A system approach for replacement strategy of hydraulic structures

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ABSTRACT: Many of the Dutch movable hydraulic structures are exceeding lifetime expectancy based on the then-current standards and regulations. Also signs of ageing become apparent, regulations (e.g. about structural safety) get more and more strict and functional requirements have often increased over time due to climate change and socio-economic developments. Therefore Rijkswaterstaat wants to ensure that these hydraulic structures (and it's system of operation) always complies to an adequate performance level. This by setting up an systematic approach replacing hydraulic structures based on their cost-effectiveness and future uncertainties. To provide useful information regarding this method a probabilistic performance framework has been set up. This framework links the performance of the object (IJmuiden Pumping Station) with the performance of the system (Noordzeekanaal & Amsterdam-Rijnkanaal) and defines, analyses and considers different measures for the object and so-called 'adaptation' pathways, providing insight in the most cost effective solutions considering future uncertainties.

1 INTRODUCTION

1.1 *Motivation*

Many of the Dutch movable hydraulic structures (storm surge barriers, locks, weirs, pumping stations, etc.) are designed and built between 1930 and 1960 with a life expectancy of about 50 to 80 years, based on the then-current standards and regulations. A large number of these structures approach their end of lifetime. This may have a significant impact on the economy and welfare due to the significance of the costs involved. It has also consequences for a smooth functioning of the infrastructure because these hydraulic structures are key elements for functions as water safety, water transport, water management or are part of a road transport network. That's why methods to provide more insight in design lifetime performance are necessary to be able to reduce impact and budget needed (Bernardini et.at. 2014, Van der Wiel et. al. 2014, Vuren et.al. 2015).

1.2 *Goal*

Goal of this study is to show that by analyzing costs and benefits of strategies in a holistic approach at a system level, while accounting for uncertainty in future development, efficiency of functional requirements and long term investments is improved. This approach should lead to transparent information about long term costs and risks of strategies. The goal of this case study is to find out if this approach is viable and whether it could lead to a more efficient use of available resources (budget).

1.3 *Case study*

This paper elaborates on a case study, which is part of the development of a holistic approach for asset management, related to the functioning of the network or system and taking into account future and uncertain developments like climate change. By using experience from case studies and translating these experiences to a more generic method, a risk and opportunity based asset management framework is developed.

The case study described in this paper, focuses on the consequences of hydraulic structures exceeding their lifetime and the development of strategies for asset management on a tactic level. In brief: a hydraulic structure can be replaced by the same modernized version. But due to external developments (economic, social, spatial, natural, etc.) new requirements could emerge which may even result in the necessity to redesign a part of the system. (E.g. as replacing a structure is an expensive and time consuming operation, the necessity for a replacement can be taken as an opportunity for the redesign of the system optimizing the role of the elements of the system anticipating on future developments). This could lead to new solutions, that are more efficient than a replacement. In this case a replacement is a sub optimal or even unnecessary investment.

For example, if a structure is supposed to have reached the end of its lifetime but is still capable of functioning with decreased requirements for some time, replacement can be postponed as long as the system or network function can be guaranteed.

The IJmuiden pumping station is used as case study because it's very suitable to our defined goal. First off IJmuiden pumping station is an important element in the water system of the North Western part of the Netherlands. Secondly, it is a key element in the water discharge for 4 regional water boards. In third place recent information regarding the expected remaining technical and functional lifetime of the pumping station is available (Van der Wiel et. al. 2015).

In the case study several options for the renewal of pumping stations or the increase of capacity in order to keep the water system functioning were identified. Also uncertainty in future (climate) scenarios was taken into account by calculating the costs and risks of the same strategy for different scenarios.

Furthermore the societal costs of each scenario were taken into account. In the case study cost and benefits were calculated. The case study does not take into account specific performance requirements on the reliability of the pumping station and on exceedance frequency of a maximum water level in the area. The expected value of damage is calculated in the model based on water levels and frequency. With this approach it is possible to compare the long term expected costs (including the risk) of different strategies (in this paper a set of measures on objects in time is called a strategy).

For our case the water system is largely simplified to show the possibilities of our approach. Furthermore damage values and frequencies are assumed or chosen if the realistic facts and figures were unavailable or too complicated for the purpose of the study.

The only failure mode in the case study is damage due to high water levels. Other failure modes, e.g. low water levels in the waterway, leading to problems in water transport, are not considered.

This paper starts with a description of our methodology with the basic assumptions and conditions, followed by a description of the water system. It ends with the results of the case study, conclusions and recommendations (Bel et. al. 2015).

2 METHOD

In this section we give an outline of the developed method. First the required information is described, followed by the way the information is combined during the analysis.

The goal of the method is to find a program of measures for the system that is the best strategy, given one or more scenario's for future demand. To achieve this an inventory and description of the system and the structures, that are part of it, are needed. This includes the timespan in which the structures are likely to reach (technical or functional) end of life, and of the future development of environmental factors (scenarios), such as the consequences of expected climate change for the system.

Next this data is analysed to develop strategies. A strategy is defined as a set of measures in the system in time. Our goal is to value these strategies which makes it for decision makers possible to compare them.

In detail, the following information is combined to get an overall image of the cost – benefit ratio for different strategies, see Figure 1;

1. For this case study the expected exceedance of the amount of rainfall in a certain period is needed. The development of which is uncertain. To represent this uncertainty, three scenarios were used: the mean, a minimum and a maximum value. In this case the expected flow rate with a certain exceedance frequency (e.g. 1/100 per year) is plotted for each year. This flow rate will increase over the years due to the expected rise in precipitation (intensity and duration). In the model we consider this flow rate to be the incoming water.
2. The difference between the incoming and outgoing flow rate results in a water level in the system. When there is a shortage in pumping capacity the water level will rise. This can be calculated using models. In this simplified case a simple relation between pumping capacity and water level was assumed. This provides a schematic relationship between the shortage in discharge capacity and the resulting water level.
3. The frequency of water level changes is important in relation to the expected societal costs. Therefore, a frequency of occurrence must be determined for every (too) high water level. This frequency of occurrence is determined based on the frequency distribution of the incoming flow rate and the available flow rate.
4. Information about the financial damage that occurs at a certain water level to determine the loss expectancy. This information is added to a model to calculate the costs and losses for each scenario.
5. The pumping capacity is considered as the control variable of the strategy, i.e. the flow rate leaving the system due to pumping. The pumping capacity has to be maintained by replacing pumps or it

can even be increased by adding pumps or increasing the capacity of existing pumping stations. This strategy leads to costs that can be estimated based on replacement and building costs. The strategy also indicates the location in the system where pumps are replaced or added. But due to the simplification of the model this is irrelevant for the case study.

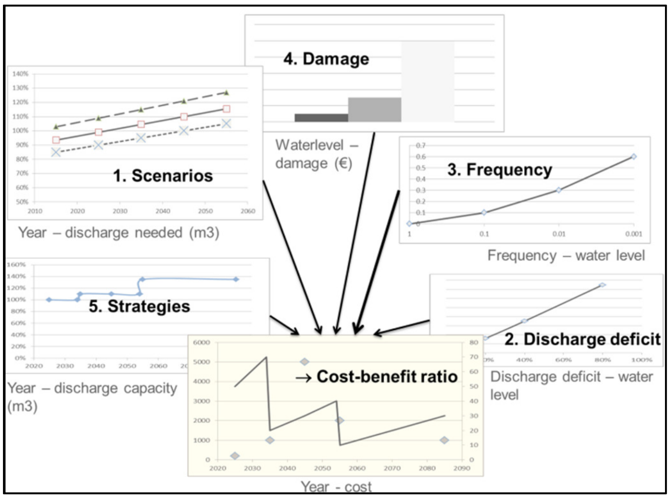

Figure 1. Image of the required information

In the next section this method is applied to the (overall) system of the IJmuiden Pumping Station.

3 SYSTEM ANALYSIS AND MODEL INPUT

3.1 *Introduction*

In order to assess the combinations of scenarios and strategies at a system level a model has been made according to Figure 2. It consists of 4 parts, the modelling of the system, the measures in time (i.e. strategies), scenarios for the development of the system and results presented as indicators for risk, cost and performance.

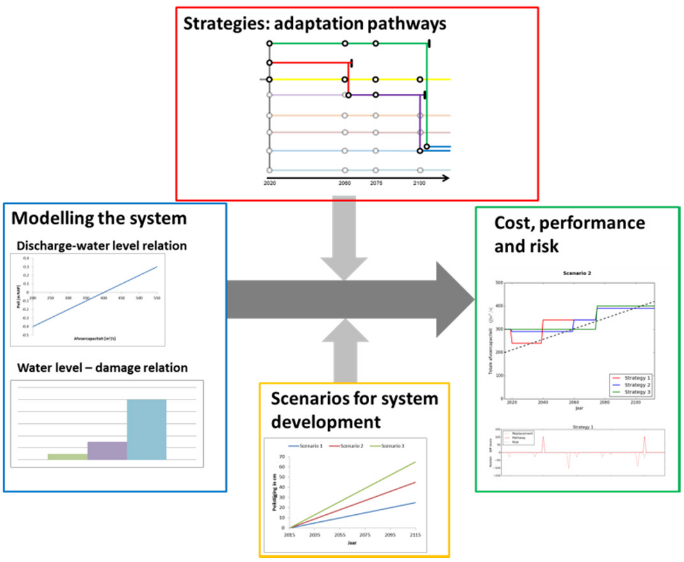

Figure 2. Set up of the model for assessing strategies at a system level.

The different parts of the model are discussed in the following paragraphs.

3.2 *Modelling the system*

3.2.1 General description of the NZK/ARK system

The NZK/ARK system contains the channels Noordzeekanaal and Amsterdam-Rijnkanaal in The Netherlands connected with the pumping station and sluices with the North Sea. This is the main system discharging water from the four surrounding water management organizations (Hollands Noorderkwartier, Rijnland, Stichtse Rijnlanden en Amstel, Gooi en Vecht), and with that the larger part of the west of The Netherlands, to the North Sea. This means, discharge of the total system mainly relies on the pumping station in IJmuiden.

The IJmuiden pumping station consists of six pumps with an estimated total capacity of 260 m^3/s. The original pumping station with four pumps was built in the 1970s and had a capacity of approximately 160 m^3/s. In the early 21st century, this capacity has been increased by adding two pumps. The pumping station is located next to a sluice, where water is mainly discharged by gravity.

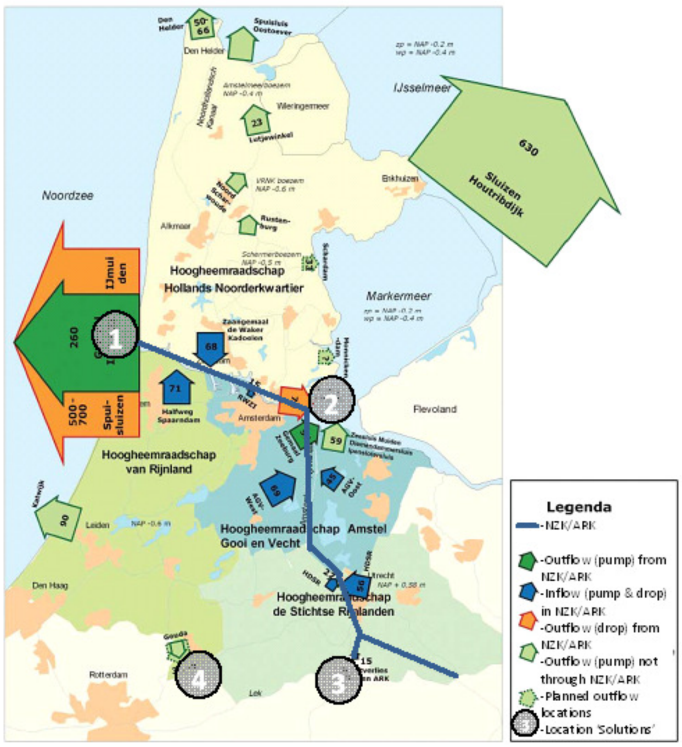

Figure 3. Points of discharge in the system NZK/ARK.

3.2.2 Physical description of the system: relation between discharge and water levels

As there are many other possible points where the discharge capacity of the system can be expanded, it is possible that in the future it may be more effective to reroute the discharge of water. Taking this into account, Table 1 provides a rough approximation of the area capacity used in this case study:

Table 1. Area capacity.

Area main water system	39,000,000 m^2
Total volume 0.1m level drop	3,900,000 m^3
Duration peak	24 hrs
Necessary pumping capacity 0.1m level drop	45.14 m^3/s (rounded to 50 m^3/s)

Based on the area of the system and a peak duration of 24 hours, an extra discharge capacity of 50 m^3/s equals a decrease of approximately 0.1 m in water level.

An important effect of this approach is that the outcome does not depend on where a pump is located. In reality there will be differences due to for instance the capacity of the discharge route, but in this study we assume that in all locations adding 50 m^3/s of discharge capacity will result in a water level drop of 0.1 m.

We found no requirements what the maximum water level and frequency should be occurring at most once in a 100 years. A LCC study (Van der Wiel et al. 2013) assumes a water level of NAP + 0.20m to be acceptable while another study reports an 'alarm level' of NAP – 0.30m to occur once in 100 years. We use these values as a reference point for our case study.

3.2.3 *Damage and effect*

To provide a good estimate for the effects of not taking actions in the different strategies of managing the NZK/ARK system, the expected loss is estimated upon the occurrence of a number of deviating levels. Managers aim for an daily average water level in the Noordzeekanaal / Amsterdam-Rijnkanaal of NAP -0.40m. Table 2 provides an overview of the relation between deviating levels, the possible consequences, control measures (not exhaustive) and the total estimated cost of damage occurring at exceedance.

Table 2. Overview NZK/ARK cost/damage effect.

Level [m NAP]	Possible effect	Possible control measures	Total loss [k€]
-0.30	-Alarm level-		75
-0.20	Water flows into sewer Amsterdam	Amsterdam needs to be sealed off from NZK / ARK at two locations	300
-0.10	Local drainage problems	-	1600
0.00	Flooding regional system	Proclamation of shut-down pumping to system	101,600

A small range of possible effects is used to illustrate how this is applied to our approach. A more thorough research of both the NZK/ARK system, as well as connected regional water systems is necessary for a realistic impact assessment. The small loss at exceeding the researched levels that follows from this study is consistent with practical experience.

3.3 *Strategies*

3.3.1 *Possible solutions*

In this case study three possible options are explored (Figure 3):

1. Expand IJmuiden Pumping Station;
2. Expand discharge capacity at 'Oranjesluizen' (i.e. enlarge the discharge capacity to the Markermeer);
3. Expand Gouda Pumping Station.

3.3.2 *Adaptation pathways*

Strategies for future developments can be easily represented with adaptation pathways. Figure 4 shows the conceptual adaptation pathways for this situation. Given the four (time) points in the future, denoted t_1 to t_4; the pathway shows that at t_1 action 1 is taken, at t_3 action 2 is taken and at t_4 again action 2 is taken. An important remark; it is always assumed that, unless dictated otherwise by the pathway, all structures are replaced 1-on-1 once they reached their end of their lifetime. So in this case this could imply that at t_2, although nothing is indicated, a structure has reached its end-of-life and will be replaced.

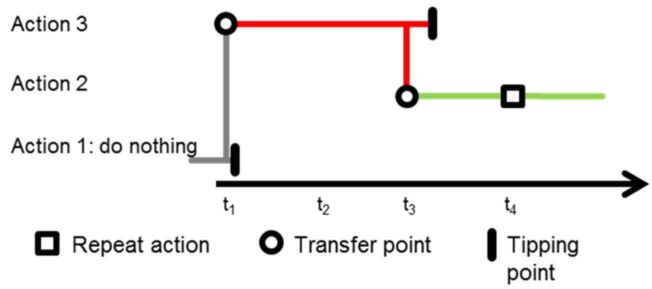

Figure 4. Concept of adaptation pathways. As denoted, 1-on-1 replacements are not indicated in the pathways.

For this case 7 different possible paths are defined next to the 'do nothing'-path, which are:

1. Remove 1 pump at Ijmuiden;
2. Remove 2 pumps at Ijmuiden;
3. Install 1 pump at Oranjesluizen;
4. Install 2 pumps at Oranjesluizen;
5. Install 3 pumps at Oranjesluizen;
6. Install 1 pump at Ijmuiden;
7. Install 2 pumps at Ijmuiden.

These numbers will also be used in the figures in the next chapter. Of course more actions could be taken, but these paths enable strategies befitting for the considered scenarios.

3.4 *Scenarios for system development*

3.4.1 *Scenarios for development of demand*

The goal of this case study is to see which management strategy of the ARK/NZK system is best, considering different scenarios. Scenarios are chosen based on their suitability to test the method. They are not based on actual scenarios for the case. In other words, the scenarios are defined by usability to illustrate the method, not usability to support the actual management demand.

The scenarios are defined as the increase in demand of discharge capacity due to more extreme rainfall and the decrease in pumping capacity due to the rise in sea level.

3.4.2 *Lifetime of structures*

The technical durability of the hydraulic structures, part of the system Lekkanaal, Amsterdam-Rijnkanaal and Noordzeekanaal, is estimated based on the condition of the civil construction and the age and design lifetime of the structures (De Bel et al. 2015). The technical end-of-lifetime of the 10 structures is estimated to be between 2023 and 2095, with the average at ca. 2059 (Van der Wiel et. al. 2014).

3.5 *Risk, performance and cost*

3.5.1 *Risk*

Risk is calculated based on the determined damages for the different water levels (see Table 2). Furthermore we assume that at a water level of NAP + 0.3 m leads to a damage level of 10^9 €, and the damage level increases quadratic from NAP + 0 m to NAP + 0.3 m. To calculate this risk, we apply the following (simple) formula:

$$Risk = \frac{1}{1000} Loss_{\frac{1}{1000} level} + \frac{1}{100} Loss_{\frac{1}{100} level} + \frac{1}{10} Loss_{\frac{1}{10} level} \quad (1)$$

3.5.2 *Costs*

The costs for removing or installing pumps are split into costs for the structure and for the pump itself. Pumps are assumed to have a lifetime of 40 years, structures have a lifetime of 100 years. Maintenance costs are assumed to be 2% of the building costs, plus they are discounted. Furthermore the maintenance costs for pump and construction are both added to the construction costs of the pumps. All costs are discounted with a 3% discount rate.

Table 3. Costs for different measures.

Action	Construction cost [M€]	Total cost in calculation [M€]
Replace pump	3	12.1
Replace structure	17	17
Build new structure with pump	20	32.1

4 RESULTS

In this section, we compare the described strategies. First these are presented as adaptation pathways, secondly results for performance (discharge), risk and costs are given.

4.1 *Adaptation pathways for different scenarios*

For all scenarios three different strategies are considered. Each strategy starts with the same action, but from 2045 strategies will be different. Figure 5 gives an example of the adaptation pathways for Scenario 1. Table 4 gives an overview for all strategies and scenarios.

Table 4. Adaptation pathways of three strategies for three scenarios. Numbers refer to paths defined in section 3.3.2.

Scenario	Strategy	2020	2045	2055	2075	2100
1	1	2	3	-	6	-
1	2	1	-	-	6	6
1	3	0	-	-	-	6
2	1	2	4	-	6	6
2	2	1	3	-	6	6
2	3	0	-	-	6	6
3	1	2	5	-	6	7
3	2	1	4	-	6	7
3	3	0	3	-	6	7

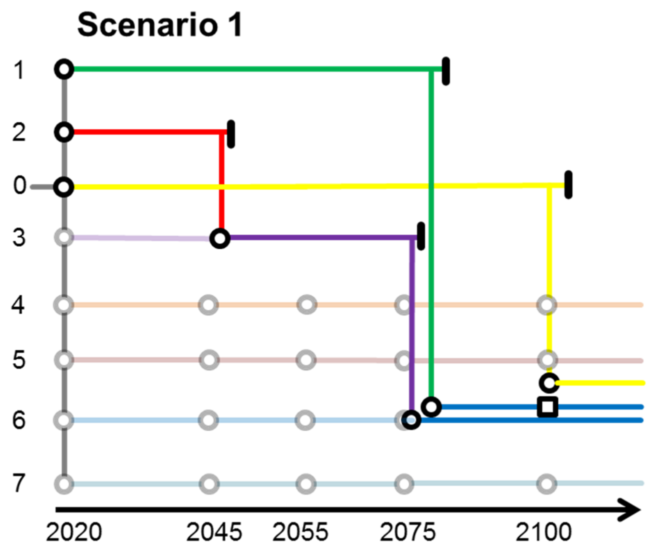

Figure 5. Adaptation pathways for scenario 1. For legend see Figure 4.

4.2 *Results for performance*

The performance of the different strategies can be measured by the discharge over time. Figure 5 till Figure 8 shows the discharge of different scenarios. These figures show that adaptations to the system are not based on the performance requirements, but on the opportunities when certain objects reach their end-of-life. Like Figure 8; In case of scenario 3, we see that after the removal of pumps in 2020, both strategies 1 and 2 spent considerable time below the performance requirement. The question is whether this is a problem from a cost or a risk perspective.

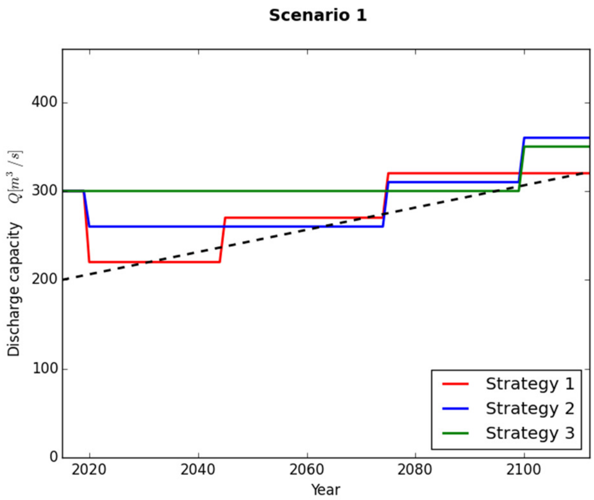

Figure 6. Discharge capacities for the three strategies for scenario 1. The black dashed line denotes the required capacity to satisfy the requirement.

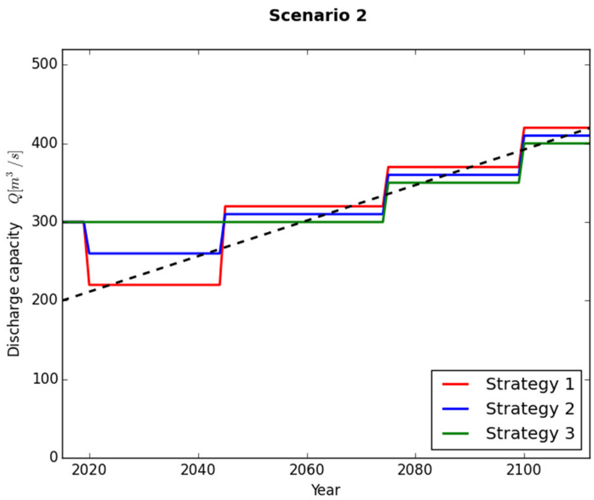

Figure 7. Discharge capacities for the three strategies for scenario 2. The black dashed line denotes the required capacity to satisfy the requirement.

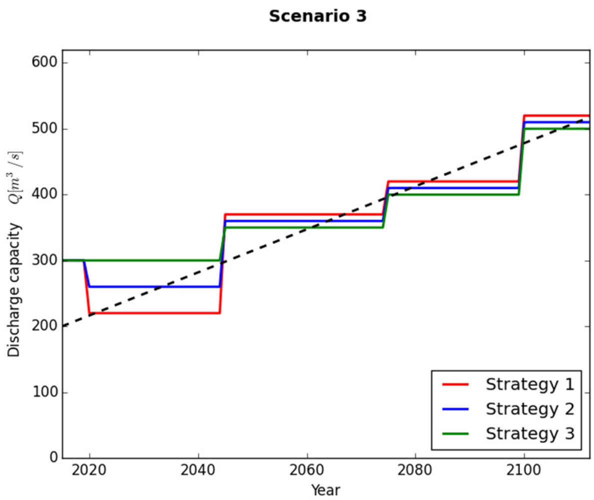

Figure 8. Discharge capacities for the three strategies for scenario 3. The black dashed line denotes the required capacity to satisfy the requirement.

4.3 *Results for cost and risk*

The effect of not intervening when the performance requirement is no longer met can be assessed based on the cost and risk that are taken during the considered time period. Figure 9 shows an example for scenario 2. Here it can be seen that due to the risk that is induced in strategy 1, even though the costs are lower than for the other strategies (dashed lines) the overall value of cost and risk together is higher (solid lines). So in this case waiting until 2045 with adding extra pumps is not an efficient solution.

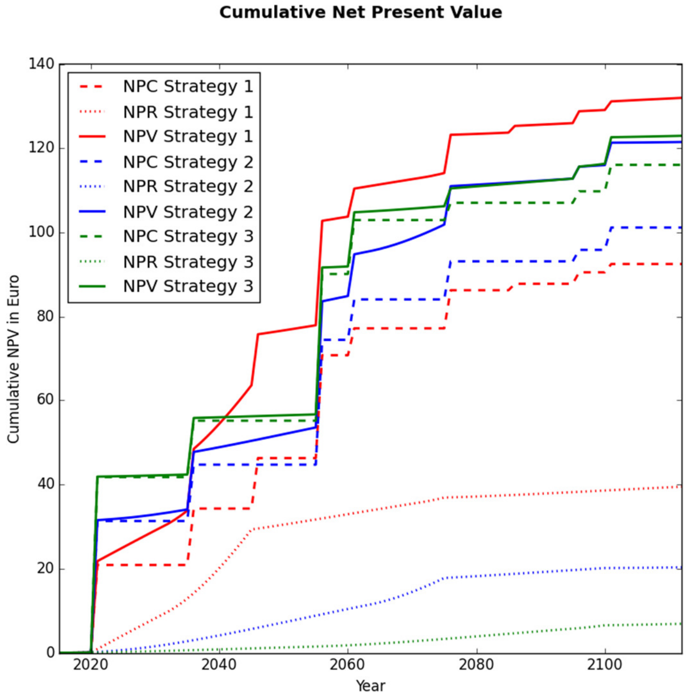

Figure 9. Cumulative Net Present Value(NPV) over time. NPV is calculated by adding the components of the Net Present Cost (NPV) and Net Present Risk (NPR) (i.e. the yearly risk). Dotted lines denote NPR, dashed lines denote NPC and solid lines denote NPV. Please note that jumps in cost are not always shown as changes in pathway, due to one-on-one replacements.

Another important point is that some strategies are cheaper on the short term but more expensive on the long term. Table 5 gives an overview of the costs for the different strategies for different scenarios as well as the average cost over 100 years for each scenario.

Table 5. Overview net present risk (NPR), cost (NPC) and value (NPV) for the different scenarios and strategies.

		Scenario 1		Scenario 2		Scenario 3		
	in M€	<2060	<2115	<2060	<2115	<2060	<2115	Average
Strategy 1	NPR	33	40	72	83	120	141	88
	NPC	46	92	83	108	95	124	108
	NPV	79	132	155	192	215	265	196
	NPR	10	20	15	33	35	66	40

	NPC	44	101	87	115	99	131	116
	NPV	54	122	101	148	134	197	156
Strategy 3	NPR	1	7	7	36	8	50	31
	NPC	55	116	90	121	102	137	125
	NPV	56	123	97	157	110	187	156

The table shows that on average strategies 2 and 3 have the same NPV. For both strategies the risks are acceptable. Strategy 1 is the most expensive because although the cost are lower, the risk is significantly higher compared to strategy 2 and 3. This is because in strategy 1 two pumps are removed leading to too high risks.

The results also show that the risk is very dominant, therefore a sensitivity analysis with a reduced risk was carried out. Table 6 shows the results for a case were all damage is 5 times lower. Here it can be seen that, when damages are 5 times lower, strategy 1 is no longer unattractive and even the most cost-effective one in some scenarios. This shows the importance of a risk-based assessment for the performance requirement as well as the long term strategies.

Table 6. Comparison of a case with normal loss and reduced loss for 100 years.

		Scenario 1		Scenario 2		Scenario 1		Average	
	in M€	normal	5x lower	normal	5x lower	normal	5x lower	normal	5x lower
Strategy 1	NPR	40	8	83	17	141	28	88	18
	NPC	92	92	108	108	124	124	108	108
	NPV	132	100	192	125	265	152	196	126
Strategy 2	NPR	20	4	33	7	66	13	40	8
	NPC	101	101	115	115	131	131	116	115
	NPV	122	105	148	121	197	144	156	123
Strategy 3	NPR	7	1	36	7	50	10	31	6
	NPC	116	116	121	121	137	137	125	125
	NPV	123	117	157	128	187	147	156	131

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 *Conclusions*

- For this research the system is bounded to one function, one unwanted event (high water level) and experience a large number of simplifications. With these constraints, approaching the replacement task from the structures' function within the system was found possible, as well as a step towards a risk based approach in which the expected loss is included as an expense.
- The integrated approach is found to be useful. This approach gives access to a larger solution space. It also makes it is possible to optimize (government) spending by taking calculated risks that are socially acceptable and financially bearable.
- The generated results for the IJmuiden pumping station case study cannot be used for real decision-making due to the large number of simplifications. This case was only used to explore the method and consider the advantages, not to generate decision information for this pumping station. For instance, we didn't take the dynamic and nonlinear behaviour of the system into account which definitely can lead to different results.
- The generated information and assumptions for this case show that there is a relation between the performance level and what is the dominant factor, costs or risks. Because, if a certain performance level is met, the costs dominate the comparison. When this performance level is not met, the risk rapidly increases and dominates the comparison. This emphasizes the importance of a risk based analysis for performance requirements as well as long term strategies for such water systems.

5.2 *Recommendations case IJmuiden*

This case can be further developed according to the described method to generate more suitable decision information. We recommend to emphasize on:

- The quantification of the losses, especially for higher water levels;
- Elaboration of the costs of management, maintenance, replacement and new constructions for different locations, as well as the lifetimes (functional and technical);
- Making a more detailed model (precipitation, pumping flow rates on different locations, water levels et cetera);
- Expanding the number of functions (shipping, water safety, level management) and unwanted events (high water level, low water level, shipping blocks).

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