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SPECIAL ISSUE

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Protecting the Rhine-Meuse delta against sea level rise: What to do with the river's discharge?

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Abstract

Sea level rise (SLR) will affect water levels and increase flood risk in river deltas. To adapt river deltas to SLR, various strategies can be followed. Many urbanised river deltas already have flood protection in place. Continuing a protection strategy under an increasing SLR, would mean higher embankments along the coast and rivers and possibly closing off the river mouths from the sea. However, closing of rivers will hamper the river flow. How to adapt river deltas and enabling rivers to discharge into the sea is a challenging question. This paper assesses impacts of SLR on flood risks in the Rhine-Meuse Delta in the Netherlands in case the current protection strategy is continued and explores two alternative protection strategies: (1) a closed system with pumps and discharge sluices and (2) an open system in which rivers are diverted to less densely populated areas. The second alternative results in a more flexible river delta, which can accommodate larger SLR. The paper shows that a systems approach and using quantitative assessments of the implications of strategies is possible. This is needed to further assess the adaptation options, so we can anticipate and adapt when needed and avoid regret of decisions.

KEYWORDS

flood risk management, Rhine, sea level rise

1 | INTRODUCTION

Sea level rise (SLR) forms an imminent threat to low-lying populated coastal zones and river deltas. SLR will increase flood risks and affect fresh water availability. According to the recent IPCC Special Report on Oceans and Cryosphere in a changing Climate (SROCC) global mean sea levels (GMSLs) may rise 0.43 m (0.29–0.59 m, likely range) in 2100 under a low emission scenario (RCP2.6) and 0.84 m (0.61–1.10 m, likely range) under a high emission scenario (RCP8.5) (Pörtner et al., 2019). However, expert elicitation studies indicate that a GMSL of 2 m rise in 2100 is possible (Bamber et al., 2019; Pörtner et al., 2019). Also, after 2100 SLR will continue. Uncertainty about future SLR beyond 2050 is largely determined by uncertainty about the emissions and ice sheet contributions, especially in Antarctica.

Adaptation to uncertain and potentially accelerated SLR is challenging and may require more drastic measures than currently planned (Haasnoot et al., 2020).

There are various options to adapt to SLR such as protection against higher water levels, accommodation through reducing the vulnerability, advance with new (higher) land seawards, or retreat landwards (Pörtner et al., 2019).

As many urbanised river deltas are very vulnerable to both coastal and river floods, they often already have some protection through embankments, sand dunes, storm surge barriers or a combination. The river deltas of the Mississippi, Rhine-Meuse, Thames, Elbe, Nile and Scheldt are a few examples of such urbanised deltas. Continuing a protection strategy under an increasing SLR, would mean higher embankments along the coast and rivers and possibly closing off the river mouth from the sea. The question then becomes*, what to do with the river discharge?*

The Rhine-Meuse delta in the Netherlands is one of these urbanised river deltas that may be heavily impacted by SLR and is facing the question how to adapt to SLR (Haasnoot et al., 2020). In 2010, the Netherlands has initiated the 'Dutch Delta Program' to develop (amongst others) flood risk management strategies. In this program, an adaptive plan was developed to cope with uncertain future changes (Van Alphen, 2016; Bloemen et al., 2017) based on exploring adaptation pathways to a range of potential futures (Haasnoot et al., 2013; Ranger et al., 2013). Such adaptive plan exists of near-term actions to prepare and long-term options to adapt as the future unfolds. The plan is supported with monitoring to detect early warning signals to further implement or reassess the plan (Haasnoot et al., 2018). The current actions in the adaptive plan are targeted to address a SLR ranging from 0.35 up to 1 m in the year 2100 relative to the year 1995. However, accelerated or continuing SLR may require different measures.

This paper uses a systems analysis of the Rhine-Meuse delta to explore what to do with the rivers to mitigate flood risk under rising sea levels and following a protection strategy. The paper starts with describing the current system and the potential effects of SLR if the current strategy is continued into the future and then discusses two alternative strategies. The paper illustrates the importance of further discussions on the future of the river system using quantitative insights of the implications of strategies and providing adaptation pathways to the future.

2 | THE CURRENT RIVER SYSTEM

2.1 | System overview

The Rhine and Meuse rivers discharge the water from a large area (220,000 km^2) in Switzerland, France, Germany, Belgium and the Netherlands. The Meuse River enters the Netherlands in the south-east. Downstream, it turns into a characteristic low-land river with a low gradient, wide floodplains and large flood-prone areas. The Meuse has a median discharge of 180 m^3/s; the highest observed peak discharge is 3200 m^3/s in 1926. The Rhine River has its source in the Alpes in Switzerland, collects water from a large catchment in Germany and France and enters the Netherlands as a lowland river. The Rhine River has a median discharge of 2000 m^3/s, a once in 10 years discharge of about 10,000 m^3/s and a maximum recorded discharge of about 13,000 m^3/s (also in 1926). In the future, high discharges may occur more frequently due to climate change. Flood events in the Rhine and Meuse rivers often coincide, due to the vicinity of their respective basins.

Just downstream of the Dutch-German border, the Rhine River bifurcates into the Waal River which discharges about two-thirds of the Rhine discharge, the Nederrijn/Lek which discharges about two-ninths of the River discharge and the IJssel River which discharges the remaining one-ninth to the IJssellake (Figure 1). At the bifurcation points, this discharge distribution is controlled by structures. Along the Dutch part of the Rhine River, embankments were designed to protect against

FIGURE 1 The lower Rhine and Meuse rivers and their delta. 1 = Maeslant Barrier which closes of the Nieuwe Waterweg (NWW), 2 = Haringvliet Barrier, 3 = Volkerak barrier, 4 = Brouwers Barrier, NR-Lek = Nederrijn/Lek. (the orange colour indicates the Rijnmond area)

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events with a probability of once in 1250 to once in 10,000 years.

The Waal, Nederrijn/Lek, and Meuse rivers flow to the west into the Rijnmond Area, which has two outlets to the sea: the Haringvliet and the Nieuwe Waterweg (see Figure 1). To protect the Rijnmond area from storm surges, barriers have been built. In the Haringvliet, a discharge sluice is built which is closed during periods of high sea water levels to prevent saline water from flowing in (see Figure 2). The Maeslant Barrier in the Nieuwe Waterweg is usually open for navigation to the Port of Rotterdam. In the current climatic conditions, this barrier only closes about once in 10 years during extreme storm surge events. River discharge is then blocked for one or two tidal periods.

The IJssel flows to the North and discharges through the IJssellake into the sea. The IJssellake is protected from storm surges by a 32 km dam (Afsluitdijk). Discharge sluices enable the flow of water from the IJssellake into the sea. To be able to maintain the IJssellake at target levels with projected SLR, the discharge capacity of the sluices is being enlarged and new pumping stations are under construction. For more in-depth discussions on this part of the system we refer to Remmelzwaal et al. (2018). In the remainder of this paper we will focus on the impacts of SLR on the Rijnmond area.

South of the Rijnmond area there are several lakes, waterways and estuaries. Currently, these do not discharge or store water from the Rhine or Meuse rivers as the Volkerrak barrier and sluices (see Figure 1) separate both. The northern lake, the Grevelingen is protected from storm surges by a permanently closed barrier.

2.2 | Impacts of SLR on the current system

To analyse the effects of SLR on the current system two situations were analysed: with and without storm surges.

2.2.1 | Situation without storm surge

The effects of higher sea water levels on river water levels in situations with an open storm surge barrier were analysed with a 1D hydrodynamic model (SOBEK 3) (de Bruijn et al. (2020)) with a simplified tidal signal without storm surge. In this model, the storm surge barriers are assumed to be open, even in cases were the SLR is above current storm levels. Figure 3 shows the effect of SLR on river water levels for different discharges and different values of SLR for the Waal and Nederrijn/Lek. As expected, the effect is highest near the coast (left side of both figures) and the effect is largest during periods of low discharges. The effect of SLR on water levels during peak flows is much smaller. During design high flows, the effect of 1 m SLR is about 0.2 m near the downstream end of the Waal in the delta (70 km from the sea).

In the Nederrijn/Lek, the river weirs limit the impact of the SLR during low-flows. Downstream of the weirs the water levels increase approximately with the same rate as the SLR. During high flows, when the weirs are completely opened, 1 m SLR results in a water level rise of about 0.7 m at the downstream end of the Nederrijn/Lek (40 km from the sea).

Figure 4a shows the *relative* water level rise in the Waal River (a factor on the SLR) for the once in 10,000-year discharge (about 16,000 m^3/s at Lobith). This graph provides an indication of the effect of SLR on the heightening and strengthening of the embankments along the river that is required to maintain the current safety standard. The figure shows that river levels in the Waal increase less than the SLRs. Up to a SLR of 2 m, they increase no more than 0.3 m/m SLR (see Figure 4a) (thus to 0.6 m water level rise) at the downstream end of the Waal. For results on all river branches reference is made to de Bruijn et al. (2020).

Figure 4 (right side) gives an indication of the length over which embankment strengthening has to be implemented to maintain the current protection levels. Dike strengthening costs in the Netherlands vary strongly and depend on the required heightening and the potential strengthening solution (in soil or with a structural


FIGURE 2 The Haringvliet barrier (left) and Maeslant Barrier (right) (source: Nogueira & Walraven, 2018)

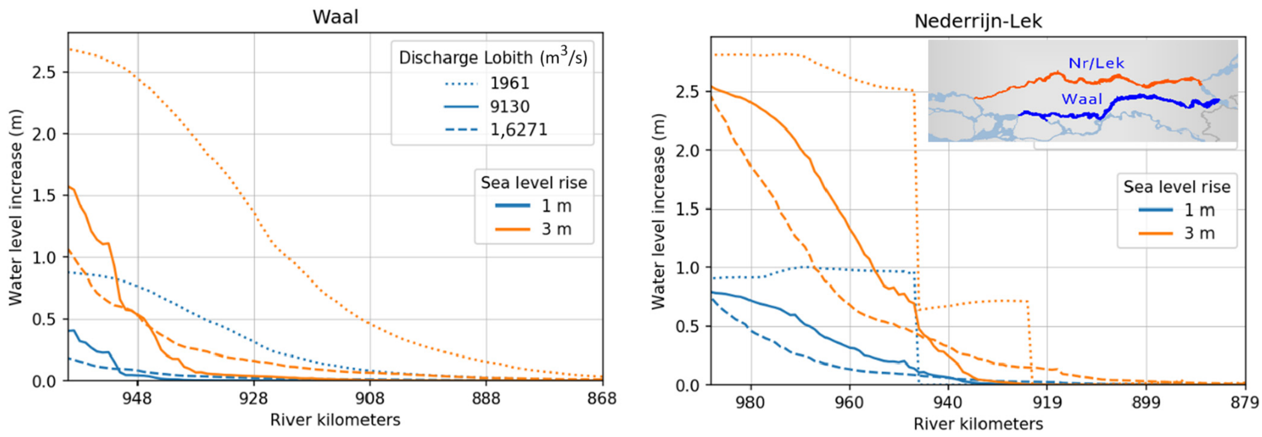

FIGURE 3 Increase in water level along the Waal river from Pannerdensche Kop to Hardinxveld (left) and along the Nederrijn/Lek from IJsselkop to Krimpen a/d Lek (right) due to 1 and 3 m SLR for average discharge (1961 m^3/s), the once in 10 years discharge (9130 m^3/s) and the once in 10,000 year discharge (16,271 m^3/s). The flow direction is from right to left. The location of these river sections is indicated in the upper-right corner

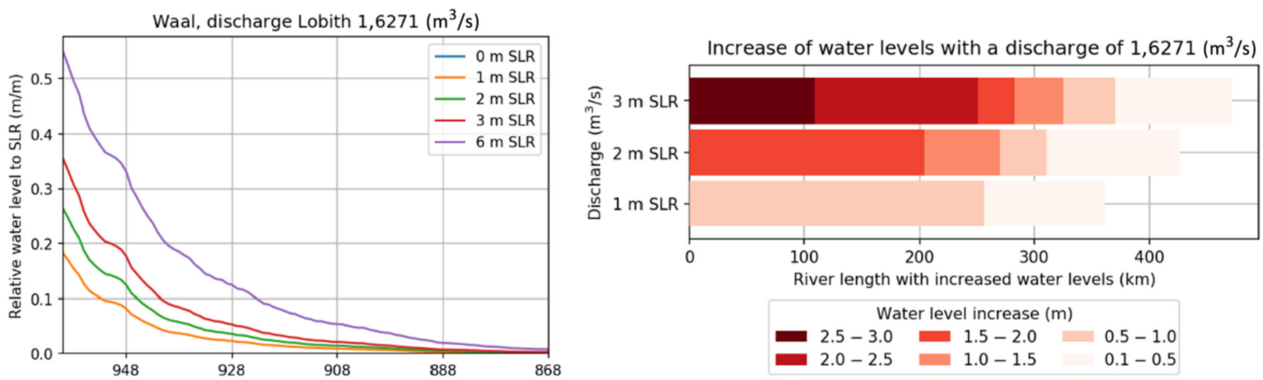

FIGURE 4 Left: Relative water level rise on the Waal river associated with a discharge of about 16.000 m^3/s at Lobith due to various levels of SLR. A value of 0.2 in this graph on the curve for 2 m SLR indicates a water level increase of 0.2 times 2 is 0.4 m right: Indication of the river length where water levels increase with a certain height for a SLR scenario of 1, 2 and 3 m. The discharge about 16,000 m^3/s is assumed to be an indicator for the embankment height. All river branches both in the upper river and tidal river part are included (right)

measure) which depends on available space, the morphological conditions, the current characteristics of the embankment, and the dominant failure mechanisms. Costs of dike raising vary generally between 5 and 20 M€ per km (Waterschap Rivierenland, 2020). Assuming that raising 0.5 m or less would cost 5 M€/km, up to 1 m 10 M €/km, up to 2 m 15 M€/km and more 20 M€/km, and assuming that the total length of the embankments is twice the length of the river, then the costs for adapting the embankments to a SLR of 1, 2 and 3 m would be respectively 6, 10 and 14 billion euro.

These numbers give a first order estimate of the differences in effort between the different SLR scenarios assuming an open river mouth. Although the effort is substantial, even with 3 m SLR it is of a similar order of magnitude as what was anticipated to be needed to strengthen all embankments in the Netherlands between 2015 and 2050 to comply with the new safety standards. This means this strategy of strengthening is feasible from a financial point of view. However, one must realise not only embankments need to be raised, but also areas outside the embankments, and outlet structures of regional waterways and drainage systems and harbours. This would increase adaptation efforts even further.

2.2.2 | Situation with storm surge

During once in 10-year storm surges, when the Maeslant Barrier is closed, the discharge of river water is hampered. In order to limit rise of the river water level, the barrier opens as soon as the surge level drops and the outside water levels are about to fall below the inside levels.

With SLR, the closure threshold of the Maeslant Barrier of NAP[1] + 3 m will be exceeded more frequently and the Maeslant Barrier will therefore close more frequently. Table 1 shows the closure frequency for different values of SLR (Haasnoot et al., 2020). With a SLR of 1 m, the barrier will need to close on average 3 times per year; with 1.5 m SLR the closure frequency is 30 times per year.

These high closure frequencies are undesired for several reasons. First, the barrier was not constructed to close that frequently. Second, each closure means the connection between the Rotterdam harbour, key to the Dutch economy, and the North Sea is closed off temporarily. Third, closure may then occur all year round instead of during the winter season only, which means the summer season cannot be used for maintenance and test purposes anymore. And fourth, closing more frequently results in a higher likelihood of a higher river discharge during a closure.

The maximum tolerable frequency of closure was estimated to be around 3–5 times a year (Haasnoot et al., 2019). This frequency will be exceeded when the SLRs with about 1 m. If the maximum allowed closure frequency is fixed at 3 times per year, then the water level threshold for closure needs to be increased when sea levels rise further (see Table 1). That would have serious consequences for especially the areas behind the barrier which are not protected by embankments. Such areas include parts of the city centre of Rotterdam and Dordrecht which host 60.000 people and several industries. Furthermore, the embankments of the protected areas need to be strengthened in order to maintain the current protection levels, sometimes with serious impact on the character of the old city centres.

The current flood risk management strategy can be continued to about 1 m of SLR. In higher SLR scenarios, the areas not protected by embankments would be flooded frequently, the Maeslant Barrier would need to close too frequently, and the embankments need to be raised substantially. Additional measures are then needed.

TABLE 1 Impact of sea level rise (SLR) on the closure frequency or closure threshold of the Maeslant Barrier

SLR (m) relative to m.s.l. 1995	Frequency of exceeding NAP + 3 m (per year)	Threshold for closure (maximum closure frequency is 3 times per year)
0.15	1/10	NAP + 3 m
1	3–5	NAP + 3 m
2	Permanently	NAP + 3.8 m
3	Permanently	NAP + 4.6 m

2.3 | Adaptation options

We identify four main options to reduce river flood risk under rising sea levels in river deltas (based on Pörtner et al. (2019):

1. Prevent or reduce the increase of the river water levels with structural measures like storm surge barriers, closing of river branches with dams combined with discharge sluices or pumps (*Protect-Closed*).
2. Strengthen and increase embankments along the rivers to cope with increasing water levels (*Protect-Open*).
3. Accept increased flood hazards and flood probabilities and mitigate impacts of flooding by changes in land use (*Accommodate*) or
4. *Relocate* to areas, which are not prone to flooding.

We focus here on the first two options since land use adaptation is difficult in this highly urbanised delta. To develop strategies, which link to one of those or a combination of the options, various measures can be used, such as (see Figure 5):

- Change the discharge distribution over the Waal, Nederrijn/Lek and IJssel to optimise the volumes of water going to the IJssellake, northern- and southern Rijnmond area;
- Open or close the three mouths of the Rhine and Meuse rivers into the sea: the Nieuwe Waterweg, Haringvliet and IJssellake.

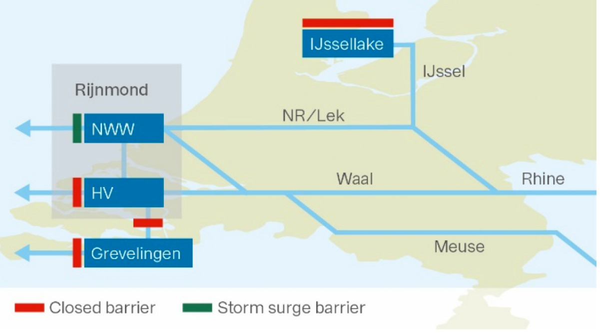

FIGURE 5 Schematic view of the Rhine-Meuse delta with all critical decision points. The figure shows discharge distribution points, locations of the Maeslant Barrier in the Nieuwe Waterweg (NWW) and dams in the IJssellake, Haringvliet (HV), and Grevelingen

When the river outlets are closed by a dam with discharge sluices, the following measures can be included:

- Add pumping capacity to allow discharge when sea water level exceeds the inland water levels;
- Add storage capacity to limit the water level increase in periods when discharges are higher than the outflow capacity to the sea, by connecting the estuaries in Zeeland (south of the Rijnmond area); this may include lake Volkerak, Grevelingen and Oosterschelde (the estuaries south of the Grevelingen; see Figure 1).

Based on the aforementioned options, we identified two alternative strategies to further assess: A 'closed' strategy and a 'river diversion' strategy. In the 'closed strategy' the outlets are closed off to prevent SLR to affect average water levels in the delta. River water is discharged by gravity through discharge sluices or pumped out. In the 'river diversion strategy' two existing river branches are closed off from the sea while one that is currently closed is reopened. The river is diverted to a new route south of the Rijnmond area.

3 | ALTERNATIVE 1: PERMANENTLY CLOSED SYSTEM

In this alternative the delta is permanently closed off from the sea by dams with navigation locks and discharge sluices (Van Waveren et al., 2015; see Figure 6). The anticipated advantage of this alternative is a reduction of highwater levels behind the dams. Furthermore, benefits are expected for the fresh water availability.

Figure 7 shows the impact of replacing the storm surge barrier with two permanently closed barriers with locks and discharge sluices on the design water levels[2] in the area. In this alternative, design water levels will decrease with about 1 m around Rotterdam, with 0.5 m in most of the western part of the area and between 0 and 0.5 m further upstream (Van Waveren et al., 2015). The largest decrease occurs around Rotterdam, directly upstream from the dams (dark blue coloured dots in Figure 7).

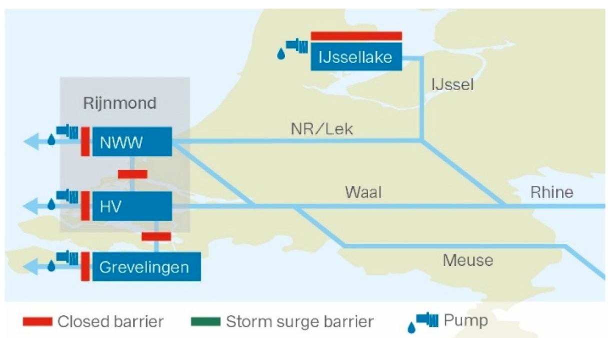

FIGURE 6 Alternative 1: The closed strategy. The Maeslant Barrier in the Nieuwe Waterweg (NWW) is replaced by dams and pumps are added

In the current situation the most hazardous events are the ones in which the storm surge barrier fails to close upon request during a storm event. In the formal safety assessment of flood defences, the probability of the barrier not being able to close is estimated to be 1/100 per closure (Chbab (2015). Since the barrier now closes about once in 10 years, the probability of an event in which the barrier should close but does not, is about 1/1000 per year. In this area flood protection levels are about 1/10,000 per year and the corresponding design water levels are therefore dominated by the non-closure events. In the alternative with permanently closed dams, failing to close is not an issue. Therefore, design water levels corresponding with this alternative are lower than those corresponding with a continuation of the current policy.

RWS (2015) considered a SLR of about 1 m to assess how much reduction of extreme water levels can be accomplished with a permanently closed dam. However, with further increasing sea levels, the flood risk will increase further. At first, the rivers will be able to discharge through outlets in this dam by gravity. With rising sea water level, pumps will be needed to discharge the river water to the sea. Discharging river water will be increasingly difficult especially when the river discharge exceeds the available pumping capacity for several days in a row. During such events, the water level will increase if the incoming discharge from upstream exceeds the combined capacity of pumps and drainage sluices.

To obtain an indication of the water levels behind the dams at different SLR scenarios and with various storage volumes and pump capacities a mass balance model was implemented in which the area behind the dams is modelled as a reservoir with a surface area of about 450 km^2. This area corresponds with the water surface of all water bodies in the Rijnmond area, including the Haringvliet and excluding the (presently disconnected) water bodies Volkerak-Zoommeer and Grevelingen (see Figure 1). The inflow of the river consists of river discharges of the Rijn river branches (Waal and Lek) and the Meuse river. The target level of the reservoir is set to the current mean sea level and to maintain this level, the inflow of the rivers is pumped to the North Sea or discharged by gravity during positive head difference (when the river water level exceeds the sea level). To maintain the target level, the pumping capacity is set to 3000 m^3/s, similar to Van Waveren et al. (2015). This capacity exceeds the average

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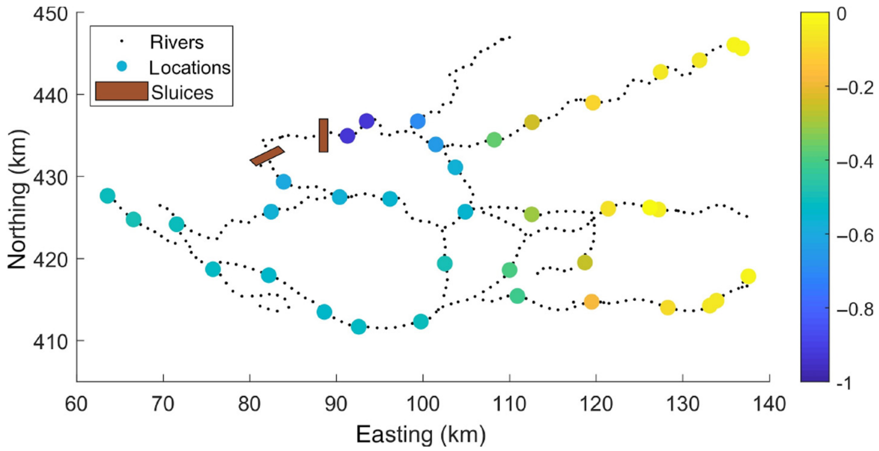

FIGURE 7 Change in design water levels* as a result of replacing the open storm surge barrier by two permanently closed dams, in the situation with 1 m SLR (based on Van Waveren et al., 2015)

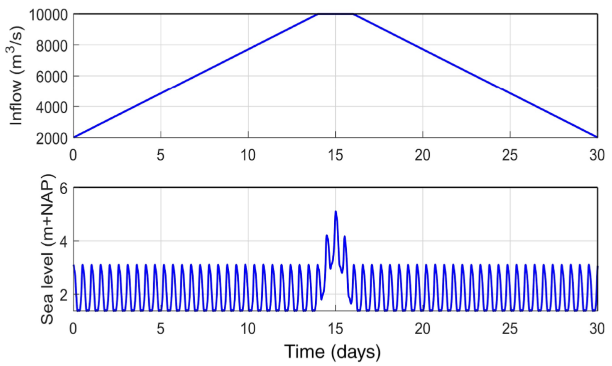

FIGURE 8 Example event: Inflow (upstream river discharge), surge and sea water level (2 m SLR is assumed)

River discharge of the Rhine and Meuse branches in the Rijnmond area. The current discharge sluices of the Haringvlietdam (17 in total, each with a width of 56.4 m and a sill of NAP − 5.5 m) are assumed to be still available to discharge water to the sea during positive head difference.

Figure 8 shows an example of a (synthetic) event that was simulated with the model. In this event, the peak discharge of the three inflowing river branches is equal to 10,000 m^3/s (which corresponds to a once in 10-year discharge); the hydrograph is trapezium-shaped (Slomp et al., 2016). The storm surge also has a trapezoidal-shaped hydrograph, which is superimposed on a simplified astronomical tide. The peak of the surge in this example is 2 m (a once in 10-year storm surge) and it coincides with the moment in which the river discharge peaks as well. A SLR of 2 m was assumed and is superimposed on the astronomical tide.

The blue line in Figure 9 (‘simulation 1’) shows the resulting water level dynamics in the area protected by the dams. In the first few days, the water level stays at the target level of NAP + 0 m. Then, the river inflow starts exceeding the pumping capacity of 3000 m^3/s which results in an increase in the water level. After a few days, the water level is approximately equal to NAP + 1.5 m. At this point, water can be discharged through the discharge sluices during low tide. This additional discharge capacity makes the water level increase at a much lower rate than the days before when only the pumps could be used. After 14 days, the storm surge starts, which leads to increased sea water levels. As a consequence, the discharge sluices cannot be used while the river discharge is at its maximum. The water level therefore increases rapidly until the water level exceeds the sea level again and the discharge sluices can be used again for discharge by gravity. The water level reaches a peak of NAP + 3.25 m. When the surge decreases, the difference in water level causes a substantial increase in discharge capacity of the discharge sluices. This causes the water level to decline rapidly, to the level of approximately NAP + 1.5 m. This lasts for a while until the river discharge decreases below the available pumping capacity. After that, the water level decreases steadily to the target level of NAP + 0 m.

This is just one example of a simulation that demonstrates the influence of the river discharge, surge, pumping capacity and discharge by gravity on the water levels in the area. We carried out a number of additional model runs to show the sensitivity of the (peak) water level to various assumptions for parameter values of the system configuration and the event characteristics (see Table 2 and Figure 9). In ‘Simulation 2’, no storm surge is included. Due to the absence of the storm surge, the peak water level is 1.3 m lower than in ‘Simulation 1’. This shows that even though a dam protects the area from direct impacts of storm surges, the surge still can have a significant impact on the peak water levels.

In ‘Simulation 3’, the peak of the surge (2 m) occurs at a later stage in the event. As a consequence, the peak of the surge and river discharge do not coincide, which is why the peak water level is 1.2 m lower than in

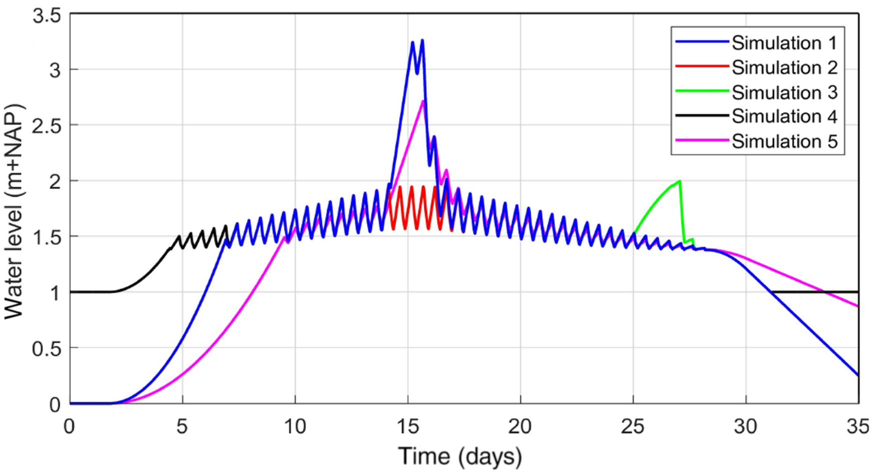

FIGURE 9 Resulting water levels for five different model simulations, assuming 2 m sea level rise

TABLE 2 Five model simulations and resulting peak water levels

Simulation:	**1**	**2**	**3**	**4**	**5**
Peak surge (m)	2	0	2	2	2
Start surge (days)	14	—	25	14	14
Storage area (km^2)	450	450	450	450	1000
Target water level (m + NAP)	0	0	0	1	0
Peak water level (m + NAP)	3.26	1.94	1.99	3.26	2.71

Note: Grey cells indicate differences with model simulation 1. All simulations are carried out with 3000 m^3/s pump capacity, 2 m sea level rise and a combined peak discharge from the Rhine and Meuse of 10,000 m^3/s.

simulation 1. This shows the relevance of timing between peak river discharge and storm surge (compound events).

In 'Simulation 4' the target water level and, hence, initial water level is increased from 0 to 1 m. As a result, the water level reaches higher values at an earlier phase, which also means the discharge sluices can be used at an earlier stage. However, this does not influence the peak water level, which is equal to that of 'Simulation 1'.

In 'Simulation 5', the total surface area is increased from 450 to 1000 km^2. This could be realised by using the waters south of the Rijnmond area, such as the Grevelingen, Volkerak and Oosterschelde as additional storage. As a result, more water can be stored, and the water levels increase at a lower rate. As a side effect, water levels also decrease at a lower rate at the end of the event. Due to the increased storage capacity, the peak level decreases 0.55 m relative to 'Simulation 1'.

The calculations show that in case of unfortunate timing (a storm surge occurring around the time when river discharges are high) the peak water level in the basin is similar to the peak sea water level during the storm. In the absence of a storm surge, the high river discharges will cause the peak water level in the basin to be equal to the water level at peak tide.

The use of this simple model illustrates the effects of the strategy. However, since the model is simplified and schematises the entire area in only one reservoir (neglecting local differences, water level slope, etc.) there are limitations on the interpretation of the results, they should be regarded as indications only.

The findings above are illustrative and only valid for the particular event under consideration. For risk-based decision making it is relevant to consider all potential flood events. Therefore, we developed a probabilistic model with three stochastic variables: height of the storm surge, peak discharge of the river, and the relative timing of the peaks. Statistics of sea water levels have been derived by fitting extreme value distribution functions through observed peaks-over-threshold series. Sea water level statistics are described by a conditional Weibull distribution (see Diermanse et al., 2015) and surge statistics were derived from these by filtering out the tide component of the sea level statistics. Statistics of river discharges were derived by generating a long synthetic time series (10,000 years) of precipitation and temperature for the Rhine and Meuse River basins and subsequently deriving a similarly lengthy discharge time series by means of a combined hydrological/hydraulic model (Hegnauer et al., 2014). In the probabilistic model we

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simulate a period of 30 days in which the peak of the river discharge is assumed to occur halfway. The timing of the peak of the surge is a stochastic variable with a uniform distribution function over a period of 30 days.

Figure 10 shows frequency curves for four different magnitudes of SLR. Most noticeable about these frequency curves is that 1 m of SLR results in an equal increase of extreme water levels in the area behind the dams. This shows that even though the dams will provide extra protection compared to the current situation with the storm surge barrier, it will not mitigate impacts of additional SLR. Currently the once in 10-year water level is about NAP + 3 m. At that level, the lowest elevated harbour areas are flooded. Water levels of NAP + 4–5 m would flood vulnerable residential and industrial areas. Additional measures or adaptation will be needed when water levels frequently exceed approximately NAP + 3 m.

Figure 11 shows water levels for 10, 100 and 1000-year return periods for different combinations of the pumping capacity and the available surface area for water storage (results for 2 m SLR). This illustrates the trade-off between increasing pumping capacity on one hand and area for storage on the other hand. It shows that the relative impact of changing the surface area increases with increasing return period. An increase in pumping capacity has a larger impact on 10-year water levels than an increase in storage area; for 1000-year water levels this is the other way around. This information could be useful for decision-makers. They may for example conclude that using the additional storage area of the Oosterschelde could be limited to very rare events only.

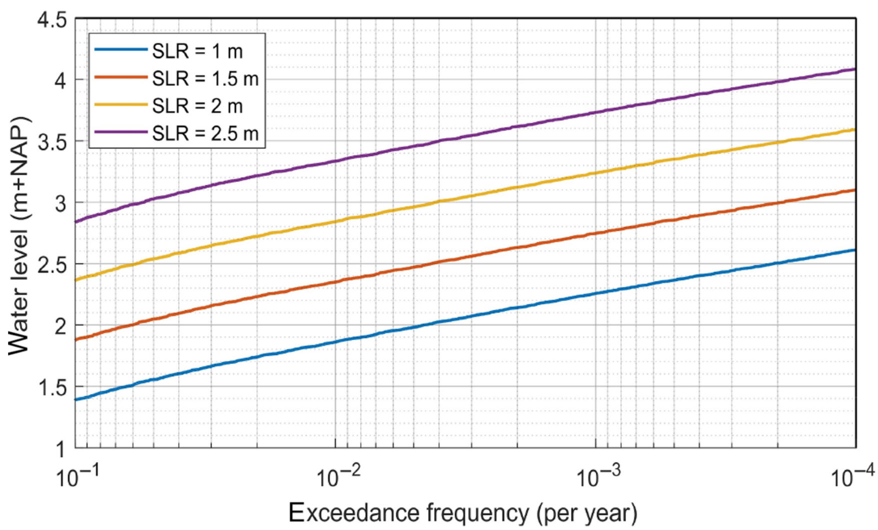

FIGURE 10 Frequency curves of the water level in the Rijnmond area for four different magnitudes of SLR (assumptions made: Pump capacity is 3000 m^3/s, storage area is 450 m^2)

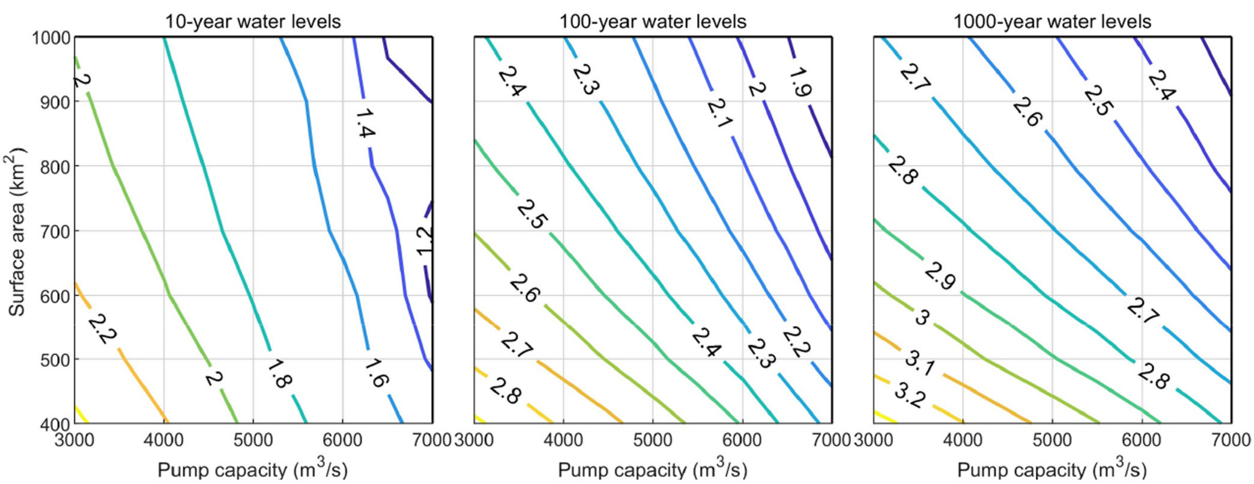

FIGURE 11 Water levels for 10, 100 and 1000-year return periods for different combinations of the pumping capacity and the available surface area for water storage (results for 2 m sea level rise)

In this alternative (permanently closed system) the effect of storm surges on the water levels in the tidal rivers is mitigated. The risk now comes from events with high river flows, more specifically from events in which the inflow exceeds the pumping capacity for a prolonged period of time. Since it is unlikely that the pumping capacity will be large enough to fully pump out the river during periods of high river flows, abundant water needs to be stored or discharged through the barrier openings during such events. Discharge by gravity is only possible if the water level at the inland side of the discharge sluices is higher than the sea level. For that reason, SLR results in an equal increase in extreme water levels behind the closed barriers, even when this water is coming from the rivers. This can be mitigated somewhat by increasing pumping capacity or storage area, but that benefit is limited to a few decimetres at most. In these calculations the pumps are assumed to be fully operational. If failure probability of the pumps would be taken into account, return values of water levels would be even higher.

Essentially, the measure of replacing the open storm surge barriers with closed dams will buy the area extra time to adapt to SLR (the time equivalent to approximately 1 m SLR), but if the sea level continues to rise, an alternative strategy is required.

4 | ALTERNATIVE 2: RIVER DIVERSION

In the sections above it was shown that, in the case of a high river discharge, the water level in the lower reaches of the rivers will rise until it exceeds the sea level and discharging through gravity becomes possible. As SLR is expected to continue and as there is a limit to the maximum water levels that cities like Rotterdam and Dordrecht can adapt to, at a certain moment in the future, these areas may have to be disconnected from part of the system to safeguard their present character.

For the situation in the Netherlands this means the layout of the water system may need to be changed in such a way that the river is diverted to a less densely populated region, south of Rotterdam and Dordrecht, where it will be in open connection with the sea: during periods of high river discharges, which typically last in the order of a few weeks, the river will flow to sea without the need for pumping. Storage of river water is required only for the duration of a storm surge event, which generally lasts 1 or 2 days.

This strategy implies a major change in the layout of the water system. It is good to bear in mind that as SLRs, the existing barriers will need to be replaced as the water levels will exceed the design values. This creates an opportunity for a new layout, which is not bound by the current structures and their present location.

In this strategy, the present Rijnmond area will be closed off from the sea by a dam (comparable to Strategy 1) and disconnected from the rivers by new dams with locks. The rivers will be diverted in a more southerly direction where they will discharge into the sea. The main inflow in the northern (Rijnmond) area comes from the Nederrijn/Lek, which reduces the inflow in the area with a factor 5 compared to the current situation. This makes it much more feasible to pump out the river discharge to the sea, even during extreme discharge events, and to maintain target water levels similar to the current levels. The Waal and Meuse will flow south of the Rijnmond area through the Grevelingen into the North Sea.

In this paper the diversion to through the Volkerak-Zoommeer and Grevelingen is studied. Alternatively, diversion through the Haringvliet or Oosterschelde could be considered (see Figure 12). In the studied option, the Haringvliet remains a freshwater lake. The combined Grevelingen and Volkerak could form an open estuary with tidal dynamics and a gradual transition between salt and fresh water. This will enhance water quality and ecology in these currently stagnant basins and will create an open route for fish migration.

Construction of this layout will involve a large number of infrastructural changes: The Haringvliet will need to be separated from the river Waal and Meuse with a dam near the location just downstream (west) of the current locks to the Volkerak (see Figures 1 and 13). The new dams protecting the northern Rijnmond area from high river flows should facilitate shipping by including locks in the dam. The dam and locks to the Volkerak

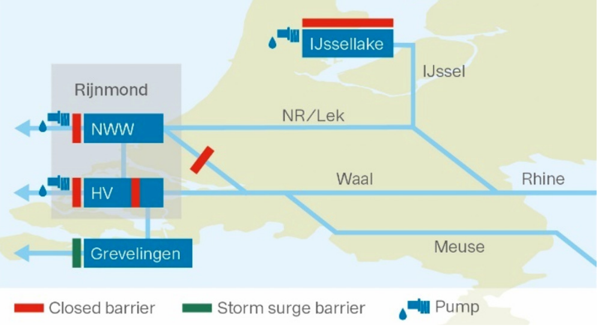

FIGURE 12 Schematic view of the river diversion strategy. Divert the rivers to the south: The dams to the Grevelingen are removed, but two new barriers are constructed to divert the Waal and Meuse in southern direction and to separate the Rijnmond area from those branches

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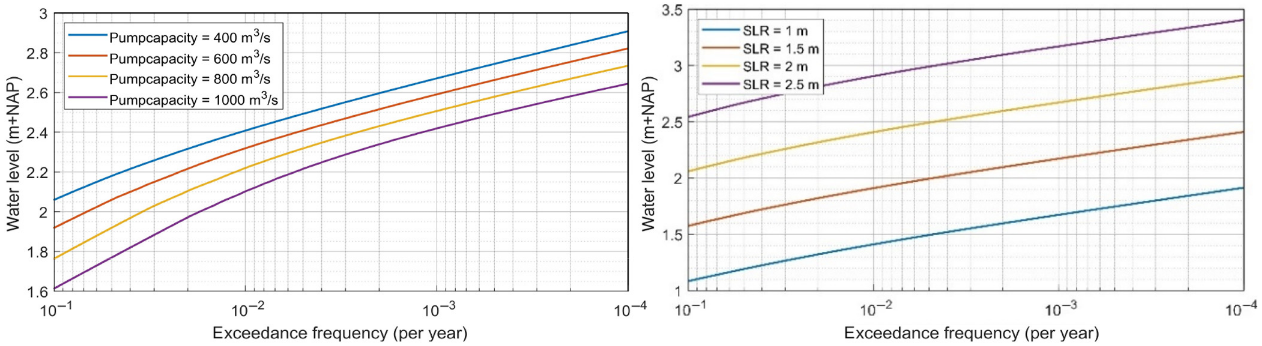

FIGURE 13 Frequency curves of the water level in the Rijnmond area for four different pumping capacities (assuming a 2 m sea level rise) (left) and for four different magnitudes of SLR (assuming a pump capacity of 400 m^3/s) (right)

become obsolete and will be removed to create an open connection for both the river and shipping. Also, an open connection will be created between lake Volkerak and the Grevelingen. And finally, the connection between lake Grevelingen and the sea is reopened: currently there is a dam with a discharge sluice, but this will have to be replaced with a storm surge barrier.

4.1 | Consequences for extreme water levels in the Rijnmond area (Rotterdam – Dordrecht)

We carried out similar simulations as for Strategy 1. We assumed inflow only from the Nederrijn/Lek, so only about 20% of the original inflow. Furthermore, we assumed the surface area for storage is reduced from 450 to 200 km^2. This includes the area of the Haringvliet.

Figure 13 shows frequency curves of the water level for four different pumping capacities and SLR scenarios. The frequency curves show that water levels for all return periods have decreased compared to strategy 1 (yellow line in Figure 11), even with a pumping capacity as 'low' as 400 m^3/s. One might argue that a lower pumping capacity could be sufficient, but with a lower pumping capacity it takes much longer to get the water level back to the target level after the event; this increases the likelihood of a second flood event occurring at a time that the level is substantially higher than the target level, which is not included in this study.

The curves also show that peak water levels in the Rijnmond area will increase at approximately the same rate as the SLR. This means at some point the pumping capacity may need to be increased to prevent frequent exceedance of high-water levels. An alternative could be to further reduce the inflow of river water by diverting additional water to the IJssellake or Waal.

4.2 | The effects on the southern river outlets

In this alternative, the Volkerak and Grevelingen together form the new lower branches of the rivers Waal and Meuse. Their conditions will be determined by the design and operation of the hydraulic structure between the Grevelingen and the sea. Since the Grevelingen is not a shipping route to sea, the barrier can be a relatively simple structure which consists of a series of smaller openings, separated by pillars. These pillars and their foundation can be designed for an 'ultimate' value of SLR, ensuring that the construction will be able to be functional under any anticipated scenario of SLR. The doors and motion mechanisms in the construction typically have a shorter technical life span, so they can be designed for a more limited value of SLR. In due time they can be replaced with higher and stronger doors and systems, provided that the concrete work, pillars and foundation, is designed for such larger forces. The building costs of the new structure are reduced by the current presence of the Brouwersdam, which enables construction of the new barrier in sheltered conditions.

In the first period after the construction, the storm surge barrier may have to close at a relatively low water level in order to allow time for embankment heightening and strengthening along the lower stretches of the river. As the SLRs, the mean water level in the basin will rise, reducing the margin towards the height of dikes presently in place. This means that either the closure frequency will increase, or embankments will need to be strengthened.

The possibility to either heighten the embankments or increase the closure frequency provides flexibility to the system and gives extra time to cope with accelerating SLR and to adapt the embankments. The possibility to change the closure frequency thus makes this solution adaptive. The closure frequency can bridge a potential gap between the rate of SLR and the rate at which the dikes are heightened.

As is illustrated in the above, the nature of the Grevelingen and the Volkerak will be determined by the flow capacity and the operation of the hydraulic structure in the new river mouth. The area can be similar to an open estuary as the Eastern Scheldt, or similar to a freshwater basin, like the Haringvliet. This depends on the closure frequency of the structure, which, if the structure is designed for that, can change over time to enable adaptation to continuing and accelerated SLR.

5 | ADAPTATION PATHWAYS

The Rhine-Meuse delta must be adapted over time when the SLRs. Since adapting the strategy takes time and requires investments, a timely exploration of options and their implications is needed. Such explorations may not only feed societal debates on the future of the Netherlands and provide valuable insights on the impacts of SLR, but they may also result in better investment planning and reduce the likelihood of regret on investments or missed opportunities.

A key decision for the Rhine-Meuse delta is by what type of structure the Maeslant Barrier should be replaced: by an improved storm surge barrier with a smaller probability of non-closure, or by a dam with discharge sluices and locks? Figure 14 provides an indication of the effect of different adaptation pathways on the design water levels in the Rijnmond area for increasing sea water levels. Three pathways are depicted, all starting from the current situation.

A first pathway is to continue the current strategy (close storm surge barrier more frequently until the maximum frequency of 3–5 times per year is reached) at some point in the future. To do so the current Maeslant Barrier with a closure failure of about 1/100 per closure will need to be replaced with an improved one with a closure failure of at maximum ones in 1000 closures. If SLR continues, the threshold for closure needs to be increased in order to maintain a maximum closure frequency of 3–5 times a year. This will result in higher design water levels in the Rijnmond area. This pathway is shown by the bright green colour. With increasing SLR, design water levels will also keep increasing and require additional adaptation measures such as improved embankments, land use adaptation measures, raising of areas outside the embankments and adaptation of drainage systems which discharge to the rivers. This would require drastic changes to the city centre of Rotterdam and Dordrecht, both directly connected to the river.

A second pathway (the blue line) involves the replacement of the Maeslant Barrier by a closed barrier with locks and discharge sluices. This could be done as a first adaptation measure right from the current situation, or later if first the Maeslant Barrier is improved by one with a smaller closure failure. If first the Maeslant Barrier is

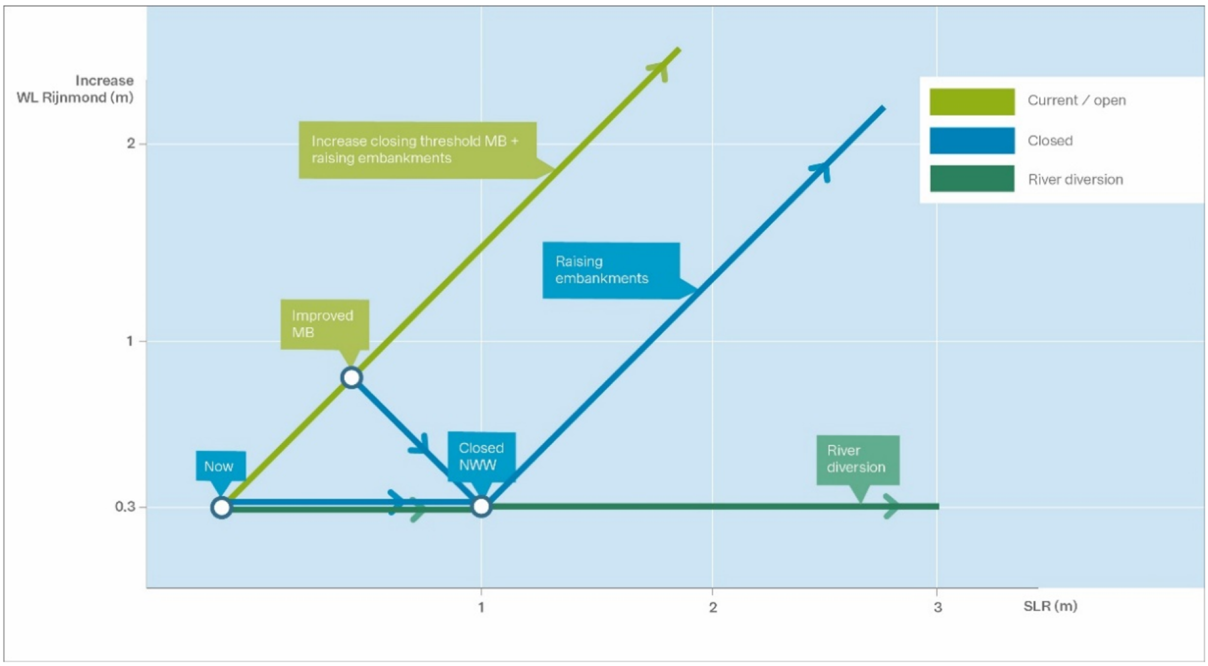

FIGURE 14 Adaptation pathways: The *X*-axis relates to SLR and the *Y*-axis to the design water level increase in the Rijnmond area (MB, Maeslant Barrier)

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improved, time is bought which may be used to adapt to the future closed system which would require large adaptations of for example the navigation sector and harbours. It would, however, also mean that investments in this barrier done to reduce the closure failure probability may become obsolete. Closure of the Nieuwe Waterweg results at first in a significant reduction in design water levels in the Rijnmond area and prevents that the normal daily water levels rise with the sea level (which happens in the first pathway) and reduces the flood frequency of the (urbanised) unprotected areas. However, with increasing SLR, the more extreme water levels will increase at the same rate as the sea water level. The resulting peak water levels depend on the storage area and pumping capacity, as demonstrated in Section 3. This closed barrier thus postpones the effect of SLR, temporarily mitigates the effect on the most frequently occurring water levels and provides time for the area to adapt.

If the sea level continues to rise, it may be considered to move from the closed strategy to the combined open/closed river diversion strategy (see Figure 14, dark green line). In this pathway, first the Nieuwe Waterweg is closed as in the 'closed strategy' and then the Rijnmond area is isolated from the rivers Waal and Meuse by directing those river branches southward and discharge to the sea through the Grevelingen by gravity. The Grevelingen storm surge barrier is in this pathway only closed during storm surges (see Section 4). In this third pathway, the Rijnmond area only has to discharge the flow from the Nederrijn/Lek. However, in this pathway also the area south of the Rijnmond area needs to be adapted significantly.

In the first pathway, the area south of Rijnmond is not connected to the river and therefore, the adaptation effort to SLR in that area is limited. In the second pathway, the Grevelingen and surrounding waters are used to temporarily store river water during peak flows. Embankments must therefore be strengthened to enable safe storage there. In the third pathway the 'normal daily' Grevelingen water levels will increase with SLR. The adaptation effort also for the surrounding areas and activities will be large.

The third pathway can keep pace with SLR, since closure thresholds and embankments may be adapted stepwise depending on the SLR rate and societal preferences. There is more flexibility in water level targets and more room for embankment strengthening than in the strongly urbanised Rijnmond area with vulnerable unprotected areas.

This discussion demonstrates the importance of exploring options in time: some decisions that need to be taken soon may be affected by scenarios and pathways for the far future. Improving barriers to resist SLR, for example, may not be needed if the dam is later removed or replaced by a storm surge barrier, investments in inland harbours may depend on our view on the closure of the Maeslant Barrier. Knowing that in two of our three pathways water levels in the Grevelingen will increase, may change our choices on investments in the area surrounding Grevelingen.

The pathways show that for the Rhine-Meuse delta adaptation is feasible, although larger SLR rates will require more drastic changes in the river system. Retreat is thus not necessary even with SLR scenario of more than 3 m (at least from a technical point of view and based on flood risk analysis).

The time-scale of the required changes depend on the rate of SLR, which is very uncertain. The threshold of about 1 m SLR will be reached between 80 and 300 years from now. The uncertainty in SLR complicates discussions significantly: for example, the closed strategy which lowers the effect of approximately 1 m SLR could be seen as a delay of being affected by SLR of 80–300 years.

These three adaptation pathways only focus on flood protection and on SLR, while there are many more dimensions to the strategy selection such as navigation, fresh water supply, salinisation, morphology, water quality and ecology. These graphs illustrate a first attempt to develop adaptation strategies and show different options. The other dimensions must be included to come to fully informed decisions. Furthermore, no full evaluation is provided here. Only some indicative implications on water levels, efforts to raise embankments and closure frequencies of barriers are shown. For a fully informed discussion, impacts on the various subregions in for example economic terms, on the usability of the land and the ecology must be assessed.

6 | CONCLUSIONS

6.1 | Conclusions for the Rhine-Meuse delta

This paper explores options to adapt the river system in the Rhine-Meuse delta to SLR using simplified mass balance calculations. Currently, the Netherlands is one of the best protected deltas in the world. Our results show that the Rhine-Meuse delta can remain safe although the current strategy needs to be adapted in case of one or more meters SLR.

The current flood protection strategy may be applied until approximately 1 m of SLR, but beyond that, alternatives are needed as then the current Maeslant Barrier will close too often or the inland water level (the threshold for closure) will become too high. Two alternative strategies and potential adaptation pathways were assessed. The 'closed strategy' results in a large reduction of the design water levels and avoids the need to adapt unprotected areas and local drainage systems discharging on the rivers. However, if SLR continues, the design water levels increase with the same rate as SLR. To cope with further increasing sea water levels, a shift can be made from the closed system towards the river diversion strategy resulting in a partly open system, which can accommodate more SLR.

This paper sketches a pathway from the closed strategy to the more drastic river diversion strategy. The paper aims to inform the decision making showing various options and their implications for various SLR scenarios. It does not intent to put forward one best option. The paper also contributes by discussing pathways over time.

We argue that discussions will be improved by using models to support understanding of the options and their effects. Simple mass balance models are often sufficient to enlarge understanding and to support a first-order assessment of options as shown in the examples within this paper. Such quantifications are needed to develop the abstract adaptation directions (e.g., protect, accommodate or retreat) to more concrete descriptions of potential solutions and their implications and enhance discussions on the future options for river deltas. Until now often either general directions of adaptation were mentioned, or very detailed measures were discussed. A systems approach discussing options and a timeline depending on SLR is not yet available.

In this paper, we focused on flood protection and the water system and only briefly mentioned other aspects. It is recommended to also consider other aspects such as navigation, fresh water supply, salt intrusion, ecology, morphology and economic opportunities of the areas in a better way.

6.2 | Lessons for other urbanised river deltas

All cities and settlements in low-lying river deltas need to adapt to rising sea levels. A systems approach in which both the SLR, coastal protection and the rivers discharge are addressed is needed to identify and assess potential options for adaptation. In many urbanised river deltas, it will be necessary to make key decision on the rivers: (a) open connection: to allow rivers to flow freely into the sea and to cope with higher river water levels by increasing embankments or spatial planning related measures, or alternatively (b) closing the delta: to keep the rising sea water levels out and to invest on increased storage capacity or pumps. In some deltas, diverting water to less vulnerable areas may be an option, in others, that may not be an option due to physical limitations, lack of space or socio-economic limitations.

The best option depends on the potential SLR scenario range, societal preferences, and the balance between the available storage space and the river discharge. Illustrative, simple mass balance calculations can inform discussions on these options. Informed discussions are needed now since adaptation takes time and these options may require decision in the near-term (e.g. to avoid development in areas that are required to temporary store river discharge) and affect the future of the delta and its communities and ecosystems significantly.

ENDNOTES

[1] NAP is the Dutch reference level, which is almost equal to the current mean sea level.

[2] Design levels refer in this case to the previous safety standards valid until 2017 on which almost embankments are still designed.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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