Document Version
Final published version

Citation (APA)
de Vriend, H., Wang, Z., van Maren, B., & Peng, Z. (2024). Rhine-Meuse-Scheldt Delta. In W. Zhang, & H. de Vriend (Eds.), *Delta Sustainability: A Report to the Mega-Delta Programme of the UN Ocean Decade* (pp. 263–292). Springer. https://doi.org/10.1007/978-981-97-7259-9_14

Rhine-Meuse-Scheldt Delta

Huib de Vriend, Zhengbing Wang, Bas vanMaren, and Zhong Peng

1 Physical Setting

1.1 River Basins

The interlocking Rhine, Meuse and Scheldt basins cover a large part of Northwest Europe, as can be seen in Figs. 1, 2 and 3. The rivers' main characteristics are however quite different, the Rhine being fed by a mixture of snowmelt, rainwater and groundwater whereas the discharge in the Meuse and Scheldt primarily originates from rainwater. With a catchment size of 185000 km^2, the average river discharge of the Rhine is 2310 m^3/s (Frings et al., 2019). The catchments and annual river discharge of the Scheldt (22.000 km^2 and 100 m^3/s; Fettweis et al., 1998) and Meuse (33000 km^2 and 250 m^3/s; Delta-Alliance, 2024) are much lower.

When entering the Netherlands, the river Rhine transports coarse sandy material, the river Meuse gravely material and the river Scheldt fine muddy sediment. Rhine and Meuse exhibit significant downstream fining, such that most of the sediment in the delta proper is fine sandy to muddy. The most complete sediment budget for the Rhine river is probably developed by Frings et al. (2019). On average 2.11 million ton of mud (silt and clay), 0.59 million ton of sand, and 0.11 million ton of gravel are annually supplied to the Rhine delta (defined by Frings et al. as the border between the Netherlands and Germany at Lobith). The amount of sediment annually delivered

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W. Zhang and H. de Vriend (eds.), *Delta Sustainability*,
https://doi.org/10.1007/978-981-97-7259-9_14

to the sea is substantially less (0.90 and 0.15 million ton of mud and sand; no gravel), due to floodplain sedimentation, but especially due to dredging. The suspended load (mainly consisting of mud) supplied by the Scheldt river is 0.24–0.29 million ton/year (Van Hoestenberge et al., 2014), calculated at the approximate landward limit of maximum salt intrusion (landward of Antwerp). Earlier estimates by Fettweis et al. (1998) were considerably larger (0.75–2.2 million ton/year). Upon entering the Rhine-Meuse delta, the Meuse transports only 0.2 million ton of sand and 0.4 million ton of mud (Frings et al., 2019), although Cox et al. (2022) mention sediment budgets with a suspended load (sand and mud) of 0.7 million ton/year and a bedload transport (mainly sand) of 0.48 million ton/year.

In the downstream reaches of the Rhine-Meuse delta large amounts of sediment settle in fairways and harbours, which are subsequently dredged and deposited in the North Sea or within the system itself. Additionally, both systems trap fine sediments, which partly originate from the sea (Cox et al., 2021; Frings et al., 2011). The annual dredging volumes are about 10 million m^3/year in both the Rhine-Meuse estuary (Cox et al., 2022) and the Scheldt estuary (van Dijk et al., 2021). All sediment dredged within the Scheldt estuary (mostly sandy, but also more muddy in its upper reaches)

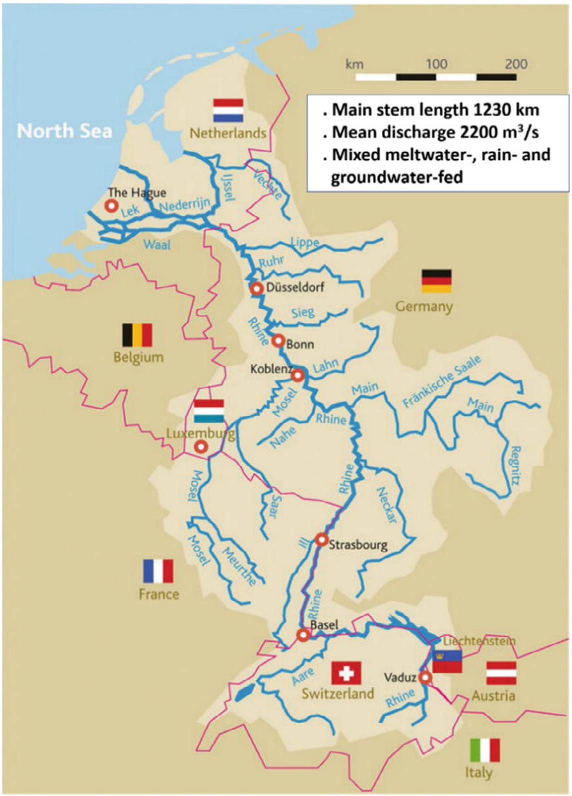

Fig. 1 Basin of the Rhine (From Schulte-Wülwer-Leidig et al., 2018)

Fig. 2 Basin of the Meuse. Modified from Pseudomas (2022)

are deposited within the Scheldt estuary. Part of the (largely muddy) sediment dredged from the Rhine-Meise estuary and deposited in the North sea is transported back into the Rhine-Meuse estuary by marine processes (van Maren & van Kessel, 2016).

1.2 *Delta Systems*

Deltaic deposits of the rivers Rhine and Meuse cover a large part of the Netherlands (Fig. 4), a country in northwest Europe, with an area of 41,543 km^2 and a population of 17.8 million people. According to Tockner et al. (2009), the delta defined in this way covers 25,347 km^2, making it the largest in Europe.

After flowing into the Netherlands, the Rhine and Meuse get connected and flow into the sea via various branches. The northernmost branch, the river IJssel, discharges via Lake IJssel into the Wadden Sea and further into the North Sea. The other branches

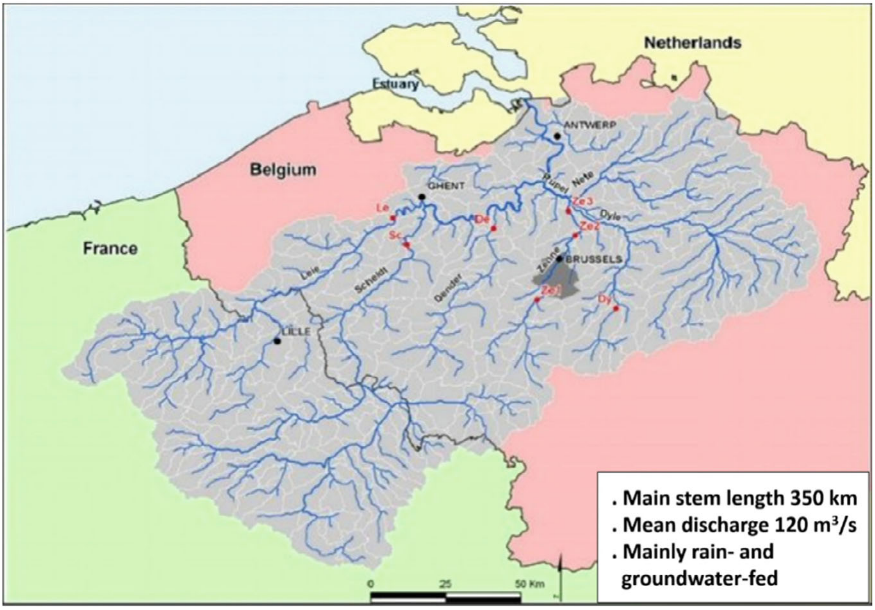

Fig. 3 The Scheldt basin. Modified from Veroustraete (2016)

discharge into the North Sea via the Rotterdam Waterway and the estuaries in the Southwesterly Delta, where the river Scheldt joins from the south.

1.2.1 Northerly Delta

In the Rhine-Meuse-Scheldt delta proper, i.e. the area influenced by tides, it is useful to distinguish between the northerly and the southerly basin. The northerly basin, with Rotterdam as the principal centre of activity, consists of a number of relatively narrow channels and waterways (Fig. 5). This figure also shows the principal human interventions in this system, meant primarily for flood protection and water management. Note the north–south directed channels, where current velocities have strongly increased since the implementation of these measures, because the northernmost channels (Nieuwe Waterweg, Nieuwe Maas) remained tidal, whereas the former estuary in the south (Haringvliet/Hollandsch Diep) has become almost non-tidal.

1.2.2 Southerly Delta

The Southerly basin is of a quite different nature, with large estuaries and sea arms like the Grevelingen (dammed off), the Eastern Scheldt (provided with a movable storm surge barrier) and the Western Scheldt (open). Figure 6 also shows the intense

Fig. 4 Main rivers in the Netherlands. Modified from https://www.rijkswaterstaat.nl/water/waterbeheer/beheer-en-ontwikkeling-rijkswateren/rivieren

urbanization in Belgian Flanders, which is driven to a large extent by port activities along the river Scheldt, the Western Scheldt estuary and the North Sea coast (Zeebrugge).

1.3 Wetlands and Ecosystems

Before 1970, the freshwater tidal marshes in the SW Delta were characterized by distinct vegetation zones closely tied to tidal inundation and exposure to tidal currents. In the lower intertidal regions, rushes prevailed, followed by reed marshes at higher elevations, and alluvial forests at the highest points. Since the estuary's closure, however, the dominant vegetation consists of extensive reeds and rushes, gradually transitioning to a large freshwater micro-tidal region known as the Biesbosch,

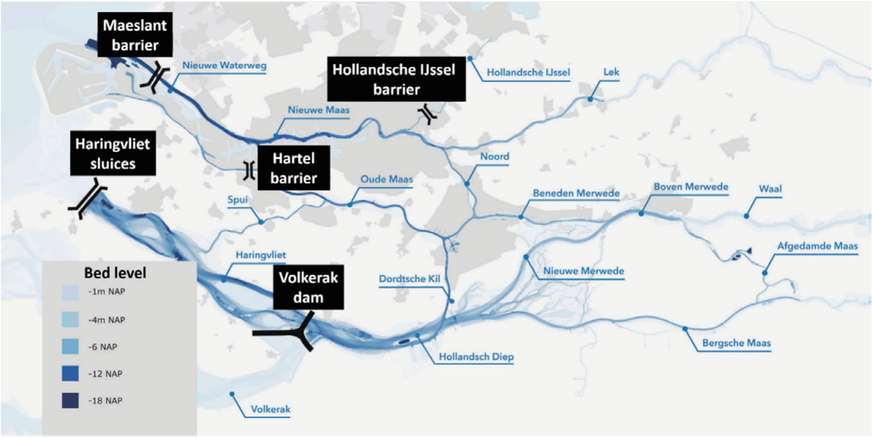

Fig. 5 Northerly basin of the Rhine-Meuse-delta (Rijkswaterstaat, 2019)

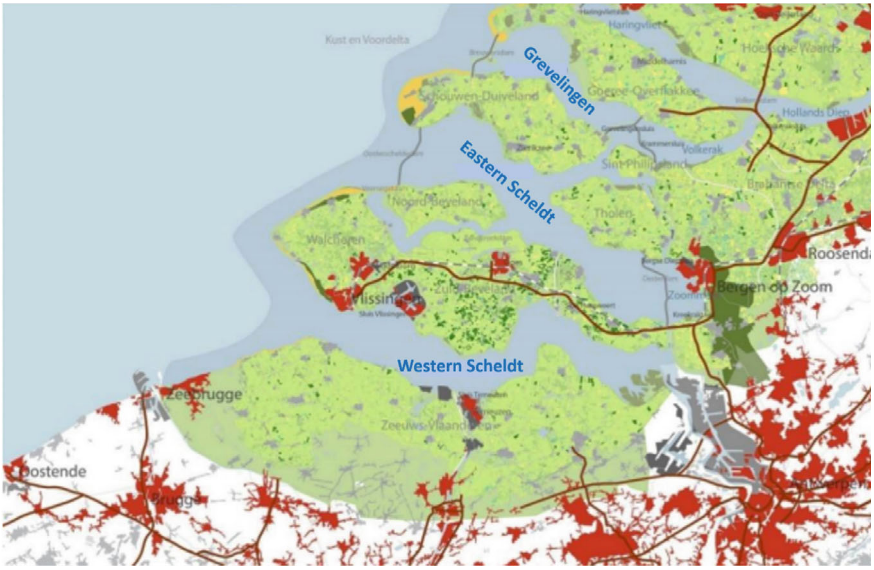

Fig. 6 Southerly basin of the Rhine-Meuse-Scheldt delta (Rijkswaterstaat, 2017)

featuring tidal forests and reed marsh areas (Nienhuis, 2008a). These freshwater tidal marshes exhibit distinct vegetation zones shaped by tidal inundation and currents. In the lower intertidal areas, Scirpus marshes dominate, while higher elevations feature reed marshes, ruderal vegetation, and alluvial forests (Van de Rijt & Coops, 1993). The evolution of vegetation is significantly influenced by the utilization of rushes, reeds, and coppice wood (Smit & Coops, 1991).

The estuarine environment in the RMS-delta encompasses encompasses both freshwater and brackish-water tidal systems, harboring a diverse range of life forms. These include unique plant species, plankton, macroinvertebrates, fish, various bird species, and mammals (Peelen in 1967; Wolff in 1973; Vaas in 1968). Additionally, the invertebrate and fish populations show distinct distribution patterns along an environmental gradient, ranging from marine species in the west to brackish-water and freshwater species in the east. Since the 1960s, a collective effort by the countries along the Rhine River has successfully reversed its decline in three crucial aspects: water quality, biodiversity, and floodplain availability. The most substantial achievements have been made in enhancing water quality. As a result, the Rhine now maintains adequate levels of dissolved oxygen for fish throughout the year.

1.4 Environmental Dynamics

1.4.1 Climate

The Netherlands have a temperate maritime climate with mild winters (min 0.7 °C) and cool summers (max 23.1 °C) according to the decadal mean (1991–2020) in station De Bilt (source KNMI.nl). The mean annual precipitation is 85 cm, with rainfall fairly evenly distributed over the year (only in spring there is slightly less rainfall). The potential evaporation is 56.3 cm (with evaporation rates exceeding rainfall between April and August)—KNMI (2024).

Temperature

Mean air temperatures in the Netherlands have risen significantly in recent decades, as shown in Fig. 7. According to the IPCC-projections (IPCC, 2014), the mean air temperature in Northern Europe must be expected to rise further, especially in winter. Higher air temperatures will lead to changes in snowmelt, which will affect the Rhine discharge regime in particular. They will also translate into higher water temperatures, hence into effects on the ecosystem and indirectly on the economy (cooling water availability for energy production). High temperature extremes (heat waves) are expected to increase markedly.

Precipitation

Precipitation in the Netherlands is about 0.9 m/year, and it has been gradually increasing over the last century (Fig. 7). The IPCC-projections show an increase in mean precipitation in Northern Europe, with more droughts and extreme precipitation events. This will influence the discharge regimes of all three rivers considered

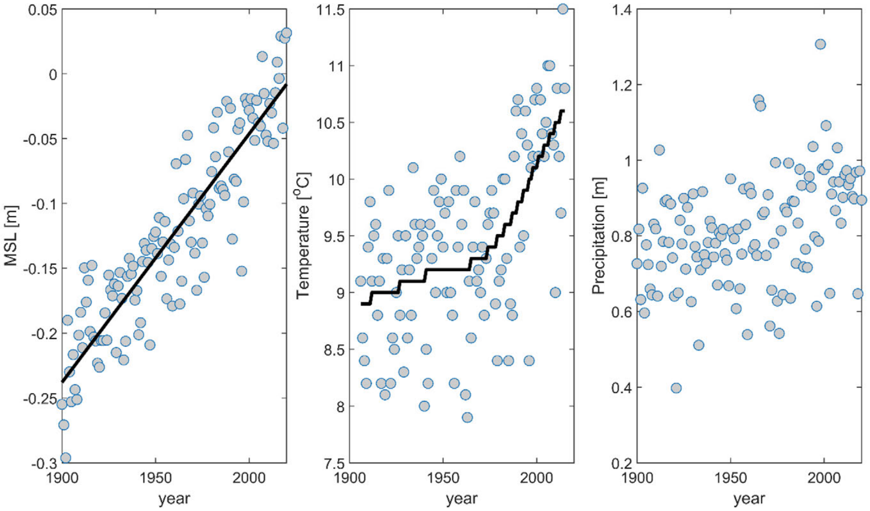

Fig. 7 Development of Mean Sea Level (MSL, left, data from www.psmsl.org/data/), annually average temperature (middle, data from KNMI.nl; trendline from https://www.clo.nl) and annual precipitation (data from KNMI.nl) measured between 1900 and 2020. MSL is defined relative to MSL in the period 2007–2020, and based on an average of measurements of yearly sea level at 7 stations along the Dutch coast (Vlissingen, Hoek van Holland, Maassluis, IJmuiden, Den Helder, Harlingen, Delfzijl). The average rise in MSL over the period 1900–2020 is 0.19 cm/year. Temperature data is measured at the main meteorological station of De Bilt

herein. Furthermore, the probability of extreme flood levels is expected to increase (e.g. Hegnauer et al., 2014).

Storminess

The North Sea and the Northwest European coasts are moderately impacted by storms (Fig. 8) and this does not appear to change in time. Neither do the IPCC climate projections show significant changes of storminess in this region.

For estuaries storm-induced surges are even more important than the storms as such. They can reach significant heights. Figure 9 shows an extrapolation of almost 120 years of data from Hook of Holland for various climate scenarios. Apart from storm surges, Bénard convection over the North Sea may lead to seiches that resonate in the harbour area of Rotterdam (De Jong & Battjes, 2010).

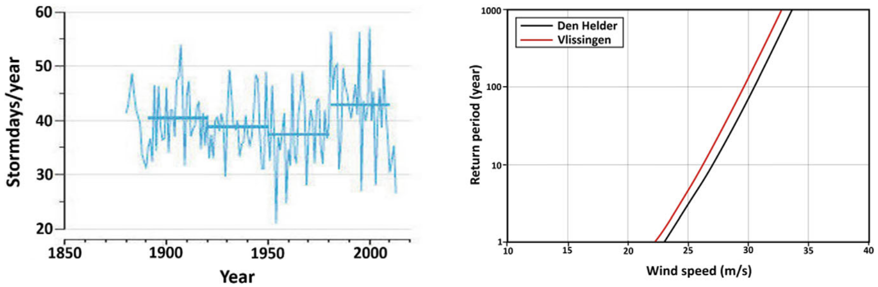

Fig. 8 Annual number of storm days on the North Sea (left) and return period of wind speed (right), both from KNMI.nl

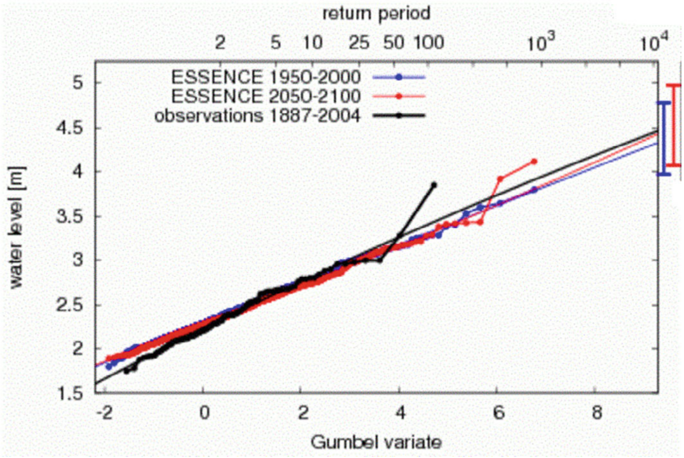

Fig. 9 Water levels at Hook of Holland extrapolated to 2100 (Sterl et al., 2008)

1.4.2 Tides

The tides in the present-day Rhine-Meuse estuary enter through its main outlet (the Nieuwe Waterweg or New Waterway). The mean tidal range is 1.9 m, with an amplitude slowly decreasing in the landward direction (Vellinga et al., 2014). Tidal propagation and circulation have been strongly modified by the various closure works executed in the past 60 years (see sections hereafter). Tides originally entered the estuary through the funnel-shaped Haringvliet, which is much wider and deeper (see Fig. 5). Tides in the Scheldt estuary are larger (3.7 m at the mouth) and increase in the landward direction (up to 5.4 m) (Wang et al., 2019).

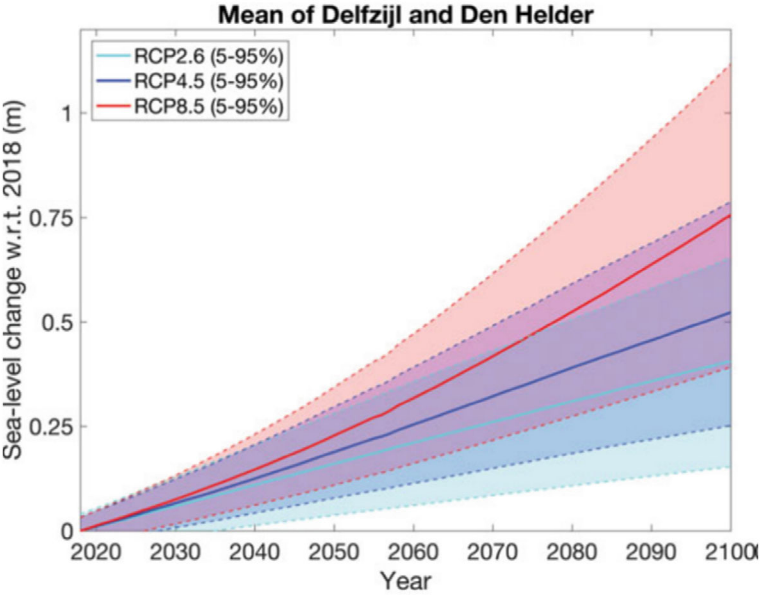

Fig. 10 Projections of future SLR in the Dutch Wadden Sea for three RCPs by Vermeersen et al. (2018), Figure from Wang and Xu (2018)

1.4.3 Relative Sea Level Rise

Water level records at tidal gauge stations along the Dutch coast are available since 1848 (Maassluis). The measured rate of sea level rise is about 2 mm/year (also see Fig. 7).

A recent study concluded that the sea level rise along the Dutch coast is accelerating (Vermeersen et al., 2018; Steffbauer et al., 2022), with a breakpoint in the early 1990s. Analysis suggests that the SLR rate increases from 1.7 ± 0.3 mm/yr before the breakpoint to 2.7 ± 0.4 mm/yr after the breakpoint.

Future sea level rise depends on the climate scenario and is very uncertain. For the Dutch Wadden Sea Vermeersen et al. (2018) made projections for the future sea level rise for three Representative Concentration Pathways (RCPs), as defined in IPCC AR5 (Fig. 10).

1.4.4 Subsidence

Subsidence in the Netherlands (see Fig. 11) is mainly due to hydrocarbon mining and peat oxidation, rather than to the compaction of recently deposited delta material. In the past millennia subsidence has been as important a factor in flood protection as sea level rise (see Fig. 12). At present most of the western part of the country lies

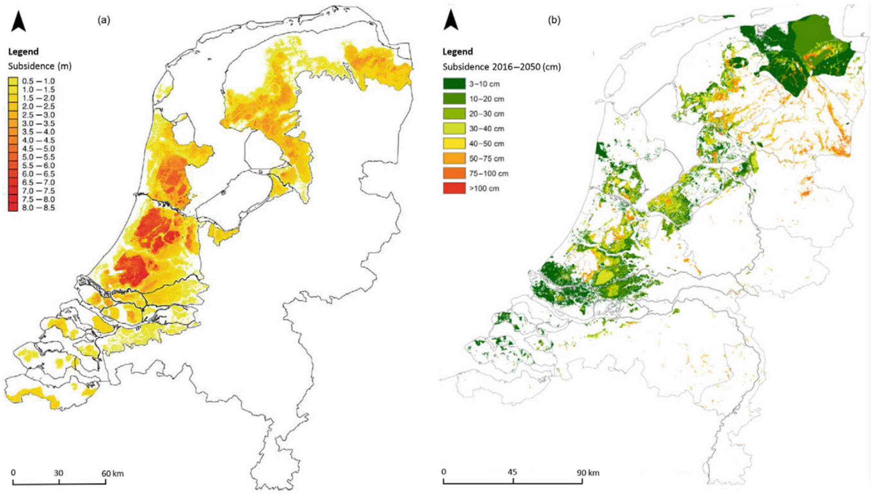

Fig. 11 Historic land subsidence (past 1000 years) due to drainage and peat mining (from Erkens et al., 2016) and expected land subsidence up to 2050 due to continues compaction of soft soils, but also due to gas extraction and salt mining (from Erkens et al., 2017). Combined figure from Stouthamer et al. (2020)

below sea level, up to almost 7 m, but also river flood levels can be well above the level of the riparian land (Fig. 13).

2 Socio-economic Characteristics

2.1 Overview

The Rhine-Meuse-Scheldt Delta has a catchment area of 243,000 km^2 and an annual river water discharge of around 85 km^3, based on data from 2005. The rivers in the delta transport an estimated 1.52 million metric tons of sediment annually. About 69% of the delta consists of water surfaces, while the remaining 31% is land, as per ASTER (2011) and OSM (2019) data. The delta's total area is estimated to range between 20,000 and 25,347 km^2. Urban land cover varies from 7.9 to 17%. The population density in areas below 10 m above sea level is 519 inhabitants per square kilometer, slightly below the national average.[1] These areas contribute significantly

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[1] The total population and population density in the area < 10 m a.s.l. was estimated by the authors by combining data from ASTER (2011) with the most detailed population statistics available on a municipal level in the Netherlands (CBS, 2024).

Fig. 12 The river Waal during a flood (Beeldbank Rijkswaterstaat)

to the economy, with a GDP contribution of 71%.[2] Per capita freshwater availability in the delta is 600 m^3, according to the Delta Programme of 2019.

Both in the Netherlands and in Belgium, there are major concentrations of population and economic activity in the delta area (Fig. 14), with Rotterdam and Antwerp as the principal ports. This also necessitates extensive infrastructures, to enable transport of goods and people. Rivers and estuaries are important parts of this transport system, which connects Rotterdam and Antwerp to entire European mainland (Fig. 15). The transport function puts high demands on these water systems, especially because ships are becoming ever larger with deeper draughts.

Agriculture is the predominant occupation in the RMS delta, with a substantial portion of urban land use ranging from 7.9 to 17%, depending on the measurement methods used (as per Corine Land Cover, 2012; Meyer & Nijhuis, 2014). Occupation patterns can also be assessed through population density. When combining elevation data from ASTER (2011) with population statistics from CBS (2024), it becomes evident that approximately 11 million people reside below 10 m above sea level in the RMS Delta. This population constitutes 63% of the nation's total population and results in an average population density of 511 inhabitants per square kilometer. It's important to acknowledge that the widespread settlement pattern in the RMS Delta

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[2] The GDP contribution of the area < 10 m a.s.l. in the NL was estimated by the authors by combining data from digital elevation map (ASTER 2011) with economic statistics on a provincial level (CBS, 2024).

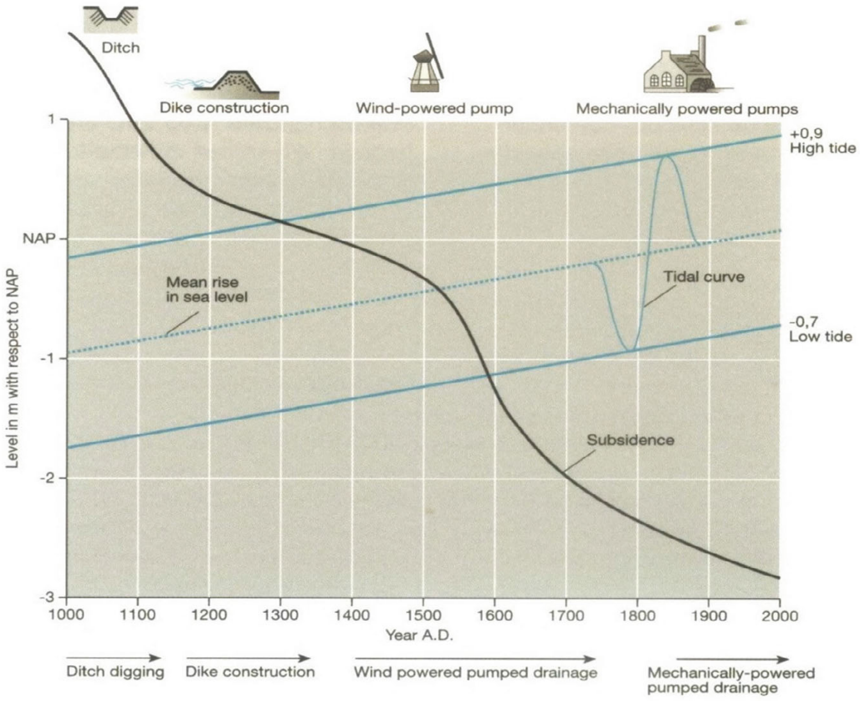

Fig. 13 Historic subsidence and seal level rise in the western part of the Netherlands (Stumpe & Tielrooij, 2000)

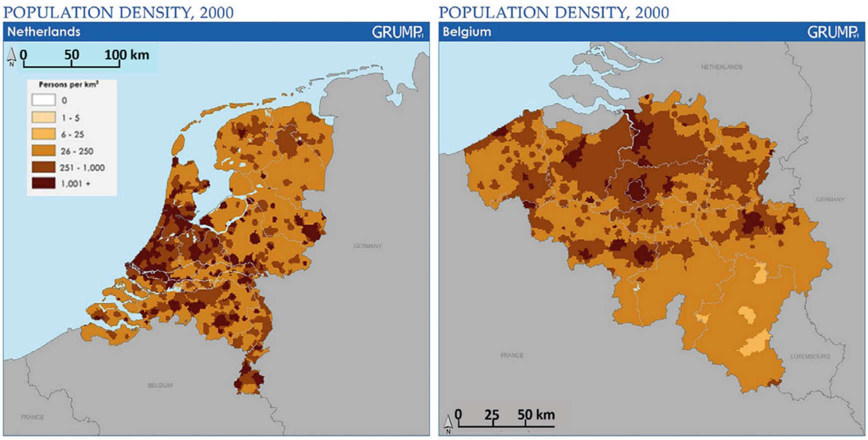

Fig. 14 Population densities in the Netherlands (SEDACMaps, 2000a) and Belgium (SEDACMaps, 2000b)

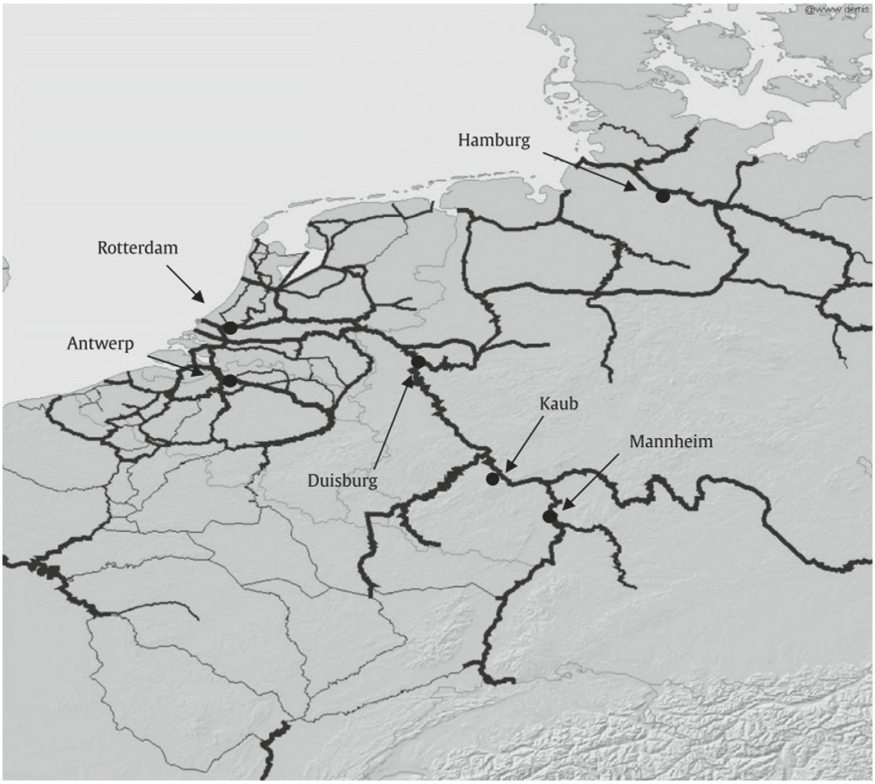

Fig. 15 Northwest-European waterborne transport network (Jonkeren et al., 2011)

has been a longstanding characteristic, driven by factors such as the fertile soil's high productivity, excellent accessibility via waterways and early road networks, and a governance model historically favoring decentralized political organizations (Boelens, 2014).

2.2 Infrastructural Works

2.2.1 Zuiderzee Closure

In 1932 a large inland sea arm, the Zuiderzee, was closed off by a dam, called Afsluitdijk (Fig. 16). The main purpose was land reclamation in order to provide for sufficient food, but it also gave major benefits to the country's flood protection and water management. The coastline was shortened by hundreds of kilometres and the large lake behind the dam now serves as an important freshwater reservoir. The downstream part of the river IJssel, the northernmost Rhine branch, turned from a

Fig. 16 Dams and land reclamations in the former Zuiderzee (Lommes, 2017)

tidal into a non-tidal river and various branches had to be shut down. At the seaside of the Afsluitdijk, the morphology of the so-called Wadden Sea is still responding to the construction of the dam (van Maren et al., 2023).

2.2.2 River Training Works

In order to improve navigability, the rivers in the delta have been subject to a variety of training works. A large part of the upstream river Meuse was canalised (Fig. 17).

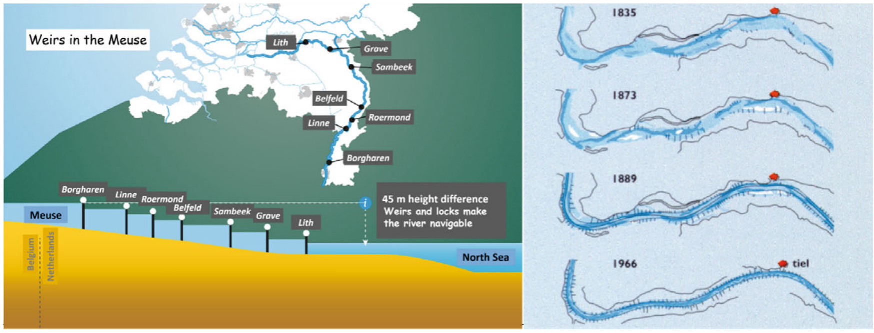

Fig. 17 Canalisation of the Maas River (left, figure from Rijkswaterstaat, 2023) and Waal branch of the Rhine River (right, from Silva et al., 2001)

The Meuse further downstream and the Rhine branches were normalized, mainly by groynes (also see Fig. 17). Furthermore, large amounts of the valuable sand and gravel were mined. As a consequence, the rivers tilted back and incised, with significant infrastructural and environmental consequences. Only recently, one has understood that sediment is a resource that should be properly managed and left in the river. This has led to a zero net abstraction policy in the Rhine branches and large-scale experiments with floodplain lowering, groyne lowering (see below under ‘Room for the River’), sediment nourishment and longitudinal dams in order to mitigate or partly undo the negative effects of former human interventions.

2.2.3 Meuse Works

Where the Room for the River program was financed by the government, an equivalent program for the upstream part of the river Meuse within the Netherlands, the so-called Meuse works, has been paid to a large extent by the revenues from gravel mining. Objectives were flood protection, nature restoration and improvement of the river as a fairway. In this part of the country the river flows in a valley, parts of which have been built up and embanked. Enhancing flood safety without shifting the burden to the embanked parts further downstream was a particular challenge.

2.2.4 Delta Works

The Delta works, triggered by the 1953 flood disaster, consist of a series of major interventions in the Rhine-Meuse-Scheldt delta proper (see Fig. 18). Estuaries were closed off by dams, sluices and movable storm surge barriers. The primary objective was to enhance flood safety by shortening the coastline.

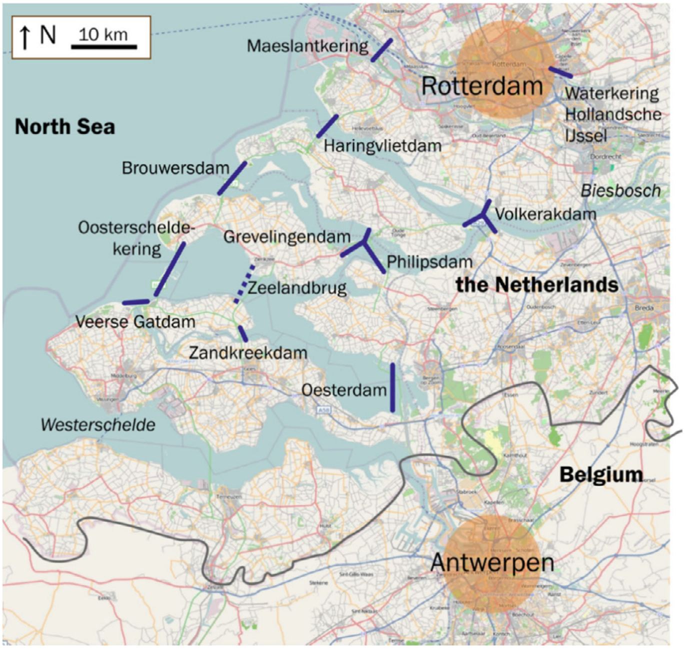

Fig. 18 Overview of the Delta works (RokerHRO, 2015)

The original plan was to close off all estuaries by dams. Only the Western Scheldt, access to the port of Antwerp, had to be left open. Public protest against the environmental impact ultimately led to the decision to leave the Eastern Scheldt open and protect it against extreme floods with a movable storm surge barrier. Clearly, the environmental impact of these engineering works was major. For example: a loss of intertidal area in the Eastern Scheldt, water quality problems in the lakes behind the dams, accumulation of polluted rivers sediment in the Hollands Diep/ Haringvliet area, erosion of the north–south oriented channels in the northern part of the delta and a loss of biodiversity in the former tidal wetland Biesbosch. This has led to a series of mitigating measures, such as allowing some tidal motion in the Haringvliet, enhancing the water circulation in the Grevelingen and nourishing sediment to intertidal flats in the Eastern Scheldt.

2.3 *Delta Management*

2.3.1 Flood and Water Management

Until Roman times, people in the lower parts of the Netherlands used to live on high grounds along the rivers, and on man-made mounds. In the Middle Ages they

Fig. 19 The Southwesterly Delta 400 years ago (left, Blaeu, 1635) and at present (right, from Bing.com)

started defending themselves against floods by dikes, often made of seaweed. Later on, they developed ever more sophisticated and efficient technology to build flood defences, remove surplus water from their land and control the groundwater level for agricultural purposes. An undesired side effect, however, was subsidence, mainly due to compaction and oxidation of peatland (also see Fig. 11).

2.3.2 Land Reclamations

The Southwesterly Delta has a long history of land reclamations and land losses (Fig. 19). Islands have been connected by land bridges and accreted further, but historic flood events led to significant losses of land, people and livestock. Figure 20 shows how the Western Scheldt has been encroached by successive land reclamations. This loss of storage area has its implications for the tidal penetration. It is one of the causes that the tidal range at Antwerp increased by about 1 m over the last century.

2.3.3 Dredging and Dumping

Since mid-twentieth century dredging activities have become important as human interference influencing the morphodynamic development of the Western Scheldt estuary. Sand mining of about 2.5 million m^3 per year between the 1950s and 2014 has caused deepening of the estuary in the order of 1 cm/year, which is much more than the present rate of sea level rise. Since 2014 sand mining is forbidden because of this serious effect. The Western Scheldt forms the entrance to Port of Antwerp. The navigation channel through the estuary has been deepened three times since the late 1970s, causing the maintenance dredging to increase to about 10 million m^3 per year. The dredged sediment for deepening and maintaining the navigation channel is deposited within the estuary to minimize sediment extraction. The Western Scheldt estuary is characterized by a two-channel system. Typically, one of the competing

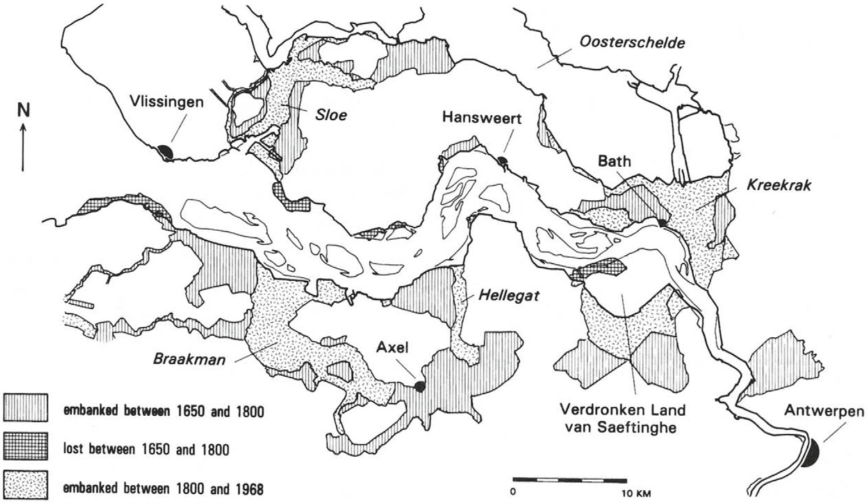

Fig. 20 Loss of storage area of the Western Scheldt mainly due to land reclamation (from Van der Spek, 1997)

channels is deepened, and dredged material is deposited in the other, impacting the multiple channel structure of the estuary (Wang & Winterwerp, 2001; Jeuken & Wang, 2010). Conserving the stability of the multi-channel system is considered as an important aspect in optimizing the strategy of dredged material disposal in the estuary.

3 Current Issues

Many of the phenomena and trends described in the foregoing constitute management challenges. Therefore, we will focus here on aspects that have not yet been mentioned.

3.1 Low Lying Land

A large part of the Netherlands lies below sea level. This in itself is a management concern, because the land needs to be protected against flooding. The flood protection approach is risk-based, where risk is defined as the probability of occurrence of a flood event multiplied by the damage done in terms of property and lives lost. Sea level rise, subsidence, climate change, increasing population density and economic activity in protected areas affect the risk level, thus necessitate regular upgrading of the flood defence system.

However, flood protection is not the only concern regarding low-lying areas, especially where these are subsiding. Saline seepage from below, for instance, may render fertile polders unfit for agriculture.

3.2 Climate Change

Recent extreme events have given a wake-up call to water management in the Netherlands. The 2021 precipitation and flooding event in 2021 made clear that flood risk cannot be managed properly by just considering the flood level statistics in the main stems of the rivers: tributaries have to be taken into account. A recent series of extreme droughts made clear that maintaining surface and groundwater reserves needs more attention and that the common policy to discharge rainwater as soon as possible needs reconsideration.

3.3 Coastal Squeeze and Loss of Intertidal Area

Typical estuarine areas like mudflats and marshes are threatened from both sides. Reclamations take away space at the land side, navigation channel dredging and (ship-) wave attack limit their extent at the water side. This so-called coastal squeeze goes at the expense of the typical estuarine habitat, hence of the high biological productivity of these systems. Initiatives such as polder abandonment, dike relocation and restoration of intertidal areas are meant to mitigate these effects (see, for instance, Fig. 21).

In the Eastern Scheldt, the loss of intertidal area is not due to coastal squeeze, but rather to the almost complete blockage of marine sediment import by the storm surge barrier. Due to the reduced tide, the tidal channels tend to become smaller and the sediment needed for this can only come from the intertidal flats. This manifests itself not only by a loss of intertidal area, but also by a loss profile of the intertidal shoals, due to which the flooding time is much shorter and birds have less time to forage. Attempts are made to compensate this by sediment nourishment on top of the intertidal flats, but as long as there is no sediment brought in from outside, this remains an internal sediment redistribution operation that does not solve the underlying problem.

3.4 Navigation Channel Maintenance

The Rhine-Meuse-Scheldt delta gives access to a Europe-wide network for waterborne transport (also see Fig. 15). This is of paramount economic importance to the Netherlands and Belgium. Natural processes such as sedimentation, but also

Fig. 21 The Perkpolder renaturalisation project two years after completion (Zuidwestelijke Delta, 2017)

the growth of waterborne transport and the ever increasing vessel size necessitate maintenance and regular upgrading of the fairways. This encompasses dredging operations, like in the Western Scheldt, but also safety measures and engineering works on bridges, locks and barriers, for instance. For some parts of the network, such as the rivers in the Netherlands, this raises the management question how far the fairway capacity can be extended without unacceptable consequences for infrastructures and river functions such as nature and riparian agriculture.

3.5 Coastal Erosion

Coastal erosion within the estuaries is not much of a problem, because most of the estuaries are embanked. Wherever necessary, erosion of the North Sea coast is compensated by regular nourishments with sand mined offshore. Clearly, accelerated sea level rise will require more and more frequent nourishments (see, for instance, Delta Commission, 2008).

3.6 Environmental Pollution

Being densely populated countries at the downstream end of river basins, the Netherlands and Belgium are facing persistent water quality problems. In the Netherlands, virtually none of the surface waters meets European quality standards. Also, the state of preservation of most aquatic ecosystems is below the standards set by the European Water Framework Directive. In the Southwesterly Delta this has led to mitigating measures, such as allowing some tidal motion into the Haringvliet/Hollands Diep, flushing the Grevelingen with sea water and making Lake Veer saline again.

Water pollution is not the only problem in the estuaries, also the bed sediment may be polluted. In many river and estuarine deposits, there is a polluted layer dating from the second half of last century. This is often covered by layer of cleaner recent deposits. Yet, there are also more recent bed pollutions. Until very recently, PFAS have been discharged into the Scheldt near Antwerp and have polluted the bed sediments of the Western Scheldt. PFAS are also found in fish and shellfish caught in these waters and people are advised not to swim there.

3.7 Biodiversity Loss

Estuaries are among the biologically most productive ecosystems of the world. Yet, their biodiversity is under threat. Not only by habitat loss due to embankments and coastal squeeze, but also by invasive species. One example is the Japanese Oyster (*Crassostrea gigas*), which covers large areas of intertidal flats in the Eastern Scheldt (Fig. 22), for instance, and has virtually outcompeted the original flat oyster (*Ostrea edulis*).

Macrofaunal studies also refer to the historical presence and decline of otters and harbor seals in the region, with pollution contributing to the latter's decline (Reijnders, 1982). The avian population in the Delta region, which had adapted to traditional farming methods, underwent significant transformations. Meadow bird populations dwindled due to the pressures of intensive land utilization, while herbivorous waterfowl thrived, primarily depending on fertilized agricultural land. This situation resulted in a noticeable clash of interests with farmers, as opportunistic species prospered in response to the increasing number of artificial habitats and the prevailing trend of afforestation (Nienhuis, 2008c).

Both fish and macro-invertebrate communities show limited species diversity, often dominated by non-native species among benthic macroinvertebrates (Nienhuis, 2008b). A significant recent development is the EU Water Framework Directive, which mandates EU member states to develop river basin management plans with the aim of achieving a good ecological status for rivers by 2015. Nevertheless, persistent eutrophication remains a significant environmental concern in the Delta's surface waters. This includes external eutrophication due to the inflow of nutrient-rich polluted water (containing nitrogen and phosphorus) and internal eutrophication driven by sulfate in systems loaded with organic material, such as floodplain and peat lakes.

Fig. 22 Japanese oysters covering a tidal flat (https://www.wur.nl/nl/show/inventarisatie-japanse-oesters.htm)

3.8 *Harbour Siltation*

Within the Rhine-Meuse-Scheldt delta there is a wide variety of ports, from very large like Rotterdam and Antwerp, via medium-sized ones like Sloe and Terneuzen/Ghendt, to fisheries harbours like Yerseke. As the North Sea water and the rivers and estuaries are laden with fine sediment, harbours tend to silt up with sediment from either side. The Port of Rotterdam, for instance, dredges 15–20 million m^3 of sediment from its harbour basins. Most of this sediment is clean enough to be used in nature restoration or dike building projects, for instance. Polluted sediment is stored in a separate basin (the Slufter), depending on the degree of pollution. Dredged material from the inner locks of the Port of Antwerp is polluted with TBT (a product used until 2003 in antifouling paint) and treated in a facility (Amoras) into dry matter (van Maren & van Kessel, 2015).

4 Measures to Solve the Problems

4.1 *The Delta Program*

In the past, many major flood protection measures, such as the closure of the Zuiderzee and the Delta Works, were taken after a major flood disaster. More recently, the Netherlands has been working proactively in finding solutions for the future problems. Since the end of the last century, various large research programmes such as Coastal Genesis I and Coastal Genesis II have been carried out to develop coastal maintenance strategies. At present the ongoing national research programme is called "Sea Level Rise".

Following the advice of the Delta Commission (2008) the Delta Fund was established for the implementation of the Delta Program, led by the Delta Commissioner. The Delta Program is meant to protect the Netherlands against high water and flooding, to ensure sufficient freshwater and to contribute to a climate-proof and water-robust organization of the country. Various solution directions (Fig. 23) and their "building blocks" (Haasnoot & Diermanse, 2022) are investigated, together with the pathways to implement them in the future.

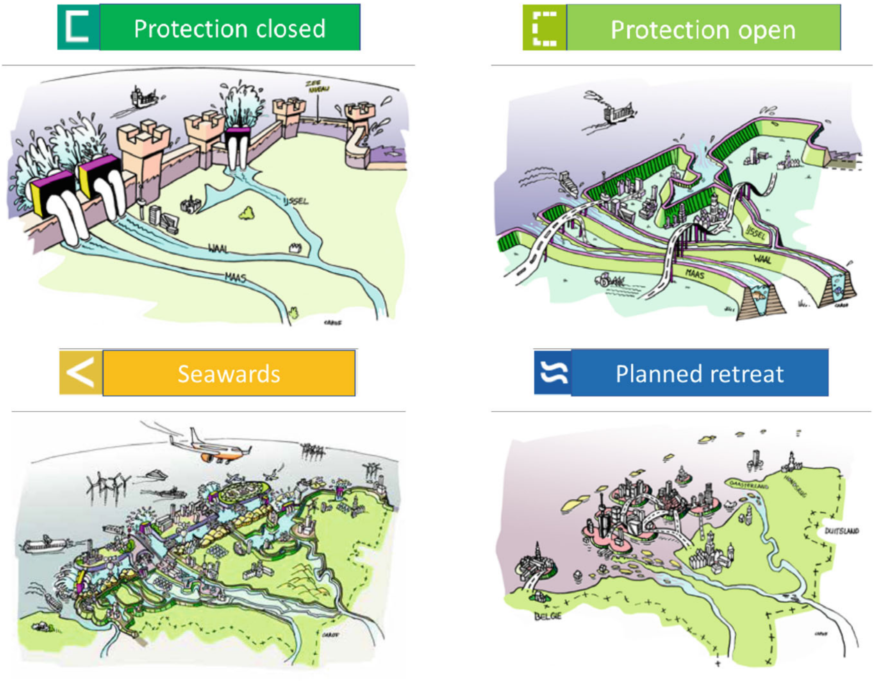

Fig. 23 The four solution directions. Adapted from Haasnoot and Diermanse (2022)

4.2 Building with Nature

As a low-lying delta country, the Netherlands has always been dealing with the threat of flooding. Nowadays the country is protected against flooding according to the highest safety standard in the world. With accelerated sea level rise the most important problem is how to maintain this high safety standard in the future. Another problem is to guarantee freshwater supply related to increasing salt intrusion and the changing flow regime of the rivers.

In managing the delta the Dutch have always considered safety against flooding as prerequisite, while the balance between socio-economic development and environmental protection is optimized. However, the consideration of these same three aspects has resulted into different solutions of the problems in different periods. During the construction of the Delta Works the closure of the Eastern Scheldt estuary was redesigned to a storm surge barrier, attributing more importance to the environmental protection. In the course of time, the philosophy of "building against nature" has shifted to "building with nature". As an example, the coastal protection is nowadays according to the rule "soft if possible, hard if necessary", making the soft measure sand nourishment preferable to hard structures. The long-term safety against flooding along the sandy coast is presently maintained by regular sand nourishments. The required amount of sand nourishment will increase with the increasing rate of sea level rise. As too frequent sand nourishments may cause ecological damage, experiments such as the "sand engine" are being carried out (see Fig. 24).

4.3 Room for the River

In the course of time, the rivers in the Netherlands have been encroached by embankments, land reclamations, building up floodplains, et cetera (see Fig. 25). This has led to a loss of fluvial habitat and higher and more rapidly propagating flood waves, hence increased flood risks. In order to mend this situation for the Rhine branches, a major river improvement program was carried out in the first two decades of this century. This Room for the River program encompassed 34 measures, such as relocating embankments, lowering floodplains, digging side channels, creating flood storage areas and building flood alleviation facilities. It has been completed in 2019.

4.4 Sigma Plan

In the densely populated Scheldt basin increasing flood levels are enhancing flood risks. In order to improve flood protection and in the meantime boost nature, the so-called Sigma plan is being implemented, aiming for completion in 2030. It consists

Fig. 24 Sand engine: a mega sand nourishment of more than 20 million m^3, following the principles of Building with Nature: ocean currents, wind and waves are gradually spreading the sand along the coast and into the dunes. *Source* https://dezandmotor.nl

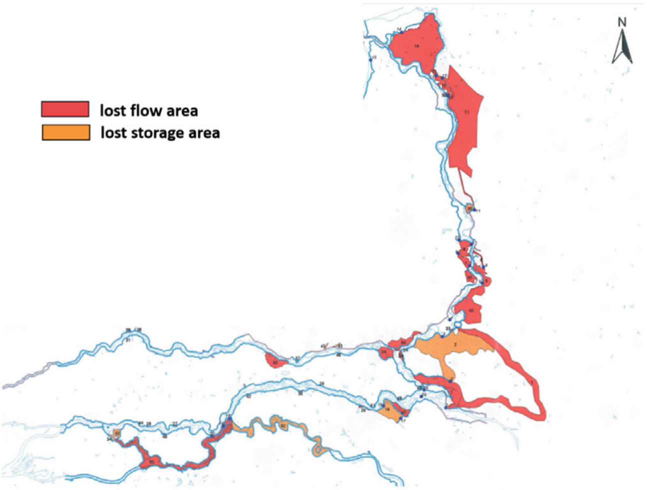

Fig. 25 Encroachment of the Rhine branches and the Meuse (Klijn & Stone, 2000)

Fig. 26 Overview of the Sigma Plan (https://www.sigmaplan.be/nl/projecten/)

of a large number of measures (see Fig. 26), such as dike reinforcements, polder abandonment and creation of storage areas.

5 Future of the Rhine-Meuse-Scheldt Delta

The Rhine-Meuse-Scheldt Delta is relatively successful in terms of ecosystem protection and biodiversity. This achievement is the result of continuous efforts in flood risk management, biodiversity protection, the promotion of nature-based solutions, and water quality control.

Efforts to conserve and restore these ecosystems will undoubtedly play a pivotal role in shaping the delta's future. This includes the preservation and rehabilitation of wetlands, the protection of critical habitats, and the implementation of sustainable land-use practices. Striking a balance between economic development and environmental conservation will be essential to ensure a sustainable future for the delta. As urbanization and industrial development in the delta region may continue to expand, these factors may impact natural habitats and water quality.

The delta will also need to adapt to rising sea levels. This adaptation may involve the promotion of ecosystem-based coastal defences, the enhancement of sandy coasts, and effective water management strategies. Ensuring a sustainable freshwater supply, robust flood control measures, and the prevention of saltwater intrusion will be vital aspects demanding ongoing attention and investment. A more resilient and sustainable future for the delta will be facilitated by advances in technology, including improved flood forecasting systems, sustainable agricultural practices, and the adoption of renewable energy solutions.

Spanning multiple countries, including the Netherlands, Belgium, Germany, and France, the Rhine-Meuse-Scheldt Delta and its catchment underscore the importance of continued international cooperation. Additionally, engaging local communities and stakeholders in decision-making processes will be crucial for addressing shared challenges and developing coordinated strategies for the delta's future. Their knowledge and input can help shape policies and projects that better align with the needs and aspirations of the people living in the region.

References

ASTER. (2011). ASTER Global Digital Elevation Map 2. Retrieved September 1, 2019, from https://asterweb.jpl.nasa.gov/gdem.asp

Blaeu, W. (1635). Zeelandia Comitatus.

Boelens, L. (2014). Delta governance: The DNA of a specific kind of urbanization. *Built Environment, 40*, 169–183.

Cox, J. R., Huismans, Y., Knaake, S. M., Leuven, J. R. F. W., Vellinga, N. E., van der Vegt, M., et al. (2021). Anthropogenic effects on the contemporary sediment budget of the lower Rhine-Meuse Delta Channel Network. *Earth's Future, 9*(7), 1–22.

Cox, J. R., Leuven, J. R. F. W., Pierik, H. J., van Egmond, M., & Kleinhans, M. G. (2022). Sediment deficit and morphological change of the Rhine-Meuse river mouth attributed to multi-millennial anthropogenic impacts. *Continental Shelf Research, 244*, 104766.

de Jong, M. P. C., & Battjes, J. A. (Eds.). (2010). Generation and prediction of seiches in Rotterdam harbor basins. In Y. C. Kim (Ed.), *Handbook of coastal and ocean engineering* (pp. 179–236). World Scientifc.

Delta-Alliance. (2024). http://www.delta-alliance.org/deltas/rhine-meuse-delta

Delta Commission. (2000). *Working together with water. A living country builds for its future* (138 pp). Secretariat Delta commission. ISBN/EAN 978-90-9023484-7.

der Spek, V. (1997). Tidal asymmetry and long-term evolution of Holocene tidal basins in The Netherlands: Simulation of palaeo-tides in the Scheldt estuary. *Marine Geology, 141*, 71–90.

Erkens, G., van der Meulen, M. J., & Middelkoop, H. (2016). Double trouble: Subsidence and CO2 respiration due to 1,000 years of Dutch coastal peatland cultivation. *Hydrogeology Journal, 24*, 551–568.

Erkens, G., Stafleu, J., & van den Akker, J. J. H. (2017). Bodemdalingvoorspellingskaarten van Nederland, versie 2017. Deltares rapport klimaateffectatlas.

Fettweis, M., Sas, M., & Monbaliu, J. (1998). Seasonal, neap-spring and tidal variation of cohesive sediment concentration in the Scheldt Estuary, Belgium. *Estuarine Coastal and Shelf Science, 47*, 21–36.

Frings, R. M., Hillebrand, G., Gehres, N., Banhold, K., Schriever, S., & Hoffmann, T. (2019). From source to mouth: Basin-scale morphodynamics of the Rhine River. *Earth-Science Reviews, 196*, 102830.

Frings, R. M., Schüttrumpf, H., & Vollmer, S. (2011). Verification of porosity predictors for fluvial sand-gravel deposits. *Water Resource Research, 47*(7), 1–15.

Haasnoot, M., & Diermanse, F. (Eds.). (2022). Analyse van bouwstenen en adaptatiepaden voor aanpassen aan zeespiegelstijging in Nederland.

Hegnauer, M., Beersma, J. J., van den Boogaard, H. F. P., Buishand, T. A., & Passchier, R. H. (2014). Generator of rainfall and discharge extremes (GRADE) for the Rhine and Meuse basins (84 pp.). Deltares.

https://help.openstreetmap.org/questions/84042/osm-historical-dump-for-2019

https://land.copernicus.eu/en/products/corine-land-cover/clc-2012 https://www.cbs.nl/en-gb

IPCC. (2014). Climate Change 2014: Synthesis Report. In Core Writing Team, R.K. Pachauri., L.A. Meyer (Eds.). *Contribution of Working Groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change*. IPCC.

Jeuken, M. C. J. L., & Wang, Z. B. (2010). Impact of dredging and dumping on the stability of ebb-flood channel systems. *Coastal Engineering, 57*, 553–566.

Jonkeren, O., Jourquin, B., & Rietveld, P. (2011). Modal-split effects of climate change: The effect of low water levels on the competitive position of inland waterway transport in the river Rhine area. *Transportation Research Part A: Policy and Practice, 45*(10), 1007–1019.

Klijn, F., & Stone, K. (2000). *Past room for the Rhine branches*. Delft Hydraulics, Report R3294.67, 31 pp. Also see: https://open.rijkswaterstaat.nl/open-overheid/onderzoeksrapporten/@239208/vroegere-ruimte-rijntakkenverslag/#highlight=Klijn,%20F

KNMI. (2024). *Climate of the Netherlands*. https://www.knmi.nl/klimaat

Lommes. (2017). A map of the Zuiderzeeworks in the Netherlands. https://commons.wikimedia.org/w/index.php?curid=54839004Dedalus. CC BY-SA 3.0.

Meyer, H., & Nijhuis, S. (Eds.). (2014). *Urbanized Deltas in transition*. Techne Press.

Nienhuis, P. H. (2008a). Changing Rhine ecosystems: Pollution and rehabilitation. In P. H. Nienhuis (Ed.), *Environmental history of the Rhine-Meuse Delta* (pp. 329–353). Springer.

Nienhuis, P. H. (2008b). Changes in biodiversity: Lower organisms, vegetation and flora. In P. H. Nienhuis (Ed.), *Environmental history of the Rhine-Meuse Delta* (pp. 481–507). Springer.

Nienhuis, P. H. (2008c). Changes in biodiversity: Birds and Mammals and their use. In P. H. Nienhuis (Ed.), *Environmental history of the Rhine-Meuse Delta* (pp. 509–535). Springer.

Peelen, R. (1967). Isohalines in the delta area of the rivers Rhine, Meuse, and Scheldt: Classification of water in the delta area according to their chlorinity and the changes in these waters caused by the delta works. *Netherlands Journal of Sea Research, 3*, 575–597.

Perkpolder: twee jaar later. (2017). https://www.zwdelta.nl/nieuws/perkpolder-twee-jaar-later/

Pseudomas. (2022). CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=120915437

Reijnders, J. H. (1982). On the extinction of the southern Dutch harbour seal population. *ICES, Marine Mammals Commission, 31*(1), 900357.

Rijkswaterstaat. (2017). Factsheet Southerly Delta Basin. *Rijkswaterstaat, Water, Verkeer en Leefomgeving* (26 pp.) (in Dutch).

Rijkswaterstaat. (2019). Het Verhaal van de Rijn-Maas-monding (56 pp.).

Rijkswaterstaat. (2023). De.7 Maasstuwen. https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/dammen-sluizen-en-stuwen/de-7-maasstuwen

RokerHRO Map of the Delta Works. (2015). OpenStreetMap CC BY-SA 3.0. https://commons.wikimedia.org/w/index.php?curid=4446902

Schulte-Wülwer-Leidig, A., Gangi, L., Stötter, T., Braun, M., & Schmid-Breton, A. (2018). Transboundary Cooperation and sustainable development in the Rhine Basin. https://www.intechopen.com/chapters/59001

SEDACMaps. (2000a) SEDACMaps—Netherlands: Population Density, 2000, CC BY 2.0. https://commons.wikimedia.org/w/index.php?curid=85088632

SEDACMaps. (2000b). SEDACMaps—Belgium: Population Density, 2000, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=85088904

Silva, W., Klijn, F., & Dijkman, J. P. M. (2001). Room for the Rhine branches in The Netherlands: What the research has taught us. http://resolver.tudelft.nl/uuid:12b2ad06-3469-49ea-a280-78e1dcc2fcb9

Smit, H., & Coops, H. (1991). Ecological, economic and social aspects of natural and man-made bulrush (Scirpus lacustris L.) wetlands in The Netherlands. *Landscape and Urban Planning, 20*, 33–40.

Sterl, A., van Oldenborgh, G. J., Hazeleger, W., & Dijkstra, H. (2008). Extreme maximumtemperaturen in de toekomst. *Meteorologica, 17*(3), 4–7.

Steffbauer, D. B., Riva, R. E. M., Timmermans, J. S., Kwakkel, J. H., & Bakker, M. (2022). Evidence of regional sea-level rise acceleration for the North Sea. *Environmental Research Letters, 17*, 074002.

Stouthamer, E., Erkens, G., Cohen, K., Hegger, D., Driessen, P., Weikard, H. P., et al. (2020). Dutch national scientific research program on land subsidence: Living on soft soils subsidence and society. *Proceedings of the International Association of Hydrological Sciences, 382*, 815–819.

Stumpe, J., & Tielrooij, F. (2000). Waterbeleid voor de 21ste eeuw. Eindrapport Commissie WB21 (50 pp.). http://resolver.tudelft.nl/uuid:102e013a-1357-4087-b9f3-387f877c793f

Tockner, K., Uehlinger, U., & Robinson, C. T. (2009). *Rivers of Europe.* Academic Press.

Vaas, K. F. D. (1968). Visfauna van het estuariumgebied van Rijn en Maas. *Biologisch Jaarboek, Dodonaea, 36*, 115–128.

Van de Rijt, C. W. C. J., & Coops, H. (1993). Tide creates room for vegetation in the Rhine-Meuse estuary. De Levende Natuur, 9468–72 (in Dutch with English summary).

Van Dijk, W. M., Cox, J. R., Leuven, J. R., Cleveringa, J., Taal, M., Hiatt, M. R., et al. (2021). The vulnerability of tidal flats and multi-channel estuaries to dredging and disposal. *Anthropocene Coasts, 4*(1), 36–60.

Van Hoestenberghe, T., Ferket, B., De Boeck, K., Vanlierde, E., Vanlede, J., Verwaest, T., & Mostaert, F. (2014). *Sediment load for the river Scheldt and its main tributaries (1972–2009).* Version 5.0. WL Report 00_029. Waterbouwkundig Laboratorium/Antea Group: Antwerp.

van Maren, D. S., van Kessel, T., Cronin, K., & Sittoni, L. (2015). The impact of channel deepening and dredging on estuarine sediment concentration. *Continental Shelf Research, 95*, 1–14.

van Maren, D. S., A. Colina Alonso, A., Engels, W. Vandenbruwaene, P. L. M. de Vet, J. Vroom & Z.B. Wang. (2023). Adaptation timescales of estuarine systems to human interventions. *Frontiers in Earth Science, 11*, 1–18.

van Maren, D. S., & van Kessel, T. (2016). Long-term effects of maintenance dredging on turbidity. *Terra Et Aqua, 145*, 5–14.

Vellinga, N. E., Hoitink, A. J. F., van der Vegt, M., Zhang, W., & Hoekstra, P. (2014). Human impacts on tides overwhelm the effect of sea level rise on extreme water levels in the Rhine-Meuse delta. *Coastal Engineering, 90*, 40–50.

Vermeersen, B. L. A., Slangen, A. B. A., Gerkema, T., Baart, F., Cohen, K. M., Dangendorf, S., Duran-Matute, M., Frederikse, T., Grinsted, A., Hijma, M. P., Jevrejeva, S., Kiden, P., Kleinherenbrink, M., Meijles, E. W., Palmer, M. D., Rietbroek, R., Riva, R. E. M., Schulz, E., Slobbe, D. C., et al. (2018). Sea-level change in the Dutch Wadden Sea. *Netherlands Journal of Geosciences, 97*(3), 79–127.

Veroustraete, F. (2016). The Solomon Isles disappear in the Pacific. In *Scientific evidence for Global and Local Sea-level rise. Climate Impacts* (vol. 1, pp. 1–10). REDSTAR-CV&M Open Access Science Publishing.

Wang, Z. B., & Winterwerp, J. (2001). Impact of dredging and dumping on the stability of ebb-flood channel systems. In *Proceedings of the 2nd IAHR symposium on River, Coastal and Estuarine Morphodynamics* (pp. 515–524).

Wang, B., & Xu, Y. J. (2018). Decadal-scale riverbed deformation and sand budget of the last 500 km of the Mississippi River: Insights into natural and river engineering effects on large alluvial rivers. *Journal of Geophysical Research: Earth Surface,* 004542.

Wang, Z. B., Vandenbruwaene, W., Taal, M., & Winterwerp, H. (2019). Amplification and deformation of tidal wave in the upper Scheldt Estuary. *Ocean Dynamics, 69*(7), 829–839.

Wolff, W. J. (1973). The estuary as a habitat. An analysis of data on the soft-bottom macrofauna of the estuarine area of the rivers Rhine, Meuse, and Scheldt. Rijksmuseum van Na-tuurlijke Historie, Leiden. Zoologische Vmhandelingen, 126, 3–242.