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Room for Sea-Level Rise: Conceptual Perspectives to Keep The Netherlands Safe and Livable in the Long Term as Sea Level Rises

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Abstract: An accelerated sea-level rise (SLR) may threaten the future livability of the Netherlands. Three perspectives to anticipate this SLR are elaborated here regarding technical, physical, and spatial aspects: Protect, Advance, and Accommodate. The overall objective was to explore the tools and measures that are available for adaptation, assess their spatial impacts, and identify dos and don'ts in current spatial issues like housing, climate adaptation, infrastructure, and the energy transition. Each elaboration was performed by a consortium consisting of representatives from private parties (engineering consultancy, project contractors, (landscape) architects, economists), knowledge institutes (including universities), and government, using an iterative process of model computations and design workshops. The elaborations made clear that a realistic and livable future perspective for the Dutch Delta continues to exist, even with a maximum analyzed SLR of 5 m, and will consist of a combination of elements from all three perspectives. This will require large investments and space for new and upgraded water infrastructure and will have large impacts on land use, water availability, agriculture, nature, residential buildings, shipping, and regional water systems. There is still a significant degree of uncertainty regarding future SLR; therefore, it is not advisable to make major investment decisions at this time. Nevertheless, some no-regret measures are already clear: continuation of the protection of the Randstad agglomeration (Amsterdam, The Hague, Rotterdam, and Utrecht) and its economic earning potential for future generations, adaptation of agriculture to more brackish and saline conditions, designation of space for additional future flood protection, extra storage capacity (for river discharge and increased precipitation), river discharge, and sand extraction (for future coastal maintenance). The research identified concrete actions for today's decision-making processes, even though the time horizon of the analysis captures centuries. Including the perspectives in long term, policy planning is already necessary because the transition processes will take decades, if not more than a century, to be implemented.

Keywords: climate adaptation; adaptation strategies; adaptive pathways; technical feasibility; spatial reservations; costs; long-term planning



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1. Introduction

The sea level is rising and will continue to do so. As a result of global warming, the projected sea-level rise (SLR) at the end of this century may range from 0.28 to 1.88 m relative to 1995, depending on the CO₂ emission scenario, and will continue rising beyond 2100. Uncertain Antarctic land ice instability may aggravate this SLR, which may impose large effects on coastal areas. Especially in highly productive and densely populated deltas, livability may be threatened by coastal erosion, salt intrusion, reduced river outflow capacities, and increased flood risk [1].

In 2019 the Dutch Delta Commissioner and Minister of Infrastructure and Water Management initiated the Sea-Level Rise Knowledge Programme. The main objectives are to establish the potential impacts of SLR on flood risk, fresh water supply, and coastal management, and to explore potential strategies to deal with this still-uncertain challenge [2]. The present strategy to deal with flood risk management consists of periodic beach nourishments of eroding coastal stretches, reinforcements of seawalls, operation of storm surge barriers, and natural drainage of river flows of the Rhine and Meuse. The first results of this knowledge programme show that, from a technical perspective, this present strategy can handle an SLR of at least 3 m, assuming no limitations in raw materials, labor, and finance. Extra space is necessary for future expansion of flood defenses, water storage, and sand extraction (for beach nourishments), while present agricultural land use in the coastal zone may need to adapt to increased salinization [3].

In a worst-case scenario, assuming continued global warming and Antarctic land ice instability, 2 m SLR may already be exceeded in 2100 [4,5]. Many planned large investments in infrastructure, sustainable energy, housing, and agriculture may face this situation, since their lifespan often exceeds 100 years. Therefore, the second objective of the knowledge programme is to explore potential strategies that are able to manage an SLR of 2 to 5 m beyond 2100. In general three different types of adaptation to SLR can be distinguished [6,7]: protect (defend vulnerable areas), accommodate (continue to occupy vulnerable areas but adapt land use to more frequent flooding and salinization), and retreat (abandon and develop on higher ground). Based on these adaptation concepts, this exploration started with an inventory of existing ideas and plans, clustered in three conceptual perspectives [2]:

- **Protect:** Mainly technical measures are used to prevent flooding, guarantee the discharge of excess water, and combat salinization of ground and surface waters. Beach nourishments can be considered to be a kind of nature-based measure, since, apart from the initial phase of dredging and pumping it on the beach or foreshore, natural materials and natural sediment transport processes are used, like waves, currents, and wind. Two variants exist regarding the protection of river mouths:
 - Maintain open estuaries and raise the dikes along coasts and rivers, in combination with storm surge barriers, to accommodate rising flood levels in estuaries and along the rivers (Protect Open).
 - Close estuaries and rivers from the sea permanently with dams or sluices, potentially requiring large pumping stations to discharge river water to the sea (Protect Closed).

The present strategy is a hybrid combination of Protect Open en Protect Closed: Protect Open Closable. Only during extreme storm surges, the Eastern Scheldt Estuary and the present open river mouths of the Rhine and Meuse are temporarily closed by barriers, favoring navigation and fish migration during normal conditions. Other former estuaries (Grevelingen, Lake Veere) are permanently closed by dams. The former Zuiderzee was closed by the Afsluitdijk, resulting in the present (freshwater) Lake IJssel (see Figure 1). Excess water is mainly drained by gravity, in combination

with pumping stations. Fresh water supply is guaranteed by intakes, canals, and reservoirs that are mainly fed by river discharge.

- Advance: Measures located seaward of the present coastline that aim to maintain the current safety against both coastal and fluvial flooding. In practice, this means reinforcement of the present coastline and building a new coastline in front of the present one, creating a coastal lake in between to temporarily increase storage capacity for river water before it is pumped to the sea. This perspective can be considered as an extended Protect Closed variant, as it reduces pumping capacity and salinization.
- Accommodate: Adapt land use to increasing salinization, waterlogging, and floods, e.g., by flood-proof buildings, salt-tolerant crops, and intensifying new investments on higher ground. The latter part can be considered to be ‘managed retreat’ measures. These relate to land-use changes and relocation of existing infrastructure in a managed process, as implemented in less densely populated areas, e.g., the UK, Colombia, and the USA [8].
- Given the dense population of the Dutch Delta and the high economic and socio-cultural values at stake, more extreme perspectives like ‘abandon’ or ‘sacrifice’ [8] are considered to be unrealistic perspectives.

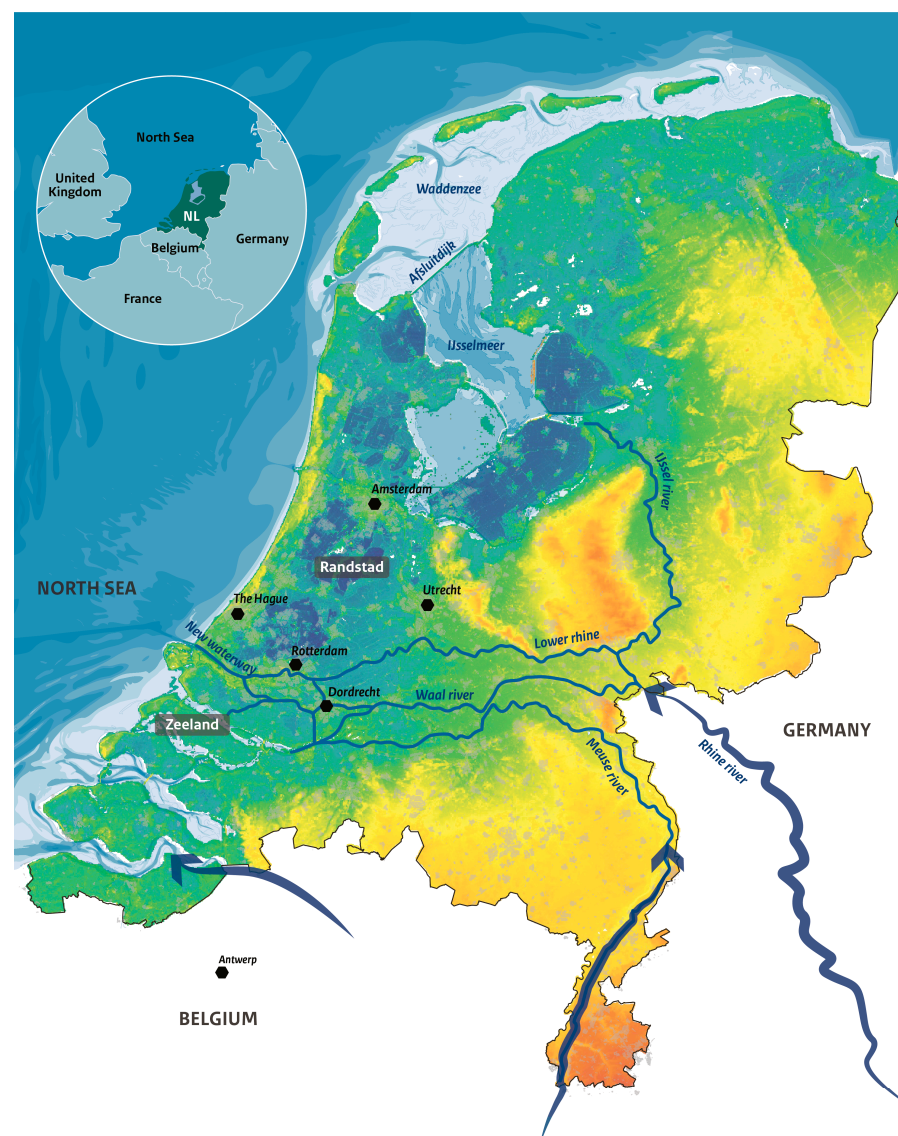


Figure 1. Location of the Netherlands and topography of its main water systems and urban areas. Colored areas: blue—water or land below MSL; green—land around MSL; yellow /orange—above MSL. See also Figure 4 for more details in the southwestern area.

Between 2020 and 2023, these conceptual perspectives were elaborated in 25 regional design workshops, in which experts in the fields of water management, land use, and spatial planning participated. These workshops raised awareness about the potential impact of SLR on future land-use and investment agendas, e.g., on infrastructure and housing. In addition, some low-regret measures were identified, e.g., reserving space for future flood defenses and water storage [9]. In the meantime, a first inventory was performed to develop two SLR adaptation strategies for the Rhine–Meuse Estuary, focusing on flood protection. This inventory sketches a pathway from the closed strategy to a more drastic river diversion strategy and recommends also considering aspects like fresh water supply and navigation [10].

For concrete policy proposals and spatial reservations, substantiation of the results from these design workshops in terms of dimensions, technical and physical feasibility, and spatial coverage is essential. Until now, an integrated elaboration of different perspectives has never been performed for the Dutch Delta. This paper presents the elaboration process, the connections with earlier work in the knowledge programme, and the main findings regarding the three perspectives, while identifying the overall conclusions and follow-up actions.

2. Materials and Methods

The elaboration and substantiation of the three perspectives required a broad field of knowledge and expertise. This was organized in three consortia, in which private parties (engineering consultants, project contractors, landscape architects), public parties (water managers, government officials), and scientists (coastal morphologists, civil engineers, ecologists, economists, historians) closely cooperated. Each consortium elaborated on one perspective, for the Netherlands as a whole, and based its work initially on the results of the design workshops. Each consortium set up a multi-disciplinary core team that drew up analyses, computations, concepts, and descriptions of each perspective. They also organized workshops with a broader group of experts to share the intermediate results and to collect knowledge and inputs for the next step. During these workshops, developers of existing plans were given the opportunity to present valuable insights from their work. In all, about fifty professionals from 20 different organizations worked in the core teams, while over a hundred experts participated in the workshops. In this way, a broad knowledge base was created, as well as a wide community of SLR experts, in the water sector and beyond.

Consistency between the three consortia was created by a common set of basic assumptions, data, and models, with members acting as linking pins between the consortia, and weekly coordination meetings of the consortia leaders.

The most important basic assumptions were formulated for the hydraulic parameters of SLR, river discharge, and salinity. Depending on the greenhouse gas emission scenario in 2100, the sea level may rise by 0.28–0.55 (low-emission scenario SSP1-1.9) to 0.98–1.88 m (very-high-emission scenario SSP5-8.5) relative to 1995–2014, while due to deep uncertainty in ice sheet processes in Greenland and Antarctica, an SLR of 2 m in 2100 and 5 m in 2200 cannot be ruled out [4]. In line with this IPCC report, the most recent KNMI National Climate Scenarios 2023 for the Netherlands also conclude that, in a worst-case scenario, SLR along the Dutch coast in 2100 and 2200 may reach 2 and 5 m (relative to 1995), respectively, corresponding to an SLR rate of 28 and 42 mm/yr, respectively [5]. It was decided to elaborate on the three perspectives for this worst-case SLR scenario, assuming that less extreme scenarios give more time to prepare and adapt, which may make the most extreme measures redundant. So, if the perspectives prove to be feasible for this extreme scenario, this will also hold for less extreme scenarios.

In estuarine areas, the effects of SLR interact with climatological effects on river discharge. For the most important Dutch rivers, the Rhine and Meuse, it was assumed

that their future design discharges will increase up to 18,000 m³/s (Rhine) and 4800 m³/s (Meuse) in 2100, and to 20,000 m³/s (Rhine) and 5300 m³/s (Meuse) in 2200. The River Rhine's 6-week average extreme low river discharge was assumed to drop to 500 m³/s in 2100 [11]. Regarding salinity, it was assumed that the salinity in coastal and estuarine areas should not exceed present levels in groundwater and intake locations.

Basic assumptions were also formulated to define the present situation and probable future policies regarding flood risk management. In each perspective, the current flood risk policy objective should be met, i.e., an individual death-due-to-flood probability of 10^{−5} per year. In the Protect and Advance perspectives, it was assumed that the present flood protection programme, tasked to meet the most recent statutory flood protection standards, will be finalized in 2050, and that after 2050 those standards will be maintained by new measures (to be explored in the perspectives). In the Accommodate perspective, the completion of the flood protection in 2050 was assumed as well, yet alternative strategies were also considered to avoid new levee reinforcements. Coastal sand nourishments, remaining feasible up to the studied 5 m SLR [3], are assumed to be continued in each perspective.

The present economic and demographic center of the Netherlands is situated in the coastal and triangular polder area of Amsterdam, The Hague, Rotterdam, and Utrecht: the so-called Randstad. From a socio-economic development lens, governing land use and spatial developments, it was assumed that, given its current critical mass, the Randstad area will remain the major economic and demographic center of the Netherlands for the foreseeable future.

The elaboration of the three perspectives builds on earlier inventories of potential strategies and analyses of the feasibility of present policies on flood protection, fresh water supply, and coastal maintenance, performed in earlier phases of the knowledge programme on SLR [3]. The same data and models were used to estimate future flood levels along the coast, estuaries, and rivers, to explore and design necessary measures to maintain the present statutory flood protection levels (like beach nourishment volumes, dike reinforcements, closure frequencies of storm surge barriers, or pumping and storage volumes (if estuaries are closed from the sea and river discharge has to be pumped out)), and to identify potential consequences, e.g., for salinity and non-protected areas outside the dikes. More details about these models are presented in [2,3,11]. While the Protect and Advance perspectives strongly build upon technical and traditional civil engineering measures (and related statistical and hydraulic models), the Accommodate perspective focuses on the adaptation of land use behind the dikes or after their realignment. How that land use can alter flexibly is a multifaceted issue, making a more exploratory elaboration and more schematic results of this perspective inevitable.

Validation of the elaboration results is difficult, since the necessary data and future extrapolations of the impacts of hydraulics on salinity and loads on flood defenses go far beyond the operational ranges of regular computational hydraulics and land-use models. As an alternative, the resulting reports were reviewed by the independent Expertise Network for Flood Protection (ENW). The ENW appreciates the way in which the three consortia, with a wide composition of knowledge and experience, elaborated the different conceptual perspectives. The ENW supports the main conclusion that it is technically possible to protect the Netherlands against SLR up to the investigated 5 m, with large impacts on land use, natural values, and society [12].

3. Results

The Netherlands has a long tradition of water management. Broadly speaking, two types of strategies have been employed in history, often in combination: (1) adaptation and using natural processes like sedimentation, and (2) technical measures to control the forces of nature, like dikes and pumping stations. In this exploration for future strate-

gies, three perspectives were elaborated, building upon past traditions and experiences, but different in their approaches in combining adaptive and technical measures: Protect, Advance, and Accommodate. In combination, these perspectives provide a wide spectrum of options from which it will be possible to select optimal combinations of measures. Figure 2 shows the principal differences between these perspectives in terms of measures, resulting flood levels, salinity, and land use.

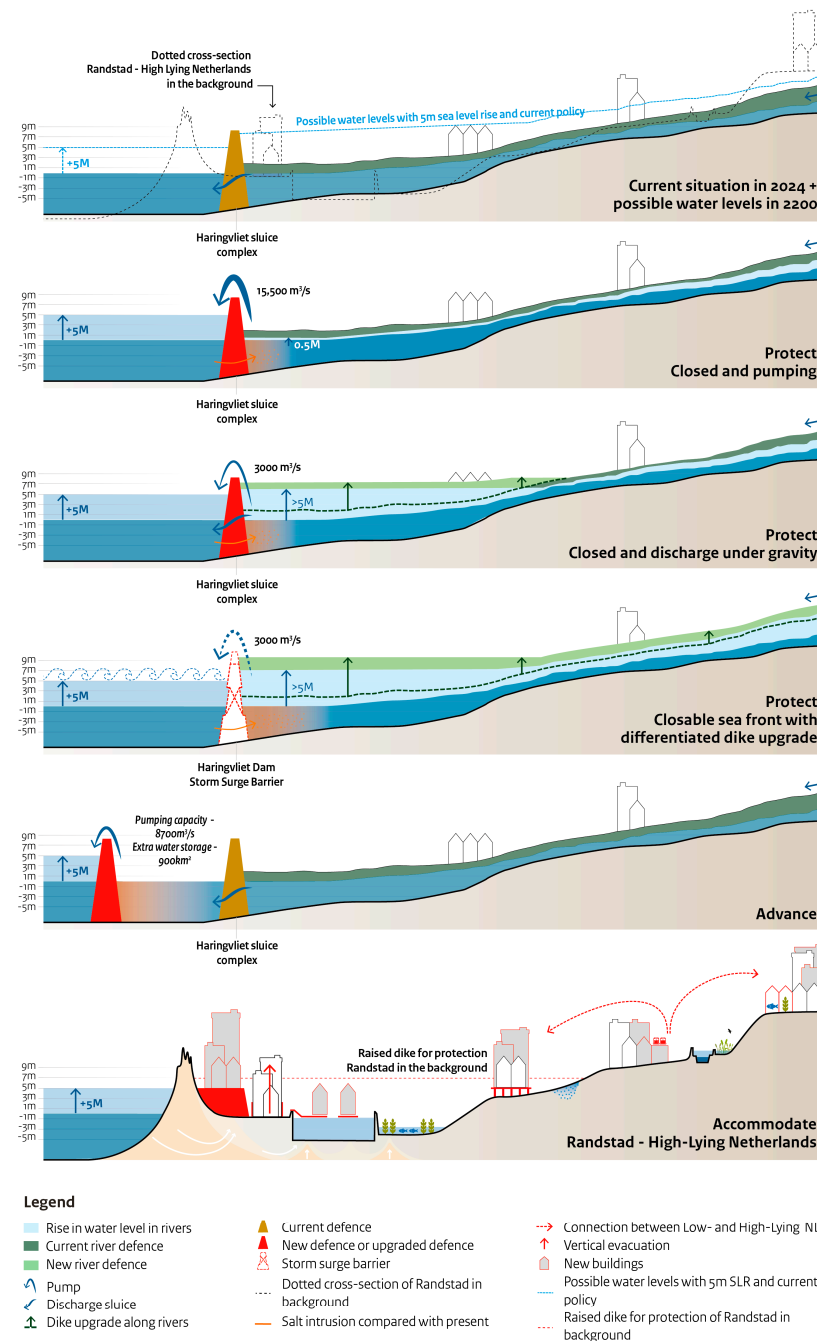


Figure 2. Cross-sections from sea to landward direction for different perspectives: The top five cross-sections show the sea, the estuarine areas, and the upper reaches of the Rhine and Meuse about 100 km inland, with five meters of SLR and extreme river discharge. The differences in water levels and salinization (reddish hue landward of sluice or dam) are caused by different combinations of measures such as closure, storage, pumping, and sluicing in the conceptual perspectives studied. Higher levels lead to dike upgrades in these cross-sections. The bottom cross-section is through land, and it shows different possible measures for the Accommodate perspective. Note that the scale of the x-axis is not equal to the scale of the y-axis.

3.1. Protect

The Protect perspective aims to maintain the present territory and land use of the Netherlands. It can be considered to be a continuation of the present (mainly technical) water management measures like flood defenses, storm surge barriers, locks, sluices, pumping stations, and beach nourishments. Within this perspective, four different strategies were explored regarding the estuaries of the rivers Rhine and Meuse (open/closable or closed) and the discharge distribution over the Rhine's tributaries (see Figure 3).

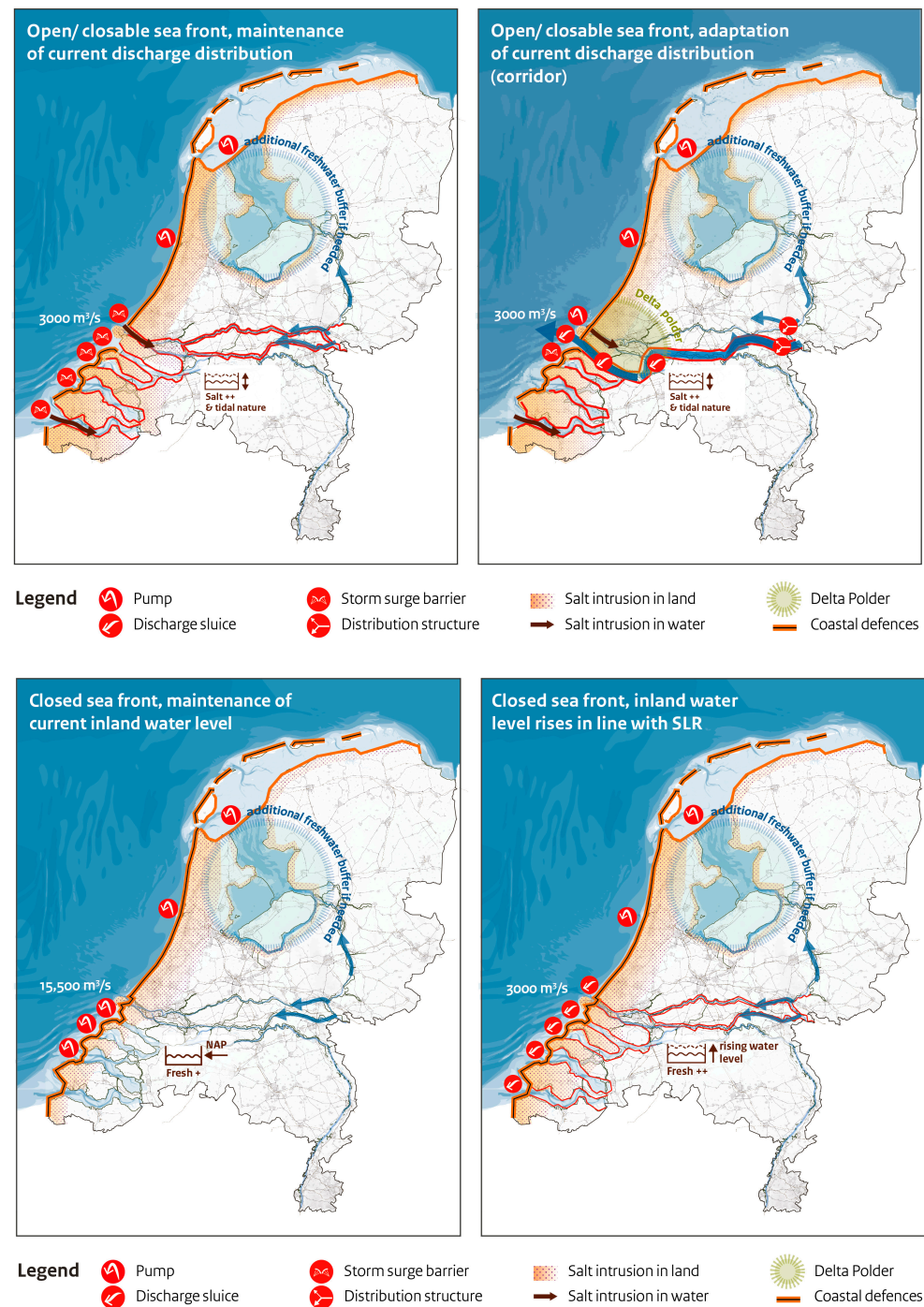


Figure 3. The four strategies studied for the Protect perspective: **top left:** an open (closable) sea front with storm surge barriers, water level rising in line with SLR, and maintenance of the present discharge distribution in the Rhine's branches; **top right:** a concentrated peak discharge on the Waal branch combined with a new polder around Rotterdam and Dordrecht (protected by flood gates); **bottom left:** a closed sea front, with either pumping (to maintain present flood levels) or (**bottom right**) sluicing with high

water levels that rise with SLR, enabling the discharge of excess river water to the sea. The Protect Open strategies favor navigation and natural dynamics but result in large dike upgrade programmes and increasing salinization. The Protect Closed strategies require large pumping volumes, which can be reduced by peak storage or sluicing excess water. The latter requires dike upgrades to combat rising river levels. The Protect Closed strategy blocks navigation, natural dynamics, and salinization. The latter is beneficial for fresh water supply and agriculture.

In the Protect Open strategy, SLR will increase flood levels along the rivers Rhine and Meuse up to 100 km upstream, making extensive dike upgrade programmes necessary to maintain the statutory flood protection standards. In the Protect Open Closable strategy, storm surge barriers protect the hinterland against extreme flood events, reducing the dike upgrade programmes (note that, in all strategies, reinforcements in the river system are necessary because of increased river discharge and soil subsidence). In an optimized Open Closable strategy, the Rhine's peak discharge is concentrated on the Waal branch and diverted south of the Rotterdam–Dordrecht urbanized area. Flood gates along this corridor prevent floods from entering this area and create an urban 'Deltapolder' including Rotterdam and The Hague. Sluices and pumping stations will maintain water levels equal to the current situation. In addition, this strategy favors fresh water supply in case of drought, and it reduces the volume needed to flush the rivers to avoid salinization.

The potential impact of SLR can also be reduced by the complete closure of the estuaries by dams or the use of additional storage areas (1000 km² in the former tidal basins in the southwestern part of the Netherlands), and complemented by large pumping stations. Two different Protect Closed strategies can be distinguished: The first (bottom right) blocks salt intrusion and uses sluices to spill the water. As a consequence, the upstream water level will rise with SLR, requiring extensive dike upgrade programmes comparable to the Protect Open strategy. The second (bottom left) also blocks salt intrusion and uses pump capacities of up to 15,500 m³/s to drain the combined peak discharge of the Rhine and Meuse rivers. In this case, the water level in the upstream area will be equal to the current situation up to a 1/10,000 per year event (about NAP +3 m, where NAP is Normal Amsterdam Peil, the official ordnance datum, almost equal to the present MSL).

The investment costs for the improvement of present and the construction of new water management infrastructure, as well as the necessary beach nourishments to maintain the coastline, amount to EUR 100 billion to 200 billion for 2 (2100) and 5 (2200) m SLR, respectively. That is an annual average of about EUR 1 billion/yr, comparable to the present level of investment. Table 1 presents the main characteristics of these four options and their differences.

To anticipate protective measures, space reservations must be made along river dikes and sea dikes, and the current estuaries should be combined into one large peak storage. In general, the footprint of a dike may increase by up to 90 m to adapt to 3 m of SLR [3]. Also, when restoring or replacing existing structures like seawalls and dams, storm surge barriers, sluices, etc., they should be designed taking a future SLR into account or, alternatively, in such a way as to allow for easy future strengthening or upgrading. Since SLR is a slow process relative to most spatial developments, protective measures may also be integrated in (urban) landscape designs. Protective measures applied in this way offer possibilities to enhance the quality of river fronts and boulevards.

Table 1. Main characteristics and consequences of the four Protect variants.

Characteristics and Consequences	Closed, Pumping and Storage	Closed, Sluicing and Storage	Open/Closable, Existing Discharge Distribution	Open/Closable, Waal Discharge Corridor
Pumping capacity (m ³ /s)	15,500	3000	3000	3000
Rise 1/10,000 Water-level (m)				(outside the Delta Polder)
2100	0.5	1	1–2	0–2
2200	0	3–4	4–5	2–4
Freshwater surplus (+) or deficit (–) (m ³ /s)				
2100	500–1000 (+)	500–1000 (+)	50–1000 (–)	<500 (+)
2200	500–1000 (–)	<500 (–)	>2000 (–)	500–1000 (–)
Costs for construction/upgrading flood defenses, sluices, pumping stations, beach nourishments (bln EUR) until				
2100	90	100	110	100
2200	170	190	180	170
Space for dike upgrade (km ²)				
2100	55	60	75	60
2200	70	130	140	95
Buildings to be abandoned in unprotected floodplains				
2100	22,000	25,000	30,000	16,000
2200	26,000	37,000	37,000	24,000
Nature	Loss of tidal nature in southwestern Zeeland–Holland delta	Loss of tidal nature in southwestern Zeeland–Holland delta	Open sea–river connection, tidal nature and estuarine transitional zones	Open sea–river connection, tidal nature and estuarine transitional zones, but only in Waal flood corridor
Navigation	Transshipment by land, possibly locks in Rhine estuary	Transshipment by land, possibly locks in Rhine estuary	Open–closable connection	Transshipment by land, possibly locks in Rhine estuary
Agriculture, horticulture in Rhine–Meuse estuary and Zeeland–Holland delta.	Existing land use can continue for the time being	Existing use can continue for the time being	Increasing demand for flushing (to mitigate salinization), causing major water shortage.	Existing land use can largely continue for the time being

3.2. Advance

The first objective of the Advance perspective is to look at the coastal flood safety of the sandy coast. It has been concluded in earlier research that the current policy (coastal nourishment) is also effective with 2 and even 5 m SLR, albeit greater volumes of sand will be required [3]. In this continued coastal defense policy, the coastal towns that currently have an open view of the sea may become coastal towns behind a dune barrier.

The second objective of the Advance perspective is to create extra storage capacity for future peak river discharges and, hence, reduce the extreme pumping capacity required in the Protect Closed strategy to maintain the present design flood levels (NAP + 3 m). As such, the Advance perspective contributes to reducing extensive inland dike upgrade programmes and additional complex flood safety measures in the built areas of Rotterdam and Dordrecht. The analysis shows that this can best be achieved by the construction of a new coastline from Walcheren to Maasvlakte 2, about 12 km seaward of the present

coastline, creating a lake with manageable water levels where future peak river discharges can be temporarily stored, before pumping the water into the North Sea (Figure 4).

Advance

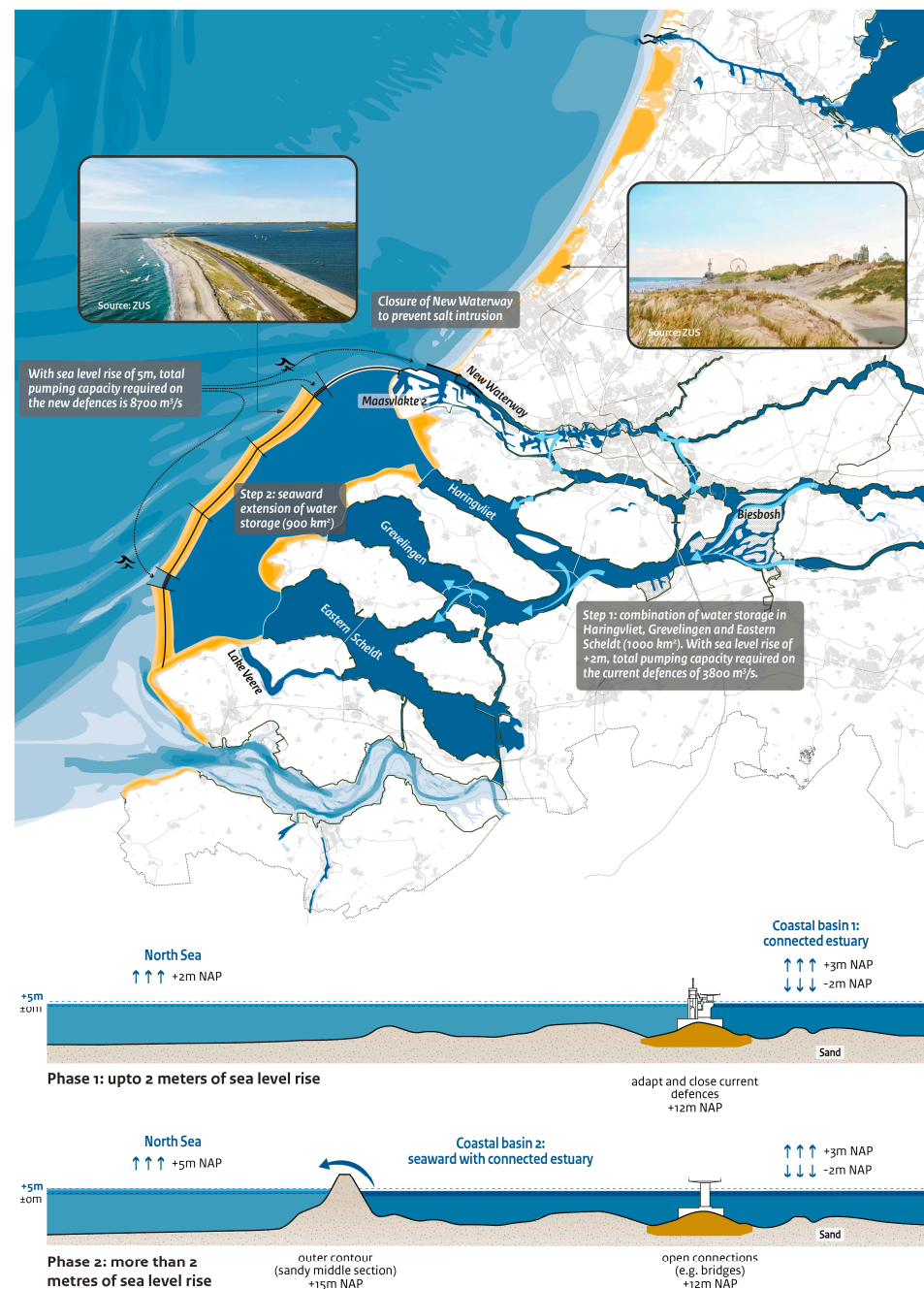


Figure 4. The Advance perspective, as it is elaborated for 5 m SLR, including the peak storage in the present water systems/former tidal basins in the southwestern part of the Netherlands (available storage surface 1000 km²), and the new coastline, creating an additional storage surface of 900 km² in front of the present coastline. As a result, the pumping capacity required in the Protect Closed strategy of 12,200 m³/s can be initially reduced to 3800 m³/s, to be gradually increased with rising SLR. In an optimized pumping strategy, anticipating peak river discharges, the required pumping capacity will be 8700 m³/s to maintain the present flood design levels. Access channels to the harbors of Antwerp and Rotterdam Maasvlakte remain open. The additional storage area creates a brackish environment, reducing inland salt intrusion, albeit with devastating effects on the coastal ecosystems.

The first step would be to increase the storage capacity within the current water system by connecting the presently separated former tidal basins of Haringvliet, Grevelingen, Volkerak-Zoommeer, and Oosterschelde (together 1000 km²) into one large peak storage area. From a SLR of around 2 m, a water storage of 900 km² could be added by creating this offshore lake. Initially, a pumping capacity of 3800 m³/s will suffice, as a large part of the river water can still be discharged under gravity into the North Sea. With rising sea levels, discharge under gravity will no longer be possible, and all of the river water will have to be pumped out. As a consequence, the required pumping capacity has to be increased, up to 12,200 m³/s. This is expected from an SLR of around 5 m. This maximum pumping capacity could be reduced to 8700 m³/s by increasing the storage capacity a few days before an anticipated river flood wave by pumping the water level in the lake to a level of NAP – 2 m. As river discharges are not dependent on SLR, the capacity of the storage lake does not need to be increased with progressing SLR. Only the pumping heights need to be adjusted. In case river discharges further increase in the future, this perspective can relatively easily be adapted by increasing the pumping capacity.

The lake is expected to become a brackish environment, as the influx of fresh water will not be sufficient to maintain a freshwater environment. As the salinity of this new storage lake will be much lower than the present salinity of the coastal waters, the long-term salinization of surface water and groundwater in the coastal inland area will be lower than in the other perspectives. This would be beneficial for the current agriculture, which is mainly dependent on fresh water. However, due to the construction of the lake, all existing valuable ecological intertidal areas behind the new coastline, with importance at a European scale, will more or less be destroyed. Some damage control could be achieved by introducing artificial tidal movement or creating compartments in the current sea branches and/or future lake to diversify salinity and water quality.

To avoid future salinization of the present river mouths Haringvliet and Nieuwe Waterweg, the current shipping corridor that connects the city harbors of Rotterdam with sea may be closed off. This would have a major impact on shipping and harbor activities, as the Maasvlakte needs to be transformed into a transshipment port in the long term. In addition, the upstream intertidal nature reserve area of the Biesbosch may be affected.

The Advance perspective can be considered as an extension of the Protect Closed perspective and includes similar costs for dike upgrade programmes. The total investment costs of the offshore lake (excluding the connections in the existing water system) are calculated at around EUR 30–35 billion, excluding the mitigation of impacts on existing functions. The annual costs for operation and maintenance of the new shoreline and pumps are estimated at EUR 250–430 million. The new coastline would be over 60 km in length and would require a sandy construction volume of 2–2.5 billion m³.

To anticipate the construction of the storage lake, offshore space reservations should be made to avoid construction works, plan development, or nature compensation projects with a long lifetime that would complicate the construction of the new coastline and lake. In addition, it is desirable to preserve existing sand storages near the second coastline to minimize future transport costs.

3.3. Accommodate

In the Accommodate perspective, the strategy of increasingly far-reaching technical water management interventions will be abandoned in favor of adaptation and using natural processes as much as possible. The existing water management infrastructure will not be ‘automatically’ upgraded anymore, nor will it be removed. The statutory individual basic level of flood protection (maximum of 1/100,000 probability of drowning per year) will partially be achieved by measures that reduce the consequences of flooding

(like flood-proof buildings, shelters, or evacuation), while other measures are taken to adapt to such challenges as increased pluvial flooding, water availability, and salinization. Water drainage will mainly be by gravity, and excessive water will increasingly be retained temporarily in designated areas. Land use will follow the logics of water and soil.

For this perspective, the Netherlands is roughly divided up into four areas, each with a distinct set of measures: the Rhine–Meuse river and estuary area, the core Randstad (mostly overlapping with dike ring areas 14 and 44), other low-lying areas, and areas at higher elevation (Figure 5).



Figure 5. Landscape impressions (images on map) and measures (in cross-section) in the Accommodate perspective: The map makes a broad distinction between the flood-prone areas in the Netherlands (dike ring 14/44, low-lying areas, rivers, and delta) and the high parts of the country. In the flood-prone areas, the Accommodate perspective requires changes to built-up areas and land use to reduce the vulnerability of the area. The area of dike rings 14 and 44 is shown separately, because further analyses led to the conclusion that this area will have to remain protected with dikes and dunes for as long as possible in order to maintain the earning capacity of the Netherlands. Blue arrows represent groundwater flow, white arrows represent saline groundwater intrusion, red arrows indicate vertical evacuation and flood proofed buildings.

An attempt to operationalize an Accommodate approach for the Randstad area demonstrates that the immediate abandonment of the current integrated protective measures of the dune system and the dike rings after 2050 is not an appropriate approach. The in situ adaptation measures that were explored in earlier studies for the Accommodate perspective, such as local ring dikes to protect cities, local elevation of assets, or new construction on mounds, make little sense, especially in the economic core of the Randstad (dike ring areas 14 and 44). Local ring dikes around the cities of Amsterdam, Rotterdam, The Hague, and Utrecht alone would double the flood defense length and, therefore, more than double the resources needed to protect against flood risk. Given the depth of the current polder system, the areas suitable for building on reasonably high mounds are extremely limited. Floating cities are a promising technology but will likely not be able to work at the scale needed. Relocation out of the risky areas would be costly, result in many stranded assets, and significantly limit the Dutch economy's earning capacity, which will be critical to pay for its long-term adaptation needs. The overall conclusion of this attempt is that, for the Randstad, the 'full-play' Accommodate perspective is not suitable. Moreover, further analysis, building on the findings of the previous phase of the knowledge programme, shows that protecting the Randstad from coastal flood risk (according to the Protect perspective) is feasible and cost-effective until 5 m SLR. In a more hybrid Accommodate perspective, this must be complemented with three parallel strategies.

- Firstly, SLR and increased river discharge will impact the deep-lying Randstad much earlier in other respects. Pluvial flooding, salinization, reduced fresh water availability, and impacts on water quality and biodiversity already need to be addressed in present times. To mitigate and adapt to these impacts, the hybrid Accommodate perspective includes a series of measures, from more localized land-use changes to nature-based solutions for local water management. SLR will aggravate the consequences of eventual future flood events. Vertical and horizontal evacuation possibilities will need to be strengthened, and infrastructure networks will need to be made more robust.
- Secondly, it has not yet been studied whether a Protect strategy for the Randstad beyond 5 m SLR remains feasible in the long run. In addition, an orderly transformation of urban, infrastructural, agricultural, and economic systems may take decades, if not more than a century. Redundancy against disastrous floods or gradual salinization can be achieved by preparing (and investing in) areas at higher elevation for future development. This includes investing in improved infrastructure connections to the economic centers across the border, so that the center of gravity of the Northwest European conurbation can gradually shift.
- Thirdly, flood risk from the Rhine and Meuse should be addressed by directing the discharge away from the Randstad towards the southwestern delta. This should be combined with the development of 'Room for the River' approaches on 'hot spot' locations, combining dike reinforcements and considerable dike relocations with allowing sedimentation and natural development processes.

In other low-lying areas of the Netherlands, where population densities are lower and where land is not so deep below the sea, adaptation to SLR can be more targeted, using such measures as 'wisselpolders' (literally 'rotational polders', where natural sedimentation is allowed to grow with SLR), local elevation and ring dikes, floating structures, and changes to agriculture to become either more 'wet', more salt-tolerant, or less land-intensive.

In the low-lying areas, as in the other three area types, the Accommodate perspective explores the transition process from the current, predominantly technological approach to one that allows the Netherlands to use land-use changes and nature-based solutions and be ready to respond to SLR, in spite of the uncertainties about the magnitude and the rate of change.

Many of the measures explored here are already part of the Dutch culture of water management, such as ‘Room for the River’, but will need to be developed further, scaled to address the challenges ahead, extended to areas behind the dikes, tailored to different types of land use, and explored in terms of costs and benefits. Continuing this process of adaptation and accommodation is now a historical imperative, and it provides the opportunity to practice through pilot projects, explore the links with transitions in other domains, mitigate negative effects and maximize co-benefits, and include ‘adaptation’ to the national narrative of intelligent water management and innovation.

4. Discussion

Sea level is rising and will continue to do so for many decades, despite potential reductions in CO₂ emissions. For the Netherlands in 2100 and 2200, in an extreme scenario with collapsing Antarctic land ice, sea level may be 2 and 5 m higher than present, respectively. Without continued flood protection measures, floods may become annual events at an SLR of 2 m. Meanwhile, salinization and periods of fresh water shortage are already increasing due to decreasing low river discharges, and SLR will aggravate this. So, doing nothing is not an option. In addition, the large present investment agendas on housing, sustainable energy, infrastructure, agriculture, and biodiversity make a long-term perspective necessary to avoid future regrets and ‘lock ins’ from present strategies in these policy domains.

This initial elaboration of the three perspectives on the national scale shows that all perspectives are technically, physically, and spatially feasible but differ distinctively in their consequences on navigation, land use, and ecological values, as well as their spatial footprints. Regarding their investment costs on technical measures, the Protect and Advance perspectives are comparable, at about EUR 100 billion and 200 billion to adapt to 2 and 5 m SLR, respectively. For the Accommodate perspective, this needs to be further elaborated.

Since it will take the next few decades to learn how climate change and related SLR will develop, it is not advisable to make major investment decisions at this time. If we manage to curb climate change and SLR to a manageable rate of several mm/year worldwide, a continuation of the present Open Closable policy looks realistic. In parallel, we need to prepare for and apply no-regret adaptive measures where possible. In case of accelerated SLR, we must continue on the same parallel track, but we will have less time to adapt, which will most likely result initially in increased numbers and size of technical measures like flood protection schemes, pumping stations, and replacing fresh water intakes.

The three perspectives were elaborated on the national scale. However, even a relatively small country like the Netherlands has large regional differences in consequences of SLR, land use, and ecological values. Therefore, none of the explored perspectives as such is the ideal national strategy to maintain the livability of the Dutch Delta. However, intelligent and adaptive combinations of measures from all three perspectives have to provide feasible SLR adaptation strategies on regional scales. The optimal combination depends on the regional characteristics of SLR, its impact, and present and expected land use. From the elaboration of these perspectives, some overall no-regret actions can be formulated:

- The Amsterdam, The Hague, Rotterdam, and Utrecht agglomeration (‘Randstad’) is the area with the highest economic productivity and population density in the Netherlands. It consists of many potentially flood-prone polders, situated in the lowest part of the Netherlands, at the mouths of the rivers Rhine and Meuse, behind the coastline of the North Sea. For the Netherlands’ economy and society, it is crucial to safeguard this economic earning potential for future generations in general, and to fund the necessary adaptation investments in particular. The most effective way to do so is by upgrading the existing flood defenses around this area. Regional ring dikes or transforming the area to artificial flood-proof mounds would be more costly

and would not create sufficient space for the inhabitants (4.4 million in 2020). The alternative, a complete transfer of these economic activities to higher grounds in the southern and eastern parts of the Netherlands in the short term, would be considerably more expensive, cause disturbing social impacts, and be difficult to organize. However, initial actions to gradually distribute the economic earning capacity from the present Randstad gravity center more evenly over the country could be a no-regret policy.

- The availability of fresh water will further decline because of a combination of SLR and other effects of climate change (like decreasing low-discharge river flows, increased evaporation, and increased water demand). In each perspective (even in the Protect Closed one, with new peak river water storage reservoirs), the volumes of fresh water available will not be sufficient to meet the increasing demand. This increased demand is dominated by the increasing SLR/salinization aspect. Regional adaptation of agriculture to salinization will become inevitable, e.g., by increasing local storage of harvested rain water and expanding the growth of salt-tolerant crops.
- All perspectives show that more room is needed for flood protection, water storage, water discharge, and sand extraction (for beach nourishments). If we designate this space accordingly now, future generations will be in the position to take the measures required, without being blocked by wrongly located assets and infrastructure developed by our generation. This will require more concrete, area-specific knowledge about the locations, ways to keep the required space free, the consequences of doing so, and the timeframe in which the space is needed. This will be elaborated further on the regional scale by water managers, land-use planners, and stakeholders. The potential measures developed in these consortia could very well be taken into account in (spatial) policy planning in other areas, like housing, energy, and infrastructure.
- Some determinant systemic decisions have to be prepared for water management issues on the national scale: the discharge distribution of the branches of the river Rhine (distribute the peak discharge proportionally, or more concentrated on the Waal Corridor), the character of the Rhine Estuary (open, closed, closable), and creating additional peak storage in the southwestern delta water systems or seaward of the present coastline. These systemic decisions will have far-reaching supra-regional implications, require robust underpinning, and should be prepared in the coming years.
- Finally, the experts that have worked on the three perspectives have concluded that the mainly technical measures that were proposed, like dams, dikes, and pumping stations, result in (major) negative impacts on the environment and natural areas with high value. The predominantly technical approaches were partially due to the focus of the research on flood safety and water availability. To overcome these constraints and limitations, it is recommended to increase knowledge on effects of the studied perspectives, e.g., on water quality, ecology, potential mitigating measures, financing mechanisms, and socio-economic trade-offs. A first step is currently being made by a new consortium exploring whether, and to what extent, nature-based solutions are able to cope with sea-level rise. Results are expected around summer 2025.

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References

1. IPCC. Summary for Policymakers. In *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2022. Available online: <https://www.ipcc.ch/report/ar6/wg2/> (accessed on 5 November 2024).
2. Van Alphen, J.; Haasnoot, M.; Diermanse, F. Uncertain accelerated sea-level rise, potential consequences and adaptive strategies in The Netherlands. *Water* **2022**, *14*, 1527. [CrossRef]
3. Ministry of Infrastructure and Water Management. *How Can The Netherlands Cope with Sea-Level Rise? Interim Report of the Knowledge Programme on Sea-Level Rise*; Kennisprogramma Zeespiegelstijging: The Hague, The Netherlands, 2023. Available online: <https://www.deltaprogramma.nl/documenten/publicaties/2024/08/06/interim-report-for-the-sea-level-rise-knowledge-programme> (accessed on 5 November 2024).
4. IPCC. Summary for policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group 1 to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf (accessed on 7 January 2025).
5. Royal Dutch Meteorological Institute KNMI. *KNMI Klimaatscenario's voor Nederland*; KNMI: De Bilt, The Netherlands, 2023. Available online: https://cdn.knmi.nl/system/ckeditor/attachment_files/data/000/000/357/original/KNMI23_klimaatscenarios_gebruikersrapport_23-03.pdf (accessed on 5 November 2024). (In Dutch)
6. Gilbert, J.; Vellinga, P. Chapter 5—IPCC Response Strategies Working Group Reports. In *Coastal Zone Management: Technical Report*; IPCC: Geneva, Switzerland, 1990. Available online: https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_III_full_report.pdf (accessed on 5 January 2025).
7. Anfuso, G.; Postacchini, M.; Di Luccio, D.; Benassai, G. Coastal sensitivity/vulnerability characterization and adaptation strategies: A review. *J. Mar. Sci. Eng.* **2021**, *9*, 72. [CrossRef]
8. Williams, A.; Rangel-Buitrago, N.G.; Pranzini, E.; Anfuso, G. The management of coastal erosion. *Ocean Coast. Manag.* **2018**, *156*, 4–20. [CrossRef]
9. Van Alphen, J.; Haasnoot, M.; Diermanse, F.; Nillesen, A. Beyond the limits of present adaptation strategies: Exploring strategies and measures to anticipate on accelerated sea-level rise in The Netherlands. *J. Coast Zone Manag.* **2024**, *27*, 640.
10. De Bruijn, K.M.; Diermanse, F.L.M.; Weiler, O.; De Jong, J.S.; Haasnoot, M. Protecting the Rhine-Meuse delta against sea level rise: What to do with the river's discharge? *J. Flood Risk Manag.* **2022**, *15*, e12782. [CrossRef]
11. Friocourt, Y.; Blaas, M.; Bonte, M.; Vos, R.; Slomp, R.; Wilmink, R.; Lodder, Q.; Brakenhoff, L.; Van Gool, S. The impact of extreme sea-level rise on national strategies for flood protection and freshwater in The Netherlands. *NHESS* **2024**, submitted.
12. ENW. Advies Reflectie op Rapport Ruimte voor Zeespiegelstijging. Available online: <https://www.enwinfo.nl/adviezen/advies-reflectie-rapport-ruimte-zeespiegelstijging/> (accessed on 6 January 2025). (In Dutch)

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