The Impact and outlook of Extreme Sea Level Rise on Flood Protection and Freshwater Systems in the Netherlands

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ABSTRACT

This paper synthesizes the national assessment of the impacts of up to 3 m sea level rise (SLR) on flood protection and freshwater availability in the Netherlands. Using exploratory, model-based analyses across coastal dunes, hard flood defenses along river-lake systems, and the Rhine–Meuse Estuary, the study finds that current flood safety levels can be technically and financially maintained up to 3 m SLR, though spatial and resource constraints intensify. Furthermore the supply of sand for coastal nourishments will be challenging due to other functions in potential sand winning areas in the North Sea (wind energy, shipping) and explosive remnants of war.

Freshwater systems are more vulnerable: salt intrusion and increased flushing demands grow sharply and ultimately exceed available river flows under severe drought and high SLR.

Key implications thus concern sand supply and logistics, reinforcement footprints in dense urban settings, barrier operation strategies, and trade-offs between salinity tolerance and water demand. To keep the flood protection and freshwaters systems up to standard, current safety activities can be prolonged but freshwater is more vulnerable.

KEYWORDS: climate adaptation; sea level rise; flood safety; freshwater

1 INTRODUCTION

The Netherlands is a low-lying, densely populated, heavily urbanized and cultivated delta of the Rhine, Meuse, Scheldt and Ems rivers. About 26% lies below mean sea level and ~60% is flood-prone. It is strongly exposed to the influences of the adjacent North Sea. Apart from flood risk and coastal erosion, the Netherlands is exposed to saltwater intrusion and salinization of its surface waters and groundwater. Due to salinization, around half of the country is dependent on freshwater supplied by the Rhine and Meuse distributed through the highly managed surface water system.

Climate observations show accelerating global and regional sea levels, with national scenarios exploring outcomes up to multiple meters by 2200 [1,2,3]. Projections of SLR derived by the Royal Dutch Meteorological Institute [3] showed an SLR of up to approximately 3 m in 2200 (83rd percentile of ensemble model results for the SSP5-8.5 emission scenario).

The Netherlands has developed and implemented a set of thorough strategies to manage flood risks and optimize freshwater supply [4–6]. The current strategies already consider an SLR of 0.85 in 2100 [7], and the recent insights raise the question of whether and how long these strategies for flood protection and freshwater can remain effective against extreme SLR.

While earlier methods have demonstrated their value in making complex issues with high degrees of uncertainty accessible to policy makers, model-based quantitative assessments of the impact of extreme SLR on flood protection and freshwater availability are not yet available for the Netherlands. The Dutch government hence initiated the national Sea Level Rise Knowledge Programme [8].

In earlier work bij Friocourt et al [43], a quantitative, model-based approach was applied to assess the impact of extreme SLR (up to 3 meters) on national strategies for flood protection and freshwater supply. The study demonstrated that current safety levels can be technically and financially maintained up to 3 meters of SLR, but spatial and logistical constraints—such as sand supply for coastal reinforcement and the operation of flood barriers—become increasingly critical. Moreover, the vulnerability of freshwater systems intensifies due to saltwater intrusion and rising flushing demands, especially during drought conditions. This work builds upon earlier publications [43] and provides additional insights and reflections on the measures which can be taken to extend the longevity of the national strategies.

This paper presents a part of the results of the Knowledge programme, trough the methodology and outcomes of the quantitative assessments of the impact of extreme SLR on the current flood protection and freshwater availability. Furthermore, we present an outlook for freshwater management and flood protection in possible adjustment to the system to keep up with the challenges SLR raises.

The work presented here is structured as follows: First, we provide an overview of the current strategies and consequential systems for flood protection and freshwater availability. We then describe our modeling approach for flood protection (both coastal sand nourishment requirements and structural safety) and freshwater availability (salinization of both groundwater and surface water), followed by the main outcomes of the assessments for current and future measures.

2 NATIONAL CLIMATE APPROACH

2.1. The Netherlands and the Dutch Delta Programme

Both flood safety and water availability are increasingly under pressure due to climate change. In 2010, the Netherlands, therefore, implemented a national policy program for adaptation to climate change: the Delta Programme [9,10]. It focuses on the themes of flood protection, freshwater availability, and spatial planning and works towards a climate-resilient design of urban and rural areas across the Netherlands through a so-called Adaptive Delta Management (ADM) approach [11]. This approach combines short-term plans with long-term delta strategies, as well as a monitoring and evaluation process. Every six years, decisions are reviewed and, if needed, updated. The Sea Level Rise Knowledge Programme [16], contributes to the update of 2026.

2.2. Flood Protection Strategy and System

The Dutch flood protection strategy is risk-based, considering both the probability of flood hazard and vulnerability (casualties and economic damage) [6]. The strategy focusses mainly on the first line of defense: preventing floods. The system consists of a network of primary flood defenses (over 3,600 km) with over 400 km2 of dunes, structural elements and about 25 barriers and dams. The required level of safety that primary flood defenses should provide is expressed as the probability of flooding per year for each segment of the enclosure.

A large part of the coastline is protected through natural dunes. Erosion in the coastal profile is compensated by regular sand nourishments on the shoreface and the beach. This aims to keep the coast line in its place and is intended to maintain the required safety level and leverage the natural, short- and long-term sediment transport dynamics cross-shore and alongshore in the beach zone and related aeolian sand transport in the dune zone [13]. This dynamic management is the preferred method for coastal protection in the Netherlands, with hard flood defenses (dikes and dams) and foreshore protection only in locations where nourishments or other sand-based solutions are technically or economically not feasible.

2.3. Freshwater Strategy and System

The Dutch freshwater strategy relies on managing and directing freshwater in the surface water system towards dedicated lakes, canals and river branches where important freshwater intakes are located. Apart from the main surface waters, reclaimed land (so-called polders) situated below sea level is prone to seepage of brackish groundwater. These polders are flushed with freshwater sourced from the main rivers [14]. The combined efforts to keep reservoirs fresh and up to required water levels and to flush saline groundwater seepage in polders put a considerable claim on freshwater resources, particularly during periods of low river flows and high evaporation. The volumetric water claim is expected to grow due to SLR. The overall freshwater policy ambition is to balance the overall water supply and demand such that actual water shortages only occur once per 20 years [15].

It is noted that, irrespective of climate change, low river discharges already lead to salt intrusion via the open river mouths of the Rhine–Meuse system [16]. Climate change is putting this freshwater management strategy further under pressure. Rising global temperatures lead to increased variability in seasonal precipitation and droughts, resulting in increasing summer water demand and periods of low river flows [12,18,19].

3 METHODS

3.1 The Modeling approach

In our modeling approach, we primarily focused on SLR but also considered other components of climate change, such as changes in temperature, precipitation and changing river flows. Timelines of SLR were used to allow a combination with other developments which influence flood protection and freshwater availability including developments in river flow and land subsidence [51]. More detail on all model input and assumptions can be found in the technical background reports [31–35].

3.2 Assessment of Flood Protection System Under SLR

3.2.1 Sand Nourishments to Maintain ‘Soft’ Flood Defenses

Required sand nourishment volumes to accommodate for SLR were modeled applying sediment budget analysis based on observational data [45]. The uncertainty in the sediment demand was assessed by taking into account multiple possible future areas (m^2) of nourishment sediment dispersal [46].

3.2.2 Assessing the Flood Safety of ‘Hard’ Flood Defenses

The modeling strategy was based on standardized methods for assessing primary flood defenses [7], the system for flood defenses. It involves comparing hydraulic loads (the forces exerted by water on flood defenses) with a failure model of the flood defense. The failure model includes the dike profile (including the immediate foreshore) besides revetments, inner dike materials, soil properties and the effect of water pressure in the dike. The hydraulic loads are modelled with a combination of hydrodynamic models and wave models for up to thousands of various circumstances. This study focused on three primary failure processes for flood defenses: dike height (overtopping and overflow), slope stability and piping. All failure processes are modelled with fragility curves.

The flood safety assessment followes a probabilistic approach using water level and wave load as the main stochastic variables. The total resulting hydraulic loads were simulated using several hydrodynamic models, including SOBEK3 [20] for rivers, IMPLIC [21] for the Eastern Scheldt and WAQUA for the Western Scheldt and Wadden Sea [43]. Waves were computed using the analytic 1-d model Bretschneider [22] for rivers or the spectral phase-averaged wave model SWAN [23,24]. These models use statistics derived from previous frequency analyses on historical records of measured seawater levels, wind and river discharges as input [25]. Wind–water level correlation was added [26,27]. The statistical analysis described seawater levels, river discharges and wind spanning from short return periods (T = 2 years) to extreme return periods (T = 100,000 years) and beyond through extrapolation.

The model output includes physical parameters required for water levels and waves for all locations stored in a database of physical stochastic variables, which is input to the probabilistic modeling tool Hydra-NL [28,29]. Hydra-NL computes the probability of occurrence of the various combinations, with the exception of hydraulic loads to the dunes that were calculated using the Riskeer software, version 22.1.2 [47]. The stochastic variables considered vary per water system. Revetments were added as a cost factor for the total cost. For storm surge barriers and hard structures, a pragmatic approach based on height was employed, assuming that these structures will be replaced once before 2200, and the total cost for this was included.

The spatial and financial impact of strengthening flood safety structures has been further assessed with the cost model OKADER [30]. In places where available space was limited and a 'traditional' dike reinforcement was not possible, we assumed that either hard vertical structures will be constructed assuming a lifetime of 100 years, or buildings will be demolished to create space for dike reinforcement. In the latter case, the financial analyses included the cost of depreciation of existing houses.

To assess the impact of potential future measures, some adjustments to the system were analysed additionally.

3.3 Assessment of Freshwater Availability Under SLR

Due to the considerable differences between salinization processes in different Dutch local water systems, a combination of models was used to assess the impacts of SLR on freshwater resources: a nationwide groundwater flow model, different surface water models and a nationwide water balance model.

SLR impacts on *groundwater* were simulated with a high-resolution groundwater flow and salt transport model [14,36]. The model comprises a variable-density groundwater flow and salt transport. The impact of SLR is superimposed over ongoing groundwater salinization. The groundwater model was used to simulate the increase in saline seepage (or salt load) to the surface water systems in reclaimed land.

The *surface water* bodies of the Rhine–Meuse Estuary (RME) are characterized by a high salinity gradient that required a detailed 3D hydrodynamic model setup in the D-Hydro software release 2022.01 [37] including the tidal cycle. Critical for freshwater availability and salinization are long-term periods of drought with low river flows. The simulations were performed with river flows of 2000 m3/s (representative of summer average flows), 1000 m3/s (representative of current dry summers) and 500 m3/s (representative of low flows under future climate).

The other main freshwater systems in the Netherlands (Amsterdam-Rijn-Canal, Lake IJssel, and Lake Volkerak-Zoom) are closed off from the sea by dams that limit salinization. Salt intrusion, however, still occurs via groundwater and more importantly, through shipping locks. This type of saltwater intrusion is characterized by a semi-stationary horizontal salt gradient, which is largely controlled by river water inflow, water demand and saltwater leakage at the locks. The canal system has been approached by a quasi-stationary 3D hydrodynamic model, to account for the vertical stratification effects and geometric complexities. The lake systems have been approached by simpler 1-dimensional box models merely based on an advection–dispersion equation, building upon the concepts developed by Nolte et al. [38] and Bonte and Zwolsman [50].

4 RESULTS

4.1 Flood Protection

4.1.1 Sand Nourishments of 'Soft' Flood Defenses

The model results show that it is technically feasible to maintain the current shoreline for the majority of the coastline and maintain the current level of flood hazard protection (expressed as a probability of flooding or dike failure), even with extreme levels of SLR of up to 3 m. Additional strengthening is, however, required in built-up areas and cities situated in the dune area where constructions prevent the growth of dunes.

The sand balance simulations show that cumulative nourishment volumes will increase with a factor of 1.5 to 3 for a 1 m SLR, and with a factor of 3 to 6 for an SLR of 5 m, compared to a scenario with no SLR (Figure 1). These estimates have a considerable degree of uncertainty, which is related to the evolution of natural morphological processes in the North Sea due to SLR, in particular the development of the active coastal zone, and policy choices on nourishments. When compared to the sediment available for extraction in the North Sea, it was found that the current legislation and regulations will result in a shortage of sediment. Especially near the Wadden Islands and the estuarine coast of Zeeland, more sediment will be needed than what is currently available. Therefore, regulations regarding spatial reservations, unexploded ammunitions and mining depths should be changed to keep the feasibility of the nourishment strategy of the Netherlands.

Additionally, sand nourishments leverage the natural geomorphological coastal processes that allow very local sand nourishments to be subsequently distributed along the coastline by natural processes [39].

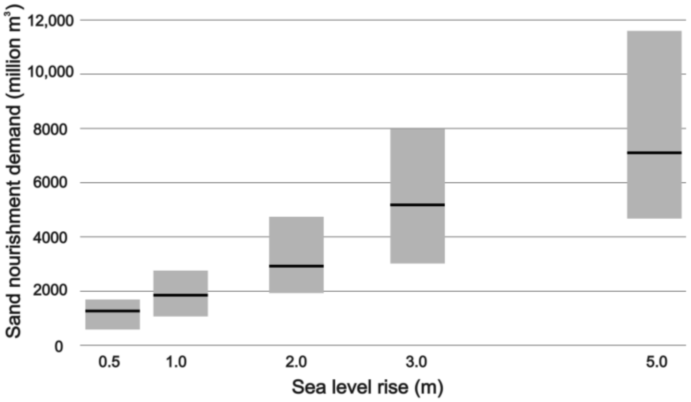

Figure 1. Sand nourishment volumes required under different levels of SLR. Grey bar indicates uncertainty range. Black line indicates expected sand nourishment volume.

4.1.2 Flood Safety of 'Hard' Flood Defenses

The simulations show that the required heightening and strengthening of dikes vary considerably (Figure 2). For an SLR of 3 m, dike segments that require heightening exceeding 5 m are found in the north of the Netherlands, decreasing to values between 1 and 4 m in the middle and south of the country, and gradually decreasing further inward along the Rhine and Meuse. Dike heightening exceeds the degree of SLR in areas where wave run-up is significant and wave growth is depth-limited, such as the northern Wadden Sea and the Western Scheldt. For instance, model results indicate that an increase of 7 m may be necessary in some places in the north of the country for an SLR of 3 m, of which about 5 m can be attributed to SLR, the remainder being due to the increased wave load (higher water heights mean that higher waves arrive at the dike; they are no longer attenuated by the foreshore).

Further inland along the Rhine and Meuse rivers, the influence of SLR gradually diminishes. However, the strengthening of the dikes remains necessary because of other effects such as soil subsidence and changes in peak river discharges. In these areas, the required increase in dike height is always smaller than SLR. Former sea dikes can cope with some level of SLR before they need to be strengthened again for higher SLR, since they were first robustly reinforced (1960–1980) before being (partially) closed off.

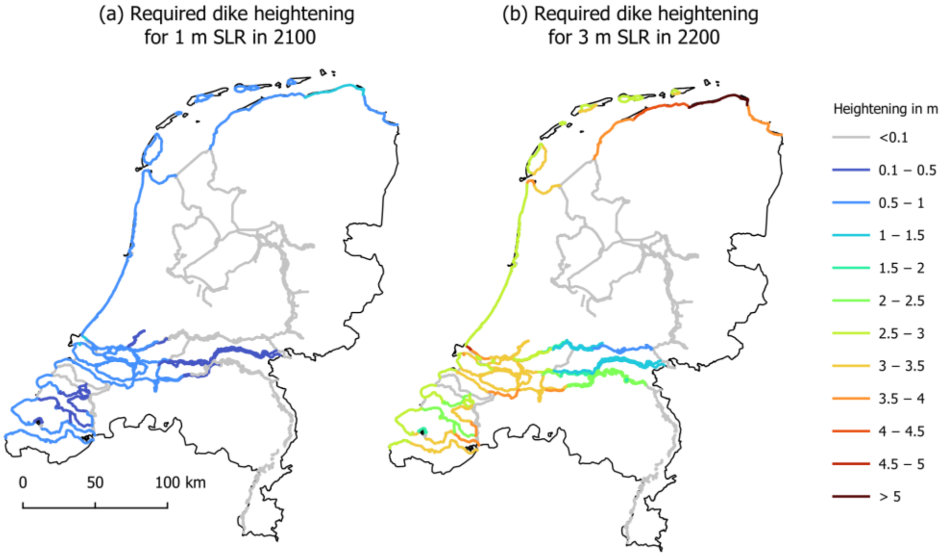

Figure 2. Required dike heightening for SLR of 1 m (left) and 3 m (right). These scenarios include dike heightening due to increasing river flows and land subsidence (modified from Zethof and Stijnen [35]).

As the sea level rises, the closure frequency of storm barriers increases if their closure level remains fixed. Eventually, the closure level can be reached at almost each high water, thereby making the concept of a barrier irrelevant. Storm barriers are designed to close only for very heavy storms (which occur rarely), to accommodate for other usages (shipping for the Europoort barriers, nature for the Eastern Scheldt barrier). For example, the closure frequency for the Europoort barrier is currently statistically once in 18 years and increases to every tidal cycle at 3 m SLR. In order to keep the closure frequency low enough, the closure level needs to increase with SLR. If the Europoort barrier closure level increases by 1.25 m under 2 m SLR, the closure frequency will become once per year. In that case, storm barriers still effectively close for extreme water levels corresponding to legal dike norms. However, the rising of the closure levels renders outer embankments more flood-prone.

Additional measures on top of current flood protection measures were analysed. The additional measures were found to be effective in bringing down the hydraulic loads, but were not found to be cost effective.

Although flood protection can be maintained at current safety levels through dike heightening, piping and stability berms, and strengthening of revetments, the implications for land use are considerable due to the space required for dike reinforcements. The footprint (width) of a dike increases by up to 90 m per meter of dike heightening, which can be difficult to achieve in densely built-up areas. Additionally, built-up areas located between dikes and open water (on relatively high areas of the floodplain) will be subject to more frequent flooding and increasing water depth. The cost analyses showed that the total cumulative nominal cost for 1 and 3 m SLR to maintain flood protection at the current safety level is around 1.5-2 times the current yearly cost for the dike enforcement program, compared to a baseline safety level in 2050. The total nominal annual costs are around EUR 0.3 and 0.5 billion per year, which is in the same order of magnitude as the currently estimated annual budget for flood protection for the period 2023–2050, thereby showing that maintaining adequate flood protection is financially achievable. Not included are costs for regional water systems that have tot adept tot the changes in the main water system, and the costs caused by increased flooding of areas on the water side of the dikes.

4.2 Freshwater Availability

Many parts of the western half of the country already experience salinization of soil and groundwater due to the seepage of brackish groundwater. This seepage is a result of the geologic past and human intervention such as land reclamation [40]. The modeling results show that seepage rates are expected to increase with SLR. The increasing seepage results in increasing salt loads from groundwater to surface water in a zone of up to 20 km from the coastline and rising river branches. Behind the coastline, the current salt loads vary geographically between 100 and 10,000 kg/ha/year. Nationwide, the total load increases with 50% at 1m SLR and up to 250% for 3 m SLR. Salinization of *surface water* is mitigated by flushing with freshwater sourced from the rivers Rhine and Meuse. The required flushing volume in polder areas varies considerably geographically. The total flushing water demand, however, increases at a higher rate than the salt load itself: about 4.5-fold by 1 m SLR, about 14-fold by 3 m SLR.

In the open Rhine–Meuse Estuary, SLR leads to a change in the balance between sea-level-induced pressure and river-discharge-driven counterpressure on the salt gradient. This causes a shift in the salt-intrusion length, *i.e.*, the position of the transition zone between freshwater and saltwater. The increase in intrusion length per meter SLR varies between 2 to 5 km along the range of typical dry-season river-discharge values: the lower the discharge, the stronger the shift per meter SLR. The intrusion length is non-linearly dependent on variation in river discharge. Conversely, compensating the increase in intrusion length due to a 1 m increase in SLR by means of additional discharge would require about 50 m^3/s to about 200 m^3/s additional river discharge for extremely low flow and intermediate dry-season flow conditions, respectively. SLR essentially aggravates the sensitivity of the system to low discharge conditions, in line with sensitivity relations such as those presented by Wegman et al. 2024, Ralston [41] and data and model analyses reported by Dijkstra et al. [42]and Van den Brink et al. [16].

The modeling for the lakes and canals (the strategic freshwater reservoirs) indicates that salt intrusion through shipping locks is the largest salinization pressure, in contrast to the contribution of groundwater seepage. This salt pressure may be reduced through specific measures at locks [17].

As salt intrusion increases, the required flushing increases substantially, putting an additional demand on freshwater resources. With all these factors combined, continuing the current practice under SLR would result in a significant increase in the quantity of freshwater required for the flushing of polder areas and other water systems and mitigating saltwater intrusion in rivers. As climate change is expected to also result in warmer and drier summers with increased evaporation and lower freshwater inflow, it is quite evident that the amount of freshwater required for flushing will be increasingly unavailable during dry summers. The pressure on the national water balance due to flushing may in theory be alleviated by accepting higher chloride levels. This would, however, potentially impact agricultural productivity, drinking water production and freshwater ecosystems.

5 DISCUSSION

The study addresses whether strategies for flood defense and freshwater availability remain applicable under up to 3 m sea level rise over several centuries, despite deep uncertainty and evolving land use. Using exploratory modeling grounded in physical laws, validated operational and new models, and extensive expert involvement, including reviews by over 300 specialists and independent committees, the approach aimed to ensure robustness and mitigate bias. While results suggest technical feasibility at national scale, uncertainties persist regarding local dike stability, storm surge barrier strength, and societal acceptability, alongside ecological and resource considerations. Reviews by Dutch expert networks [39,48,49] confirm reliability but highlight limitations, emphasizing that long-term strategy depends on more than technical measures. The findings provide quantitative input for adaptive planning within the Dutch Delta Programme's iterative cycle, acknowledging that refinements and broader climate pressures will shape future decisions.

6 CONCLUSION

This first nationwide quantitative assessment shows that sea level rise (SLR) will require significant reinforcement of flood defenses across the Netherlands, with dike height increases at least equal to SLR. No hydraulic tipping points were found up to 3 m, though spatial constraints, sand supply, and resource availability pose major challenges. Freshwater systems are more vulnerable: while increased flushing can initially counter salinization, beyond 2–3 m SLR river flows become insufficient to keep polders and surface waters fresh. The findings inform near-term decisions on dike upgrades and water diversions and feed into long-term adaptation pathways under Adaptive Delta Management. Future work will address technical, ecological, and socioeconomic aspects, including additional storage, new storm surge barriers, and land-use shifts toward salinity tolerance to extend strategy longevity and identify low-regret measures under deep uncertainty.

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