme value distribution. The return periods for 0.10 cm, 0.30 cm and 0.80 cm SLR are depicted in green red and purple. The new return periods were determined by adding the reduction of Q_{weirs} to Q_{pumps}. Left) The new return periods can be compared to the current maximum pump capacity (dashed yellow) and if an extra pump is added (dashed light-blue). Right) In this subplot target water level is increased with 0.20 cm, so less free discharge capacity is lost. This results in different return periods than the left, especially for 0.30 cm SLR.

Table 2. Reduction of volumes to be freely discharged as the sea level rises for 10 cm, 30 cm, 80 cm. Calculated for a target level of NAP-0.40 m and NAP-0.20 m, from (Vermeulen et al., 2021).

	Reduced free-discharge volume	
	Target level	Target level
SLR	NAP 0.40 m	NAP 0.20 m
10 cm	33 %	22 %
30 cm	90 %	59 %
80 cm	99 %	98 %

5.2 *Precipitation patterns*

In this section the effect of an increased Q_{in} during extreme rainfall events on the required pump capacity is analysed, while Q_{out} and Q_{weirs} remain constant. Possible future precipitation sequences were generated with the KNMI Transformer (Bakker, 2015) for 2030, 2050 and 2080 (Figure 6, left) conform the Wl scenario.

The return period of extreme rainfall events are shown in Figure 6. Even for an 1/100 year extreme rainfall event in 2080, it will only result for a 10 cm increase of the water level. This will not result in many issues, as the 10 cm lie between the regulatory margins and the extra volume can be disposed of by the current pump capacity (van Veen, 2022). However, it's difficult to determine how the effects of both sea level rise and extreme rainfall events will coincide with current modelling. The higher volumes of precipitation may not lead to an extension of the complex, but they are likely to lead to a higher required Q_{out} over multiple days. If such a period would coincide with a period when little to no free-discharging is possible, extra pump capacity might be required.

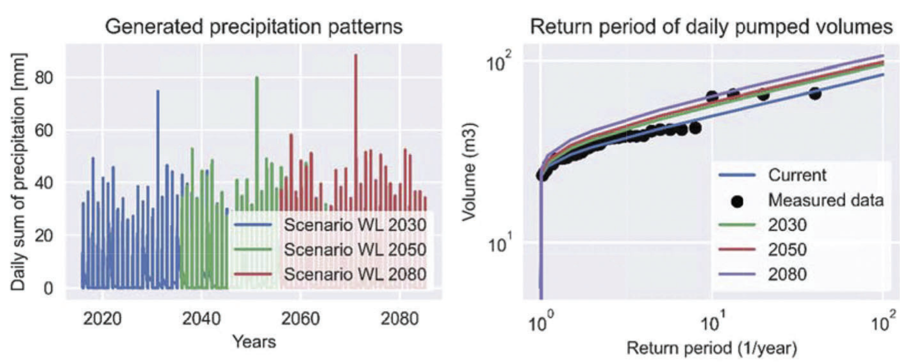

Figure 6. Left) Generated sequences of daily precipitation with the KNMI transformation tool (KNMI, 2022b), with "real" historical data in blue. Precipitation station: Wijk aan Zee. Right) Extreme value analysis of the daily sum of precipitation of the historical data from the weather station Wijk aan Zee and the generated sequences from the right figure.

6 CONCLUSIONS

The analyses in the previous sections provide an indication of the effect of climate change on the return periods of pumping volumes during extreme events. Additionally, they show the sensitivities in the system. The system seems to be dependent on the capacity of free-discharging during extreme water events, which will likely reduce as sea level rises. The system seems to be less sensitive to more extreme precipitation events.

In reality, the system is more complex and several crude assumptions were necessary in this analysis. Most importantly, the change of the capacity of free discharging was calculated by uniformly adding the sea level rise to the water levels of an one-year historical time sequence, not taking into account the impact on tides. Secondly, the assumption of a current 50 \%/50 \% distribution between pump and weir discharging is quite straightforward, as it varies under seasonal trends and differs for daily and extreme conditions. Though the free-discharging data is currently not available, it will most likely be in the future.

Additionally, the maximum pump capacity could be lower than displayed in Figure 6, as the pumps cannot operate during low tide or very high water levels. Therefore the exact maximum pumping capacity varies per extreme event, which was not included in this general analysis. However, if the real maximum capacity was overestimated due to a long period of low water levels, it is likely that free-discharging is was possible. Discharging via the weirs has a higher discharge capacity than the pumps themselves, which can compensate the overestimation of the pump capacity.

Finally, the influence of the failure probability of the pumping station has not been included in this analysis. The interaction between failure probability of the pumps and the water system is not included in this paper, but it is very important to include this in the future. Malfunctions of the pumps can influence the return period of exceedance of the critical water level. If a malfunction coincides with an extreme water event, more pumping capacity will be necessary to maintain a constant return period of exceedance of the critical water level.

The complexities of the system cannot be included in a straightforward analysis. Therefore a different approach will be explored in the future. Modelling the system with neural networks will probably be a feasible for this problem due to the node-like structure of the channel and the high availability of data. This method has already been applied successfully in the field of water management (Palmitessa et al., 2022). Additionally, more research is required on the effect of sea level rise on tidal harmonics and storm surges. Recent studies predict that tidal amplitudes in the North Sea may increase (Deltares, 2020, Idier et al., 2017), so the window for free-discharging might not decrease as much as was assumed in Vermeulen et al. (2021). Due to the sensitivity of the system to free-discharging, it is important to provide a more detailed estimation in the future.

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