Ministry of Infrastructure and Water Management

Sea level rise and the Netherlands: how can we keep the country safe and liveable?

Key findings of the Sea Level Rise Knowledge Programme

Sea level rise and the Netherlands: how can we keep the country safe and liveable?

Key findings of the Sea Level Rise Knowledge Programme

June 2026

The sea level rise is accelerating worldwide, including off the Dutch coast. This is one of the consequences of climate change. Since sea level rise can have major consequences for the low-lying Netherlands, the Minister of Infrastructure and Water Management and the Delta Programme Commissioner took the initiative to establish the Sea Level Rise Knowledge Programme back in 2019. After a period of six years, the Knowledge Programme has been completed and the results are now available.

The key question addressed by the Knowledge Programme was: can we keep the Netherlands safe and liveable? The focus is on protection against flooding and salinisation of freshwater. This report summarises the results and looks at what they mean for the Dutch approach.

Table of Contents

Summary

About the Sea Level Rise Knowledge Programme

The sea level rise is accelerating worldwide, including off the Dutch coast. This is one of the consequences of climate change. Since sea level rise can have major consequences for the low-lying Netherlands, the Minister of Infrastructure and Water Management and the Delta Programme Commissioner took the initiative to establish the Sea Level Rise Knowledge Programme in 2019. After a period of six years, the Knowledge Programme has been completed and the results are now available.

The key question addressed by the Knowledge Programme was: can we keep the Netherlands safe and liveable? The programme focused on protection against flooding and salinisation of freshwater. This report summarises the results and outlines their significance for the Dutch approach.

Can we keep the Netherlands safe and liveable in the centuries to come?

The short answer to this question is: for now, yes, but only under certain conditions. To continue living here, we must continuously work to improve our flood protection and be willing to keep investing in it. We will also need to cope with less freshwater: the salinisation that is already increasing will be intensified by rising sea levels.

Keeping the Netherlands safe and liveable is placing increasing demands on the limited space, energy and raw materials such as sand and clay: for increasingly higher and wider dikes, more large pumping stations, stronger storm surge barriers, dynamic land-water transition zones, modified construction methods and significantly more coastal sand nourishment. We will also need to adapt our land use to accommodate increasing salt-water intrusion in coastal provinces. At times, all this will call for complex choices that have societal consequences and require higher budgets. It will enable us to continue to live in the Netherlands, in principle up to 5 m of sea level rise.

The sea level will continue to rise, but the speed is uncertain. This also depends on worldwide carbon emissions. The faster the sea level rises, the greater the task we face. If we carefully monitor the changes in the climate, in sea level and in society, and continue to develop new and improved ways of dealing with them, we will still be able to act based on the best knowledge available. Not too soon and not too late. Even in the case of unexpected developments.

What issues are caused by the sea level rise?

As the Knowledge Programme shows, the first issues are already at play and new issues are quickly emerging. Increasingly, there is insufficient freshwater to keep all of the polders in the coastal region as fresh as they are now. This is primarily due to declining summer discharges from rivers caused by climate change. However, this salinisation will increasingly be intensified by rising sea levels. We also face the major ongoing challenge of maintaining the coastline by means of increasingly large sand nourishments and continuing to increase the height and width of the dikes.

The Netherlands will increasingly become lower relative to sea level. It will become ever more difficult to discharge surplus rain water and river water into the sea during wet periods. Currently, we are still able to discharge excess water to the sea under the force of gravity . Within just a few decades, the discharge will largely be reliant on pumps in increasing numbers of places, including the Afsluitdijk and IJmuiden. This will require more energy and increase the reliance on technology.

The storm surge barriers will need to close more often. It may become desirable to increase the closure threshold to limit the closure frequency; this will place additional demands on the dikes behind the barriers. In any case, all of the storm surge barriers will need to be replaced in the second half of this century as they will reach the end of their intended lifespan. This lifespan could potentially be extended, an issue that is currently the subject of research.

What potential ways are there for dealing with the consequences of sea level rise?

There are various options for dealing with sea level rise. We can widen the current approach or apply new solutions, such as damming the New Waterway (using megapumps to discharge the river water to the sea), transforming the Rijnmond-Drechtsteden region into a polder, establishing a large coastal lake to serve as a buffer for high river discharges, completely reopening dammed coastal inlets and allowing land-water transition zones to rise in line with the sea level. Whatever we opt to do, there will be major consequences: for shipping, ports, the space available in urban areas, safety in unembanked areas, in agriculture and in nature.

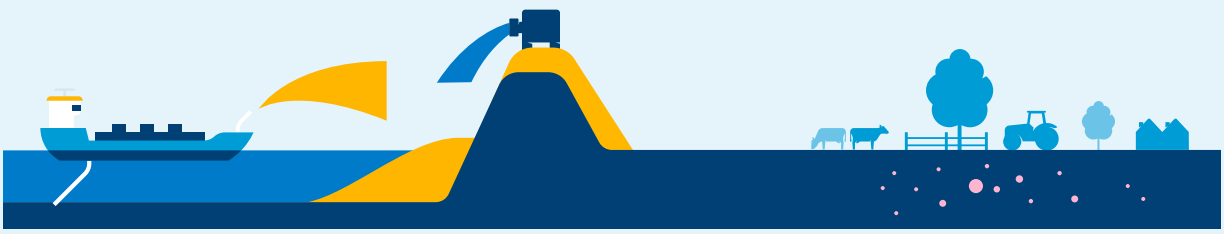
Keeping the basics in order:

Keep the coastline in place by means of more and larger sand nourishment operations.

Make dikes ever higher and stronger.

Use increasing numbers of pumps to combat excessive water and salinisation.

Combat salinisation where possible, live with salinisation where necessary.



Keeping the basics in order at all times

We can continue to protect ourselves from flooding to meet flood safety standards. Moreover, we inevitably need to deal with more severe salinisation, but this will involve an *essential precondition*. It will only be possible if we keep the basics in order at all times:

1. maintaining the coastline by means of more and larger sand nourishments;
2. continually reinforcing dikes and other flood defences;
3. extra pumping capacity to discharge water to the sea;
4. combating salinisation as efficiently as possible where this can be done and accepting increasing salinity levels where we need to.

This will ensure that the additional steps required to combat sea level rise are feasible and possible for subsequent generations.

Making choices: not too soon and not too late

From a technical standpoint it is feasible to continue our current approach for the time being, depending on the rate of sea level rise Overall, this will be less complex and radical than switching to a different strategy. But it will demand major investments and some key decisions in the short term:

- Basics in order: how will we ensure the availability of sufficient space, materials, manpower, knowledge and financial resources in order to upscale as soon as is necessary?
- Dealing with salinisation: how will we distribute the scarce fresh water in periods when it is in short supply?
- Natural processes: where will we allow land-water transition zones to rise in line with the sea level to ensure robust flood risk management?
- Rhine water distribution: how will we distribute the Rhine discharge between the Waal and the IJssel during high and low flows, for flood risk management and freshwater availability?
- IJsselmeer water levels: do we wish to create greater flexibility in the IJsselmeer level management for a larger freshwater buffer, reduced flooding and robust nature?
- Storm surge barriers: timely replacement to ensure that they continue to function effectively. The first replacements will be in the second half of this century. The Maeslant barrier (from 2070) and the Eastern Scheldt barrier (from 2080), among others, will then be reaching the end of their intended lifespan. Another question that is likely to emerge sooner is the water level at which we wish to close the storm surge barriers: should we maintain the current closure level (which means that the barriers will close more often) or increase it (which will require higher dikes and leave unembanked areas facing higher water levels)?

If we continue with the current approach in the period ahead, preparations for the second replacement of the storm surge barriers will come into view in around 100-150 years. We will then need to focus again on the future of the storm surge barriers: at the end of the next century, will we be replacing them again with even higher and stronger storm surge barriers? That is technically possible, but the impact of sea level rise on other functions will become increasingly significant, especially if the rise in sea level turns out to be rapid. Other (combinations of) solutions will then need to be considered, especially for the (former) coastal inlets and estuaries. We will need to prepare for these choices in good time:

- Will we opt for open, closable or dammed coastal inlets and estuaries? None of these are new solutions, since they are all already in use in the Netherlands. Depending on the speed of the sea level rise, this moment maybe sooner or later. In cases where we opt for a different solution, we will need to factor in a long preparation time.

Other societal and economic developments could also justify making these choices at an earlier stage.

If we continue with the current approach...

Prepare for major decisions now

- How will we ensure sand and clay remain available for sand nourishment and dike upgrades?
- How will we keep space available for dike reinforcements?
- How will we distribute the scarce fresh water?
- Enable land-water transition zones to rise in line with sea level for robust flood risk management?
- How will we distribute the Rhine water in the event of high and low river discharges?
- More flexible level in IJsselmeer for larger freshwater buffer and nature?
- Maintain or increase storm surge barrier closure levels?
- Replace all storm surge barriers: end of lifespan.

Major decisions in 100 to 150 years

For each coastal inlet/estuary:

- **Open** connection with the sea
- **Closable** with storm surge barrier
- **Dam** coastal inlet/ estuary

Or sooner, *if other developments demand it*

What next?

Thanks to the Sea Level Rise Knowledge Programme, we now understand the potential options for dealing with sea level rise, seen from the perspective of water management. However, the best approach will also depend on other spatial, economic and societal preferences and developments. Ultimately, it will involve decision-making at political level.

In order to ensure that that decision-making is effective, we will need to do the following:

1. Always be prepared for major choices: in the wake of the 1953 disaster and the threat of river flooding in the 1990s, the Netherlands was able to take effective action at incredible speed, because the plans were already in place. Also today, we need to always have effective plans in place, given the uncertainty about the rate of sea level rise. For that to happen, we will need to continually improve our knowledge about the consequences of sea level rise and the potential solutions.
2. Learn from experiences: we can take stock of 30-70 years of experience with the Delta works, other programmes, and experiences here and abroad involving adaptations in land usage in response to salinisation. Not only in terms of hydraulic engineering, but also socially, economically and ecologically.
3. Broaden the perspective: how can other stakeholders deal with the sea level rise, how do the functions interact with each other and which transitions are taking place? This can result in new insights and even provide new solutions. A cohesive perspective for the future water management of our delta that also takes account of other spatial choices can prevent disinvestments as far as possible.

1

1 Introduction

1.1 Background

The sea level is rising worldwide. This process has been happening for a very long time, but has accelerated in recent decades. In the Netherlands, this will have consequences for flood protection and freshwater availability: if we take no additional action, the risk of floods will increase and the water will become saltier in various places. The question is how we should deal with this. In order to understand this, the Sea Level Rise Knowledge Programme was launched in 2019 with four key questions, at the initiative of the Minister of Infrastructure and Water Management and the Delta Programme Commissioner (see Figure 1).

As part of this programme, government authorities, knowledge institutes and consultancies have been investigating what consequences sea level rise could have for flood risk management and freshwater in the Netherlands and what actions we can take to deal with this. The interim report on the results was published in 2023. In 2026, the Knowledge Programme was completed and the final results made available.

1.2 Purpose of this report

This report summarises the results of the Sea Level Rise Knowledge Programme and the choices that emerge from it. Appendix 3 provides an overview of the knowledge products from the knowledge programme.

The report provides an answer to the question of whether and how the Netherlands can live with sea level rise and what we can do right now to ensure that solutions remain feasible in the future. It shows which issues occur successively as the sea level rises further, what solutions will then be possible and what the consequences of these will be for living and working in the Netherlands.

Armed with this knowledge, the Netherlands can prepare for life with sea level rise. The results have been used in to the six-yearly review of the National Delta Programme scheduled for 2026: government authorities and knowledge institutes will then assess whether the course chosen by the Delta Programme is still the right one for protecting the Netherlands from flooding and water shortages now and in the future and ensuring that the water management system is made climate proof. The results will also serve as important input for the updating of water policy in the new National Water Programme.

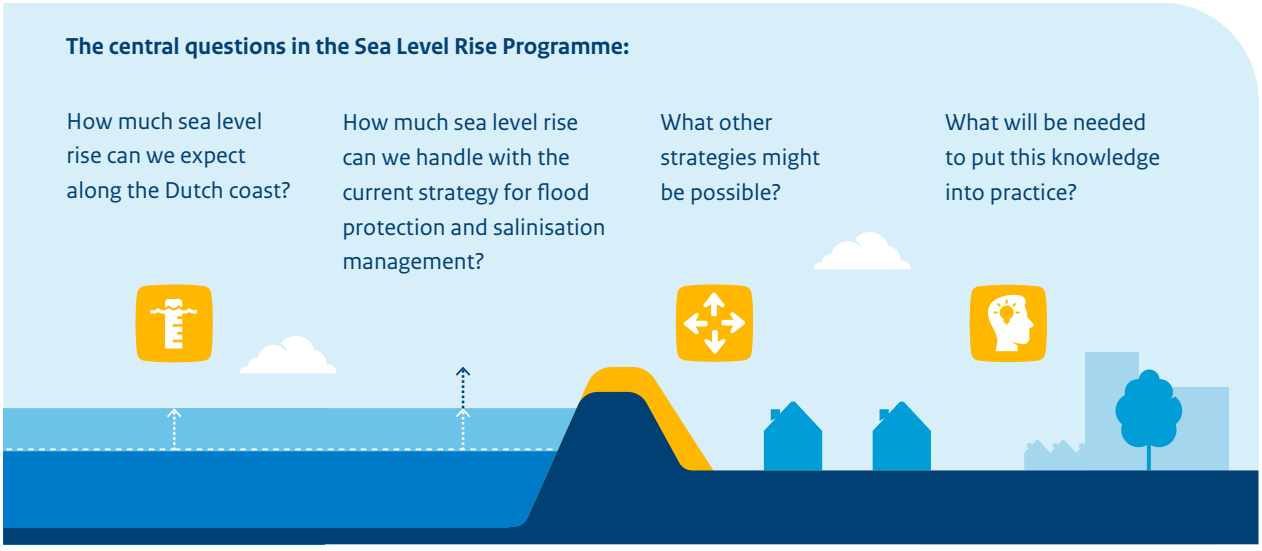


Figure 1 The central questions in the Sea Level Rise Knowledge Programme.

1.3 Programme development

The Minister of Infrastructure and Water Management and the Delta Programme Commissioner share responsibility for commissioning the Sea Level Rise Knowledge Programme. The research for it was commissioned by the Ministry and the Delta Commissioner's Staff, in collaboration with the Royal Netherlands Meteorological Institute (KNMI), Rijkswaterstaat, Deltares and other knowledge institutes and engineering consultancies. The Delta Programme regions were intensely involved in this. Four consortia developed conceptual perspectives for the long-term. The Expertise Network for Flood Protection (*Expertisenetwerk waterveiligheid*) and the Freshwater and Drought Expertise Network (*Expertise Netwerk Zoetwater en Droogte*) provided advice on the underlying assumptions and the research results.

1.4 Reading guide

Chapter 2 aims to summarise the answer to the question: can we live with sea level rise and what demands will that involve, societally and financially? Chapter 3 takes a more detailed look at the issues that result from sea level rise, in terms of flood protection and combating salinisation, and what options we have for dealing with these. Chapter 4 explores the results' significance in terms of decision-making. Central to this are the strategic choices that emerge from the knowledge programme: dealing with the uncertainty with regard to the speed of sea level rise and the considerations at play in choosing solutions.

Appendix 1 provides in-depth information about the speed of the sea level rise. Appendix 2 includes two figures that explore, in broad outline, the various issues that arise successively depending on the extent to which the sea level rises and when these issues may be expected to occur. Appendix 3 contains a list of the reports produced as part of the Sea Level Rise Knowledge Programme that also form the basis for this final report.

2

2 How will Dutch people be affected by sea level rise?

2.1 Why is sea level rise an issue for the Netherlands?

Life in a delta has significant benefits: these include a continuous supply of freshwater via the rivers, a flat land with fertile soils and strategically positioned seaports. All of this is offset by the fact that living close to the sea involves risks, especially for a low-lying country like the Netherlands: the sea can cause devastating floods. In addition, the saline sea water in a Delta naturally mixes with fresh inland water (salinisation).

Not only does this make the natural environment in the delta so special; it also has consequences for the ways in which land and water can be used. Dealing with floods and salinisation has been part of our existence since time immemorial.

But the task of protecting against floods and dealing with salinisation is made more challenging as a result of sea level rise. Figure 2 shows that the consequences will be far-reaching unless additional efforts are made.

Loss of land

We are gradually losing land because the coastline is shifting inland: waves and tidal currents will increase coastal erosion.

Risk of flooding

The chance of a flood is increasing: water levels and waves are becoming higher and our dikes and other flood defences are not equipped to handle that.

Salinisation

In coastal provinces, salinity levels of the inland waterways are frequently becoming too high for the existing agricultural use: seawater is increasingly intruding inland, via open connections (such as the Nieuwe Waterweg), sea locks and groundwater.

Figure 2 The consequences of sea level rise in the Netherlands if we take no additional action.

2.2 Will we stay safe and continue to have enough freshwater?

Key findings

The sea level is rising and this will inevitably affect us. In order to continue living in this low-lying delta, we will need to continue to improve our flood protection, upscale the current approach and be willing to continue to invest. We will also need to adapt to circumstances with less freshwater: the salinisation that is already increasing will be intensified by rising sea levels.

Keeping the Netherlands safe and liveable is placing increasing demands on the limited space, energy and raw materials such as sand and clay: for increasingly higher and wider dikes, more large pumping stations, stronger storm surge barriers, dynamic land-water transition zones, modified construction methods and significantly more coastal sand nourishment. We will also need to adapt our land use to accommodate increasing salt-water intrusion in coastal provinces. At times, this will call for complex choices that have consequences for society and cost more money. However, it will enable us to continue to live in the Netherlands, in principle up to 5 m of sea level rise.

The sea level will continue to rise, but the speed is uncertain. This will also depend on worldwide carbon emissions. The faster the sea level rises, the greater the task we face. If we carefully monitor the changes in the climate, in sea level and in society, and continue to develop new and improved ways of dealing with them, we will still be able to act based on the best knowledge available. Not too soon and not too late. Even in the case of unexpected developments.

Flood protection

Our delta enjoys excellent protection. If we continue to invest, this will remain the case, or at least up to 3 m of sea level rise and in principle up to as much as 5 m if sea level rise is not too rapid. From a technical standpoint it is feasible to continue our current approach for the time being for protecting against floods: making dikes increasingly higher and stronger, maintaining the coastline with more and larger sand nourishments, closing storm surge barriers more frequently and replacing new storm barriers in good time, providing permanent protection for residents and businesses in unembanked areas, potentially increasing water levels in the IJsselmeer area and using (more) pumps to discharge water. For such functions as shipping, port activities and agriculture, the consequences will therefore be *relatively* limited, because the structure of the water systems will largely remain the same.

However, there will certainly be an impact on society. If, in 2050, all of the primary flood defences meet the statutory requirements, as set out in the current Flood Protection Programme, we will need to continue to reinforce these defences after that. In 150 years, the sea level could be up to 3 m higher in a worst-case scenario. That would not only require the defences to be higher (by several metres), but also wider (by up to tens of metres),across a length of over 2,000 km. These flood defences are located in the densely built-up Rhine-Meuse estuary, along the major rivers (up to far upstream), the Eastern Scheldt and the Western Scheldt and the mainland coast of the Wadden Sea. The space required for the dike reinforcements is currently in use for other purposes and will also compete with demand

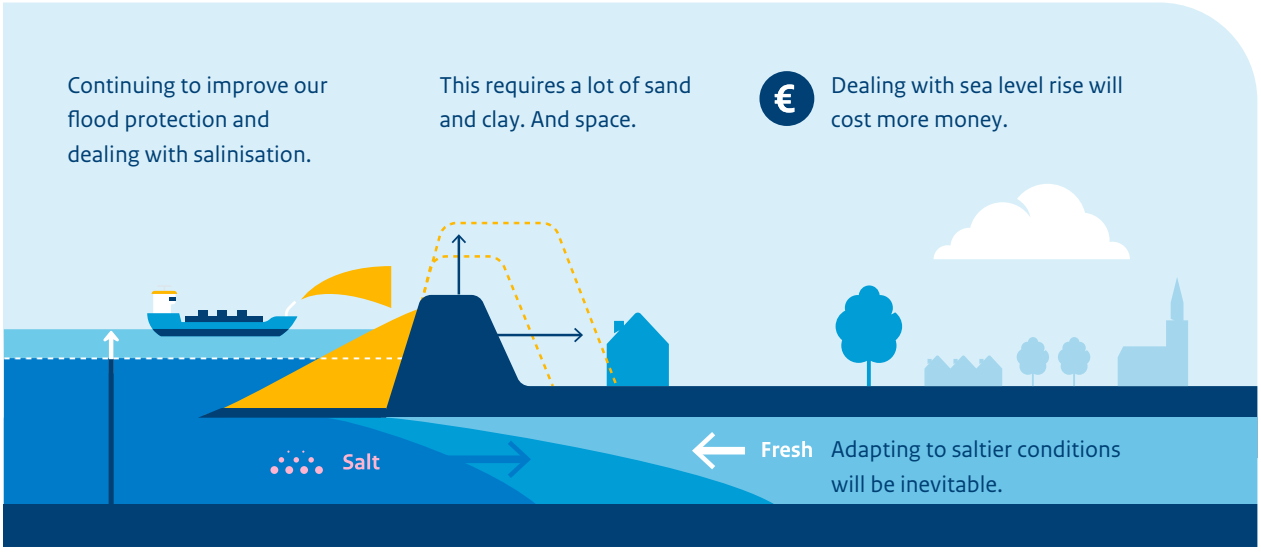


Figure 3 The conclusion of the Sea Level Rise Knowledge Programme in broad outline.

compete with demand for space to accommodate new housing, infrastructure and nature. At the end of this century, we will need to replace all of the storm surge barriers with new ones as they reach the end of their lifespan; this will require major investments. For coastline maintenance, the increased need for North Sea sand could be more than three times the current requirement in 150 years. Widening the possibilities for extracting it will be extremely complex, partly because of the many cables and pipelines, and will compete with demand for sand for onshore infrastructure.

If we continue with the current approach for the time being, preparations for the second replacement of the storm surge barriers will come into view in around 100-150 years. From a technological point of view, it will still be possible to continue the current approach (building higher, stronger storm surge barriers), but the interventions required and the impact of sea level rise on other functions will continue to increase. By then other solutions ought to be considered, especially in the Rijn-Maas estuary and along the lower reaches of the Lek, Waal and Maas: in this heavily urbanised area, we will not only need to cope with the rise in sea level, but also continue the safe river discharge to the sea. Other solutions could include: damming the New Waterway (using megapumps to discharge the river water to the sea), transforming the Rijnmond-Drechtsteden region into a polder, establishing a large coastal lake to serve as a buffer for high river discharges, completely reopening dammed coastal inlets and allowing land-water transition zones to rise in line with sea level. Every solution we opt for will involve major consequences: for shipping, the port, the space available in urban areas, safety in unembanked areas and in nature. The consequences of each solution may turn out positively or negatively for different functions.

Salinisation and freshwater

We limit salinisation in coastal provinces by using fresh river water to push the salt back and flush it out to sea. In dry summers, this approach is already reaching its limits: in recent years, there have been several occasions when there has been insufficient freshwater to meet demand. This is going to happen with increasing frequency. The effect of climate change means that there will be less fresh river water to combat salinisation in the short term and the amount of saltwater in our water systems will gradually increase as the sea level rises. By taking additional measures, we can reduce or delay the salinisation to some extent: more effectively holding back the salt at sea locks, flushing salt water back to sea more efficiently, distributing the river water in a different way and increasing the freshwater buffer in the IJsselmeer area. Salinisation will continue to increase despite these measures and freshwater shortages will increase in dry summers.

From 0.5 m of sea level rise, twice as much fresh river water will be needed in a dry summer to ensure that all polders susceptible to salinisation remain as fresh as they currently are. If we use all of this water to continue to flush the polders, this will affect the availability of freshwater elsewhere in the country. Settling for a higher salinity in a number of polders could be an option, ensuring that more freshwater remains available for other areas and users. This could have consequences for existing cultivation and nature in the areas subject to saltwater intrusion. Moving forward, more advanced solutions may emerge, such as allowing the bed of the New Waterway to rise in line with the rise in sea level (while maintaining navigable depth) or even periodically closing off river branches in Rijnmond-Drechtsteden. Even with these methods, further salinisation can ultimately not be prevented. Whatever solutions we choose, we will always need to live with the fact that there will be less freshwater in the summer and higher salinity levels in coastal provinces.

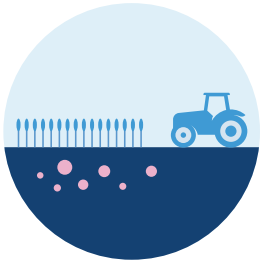
The increasing salinisation also has consequences for the use of space. In areas susceptible to salinisation, we will need to adapt our land use in order to cope with higher salinity levels and larger peaks in those levels. Measures aimed at continuing to combat salinisation as effectively as possible will require additional space: for example large pumps at locks and discharge sluices and more extensive infrastructure to flush waters that are affected by salinisation.

2.3 How will living and working in the Netherlands change?

Despite the sea level rise, we will be able to continue living in the Netherlands for at least the coming centuries. However, the sea level rise will have consequences for residents, businesses, social sectors and nature. We will have to face some of the consequences whatever happens, whereas others will depend on the measures we take on flood risk management and dealing with salinisation.

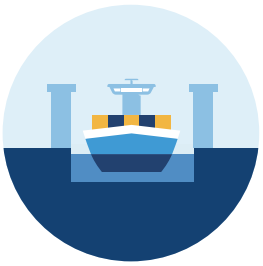
The consequences of sea level rise will not happen overnight. We have time to adapt functions to fit the new circumstances. In any case, part of the impact can be limited by means of additional measures. What is certain is that, without measures to manage the risk of flooding and availability of water, the impact will be much greater: there will a higher probability of flooding and a stronger increase in salinisation.

In any case, sea level rise will have the following consequences for working and living in the Netherlands:



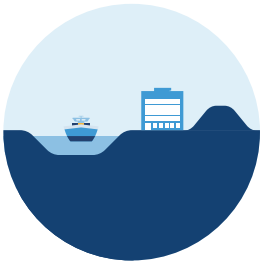
Agriculture and horticulture

We cannot prevent the salinisation of part of the low-lying Netherlands, especially polders in the coastal provinces.
Current land use such as farmland and nature areasare often vulnerable to salinisation and greater fluctuations in salinity levels. Adapting to these kinds of conditions will be unavoidable.



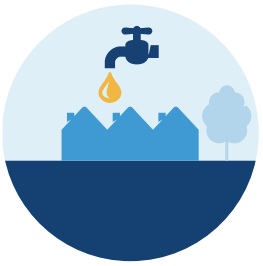
Shipping and ports

Storm surge barriers will gradually need to close more frequently. Every closure will result in delays for shipping. Ports will not always be accessible. It is possible to limit the number of closures by closing storm surge barriers at a higher water level, although this will require higher dikes.



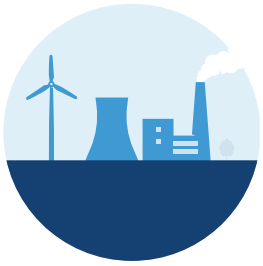
Buildings and activities in unembanked areas

Without any additional measures, unembanked areas in the Rhine-Meuse estuary will be flooded more often and ultimately permanently, especially if we start closing storm surge barriers at a higher water level (see above). This can cause serious damage to housing and businesses and increasing safety risks.



Drinking and cooling water

The water at some freshwater intake points will exceed the standard of 150 mg of chloride per litre. The drinking water sector will need to adapt in response, by means of desalination or relocating intake points, for example. The freshwater lenses in the dunes will reduce in size, which will have consequences for drinking water companies who use them to store and treat drinking water. The salinisation of cooling water intakes will also call for adaptations in industry.

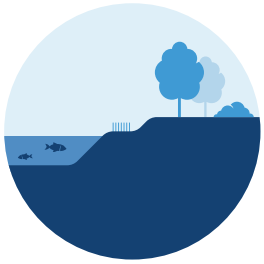


Energy supply

We will need to use more pumps and pumping stations to protect against flooding and to discharge water affected by salinisation. This will require investment in construction and maintenance and consumes energy. This also applies to other methods of salinity management, such as bubble curtains (salinity barriers) and structures for flushing.

Water management

Water management will become even more intensive. The increasing reliance on technical management measures, such as pumps, will require more management and maintenance, more energy and effective protection against disruption and terrorism.



Nature

As water levels rise, valuable intertidal areas and land-water transition zones will become submerged, threatening birdlife. Extracting more sand for sand nourishment will probably have more impact on nature in the North Sea. The increasing use of pumps will make it more difficult for migratory fish to swim to and from their breeding areas. Closing the Eastern Scheldt barrier more frequently will have negative consequences for the ecological quality of the Eastern Scheldt. In various places, salinity levels will be subject to greater fluctuation, with higher peaks. The existing natural environment will not always be able to withstand this.

These consequences will inevitably result in transitions This need not be negative: transitions can create opportunities for mobilising other desired or necessary developments at the same time. Moreover, other countries will face similar transitions. Gaining knowledge and experience of new solutions and transitions is therefore likely to offer opportunities to export knowledge and expertise and for effective collaboration and coordination with neighbouring countries.

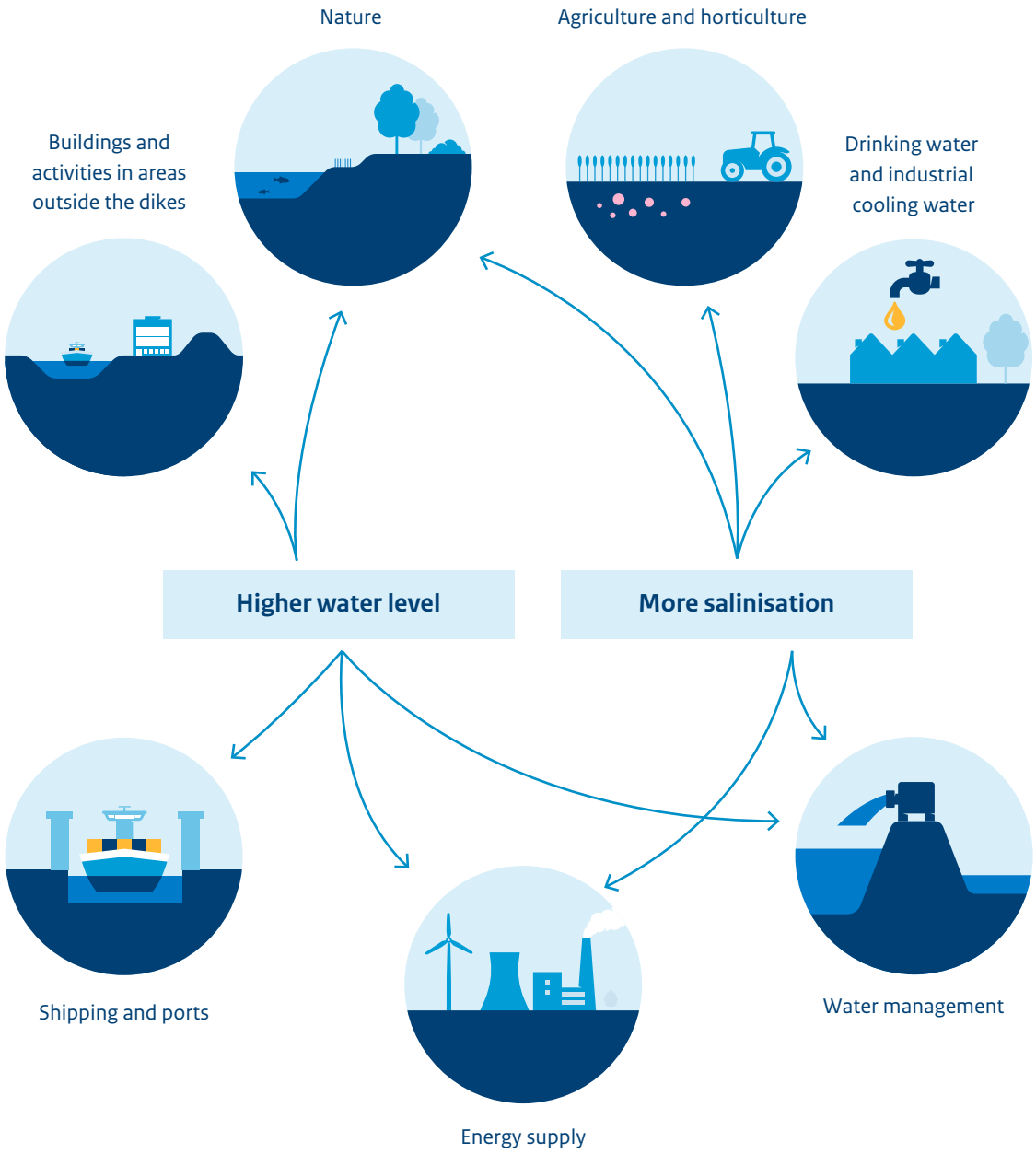


Figure 4 Various functions will face consequences as a result of the higher water levels and salinisation caused by the rise in sea level. The figure shows this link for a number of functions explained in the text. It is not the full picture of the consequences.

2.4 Will flood risk management and ensuring water availability remain affordable?

Sea level rise is set to cost us and future generations more money. However, effective protection against flooding and salinisation will still be affordable, assuming that the Netherlands remains a relatively prosperous country in the future.

Increasing costs

If we intend to maintain flood protection at the current statutory level and limit salinisation as far as possible, the efforts required to achieve this will increase as the sea level rises further. The costs of flood risk management and freshwater will increase. The annual costs for dike reinforcements will remain around the same level as the current Flood Protection Programme and can be expected to increase by 1.5-2 times over time. Sand nourishment will cost 3-7 times as much as now, depending on the speed of the rise in sea level. There will also be increasing costs for pumps, protecting unembanked areas, combating salinisation, distributing the available freshwater and making adaptations to the existing network of smaller regional waters. Changes to the way in which land is used, because of salinisation, for example, could also involve additional expenditure.

There are various ways in which we can approach flood protection and salinisation (see 3.3). The costs will vary depending on the solution but will be in the same order of magnitude, providing that the chance of flooding remains at the current statutory level. How the costs are spread over time may however change.

For now, we are effectively able to protect all parts of the Netherlands from floods. Relocating residents and activities to high areas of the Netherlands is not necessary for now and would in any case make little sense economically: relocating housing, businesses and land use will cost substantially more than continuing to invest in dike reinforcements in low-lying areas of the Netherlands. During any such transition, we would need to continue to guarantee protection from flooding in low-lying areas of the Netherlands. Should we fail to do that, the likelihood of floods would increase during the transition. This would result in major social unrest and financial uncertainty. In that case, investing in liveability and amenities in low-lying areas of the Netherlands during the transition, with a population that is shrinking, would be very difficult. Relocation will only prove necessary if the sea level continues to rise very significantly in the very long term.

The benefits will continue to (significantly) outweigh the costs

The benefits of the measures set against the costs: the country will remain safe and liveable and we will maintain a reliable flood risk management system and robust freshwater supplies. Currently, the benefits far outweigh the costs: we have a very cost-effective way of protecting ourselves from damage by water. It would appear that this will remain the case in the future, although it may start to become more expensive. Some of the transitions initiated (in part) by sea level rise can also prove beneficial for society. If we were to opt to relocate residents and businesses from the low-lying Netherlands (see above), the costs and benefits would become severely imbalanced.

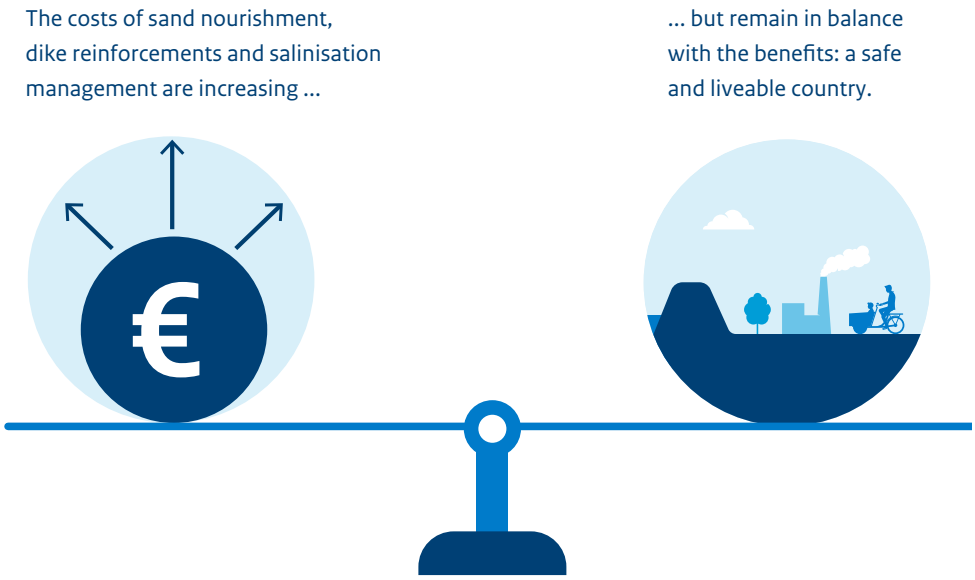


Figure 5 The cost of reliable flood risk management and robust freshwater supplies will increase, but will be outweighed by the benefits.

3

3 In depth: what issues will emerge as a result of sea level rise and how can we deal with them?

3.1 How quickly will the sea level rise?

Sea level rise is the consequence of climate change. The oceans are expanding as a result of global warming and continental ice sheets are melting. We cannot accurately predict how quickly the sea level will rise. This will depend on the speed of climate change. This itself will depend on worldwide carbon emissions in the coming decades.

High and low scenarios

Although there are plenty of plans for limiting carbon emissions, the extent to which worldwide emissions will actually change is uncertain. Because of this, the International Panel on Climate Change (IPCC) is drawing up a range of scenarios for climate change in which carbon emissions increase or decline to a greater or lesser extent. The KNMI is adapting these global scenarios into scenarios for climate change in the Netherlands. These scenarios are regularly adjusted in line with new knowledge. The most recent climate scenarios are from 2023. Each scenario includes forecasts for the rise in the sea level off the Dutch coast (see Appendix 1).

The KNMI'23 scenarios show the predicted bandwidth for the sea level rise of the Netherlands. This bandwidth is based on a scenario with low carbon emissions and a scenario with high carbon emissions (see also Appendix 1):

- Optimistic view: low scenario. There will be only limited sea level rise in the scenario in which greenhouse gas emissions significantly decline (scenario SSP1-2.6). In this scenario, the sea level off the Netherlands will have risen by around 50 cm by 2100 compared to the average sea level from 1995 to 2014.

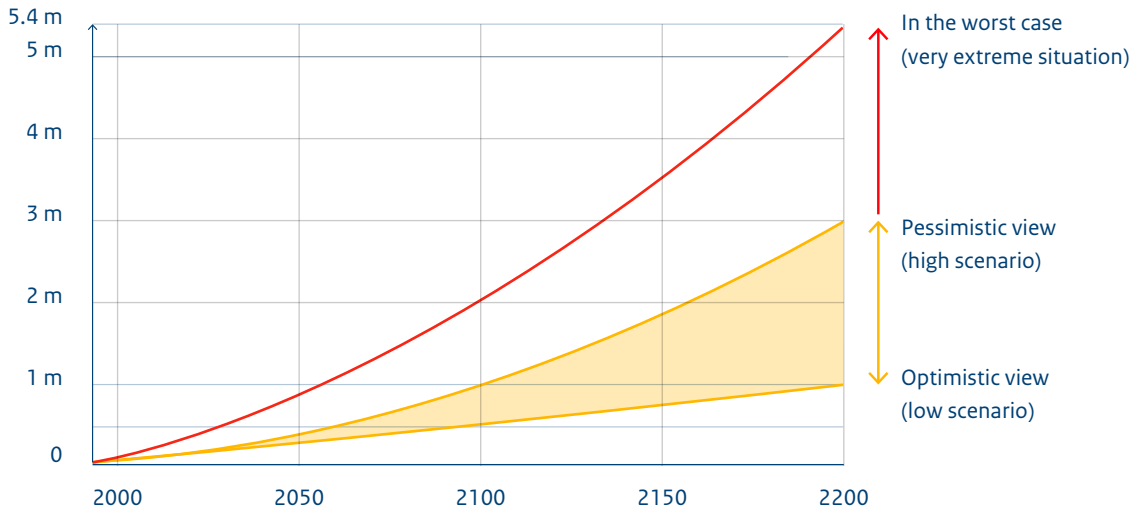


Figure 6 Scenarios for sea level rise off the coast of the Netherlands. The yellow zone indicates the bandwidth forecast for the average rise in sea level, depending on worldwide carbon emissions. This is the bandwidth between the high and low scenarios (see also Figure 18 in Appendix 1). The conclusions in this report are based on this bandwidth. The red line indicates how rapidly the sea level will rise if the Antarctic ice sheet becomes unstable. This extreme situation was used as a stress test in this report.

- Pessimistic view: high scenario. A sharp rise in sea level will occur in the scenario in which no measures are taken to reduce greenhouse gas emissions (scenario SSP5-8.5). In this scenario, the sea level off the Netherlands will have risen by around 1 m by 2100 compared to the average sea level in the period 1995-2014.

The issues caused by sea level rise discussed in this report are based on the bandwidth between this low and high scenario for carbon emissions.

Worst-case scenario

The speed at which the Antarctic ice sheet melts will have a significant influence on the speed of sea level rise. There are signs that this ice sheet could become unstable, accelerating the speed of melting. Based on the literature, the KNMI has extrapolated what the maximum speed of the sea level rise could be in that case. In this very extreme case, the sea level off the Dutch coast could have risen by 2 m by 2100 and by more than 5 m by 2200. This situation has not been factored into the scenarios with high and low emissions. The likelihood of this actually happening is small, but the consequences are major. The Sea Level Rise Knowledge Programme has used this knowledge for the purposes of a stress test: what if this actually becomes a reality (see 3.4)?

Influence of river discharge and subsidence

Because of climate change, the discharge from the major rivers will change: river discharge is expected to be higher in winter and lower in summer. In much of the country, this change will coincide with the consequences of sea level rise. The combination of sea level rise and higher river discharges in winter will make the task of flood protection more difficult: the combination of sea level rise with lower river discharges in summer will make the task of dealing with salinisation more difficult (see Figure 7). This is why the Sea Level Rise Knowledge Programme has included work with scenarios for river discharges.

Because of climate change, evaporation will increase in the summer and precipitation will decline. This will increase the water demand for the purposes of water level management and irrigation. The effect of the changes in the demand for water on salinisation has been taken into account in the analyses.

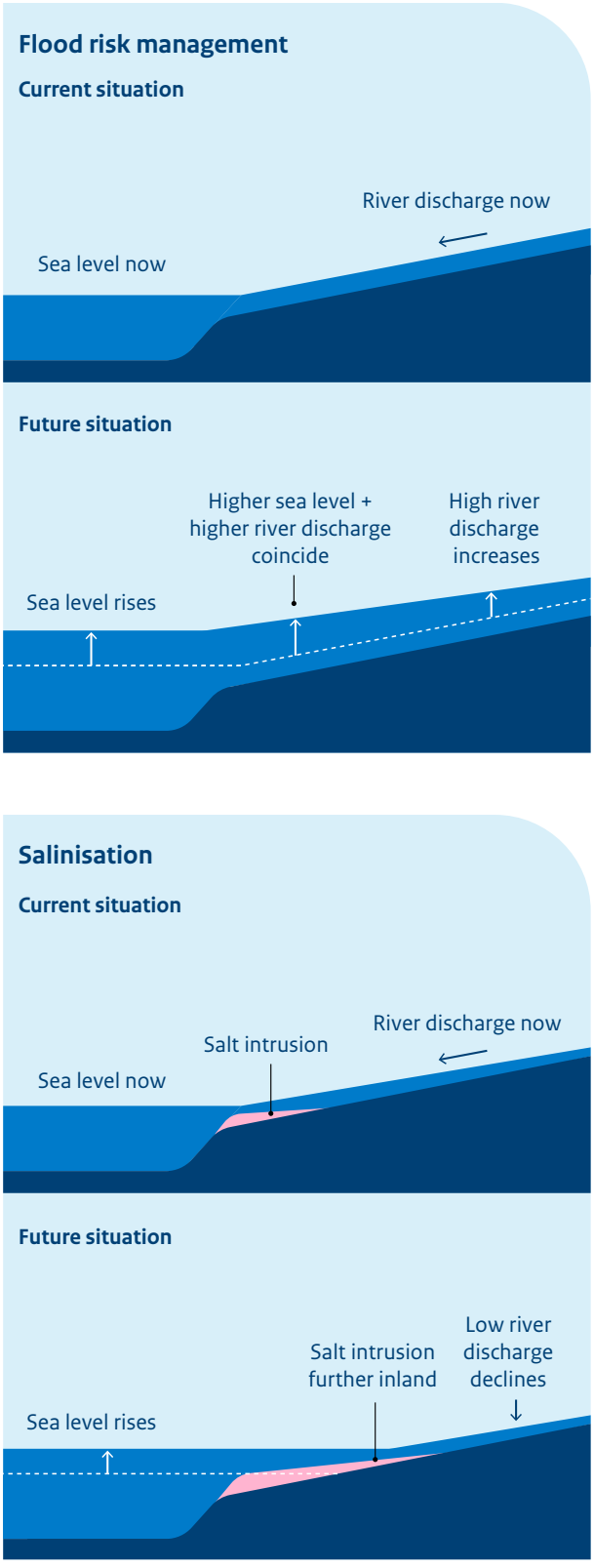


Figure 7 River discharges will change as a result of climate change. This will intensify the challenges created by sea level rise.

For various reasons, the land in the Netherlands is subsiding in some places more than others. At local level, the combination of subsidence and sea level rise can intensify the challenges involved in protecting against flooding and dealing with salinisation. This is why the Sea Level Rise Knowledge Programme takes account of the future subsidence.

3.2 What successive issues will emerge as a result of sea level rise?

As the sea level gradually becomes higher, new issues relating to flood protection and combating salinisation will occur successively. Figure 8 shows these issues in broad outline. This assumes that we will maintain flood protection in line with the current approach and statutory standards and aim to keep freshwater fresh for as long as possible in order to meet the demand for water. This section looks at the issues in more detail.

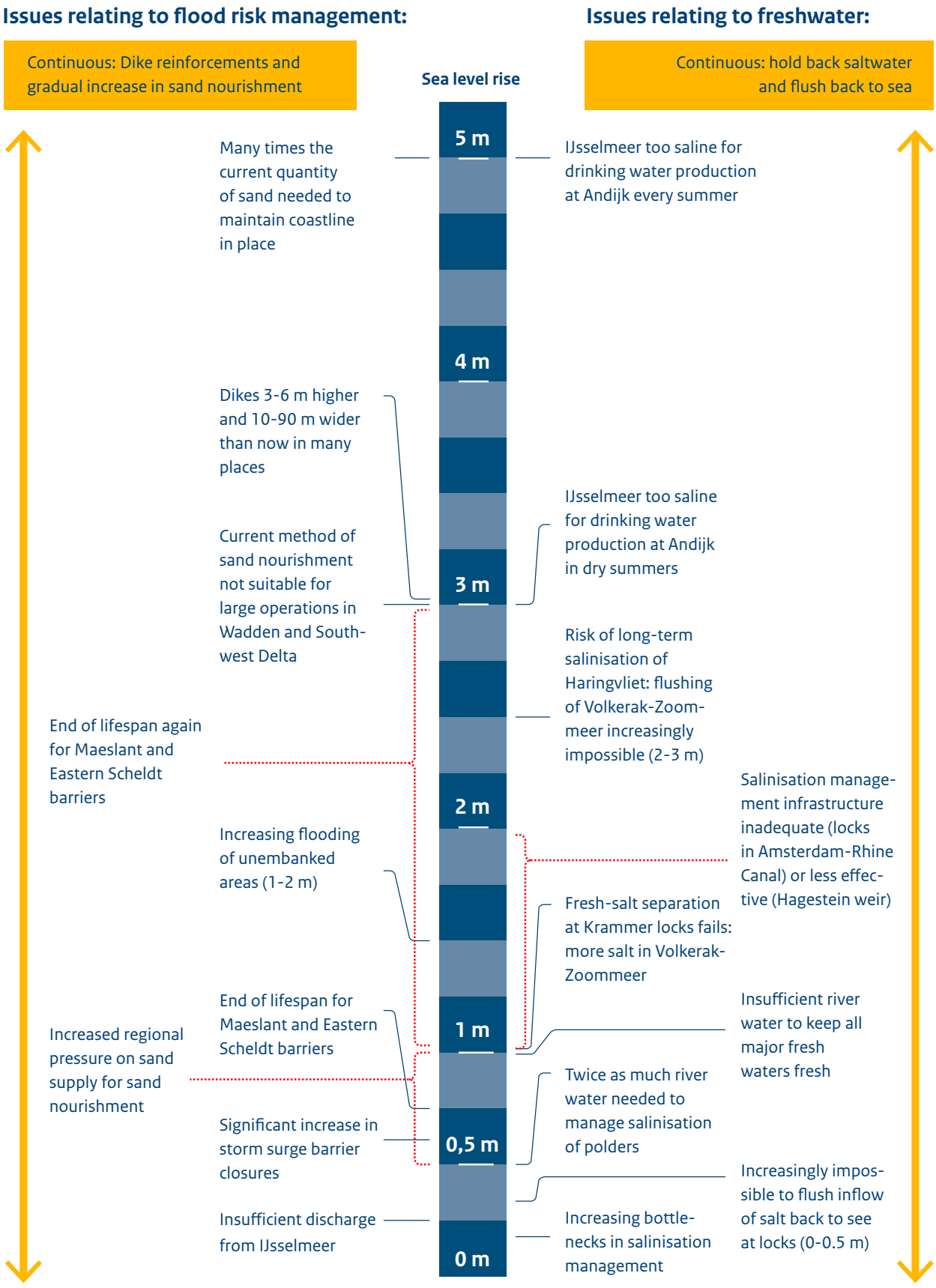


Figure 8 The figure shows which issues will emerge in the current approach to flood risk management (left) and freshwater (right) as the sea level continues to rise.

The speed of the rise in sea level will determine when these issues occur. Figure 9 provides an indication of this, based on the climate scenarios described in 3.1 (bandwidth between the low and high scenario).

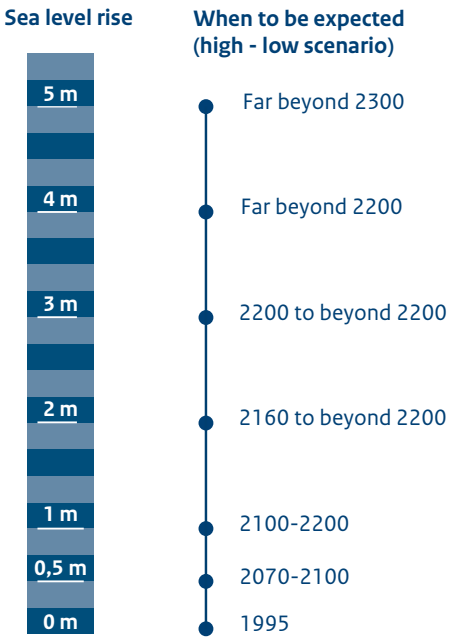


Figure 9 Indication of the timescale in which a certain degree of sea level rise can be expected based on the bandwidth between the low and high scenario for sea level rise (see 3.1).

Issues relating to flood protection

From now on, ongoing efforts will be required to keep the dikes in order and the coastline in place. Without new dike reinforcements and increasingly larger sand nourishments, the risk of flooding will increase and we will lose land along the coast. By 2050, the current Flood Protection Programme for dike reinforcements will have been completed. All of the primary flood defences will then meet the statutory standards, but that will not remain the case. Dikes generally last 50 to 100 years and sea level rise means that increasingly higher and stronger dikes will be needed, especially in combination with higher river discharges and subsidence. In order to maintain the coastline, we are currently replenishing 11 million cubic metres of sand every year. As the sea level rises further and faster, more sand will be needed.

Even before 0.5 m of sea level rise, it will no longer be possible to discharge excess water from the IJsselmeer fast enough into the Wadden Sea. The discharge sluices and pumps now in place do not have sufficient capacity for that. In the event of high discharge from the IJssel and a lot of rain, the water level in the IJsselmeer will frequently exceed the agreed level. This can lead to flooding in surrounding areas. At 0.5 m of sea level rise, similar problems will emerge with the discharge of water at IJmuiden (based on the existing pumps) and the Krammer locks and at 1 m of sea level rise, the Bath discharge sluice will be affected. This could lead to flooding around the Amsterdam-Rhine Canal and North Sea Canal and the Volkerak-Zoommeer.

From 0.6 m of sea level rise, the storm surge barriers will close so often that this will threaten operational management. The barriers will need to close more often because the closure level will occur more frequently due to sea level rise. This will accelerate wear and tear. More frequent closures will also have consequences for shipping (Rhine-Meuse estuary) and nature (Eastern Scheldt).

At 0.7 m of sea level rise, the Maeslant barrier (from 2070) and the Eastern Scheldt barrier (from 2080) will be reaching the end of their intended lifespan. These storm surge barriers are crucial for flood protection in the Rhine-Meuse estuary and around the Eastern Scheldt.

Even before 1 m of sea level rise is reached (around 2100), it will no longer be possible to extract the North Sea sand needed for coastal nourishment within the existing reservation zone. In the reservation zone (NAP -20 m up to 12 nautical miles from the coast), there is sufficient sand present. However, this is not available for sand extraction in some areas partly as a result of cables and pipelines, unexploded ordnance and protected nature.

At 1 to 2 m of sea level rise, the higher water levels will frequently cause flooding and sometimes even safety risks in unembanked areas. These are the unprotected riparian zones on the waterside of the dikes. In the Rhine-Meuse estuary in particular, the higher-lying unembanked areas are intensively used. By 2030, there will be approximately 40,000 homes there, with around 60,000 residents and many businesses.

At 1 to 3 m of sea level rise, the storm surge barriers that were replaced at 0.7 m of sea level rise will again reach the end of their functional lifespan (end of the next century).

From 3 m of sea level rise, other methods will be needed to replenish sand along the North Sea coast for the Southwest Delta (Voordelta) and the Wadden Islands. It will not be possible to replenish the required amount of sand rapidly enough using the existing nourishment methods (on the foreshore and the beach). This will still be possible for the Holland Coast area.

At 3 m of sea level rise, the dikes will need to be 3 to 6 m higher in many places than on the completion of the dike reinforcement programme currently running (Hoogwaterbeschermingsprogramma). During each round of dike reinforcement, most dikes are not only made higher, but also wider. At around 3 m of sea level rise, this will require a strip of tens of metres (10-90 m and locally even more). Especially in urbanised areas, most of this space is built up.

At 5 m of sea level rise, much more sand will be needed to maintain the coastline: off the Holland Coast area, we will need to replenish 2.5 times as much sand as now, 3.5 times as much for the Southwest Delta and around six times as much for the North Sea coast of the Wadden Islands.

Issues caused by salinisation of freshwater

From now on, salinisation management will face more frequent problems in dry summers. The Netherlands' position close to the sea means that saltwater intrudes inland, via estuaries, sea locks and seepage. We combat this salinisation by pushing the salt back and flushing it away with fresh river water. Because of climate change, the amount of river water in the summer is decreasing. This is already causing issues with salinisation in very dry summers, and these will worsen as the sea level rises further and there is more salt intrusion inland.

Somewhere between now and 0.5 m of sea level rise, there will be several sea locks where discharge via gravity will no longer be effective as a means of flushing the salt intrusion that enters as ships pass: at the locks in the Afsluitdijk, the sea lock at IJmuiden and the Krammer locks. In dry summers, the salinity levels in the IJsselmeer, Amsterdam-Rhine Canal and the Volkerak-Zoommeer will temporarily increase as a result of this.

From 0.5 m of sea level rise, twice as much fresh river water will be needed in a dry summer to ensure that all polders susceptible to salinisation remain as fresh as they currently are. The use of this additional river water will affect freshwater availability elsewhere, requiring choices to be made with regard to distribution.

Around 1 m of sea level rise, there will not be sufficient river water to ensure all major freshwater systems are kept fresh and make sufficient water available for water users.

At around 1 m of sea level rise, the fresh-salt separation system installed at the Krammer locks in 2025 will no longer be able to operate. This will result in additional salt in the Volkerak-Zoommeer (the most important freshwater buffer for the Southwest Delta) and demand for freshwater for flushing the lake will increase.

From 1 to 2 m of sea level rise, substantially more river water will be needed to combat salinisation of polders in the Rhine-Meuse estuary, even in less dry periods (when there is still sufficient river water). The infrastructure used to get water into the Rhine-Meuse estuary will have insufficient capacity from 1 to 2 m of sea level rise. Locks affected will include those in the Amsterdam-Rhine Canal (Bernhard locks and Irene locks).

At between 1 and 2 m of sea level rise, the weir at Hagestein will no longer be able to operate. This will remove the control mechanism for directing river water to the Lek as a means of combating salinisation. The upstream effects still remain uncertain.

From 2 to 3 m of sea level rise, the risk of long-term salinisation of the Hollandsch Diep will increase significantly in a dry summer. As a result of this, flushing the Volkerak-Zoommeer with freshwater will become impossible increasingly often.

From 3 m of sea level rise, the water in the IJsselmeer at the Andijk drinking water intake point will regularly exceed 150 mg of salt per litre in a dry summer. This will make the water too saline for current drinking water treatment methods. This will happen every summer from 5 m of sea level rise.

3.3 What is the range of potential solutions?

The Netherlands has a history of water management that dates back for centuries. In broad outline, we have applied three key strategies, often in combination: taking advantage of natural processes (e.g. in land reclamation), using technical means to direct, hold back and manage the water (such as weirs, dams and storm surge barriers) and adapting spatial planning and the way we configure land use in line with changing conditions (e.g. adapting cultivation to cope with increasing salinisation).

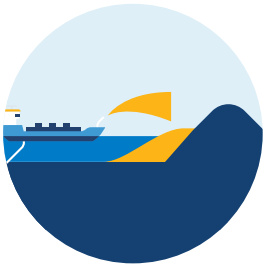
The current approach to flood risk management and fresh-water features elements of all three strategies. The Sea Level Rise Knowledge Programme has investigated whether we will be capable of dealing with the rise in sea level if we continue the current approach and whether there are other options. Overall, this endeavour has highlighted the range of potential solutions for tackling the issues caused by sea level rise.

Continuing the current approach

Continuing the current approach will mean:

- we continue to protect ourselves from floods by means of coastal sand nourishment and strong dikes, dams and storm surge barriers;
- in the future, the Eastern Scheldt and the Nieuwe Waterweg will maintain an open connection to the sea under normal conditions and we will use storm surge barriers to close them in the event of a storm surge;
- we will use river water to hold back saltwater and flush it to the sea and distribute the freshwater as effectively as possible across the country.

The Sea Level Rise Knowledge Programme has investigated the possibilities and consequences of continuing on this course, up to a sea level rise of 5 m. The most important results are summarised on the next two pages.

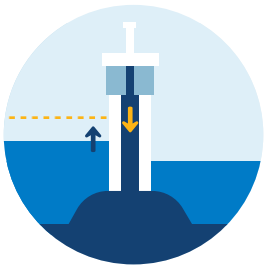


More sand nourishment, stronger dikes

Part of the existing policy involves maintaining the coastline and ensuring that the dikes always meet the statutory standards. As the rise in the sea level increases, we will need to replenish more sand along the coast and make the dikes higher and wider. This will enable us to continue to protect against flooding at least up to 3 m of sea level rise and in principle up to as much as 5 m if sea level rise is not too rapid.

Currently the coastal sand is replenished on the foreshore or directly on the beach. For large quantities of sand, relatively new methods such as sand motors (*zandmotoren*) and nourishments between the Wadden Islands (on ebb-tidal deltas) will be used; these have already been the subject of successful experiments.

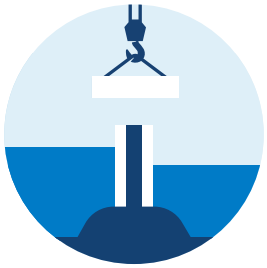
Sizeable quantities of North Sea sand will be needed for the nourishments. The dike reinforcements will involve the use of large quantities of sand and clay. Ensuring that the dikes are made sufficiently sturdy also requires space. At 3 m of sea level rise, this will require an additional strip of 10 to 90 m and locally even more.



Closing storm surge barriers more frequently or at a higher water level

As the sea level rises, the storm surge barriers will close more frequently, if we maintain the current closure level. This will accelerate the wear and tear of storm surge barriers and operational management will become more difficult. We can limit the number of closures by gradually increasing the closure level. This has advantages for the lifespan of the storm surge barriers. The disadvantage is that the water level in the Eastern Scheldt and the Rhine-Meuse estuary will increase, necessitating higher and wider dikes and causing unembanked areas to be affected (even) more often by even higher water levels.

The effect of this in Rijnmond-Drechtsteden will be particularly far-reaching: there is little space there for dike reinforcements and the unembanked areas are subject to intensive use. If additional measures are applied, the water level in Rijnmond-Drechtsteden could be reduced by several decimetres when the barrier is closed, for example by pumping some of the river water out to sea and/or expanding the existing emergency storage in the delta waters. The impact of measures of this kind will rapidly decline if the sea level continues to rise.



Replacing storm surge barriers when they no longer function

Part of the current approach involves replacing infrastructure such as storm surge barriers when they have reached the end of their lifespan (after 100 years) or if they are no longer sufficiently safe for other reasons (e.g. because of sea level rise). The new storm surge barrier will be stronger and higher, in order to match the anticipated rise in sea level and river discharges in the next hundred years. The storm surge barriers in the New Waterway, Haringvliet and Eastern Scheldt are due for replacement for the first time in the course of this century (see 3.2). The preparation, decision-making and realisation involved in these replacements takes 20-30 years. Replacement requires substantial investments. It may be possible to delay the timing of replacement by means of limited measures.

Protecting unembanked areas from flooding

Unembanked areas will face higher water levels as a result of sea level rise. Up to around 1 m of sea level rise, it will be possible to limit the risk to housing and businesses in unembanked areas by means of relatively simple and low-cost measures, such as flood gates, valves and mobile barriers. After that, structural measures such as quay walls or land elevation will need to be considered or the methods highlighted above for reducing the water level (emergency storage, pumps).

Increasing numbers of pumps

When the water level in the IJsselmeer is at risk of becoming too high, we allow the water to flow away into the Wadden Sea. Currently, this can largely be discharged under gravity, but the rise in sea level means that we already need to use the pumps in the Afsluitdijk more often and increasing numbers of pumps are needed. This results in increased energy consumption. We can continue slightly longer discharging under gravity by increasing the average winter water level (in day-to-day conditions) by 30 cm after 2050; this option has been left open in the current policy. From 1 m of sea level rise, the water discharge will, nevertheless, be entirely reliant on pumps. By continually adding pumping capacity, we will be able to maintain the (heightened) water level up to 5 m of sea level rise. On the sea-facing side of the Afsluitdijk, the water level will then be permanently (much) higher than on the IJsselmeer side.

We will gradually need to increase the use of pumps for water discharge at all sea locks and discharge sluices. Eventually, we will be completely reliant on pumps for these, for example at IJmuiden (from 0.4 m of sea level rise), the Krammer locks (from 1.5 m of sea level rise) and Bath (from around 2.5 m of sea level rise). For salinisation management, the use of pumps will become effective even earlier.

Combating salinisation and adapting land use

As a result of the rise in sea level, there will be more salt intrusion via the New Waterway (which is in open connection to the sea) and the sea locks (sluice gates and discharge sluices). Saltwater seepage (when old seawater seeps upwards from the ground) also increases the salinity of surface water. The current approach involves using fresh river water to flush away the salt as much as possible. Because of climate change, the amount of water flowing through the rivers will gradually reduce and the demand for water for irrigation and water level management will increase. As a result of this, it will be increasingly difficult to keep the water as fresh everywhere as it is now. If this becomes a serious issue, we can opt for a deliberate and controlled reduction in the freshwater content of parts of the main water system and/or polders in coastal provinces. This way, salinisation can occur in a more predictable way and other parts can remain fresh more often. Where salinisation occurs increasingly frequently in the summer, changes in land use and nature management will be inevitable.

Other options

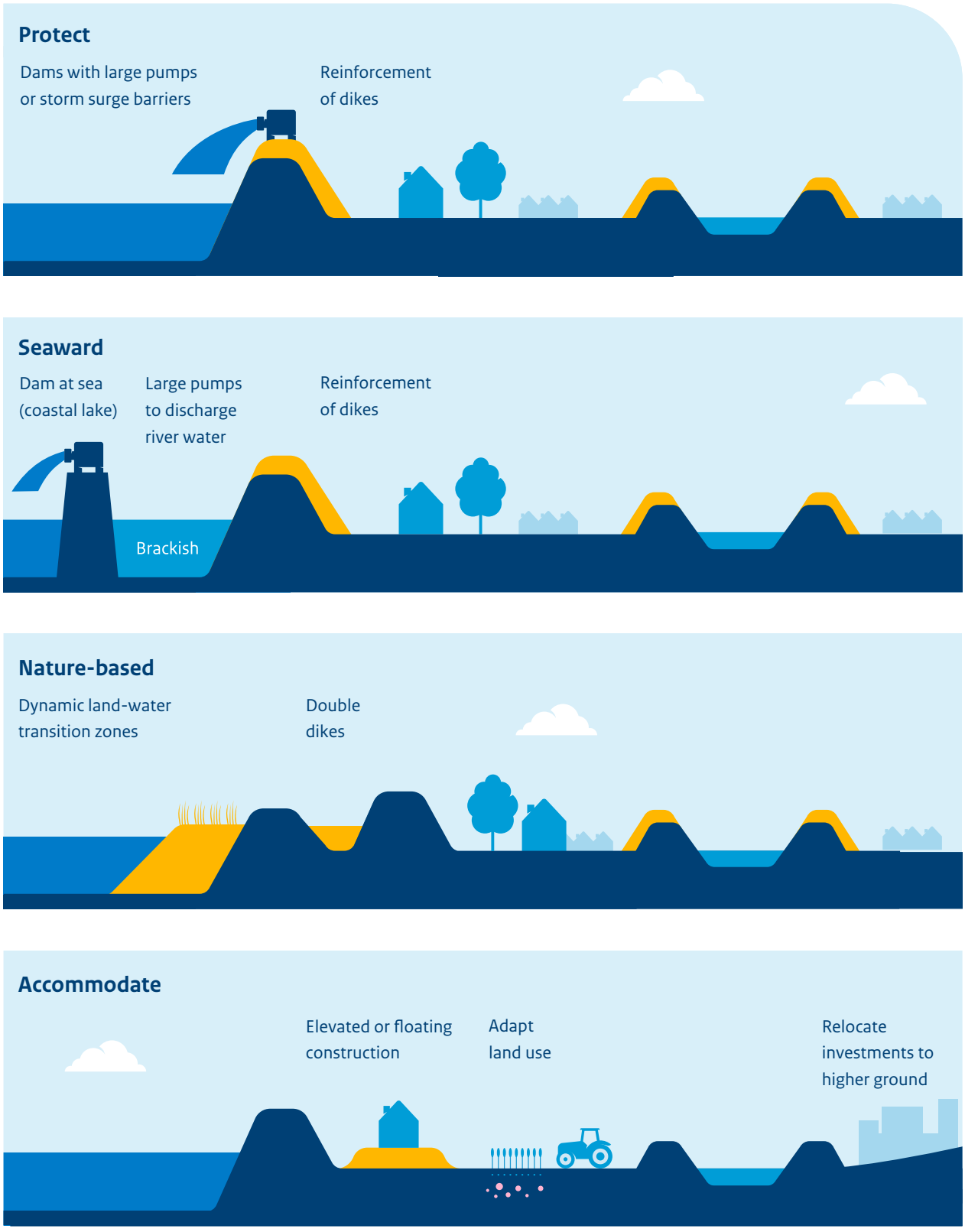
As well as continuing the current approach, there are other potential options for combating sea level rise. The Sea Level Rise Knowledge Programme has commissioned the development of a number of conceptual long-term perspectives (2 and 5 m of sea level rise) that include many of the range of potential measures:

Accommodate, Protect, Seaward and nature-based. Each perspective includes its own combinations of the three strategies traditionally applied in the Netherlands: taking advantage of natural processes, directing, holding back and managing the water and adapting land use to changing conditions (see 3.3).

Four perspectives for the long term

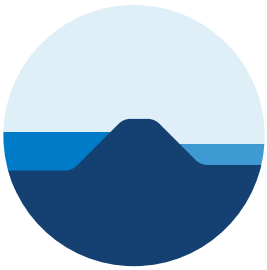
As part of the Sea Level Rise Knowledge Programme, four consortia of government authorities, knowledge institutes and NGOs have each developed a perspective for dealing with sea level rise in the long-term:

- **Protect**: we continue the current water management primarily by hydraulic engineering methods, such as dike reinforcements, storm surge barriers, sand nourishment, locks and sluices, weirs, pumping stations and pumps. At the same time, we can opt for closable coastal inlets and estuaries (with a storm surge barrier) or dammed coastal inlets and estuaries (with pumps to discharge excess water).
- **Seaward**: we build a dam at sea, creating a large coastal lake in which to store high river discharges. This will require less pumping capacity for the discharge of river water than damming estuaries.
- **Nature-based**: we take advantage of the natural processes to capture sand and silt, enabling the transition from sea to land to grow in line with sea level rise. This will mitigate the impact should any dike breach occur. Intertidal areas, which have in the past been lost because of (hydraulic engineering) infrastructure in many places, will increase in size, making the natural environment more robust.
- **Accommodate**: we adapt land use and society as much as possible to accommodate the consequences of sea level rise. We will primarily opt for measures that limit the consequences of floods. Examples could include elevated or floating construction, salt-tolerant agriculture and relocating housing and employment to higher-lying areas of the Netherlands.



10 Four long-term conceptual perspectives for the future of the Netherlands have been investigated.

For each perspective, an examination has been made of what the Netherlands would look like if the perspective is applied consistently from 2 m of sea level rise onwards. In practice, a more obvious approach would be to combine the building blocks of the different perspectives and attempt to tailor the approach for each region. The most important building blocks are summarised below around six themes.



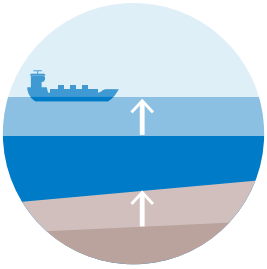
New dams

Ordinarily, the New Waterway and the Eastern Scheldt are in open connection to the sea. Sea level rise will therefore lead directly to higher water levels in these coastal inlets. In the Haringvliet, the water levels will also rise if we continue to discharge river water to the sea under gravity. If we completely dam these coastal inlets, the water level could in theory remain at the current level as the sea level rises. This will limit the need for dike reinforcements. Seaward of the dike, the water would then be increasingly higher than on the land side. We will need to use pumps to discharge the water in the Lek, Waal and Meuse out to sea. This will call for very large pumping complexes that require space and a lot of energy.

Damming will also impede shipping. The Port of Rotterdam will maintain an open connection to the sea, but shipping from and to the inland waters will enter any potential new dam via inland shipping sluice gates/locks. There are several reasons why damming the Western Scheldt is not the obvious option. Salinisation in the New Waterway and the Eastern Scheldt will be reduced by damming, but there will not be sufficient river water to create new freshwater buffers here. Experience from the Delta Works shows that damming results in major losses of tidal nature and creates bottlenecks in fish migration corridors. Water quality problems will also emerge and new demands will be placed on water in order to maintain good water quality.

By building a new dam in the North Sea seaward of the Southwest Delta, we can create an extra storage zone for high river discharges. This will result in a large offshore lake of brackish water, potentially running from the Maasvlakte to the Eastern Scheldt. There will be pumps on the dam to discharge river water. These pumps will also be substantial, but considerably smaller than the pumps needed for damming the New Waterway and Haringvliet. This storage zone will mean that, when replaced, the Eastern Scheldt barrier and Haringvliet locks will not need to be as high or strong in the face of rising sea level. By keeping the Maasvlakte and Western Scheldt on the outside of this coastal lake, the ports of Rotterdam and Antwerp will remain freely accessible to shipping from the sea. The coastal lake will result in significant loss to (tidal) nature. Large quantities of sand will be required for construction and maintenance of the dam, further increasing the pressure on sand extraction for coastal nourishment.

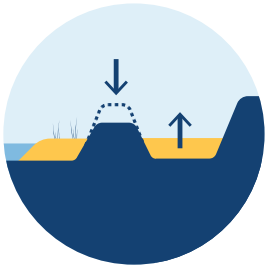
Figure 11 The location of the coastal lake featured in the research.



Holding back salinisation via the New Waterway

As a result of the rise in sea level, there will be more salt intrusion via the New Waterway which is in open connection to the sea. This salt intrusion can partly be limited by allowing the bed of the New Waterway to rise in line with sea level. As a result of this, the strong salt undercurrent will reach much less far inland. This will have no consequences for shipping: the depth of water will remain the same.

Another potential solution involves the construction of new flood defences in order to close off a number of watercourses in Rijnmond-Drechtsteden temporarily in dry summers: in the Hollandsche IJssel, Lek, Oude Maas and Hartelkanaal. When these flood defences are closed, less river water will be needed to keep these watercourses fresh. These closures can be long-lasting, from several weeks to months. If the flood defences were to include sea locks, too much salt would continue to enter. This is why there will only be locks to enable in inland shipping to pass through. This will have consequences for shipping as a whole.

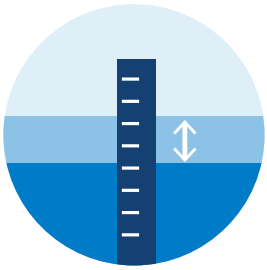


Enabling land-water transition zones to rise in line with sea level

Alongside the Delta waters in the Southwest Delta and along the Wadden Sea, mudflats and salt marshes occur naturally on the areas between sea and land. In the case of well-developed land-water transition zones, dikes will not need to be as high and the consequences of any dike breach will be less significant. These intertidal zones are essential for the ecosystem in these waters. If the land-water transition zones rise in line with sea level, they will continue to serve these functions. This process requires the natural processes of sand and silt and sufficient space alongside the dike on which this sediment can rest. If the sea level rises too rapidly and this process does not keep up, we can give nature a helping hand through nourishments.

There is sufficient sand and silt dynamism alongside the Western Scheldt and the Wadden Sea. We can already create land-water transition zones that rise in line with sea level in these areas. This will however require space, for example in order to build a second dike inland of the current dike and enable sand and silt to flow into the area in-between at times of high seawater. This process of ‘co-growth’ is not yet possible along the other sea inlets in the Southwest Delta: dams and storm surge barriers impede the natural processes there. When we ultimately replace the storm surge barrier in the Eastern Scheldt with a new one, we can opt for a design that causes less disruption to this dynamism, giving the ‘co-growth’ process more chance of success. The complete removal of the dam or storm surge barrier is the most effective means of ensuring natural sediment and water dynamism and land-water transition zones that rise in line with sea level. In that case, safety can be improved by further increasing the height of the dikes around the coastal inlets. Just like the construction of the storm surge barriers and dams, their removal will also have major consequences within the water system. More in-depth research will be required to gain a good understanding of the consequences and potential risks.

The removal of the Afsluitdijk would not be advisable: this would deprive the country of its largest supply of freshwater. It would also require major dike reinforcements in a large area and result in relatively little new intertidal area.

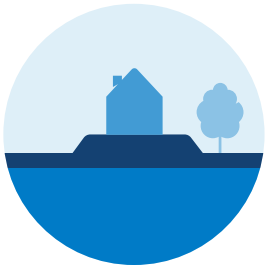


Natural water level management

The IJsselmeer and Markermeer are currently managed to maintain a low level in the winter to allow any excess water from the area to flow away easily into the IJsselmeer. In the winter, we aim for a higher level in order to create a large freshwater buffer. While this water level management is effective for utility functions, it has precisely the opposite effect on natural water level fluctuations. The unnatural water level management creates problems for (ecological) water quality and nature. The water level becomes more natural if we raise the winter level to a limited extent and allow it to fall more significantly in the summer. This results in a larger freshwater buffer. Combined with the establishment of wide land-water transition zones, it also creates better opportunities for water quality in the ecosystem. The freshwater buffer can be further enlarged by discharging more rainwater in the spring via the IJssel and less via the Lek and Waal.

Deltapolder

If we establish Rijnmond-Drechtsteden as one large polder ('Deltapolder'), we can limit dike reinforcements in this region. The polder will be sealed off with dams on the sea and river sides and the water level regulated using inlet structures and pumps. To the south of the Deltapolder, we will direct water from the Waal and Meuse via the Haringvliet to the sea. In winter, it may even be an option to discharge more Rhine water via this route in order to limit dike reinforcements along the IJssel and the IJsselmeer. At Hoek van Holland, there will be pumps to discharge water from the Lek and Hollandsche IJssel to the sea. This will require substantial pumping capacity, but significantly less than the complete damming of the New Waterway and Haringvliet. A Deltapolder can have benefits for freshwater if it only includes locks that allow passage of inland shipping and no sea locks. As a result of this, less salt would enter the polder via this route than with the current set-up. Nevertheless, there could still be considerable salinisation caused by saltwater seepage and subsidence; this has not yet been investigated.



Hazard mitigation and moving to higher ground

Another completely different perspective involves accommodating the changing circumstances by limiting the impact of floods: for example by means of housing on artificial mounds, floating construction or water-resistant construction, a lot of water storage and gradual adaptations in land use.

Locally, these measures can prove an interesting addition to other solutions. If we focus exclusively on this strategy and do not continue to reinforce the dikes, this would mean that housing and employment would proactively relocate to the east of the country. That would be a radical transition with significant social and economic consequences and uncertainties. Since there are sufficient options for continuing to protect the whole of the Netherlands from flooding for the time being, in principle up to a sea level rise of 5 m, it is not necessary or sensible to anticipate this kind of transition at this stage (see also 2.4). It may well become necessary in the distant (not yet foreseeable) future, if the sea level continues to rise after several centuries or does so too rapidly.

3.4 Does this give us sufficient options for living with sea level rise?

The previous sections show that the rise in sea level will create a large number of issues relating to flood protection and dealing with salinisation. There are also various ways in which to take action, both building on what we are already doing and by other means. The question is whether this gives us sufficient options for living with sea level rise.

Overall picture: yes, if we keep the basics in order

In summary, it would seem that we can live with sea level rise in the Netherlands for the time being: we have sufficient options for continuing to protect ourselves from flooding according to the current standards and to deal with the inevitable further salinisation. A key condition for this will be to maintain the favourable starting position we currently have in the Netherlands by continuing to invest in it: maintaining the coastline with sufficient sand nourishments, ensuring dikes and other flood defences continue to remain high and strong enough, combating salinisation efficiently where possible, but also learning to live with it where we need to. For the discharge of water out to sea, we will need to use increasing numbers of pumps. If we ensure the basics remain strong, the additional steps required to combat sea level rise will be feasible and possible for subsequent generations.

In order to keep the basics in order, we will need to ensure a constant availability of sufficient space, materials, manpower, knowledge and financial resources in order to upscale as soon as it becomes necessary.

Armed with these strong basics and other long-term options (see previous section), we can maintain the current level of protection against flooding for now: in any case up to a rise in sea level of 3 m and in principle up to 5 m if the sea level does not rise too rapidly. Salinisation is a different story: it is inevitable that parts of the Netherlands will face more frequent and/or stronger salinisation than is currently the case; this process has already started. This is not only due to the rise in sea level, but also other consequences of climate change, particularly declining river discharges in the summer and as a result of subsidence.

Adaptation of the regional water system

The Sea Level Rise Knowledge Programme focused its investigations on the major water systems (the main water system) and the associated flood defences and infrastructure (the primary flood defences, storm surge barriers, large weirs and locks, etc.) This is where the direct consequences of sea level rise are most significant in terms of flood risk management and freshwater. Sea level rise will also have consequences in the smaller, regional waters. Many of these consequences will depend on what happens in the main water system. Equipped with the knowledge gained about the main water system, it will now be possible to investigate the consequences for the smaller, regional waters in greater detail.

Stress test: what if the sea level rises much faster?

The points at which the various issues caused by sea level rise are expected to occur has been based on the KNMI's low and high scenarios (see 3.1). The KNMI has also analysed what will happen in the event of accelerated melting of the Antarctic ice (see 3.1). This would result in much faster sea level rise than is accounted for in the scenarios. If this large ice sheet begins to melt rapidly, the sea level could already be 2 m higher by the end of this century and 5 m higher a century later. After that, the rise in sea level would continue at an even faster pace. In that case, the issues would affect us much sooner.

For the purpose of a stress test, research has been conducted on whether we can continue to protect the Netherlands from flooding and salinisation in that case. The results reveal that it will be possible in that situation to upgrade the dikes and other flood defences according to the current flood protection requirements, in principle up to 5 m of sea level rise. Salinisation will continue more rapidly, forcing us to adapt land use to accommodate more saline water at a faster pace. We will need to take much larger steps in each generation and radical solutions will need to feature much sooner (see Figure 12). This will involve higher costs and prove very demanding to put into effect. This is why limiting sea level rise as much as possible (mitigation) is and will remain of vital importance.

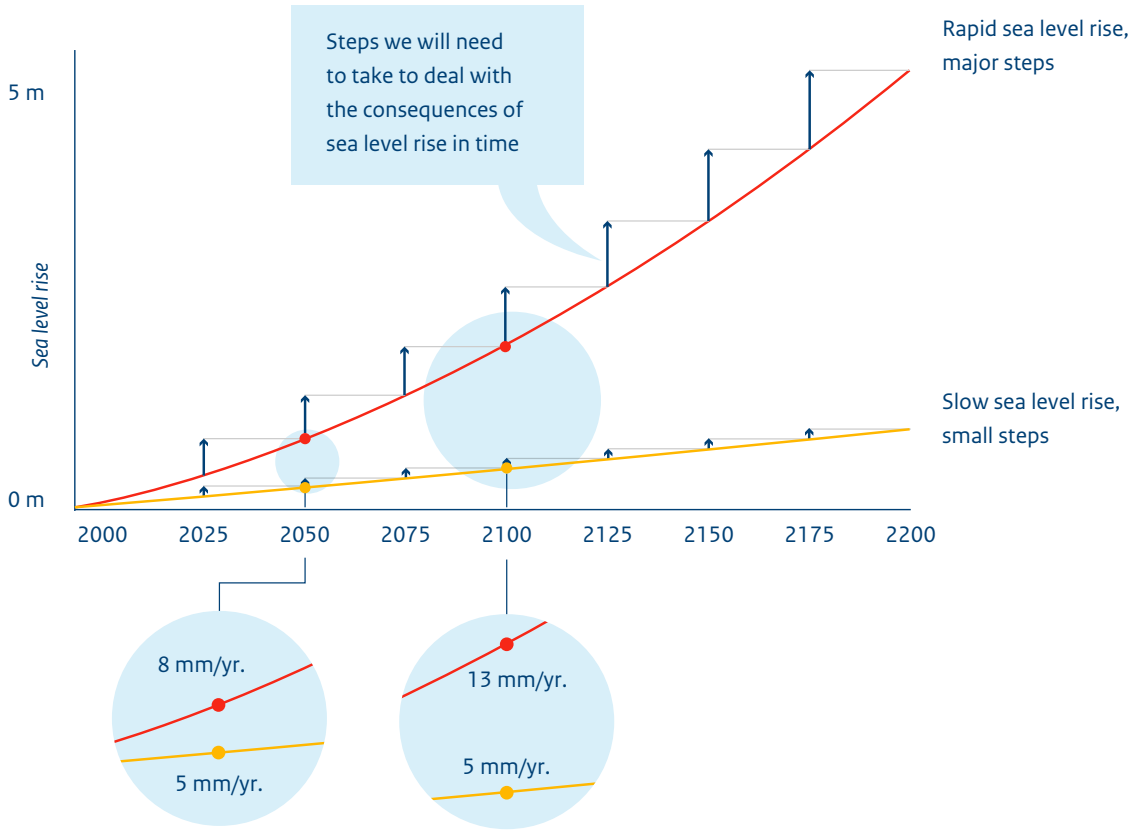
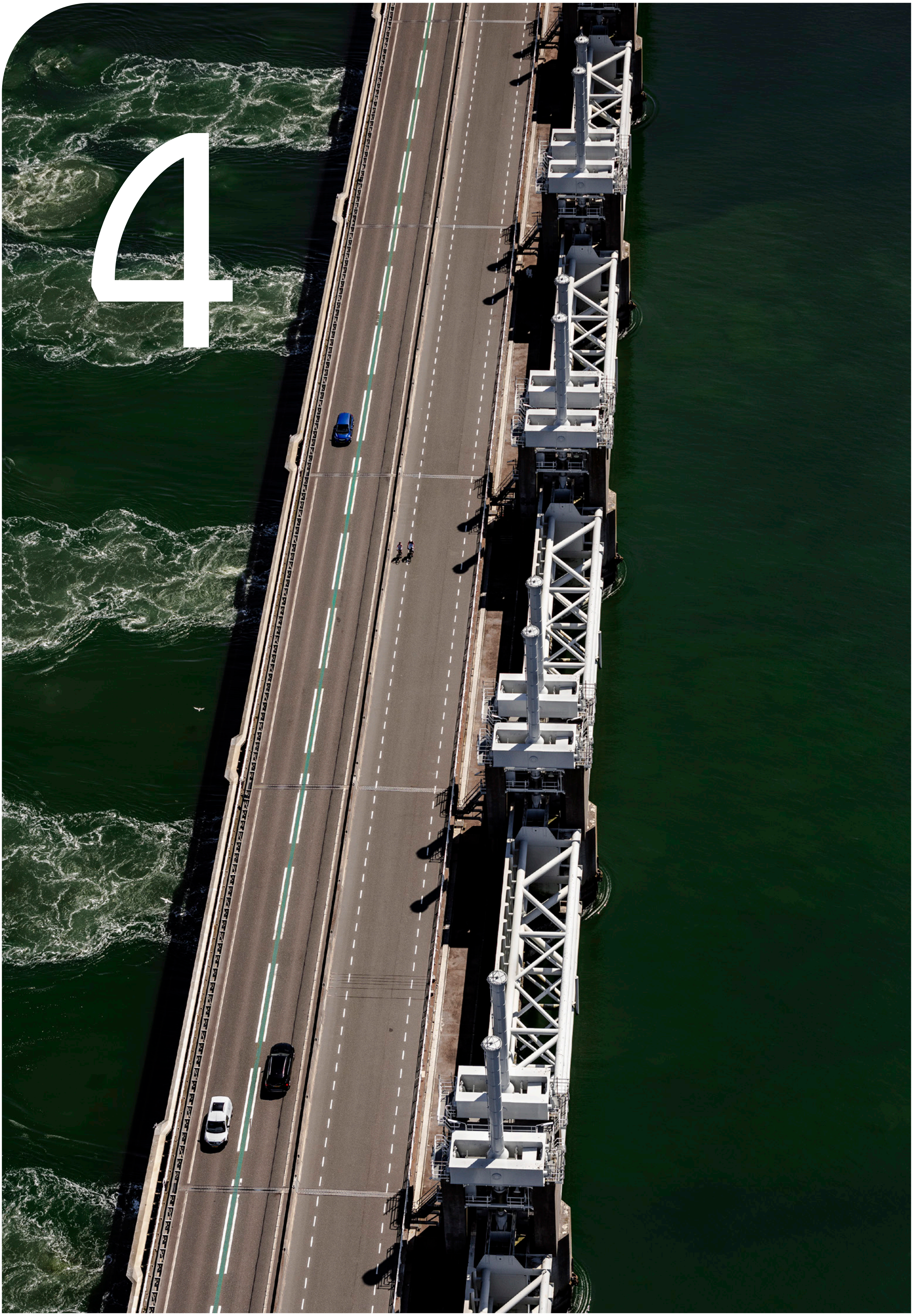


Figure 12 Rapid sea level rise will require larger steps for each generation than slow sea level rise.


4

4 The way forward: what does this knowledge mean for policy choices?

4.1 Which strategic choices can we make, now and in the future?

The Sea Level Rise Knowledge Programme shows that we can live with sea level rise in the Netherlands under certain conditions: we have sufficient options for continuing to protect ourselves from flooding according to the current standards and to deal with the inevitable further salinisation. This will not happen automatically: we will need to continue to maintain the favourable starting position in terms of flood risk management and freshwater and ensure we make timely choices.

Keeping the basics in order at all times

We can continue to protect ourselves from flooding according to the required standards and deal with the inevitable ongoing salinisation, providing that we always ensure that the basics remain strong. We will need to continue to invest in this, whatever strategy we opt for (see Figure 13):

1. maintaining the coastline continually by means of ever larger sand nourishments;
2. continually reinforcing dikes and other flood defences;
3. using increasing numbers of pumps to discharge water to the sea;
4. combating salinisation as efficiently as possible where this can be done and learning to live with salinisation where we need to.

The efforts required to achieve this will vary according to the strategy. By keeping the basics in order, any necessary additional measures will be feasible and achievable for subsequent generations.

Making choices: not too soon and not too late

The Sea Level Rise Knowledge Programme shows that the current approach and measures based on it can still continue to protect against flooding for a long time. This will not prevent the inevitable continued salinisation, but will limit it to some extent. Switching to a completely different strategy is also possible. This could include replacing storm surge barriers with dams, removing existing dams and flood defences or periodically closing off watercourses in Rijnmond-Drechtsteden to limit shortages of fresh water. Every choice will have its consequences. The Sea Level Rise Knowledge Programme shows us which choices we will need to prepare for (see Figure 14).

Figure 13 We can deal with sea level rise if we continue to keep the basics strong.

In terms of technology, we can make good progress by applying the current approach based on existing knowledge, depending on the speed of the rise in sea level. However, switching to a different strategy may become necessary sooner for spatial or economic reasons. The way in which our water systems are organised and the related functions (such as shipping, the Port of Rotterdam, agriculture, nature) are completely attuned to each other. This is why continuing with the current approach is less complex and radical than switching to a completely different strategy. This does not mean that continuing the current approach will be easy. It will require major short- and medium-term choices and some big decisions:

- *Basics in order:* How will we ensure a constant availability of sufficient space, materials, manpower, knowledge and financial resources in order to upscale as soon as is necessary?

- *Dealing with salinisation:* How will we distribute the scarce fresh water in periods when it is in short supply? This is already an urgent question. A decision about it requires various factors to be taken into account, for example: in which areas will we continue to combat salinisation with large amounts of – frequently scarce – freshwater and in which areas will water users have to learn to deal with salinisation, what level of salinisation of our freshwater buffers will be acceptable in periods of drought and to what extent are we willing to accept local flooding in order to prevent water shortages?

- *Natural processes:* In which areas will we take advantage of the natural processes of sand, silt and water for flood risk management? If we intend to allow land-water transition zones to rise in line with sea level rise, time will be a key factor. The sooner the nature-based solutions start, the more benefits they can deliver. Along the Western Scheldt and the Wadden coast, there is already sufficient dynamism and silt present to apply this concept, but space is required to achieve it. This will also make tidal nature more robust.

- *The distribution of Rhine water:* How will we distribute the Rhine water between the Waal and the IJssel, in the event of high and low discharges? This is one of the mechanisms we can deploy in order to reach solutions for dealing with salinisation and protecting against floods.

- *Water level in the IJsselmeer area:* We could choose to create greater flexibility in water level management in the IJsselmeer area, in order to continue to discharge under gravity for longer, for a larger freshwater buffer, reduced flooding and robust nature.

- *Replacing storm surge barriers and closure level:* Storm surge barriers have a lifespan of around 100 years. If we continue with the current approach, we will need to replace them in time in order to ensure that they continue to function effectively. The first replacements will be in the second half of this century: the Maeslant barrier (from 2070) and the Eastern Scheldt barrier (from 2080), among others, will then be reaching the end of their intended lifespan. This also relates to the question of the water level at which we wish to close the storm surge barriers: should we maintain the current closure level (which means that the barriers will close much more often) or increase it (which will require higher dikes and leave unembanked areas facing higher water levels)?

If we continue with the current approach for the time being as described above, preparations for the second replacement of the storm surge barriers will come into view in around 100-150 years. From a technological point of view, it will still be possible to continue the current approach (building higher, stronger storm surge barriers), but the interventions required and the impact of sea level rise on other functions will continue to increase, especially if the sea level rises rapidly. We will then also need to consider other (combinations of) solutions, especially for the (former) coastal inlets and estuaries. We will need to prepare for these choices in good time:

- *Will we opt for open, closable or dammed coastal inlets and estuaries?* We currently have all of them in our delta. These choices are not intended to last forever. Just like now, a different solution for each coastal inlet will also be possible in the future. Opting for a different solution will involve major changes in water management, including in water levels, salinity, seepage and water quality. These changes will have an impact far beyond the specific coastal inlet and have consequences in such areas as agriculture, fishery, shipping and nature. In cases where we opt for a different solution, we will need to factor in a long preparation time.

Holistic assessment

The best approach and the best time to make choices will not only depend on the interests of water management, but also spatial, economic and societal preferences and trends. Every choice will have an impact on functions that matter to us, the possible use of land, water quality and nature. Ultimately, it will involve an assessment at political and administrative level.

The result need not be the same everywhere. The preferred solution can vary for each region or coastal inlet. It will however be necessary to ensure a coherent approach at national level since the water systems are all interconnected and choices in one region will have consequences for other regions. As part of this national coherence, a more tailored approach will be possible at regional level.

Figure 14 The major decisions we will need to prepare for, in the short and long term.

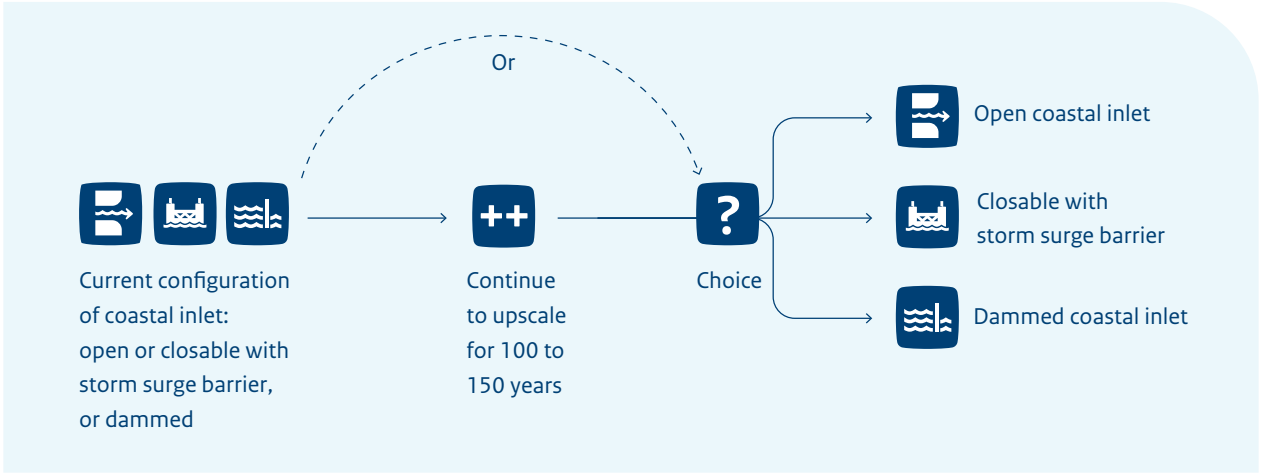


Figure 15 With additional effort, the (former) coastal inlets can be maintained in place within the existing system for the next 100-150 years (open, closable with storm surge barrier or dammed). After 100-150 years, a different solution can be considered for each coastal inlet. Other societal and economic developments could also justify making these choices at an earlier stage.

Continually reinforcing dikes and other flood defences

Strong dikes will always have a pivotal role to play in our flood protection, in every climate scenario and every strategy. Because of sea level rise, the dikes in much of the country will need to be continually higher and stronger. This involves a total length of more than 2,000 km. The increasing river discharges and subsidence will also necessitate stronger dikes. The dikes are reassessed every 12 years: does this dike still meet the standards? If an upgrade is needed, a design will be devised that will last for 50 to 100 years, taking account of the expected rise in sea level and the change in river discharge in that period. If the sea level and river discharge increases faster than expected, we will need to upgrade the dike sooner. New knowledge about the strength of dikes and policy choices can also have influence on the pace of dike reinforcements. Ensuring that the full length of dikes and other flood defences are high and strong enough at all times is a major logistical challenge. It requires money, human resources and space. The faster sea level rises, the more difficult this becomes to achieve.

4.2 How can we deal with the uncertainty of the speed of sea level rise?

The speed of sea level rise will largely determine the best approach we can take for dealing with it and when we need to take new steps. But there is real uncertainty about the speed of sea level rise. Current scenarios indicate that the sea level could have risen by just a few decimetres by the end of the century, but they also show it could be more than a metre. There is also uncertainty with regard to the effect that climate change will have on river discharges. The coming decades will show whether the world has been successful in sufficiently reducing greenhouse gas emissions to mitigate climate change. It may then become clearer which scenarios for climate change and sea level rise are more or less likely, but uncertainty about future development will remain. There is no point in waiting for certainty.

The question is whether, *given this uncertainty*, the Netherlands can make the right choices in time, in order to ensure that we are always well protected from flooding and prepared for salinisation where we cannot prevent it. The Sea Level Rise Knowledge Programme results in the following picture:

1. *Continue to invest in strong basics*
   Ensuring that the basics remain strong (see 4.1) really is the basis for every potential future with a rise in sea level, for ourselves and for future generations. By always ensuring that the basics are in order, we can reduce the additional efforts required as a result of sea level rise and anticipate faster or slower sea level rise in ways that are less radical.

   If we are to be successful in ensuring that the basics remain strong, it will be important to make available sufficient space, raw materials and financial resources and to adapt land use to cope with salinisation where we cannot prevent it.

2. *Start small and learn to live with salinisation*
   If we keep the basics strong and sea level rise is not too rapid, we will initially be able to keep pace with the consequences of sea level rise by means of relatively small additional steps: closing storm surge barriers more often and replacing them when they are outdated, installing additional pumps, taking measures to reduce salinisation at locks and discharge sluices, etc. We will be able to go some way towards mitigating increasing salinisation in the coastal provinces, but we will not be able to prevent it everywhere and at all times. The need to adapt land use is not a choice but a necessity.

Step-by-step approach to an ongoing challenge

The rise in sea level makes it clearer than ever that the Netherlands' ongoing challenge with water will never be over. When the Delta Works were completed, we were convinced that the Netherlands was safe. We now know in advance that sea level rise will continue for centuries. Each generation will need to take the next step, but how big these steps will be is uncertain. This places new demands on the solutions and on decision-making. Our task is not just to resolve the issue in the here and now, but also to ensure that the subsequent steps remain possible.

3. *Always prepared for major choices*
   Following the floods of 1953, the Netherlands was able to agree and implement the Delta Plan in a relatively short period of time. The first dams were completed within seven years (Veerse Gatdam and Zandkreekdam). The entire Delta Plan was achieved within 50 years, an unparalleled speed for a plan of this magnitude. Even after the river region almost flooded in 1993 and 1995, the Netherlands was able – after first ensuring that the dikes were in order – to implement a highly innovative solution at rapid speed: creating more room for the river. We can learn a lesson from this. This rapid reaction to major disasters was partly made possible *by the fact that ideas about it had already been developed*.

   If the sea level unexpectedly starts to rise quickly, for example because of rapid melting of the Antarctic ice sheet or as a result of as yet unknown processes, we will need to be able to take major steps quickly to ensure flood protection remains at an acceptable level and to deal with salinisation. Ideally, we would take these steps before a disaster occurs this time. This will be possible if we always remain prepared: by effectively monitoring sea level rise, continuing to search for and research new solutions, experimenting with these on a small scale and applying new insights to develop improved strategies. This will enable us to remain flexible and *in control*.

4. *Learning from experiences*
   The Delta Works were built in the period 1958-1997. We now have 30-70 years of experience with the solutions we applied: dams, storm surge barriers, open coastal inlets, fresh and salt water systems, combating salinisation at locks, etc. All of these solutions are included in the range of options for dealing with sea level rise. We can improve knowledge about these options by now taking stock of the Delta Works: how did the Delta Works turn out, not only in terms of hydraulic engineering, but also in terms of society, the economy and ecology? Evaluating other programmes and projects will also provide an opportunity to add to and improve knowledge about living with sea level rise, such as knowledge about adapting land use to salinisation.

5. *Broadening the perspective*
   The Sea Level Rise Knowledge Programme has adopted the perspective of water management to examine the issues that will result from sea level rise and the potential solutions. It has resulted in a solid knowledge base. However, water management is not an end in itself, but serves the functions and values of society. These include safety, port accessibility, agriculture, housebuilding, nature, water quality and the quality of the living environment.

The good news set out in the Sea Level Rise Knowledge Programme is that there are several options for living with sea level rise. None of these possibilities will be easy since they will all require significant ongoing efforts. Carefully considered choices between solutions will therefore call for a broadening of the perspective. How will sea level rise influence other functions, what transitions will take place, what will that mean for spatial planning in the Netherlands and the way in which we organise decision-making about it? That can result in new insights and even provide new solutions. It can also result in a different balance of costs, benefits and risks. A cohesive perspective for the future water management of our delta that also takes account of other spatial choices can prevent the need for disinvestments.

Relocating is the last resort

Based on the current scenarios for sea level rise, we will still be able to keep all parts of the Netherlands safe and liveable for a long time. We will also be able to continue to protect low-lying parts of the Netherlands from flooding, including the Randstad, in principle up to 5 m of sea level rise. As long as that remains possible, it makes no societal, financial or economic sense to relocate the residents and businesses of the low-lying Netherlands to higher parts of the country.

Sea level rise is set to continue for centuries, even if greenhouse emissions stop completely. There may then come a time when we can no longer maintain the flood risk in low-lying sections of the Netherlands at an acceptable level. Based on current knowledge, that will be in the distant future, well after 2200. The exact date will depend on the speed of this rise in sea level.

4.3 What considerations will play a role in future choices?

A range of different considerations – alongside the actual effect of solutions – will have a role to play in future choices about dealing with sea level rise. Some examples are set out below.

Clarity for other functions

For the future spatial planning of the Netherlands, it will be advisable to have clarity about the organisation of the water system, to enable functions to anticipate this and take account of it in any investments. For example, the choice about partially or completely closing the New Waterway is of relevance for the Port of Rotterdam, shipping, housing and businesses in unembanked areas, for nature and for agriculture. If functions require a lot of time to adapt, clarity at an early stage will be essential in ensuring that solutions can be implemented in time.

Benefiting from land-water transitions that rise in line with sea level

Dikes are and will always remain essential for flood protection. In some places, we can boost the robustness of flood risk management by means of a combination of dikes and land-water transitions that rise in line with sea level, for example along the Wadden coast and the Western Scheldt. This will limit the consequences of any flood. These transition zones will also help boost the iconic tidal nature that has disappeared on a large-scale over the last two centuries, mainly as a result of flood defences. The sooner that land-water transitions that rise in line with sea level are initiated, the greater the benefits. This could be taken into account in planning the necessary measures, such as moving dikes further inland. Careful consideration of further measures for restoring the natural processes, such as removing storm surge barriers and dams in the Southwest Delta, will require more in-depth research into the potential effects and risks and additional time and money to reinforce dikes.

The amount of money (and time) that we have to invest

All solutions cost money and some are more expensive than others. The amount of money available will therefore partly determine which choice we can and wish to make. In this, the amount of time we have to implement measures is also a key factor: if we can spread major investments over a long period, the annual investment will be easier to bear. This also makes implementation easier. The proviso here is that measures will need to be ready in time. The most important way of 'buying' time will be reducing carbon emissions in order to slow down the rise in sea level. Rapid decision-making about any measures will also help to buy time.

Continuing to combat salinisation will ultimately involve expensive interventions. Careful consideration of interventions of this kind not only requires an understanding of the benefits that outweigh the costs (how much salinisation damage will be prevented) but also calls for insight into how water users will cope if the intervention is not applied. In one place, an expensive intervention could (temporarily) prove an effective solution. In another place, a strategy of transformation and adapting to salinisation might be more cost-effective and provide a more sustainable option for users.

Sharing the benefits and burdens

Dealing with sea level rise also comes down to an issue of distribution. Any chosen solutions will benefit society as a whole, but could have disadvantages for specific sectors oraindividuals. For example, raising the closure level of the Maeslant barrier may be beneficial for the lifespan of the barrier (replacement costs come later) and for shipping (no additional blockages), but disadvantageous for space in the city (higher and wider dikes) and housing and businesses in unembanked areas (higher water levels).

Sharing the benefits and burdens across generations will also play a role, the choices and investment decisions we make now can have repercussions for future generations. This is why it is important not to shift the burden of tough choices and capital investments onto future generations.

What kind of country do we want to live in?

What the best choice will be will not only be determined by the value of effective protection from floods and dealing with salinisation. Other values will also determine how liveable our country is: where and how do we want to live, work and spend our leisure time, what value do we attribute to water quality and nature and what do we wish to spend money on? In other words: what kind of country do we wish to live in and what kind of country do we want to leave behind us?

Appendices

Appendix 1 How fast will the sea level rise?

A great deal of research is being conducted into sea level rise across the world and in the Netherlands. In recent years, the Sea Level Rise Knowledge Programme has been providing new knowledge that makes it possible to determine sea level rise in the North Sea with greater precision. It was already known that the worldwide rise in sea level is accelerating. Based on recent studies, there is growing consensus that the acceleration is also visible from observations off the Dutch coast.

The sea level is expected to rise even further because of global warming. The speed of the rise in sea level is uncertain: it depends on numerous factors, including the extent to which worldwide carbon emissions will decline. In 2023, the KNMI compiled new climate scenarios for the Netherlands, and these included sea level rise. These scenarios vary from a low rise to a high rise in sea level and in a worst-case scenario to a very extreme rise. The consequences of sea level rise in the Netherlands will depend in part on other effects of climate change, and especially the impact on extremely high and low river discharges.

Underlying assumptions

IPCC climate scenarios
Every six to eight years, the Intergovernmental Panel on Climate Change (IPCC) summarises the insights from worldwide research into climate change in a series of reports. The KNMI takes the IPCC insights into the processes of climate change as the starting point for the sea level rise scenarios for the Netherlands and supplements them with recent developments in the specialist field and specific knowledge about sea level rise in the North Sea.

Improved models for sea level rise in the North Sea
The KNMI climate scenarios also include expectations for future sea level rise off the Dutch coast. As part of the Sea Level Rise Knowledge Programme, the KNMI has developed new methods in order to obtain better data from both the models and the observations. These were then tested by using it to 'predict' sea level rise over the last 30 years. The results effectively matched observations over this period. The KNMI used the method in the KNMI'23 climate scenarios, ensuring that observations provide a good reflection of expectations for the future.

New KNMI methods

The sea level in the North Sea is currently rising, primarily because the nearby Atlantic Ocean is warming up as a result of climate change The warmer ocean water expands, causing the sea level to rise. Measuring the rise in sea level is a complex process. Observations of the water surface, using satellites, for example, show the combined effect of the sea level and such factors as wind surge. This effect can be filtered out of the observations. The KNMI has developed a new method for doing this. Additionally, the KNMI has devised a method to select climate models that are a good fit with the observed trend. Overall, these advances have resulted in a significant improvement in knowledge about the expected sea level rise in the Netherlands. The new methods have also attracted a lot of interest worldwide.[1]

Results of research into sea level rise

The results of the research are summarised below based on three questions: what contribution does Antarctica make to sea level rise; how rapidly has the sea level been rising so far; and what are the scenarios for future sea level rise off the Dutch coast?

[1] Keizer, I., Le Bars, D., de Valk, C., Jüling, A., van de Wal, R., and Drijfhout, S. (2022) The acceleration of sea-level rise along the coast of the Netherlands started in the 1960s, Ocean Sci., 19, 991–1007.

What contribution is Antarctica making to sea level rise?
Global warming has various effects that contribute to worldwide sea level rise: the warming ocean water expands, ice sheets melt, glaciers melt and water currently stored on land is released. Currently, melting land ice (ice sheets and glaciers) is the largest contributor to sea level rise. The contribution made by the melting ice sheets of Greenland and Antarctica is continuing to increase. In the period 2009-2018, the Greenland ice sheet lost seven times more ice than it did from 1992 to 2001; the Antarctic ice sheet lost four times as much ice. Because the Antarctic ice sheet is so much larger than its counterpart in Greenland, the amount of Antarctic melt water may increase more than melt water from Greenland in the (near) future, especially if the Antarctic ice sheet becomes unstable.

The melting of the Antarctic ice sheet will also have a stronger effect on sea level rise near the Netherlands than the melting of the Greenland ice sheet. The Sea Level Rise Knowledge Programme has therefore contributed to research on the mechanisms that may lead to the faster melting of Antarctica. The research shows that melting in Antarctica is increasing mainly because of the warming of the seawater. The warmer water causes the ice to melt below the surface. As a result, there is more ice calving (iceberg formation). The calving is also inhibited less by the ice shelves floating in front of the ice sheet because they become thinner and break faster in the warmer water. Where ice shelves disappear, ice cliffs form that can collapse under their own weight.

KNMI Antarctica study

The KNMI has used a range of climate and ice sheet models to calculate how the Antarctic ice sheet is responding to the warming of the surrounding ocean. The calculations were calibrated with satellite observations of mass loss from the Antarctic ice sheet. In this way, ocean warming, as predicted in a range of climate models, has been converted into Antarctic melt. These data form the basis for Antarctica's contribution to sea level rise in the KNMI'23 climate scenarios. In turn, the melt water affects ocean warming, further reinforcing Antarctic melt.

How rapidly has the sea level been rising so far?
Between the beginning of the Common Era and 1800, there was virtually no sea level rise: the world average fluctuated around 0 mm per year between the years 0 and 1800. The sea level began to rise in the course of the nineteenth century. During the last century, the sea level rose at an average rate of 1.7 mm a year (between 1901 and 2018). However, since the late 1960s, measurements have shown ever faster acceleration: approximately 2.3 mm per year between 1971 and 2018 and 3.7 mm per year from 2006 to 2018.

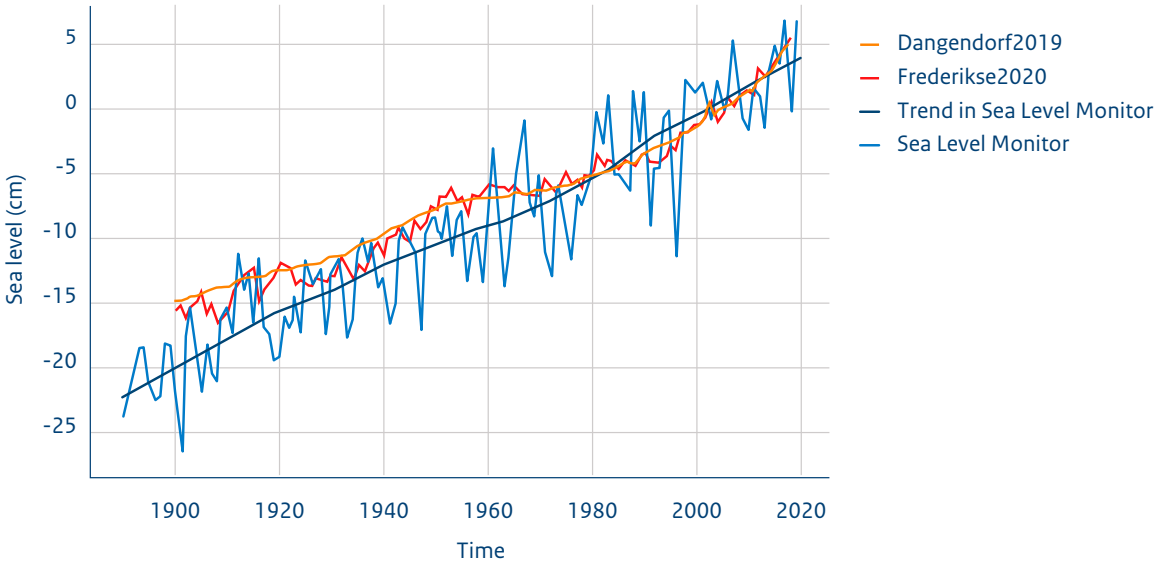


Figure 16 Reconstruction of sea level rise based on a range of studies. The orange and red line shows the global sea level rise, the blue lines the sea level rise for the Dutch coast. Source: KNMI

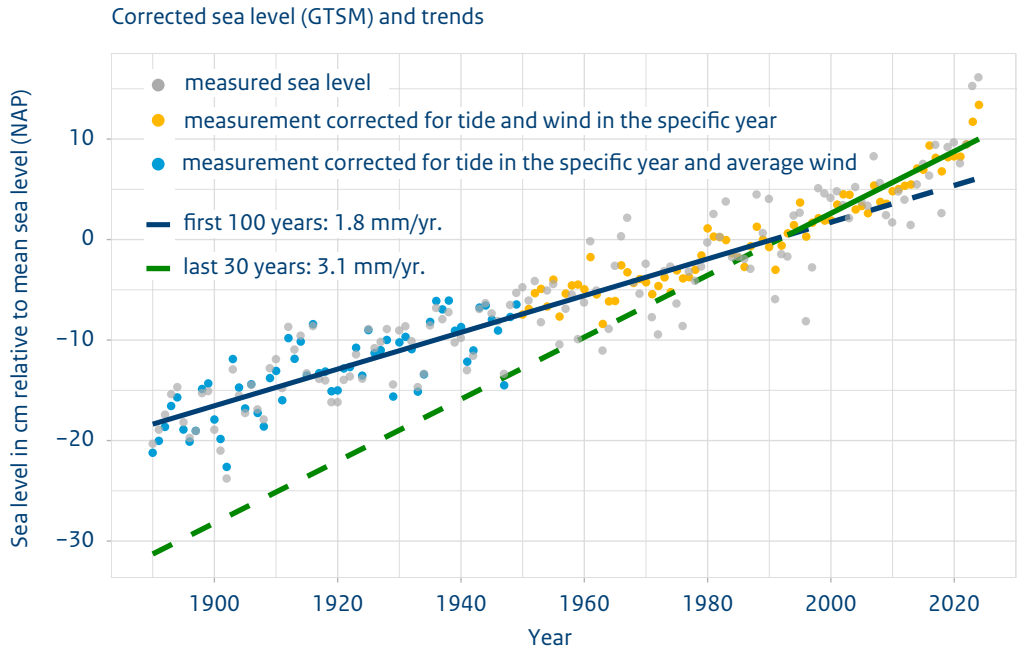


Figure 17 The annual average water levels off the Dutch coast (based on observations) show an increasing trend and a faster increase in recent years. Source: Zeespiegelmonitor (Sea Level Monitor) Deltares (2022)

Analyses conducted by Deltares show that acceleration has also taken place in the coastal area of The Netherlands . The sea level off the Dutch coast has risen by almost 25 cm since 1890. This equates to an average of around 1.8 mm per year, close to the global average. However, by correcting the average water level to account for the combined effect of wind and tides, Deltares was able to identify a change in the trend: this shows that the sea level off the Dutch coast has risen by an average of 2.9 mm a year over the past thirty years, faster than previously. A team from Delft University of Technology reached the same conclusion independently of Deltares and the KNMI.

By means of monitoring, Rijkswaterstaat keeps a close eye on the sea level rise off the coast. In coordination with the KNMI, Deltares maintains the Sea Level Monitor, the annual report on sea level rise off the Dutch coast. The data are used by Rijkswaterstaat and others to support coastal management.

What are the new sea level rise scenarios for the Dutch coast?
The speed of the rise in sea level depends on the increase in temperature and therefore on carbon emissions. Despite the numerous plans for cutting emissions, it is uncertain to what extent they will actually succeed. The IPCC therefore works with a range of scenarios in which emissions increase or decrease to a greater or lesser extent. These two scenarios form the bandwidth for the expected sea level rise for the Netherlands:

- The least sea level rise is seen in the scenario in which greenhouse gas emissions significantly decline and there is also carbon storage after 2050 (scenario SSP1-2.6). In this scenario, the global mean temperature rises by approximately 1.8 degrees by 2100.
- The strongest sea level rise occurs in the scenario where no action is taken to reduce the emission of greenhouse gases (scenario SSP5-8.5). In this scenario the global mean temperature will rise by approximately 4.4 degrees by 2100.

Scenario/ timeline	Sea level rise[2]		Rhine discharge[3]		Meuse discharge[4]		Based on IPCC scenario
	2100	2200	2100	2200	2100	2200	
Low (optimistic)	0.5 m	1 m	15,500 m^3/s	15,500 m^3/s	3,800 m^3/s	3,800 m^3/s	SSP1-2.6
Moderate	0.75 m	2 m	15,900 m^3/s	16,100 m^3/s	3,900 m^3/s	3,900 m^3/s	Between SSP1-2.6 and SSP5-8.5
High (pessimistic)	1 m	3 m	18,400 m^3/s	20,300 m^3/s	4,500 m^3/s	5,100 m^3/s	SSP5-8.5
Very extreme (worst-case)	2 m	5.4 m	18,400 m^3/s	20,300 m^3/s	4,500 m^3/s	5,100 m^3/s	SSP5-8.5 including Antarctica instability

Table 1 The extent of sea level rise and the maximum river discharge in various climate scenarios, based on the timelines and reference values applied in the Sea Level Rise Knowledge Programme.

As part of the Sea Level Rise Knowledge Programme, a range of timelines were developed that together indicate a bandwidth for the potential extent of sea level rise (Table 1). These timelines have been used to demonstrate the consequences of sea level rise in the Netherlands and explore potential solutions for the future. The timelines have been based on the IPCC scenarios and are in line with the KNMI'23 scenarios that were published during the course of the knowledge programme. The scenarios also took account of continued subsidence and the fact that river discharges will also change because of climate change.

After 2100, the pace of the rise in sea level will increasingly depend on the extent of warming and whether or not part of the Antarctic ice sheet becomes unstable. This effect has not been factored in to the Low, Moderate and High timelines. For this reason, a very extreme situation was modelled, factoring in an accelerated melt of the Antarctic ice sheet. This shows that, if the Antarctic ice sheet is less stable than shown in the standard models, a sea level rise off the Dutch coast of 2.5 m by 2100 and 17.5 m by 2300 cannot be ruled out (low likelihood, major impact). The possibility of the ice sheet becoming unstable and the extent of warming are the two biggest uncertainties in determining future sea level rise. The IPCC has stated that the oceans, and particularly the ice sheets, respond very slowly to changes in the climate[5]. It takes hundreds or thousands of years for the ice sheets to reach a new equilibrium. Until then, they will continue to shrink and sea level rise will continue. The rate at which this happens depends to a major extent on how much temperatures increase. The larger the temperature increase, the faster the sea level rise and the more extensive and expensive the adaptation measures needed.

[2] The figures for the sea level rise apply relative to the average for 1995-2014. The extent of sea level rise has been rounded to 25 cm in the case of a sea level rise below 1 m, to 50 cm for a sea level rise between 1 and 3 m and to 1 m for a sea level rise of more than 3 m. This rounding has been coordinated with the KNMI for the purposes of this report. The best value for the moderate scenario by 2200 is 1.75 m. For practical reasons, Rijkswaterstaat has rounded this to 2 m in the analyses.

[3] The Rhine discharge in a situation with the likelihood of 1/1,000 per year, rounded to 100 m^3/s.

[4] www.ipcc.ch/assessment-report/ar6/

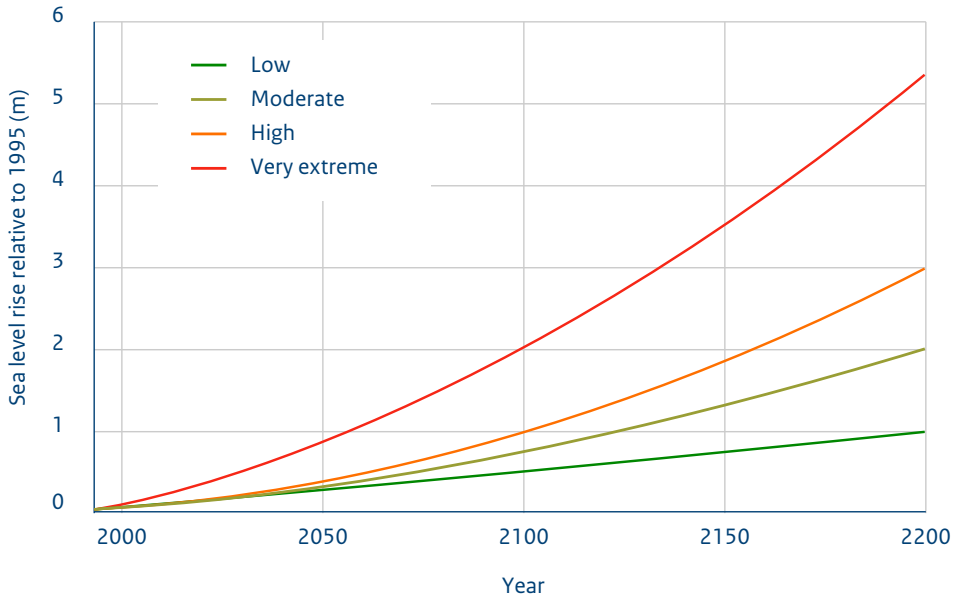


Figure 18 Timelines for sea level rise in three scenarios for carbon emissions (low, moderate and high) and in a very extreme situation in which the Antarctic ice sheet becomes unstable.

Changes in the Gulf Stream

The Gulf Stream in the northern Atlantic Ocean (AMOC) has a significant influence on the Dutch climate. Because of it, we have relatively mild winters and summers. Recent research has shown that the AMOC slowed by around 10% between 2004 and 2023.[6] If the Gulf Stream weakens because of climate change, Europe will become the outlier in global warming: it will initially heat up less quickly than elsewhere or even become colder, especially in winter. The slowing will influence the climate: there will be more dry periods in summer and wetter periods in winter. The combination of these changes can result in additional sea level rise because the sea becomes fresher. Ice formation can also play a role and alter wind patterns. The extent to which these consequences will happen will depend on the change in the Gulf Stream, which remains uncertain.

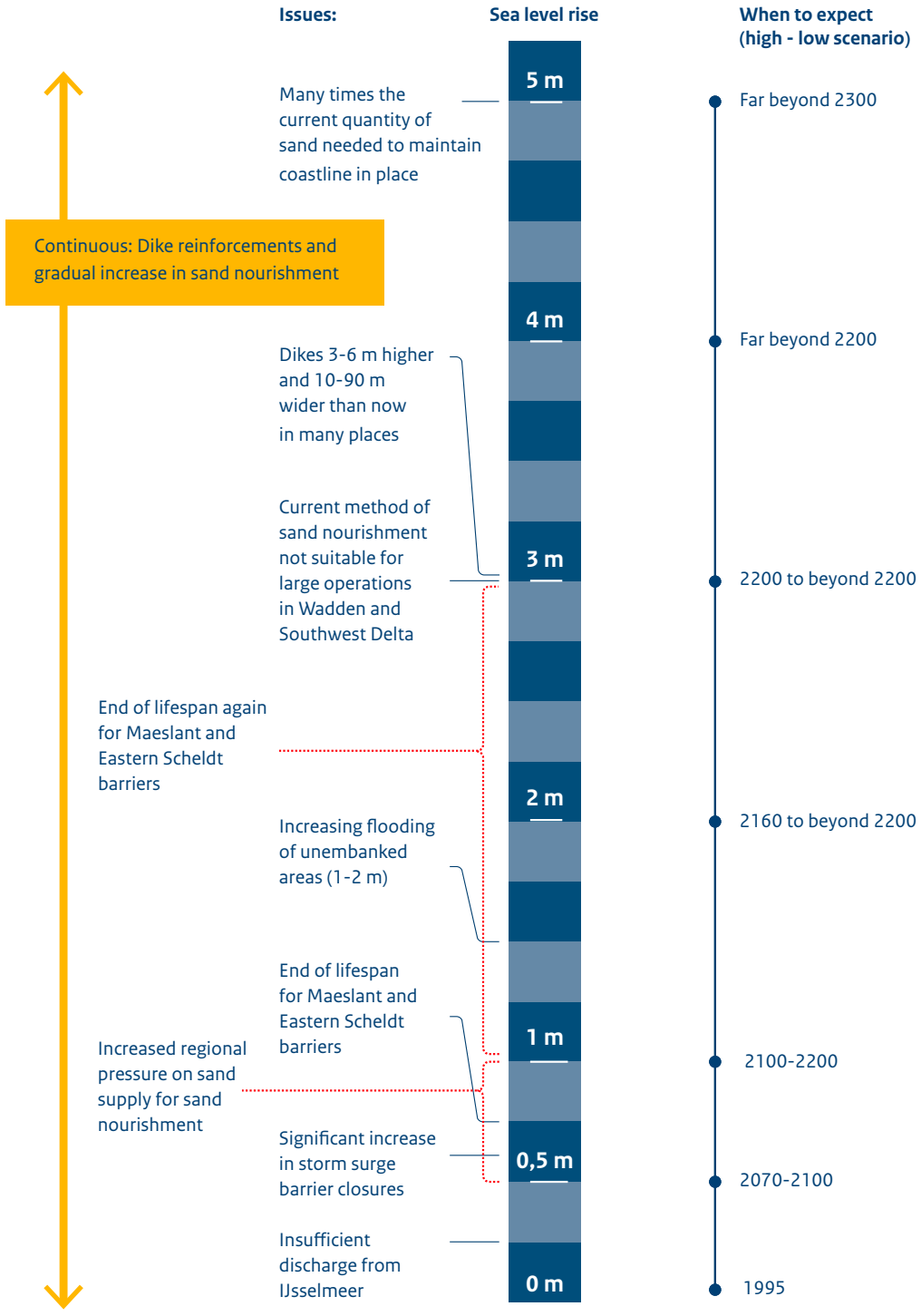
Climate models show that, in the 21st century, the AMOC can slow by around 40%[7]. By 2100, this will result in an additional sea level rise of 0 to 30 centimetres along the Dutch coast[8]. This contribution (including the high level of uncertainty) has been included in the timelines for sea level rise developed by the Sea Level Rise Knowledge Programme and in the KNMI'23 scenarios. The effect of the slowing of the AMOC on atmospheric variables has also been factored into the KNMI'23 scenarios, because the atmosphere in the climate models responds to the different oceanic conditions. There is a possibility that the AMOC will slow more rapidly than the climate models predict. In a worst-case-scenario, in which the AMOC comes to a complete standstill, the sea level along the Dutch coast would rise by 60 cm in the next 100 years, solely as a result of this change in oceanic circulation[9,10]. In that case, the total sea level rise for the Netherlands would be approximately 30 cm higher by around 2100 than indicated in the timelines in Table 1 and Figure 18.

[6] agupubs.onlinelibrary.wiley.com/doi/10.1029/2025GL115055.
[7] Weijer, W., Cheng, W., Garuba, O. A., Hu, A., and Nadiga, B. T.: CMIP6 Models Predict Significant 21st Century Decline of the Atlantic Meridional Overturning Circulation, Geophysical Research Letters, 47, e2019GL086075, https://doi.org/10.1029/2019GL086075, 2020.
[8] Le Bars, D. and Drijfhout, S.: Connecting the Past and the Future to Build Regional Sea-Level Projections, Earth's Future, 13, e2024EF005623, https://doi.org/10.1029/2024EF005623, 2025.
[9] Katsman, C. A., Sterl, A., Beersma, J. J., Van den Brink, H. W., Church, J. A., Hazeleger, W., ... & Weisse, R. (2011). Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta – the Netherlands as an example. Climatic change, 109(3), 617-645.
[10] Van Westen, R. M., Katsman, C. A., and Le Bars, D.: Dynamic and Steric Sea-level Changes due to a Collapsing AMOC in the Community Earth System Model, EGUsphere, 1–25, https://doi.org/10.5194/egusphere-2025-5102, 2025.

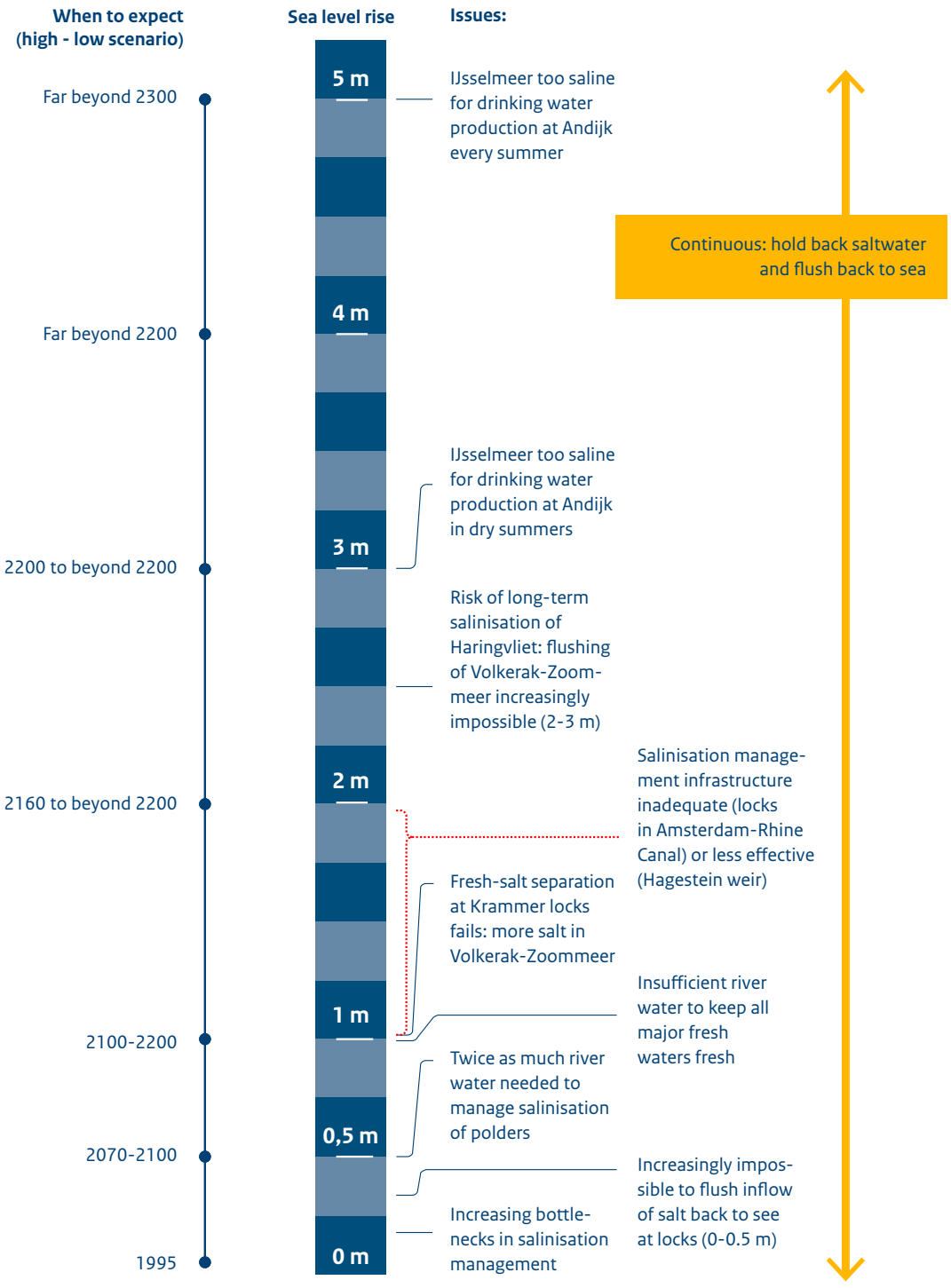
Appendix 2 Issues for flood protection and salinisation management

The figures below show in broad outline which issues will occur successively as the sea level rises further. These issues are explained in section 3.2.

Issues relating to flood risk management



Issues relating to freshwater:



Appendix 3 The knowledge base: overview of background reports

This Appendix contains a list of the reports produced in Dutch as part of the Sea Level Rise Knowledge Programme that also form the basis for this final report.

- **Nederland en de zeespiegelstijging. De gevolgen voor waterveiligheid en zoetwater, Rijkswaterstaat, 2026**
  - *Systeemanalyse Zandige Kust - Zeespiegelstijging en de voorkeurstrategie voor de zandige kust. Sedimentbehoefte, suppletievolumes en houdbaarheid strategie bij versnelde zeespiegelstijging*, Rijkswaterstaat, 2026
  - *Syntheserapport Waterveiligheid fase 2 incl oprekmaatregelen*, HKV, December 2025
  - *Synthese bevindingen KP ZSS Systeemanalyses Zoetwater*, Rijkswaterstaat, December 2025
  - *Impactanalyse Kennisprogramma Zeespiegelstijging*, Royal Haskoning DHV, 2025:
    - Deelrapport *Huidige Strategie*
    - Deelrapport *Oprekmogelijkheden: Zoetwaterbeschikbaarheid*, Waterveiligheid, Zandige Kust
    - Deelrapport *Lange Termijn Denkrichtingen: Zeewaarts, Meebewegen, Beschermen Gesloten A1, Beschermen Gesloten A2, Beschermen Open B2*
    - Deelrapport *Nature Based Solutions: Alternatief 1 & 2*
    - Deelrapport *Kostenraming strategieën zeespiegelstijging*

- **Ruimte voor zeespiegelstijging 2, Kennisprogramma zeespiegelstijging, 13 November 2025:**
  - Rapport *Beschermen, consortium Beschermen*, 15 February 2024
  - Rapport *Zeewaarts, consortium Zeewaarts*, 16 February 2024
  - Rapport *Meegroeien, consortium Meegroeien*, 10 October 2025
  - Rapport *Meebewegen, consortium Meebewegen*, 10 November 2023
  - Rapport *Indicatieve kosten en effecten van oplossingsrichtingen voor extreme zeespiegelstijging*, 2026

- **Tijdlijnen voor beslismomenten bij zeespiegelstijging, Haskoning, Infram, 20 October 2025**

- **Volgens het boekje, Nederlandse School voor Openbaar Bestuur, April 2025**

- **Tussenbalans van het Kennisprogramma Zeespiegelstijging, Kennisprogramma Zeespiegelstijging, November 2023**

A full list of these sources and publications can be found at:
- www.deltaprogramma.nl/kennisprogramma-zeespiegelstijging (see bibliography)
- www.rijksoverheid.nl/documenten
- open.rijkswaterstaat.nl/open-overheid/onderzoeksrapporten

Colophon

This brochure was produced by the Sea Level Rise Knowledge Programme, an initiative of the Minister of Infrastructure and Water Management and the Delta Programme Commissioner.

Supervision
Ministry of Infrastructure and Water Management
Delta Programme Commissioner's staff
Rijkswaterstaat

Text and editing
Renske Postma, Bureau Met Andere Woorden

Translation
MediLingua B.V.

Design
VormVijf

Photography
p. 8 Storm on the coast of Zeeland: Tineke Dijkstra
p. 10 Urk seen from the IJsselmeer: Ivo Vrancken
p. 11 Coast at Pettemerduinen: John Gundlach
p. 16 Grote Kerkvliet weir, Polsbroek junction: Tineke Dijkstra
p. 19 Hagestein weir and lock complex: Tineke Dijkstra
p. 22 Water level gauge at Hoek van Holland: Mischa Keijser
p. 36 The Eastern Scheldt barrier: John Gundlach
p. 43 Coastline of the polder in Noord-Groningen Wadden Sea: Ivo Vrancken
All images are from the National Image Centre (*Rijksbeeldbank*)

The following government authorities, knowledge institutes and consultancies collaborated on the Knowledge Programme:

- Deltares
- KNMI
- Maatschappelijke Klankboord Groep (Civil-society Advisory Group)
- Netherlands School of Public Administration (NSOB)
- Protect Consortium
- Accommodate Consortium
- Nature-based Consortium
- Seaward Consortium
- Arcadis
- Haskoning
- HKV
- Hydrologic
- Infram
- Plannenmakers
- Sweco
- Witteveen + Bos

And everyone else who made a contribution.

This brochure was produced by:

The Sea Level Rise Knowledge Programme, an initiative
of the Minister of Infrastructure and Water Management
and the Delta Programme Commissioner.

https://www.government.nl/ministries/ministry-of-infrastructure-and-water-management
https://english.deltaprogramma.nl