How to keep the Netherlands safe and liveable for future generations as sea levels rise? Current approach, a solid basis!

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ABSTRACT

The Netherlands is one of many densely populated deltas in the world. In areas such as these the availability of fresh water and the proximity to the sea are simultaneously a blessing and a threat. Over centuries, the Dutch delta has developed into a safe and prospering area, relying on a comprehensive system of flood defences and an intricate water system. Due to global climate change and socio-economic developments both the system of flood defences and the water system will be under increased pressure in the future. The Netherlands in particular needs to find ways to cope with sea level rise (SLR) to keep the delta safe and liveable for generations to come.

Through the Knowledge Programme on Sea Level Rise, a coherent series of studies has been performed in order to understand the consequences of a SLR of up to 5m for the water system and the options for action. Model based studies have shown that the current approach for flood risk management technically could be prolonged up to a SLR of 3 to 5m. While consequences for the economy, nature and society increase with the sea level over time, other perspectives may become attractive. Four alternative conceptual perspectives have been explored by multidisciplinary teams, leading to useful building blocks. However, up to 5m of SLR, levees and beach nourishments remain basic elements in all different perspectives.

The current approach provides a solid basis for the future and from a flood protection perspective there is no necessity to make major changes now. However, as transition processes will take decades, it is advisable to prepare in a timely manner. Foreseeable future adaptation should be taken into account in today's spatial planning and decision-making processes. The adopted structured, policy driven knowledge development may be a valuable approach for other regions and subjects.

KEYWORDS: Netherlands, climate adaptation, sea level rise, Knowledge Programme, flood protection

1 INTRODUCTION

Because of its geographical location, with around 50% of the surface of the country being flood prone, flood risk and water management are key to the safety and prosperity of the Netherlands. Flood protection and water management systems are never 'finished', but after the Delta works and the Room for the River programme, recent efforts seem to have mainly been aimed at the optimization of the existing system. However, adaptation to climate change in general and SLR in particular may implicate larger changes in the future. The publication of a paper (De Conto and Pollard, 2016) on possible extreme SLR through accelerated mass loss of Antarctic ice and a subsequent report on possible consequences for the Netherlands (Haasnoot et al. 2018), led to a range of articles and opinions in the media on the (possible absence of a) future for the Netherlands. Although several studies in the past addressed the subject of SLR in the Netherlands (PBL, 2007) no detailed studies of the consequences had been performed so far.

Therefore in 2019, a national research programme was developed by the Ministry of Infrastructure and Water Management and the Delta Commissioner in order to create a sound knowledge basis as a starting point for policy development.

1.1 Scope of the Knowledge Programme on Sea level Rise

The knowledge programme consisted of several 'tracks' each with a different focus. Main objectives and budget of the programme were determined before the programme started. Throughout the duration of the programme however, a certain amount of flexibility was permitted to make changes in method or focus. As the programme aimed to develop information for flood risk and water management, it was policy oriented. Resulting in a programme considered very technical within the policy environment, and at the same time very policy focussed within a scientific environment. In order to create the most objective value possible, the developed knowledge has consciously been reported separately from the associated policy discussion, that is taking place within the ministry and the delta programme.

Because of the importance of flood risk and water management for the perdurance of the Netherlands and the huge potential impact, a SLR of up to 5 m was taken into account. Such is in line with the recommendation in the sixth assessment report of the IPPC (IPCC, 2023) for exposed countries to take extreme scenarios into account. Because of the large uncertainty of the speed and amount of SLR in the future, studies were performed scenario independent whenever possible, in order to be able to translate results to different (future) scenarios. In case this was not possible, several different working scenarios were taken into account in order to obtain as much information as possible. The most extreme working scenario consisted of 2 metres (m) of SLR in 2100 and 5.4m of SLR in 2200, which would be well above the 17th to 83rd percentile range of SPS5-8.5 and in the order of the *low likelihood high impact* storylines of the SLR scenarios for the Netherlands (KNMI, 2023). This most extreme scenario is considered to be a 'stress-test-scenario', and has also been used to develop the alternative conceptual perspectives.

The different tracks consisted of:

a) Research on SLR itself: contributing to the development of different scenarios for SLR to be expected on the Dutch coast in the future, and the interpretation of sea level measurements/SLR measured at present. An important goal of this track was to participate in international knowledge development. It is the most academic part of the knowledge programme.
b) A series of **system oriented studies** on effects of SLR on 1) flood risk management of the main water system (sea, main rivers and big lakes), and 2) on salination, both within the water system and through salty seepage. These studies involved modelling and took several years.
c) Development of several **alternative conceptual perspectives** to keep the Netherlands safe and liveable in the future. These studies had a more explorative character, although more or less information from the system oriented studies could be used, depending on the nature of the conceptual perspective.
d) Communication, participation and decision-making; Special effort has been put into communication of current findings to inform politicians and the general public. A group of representatives of different NGOs (e.g. on nature conservation) and sectors (e.g. on agriculture, sand extraction, recreation) has been kept up to date of developments and results, leading to a grown consciousness on difficulty of future choices in water management and the necessity of adaptation (of sectors)to SLR. Additionally, conceptual reflection has been organised on public decision-making under high uncertainty (van der Steen et al., 2025).

This publication focusses mainly on flood risk management aspects of b) the system oriented studies (under 2) and c) the alternative conceptual perspectives (under 3). General aspects of a) and d) are part of the discussion (under 5).

2 SYSTEM ORIENTED STUDIES

The main aspect of the current Dutch approach for flood risk management consists of statutory standards for flood protection infrastructure, stipulated in law. Standards have been deducted using risk assessments. Standards provide at least a *base level of flood protection*, the probability of an individual drowning in a flood will not exceed 1/100,000 per year. Standards provide a higher protection whenever appropriate, following the outcomes of local cost-benefit analyses and group risk assessments. The resulting standards are expressed as 'a maximum permissible probability of failure per year' and prior to exceeding this maximum, infrastructure should be upgraded. This means that higher expected river discharges and rising sea levels will over time require stronger levees, dunes, dams etc.. The current set of standards has been introduced in 2017 and is planned to be completely met in 2050. Counter-intuitively this is leading to a progressive risk reduction towards 2050, in spite of climate change.

On top of the standards there are regional strategies defining how national and regional authorities, together with other regional and local parties, want to achieve the required safety level. An example is the 'closable-open' strategy in the highly urbanised and industrialized region of Rotterdam. In this region the Maeslant barrier ensures easy access to the port and the hinterland from the sea on a daily basis, while protecting the area from extreme water levels during storm surge, thus reducing the necessary dimension of levees behind the barrier as well as the amount of water nuisance in unprotected areas.

Both the standards for flood protection infrastructure and the regional strategies are taken as a premise for the system oriented studies. The effects of SLR combined with expected development of (extreme) river discharges are taken into account to calculate hydraulic loads for 0.5, 1, 2 and 3 m of SLR. These hydraulic loads have been extrapolated to 5 m of SLR to extend the range of the assessments. Under different climate scenarios different combinations of sea level and river discharges are expected, hence different hydraulic loads have been determined.

2.1 Sandy coast

Part of the system studies focused on the impact of accelerated SLR on the sustainability and adaptability of the coastal management strategy. This strategy aims to maintain the coastline dynamically through sand nourishments, ensuring safety and preserving functions and uses of dune areas while allowing the coast to gradually rise with sea level (Lodder and Slinger, 2022; Brand et al. 2023).

Currently, about 11 million m³ of sand is added annually via beach, shoreface, and channel nourishments. Estimates of future nourishment demand have been made based on assessment of the current sediment budgets, conceptual and numerical modelling. These assessments indicate that the long-term goals can likely be met by allowing the most active parts of the coast (between approx. –8 m MSL and the first dune row) to rise with sea level. Sand nourishments spread within this zone.

The sand demand will increase significantly in the future: under the extreme scenario of 2 m SLR in 2100 and 5.4 m in 2200, the annual nourishment demand is estimated to be 4× current levels by 2100 and 5× by 2200. However, there are significant regional differences. The Northern part of the coast (Wadden Coast) requires up to 7× more sand, while the middle part (Holland Coast) and Southern part (Delta Coast) are estimated at 3.5× and 2.5× respectively.

To supply these nourishment volumes, innovations in nourishment techniques are likely to be needed. In addition to the current nourishment types, larger scale nourishments are needed. These innovations include nourishment forms but also should address aspects like emission reduction and reduction of environmental disturbance.

Overall it is concluded that the coastal management strategy is sustainable and adaptable.

2.2 Flood protection structures

In order to assess the necessary adaptation of the (system of) primary flood defences, a standardized method based on models has been used. It consists of combining hydraulic loads (forces from water), with failure models of the flood defence, which includes the dike profile, foreshore, revetments, dike materials, soil properties, and water pressure effects. Hydraulic loads were deducted using hydrodynamic and wave models for thousands of combinations of surge water level, river discharge (River Rhine and Meuse) and wind properties. The study focused on three main failure mechanisms: *dike height* (overtopping and overflow), *slope stability* and *piping*. All failure processes were modelled using fragility curves.

The flood safety assessment used a probabilistic approach, with water level and wave load as key stochastic variables. Hydraulic loads were computed with models such as **SOBEK3** for rivers (Rhine and Meuse), **IMPLIC** for the Eastern Scheldt and **WAQUA** for the Western Scheldt and Wadden Sea. Waves were modelled using a fetch approach for the rivers and **SWAN** (coastal areas). Inputs were based on statistical analyses of historical seawater levels, wind, and river discharge, covering return periods from years up to 100,000 years. The spatial and financial impacts of reinforcement were assessed with a dedicated cost model (OKADER). Where plan view space was limited, hard vertical structures or demolition of buildings were assumed for the necessary flood defence upgrades, with costs including depreciation of existing houses.

- **Variation in dike heightening**
  Simulations show large regional differences. For 3 m SLR, required dike heightening exceeds 5 m in the northern part of the country (up to 7 m in some Wadden Sea areas), decreasing to 1–4 m in central and southern regions and further inland along the Rhine and Meuse. Extra height beyond SLR is mainly due to wave run-up and depth-limited wave growth.
- **Wave dynamics and foreshore effects**
  Higher water levels allow larger waves to reach flood defences, increasing wave setup and reducing bottom friction. Seabed growth (sedimentation) slightly reduces required heightening (≈1 m less), while foreshore vegetation improves stability but does not affect dike height.
- **Storm surge barriers**
  Rising SLR drastically increases closure frequency if closure levels remain fixed. For example, the Maeslant barrier would close every tidal cycle at 3 m of SLR. Raising closure levels reduces closure frequency but makes outer embankments more flood-prone. For areas protected by both barriers and dikes, required dike heightening is roughly equal to SLR.
- **Land Use**
  Dike reinforcement requires significant space: when there is 3m of SLR an extra width of 50-150m is needed, in extreme cases up to 200m. This is especially challenging in urban areas. Built-up floodplain areas will face more frequent flooding.

2.3 Findings on current approach

The results have shown that it is *technically possible* to protect the Netherlands against flooding using the current approach, up to 3 m of SLR, possibly 5 m (Friocourt et al. 2025). However, this requires major ongoing efforts and spatial adjustments. With continued SLR, larger sand nourishments, stronger dikes and more frequent barrier closures will be needed, as well as increased pumping capacity to drain low lying areas. Furthermore, areas without flood protection will experience frequent or even permanent inundation. This includes some urban areas.

"Technically possible" means designs can withstand the studied SLR, but societal impacts are not yet (well) assessed. The availability of clay and sand and space for e.g. wider dikes is crucial. Logistics could become a major challenge if SLR accelerates, requiring simultaneous action in many places. Furthermore, the actual societal challenge is larger than here presented since SLR also effects the fresh water supply and other aspects of society such as space for nature and recreation, risk perception etc. These factors will co-determine how long the current approach remains viable in practice. This raises the question what other strategies for adaptation could look like. To address this question alternative conceptual future perspectives have been developed.

3 CONCEPTUAL FUTURE PERSPECTIVES

Based on an inventory of existing 'plans' for the future of the Netherlands, different conceptual perspectives were determined: Protect (2x), Advance (seaward) and Accommodate (Haasnoot et al. 2020). The existing plans were deconstructed into 'building blocks'; measures that can be combined in order to find new possible strategies (Haasnoot and Diermanse 2022). Government authorities, knowledge institutes, and stakeholder organizations explored how these building blocks could be used to address the long-term consequences of SLR, leading to regional drafts of designs for each of the conceptual perspectives. In order to get a better idea of their feasibility and of the resulting alternative solution space at hand, a more detailed and technical description and design was needed. These were elaborated for the three above perspectives, as well as for a fourth perspective that was introduced in 2024: Grow.

To obtain the best possible results in a short period of time, a co-creation process was chosen. For each of the perspectives a multidisciplinary team was formed, consisting of e.g. hydraulic engineers, landscape architects, morphologists, ecologists, cost experts, etc., from various types of organizations: consultancy firms, designers from architects' firms, scientists from knowledge institutions and universities, government authorities, project contractors and NGOs and stakeholder organizations. A so-called 'core team' was responsible for designs and descriptions, analyses and calculations for the specific conceptual perspective of their attention. While a wider group was used to reflect upon results and to collect knowledge and input for the next step. In less than ten months, in a series of working meetings of the core teams and hackathons with the wider group, each team finalized a more detailed elaboration of its specific perspective: a landscape design including a more detailed and technical description of measures (Web-1). This formed the basis for an assessment of its effectiveness and feasibility. The conceptual perspectives have been developed for a SLR of 2 and 5.4 m in resp. 2100 and 2200 by means of a stress test; as alternatives are expected to be especially useful, and maybe sooner necessary, under extreme conditions. A short description of the perspectives is given below.

3.1 Protect

In the perspective Protect, the Netherlands is being kept safe and liveable by building upon the current approach to water management using hydraulic engineering works to direct, divert, and control water. This means upgrading dikes, storm surge barriers, locks, dams and pumping stations. In this way, the delta is protected against flooding, and the water system for both freshwater usage and excess water drainage can be optimised. With sand nourishments, the coastline is kept in place, and rises with the sea level. Different decisions are to be made concerning the configuration of the delta, in this study leading to four different alternatives:

1. Sea fronts closable with storm surge barriers, with two options;
   a) maintaining the current discharge distribution over the river branches
   b) adapting the current discharge distribution over the river branches during high river flows; and
2. Sea fronts closed by dams, with again two options;
   a) maintaining the current inland water level using pumping stations
   b) increasing the inland water level with SLR enabling discharging of river water by using gravity forces as much and as long as possible.

3.2 Advance

In the perspective Advance the Dutch delta is extended in seaward direction by building a large 'lake' in front of the coast of the southwestern part of the delta. This constructed lake creates extra storage capacity for peak discharges of the Rhine and Meuse, such that less pumping capacity is required to discharge flood peaks from the river.

The perspective can be considered as an extension of the protect-closed perspective in the previous paragraph. Like the protect-closed perspective, it may reduce salinization problems in this part of the delta. The construction of the lake requires technical measures: dams, nourishments, break waters, pumping stations and ship locks. A new coastal lake would have a major impact on nature and ecology as the dynamics (water, waves, sediment) would be drastically altered.

3.3 Grow

The perspective Grow is based on the principles of nature based solutions (NBS). In this perspective, the Netherlands remains safe and liveable by making use of the natural processes that built the delta. This can be achieved by on the one hand stimulating the natural dynamics of water, sand and silt, and at the same time creating space to capture sand and silt, leading to transition zones between sea and land that grow along with SLR. These growing transition zones contribute to flood protection and provide a robust ecosystem. This could provide a flexible, climate-resilient alternative to the current approach, comparable to the current coastal management strategy for the sandy coast (see 2.1). However, in some places where this perspective could be applied existing traditional infrastructure impedes or limits both the exchange of sediment necessary for optimal siltation processes and a gradual freshwater-saltwater transition important for ecology. In these cases, dams and storm surge barriers would need to be removed or adapted in order to create the right conditions. On the long run annual SLR many exceed sedimentation speed and reduction of intertidal flats will occur, or additional nourishments will be necessary.

Although natural processes are heartily welcomed in the delta in this perspective, to preserve protection against flooding, this is only possible in combination with traditional dikes. And in order to optimise availability of fresh water, one of the two developed strategies combines open estuaries in the southern part of the with a closed off Rotterdam area (Protect). Hence, building blocks in this perspective are: nature-friendly storm surge barriers, transition zones between sea and land that grow along with SLR; either between dikes or as vegetated foreshores in front of dikes, (restored) tidal basins (former inlets along the coast), and nourishments and measures to accelerate or supplement natural accretion.

3.4 Accommodate

In the perspective Accommodate, land use and society is adapted as much as possible to the effects of SLR. The assumption is that existing water infrastructure and engineering works will not be further upgraded after 2050 (but neither will they be removed). Everyone will retain the base level of flood protection (see under 2).

Special attention has been given to the Randstad urban agglomeration, the low-lying economic heart of the Netherlands, including the Port of Rotterdam. It is important for the Netherlands to maintain its earning capacity in order to adapt to climate change. After extensive exploration of alternative ways to keep this area fully functioning, it was concluded that the only cost-effective way to do so, is by continuing a 'protect-perspective' with hydraulic engineering infrastructure for as long as possible.

Other parts of the country may use building blocks that mitigate the consequences of flooding, for example raised or floating housing, evacuation plans, and water-robust vital networks (electricity, drinking water). To cope with more saline conditions, one can think of salt-tolerant agriculture, or 'footloose' agriculture. Encouraging investments in higher situated parts of the country, is also part of this perspective. It was not possible within the available timeframe to obtain a fully developed landscape plan.

3.5 Findings on alternative perspectives

The programme shows different options to design a realistic and liveable future for the Dutch Delta, and delivers a vast amount of useful building blocks. However, it seems unlikely that one of the conceptual perspectives will suffice to obtain a future-proof country. Most probably a combination of elements from all four conceptual perspectives is required (van Alphen et al., 2025). The performed research can serve as a knowledge basis and a source of inspiration.

4 IMPACTS, COSTS

Current land use and functions are highly optimised. Multiple developments, such as housing, industry and the energy transition, need more space. The impact of SLR on all of these socio-economic functions will in any case be negative compared to *the current situation*. Adaptation measures always ask space and construction materials and a serious increase of salinization is unavoidable in the end. It is possible to estimate the amount of space needed for adaptation to SLR on the long run, for different perspectives or using a combination of building blocks. It is difficult however, to determine impact in general, as land use and functions develop over time as well. Future SLR in itself may stimulate transformation of sectors, due to foreseeable effects, such as the reduction of the availability of fresh water. The impact in the end will be specific for a certain area and will depend on the amount of SLR, on water management and on the adaptability of future land use and functions.

To continue the *current strategy,* upgrading and replacing existing water management infrastructure such as levees, dams and storm surge barriers is necessary, as well as continuing beach nourishments to maintain the coastline. This will result in costs of approximately EUR 200 billion in 2200, with a SLR of 5.4 m, meaning an increase by 1.5 to 2 times the current cost of the strategy. In the *Protect perspective*, investment costs are comparable, amounting to EUR 100 billion in 2100 to 200 billion in 2200, for resp. 2 and 5.4 m of SLR. Different water management infrastructure will be realised and upgrading of levees and beach nourishments are still necessary. For the *Advance perspective* an extra EUR 30-35 billion should be added for the construction of the artificial lake. For the *Grow perspective* two different strategies have been assembled, leading to an extra estimated EUR 21-40 billion.

Costs of the Accommodate perspective could not be estimated based on the outcome of the co-creation study. In a case study (outside the programme) for the province of North-Holland, costs were estimated for several possible interpretations of an Accommodate perspective. The costs of the variant yielding the lowest total costs were around 60 times higher than those of the Protect perspective (Kolen, 2025). A more detailed overview of comparable costs of alle alternatives is yet to be concluded.

Costs have a large, but not calculated bandwidth. Costs for areas that are not protected by dikes and will be more sensitive to flooding in the future, costs for the regional water systems, or benefits that may occur are not included.

5 CONCLUSIONS AND DISCUSSION

5.1 The current approach for now most attractive.

The current flood risk management approach has been shown to be technically effective up to 3-5 m of SLR. However, its actual feasibility depends on multiple factors, like the availability of resources such as sand an clay. Different alternative conceptual perspectives provide useful building blocks for the future and these also need resources and space. Besides, the larger **i**nterventions are, the more impact they will have on land use and 'functions'. As land use and water management co-developed over time, continuing the same approach has the least impact for at least the decennia to come. Over time, SLR will have increasing impact and other configurations of the water system might become more attractive.

5.2 Major decisions will be complicated decisions

Both the coherence within the water system, and the coherence between the water system and land use and functions, ask for a comprehensive approach to future decisions. Strategies for flood risk management can't be seen separately from those for fresh water management, and both should serve a safe, pleasant and sustainable environment and a thriving economy. Certain decisions do not only have large regional consequences for land use and functions, but influence large parts of the main water system, and therefore (land use and functions in) other regions or even the country as a whole. As positive and negative effects vary between regions and functions, obtaining sufficient political and societal support will be complex.

A first reflection on the difficulty of decision-making in regard to SLR pointed out the importance of 'unknown unknowns'. If decisions are only taken when there is certainty, they will never be taken. Moreover, if a specific choice or development is presented as a true 'solution', this reduces the flexibility to keep on adapting in the future. An alternative approach could be *enlarging* the scope of decisions, this may lead to a larger solution space and a different balance of positive and negative effects (van der Steen et al., 2025). Still, coherence within the water system should always been taken into account.

5.3 There seems to be time, but..

Renovation and replacement of 'dominant' flood risk infrastructure, such as storm surge barriers, will lead to natural decision moments for future strategies. As these aren't expected the next decades, there seems to be sufficient time for a step-by-step approach. However, should 'sedimentation' be used as a building block in order to raise land in the estuaries, then this strategy should be implemented in time to be effective. Moreover, the availability of fresh water will become an issue earlier than flood protection. Any measures that could be implemented in the main water system should be seen in a broader perspective. In the end other developments, like the energy transition and housing, may lead to earlier decision-making. This could either accelerate decision-making for flood protection or limit future possibilities.

Adaptation itself takes time, too. Necessary knowledge should be collected, difficult decisions taken and measures implemented (Haasnoot and Diermanse, 2022). Moreover, changes in the water system may require additional adaptation or mitigation measures. Replacing a storm surge barrier by a dam for example, will heavily impact shipping and harbour activities. Therefore additional time or early decisions may be needed. In any case, timely preparation is essential. At the same time, it is economically costly to replace either structure or strategy much earlier than necessary. Balance is needed.

5.4 Structured knowledge development

In order to address the subject of SLR, a 'knowledge programme' in a policy context has been organised; a new approach for the Netherlands. Although a formal evaluation hasn't been performed yet, we would like to point out some specific aspects.

First of all, the comprehensive approach, with different tracks focussing on different aspects, worked well in itself. However, the flexibility to adapt the programme when necessary was just as important. During the programme, it appeared to be easier to attend to certain parts of the initial plan in a later phase, such as the operationalisation of 'early warning signals'. The co-creating process around different conceptual perspectives developed during the programme, and the extra perspective Grow was added because information on the potential of nature based measures was lacking.

Reporting the developed knowledge separately from the associated policy discussion, keeping the reports as objective as possible, seems to work well. In general results are being embraced. At the same time, the orientation of the studies towards policy issues is very useful. The results provide important information for the (regular) updating of the current strategies for water management in the Netherlands. Although time span addressed is beyond the lifetime of the waterworks, the results also provide a certain comfort to continue investing in the current system and endorse its importance for the future.

SLR in the order of two to five metres will have a major impact and adapting to it will in any case require enormous efforts. There are no easy solutions. The developed knowledge provides a good start for discussions about the future, but it isn't fit for decision-making yet. More insights are needed, but uncertainty will remain and decisions should be taken in time. In any case, the current approach is viable and can be used as a solid basis for future choices.

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