

Stability of intertidal and subtidal areas after Delta21 plan

Evaluating the consequences for the morphological development produced by the intervention

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Cover: View of Kwade Hoek and the Haringvliet sluices in the Haringvliet mouth. Photography by Jacques van der Neut.



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Summary

In recent years, there has been an increasing need for solutions against the threats that SLR and climate change represent for coastal systems, especially in low lying areas like the SW Dutch coast. Simultaneously, awareness of the impacts that human activities have on natural environments has surged. Integrated and sustainable solutions are necessary.

The Delta21 plan proposes an integrated plan for flood-protection, energy storage, and natural ecosystem restoration for The Netherlands, specifically for the Haringvliet estuary. This large-scale intervention will produce large disturbances in the system. Despite the resilient character of tidal basin systems (Z. B. Wang et al. 2009), the evaluation of the intervention's effects, in terms of the initial response and the variations in the mechanisms driving morphological changes is compulsory. Assessing the bed level changes is especially important, considering the valuable intertidal and subtidal ecosystems present in the Haringvliet mouth. It is essential to guarantee their preservation despite the large disturbances.

The evaluation of the Haringvliet mouth response is performed employing a long-term morphodynamic 2DH computational simulation to forecast the response of the system. The models implemented for the simulation are the Delft3D-FLOW and Delft3D-WAVE. To reduce computational times, the modeling approach applies input reduction and acceleration techniques. The hydraulic forcing is schematized (morphological tide, waves, and discharges) while maintaining the seasonal character of the input. A variable morphological acceleration factor (MF), depending on the wave condition is applied. The variable MF allows us to employ low values during strong-episodic conditions and larger during more regular conditions. The approach is especially beneficial in the presence of oscillating forcings that are also enhanced by the MF.

Finally, the impact of the D21 plan on the Haringvliet mouth is assessed by studying the alterations to the hydrodynamic regime, the related net sediment transport pathways, and the observed bed level changes. The analysis of the resulting morphological evolution focuses on the variations of the intertidal and subtidal zones and the mechanisms behind them.

We showed that the tidal regime shifts again towards a long-basin regime once the D21 is implemented. The intervention also causes the emergence of new subtidal and intertidal areas, mostly within the Tidal Lake, resulting from the redistribution of the material from the main channel. The original intertidal and subtidal areas, formed by the Hinderplaat and Slikken van Voorne, are almost undisturbed. This behavior guarantees the preservation of the intertidal and subtidal ecosystems. The results also show that despite the initial dredging activity necessary for the D21 plan implementation, which decreases the extent of shallow areas, the emergence of intertidal and subtidal features balances the negative effect as long as no further dredging is performed. The TL shows a net sediment export of material at both control cross-sections (the Haringvliet Dam and the new TL inlet). The findings of the morphological development agree with the known morphology and processes of mixed-energy tidal inlet systems, despite the large-scale intervention.

This study provided the opportunity to evaluate the emergence of typical tidal features in a highly disturbed system, where the tidal inlet is shifted further offshore. To achieve an accurate forecast, anthropogenic forcing signals also had to be considered and extrapolated to long-term morphodynamic simulations. The forecasting of large-scale anthropogenic interventions in sensible systems, such as tidal estuaries, is performed successfully by adapting an existing model. The development of this type of study will be increasingly relevant in the future for the evaluation of measures against SLR during conceptual project stages.

Samenvatting

In de laatste jaren was er toenemende behoefte aan oplossingen voor de bedreigingen die zeespiegelstijging en klimaatverandering voor kustsystemen vormen, vooral in laaggelegen gebieden zoals de Nederlandse zuidwestkust. Tegelijkertijd is het bewustzijn van de impact die menselijke activiteiten op natuurlijke omgevingen hebben enorm toegenomen. Geïntegreerde en duurzame oplossingen zijn nodig.

In het plan Delta21 wordt een integraal plan voorgesteld voor hoogwaterbescherming, energieopslag en natuurlijk ecosysteemherstel voor Nederland, specifiek voor het Haringvliet-estuarium. Deze groot-schalige ingreep zal tot grote verstoringen in het systeem leiden. Ondanks het veerkrachtige karakter van getijdenbekkensystemen (parencite Wang2009, de evaluatie van de effecten van de interventie in termen van de initiële respons en de variaties in de mechanismen die morfologische veranderingen aansturen is verplicht. Het beoordelen van de bodemveranderingen is vooral belangrijk, gezien de waardevolle intergetijden en subgetijden ecosystemen in de Haringvlietmonding. Het behoud ervan ondanks de grote verstoringen is essentieel.

De evaluatie van de Haringvlietmonding-respons is uitgevoerd met behulp van een lange termijn morfodynamische 2DH-computersimulatie om de respons van het systeem te voorspellen. De modellen die voor de simulatie zijn geïmplementeerd zijn de Delft3D-FLOW en Delft3D-WAVE. Bij de modelbenadering zijn inputreductie en versnellings technieken toegepast om de rekentijden te verkorten. De hydraulische krachten zijn schematisch weergegeven (morfologisch getij, golven en afvoeren) met behoud van het seizoenskarakter van de input. Een variabele morfologische versnellingsfactor (MF) is toegepast afhankelijk van de golfconditie. De variabele MF stelt ons in staat om lage waarden te gebruiken tijdens extreme condities en hogere waarden tijdens meer regelmatige condities. De aanpak is vooral gunstig in de aanwezigheid van oscillerende krachten die ook door de MF versterkt worden.

Ten slotte, de impact van het D21-plan op de Haringvlietmonding is beoordeeld door de veranderingen in het hydrodynamische regime, de bijbehorende netto sedimenttransportroutes en de waargenomen bodemveranderingen te bestuderen. De analyse van de resulterende morfologische evolutie was gericht op de variaties van de intergetijden- en subgetijdengebieden en de mechanismen erachter.

We hebben laten zien dat het getijdenregime weer naar een lang-bassinregime verschuift zodra de D21 is geïmplementeerd. De ingreep veroorzaakt ook het ontstaan van nieuwe subgetijden- en intergetijdengebieden, meestal binnen het Getijdenmeer, als gevolg van de herverdeling van het materiaal uit de hoofdgeul. De oorspronkelijke intergetijden- en subgetijdengebieden, gevormd door de Hinderplaat en Slikken van Voorne, zijn nagenoeg ongestoord. Dit gedrag garandeert het behoud van de intergetijden en subgetijden ecosystemen. De resultaten laten ook zien dat ondanks de initiële baggeractiviteit die nodig is voor de uitvoering van het D21-plan, waardoor de omvang van ondiepe gebieden afneemt, de opkomst van intergetijden- en subgetijdenkenmerken het negatieve effect compenseert zolang er niet verder wordt gebaggerd. Het Getijdenmeer laat een netto sedimentexport van materiaal zien bij beide controledoorsneden (de Haringvlietdam en de nieuwe Getijdenmeer-inlaat). De bevindingen van de morfologische ontwikkeling komen overeen met de bekende morfologie en processen van getijdeninlaatsystemen met gemengde energie, ondanks de grootschalige interventie.

Deze studie bood de mogelijkheid om het ontstaan van typische getijdenkenmerken te evalueren in een sterk verstoord systeem, waarbij de getijdeninlaat verder uit de kust wordt verschoven. Om een nauwkeurige voorspelling te krijgen, moesten ook antropogene krachtsignalen worden overwogen en geëxtrapoleerd naar morfodynamische simulaties op lange termijn. Het voorspellen van grootschalige antropogene interventies in gevoelige systemen, zoals getijdenestuaria, is met succes uitgevoerd door een bestaand model aan te passen. De ontwikkeling van dit type onderzoek zal in de toekomst steeds relevanter worden voor de evaluatie van maatregelen tegen zeespiegelstijging tijdens conceptuele projectfasen.

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1

Introduction

This chapter aims to guide the reader into the context of the topics this research treats. Section 1.1 and Section 1.2 provides a general background of the global situation that motivated this research. Then, Section 1.3 and Section 1.4 introduces the study area. Section 1.5 explains the characteristics and objectives of the proposed plan (Delta21) to face climate change challenges. Finally, Section 1.6 and Section 1.7 state the problem and the research questions for this study.

1.1. Background

In the last years, there is an increasing awareness of the impacts that human activities have on natural environments. Infrastructure projects nowadays also aim for a lower footprint, sustainability, and even the improvement of natural ecosystems. The perfect example is the "Building with Nature" initiative in hydraulic engineering projects, which uses the forces of nature to produce value for the environment, economy, and society (Ecoshape 2020).

Worldwide, concern regarding climate change has led to several studies that assess its magnitude, the consequences for the planet, and the human contribution. The Intergovernmental Panel on Climate Change (IPCC) reports in their latest edition (2014) the observed changes and the predictable future ones (IPCC Panel 2014). Coastal systems and low lying areas, like The Netherlands Delta system, are most vulnerable.

Lavooij et al. (2019) have initiated an integrated solution: the Delta21 plan in the Haringvliet mouth; a land reclamation that incorporates flood safety contributing to regulate water levels at Dordrecht (no higher than NAP +3.0 m once every 10,000 years), storage for renewable energies, and natural ecosystems restoration in the Haringvliet.

1.2. Renewable energies and Sea Level Rise

One of the main concerns nowadays is global warming and the associated sea-level rise (SLR). The reported mean SLR for the period 1901-2010 is 0.19 m, with a mean rate between 1993 and 2010 of 3.2 mm/year. Based on this rate, the projections for future SLR show levels between 0.45 and 0.82 m for 2100, at probably higher rates. Coastal systems and low areas face one of the highest risks, as they are prone to submergence, flooding, and erosion due to sea transgression. Local adaptation capacity is essential but may reach a limit for many systems around the world, under the 1 m SLR (IPCC Panel 2014).

In countries like the Netherlands, large low lying areas forming estuaries and wetlands, i.e., the SW delta area and the Dutch Wadden Sea, represent rich natural and economic resources. In the case of the North Sea, sea-level fluctuations are related to variations in the wind and might be much larger than the global mean (Tank et al. 2015). The KNMI predicts, specifically for the Dutch case, sea-level rise between 0.5 and 1.0 m, for the next 80 years. KNMI's assessment of climate change scenarios also reports that the main impacts for the Netherlands will be an increased SLR, a small increase in storm surges, and increasing peak discharges of the Rhine, Meuse, and smaller rivers. The situation threatens the Dutch Delta and flood defenses in the whole Dutch coastal system.

One of the global commitments to counteract global warming is the zero-emissions goal by 2050 to reduce temperature increase below 2°C (Paris Agreement) (European Commission 2020). Presently, there is a great interest in developing technologies and strategies for the exploitation of renewable energies (e.g., solar, wind, and more recently, ocean energies) to achieve the goal.

Ocean energies refer to the energy harvested from the oceans, namely wave energy, tidal energy, salinity, or temperature gradient. A recent proposal is using pumping power plants as a source for hydro-power. The series of dams built as part of the Delta Works in the SW Dutch Delta provides an excellent opportunity for this kind of energy generation. A project is already under development at the Grevelingen, where an opening in the Brouwersdam will let a returned tidal motion into the estuary improving water quality and natural value. At the same time, it allows installing a tidal power station to generate sustainable energy with the ebb and flood currents (*Getij Grevelingen* 2020).

1.3. The Voordelta

One of the most vulnerable areas in the Netherlands to climate change is the estuaries in the SW of the country, the Voordelta. The Voordelta is a system of ebb-tidal deltas from the Rhine, the Meuse, and the Scheldt river estuaries that extend c.10 km offshore and c.90 km along the coastline with a total area of 1,155 km² (Elias et al. 2016). The estuaries from south to north are the Western Scheldt, Eastern Scheldt, the Grevelingen, the Haringvliet, and the Brielse Maas. The ETD's extend from Zeebrugge in Belgium to Hoek van Holland in the north. An overview of this area and its location in the Netherlands is shown in *Figure 1.1*. The estuaries were closed as part of the Delta Works after the major flood event in 1953 that caused almost 1800 casualties. *Figure 1.1* shows the locations of the Delta Works in red lines.

The Haringvliet dam is a sluice system dam completed in 1971. The sluice system, composed of a series of 17 sluices of 56.5 m each (a cross-section of approximately 1 km wide), allows control over the upstream river water levels (Van der Spek et al. 2015) and a maximum discharge capacity of 25,000 m³/s (Colina Alonso 2018). The discharge into the sea only flowed during low water periods of the tidal cycle, becoming a freshwater reservoir. The construction of the Grevelingen Dam to the south started in 1965 and was completed in 1971. This dam is completely closed with a siphon system that allows the circulation of saltwater into the system. This estuary became a saltwater lake (Z. B. Wang et al. 2009).

These enormous interventions triggered morphological changes in the Voordelta that can still be observed today. Even though the construction of these series of dams, and others further inland, produced the separation of the estuaries, the ebb-tidal deltas are bounded at their seaward end. Elias et al. (2016) makes the first integral analysis of the morphological evolution for the entire Voordelta. In this research, we assume that the evolution of the Haringvliet will also be linked to the other ETD by sediment budgets in the delta and the long-shore transport from south to north.

At present, sea-level rise threatens the flood defenses previously described and the Voordelta. During the 1965-2010 period, a rise in the order of 0.10-0.15 m was registered, the Voordelta's natural response to counteract it was not observed in its morphological changes (Elias et al. 2016).

1.4. The Haringvliet

With the closure works, the SW Dutch delta was divided into two subsystems: the northern basin consists of the Haringvliet and the Nieuwe Waterweg and the Eastern Scheldt southern basin (Van der Spek et al. 2015). The northern basin has the contributions of the rivers Rhine and Meuse. The Haringvliet estuary is formed by the water bodies of the Nieuwe Waterweg, the Haringvliet (80 km²), Hollandsch Diep (38 km²), and marshland Brabantsche Biesbosch (10 km²), with a total length from the dam to Brabantsche Biesbosch of 64 km. Before the damming, it was a dynamic brackish tidal inlet (Van Wijngaarden et al. 2002).

After the damming, the river discharges flow into the sea during low-water of the tidal cycle, and a semi-stagnant freshwater lake formed behind the dam (Van der Spek et al. 2015). The limited remaining basin is bounded to the north by the dikes built for the land reclamation of the Slufter and the two Maasvlakte; to the east, the Brielse Gat and Slikken van Voorne are found; to the southeast, the basin is limited by the Haringvliet Dam, and to the southwest, the wide beaches of Goeree are located. The Haringvliet mouth and its ebb-tidal delta with its principal features are shown in Figure 1.2.

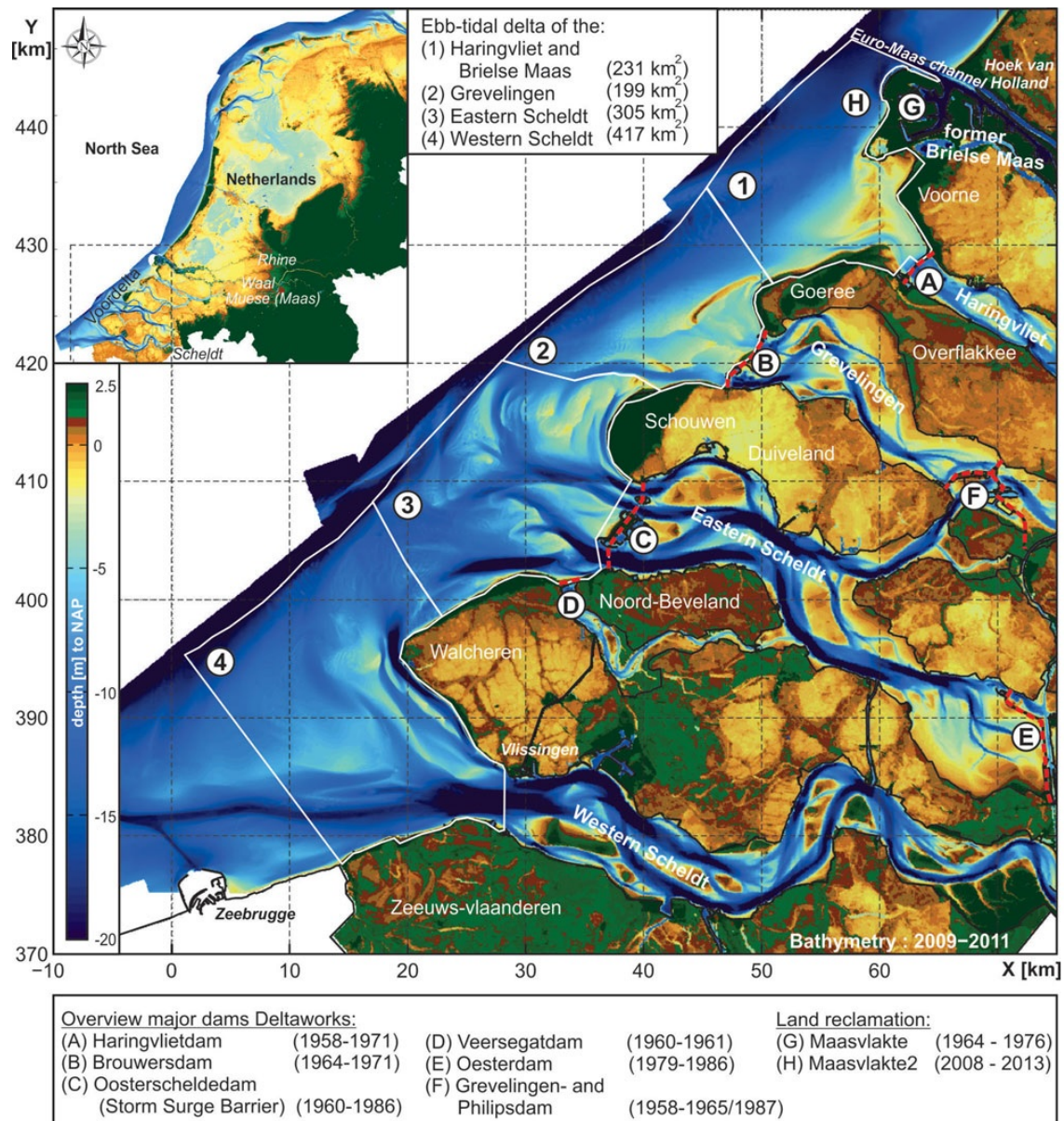


Figure 1.1: **Location and overview of the Voordelta estuaries and their ebb-tidal deltas.** The ebb-tidal delta's areas are delimited by white polygons, and the major dams constructed during the Delta Works are marked in red. Depths are referred to NAP (Normaal Amsterdams Peil), Dutch ordnance datum. The Haringvliet mouth and its ebb-tidal delta are located at the north-east of the Voordelta, and the location of the Haringvliet Dam is marked with A (Elias et al. 2016).

The damming of the estuary resulted in the reduction of the estuary's tidal prism, decreasing tidal current velocities, and the sediment supplied by them. The shore-normal tidal influence decreased while shore-parallel tidal currents became more important. The area developed into a short-basin with velocities offshore and inside the basin almost in phase. The basin shows a circulating pattern, the currents enter through the Slikgat channel (2) at the south and leave through the Hindergat (5) at the north during the flood period, and inversely during the ebb period (Tönis et al. 2002). There was a

relative increase of wave-driven sand transport in the net landward direction, resulting in the erosion of the ebb-tidal delta front and continuous landward migration of the delta (Elias et al. 2016).

In recent years, many land reclamation projects have taken place north of the Haringvliet as a result of the Port of Rotterdam's expansion (i.e., Maasvlakte 1 (MV1), Slufter and Maasvlakte 2 (MV2)). These land reclamations have progressively sheltered the Haringvliet's ebb-tidal delta (ETD) from north-easterly waves and blocked northward long-shore sediment transport (Elias et al. 2016). As a consequence, the sheltered area behind the reclamations depicted in Figure 1.2 (7) has been silting ever since; this is the Slikken van Voorne. The current study is developed within the Delta21 (D21) plan, a large scale intervention, still in the conceptual phase of the project at the moment of this research. The D21 plan is explained in the following section.

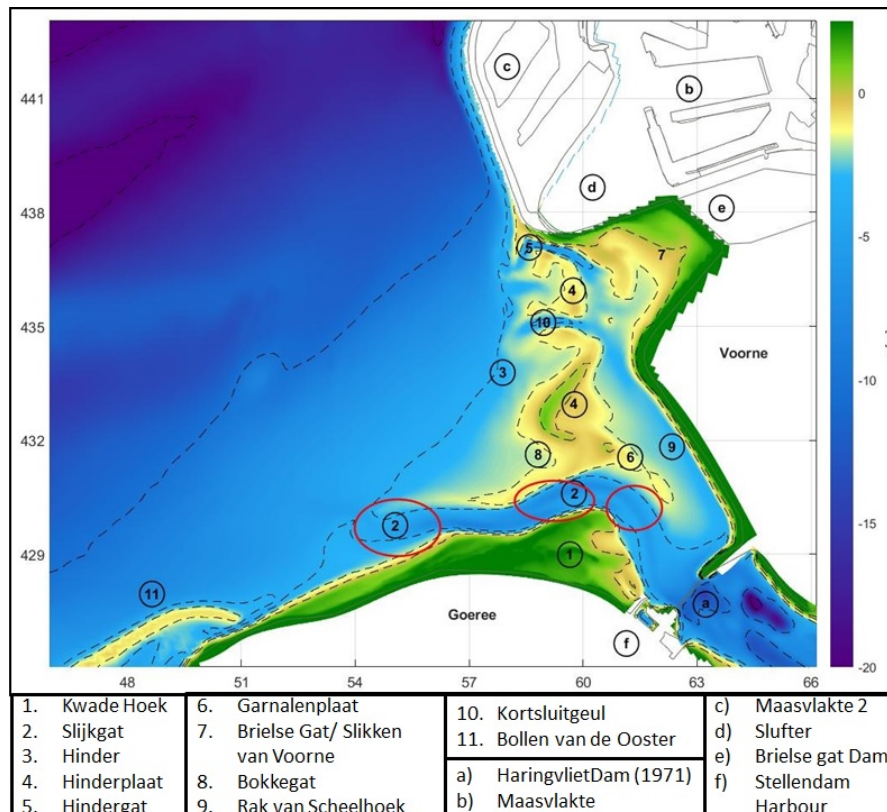


Figure 1.2: **Overview of the Haringvliet mouth and its principal shoals, channels, and structures, 2018 bathymetry data.** The shoals and channels are identified with numbers, and interventions are identified with letters. Currently, the main tidal channel is the Slijkgat to the south (2), and the principal (mega) shoal is the Hinderplaat (4). At this stage, the Garnalenplaat (6) and the Hinderplaat are practically merged. Tidal currents also flow at the north through the Hidergat (3), and a more recent channel has developed, the Kortsluitgeul (10). It cuts through the Hinderplaat, dividing it into a northern small shoal and a bigger one to the south. The red circles indicate areas where the Slijkgat channel has to be dredged continuously.

1.5. Delta21 Plan

Delta21 is an integrated proposal that aims to face future challenges for The Netherlands in three different areas: (1) flood protection, (2) energy storage, and (3) improvement of natural and environmental values. Located at the Haringvliet mouth, Figure 1.3 shows the plan view of the Delta21 project with its main components: the Valmeer or Energy Storage Lake (ESL), the Getijmeer or Tidal Lake (TL), a siphon between the ESL and TL, and a pumping-power station (PPS) between the TL and the North Sea (design and alternatives of the PPS are available in Ruiz Ansorena (2020) and Paasman (2020)).

The main strengths of the project are a new and more flexible flood defense that considers higher peak discharges, updated SLR rates, and stronger storm surges. The Delta21 plan would allow the recovery

of the tidal motion in the estuary by a permanent opening of the Haringvliet Dam. A new barrier will be built and will only close during extreme storms or extreme river discharges (see (d) in [Figure 1.3](#)). It will restore natural ecosystems, fish migration, and will improve water quality in the estuary.

In the presence of the worst-case scenario of SLR (0.85 m in 2100) during a storm event, the Delta21 plan must guarantee the water levels upstream in the Haringvliet to be low (water levels at Dordrecht should not be higher than NAP +2.5 m). Under this scenario, other flood defenses, such as the Maeslantkering, must also be considered. With increasing SLR, the Maeslantkering probability of failure increases as the frequency of closing also increments. The goal with Delta21 is to keep the closing frequency to once every 10 years, despite SLR and storm surges. The following explanation of the system's functioning is retrieved from the most recent version of the Delta21 plan (Lavooij et al. 2019).

Energy Storage Lake

The ESL will allow the storage of a water volume up to 350 Mm³, available to be pumped in and out every 12 hours. This concept contributes to solving the existing imbalance in renewable energies. The current policy combines shortages and overcapacity with shutdowns. During the day, most of the green energy is produced (e.g. solar), but at periods of lower demand, this results in an overcapacity. Inversely, during early morning or evening, the demand is the highest, and less energy production is available causing shortages. To guarantee the supply and the system's balance, curtailment, mostly in solar and wind energy, needs to be the practice: during excess generation green-energies are shut-down to avoid congestion (Bird et al. 2014). To ensure continuity is then necessary to maintain the production of conventional (mostly fossil) energy sources (Lavooij et al. 2017).

The ESL dam-like structure, dredged with a bottom at NAP - 22.5 m, and its profile will be constructed mostly by sandy dunes ideally from the dredged material; in a building-with-nature philosophy. This concept also gives adaptation capacity against SLR. During storm surge events, or peak river discharges a maximum discharge of 10,000 m³/s must be discharged into the sea through the ESL. A siphon between the ESL and the TL (location (c1) in [Figure 1.3](#)) will conduct the excess water volume (in the TL) to the ESL, and subsequently, the PPS at the ESL will pump it into the North Sea (c2); both must be able to discharge the mentioned volume.

The minimum head for the pumps is 5 m, the maximum level at the ESL is NAP -5 m. With a bottom at NAP -22.5 m, the maximum working head is 17.5 m. The lake must be able to store energy in 12 hour periods, being able to produce energy during high demand (morning and evening), and store during low demand (day). The operation of the pumping station will produce discharges between the ESL and the North Sea in an approximately 24-hour cycle, taking roughly 12 hours to empty the lake while consuming energy and 12 hours to fill the lake again while producing energy. The maximum discharge capacity for both operations is 10,000 m³/s.

Tidal Lake

The Tidal Lake (TL) (b) is delimited by the ESL to the north-west, a dike and barrier to the west (d) , and the current coast and Hringvliet Dam to the south-east. Through the opening, the tide will be allowed to flow into the TL and further upstream into the estuary through the open sluices at the Haringvliet Dam.

Only during peak flood events, the siphon will allow discharges of 10,000 m³/s or larger to flow into the ESL, and the barrier will be closed. For lower discharges, it is assumed that the normal opening is enough to discharge the river volume into the sea. Also, during storm surge events that threaten the rise of water levels inland, will the barrier between the TL and the sea be closed. This artificially formed lake will work as a buffer area to control water levels between the river, the ESL, and the sea.

Haringvliet Sluices

One of the main concerns of the salt wedge returning into the Harinvliet estuary is the impact on freshwater intakes. To avoid compromising the freshwater supply to the NW Brabant and South Holland

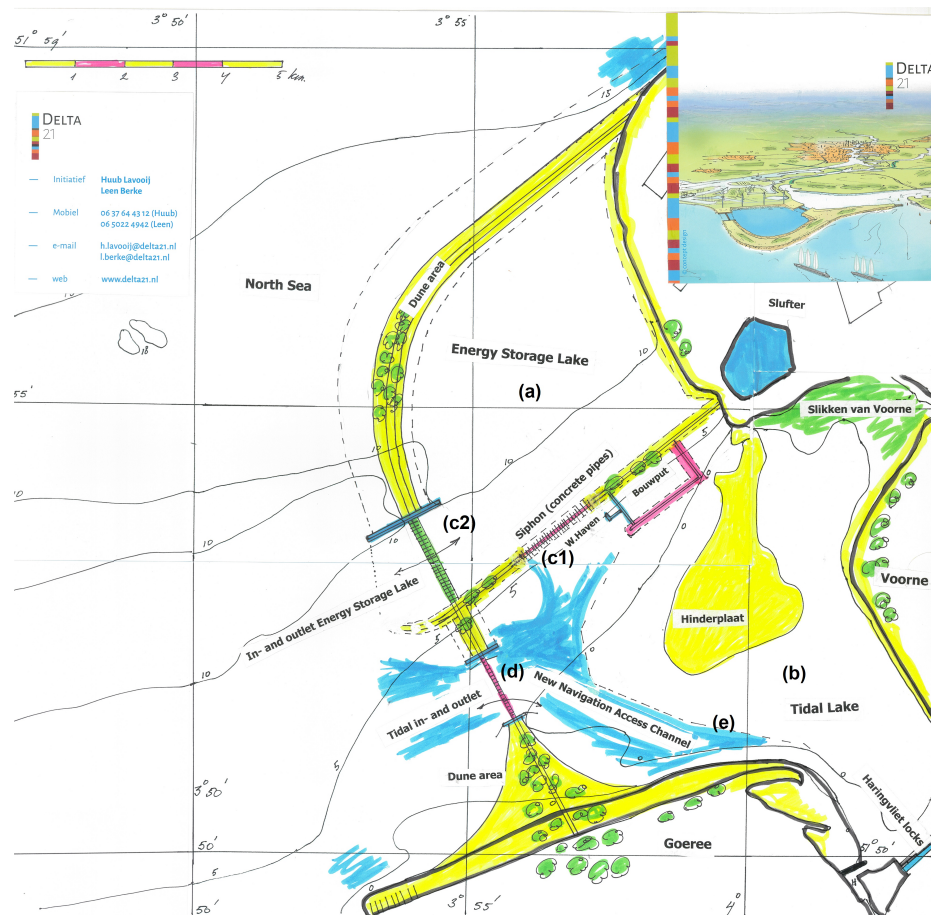


Figure 1.3: **Conceptual plan view of the Delta21 intervention.** Main components are indicated by letters: (a) Energy Storage Lake (ESL) located to the north of the complex and west from the Maasvlakte 2; (b) Tidal Lake (TL) located at the Haringvliet mouth and south from the MV2, and ESL; (c1) siphon between ESL and TL for extreme river discharges; (c2) pump storage station for filling and emptying of the ESL to/from the North Sea; (d) new Storm Surge Barrier between the TL and the North Sea; (e) enlarged and re-orientated Slikgat for tidal currents to flow through it, the only opening to the sea.

islands, new freshwater intakes are proposed further upstream, at Strijensas and Roode Vaart. When the Rhine river discharges at Lobith are lower than $1,000 \text{ m}^3/\text{s}$, a temporal partial closure of the sluices is proposed (less than 10 days/year). With Rhine river discharges greater than $1,000 \text{ m}^3/\text{s}$, the Haringvliet sluices will stay fully open.

Environmental impacts

The layout of the ESL and TL are covering the entire Haringvliet mouth and its ebb-tidal delta within the Natura2000 area (see Figure 1.3 and Figure 1.4). A recent study by (Van Dam et al. 2020) assesses the impacts of the Delta21 project to Natura2000. The main affected habitats in the Hinderplaat and Slikken van Voorne along with the species dependant on them, are listed in Table 1.1.

The report also mentions that according to Natura2000 legislation, any loss of habitat or disruption of species must be prevented and can be compensated only by providing the same area and type of lost habitat in another place. Van Dam et al. (2020) report a loss of **H140** habitats, intertidal silt- and sandbanks of high and low dynamics, of 90 ha and 50 ha at the Hinderplaat and Slikken van Voorne respectively.

This is how the idea of an artificially nourished sandbank at the seaside of the TL is considered. Aiming to compensate for the probable loss of natural intertidal and subtidal habitats that the Haringvliet's ETD offer. An area designated for the creation of new shallows that resemble the present habitat could be a compensation.

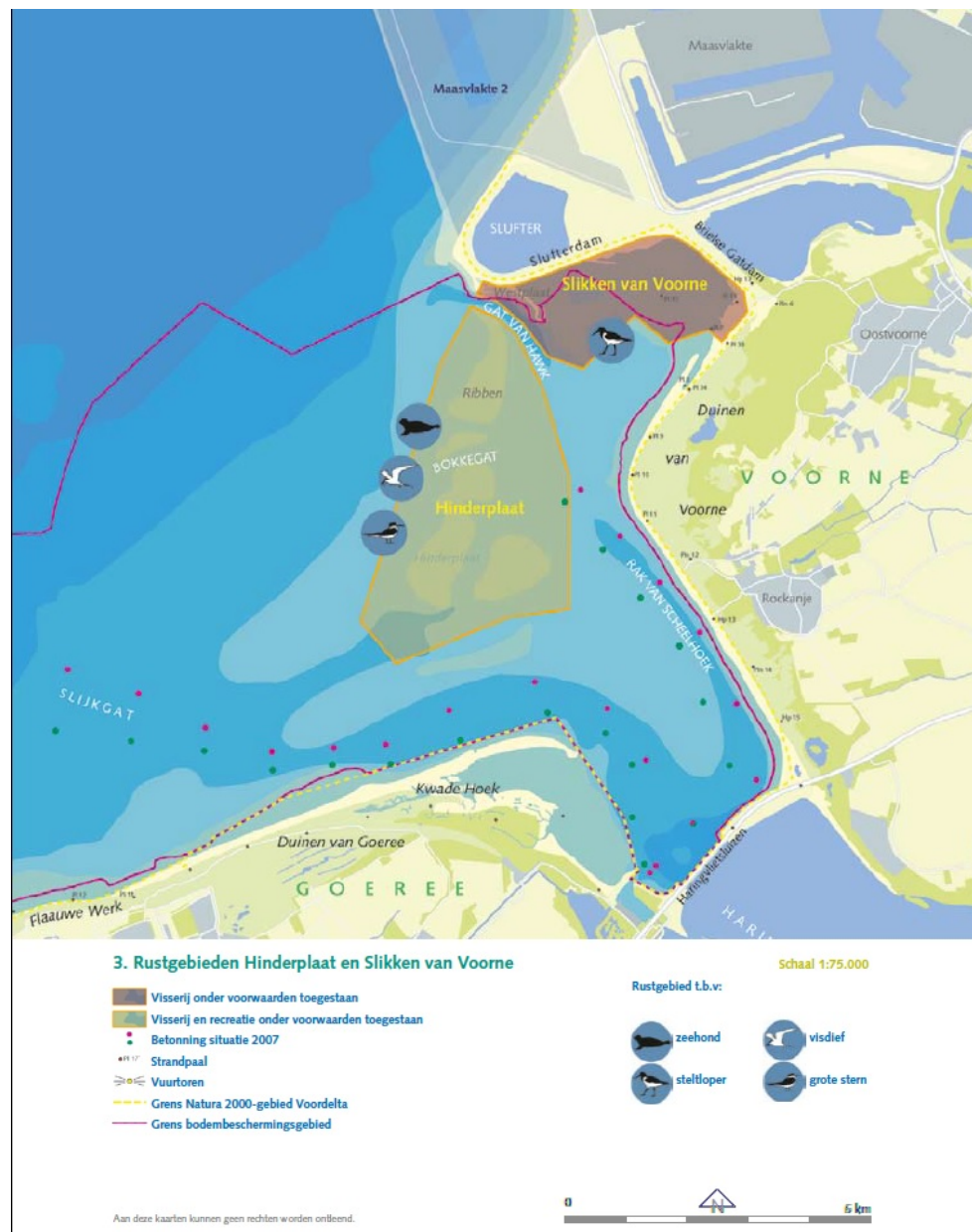


Figure 1.4: **Overview of the Natura2000 area in the Haringvliet mouth.** The indicated areas at the Hinderplaat and Slikken van Voorne are home for resting activities of seals, terns, stilts and ducks (Rijkswaterstaat 2008). The D21 plan, specifically the TL, lies over those areas.

Table 1.1: **Affected habitats and related species in the Hinderplaat and Slikken van Voorne.** The Delta21 intervention in Natura2000 area impacts habitats and specific species (Retrieved and modified from Van Dam et al. 2020 and Rijkswaterstaat 2008). The main habitats influenced are those of intertidal and permanently flooded, silt and sandbanks.

Area	Hinderplaat (ca. 1250 ha)	Slikken van Voorne (ca. 550 ha)
Habitats	H110 Permanently flooded sandbanks H140B Intertidal silt and sandbanks (high dynamic).	H110 Permanently flooded sandbanks H140A Intertidal silt and sandbanks (low dynamic). H1310 Salty pioneer vegetation H1320 Spartina swards H1330 Atlantic salt meadows H2110 Embryonic dunes
Species	H1365 Common seal A191 Large tern A193 Common tern	Diverse type of Stilts Ducks

1.6. Problem Statement

There is an increasing need for integrated solutions in coastal interventions to counteract SLR and climate change negative impacts, especially in low-lying areas and erosive coasts. Systems like the SW Dutch Delta are rich natural tidal ecosystems. In estuaries and wetlands, the intertidal and subtidal zones provide an excellent source of nourishment and rest for diverse species. Tidal inlet systems are resilient systems that, despite disturbances, in a decadal time-scale, will tend to an equilibrium state (Escoffier 1940; Davis et al. 1984; Stive et al. 2003; Kragtwijk et al. 2004; Z. B. Wang et al. 2009; Z. B. Wang et al. 2012). At the scale of the morphological elements within the tidal basin, i.e., ebb-tidal delta (ETD), flood-tidal delta (FTD), intertidal flats, tidal channels; the behavior is more dynamic.

If tidal inlet systems are intervened, the long-term consequences at the scale of their main components, as well as at the scale of individual basin elements, need to be evaluated. It is even more important for interventions on the scale of the Delta21, which implies large changes in the system's hydrodynamics and the construction of new structures in the basin. The need for forecasts of the tidal inlet systems' response to interventions of this magnitude through morphological modeling arises. It is especially important to determine the evolution of valuable ecosystems like the intertidal and subtidal zones after (large-scale) interventions. Under a compensation scheme, new shoals can be created if others are degraded. The natural positive feedback processes and high dynamics in the system at the scale of shoals could be used to promote the growth of such features (Ridderinkhof et al. 2016; Harrison et al. 2017; Elias et al. 2019). The question arises if such cascade-up behavior can be anticipated and applied to maintain and/or enhance the growth of shoals in the intertidal and subtidal zones around an emerging ETD in a completely disturbed system.

1.7. Research Questions

The objective of this study is to evaluate the stability and evolution of the intertidal and subtidal areas in the Haringvliet mouth as a consequence of the large-scale Delta21 intervention.

The Delta21 intervention will generate large scale morphological changes in the Haringvliet mouth. It is essential to assess what will the overall behavior of the system be with the new configuration, and how it differs from the present situation. No morphological studies, specifically at the new inlet, have been conducted so far.

Regarding the present situation, studies usually evaluate the evolution of the Haringvliet without considering the MV2 influence, even though it has produced large changes in the morphology, the bed composition, and the dynamics of the area (De Vries 2007; W. De Winter 2014; Colina Alonso 2018).

Once a general understanding of the behavior of the new system is acquired, it is necessary to evaluate the stability of the intertidal and subtidal areas under such evolution. Compensation in the form of intertidal and subtidal shoals might be necessary and the best location and shape to create them also needs to be studied. It was detected from the literature review that shoals' growth and interactions at the smallest scale could cascade-up to generate changes at bigger scales. These mechanisms are still not widely understood. An opportunity to further study processes at the shoal scales arises.

Therefore, the general research question stands:

What will the morphological behavior and evolution of the intertidal and subtidal areas in the new system (with D21) be?

To answer the main research question, a top-down methodology is employed, and in the same sense, the following sub-questions are formulated to help answer it. They are divided into two categories related to the two main objectives of the study:

Objective 1 Investigate the prevailing processes driving morphological changes in the present system (with MV2) and once the D21 plan is implemented.

The related research questions are:

1. How has the hydrodynamics of the Haringvliet mouth evolved since the Maasvlakte 2 was built?
2. How have the morphological features of the Haringvliet mouth evolved since the MV2 was built?
3. What will the overall expected behavior of the Haringvliet mouth be in the presence of Delta21 and how it affects the water motion?
4. What will the dominant sediment transport patterns be and its related effect on the morphology?

Objective 2 Evaluate the stability of the intertidal and subtidal zones after the D21 intervention and assess the possibility of the creation of a sandbank as compensation.

The research questions are:

5. How the intertidal and subtidal zone at the Haringvliet mouth will behave under the D21 influence?
6. How will an artificially nourished sandbank located at the seaward side of the Tidal Lake behave under the new conditions?
7. Will the configuration of the nourished sandbank help trigger its own growth by taking advantage of bypassing mechanisms?

1.8. Research approach

According to the demands of the present research and its goals, the overview of the proposed approach is shown in the flow chart of [Figure 1.5](#). The present section refers to the methodology followed for the entire study. The last stage, the modelling study is further elaborated in Chapter 4 Section 4.2.

1.8.1. Literature Review

The first stage of the project is focused on a literature review. This phase of the project will help become familiar with the fundamentals and state of the art in tidal inlet systems. During this stage, the goal is to get acquainted with the recent developments in morphological dynamic equilibrium and sediment transport mechanisms in tidal inlets, as well as with the fundamentals of the intertidal and subtidal zones. These concepts are the reference points to assess the stability of the original and potentially new shoals.

The literature study is meant to gather general information of the study site, its evolution due to the known interventions and the governing conditions, by examining previous research studies of the Haringvliet. During this stage, it is also important to determine the available data necessary for later stages of the study. The aim is to gather relevant information that will help understand the evolution of the system and determine boundary conditions. This stage also helps to identify the best approach to evaluate the stability of intertidal and subtidal areas and the research gap where this study can converge.

1.8.2. Site characterization

In the second stage of the project, the goal is to understand the specific study site. The gathered information is analyzed to identify and select relevant processes and features that will help describe and predict future evolution under Delta21 influence. The selected criteria will be classified in those related to the general theory of morphology and dynamic equilibrium in tidal inlets and those related to the study area (hydrodynamic and morphodynamic conditions). The derived considerations will serve as the basis for the following stages: the derivation of hypotheses for the situation presented by the case study and the modeling study to prove the hypothesized behavior.

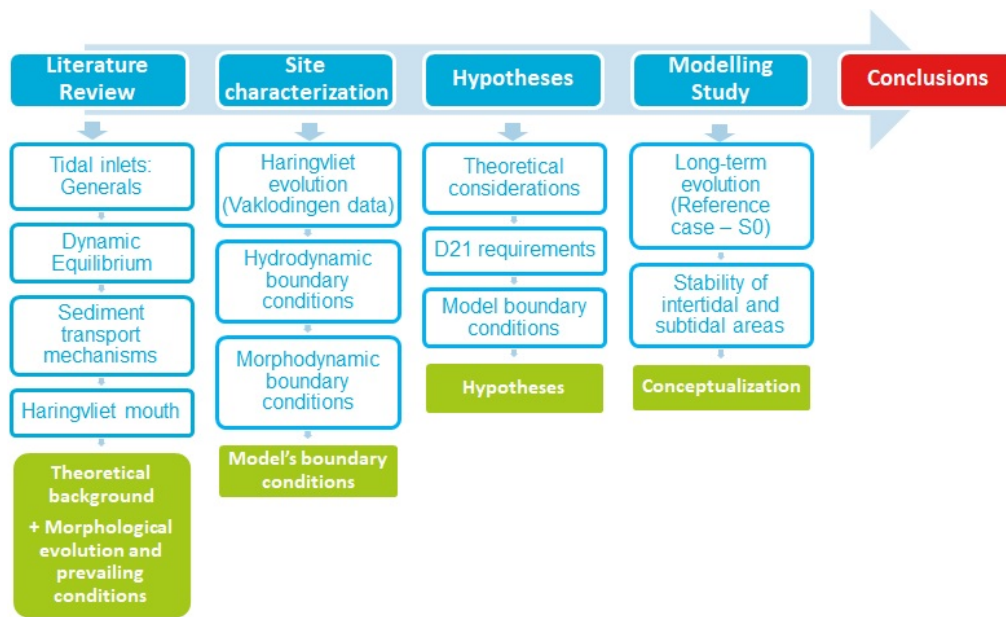


Figure 1.5: **Flow chart showing the proposed methodology for the project.** The Literature review and Site Characterization stages are preliminary and involve a thorough review of existing literature and state of the art regarding ETD and the Haringvliet mouth. The Hypotheses stage aims to predict and plan the following stage: the Modelling Study, which will aid in predicting the behavior of intertidal/subtidal areas under the D21 intervention. The green panels indicate the outcome of each stage in the research.

1.8.3. Hypotheses

The third stage of the project is focused on deriving a hypothetical prediction of what is expected to occur with the D21 intervention in the Haringvliet mouth. The hypothesis would be based on the criteria derived in the previous stage, considering the main processes in the system, the theoretical concepts, and the specific conditions at the Haringvliet. The requirements from the D21 operation are also considered. The goal of the hypothetical development is to generate an expected scenario that will help identify main drivers in the evolution of the new system. The hypotheses generated can later be compared to the model's results to finally provide an explanation of the expected behavior in the new system.

1.8.4. Modelling Approach

The predictive character of the study generates the need to implement a numerical model to assess the effects on the Haringvliet's hydrodynamics and morphology. The objective is to evaluate the consequences of a specific project that involves under the combined forces of tides, waves, river discharge, and pumping operations. A process-based model is necessary to observe morphological evolution and evaluate the mechanisms producing the bed level changes (Herrling et al. 2018).

Previous studies have implemented similar models to evaluate the evolution of specific features in the Haringvliet mouth before (e.g. De Vries 2007, R. De Winter 2008, Colina Alonso 2018). A process-based Delft3D model is chosen to perform the hydrodynamic and morphodynamic simulations. Chapter 4 elaborates on the modeling approach applied to implement all the boundary conditions in the system (Section 4.2).

Based on the model results, the hypotheses will be assessed and conceptualization of the overall behavior under the new hydrodynamic regime driving sediment transports and bed level changes will be elaborated to schematize the D21 impacts and the evolution of a tidal inlet system under a large-scale intervention.

2

Theoretical Background

The present chapter is intended to provide the theoretical background for this research based on the literature study developed. Firstly, Section 2.1 elaborates on the generals of tidal environments and its features. Then, Section 2.2 presents the state of the art regarding transport processes in tidal environments.

2.1. Tidal environments

In tidal environments, even though tide forces tend to dominate, it is the relative importance of wave and tide forces that determines the coastal characteristics. In the presence of low wave energy and higher tide influence (high tidal ranges), coasts develop wide low-gradient tidal flats in the intertidal zone ¹, and subtidal zone ². These systems are characterized for very fine sediment on the flats and the wetlands in the upper intertidal zone (Bosboom et al. 2015).

Tidal inlets and the related features can also be explained by the balance between the eroding force of waves and the building force of the tide (Z. B. Wang et al. 2009). This equilibrium situation has been studied widely (e.g., Van de Kreeke 1992, Z. B. Wang et al. 2012, Elias et al. 2016, De Vries 2007), and will be further addressed later on. In general, two typical morphological near-equilibrium types of basins can be distinguished in the Dutch basins, rectangular tidal lagoons characteristic of the Wadden Sea and funnel-shaped estuaries, characteristic of the Scheldt basins (Stive et al. 2003).

Tidal inlets are an interruption in coastlines, evidence of their sediment sink properties. The combined action of waves and currents lead to long-shore transport of sediment, i.e., the littoral drift; the material then is transported and deposited to the inlet, either imported into the basin or exported seaward (De Swart et al. 2009). Periodical release of material through the inlet, in benefit of adjacent beaches, can be observed in every sedimentary coast, thus also controlling coastline evolution (Kana et al. 1999).

Typical geometry of tidal basins consists of two macro-scale morphological entities, the ebb-tidal delta in the seaward side and a flood-tidal delta in the back-barrier area, both formed by channels and adjacent shoals, counterparts in the same system and ultimately connected by a main inlet channel (Z. B. Wang et al. 2012). When the width scale of the inlet channel exceeds a specific tidal length scale, instability mechanisms are triggered, causing the development of alternating bars and channels (Stive et al. 2003). The morphological features in Figure 2.1 are the main ebb-channel, marginal flood channels, channel margin linear bars, swash platforms, and bars, a terminal lobe, and flood- and ebb-tidal deltas (FTD and ETD). The characteristic branching channel structure guarantees the water supply during flood and drainage during ebb. The model in Figure 2.1 was developed by Boothroyd (1985).

The elements of a tidal inlet shape an extremely dynamic system, each with its characteristic behavior and at their own scale. Many studies (Sha et al. 1993; Kana et al. 1999; Masselink et al. 2006; Elias et al. 2016; Ridderinkhof et al. 2016; Elias et al. 2019) have focused on describing the behavior at scales smaller than the macro-entities, and have tried to understand the driving mechanisms dictating their morphological evolution, characteristic geometries and dynamic behavior.

¹The intertidal zone is the area exposed during low water and submerged during high water of the tidal cycle.

²The subtidal zone is an area only exposed during extreme low tides

The mechanisms driving morphology can be better understood as net sediment transports and by-passing processes which, with sufficient transport capacity, will carry sediment in the form of bed- or suspended-load, or even as shoal migration (see Section 2.2.1).

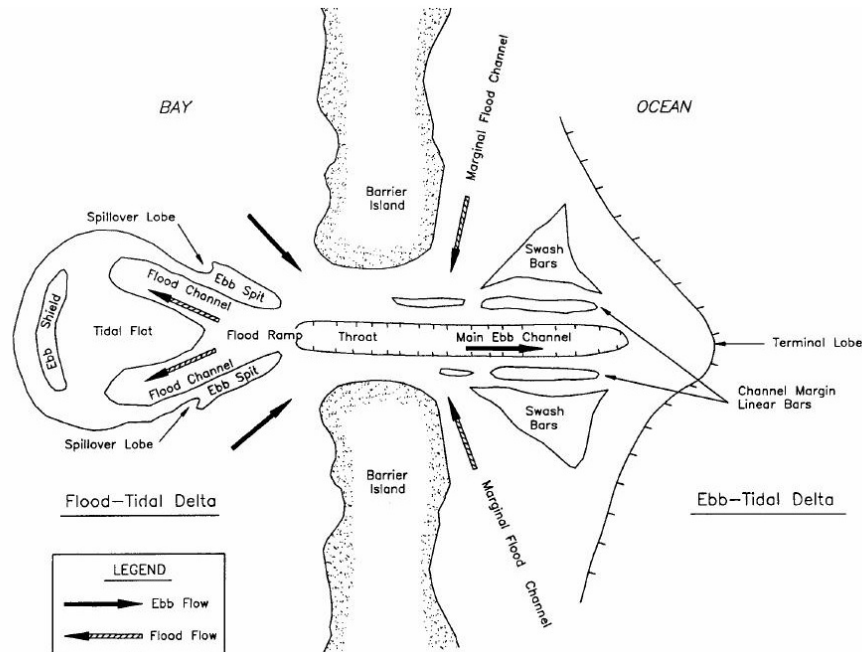


Figure 2.1: **Tidal inlet model and its morphological elements Boothroyd 1985.** A flood-tidal delta grows in the sheltered, back-barrier area and the ebb-tidal delta grows offshore as currents leave the inlet during the ebb period of the tidal cycle, forming the characteristic lobate shape. Both joined by the tidal inlet. Both macro-scale elements develop smaller features within as channels and shoals, part of the same sediment sharing system. Figure retrieved from Bosboom et al. 2015.

2.1.1. Tidal Basin Elements and Characteristics

Reference to empirical observations has been a tool to understand the development of tidal basins and coastal inlets. For example, the geometry of the basin, in combination with the tidal range, determines the tidal prism flowing through the inlet (Davis et al. 1984). Consequently, the tidal prism determines the inlet's cross-section necessary to convey the water volume (O'Brien 1969). Details of these relations is addressed in Section 2.1.4. The volume of the material stored in the ebb-tidal delta is also related to the tidal prism.

The elements of a tidal inlet system are interconnected and show a cyclic behavior (channels and shoals). However, the knowledge of the intertidal zone is still very restricted; the channel-shoal interaction is an unsolved problem (Z. B. Wang et al. 2012). The main characteristics of the elements are the following:

Tidal Inlet Areas dominated by tide-driven currents and the volumetric exchange, namely the tidal prism. The net sediment transport through the channel is influenced by the tidal asymmetry (Kana et al. 1999). A classification by (Galvin 1971) for the planform geometry of inlets establishes that the orientation/symmetry of the inlet and its ETD depends on the offset of the adjacent coast. If the sediment supply from updrift is sufficient, an updrift offset might be developed, the updrift coast accretes seaward of the downcoast strandline, especially if the ETD's are small. In Kana et al. (1999), also a process-response model is given, treating the symmetry of the plan characteristics. The inlet could be in an unstable position due to spit growth (migrating), be stable with an asymmetric ETD (dominant longshore transport in one direction), or be stable and symmetric (no dominant longshore transport). More recent developments regarding ETD and inlets orientation and geometry are also developed by (Sha et al. 1993; Fitzgerald et al. 2000).

Channels Dominated by tide-driven currents, flood channels are preferred by flood currents entering

the basin through the path of least resistance while water is still flowing out through the main ebb-channel. They can be considered as the flow area lying below MSL.

Tidal flats and swash bars Its formation is mostly controlled by the exposure to wind waves during the tide-driven variable water levels (De Swart et al. 2009). The area is dominated by wave-driven currents (Kana et al. 1999) and can be defined as the area lying above MSL that serves to accommodate the tidal prism.

Understanding ebb-tidal deltas (ETD), its characteristics, and behavior, is one of the core needs in this research, and they will be treated separately.

2.1.2. Ebb tidal deltas

The concept of ebb-tidal deltas is widely covered by many researchers (Sha et al. 1993; Kana et al. 1999; Z. B. Wang et al. 2009; De Swart et al. 2009; Elias et al. 2016; Elias et al. 2019). The ETD and the tidal basin form a sediment sharing system (Z. B. Wang et al. 2009). The different patterns of ebb- and flood-directed currents cause the presence of tidal residual circulations that seaward from the inlet are ebb-directed. Under the assumption that net sand transport is the result of material being stirred up from the bottom and transported by the residual currents, at the seaward end of the outflow, a delta emerges, namely the ebb-tidal delta (ETD) (De Swart et al. 2009).

As tide-driven currents leave the tidal inlet, they transport material in the offshore direction. The flow velocity decreases seaward, losing its transport capacity, and progressively depositing material. Wave-breaking over the shallow sand deposits produce landward directed transport opposing the ebb flow and limiting the seaward extension of the ETD. The extension, size, and orientation of the ETD are determined by the relative dominance of tide and wave energy. In wave-dominated inlets, the ETD will be pushed close to the throat, and in tide-dominated systems, it will extend in the offshore direction (Elias et al. 2016).

The result of tide-wave current interactions is the characteristic lobate form shown in Figure 2.1, along with the swash bars at either side of the channel and the terminal lobe where ebb-currents and wave-generated currents ultimately encounter (Kana et al. 1999). The large volumes of sand brought by the littoral drift along the coast can be stored in the FTD and ETD, constantly exchanging sediment in and around the outer delta (Elias et al. 2019). Offshore from the ETD, long-shore sediment transport by oblique incident wave-breaking dominates.

The ETD characteristic geometry and morphological variation can be better explained by its relation with the tidal prism (Equation A.5) but, it is also determined by the prevailing wave direction (Z. B. Wang et al. 2009). A study by Vegt et al. (2009) demonstrates the formation of the ETD and its empirical relationship with the tidal prism. They also concluded that the orientation of the main channel in the outer delta depends on the phase difference between the tidal current along the coast and that through the inlet (tidal asymmetry), agreeing with Stive et al. (2003).

Additionally, recent studies regarding ebb-tidal deltas and tidal inlets have also focused on the impacts due to relative sea-level rise (RSLR). Dissanayake et al. (2012) reflects that under a scenario of low SLR (≈ 0.20 cm), tidal flats remain relatively stable over a period of 110 years, which the author defines as a tipping point for the maintenance of the flats. Although, as IPCC Panel (2014) predictions show, SLR will probably be greater than this number. Under that scenario, the study indicated that the tidal flats get drowned.

Ebb and flood channels

In the model of Figure 2.1, flood and ebb channels are shown as different paths for the flow during each tidal period. Certain instabilities might trigger the existence of alternating bars and channels. The curvature of the channels induces secondary flows due to a water level gradient in the channel's cross-section. The secondary flow promotes the build-up of the shallow inner bend. In a 2DH scheme, water level set-up and set-down patterns also induce horizontal circulations currents with a similar effect. There are two general modes for the build-up of sills at the end of flood-channels, forking

and sidetrack (see [Figure A.1](#) to [Figure A.3](#)) (Stive et al. 2003). The channel-shoal interaction is still unsolved problem and the flooding and drying of the shoal parts is still a modelling challenge (Z. B. Wang et al. 2012).

Ebb-tidal delta Geometry

Efforts to understand how the ETD evolves, relating their geometry to the prevailing conditions, have been widely made. The direction of the dominant wave energy flux will influence the geometrical orientation of the ETD and its protrusion in the seaward direction. Another factor inducing ETD asymmetric is the phase difference between the long-shore tidal wave and that at the inlet (Stive et al. 2003). If both processes act cooperatively, the asymmetry of the ETD is guaranteed. Otherwise, the geometry will depend on the relative importance of each of them (Sha et al. 1993; Stive et al. 2003). When the transport by tidal currents prevails, a nearly symmetric delta emerges since the ebb flow behaves as a free turbulent jet leaving the inlet. During the flood period, in contrast, an inflow of irrotational fluid occurs.

If the effect of wave-driven currents is also important, the main ebb channels tend to bend in the downdrift direction. Nevertheless, ETD in the Wadden Sea shows an updrift orientation. Aiming to understand the mechanisms behind these variations, Sha et al. (1993) developed a model related to the prevailing littoral drift and the interaction of the inlet and long-shore tidal currents. The model is based on observations of the ETD of the Wadden Sea and at the SW Dutch coast.

Before the Delta Works, the ETD of the SW Netherlands had characteristic main ebb-channels bifurcating updrift and downdrift in the seaward direction. Small flood channels were present at both sides and the main ETD shoals had a triangular shape pointing landward. This geometry is characteristic of systems with large tidal prisms. The interactions between the long-shore tide and that at the inlet favored the formation of the triangular-shaped shoal, namely long-shore maximum currents coincided with slack periods in the inlet (Sha et al. 1993).

Additionally, the described tidal regime is related to the reduction of the tidal range in the long-shore flood direction (to the north). When the tidal wave approaches an inlet along the coast from the left, the tidal amplitude is slightly larger at the left side than at the right. This situation promotes the development of deeper channels to the left of the ETD. This is the case for the SW coast of the Netherlands, including the Haringvliet. The model presented by Sha et al. (1993), applicable for coasts with decreasing tidal range in the flood direction is presented in [Figure 2.2](#).

The geometries shown in the figure marked as **D** and **E** correspond to ETD developed under large tidal prisms, with a dominant wave energy direction in the east-west and west-east direction, respectively. The geometry in **F** represents a geometry characteristic of systems with small tidal prisms and westerly dominant wave conditions. The geometry in E model is representative of a situation close to the case of the Haringvliet estuary before the damming whereas F could be more characteristic of the present situation (after the damming). However, as observed in [Figure 1.2](#), the main channel of the Haringvliet ETD has evolve towards the left. The better development of the ebb channels to the left in the SW Netherlands is probably related to the southward long-shore increase of the tidal range.

In an idealized numerical model, Vegt et al. (2009) analyze the the spatial asymmetry of ETD under the influence of large-scale long-shore tidal currents. The study shows that the asymmetry of the delta depends on the magnitude of cross-shore and alongshore tidal currents, their phase difference and the width of the inlet. For small phase differences the ETD is asymmetric and the orientation is towards the direction that opposes that of the alongshore tidal flow. If the phase difference is close to 90°, almost symmetric deltas are predicted. This study quantitatively confirms the findings by Sha et al. (1993).

2.1.3. Intertidal bars and subtidal bars

Other important features to be aware of when treating coastal morphology in shallow areas are intertidal and subtidal bars, as they play an important role in beach stability. During storm events, wave energy will be highly dissipated on the submerged bars, reducing the eroding power arriving at the

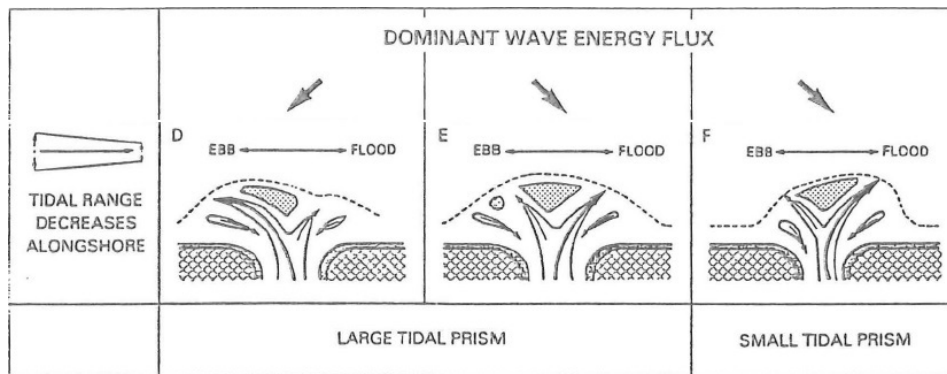


Figure 2.2: **Model by Sha et al. (1993) for the ETD geometry in function of the wave direction and interaction of inlet and offshore tidal currents.** Geometries shown in D, E, and F correspond to a decreasing tidal range in the flood long-shore direction, case of the SW Dutch coast. D and E model correspond to ETD developed under large tidal prisms, with westerly and easterly dominant wave energy, respectively. E model represents a situation close to the case of the Haringvliet estuary before the damming, whereas F is characteristic of the present situation (after the damming).

coast. Tidal residual circulation cells and the divergence of the sediment transport produced in them are responsible for the formation of tidal bars (De Swart et al. 2009).

De Swart et al. (2009) summarizes the morphodynamics of tidal inlet systems, a comparison is made for the evolution of bar features between short and long basins. In short basins, idealized models that consider the advective terms in the shallow water equations showed the spontaneous emergence of bars inland and seaward, that form branching features along with the channels. Bars that are formed in the seaward side of the basin, where relatively large depths are found, result from tidal circulation cells that produce advective sediment transport from the channels to the shoals. The features formed at the inland side are the result of diffusive sediment transport. In long-basins tidal bars separated by meandering tidal channels, either flood- or ebb-dominated, are present. In this case, bars have horizontal length scales much smaller than the length of the basin.

In long basins, two types of behavior are described: in the seaward part, ebb-channels meanders, and flood channels are straight and end in a bar. Further inland, both channels meander. The former type might be caused by the progressive character of the tidal wave, whereas in the latter case, the tide has a standing nature. 3D processes are not crucial for the emergence of channels and bars in the 2D depth-averaged model (De Swart et al. 2009).

Bars build up under calm wave conditions and migrate landward while during storm events, they are flattened, and they probably migrate seaward. Masselink et al. (2006) states that the morphological response is related to relaxation times and morphological feedback. The main difference between intertidal and subtidal bars lies in the dominant importance of water level variations related to the tide and wave processes in shallow water, restricted to the swash and the surf zone.

The response of subtidal bars depends on its position relative to the breakpoint; bars outside the surf zone will be pushed landward by shoaling waves, and those inside the surf zone will be forced seaward by return currents produced by breaking waves.

Relevant concepts in Masselink et al. (2006) study are the "relaxation time" and the "morphological feedback". The larger the relative tide range (ratio between tide range and wave height), the shorter the residence time for swash and surf zone processes and higher importance for shoaling processes. On the other hand, positive feedback between the bars and the hydrodynamic forcing will probably encourage its growth. Critical factors for the growth or spread of the bar are the size of the bar, location in the intertidal profile, intertidal morphology, and hydrodynamic conditions.

Further details on the types of intertidal bar systems, a summary of the theories related to their origin, and migration between the subtidal and intertidal zones can be found in Masselink et al. (2006) along

with their results on the morphodynamic response on the different intertidal bar systems.

2.1.4. Dynamic Equilibrium and empirical relations.

Dynamic equilibrium implies that the morphology is in balance with the physical processes (Van der Spek et al. 2015). The stability of tidal inlets is then determined by the competing force tidal- and wave-driven currents, the former moving the material deposited at the tidal inlet by the littoral drift, brought by the latter, the wave-driven currents (Van de Kreeke 1992).

Escoffier (1940) developed a morphodynamic model for the tidal inlet equilibrium based on two theoretical assumptions: (1) the maximum current speed in Escoffier's diagram is a measure of the transport capacity of the inlet currents, and (2) sand is carried into the inlet by the littoral drift, and when the maximum velocity at the inlet equals an equilibrium velocity, the transport capacity at the inlet is just sufficient to remove the sediment from the inlet. Escoffier's diagram is depicted in Figure 2.3.

In Escoffier's model, the maximum current velocity curve is plotted as a function of the cross-sectional area and intersects the horizontal of the equilibrium velocity at two points, at A_1 and A_2 (see Figure 2.3). A_1 is an unstable point, velocities lower than the equilibrium velocity means insufficient transport capacity with an accreting tendency producing the closure of the inlet, marked in the figure with No. 1. Velocities larger than the equilibrium velocity produces more transport capacity than necessary, increasing cross-sectional areas and tending towards the second intersection point, the stretch of the curved marked as No. 2. At A_2 , velocities lower than the equilibrium produce sedimentation in the inlet due to the lower transport capacity, larger velocities will tend to erode the cross-section, therefore converging to A_2 point again; this is a stable equilibrium point.

As indicated in the figure, the equilibrium interval for a given inlet extends from A_1 to infinity, and inlets with cross-sectional areas in that interval are stable. Therefore a stable inlet's cross-section will show changes in time associated with seasonal forcing (storm activity) with oscillating cross-sectional areas about the equilibrium value of A_2 , or long-term trends (Van de Kreeke 1992).

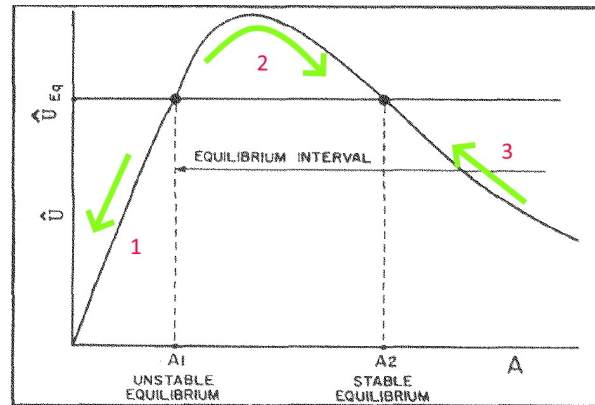


Figure 2.3: **Escoffier's Diagram of his morphological model for equilibrium cross-sectional area of inlets.** The diagram shows 2 equilibrium points. A_1 is an unstable equilibrium as variations in the maximum inlet velocity will produce divergence of the position of the inlet in the diagram. Section marked with No. 1 is a decrease in maximum inlet velocities, sediment transport capacity and therefore cross-sectional area, leading to closure of the inlet. Section No. 2 corresponds to increasing (above needed) velocities, sediment transport capacity and erosion of the cross-section; leading to the second equilibrium point A_2 . A_2 is an stable point as decreasing velocities from this position will lead to decreased transport capacity and accretion of the section, converging back to the stable point.

The inlet velocity has to satisfy the hydraulic conditions, i.e., the maximum velocity of the inlet is a function of the cross-sectional area. Under the dynamic equilibrium assumption, empirical relations have been derived for the relationship between the equilibrium cross-sectional area in the inlet and the tidal prism. For the relations the reader is referred to Appendix A.

Ideally, any system will try to evolve towards a stable equilibrium, explained by the relation between

tidal propagation and basin geometry. Basins with relatively shallow channels require wide flats to create zero asymmetry-induced transport and promote dynamic equilibrium. Basins with relatively deep channels require narrow flats (Stive et al. 2003).

Kragtwijk et al. (2004) studied the time scales related to the ETD and other units, and their responses to disturbances, through an empirical model. The smallest scale will dominate the initial response, and sediment exchange will occur among the closest units within the system. This scale is then damped, and the longer scale prevails if equilibrium has not been reached, looking for sediment sources (or sinks) from outside the tidal system, e.g., adjacent coasts.

The interaction between the tidal inlet and basin with the adjacent coast comes from the fact that inlets are an interruption in the coastline. The combined effect of waves and tidal currents enable the littoral drift to bring and deposit sediment at the inlet. The material can either be transported into the basin and exported again or bypassed by the currents over the shoals in the ETD and its periphery from the updrift side of the inlet to the downdrift side.

Studies such as Elias et al. (2016) and Z. B. Wang et al. (2012) have shown that tidal systems as the Western Scheldt or the Wadden Sea in the Netherlands are robust and resilient to anthropogenic changes as long as the balance between the prevailing hydrodynamic conditions is not significantly altered.

2.1.5. Tidal propagation in basins

In the case of an ideal tidal wave, spatially uniform over the tidal excursion of a water parcel and has a sinusoidal varying magnitude over the tidal period, no net sediment transport is produced because each particle would return to its original position. When this is not the case, a residual transport results which would ultimately produce the morphological evolution of the area (Z. B. Wang et al. 2012).

Deviations of this "ideal" wave are characteristic of shallower areas as those in the nearshore zone. In relatively deep water, the tidal wave has a progressive character, and water level and velocity are in phase. As the tide travels towards depth-decreasing areas, the effect of bottom friction becomes more important, deforming the shape of the water level elevation. Bed friction then introduces a phase difference between vertical and horizontal tide that in coastal waters and basins vary between zero and $\pi/2$; if there is such a difference, the velocity peaks before the tidal elevation.

Assuming that the tide will mainly propagate into a basin through the main channel, which will transport the majority of the ebb and flood discharge, an approximation of the tidal propagation can be made with a set of 1D equations: balance equations for mass and momentum in the direction of the channel axis.

Considering a prismatic channel whose cross-section is representative of the flow carrying area only and with a constant bottom slope, the mass balance equation results in Equation 2.1 and the momentum balance in Equation 2.2. The first term in Equation 2.2 is the change in momentum, the second term is the advection term (in- and out-flow of momentum), the third term refers to the pressure gradient, and the last term to bed friction. For small ratios of the tidal amplitude to the water depth (a/h), the second term (advection) can be neglected. Assuming a linear friction law ($\tau_b = \rho c_f |u|u \approx \rho r u$) and by combining both equations the propagation of the tide into a basin can be approximated by Equation 2.3.

$$\frac{\partial}{\partial x}(hu) + \frac{\partial \eta}{\partial t} = 0 \quad (2.1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial \eta}{\partial x} + \frac{\tau_b}{\rho h} = 0 \quad (2.2)$$

$$\frac{\partial^2 \eta}{\partial t^2} - gh \frac{\partial^2 \eta}{\partial x^2} + \frac{r}{h} \frac{\partial \eta}{\partial t} = 0 \quad (2.3)$$

Where,

h Water depth.

u Mean flow velocity in the cross-section.

η Water level elevation.

τ_b Bed friction.

r friction coefficient.

ρ water density.

The first two terms of Equation 2.3 correspond to the classic wave equation and is inertia dominated, correspondent to a linear progressive wave. The last two terms of the equation are characteristic of a diffusion-like equation and describe a friction-dominated propagation, which is the case in many shallow tidal basins.

The effect of the bed friction over the tidal wave is the damping of the sinusoidal shape of the wave, both the vertical and horizontal tide, due to the tidal energy dissipation. In long basins, all the tidal energy is then dissipated before the tide reaches the end of the basin.

Taking the last two terms of Equation 2.3 and using a tidal diffusion coefficient of $D = gh^2/r$ the propagation equation is reduced to Equation 2.4 and the solution for the equation is shown in Equation 2.5.

$$\frac{\partial \eta}{\partial t} = D \frac{\partial^2 \eta}{\partial x^2} \quad (2.4)$$

$$\eta(x, t) = ae^{-kx} \cos(\omega t - kx); k = \sqrt{\frac{\omega}{2D}} \quad (2.5)$$

Substituting the solution in the continuity equation leads to the tidal velocity solution (Equation 2.6). The equation yields that the velocity leads the surface elevation by 45°. This also shows that the diffusion coefficient really depends on the flow magnitude and therefore varies over the tidal period. This non-linear character means that the basin deforms the tidal wave as well as dampens it, producing the loss of its sinusoidal characteristic.

Important to stress that during slack water, friction does not dominate, and the last two equations do not describe the propagation of the tide. The tide would have a more progressive character. In reality, the incoming tidal wave is partly damped and will have a partly propagating and partly standing character, the latter produced by an undamped wave that reflects at the end of the basin.

$$u(x, t) = \frac{a}{h} \sqrt{\omega D} e^{-kx} \cos(\omega t - kx + \pi/4) \quad (2.6)$$

2.2. Sediment Transport in tidal environments.

Long-shore sediment transport along coasts gets interrupted by tidal inlets. In these cases, sediment has to follow a longer path to bypass the inlets. Studies have tried to explain the physical mechanisms behind the tidally averaged sediment transport at inlet systems (e.g. Van de Kreeke et al. 1993, Z. B. Wang et al. 1999, Vegt et al. 2009, De Swart et al. 2009, Chu et al. 2015) and furthermore, what are the mechanisms that promotes this transport to bypass the inlet towards the down-drift coast (e.g. Elias et al. 2019, Herrling et al. 2018 or Ridderinkhof et al. 2016). Transport patterns around an inlet become more complicated due to residual currents and their 3D character.

Therefore, transport processes must be considered as they enable sediment for motion and bypassing at the tidal inlets. The transports can be classified by their driving force (tide- wave-, density-driven transport); by their direction (long-shore or cross-shore); or by the transported sediment (if it is coarse or fine sediment transport).

In mixed-energy inlets, sediment gets partitioned between wave and tidal flows. Wave-generated flows transport and dominate over the shallowest areas (shoals and beaches). Tide-generated transport dominates in the inlet and channels and tends to occur in depths higher than the wave-breaking zone (Kana et al. 1999).

2.2.1. Long-shore transport and bypassing

One of the initial researches regarding the importance of sediment bypass was conducted by Bruun et al. (1961), who proposed a ratio between the tidal prism and the long-shore littoral drift. High ratios (>300) mean the bypass is conducted through the tidal inlet, whereas for small ratios, the bypass is through shoals in the ETD.

Conceptual models and studies regarding bypassing mechanisms are widely available (e.g. Elias et al. 2019, Herrling et al. 2018 or Kana et al. 1999, Fitzgerald et al. 2000). However, they all agree on the need to study sediment transport paths further. Fitzgerald et al. (2000) report identifies a total of 9 models, six of natural inlets and three of jettied inlets, to explain the relation of the evolution of inlets with bypassing. The relevant models for this research are presented in Figure 2.4.

Herrling et al. (2018) study evaluates bypassing at mixed-energy barrier islands, making a distinction between 3 principal mechanisms: flow-bypassing and bar welding, sediment recirculation and ebb-delta periphery bypass. Their results show that the preferred mechanism for bypassing is strongly related to the sediment grain size classes, where the finest sediment prefers bypass along the ebb-delta periphery.

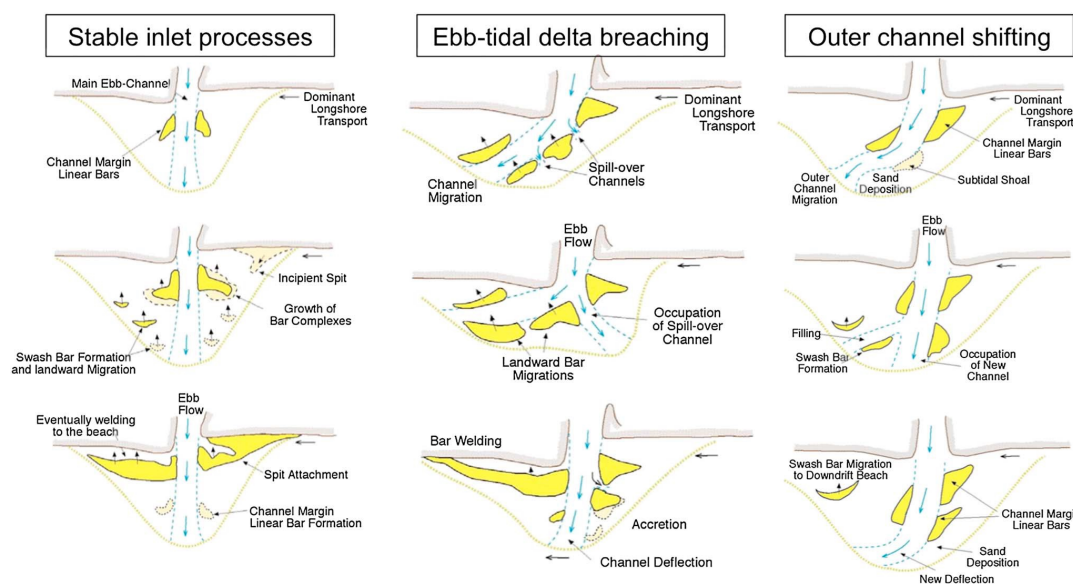


Figure 2.4: **Conceptual models for bypassing processes (Fitzgerald et al. 2000)**. Retrieved from Ridderinkhof et al. 2016. According to the system behavior and configuration, after the implementation of Delta21, the seaward side might develop one of this shapes of ETD. If transport from updrift is important, second and third models might develop. If tidal currents are more in equilibrium with wave-driven forces a more symmetrical delta may evolve.

Bypassing via shoal migration is one of the mechanisms that still raise several questions. Kana et al. (1999) defines 3 stages for shoal bypassing. First, the shoal detaches from the swash platforms, probably triggered by an excess build-up of material. Subsequently, the shoal attaches to the shoreline, and it is pushed further landwards. Finally, it is spread along the coastline by wave-breaking driven flows. Volumes bypassed by this mechanism are comparable to large nourishment for the adjacent beach. Hence, the frequency and magnitude of this bypass will ultimately control the evolution of the downdrift coast.

According to the study by Kana et al. (1999) and previous studies, the shoal is located at the flanks of the ETD, once it is free of the influence of ebb-tidal flows, will inevitably migrate landwards and at fast rates, once a portion of the shoal becomes emergent at low tide.

Elias et al. (2019) concluded through the analysis of high-frequency bathymetric data of Ameland inlet in the Netherlands, that changes at the scale of the ebb-tidal delta can be driven by interactions with the bigger scales (the whole inlet system), but can be very much also triggered through interactions originated at the smallest scales, resulting in downdrift shoal migration and inlet shifting.

The study by Ridderinkhof et al. (2016) went further in determining the conditions that are necessary and sufficient for the growth and migration of shoals in the ebb-tidal deltas through an idealized model. Their conclusions state that wave processes are the main driver for the shoal migration, whereas sediment transport by asymmetric waves prevents the shoal's diffusion and helps it reach the downdrift coast. Finally, they concluded that the shoal growth is triggered due to an imbalance between the prevailing wave conditions and the bathymetry.

Harrison et al. (2017) revealed that transitions in the ETD may result from non-seasonal forcing, e.g., storm conditions. During such conditions, an imbalance occurs. The morphodynamic conditions reach a "tipping point" and may produce morphology changes at the basin scale originated at smaller scales that scaled-up. Little research has been conducted on the threshold that drives such changes.

2.2.2. Coarse and fine sediment transport

The net sediment transport is what will ultimately define the morphological evolution of a tidal basin. It is essential to differentiate between the transport of relatively coarse sediment (sand: grain sizes larger than $62.5 \mu m$) and fine sediments (mud: grain sizes smaller than $62.5 \mu m$). In the case of coarse sediment transport, mostly as bed-load, the processes that contribute to its net transport are tide-averaged residual currents and horizontal tide asymmetry due to higher tidal components (overtides). Other sources of overtides are nonlinear shallow water terms and nonlinear bottom friction.

Conversely, fine sediment transport, mostly transported as suspended load, is produced by the asymmetry of the slack water periods. The spatial settling lag effect promotes a net transport in the direction of the decreasing tidal current and/or depth, in the direction of the peak current that has the subsequent longest slack tide. The joint effect of the tidal asymmetry and local inertia results in net sediment transport controlled by the duration of the asymmetry of the tidal velocity curve (De Swart et al. 2009).

In the case of coarse sediment classes, the material is assumed to respond instantaneously to the flow conditions, and a quasi-steady approach can be applied; the net transport of bed-load will occur in the direction of the peak current. It has been demonstrated that the dependence of bottom friction on the depth causes flood-dominant transport, and hypsometric effects caused by tidal flats along the sides of the basin promote ebb-dominated transport (De Swart et al. 2009).

Van de Kreeke et al. (1993) derived an expression for the long-term average transport as bed-load. The expression shows a dominant contribution of a residual flow velocity u_0 , the amplitude of the M2 tidal current, and the amplitudes and phases, relative to M2, of the M4 and M6 components (Bosboom et al. 2015). Their formulation applies as long as the residual current u_0 is small compared to the amplitude of the M2 constituent (Stive et al. 2003).

Regarding the transport of fine material, sediment no longer responds instantaneously to the flow condition as there is a lag due to its longer settling time. During slack periods, the material tends to settle. A net transport is caused if there are differences in the currents around slack water at the end of the flood cycle compared to the slack water at the end of the ebb cycle (Z. B. Wang et al. 2012). The sediment concentration will tend to follow the equilibrium concentration (given by the flow condition). When the flow direction reverses, the concentration will not follow instantaneously, promoting an asymmetry in the net sediment transport patterns.

2.2.3. Tide-induced residual transport of coarse sediment

Assuming that in the study area the morphological changes will be the result of residual transport of coarse sediment, a deeper understanding of the mechanisms that produce it is sought. Residual sediment transport is what ultimately will dictate morphological changes in a tidal environment. The main tide-related mechanisms contributing to residual transports of coarse sediment are tidal asymmetry and tide-average residual currents. The former refers to the skewness of the tidal wave and the effect of overtides in the tidal signal. The latter is related to secondary flow patterns such as residual currents in the inlet, Stoke's drift effect of a (partly) progressive tidal wave and bathymetry- or Coriolis-induced residual currents.

The net sediment transport patterns is then assumed to be mainly due to the tide asymmetry. Tide asymmetry is the result of non-linear interactions. One source is the effect of shallowing coastal waters, and a second source is the bottom friction. The distortion of the water surface elevation is approximated by the introduction of higher harmonics to the tidal signal, with a period of a fraction of the main tidal component.

The interactions between different tidal components will produce an asymmetry that might produce a tidally averaged residual sediment transport. Asymmetry can be defined about an axis at the time of slack water when $t = t_0$ and (1993):

$$|u(t_0 + t)| = |u(t_0 - t)| \quad (2.7)$$

Interaction of the main tidal component M_2 and its first even overtide M_4 will be symmetric only when there is a phase lag between the constituents of $\beta = \pi/2$ or $\beta = 3\pi/2$. For $-\pi/2 < \beta < \pi/2$ flood velocities are larger and flood duration is shorter; when $\pi/2 < \beta < 3\pi/2$ ebb duration is longer and ebb-velocities larger. The velocity can be expressed by Equation 2.8, where $\hat{u}$ is the amplitude of M_2 tidal current, $\hat{u}_4$ the amplitude of M_4 tidal current and σ the angular frequency of M_2 component.

$$u(t) = \hat{u} \cos \sigma t + \hat{u}_4 \cos(2\sigma t - \beta) \quad (2.8)$$

When M_2 and its first odd tidal constituent M_6 interact (velocity signal in Equation 2.9), the signal is only symmetric when the phase angle of M_6 relative to M_2 is $\gamma = 0$ or $\gamma = \pi$. In the equation, $\hat{u}_6$ is the amplitude of the M_6 tidal current, and all other variables are as previously explained.

$$u(t) = \hat{u} \cos \sigma t + \hat{u}_6 \cos(3\sigma t - \gamma) \quad (2.9)$$

Assuming the rate of the bed-load transport is a function of the local velocity, the following power law can be applied:

$$q = f|u|^n \quad (2.10)$$

Where,

q sediment transport rate per unit width [$\text{m}^3/\text{s}/\text{m}$].

f function of sediment- and fluid characteristics.

u depth averaged velocity.

n number varying between 3 and 5.

For the case of Equation 2.8, the tide-averaged bed-load transport is then in flood direction for $-\pi/2 < \beta < \pi/2$, ebb-directed when $\pi/2 < \beta < 3\pi/2$ and when $\beta = \pi/2$ or $\beta = 3\pi/2$ the tide-averaged coarse sediment transport is zero. The value of β determines the direction of the tide-average bed-load transport. When considering Equation 2.9, it results that the tide-averaged bed-load transport is zero for all γ values. Figure 2.5 shows the resulting signals of the previously described interactions of M_2 with M_4 and M_6 . Van de Kreeke et al. (1993) make an approximation for the tide average transport of coarse sediment considering a set of 5 tidal current constituents (M_2 , M_0 , M_4 , M_6 and S_2) and a set of 8 constituents (M_2 , M_0 , M_4 , M_6 , S_2 , N_2 , MS_4 and K_1). They found that considering the reduced set of constituents already produces the net sediment transport patterns in good agreement with measurements obtained from a case study at the Ems estuary.

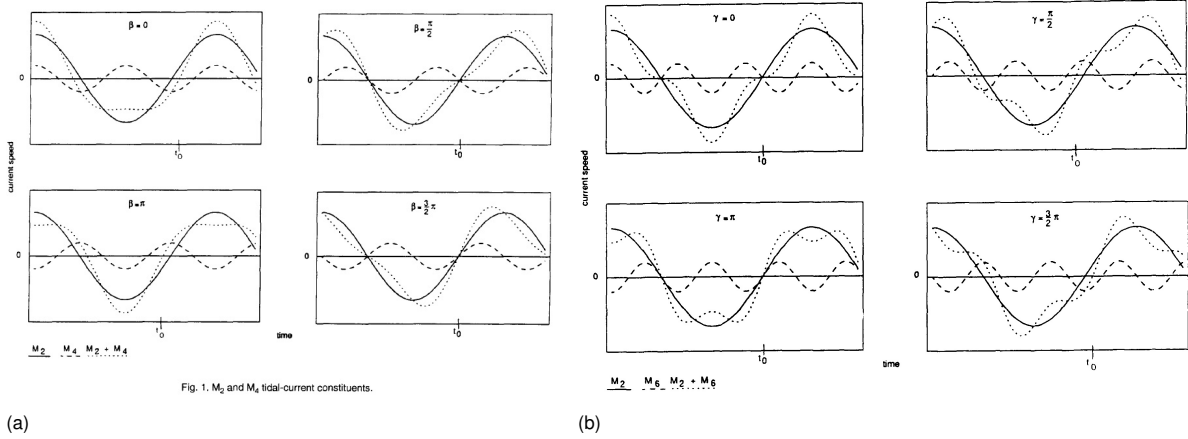


Figure 2.5: **Main component M_2 interaction with its higher harmonics for representative values of the phase lag between components** (a) First even overtide M_4 (b) First odd overtide M_6 (Van de Kreeke et al. 1993).

The approximation derived is shown in Equation 2.11. It assumes that the velocity field is dominated by the M_2 tidal current constituent (M_2 has a much bigger amplitude than the other tidal constituents) and that u_0 is the Eulerian residual current is sufficiently small $u_0 \ll \hat{u}$.

$$\frac{\langle q \rangle}{\hat{u}^3 f} = \frac{3}{2}\varepsilon_0 + \frac{3}{4}\varepsilon_4 \cos \beta + \frac{3}{2}\varepsilon_4 \varepsilon_6 \cos(\beta - \gamma) \quad (2.11)$$

$$\varepsilon_4 = \frac{\tilde{u}_4}{\hat{u}}, \quad \varepsilon_6 = \frac{\hat{u}_6}{\hat{u}}, \quad \varepsilon_0 = \frac{u_0}{\hat{u}}, \quad \varepsilon_2 = \frac{\hat{u}_2}{\hat{u}} \quad (2.12)$$

The equation shows that only the interaction of M_2 with the Eulerian residual velocity (first term), the M_4 constituent (second term), and the triple interaction with M_4 and M_6 produces net bed-load transport. Interactions with S_2 cause sediment fluxes varying in time with the beat frequency (a period of around 14 days), and in the long-term (in the order of several months), their influence is averaged out.

The approximation is validated with the Ems Estuary case, located in the Wadden Sea along the Dutch-German border, characterized by a semi-diurnal tide with a dominant constituent M_2 of ≈ 1.0 m amplitude. For further detail, the reader is referred to Van de Kreeke et al. (1993).

The $u_0 \ll \hat{u}$ assumption is not always valid. In an estuary with significant river discharges, the residual current will be mostly dictated by the river discharge. The situation is then extended by Chu et al. (2015).

Study area: the Haringvliet mouth.

The present chapter presents the characterization of the study area. It starts with a compilation of previous studies in the same site in Section 3.1 followed in Section 3.2 by the evolution of the mouth of the estuary along the years and as a result of numerous interventions. The hydrodynamic and morphological characteristics in the area are treated in Section 3.3 and Section 3.4 respectively.

3.1. Previous studies in the Haringvliet

It is now important to define the present conditions of the study area. The Haringvliet estuary is known to be part of the interventions undergone during the Delta Works. The construction of the Haringvliet Dam just landwards from the mouth limits the river discharge towards the sea during low tide, totally limiting saline water to flow upstream. This intervention triggered important morphological changes in the estuary that have not stopped, mostly because of more recent interventions.

Several studies have focused on understanding the response and evolution of the coastal morphology of the Haringvliet mouth to interventions. Some are focused in the specific coastal change (Smit 2020; Colina Alonso 2018; De Vries 2007; W. De Winter 2014; R. De Winter 2008; Elias et al. 2016; Van der Spek et al. 2019; Van der Spek et al. 2015; Tönis et al. 2002); others have focused on determining the sediment budget (Wegman 2015; Elias et al. 2016; Tönis et al. 2002) and others in understanding the representative coastal processes for this site (Colina Alonso 2018; De Vries 2007; R. De Winter 2008).

Many of the mentioned studies have involved the implementation of computational models for the study of the phenomena (Colina Alonso 2018; De Vries 2007; Wegman 2015; R. De Winter 2008). De Vries (2007) builds upon an existing model of the Haringvliet in which she derives new water level and Neumann boundary conditions. She also derives a new set of wave conditions that are related to wind and surge conditions, and a specific discharge scenario. The discharge regime is derived based on data for 1986-2005 and the Program of the Haringvliet Sluices Discharge of 1984. In a later study, Colina Alonso (2018) applies the same model with the conditions derived before to assess the morphological evolution of the Hinderplaat and the peak discharges of 1995. Both studies assume a discharge regime where there is flow only during high tide and is imposed as harmonic components. A summary of the most relevant hydrodynamic information for the present study is elaborated in the following sections.

3.2. Evolution: Closure works

The closure of the Haringvliet was completed in 1970 and was achieved by a dam with a series of 17 sluices, each 56.5 m wide, 1 km in total. Before the damming, the estuary had characteristics of a long basin: currents lead the water level surface by less than 90°. After the construction of the dam, measurements revealed that currents and water levels are nearly in phase, characteristic of a short basin (Tönis et al. 2002). The Haringvliet had large river discharges and strong tidal currents in a mixed-energy system. Relative to the tidal influence, waves had a lower impact on the ETD morphological evolution than after the closure.

Because of the damming, the tidal prism in the estuary decreased along with the shore normal tidal

flow; shore-parallel flows became more important in the flood and ebb channels. There was also a relative increase of wave-dominated currents resulting in a regime shift from mixed-energy to wave-dominated. In terms of sediment transport, supply by ebb-currents decreased, and wave-driven transport relatively increased (Van der Spek et al. 2015). A decreased tidal prism and tidal currents are unable to maintain an ebb-tidal delta of that size, and the ETD is susceptible to reshaping (erosion) by wave-driven forces.

Figure 3.1 shows the Haringvliet's mouth change over the years, starting with the state before closure, assumed by some authors to be an equilibrium state (e.g., Terwindt 1973; Tönis et al. 2002), until the present state (2015). The mentioned reshaping of the ETD is clear, already in 1972 snapshot, shortly after the intervention. The formation of a shoal parallel to the coastline is visible, agreeing with decreased shore-normal tidal currents and reshaping by waves. The long-shore orientated sandbank, characteristic of wave-dominated environments, is the Hinderplaat. It later spread and continued its landward migration, as shown in the 2015 snapshot.

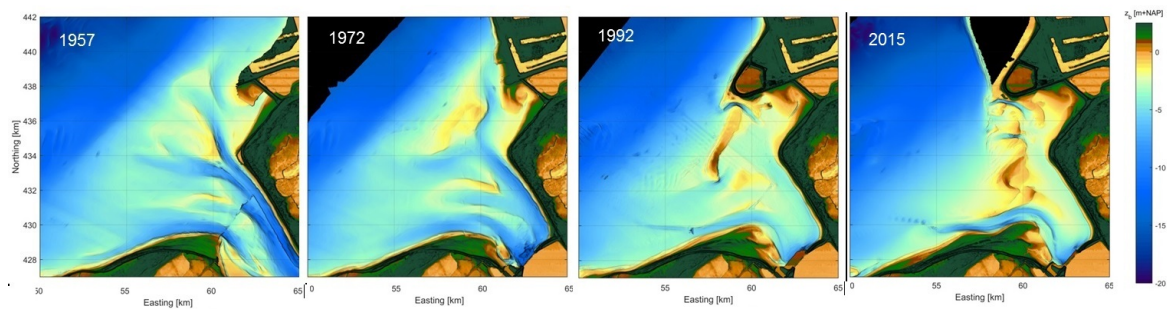


Figure 3.1: **Overview of the morphological evolution in the Haringvliet; snapshots of representative moments.** Before the closure (1957): shore-normal shoals and tidal currents with bifurcating ebb-channels. Initial response after closure (1972): decrease of shore-normal tidal currents and relative increase of wave-driven currents. Elongated Hinderplaat (1992): landward migration and southern extension of an elongated Hinderplaat, aligned with the Slufter coast-line, characteristic of wave-dominated environments. Present state (2015): spread of the ETD, continued landward migration and accretion of the sheltered (landward) side of the mouth, alignment with the MV2 coast-line. (Retrieved and modified from Colina Alonso 2018)

The effect was a strong erosion in the ETD shoreface and landward migration, while strong sedimentation took place in the landward (sheltered) area of the delta (R. De Winter 2008). The dynamics promoted the growth of the Hinderplaat and other shallow areas, mostly between the -3 m to 1 m wrt. NAP depths (Dam et al. 2006). The contour lines of the delta follow the adjacent coastline caused by strong long-shore tidal currents. Observe in Figure 3.1 the SW-NE orientation of the shoal in the 1972 snapshot compared to the NNW-SE orientation of the delta depicted in the snapshot of 1957, parallel aligned to the estuary axis.

The features in the 1957 snapshot also agree with the ETD model described by Sha et al. (1993). A decreasing tidal range along the coast and northwards with relatively large water level gradients produces an offshore-inland tidal currents interaction such that horizontal and vertical tide have a phase difference of 3 hours. This tidal regime produces seaward bifurcating ebb-channels with slightly deeper channels to the left of the ETD with a small asymmetry. After the damming, the tidal prism decreased, and the current interaction showed almost no lag between the tides. The Slijkgat as ebb-channel became more important, and the ETD became more asymmetric.

As along-shore currents became more important, the orientation of the shoals shifted from shore-normal to shore-parallel. This result was an elongated Hinderplaat that created a sheltered back-barrier area enhancing siltation in the basin and its channels. The Hinderplaat progressively eroded in its shoreface, increasing in height and decreasing in width. Long-shore transport also produced its elongation to the south. The change in tidal phases due to the transition from long to short basin caused the transition from the fork-shaped delta seen in the 1952 bathymetry (Figure 3.1) to a southward directed main ebb-channel (Tönis et al. 2002). The effect was further enhanced by dredging activities.

The flow concentration through the sluices produced scour pits 22 m deep at the NE side, making a connection between the main flood channel Slijkgat and the ebb channel Rak van Scheelhoek. Eventually, this channel lost importance (see [Figure 1.2](#) for the location of the channels and shoals). After the damming, channels tended to decrease their cross-sectional area and increase their bed level. The channels were too big for the water volume flowing through them (Z. B. Wang et al. 2009). The Rak van Scheelhoek channel's depth has decreased approximately 5 m since the closure (Dam et al. 2006). In general, the channels have silted up with sand and predominantly mud; layers up to 7 m were reported in some areas (Elias et al. 2016).

Eventually, channels like Gat van de Hawk silted up, and new channels emerged, such as the Hinderplat (dredged) and the Kortsluitgeul, naturally developed by the currents. The Kortsluitgeul now divides the most recent mega-shoal shape of the Hinderplat in two. The Slijkgat showed a recent trend (last 17 years) to transport larger water volumes, eroding the channel bottom and accreting in the surrounding areas, becoming the main tidal channel. The river discharge is mainly transported through it, ultimately dictating the morphology of the channel. During periods of low discharges, the Slijkgat accretes and tends to an equilibrium state that is disturbed by high winter discharges driving it away from that "equilibrium" (R. De Winter 2008).

Elias et al. (2016) also remark that due to the now-limited cross-shore tidal currents, along-shore sediment transport became dominant. Since the net sand volume in the delta has not decreased as the dam does not allow sediment back into the estuary, the cause for sediment loss/gain in the system is through the interaction with adjacent ETD by long-shore sediment transport northwards. The study estimates the sediment budget for the whole Voordelta, revealing that the Haringvliet and the Grevelingen are transit areas. Sediment coming in from the southern edge of their ETD is in the same order of magnitude as that going out at the northern edge. Conversely, volume changes in the 1965-2010 period are not significant (in the order of the accuracy of measurements) with slightly increasing volumes for the Haringvliet (Elias et al. 2016).

The Haringvliet basin has been a sediment sink for the sediment provided by adjacent coasts due to the location of the closure (relatively landwards) (Z. B. Wang et al. 2009). This can also be inferred due to the slight flood-dominance trend (De Vries 2007) that will be further elaborated in Section 3.3. Since the construction of the dam, the area upstream from it has behaved as a sink of riverine sediments, contributing practically no material to the mouth. Even before the damming, the river contribution was negligible (Ye 2007). The main source of material to the system is from marine origin brought by the long-shore drift from the southern deltas.

The large sediment input that provides the increased volumes for the Haringvliet ETD is supplied by the Grevelingen eroding delta front and sand nourishments of Goeree's coastline. The consequence is an expansion of the recurved spits at Kwade Hoek (see no. 1 in [Figure 1.2](#)). Next to Kwade Hoek, the only remaining main tidal channel is the Slijkgat (no. 2), also the main access to Stellendam harbor and regularly dredged to maintain its minimum depth of 5.5 m (Elias et al. 2016).

A more recent observed development was approximately after 1993. Between 1993 and 1995, discharges over 7,000 m³/s were registered at the Haringvliet sluices. The largest was registered in February 1995, reaching a day-averaged discharge of 9,015 m³/s. These events showed a crucial contribution to the breach of the Hinderplat and triggered a series of changes in the Haringvliet ETD (Colina Alonso 2018). New channels emerged, further eroded by tidal currents in and out of the basin. Lowering and landward shift of the shoals resulted in a complete loss of the elongated form of the Hinderplat. The process is depicted in [Figure 3.2](#).

Colina Alonso (2018) makes a detailed study of the evolution of the Haringvliet ETD. In the analysis, she concludes that as the Hinderplat increased in height and decreased in width, its breach was facilitated during the high discharge period between 1993-1995. The breaching resulted in the creation of several ebb channels that gradually became more important. The transition can be observed in [Figure 3.2](#) for 2001. The landward migration continued, finally producing the spread of the Hinderplat to the shape that has nowadays (see 2015 in [Figure 3.2](#)).

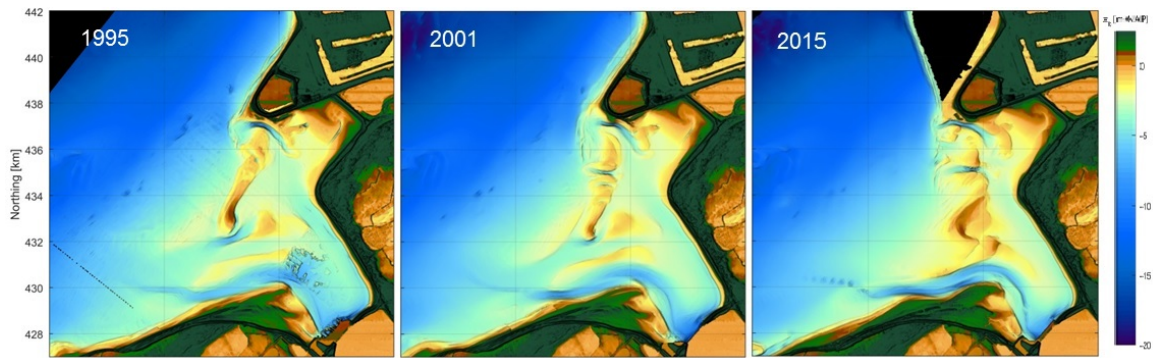


Figure 3.2: **Overview of the Hinderplaat breaching event around 1995.** At the 1995 snapshot (one of the years with extreme discharge events) the initial formation of a channel through the elongated Hinderplaat can be seen in the north side of the shoal. This allowed increasing tidal currents through the new channel, spreading the sediment available in the shoal. By year 2001, a clearer channel can be depicted through the Hinderplaat. Additionally, the continuous landward migration of the shoals have produced the growth of the Hinderplaat in the shape shown in the 2015 bathymetry and can still be seen today. In the black areas, no bathymetry information was available. (Retrieved and modified from Colina Alonso [2018](#)).

3.2.1. Other interventions

Colina Alonso ([2018](#)) makes a summary of the interventions implemented in the Haringvliet, apart from the closure works, the Port of Rotterdam expansions stand out. Dredging and nourishing operations have also been present.

The port expansion includes: first, the Maasvlakte 1 (MV1) constructed in 1964-1976 over a large shoal on the coast of Rozenburg in Voorne. Then the construction of the Slufter Dam took place, a storage dam for contaminated dredged material, as a reclaimed area from the Haringvliet ETD during 1986-1987. Then, between 2008-2013 the massive land reclamation that originated the Maasvlakte 2 (MV2) took place. The reclamations increasingly sheltered the ETD from north and north-westerly waves. Particularly with the Maasvlakte 2, the coastline north of the Haringvliet ETD protruded to the west more than the outer delta ever had (Van der Spek et al. [2015](#)). The MV2 construction also meant a change in long-shore tidal currents. [Figure B.1](#) shows how the tidal currents contract at the MV2 as it protrudes west (a total of 8 km including both Maasvlaktes) from the smoother coastline (Vegt et al. [2009](#); De Groen [2014](#)).

Dredging activities have mostly taken place in the Slijk gat channel for access to the Stellendam harbor, (f) in [Figure 1.2](#). The most recent dredging scheme is a fairway of 100 m wide and NAP -5.5 m deep, centered below a dredged cross-section 200 m wide at NAP - 4.0 m. According to the Port of Rotterdam, responsible for the dredging activities, the most problematic areas, where intensive dredging activities are needed to maintain the shipping access to Stellendam harbor, are marked with red circles in [Figure 1.2](#). The first area from east to west is located just before the bend where the Slijk gat turns around Kwade Hoek. The second area is where a sill is formed where ebb- and flood-currents meet, and the last area is further offshore, where the Slijk gat meets the sea (W. De Winter [2014](#)). For a detailed figure of the areas and the local bathymetry, see [Figure B.2](#).

Finally, nourishing takes place at the coast of Goeree and Voorne to strengthen the coastline and dunes, an artificial addition of material to the system. Another artificial source has proven to be the Slufter dam. During its construction (1986), an increase in the sand volume in the ETD was observed (Tönis et al. [2002](#)). Similarly, W. De Winter ([2014](#)) also observed increased sedimentation around the time of the MV2 construction (2009-2012).

3.2.2. Present situation

Since the closure of the estuary, the operation policy of the sluices was to maintain them partly open when discharges at Lobith ¹ were 1,500 m³/s or higher. The freshwater discharge through the sluices

¹Lobith (51° 51' 1.44"N, 6° 6' 12.96"E) is where the river Rhine enters The Netherlands.

was estimated in about $22 \cdot 10^6 \text{ m}^3$ per tidal cycle ($\approx 990 \text{ m}^3/\text{s}$) (Van Vessem 1998).

To improve water quality in the Haringvliet, from 2018 on the Kierbesluit policy was implemented. It consists of the permanent partial opening of the sluices, allowing saline water to enter the estuary and create a gradual transition zone. Only during extreme low river discharges the sluices are closed, thus ensuring that saltwater does not reach freshwater intakes upstream at Roode Vaart and Strijensas (Rijkswaterstaat 2018). However, nature restoration has not improved as expected, and nature organizations have advised full restoration of the Haringvliet (Lavooij et al. 2019).

Regarding morphological evolution, in the work of (Elias et al. 2016) and (Van der Spek et al. 2015) the Haringvliet evolution is conceptualized. They distinguish 3 phases, starting from a dynamic equilibrium existent before the damming; a second phase characterized for a distorted state result of the regime shift provoked by the damming, and finally, the breaching and formation of a coastal plain. More recently, Colina Alonso (2018) divides the final phase into (3a) the erosion and breaching of the Hinderplaat, followed by (3b) the spreading and disappearing of the ETD due to a destabilization of the system.

Some studies (e.g. Tönis et al. 2002, W. De Winter 2014) argue that the basin despite all the interventions, was approaching to an equilibrium condition. Tönis et al. (2002) estimated an adaption scale of 11 years based on sediment volume changes, which were approximated by the classical exponential function, based on data until 1998. The study also predicted that 99% of the equilibrium volume would be reached by 2020. However, the port extensions interrupted the trend towards the equilibrium state. Furthermore, W. De Winter (2014) also determines that although the land reclamation projects did represent an interruption, the rate of changes has decreased substantially, showing a new trend towards an equilibrium state.

3.3. Hydrodynamics of the Haringvliet

The study area for the present research is presented in Figure 3.3, which includes The Haringvliet and Hollands Diep, the Haringvliet ETD, and the area $\approx 20 \text{ km}$ offshore from the coast of Goeree. The blue dots show the locations of relevant measuring stations such as the *Haringvliet 10* station and *Haringvliet Sluices* station for water levels and *Bovensluis* station for river discharge.



Figure 3.3: **Overview of the total study area for the present research.** The study area includes the Haringvliet mouth from the Maasvlakte 2 to the north-east to the coast of Goeree in the south-west and the Haringvliet and Hollands Diep, extending until approximately 50 km upstream from the present location of the Haringvliet Dam. The area is marked in a red polygon, and locations of measuring stations for different data are marked with blue dots (*Europlatform* station lies approximately 40 km from the Haringvliet mouth, further offshore than the limits of the map).

3.3.1. Tide water levels and currents

The tide in the Dutch coast is semi-diurnal, with a daily inequality mostly shown during spring-tide. It presents seasonal spring-neap variability, and the tidal range decreases from south to north because of the amphidromic point in the North Sea basin: at Vlissingen in the south of The Netherlands has a range of about 4 m and decreases quickly to 1.7 m at Hoek van Holland, approximately 75 km northwards along the coast (Sha et al. 1993). Before the construction of the Haringvliet dam, the average tidal range inside the basin was approximately 1.85 m (Van Wijngaarden et al. 2002). After the damming and before the construction of the MV2, it was between 2.1 m (De Vries 2007) and 2.3 m (R. De Winter 2008) seawards from the Haringvliet Dam.

Before the damming, the basin had characteristics of a long basin, the tidal motion and salinity intrusion reached approximately 50 km landwards (measured from the present location of the dam) into the area called Biesbosch, further upstream from the proposed location of the new fresh-water intakes.

Because of the relatively large difference in tidal range along the SW Dutch coast, significant longshore water level gradients at low and high tide are present (Sha et al. 1993). The result is a phase difference between the tidal velocities in the estuary and offshore, and horizontal and vertical tide, showed a lag of less than 90° or approximately 3 hours (Figure 3.4c) before the construction of the dam. After the closure, the system changed into a short basin system; the currents now leading the water level by 90° and almost no phase difference between currents offshore and in the basin (Figure 3.4d) (Tönis et al. 2002). Furthermore, because of its long basin character before the damming, the currents at the Haringvliet mouth showed 4 distinctive phases (see Figure 3.4a) that were practically lost later (Figure 3.4b). The phases before the damming are explained by Tönis et al. (2002) as:

1. At high tide, flow currents are in flood direction offshore and inside the estuary.
2. Approximately 3 hours after high tide, the current offshore are flood-directed while inside the estuary is in ebb direction.
3. At low tide, flow currents are in ebb-direction inside and outside the basin.
4. Approximately 3 hours after low tide, currents inside the basin are in flood direction, and ebb-directed offshore.

After the damming the phases are not clearly appreciated anymore and show a circular pattern:

1. Currents enter at the south side and leave at the north. At sea, as well as in the basin, they are in flood direction.
2. Approximately 3 hours after high tide, currents inside the basin are in ebb direction while offshore are still in flood (north) direction.
3. At low tide, flow currents enter from the north and leave from the south.
4. Approximately 3 hours after low tide, the currents at sea are ebb-directed while inside the basin are in flood direction.

In the tidal signal retrieved from Delft Dashboard (DDB)², for the year 2019 (Van Ormondt et al. 2020), Figure B.3b shows the signals at *Haringvliet 10* station, in front of the coast of Goeree, and at the *Haringvliet sluices* in the Slijk gat channel (see locations in Figure 3.3). The signals prove to be almost in phase. Figure B.3a shows the signal for the entire 2019 and Figure 3.5 for the months of September-October. The tidal water levels show an important spring-neap variation and even range differences between spring periods. The mean tidal range is derived as 2.06 m.

Due to a reduced shore-normal tidal influence, flow velocities decreased by about 35-80%. Moreover, the maximum flood currents became larger than the maximum ebb resulting in a flood dominant basin.

²DDB is an open-source software package part of the OpenEarth initiative. The tool uses publicly available online datasets for bathymetry, topography, and tidal constituents to generate model geometries and ocean boundary conditions. The tidal data is obtained from reverse tidal models like TPXO or observation data in the form of tidal predictions based on constituents' tidal database e.g. IHO or XTide (<http://www.flaterco.com/xtide/>). For the current study and the information shown in the present section, tidal information from XTide station *Haringvliet 10* was retrieved for the year 2019.

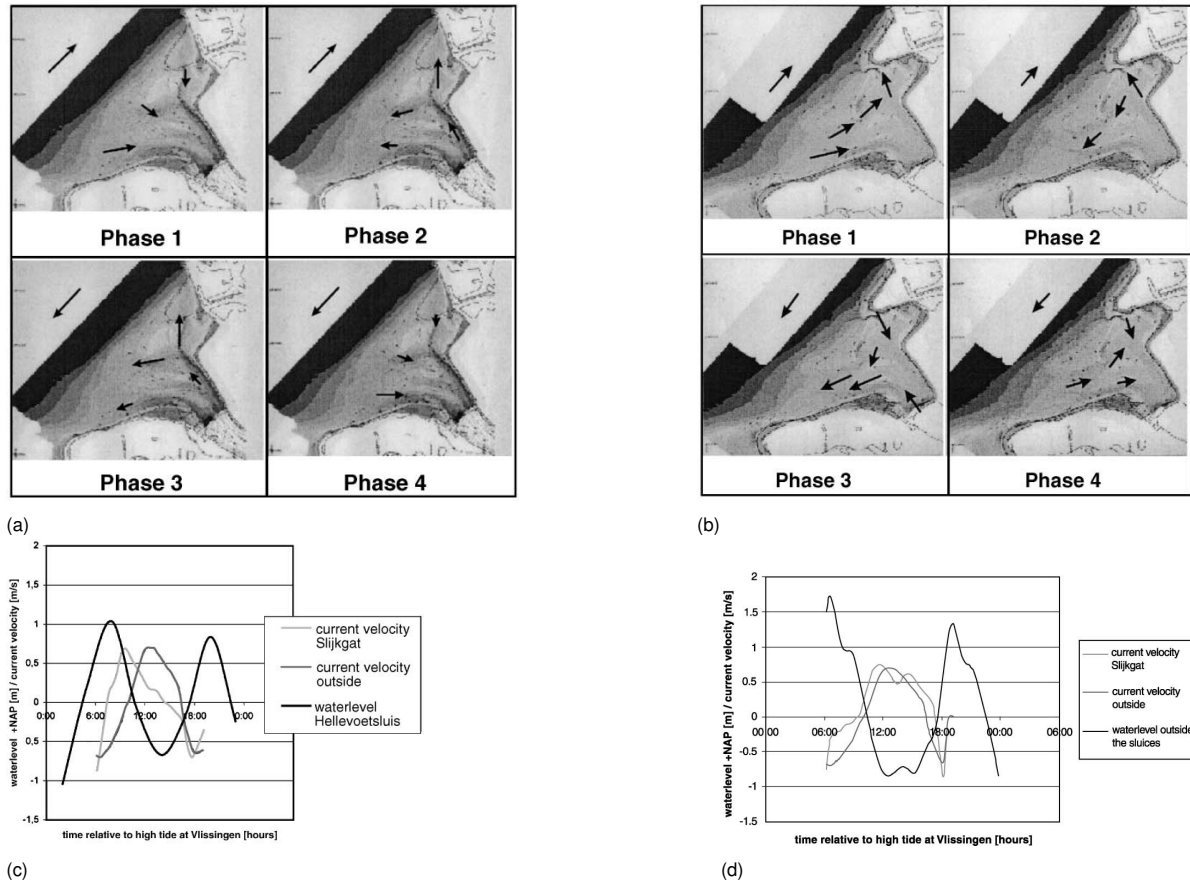


Figure 3.4: **Tidal current directions in the Haringvliet mouth during the tidal cycle showing 4 phases.** (a) Four-phased tidal cycle before closure (b) Phases of the tidal cycle after closure showing a more circular pattern. (c) The water level at the Haringvliet Dam and tidal current signal at the Slijkgtat and outside the basin before the closure, the phase-lag between vertical and horizontal tide is less than 90° , and current velocities outside and inside the basin are out of phase. (d) The water level at the Haringvliet Dam and tidal current signal at the Slijkgtat and outside the basin after the closure, the phase lag between vertical and horizontal tide of nearly 90° and velocities inside and outside the basin are in phase (Tönis et al. 2002).

Van Vessem (1998) reports velocities in the order of 0.77 m/s and 0.63 m/s during flood and ebb respectively at the Slijkgtat channel. Close to the dam, maximum velocities have even decreased to 0.3 m/s (Wegman 2015).

After the damming, the tidal prism decreased considerably. Louters et al. (1991) reports a decrease from 460 Mm^3 to approximately 6 Mm^3 , while Van Wijngaarden et al. reports a reduction from 308 Mm^3 to 15 Mm^3 . The tidal range also decreased to approximately 0.30 m and is the result of the tidal motion entering the Haringvliet from the northern border, connected to the Nieuwe Waterweg (Van Wijngaarden et al. 2002).

The interaction between tidal currents offshore and inside the basin is also related to the evolution of the morphological features of the ETD, as explained by Sha et al. (1993) and elaborated in Section 2.1.2. Before the damming, the estuary had a large tidal prism, and with the tidal regime showing a phase lag of a quarter of the tidal cycle, the evolution of bifurcating ebb-channels and more symmetric ETD is promoted (Sha et al. 1993). These features are clearly depicted in Figure 3.1 in the snapshot of 1957 before the damming of the Haringvliet.

After the damming, as the cycle is lost, tidal prism decreased, and long-shore tidal currents became more important than cross-shore currents, the main ebb channel (Slijkgtat channel) turns more to the left and the ETD is asymmetrical to the right.

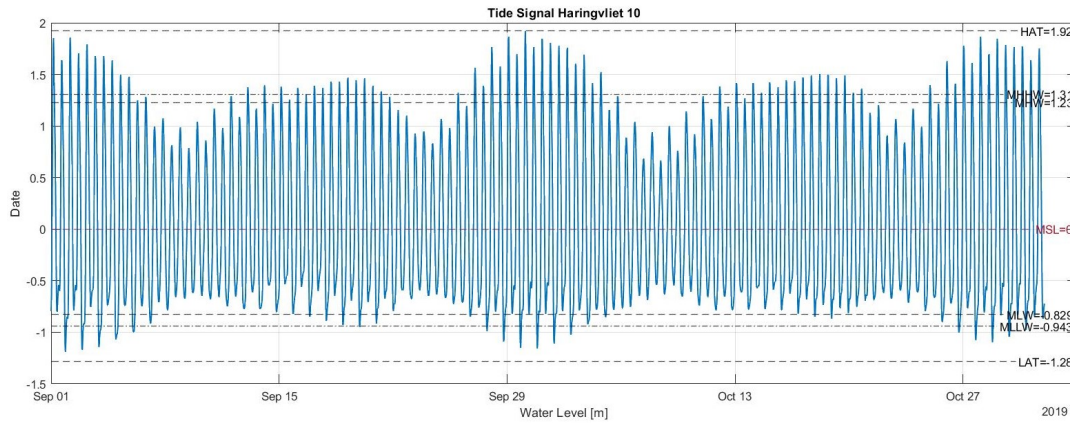


Figure 3.5: **Tidal signal at the Haringvliet mouth for different time periods.** The tidal signal is retrieved from *Delft Dashboard* (Van Ormondt et al. 2020) for the year 2019 at Xtide Tidal Station *Haringvliet 10* (51° 52'0.12" N, 3° 52'0.12" E). Tidal signal of a 2 month period with clear variations in the spring-neap cycles and the daily inequality, larger during spring tides.

In a hydrodynamic study by R. De Winter (2008), the tidal volume (sum of the absolute volume through a cross-section during ebb and flood) was estimated for the different channels for a 2003 bathymetry. This bathymetry already shows a spread mega-shoal Hiderplaat. The study estimates the flow distribution in the channels and concluded that the percentage of tidal volume flowing through the Slijkgat from 1986 to 2003 has increased to 65.7%. For the present study is important to take this into account since once the Delta21 project is implemented, all the tidal volume will flow through a modified Slijkgat and out into the North Sea through the new Tidal Inlet. The depth of these features will therefore be an important parameter in the future development of the system and outer delta.

3.3.2. Waves

The wave climate in the Voordelta and the Haringvliet mouth mainly depends on local wind currents that generate waves in the shallow North Sea basin. The significant wave height is approximately 1.3 m from WSW directions and a mean wave period of 5 s (Elias et al. 2016). Figure 3.6 shows the wave climate offshore from the Haringvliet at the location of the *Europlatform* (52.00° N, 3.28° E). Figure 3.6a shows the schematisation derived by Colina Alonso (2018) for the period 2006-2012 data, while Figure 3.6b shows the wave rose for the same location.³ From Figure 3.6 is clear that south-westerly waves (WSW to W) and waves from NNW to NNE are important in the area. Waves up to 2.5 m from 245° direction (WSW) have a probability of occurrence of 8.9% and waves up to 2.0 m from 355° direction (NNW) occurring 6.8% of the time. Because of the continuous land reclamations north of the Haringvliet dam, the area has been progressively sheltered from the influence of north to north-easterly waves. After the damming, the decreased tidal currents relatively increased the importance of wave energy fluxes arriving at the ETD. Wave induced currents caused a net landward sediment transport, and accretion in the ETD induced wave-breaking further seaward, with more energy dissipated in the flats' front. Figure 3.6b shows the importance of north-westerly waves further offshore, but wave energy fluxes from southwest to west directions showed to be most dominant on the ETD (for a situation without the MV2) (Colina Alonso 2018).

A recent study by Smit (2020) reflects the sheltering effect on the present state of the Haringvliet mouth. Figure 3.7 shows the wave propagation direction resulted from a computational model for waves coming from SW, North, and all directions. The wave directions clearly show how the area immediately downstream of the Haringvliet Dam is extremely shelter, and waves hardly reach it anymore. The trend is expected to be enhanced when considering further land reclamation in the area, such as the Delta21 intervention.

It is also important to know the seasonal distribution of the waves. Figure 3.8 shows the wave climate

³The wave rose in Figure 3.6b and all wave data from Argoss (2020) is based on a wave model with 81816 model records analyzed for the years 1992-2019 and retrieved from <http://www.waveclimate.com> in March, 2020.

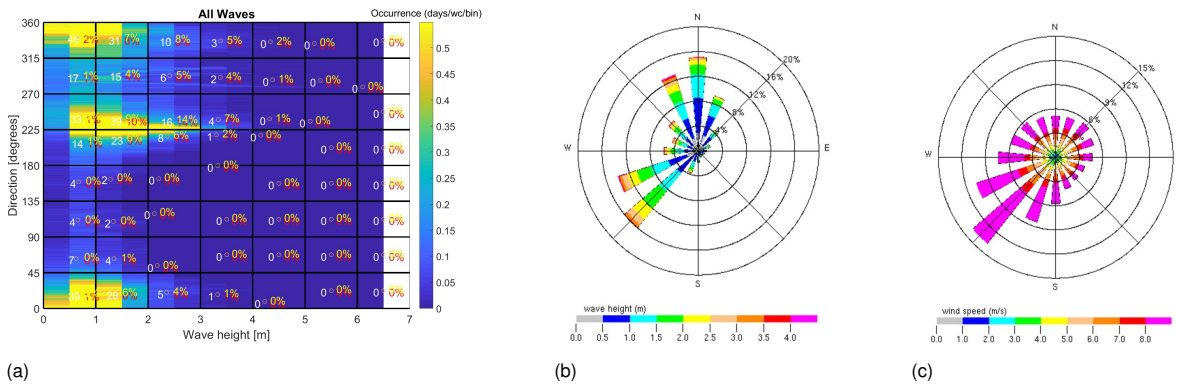


Figure 3.6: **Wave and wind climate at an offshore location from the Haringvliet mouth.** (a) Schematised wave climate for 2006-2012 data at the *Europlatform* station (Colina Alonso 2018), most waves coming from NNE, WSW, and NNW to N. (b) Wave rose for the same location, based on a wave model of 81816 model records for 1992-2019, retrieved from Argoss in April 2020. The rose shows the dominance of waves from the same directions as the schematization in (a). (c) Wind rose for the *Europlatform* location (Argoss 2020), showing dominant wind directions from SSW to WSW.

throughout the year at the *Europlatform* location. It shows that waves up to 1.5 m have an equal probability of occurrence. While higher waves (> 2.00 m) are more likely to happen during the winter season that can be observed to be from October to March. Waves between 1.5 to 2.0 m are more probable to be expected from October to February, and waves of 4.5 to 5.0 m are still expected during those months while the rest of the year not at all.

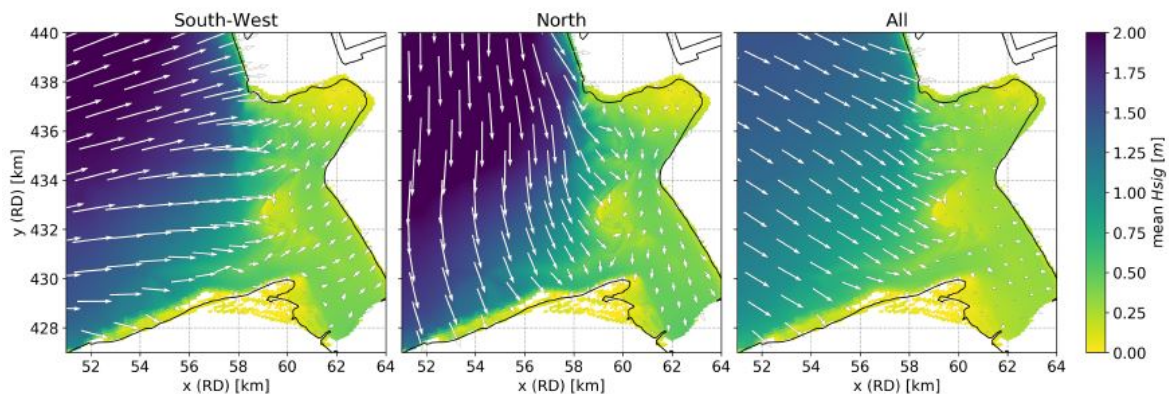


Figure 3.7: **Wave propagation direction for 2018 statebathymetry at the Haringvliet mouth.** The model shows that when waves come from SW direction they impact the ETD almost in a shore-normal direction (left figure). Waves from the North refract towards the ETD contours (middle figure). In both cases waves hardly reach the sheltered area of the mouth behind the shoals. When the model is forced with waves from all directions (right figure) the back-barrier area receives even less influence from the waves. (Model results retrieved from Smit 2020).

3.3.3. Wind and surge level

Wind residual currents can become an important mechanism for sediment transport in shallow areas as Colina Alonso (2018) found in her study of the Hinderplaat. The wind at the site is generally southwesterly with mean mild speeds of 7.5 m/s measured at the *Europlatform* and *Lichteiland Goeree* stations (Rijkswaterstaat 2020c). However, winds from the northwest can cause water level set-up up to 1.5 m due to a long fetch in this direction (R. De Winter 2008). During storm conditions, water-level surges can be bigger, levels higher than 2.0 m have been measured at the study area (Elias et al. 2016). Under such storm conditions, the water level at the Haringvliet sluices is higher (nearly 0.30 m) than at the seaside (De Vries 2007).

lower	upper	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	0.5	0.0082	0.00967	0.01383	0.018	0.018	0.018	0.024	0.023	0.016	0.009	0.007	0.009	0.174
0.5	1	0.0167	0.018405	0.02443	0.03	0.031	0.032	0.03	0.029	0.027	0.025	0.022	0.016	0.302
1	1.5	0.0194	0.018327	0.01977	0.018	0.021	0.02	0.019	0.018	0.018	0.022	0.019	0.018	0.231
1.5	2	0.0149	0.013258	0.01171	0.009	0.01	0.008	0.008	0.01	0.01	0.014	0.015	0.016	0.139
2	2.5	0.0116	0.008111	0.00857	0.004	0.004	0.003	0.003	0.003	0.006	0.008	0.01	0.012	0.081
2.5	3	0.0075	0.005381	0.00382	0.001	0.001	8E-04	6E-04	0.001	0.003	0.004	0.006	0.007	0.042
3	3.5	0.0039	0.002652	0.00195	4E-04	3E-04	6E-04	2E-04	5E-04	1E-03	0.002	0.002	0.004	0.020
3.5	4	0.0016	0.001326	0.00059	2E-04	0	8E-05	8E-05	8E-05	7E-04	8E-04	8E-04	0.001	0.008
4	4.5	0.0005	0.000546	0.00017	8E-05	0	0	0	8E-05	2E-04	3E-04	5E-04	5E-04	0.003
4.5	5	0.0004	0.000156	0	0	0	0	0	0	0	8E-05	2E-04	2E-04	0.001
5	5.5	8E-05	0	0	0	0	0	0	0	0	0	8E-05	0	0.000
5.5	6	0	0	0	0	0	0	0	0	0	0	0	0	0.000
6	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0.000
6.5	7	0	0	0	0	0	0	0	0	0	0	0	0	0.000
total		0.0849	0.077832	0.08483	0.082	0.085	0.082	0.085	0.085	0.082	0.085	0.082	0.085	1.0000

Figure 3.8: **Probability of occurrence of the yearly wave climate at the location of the Europlatform.** The color scale indicate the probability magnitude from highest in red to lowest in green. The distribution shows how waves between 1.5 to 2.0 m are more probable to be expected from October to February and waves of 4.5 to 5.0 m are still expected during those month while the rest of the year not at all. *Normalized from Argoss (2020).*

3.3.4. River Discharge

The discharge at the Haringvliet sluices depends on that of the Rhine river and the river Meuse. The contribution of the Rhine has a bigger impact on the Haringvliet with an average discharge of 2,300 m³/s than the Meuse with an average discharge of 230 m³/s (Van Wijngaarden et al. 2002). On average, 30% of the drained river volumes are discharged through the Nieuwe Waterweg and 70% through the Haringvliet to the North Sea (Rijkswaterstaat 2020a). A study by Wijngaarden (1998) showed that under normal conditions and the sluices completely open, the discharge through them was 1,000 m³/s. Although, the real discharge through the Haringvliet before the damming is unknown (Wegman 2015).

Small discharges (< 2,000 m³/s) generally flow through the Slijkgtat towards the North Sea with minimum influence over ebb-currents. For discharges between 2,000 – 4,000 m³/s, the outflow follows the Slijkgtat, the Rak van Scheelhoek, and the Hindergat. For large discharges (> 4,000 m³/s), the outflow covers the entire Haringvliet mouth (De Vries 2007).

The highest river discharges through the locks of the Haringvliet were observed in the period 1988-1995, the highest being in February 1995 of 9,015 m³/s with an 8 days duration, possibly associated with the Hinderplaat breach. The mean yearly discharge is between 1,000-2,000 m³/s and is smaller to 2,000 m³/s 89.9% of the time. Data for the period 2009-2015 can be observed in Figure 3.9 for records at the Haringvliet sluices (51° 50'9.60"N, 4° 3'17.64"E) and Bovensluis station (51° 41' 33.00"N, 4° 29'36.24"E) (see Figure 3.3 for the locations). The figure shows a big similarity in the discharges at both stations with a correlation coefficient of $R^2 = 0.976$, especially for higher values when the Haringvliet sluices are not closed, and the river flow is allowed to discharge into the sea directly through the sluices. For a scenario where the Haringvliet sluices will remain open, like the one proposed in the present study, historic discharge data from the Bovensluis station can be used as a boundary condition (see Section 5.2.5).

Steijn et al. (2001) derived a schematized regime of the discharge program of 1984 for the Haringvliet sluices and the Nieuwe Waterweg (LPH84) into 3 classes: high, normal, and low discharge. Each discharge class is associated with a probability of occurrence and a discharge factor F_Q that is later linked to the wave conditions. The factor F_Q is computed based on the erosive capacity of the discharge on the channels at the mouth and taking into account that the weighted average of all discharges must be approximately the average yearly discharge measured for a long period. It is the ratio between the discharge imposed in the Haringvliet sluices and the average discharge (estimated as ≈ 550 m³/s

averaged over the tidal period) and can be seen in Table 3.1.

This schematisation is used by De Vries (De Vries 2007) and Colina Alonso (Colina Alonso 2018) in

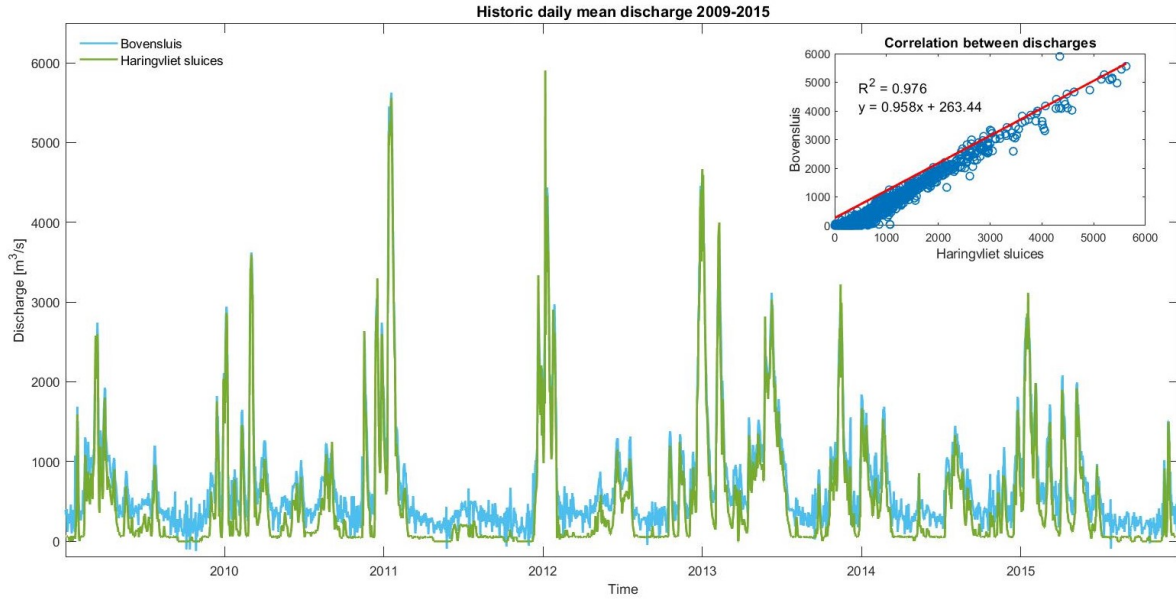


Figure 3.9: **Discharge data for the Haringvliet sluices and Bovensluis station for the period 2009-2015.** A high correlation between discharges at both stations can be observed ($R^2 = 0.976$), specially for discharges above approximately 800 m³/s as the discharge is not contained by the Haringvliet Dam and is allowed to flow into the sea.

their study. De Vries (De Vries 2007) combines river discharges with the wave conditions for the modeling scenarios taking into account that results from Steijn et al. (2001) show that high river discharges hardly ever happen simultaneously with storm conditions. This must also be taken into account for the schematization in the present study. The discharge strategy for the Haringvliet sluices will be different from the present Kierbesluit to allow the tidal intrusion further upstream. This discharge regime will also define the scenarios for this study.

Table 3.1: **Discharge regime LPH84 derived by Steijn et al. (2001) for the Haringvliet sluices and the Nieuwe Waterweg.** The normal discharge regime in the Haringvliet is represented by a discharge of 897 m³/s and the high discharge regime by a 5,045 m³/s discharge. For the Nieuwe Waterweg both regimes are represented by a 1,695 m³/s discharge, discharge allowed to flow through the Port of Rotterdam's entrance.

Regime	Occurance	$Q_{Haringvliet}$	F_Q	$Q_{NieuweWaterweg}$
[-]	[%]	[m ³ /s]	[-]	[m ³ /s]
High	2.9	5045	9.84	1695
Normal	51.1	897	1.75	1695
Low	46	41	0.08	1103
Mean	100	624	-	1431

3.3.5. Hydrodynamic classification

As mentioned in Section 3.2, after the closure, the Haringvliet mouth shifted from a mixed-energy system towards a wave-dominated basin. R. De Winter (2008) classified the different areas of the Haringvliet based on Davis et al. (1984) classification and the local wave conditions; areas offshore from the MV2 are mostly wave-dominated, whereas the sheltered locations are classified as tide-dominated. The river discharge is not considered.

3.4. Morphology and morphodynamics

3.4.1. Bathymetry

The *Vaklodingen* dataset is gathered by Rijkswaterstaat based on echo-sounding surveys of the Dutch coast. The dataset covers the entire Haringvliet mouth and its ebb-tidal delta up to the NAP -20 m depth contour with a grid resolution of 20 m. The Vaklodingen datasets were used in previous modeling studies for the Haringvliet ETD (e.g. Elias et al. 2016, Van der Spek et al. 2019 or Colina Alonso 2018). Datasets for the years 2009, 2012, and 2015 (and possibly 2018) will be used in the present study and are presented in Figure 3.10. Additionally, for the estuary area, surveys from Rijkswaterstaat are also available and are obtained such that they are representative for 2016 (Rijkswaterstaat 2020d).

The data shows the behavior described in Section 3.2, erosion patterns in the delta front, and sedimentation in the sheltered landward areas, for all periods. The pattern is also shown for the Bollen van de Ooster to the south-west of the figures. Channels where tidal currents flow in and out the small basin present erosion while the shoals increase their bed level, especially in the landward side. The erosion between the Hiderplaat and the Garnalenplaat in the 2012-2015 period leads to their eventual union into a bigger super-shoal, see Figure 3.10 for the year 2018.

The main tidal channel, the Slijkgat, shows the sedimentation trends described by De Groen (2014) (see Figure 1.2 and Figure B.2), at the north and north-east of Kwade Hoek and at the end of the channel where the increased depths and lower velocities allow the sediment to settle. The mentioned patterns will be used to compare the model results for long term simulations for the same periods for a qualitative assessment of its prediction qualities (see Chapter 6).

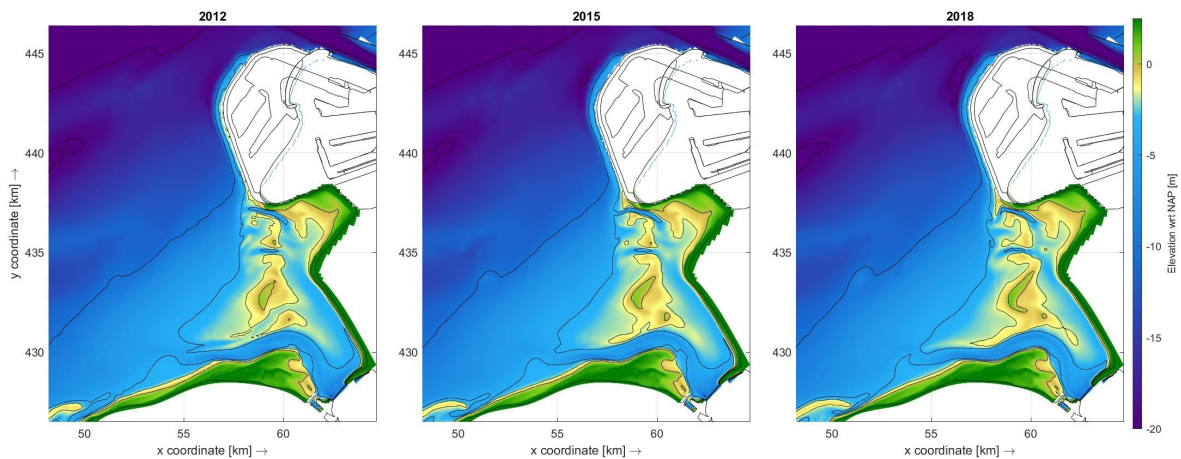


Figure 3.10: **Vaklodingen bathymetry data-sets (a) 2012 (b) 2015 (c) 2018**. Complete maps have been compiled by filling data from the closest years with measurements available. River bathymetry is only retrieved for the 2018 case.

The accuracy of the *Vaklodingen* dataset has been assessed by Wiegmann et al. (2005) and Perluka et. al (2016), estimated between 0.11 m and 0.40 m. The errors originate from: (1) stochastic errors due to individual data outliers, (2) systematic errors due to the instruments, and (3) systematic errors due to user's measuring and handling of the data.

3.4.2. Bed composition

In general, sediment fractions in the coastal zone show strong segregation due to wave processes in the cross-shore direction. Fine sediments can be found near dune foot, coarser material near the waterline (swash processes), and a growing fining towards deepwater (Z. B. Wang et al. 2012). Trends in the grain size distribution in the coastal areas may also be helpful to indicate the transport patterns. During prevailing conditions, gradual coarsening of erosion areas are expected as fine material leaves the bed. Sedimentation areas experience a fining bed due to the incoming material (Terwindt 1973).

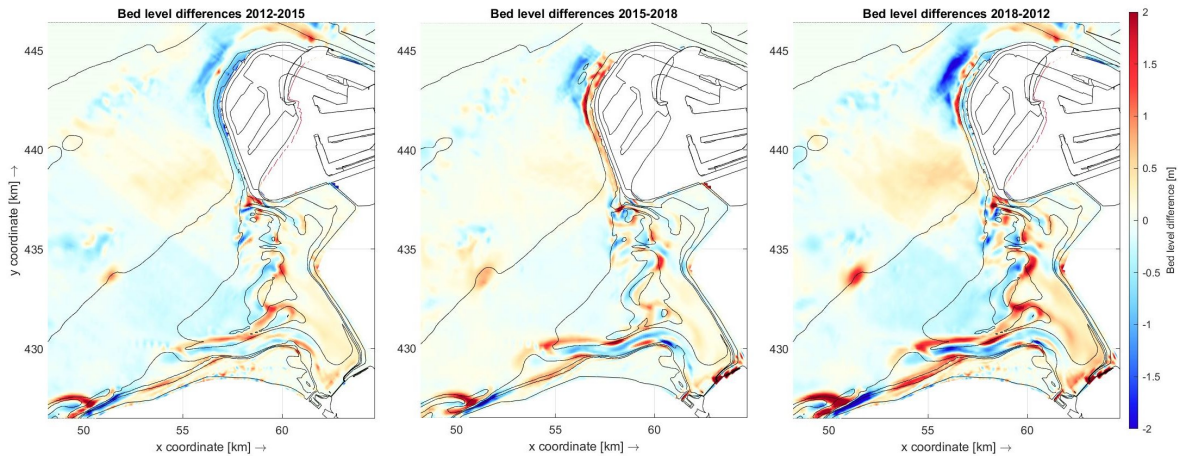


Figure 3.11: **Bed level differences for the periods (a) 2012-2015 (b) 2015-2018 and (c) 2018-2012.** In all periods, the eroding of the delta front is observed along with the siltation of the sheltered areas behind the ETD. Channels show an eroding trend while shallows continue to accrete in the landward side. The patterns in the Slijkgat show the problematic sedimentation areas to the north and north-east of Kwade Hoek, and where the channel flows into the sea to deeper water.

Close to the period after the damming of the SW Dutch estuaries, a gradual fining of the submerged delta at the Eastern Scheldt towards the Haringvliet was observed, indicating the northward sediment transport patterns along the coast. Additionally, the riverine contribution of sediments was already negligible before the damming of the Haringvliet. The upstream region of the Haringvliet (upstream from the sluices) acts as a sink of riverine material, supplying almost none to the mouth. Therefore, the main source of sediments is marine (Ye 2007).

The Slufter and MV2 land reclamation, have produced increasing sheltering of the mouth changing the dynamics of the area and varying the bed composition as well. Figure 3.12 shows a survey from 2001 by Koomans (2001); the situation presented in Figure 3.12a is already quite different from previous studies (e.g. Van Vessem 1998; Terwindt 1973). At the sheltered side of the ETD, grain size is generally $D_{50} < 75 \mu m$ except immediately downstream from the sluices (where a scour pit is located) and at the coast of Goeree. The seaside of the ETD shows a bed composed of a material with $150 \mu m < D_{50} < 250 \mu m$. At the Slijkgat, Middengeul, and the Bokkengat the grain size is $200 \mu m$.

Due to the decreasing dynamic environment at the mouth consequence of all the interventions over the years, the decreased flow velocities resulted in higher mud concentrations at the Haringvliet mouth. Figure 3.12b shows the mud content distribution at the mouth. The highest concentrations reach 90% just east from the Haringvliet sluices. Most of the sheltered area present mud contents of 60-80% including the Slijkgat, seawards of the ETD mud contents $< 20\%$ are found. At the Kwade Hoek and just outside the sluices, the mud content is the lowest and almost absent at the Middengeul and Bokkengat (Koomans 2001).

Another consequence of the sheltering effects is the infilling of channels with mud, reaching thicknesses between 4.8-7.5 m, not easily eroded (Elias et al. 2016). Ye (2007) showed that waves are mainly responsible for the transport of cohesive material to the north. A model developed by Dam et al. (2006) for predicting morphological changes in the Haringvliet implements a sand-silt model against sand or silt only. The former accounts for the interaction between sand and silt content in the erodible layer of the model. The silt only model computes the erosion of each fraction independently. The first approach, the silt-sand ratio to define the type of transport (cohesive for mud/silt or non-cohesive for sand). The second approach depends only on the availability of sediment on the top layer, which might result in unrealistic erosion from either fraction.

The results showed that the sand-silt model shows a more realistic development of the Haringvliet mouth as the approach dictates a cohesive behavior of the Rak van Scheelhoek channel, hard to erode while the Slijkgat channel erodes easier due to its sandy characteristic. The sand or silt independent

model produces the unrealistic erosion of Rak van Scheelhoek, triggering important morphological changes towards the Hinderplaat, not really observed in reality (Dam et al. 2006). The study shows that bed composition can be essential for reproducing real development in morphological models.

Similarly, suspended sediment concentrations must be considered. Under normal discharge conditions, silt concentration is between 30 to 70 mg/l and can reach up to 90 mg/l due to wave action. The suspended material consists of 15 to 30 % of very fine sand or mud ($< 63\mu\text{m}$). The average suspended material concentration immediately east from the sluices is 20 mg/l; approximately 60-75% of it is mud. Under such conditions, suspended sediment concentrations at the mouth are 2 to 5 times larger than along the waterway upstream (Van Vessum 1998).

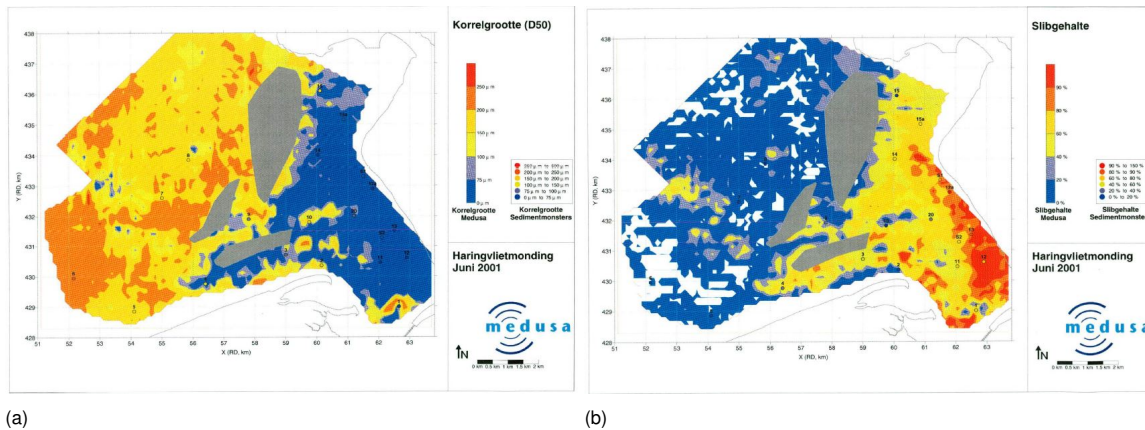


Figure 3.12: **Bed material distribution at the Haringvliet mouth.** (a) Median grain size D_{50} , shows the highest values at the seaside of the ETD, just out from the Haringvliet Dam and along the Slijkgat channel. The smallest values ($< 75\mu\text{m}$) are located mostly in the sheltered area behind the ETD, to the north-east of the dam and along the Rak van Scheelhoek channel. (b) Silt content shows the highest content north-east from the dam and along the Rak van Scheelhoek channel and some locations along the Slijkgat. Lower silt content is observed in the seaward side of the ETD, location at the Goeree coast, and the Bokkegat. Gray areas are shallows where no measurements were taken. (Retrieved from Koomans 2007).

3.4.3. Sand Balance of the Haringvliet

Finally, a gross sand balance of the Haringvliet is addressed in Elias et al. (2016), who estimated that approximately 3.5 mcm/y (million cubic meters per year) of sand bypasses the Haringvliet with an increase of the ETD volume of 0.2 mcm/y. Similarly, Van Vessum (1998) reported 3.1 mcm/y being imported to the basin with most sedimentation occurring above the NAP -4 m depth contour, no export volume is reported.

3.4.4. Transport processes in the Haringvliet

According to De Vries (2007) the most important processes in the Haringvliet mouth are tide-driven currents mainly transporting material into the basin (flood dominance); net long-shore transport due to oblique incident waves towards the north; cross-shore transport eroding the ETD front and depositing material landward; discharge-driven currents; circulation currents around the shoals due to water level gradients and wind-driven residual currents.

The latter proved to be extremely important in the shallower areas of the Haringvliet mouth but, the need for wave processes is fundamental to stir up the sediment and make it available for transportation (Colina Alonso 2018). In the case of tidal-currents, the same conclusions were drawn by De Vries (2007): wave influence makes the difference between significant and non-significant morphological changes for other transport mechanisms. Nevertheless, the prevailing wave conditions at present may differ from those of the studies because of the sheltering effect of the MV2.

On the other hand, high river discharges by themselves are capable of producing large morphological changes, producing strong currents in the ETD, and inducing the erosion of present channels or the

creation of new ones (De Vries 2007; Colina Alonso 2018). These modeling studies concluded that for the situation of an elongated Hinderplaat, before the construction of the MV2, WSW wave conditions showed the highest transport rates. WNW to N regular wave conditions play an essential role in the evolution of the Hinderplaat and other shoals in the ETD. Furthermore, from Figure 3.7 for the 2018 state, it is clear that SW waves are still reaching the area and might still be of importance for the morphological development. This direction is progressively becoming more shore-normal to the ETD front.

3.4.5. Sediment Transport Patterns

The previously explained transport mechanisms will produce residual sediment transport that will ultimately drive the morphological changes. The net sediment transports have characteristic pathways that will depend on the present bathymetry and the mentioned driving processes. Colina Alonso (2018) developed a series of model simulations with varying processes and magnitudes to determine, firstly, which are the most important ones, and secondly, how they influence the sediment patterns. Figure B.4 show the results for SSW to WNW conditions.

The figure shows strong sediment transport patterns from the coast of Goeree towards the Haringvliet mouth. Over and along the Hinderplaat high transport rates are also observed for these conditions, especially for the WSW case. For WNW conditions, sediment transports in the offshore-northward direction and landward transport over the shoal. These patterns are consistent with theory as lower rates are observed for more perpendicularly incident waves.

The present morphology of the ETD shows a delta front with a more parallel alignment to the MV2 coastline, different from the elongated Hinderplaat, aligned with the Slufter (see Figure 3.2). Therefore, the wave conditions that will generate the highest transport rates will differ from the results of the mentioned studies. However, it can be suspected that it will be due to SSW to WSW wave conditions (see also Figure 3.7).

4

Hypotheses and Modelling approach

This chapter treats in Section 4.1 the hypotheses of the system evolution due to the Delta21 intervention based on a conceptual model. Section 4.2 presents the modeling approach to prove the stated hypotheses and answer the research questions of this study.

4.1. Hypotheses

Related to the findings of the literature study concerning the general theory of tidal basin systems, and the specifics of the study area, a hypothetical conceptualization of the Haringvliet mouth under the Delta21 intervention is made. The system is considered to develop freely, i.e., no maintenance dredging at the Slikgat is performed, a nourished sandbank in the seaward side is not considered either. The objective of the conceptual model is to give an insight into how the system could evolve under the D21 conditions. Figure 4.1 is the hypothetical model. It helps derive specific hypotheses that will serve as a guide for the first simulation stage of the present study.

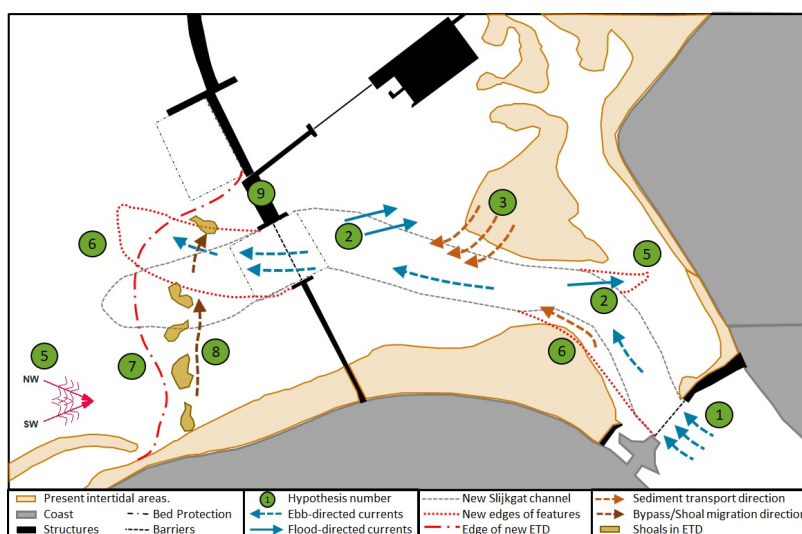


Figure 4.1: **Hypothesised model of the system's evolution due to Delta21 intervention.** With the intervention as the Delta21 plan proposes the system is expected to face significant morphological changes. New features are expected to emerge just outside the new tidal inlet generating features characteristic of an ebb-tidal delta. Important changes are also expected to happen inside the Tidal Lake (present ETD), as river discharge will flow more constantly. Features presented in the figure are exaggerated for representation purposes.

1. The constant river discharge passing through the Haringvliet Dam will hinder flood currents into the estuary. River material will flow into the estuary again, promoting the siltation of the TL.
2. Flood currents flowing into the Tidal Lake will look for the easiest path and will not necessarily follow the Slikgat channel upstream of the Haringvliet dam.
3. Ebb-currents will promote the transport of sediment from the Tidal Lake (former Hinderplaat) to the seaward side.

4. SW to NW wave conditions will become more shore normal and will become important for the development of the outer delta.
5. New flood chutes will be formed over the deposited material inside the Tidal Lake, developing a new flood tidal delta.
6. Flow in the Slikgat will look for a more efficient path, shifting the orientation of the channel towards the east. Erosion at Kwade Hoek will be induced smoothing the edge.
7. A terminal lobe will be formed between the coastline of Goeree and the edges of the ESL. The conditions might be proper for the development of a more symmetric ETD.
8. Sediment transport along Goeree's coast will form shoals at the updrift edge of the Slikgat. Sediment accumulation will enable sediment bypassing downdrift, induced by SSW-WSW wave conditions, in the form of shoal migration or sediment transport loads.
9. The area downdrift between the developing ETD and the edge of the ESL will be mostly a sheltered area, attracting sediment for deposition.

4.2. Modelling Approach

A process-based Delft3D model is chosen to forecast the evolution of the Haringvliet mouth in the presence of the D21 plan. The model predicts the hydrodynamics of the new system by resolving the Shallow-Water Equations (SWE). To simplify the model and reduce computational times, the model neglects 3D effects. The SWE are depth-averaged. Changes in bathymetry are the result of the prevailing flow conditions, and simultaneously they are depth-dependent. To account for this positive feedback between hydrodynamics and morphology, a morphodynamic model is implemented, i.e., bed elevation is updated each time-step the result of the prevailing hydrodynamic conditions.

The modeling approach is based on the two main goals: achieving a long-term realistic evolution of the study site within acceptable computational times and assessment of original and new intertidal areas. An overview of the techniques to implement the long-term model is elaborated in Section 4.2.1, the specific implementation is addressed in Chapter 5. The model simulations for the assessment of intertidal areas are elaborated in Section 4.2.2. The process is depicted in Figure 4.2 and the first simulation exercise corresponds to the **S0** stage. The second stage will be covered by simulations **S1**. The relation of each stage with the research questions is presented in Table C.1.

4.2.1. Long-term simulation

To predict the evolution of the system with the Delta21 plan implementation, firstly, a long-term simulation is performed. Long-term morphological simulations represent a challenge. Reducing computational times while still having a proper representation of the prevailing forcing conditions is the key problem. The forcing needs to be schematized by input reduction procedures in combination with acceleration techniques, i.e., a morphological acceleration factor (MF).

Both approaches are applied for this long-term simulation, input reduction through schematization of the tide, discharge, waves, and wind, combined with MF values, in an online approach (see Chapter 5). An online approach implies that bed level changes are updated each hydrodynamic time-step and multiplied by MF. It is also important to consider that during morphological simulations, each of the reduced wave conditions should be simulated for the duration of full morphological tides to account for the natural random phasing between waves and tides, especially when a morphological tide is implemented with a morphological acceleration factor (Lesser 2009).

The MF acceleration technique is based on the principle that changes in the currents happen at a much smaller time-scale than morphology changes. A linear relation between the morphological response and the hydrodynamic forcing for each time-step is assumed, and the bed level changes are multiplied by this value (Ranasinghe et al. 2011). The updated bathymetry is fed to the hydrodynamic computations for the next loop; the modeling scheme is shown in Figure 4.3.

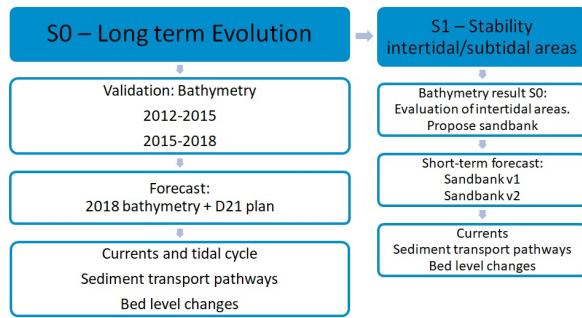


Figure 4.2: **Process of the modeling study for the different scenarios.** S0 simulations focus on the long term development of the system and its behavior once Delta21 is implemented, whereas S1 simulations focus on evaluating further the stability of intertidal areas by applying short-term simulations for the initial response.

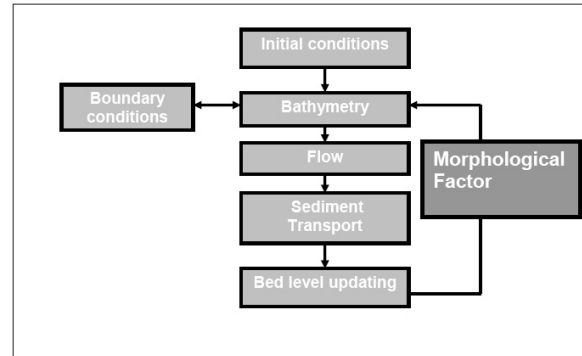


Figure 4.3: **Model approach flowchart.** MorFac implementation, bed level each hydrodynamic time-step is multiplied by the MorFac for morphological acceleration.

When the concept is applied in coastal situations with time-varying forcing conditions such as oscillating tidal currents, it becomes slightly less straight forward. The applied hydrodynamic forcing must match the desired time scale of the morphodynamic changes. Therefore, it is also recommended to apply small factors for extreme events of the forcing and larger ones during milder and relative constant hydrodynamic conditions (Roelvink 2006). The implementation of a variable MorFac becomes necessary, depending on the specific wave condition forcing the model. The implementation is further explained in Section 5.4.

A virtual reality approach is followed, the MF in the long-term model is validated for the periods 2012-2015 and 2015-2018 Vaklodingen data, both under the "No Delta21" scenario ¹. The forecast for the Delta21 implementation will be performed for a time frame of 3 years, also the validation period. The modeling exercise requires modifications to the model, i.e., the extension of the grids, to take into account the returned tidal motion to the estuary (see Chapter 5) and extend the higher resolution wave-grid further offshore.

The downside of this approach is that the calibrated/validated model is likely to deviate from the "true" evolution the farther the simulation progresses past the calibration/validation period, which should be similar to the duration of the forecast period (Dissanayake et al. 2012). The goal of this simulation is to have a first impression of the system's response to the Delta21 intervention. The proposed time-frame of 3 years is considered acceptable. The results for this modeling stage are presented in Chapter 6 from which a conceptual model is derived in Section 8.1.

4.2.2. Short-term simulations

The second stage of the modeling study is the assessment of the stability of intertidal areas, original or new. This stage is identified as S1 in Figure 4.2. Short-term simulations will be carried out to observe the influence of the different forcing and determine which of them have a bigger influence on sediment transports and morphological changes that might produce positive feedback in the evolution of new shallow areas.

The analysis is conducted by short-term morpho-static simulations **S1**. The simulations will be performed for specific wave conditions to evaluate sediment transports generated that will generate morphological changes in the new shallow areas of the system. A lower constant MF=5 is implemented. Each simulation will correspond to a constant wave condition (and corresponding wind) and regular discharge conditions (see Section 5.2.5). The assessment will be done for at least two configurations of a nourished sandbank outside the TL. The results of this modeling stage are presented in Chapter 7 from which a conceptual model of the stability of the intertidal/subtidal features is derived in Section 8.2.

¹The "No Delta21" scenario implies that the current policy for the Haringvliet sluices applies, the Kierbesluit.

5

Model Set-up

The present chapter explains the process of the model set-up, focused on the long-term simulations, although it also mentions the considerations for the short-term simulations. Firstly, Section 5.1 presents the considered general scenarios of the system, based on the Delta21 operation. Secondly, the model set-up is explained in Section 5.2, explaining the grid and bed schematization, the flow boundary conditions (tide, discharge, and waves), and finally, the transport considerations. Section 5.3 elaborates on the model's calibration. The morphological model implementation for a long-term run, along with the validation periods to choose the implemented MF values, are presented in Section 5.4.

5.1. Delta21 scenarios and operation.

According to the operational conditions of the Delta21 plan and the hydrodynamics explained in Chapter 3, the scenarios shown in Table 5.1 are derived. The scenarios are based on discharge data for the *Bovensluis* station (51° 41' 33.00"N, 4° 29' 36.24"E) during the period 1997-2017 (Rijkswaterstaat 2020c).

D1 scenario corresponds to the situation where the sluices at the Haringvlietdam are closed due to low discharges from the river ¹. Delta21 plan sets this condition to be when discharges at Lobith are less than 1,000 m³/s, translated in discharges in average less than 230 m³/s (see Section 5.2.5 and Appendix D for the derivation). Under such a scenario, no discharge would flow into the Tidal Lake (nor into the ESL).

Scenario **D2** and **D3** are related to more regular discharge regimes with a probability of occurrence of 37% and 36% of the year, respectively. Under these conditions, the Haringvliet Dam is completely open, allowing the tide to flow in and out of the estuary through the Tidal Lake. The siphon between the Tidal Lake and the ESL stays closed.

The high regime scenario **D3** corresponds to a regime of a mean discharge of 2,126 m³/s happening 11.4% of the year. During such higher discharges, the situation regarding the Haringvlietdam and the siphon is maintained. **D4** scenario corresponds to extreme discharges (according to the Delta21 boundary conditions, of 10,000 m³/s or larger). In case of such extreme discharge, the new Storm Barrier will be closed to funnel all the flow into the ESL through the siphon between it and the TL.

According to Steijn et al. (2001), storm conditions are more probable to occur combined with low to regular discharges and hardly ever happen during high to extreme discharges. Therefore, storm conditions will only be combined with **D1** and **D2** discharge scenarios, and for scenarios **D3**, the new Storm Barrier will be considered to be always open.

The class corresponding to a high discharge regime has an upper bound at 7,000 m³/s since, in the 20-year record (1997-2017), the maximum registered discharge was 6,575 m³/s. Only during the 2014-2017 period, the discharge did not exceed 3,500 m³/s. The extreme discharge depicted in scenario **D4** is then considered to have a very low probability. This is why scenarios **D1** and **D4** will not be considered in the schematization of the discharge for the long term simulations (see Section 5.2.5).

¹ The Haringvliet sluices are only closed in the case of this scenario

Table 5.1: **Derived Delta21 scenarios to consider in the modeling exercises.** Scenarios **D1** and **D4** will not be considered for the schematization of the long term simulation. Scenarios **D2** and **D3** show more regular conditions and will be the ones taken into account for the schematization.

Scenario	Discharge Regime	Discharge Classes	Probability of occurrence	Haringvliet dam	Siphon (w/ ESL)	Storm	Tidal Lake Storm Barrier
[-]	[-]	m ³ /s	[%]	[-]	[-]	[-]	[-]
D1	Low	0-230	0.111	closed	closed	Yes	closed
D2	Regular	230-500	0.3734	open	closed	Yes	closed
		500-1500	0.3641	open	closed	Yes	closed
D3	High	1500-3000	0.1141	open	closed	No	open
		3000-7000	0.0338	open	closed	No	open
D4	Extreme	>10,000	0.00027	open	open	No	closed

Related to the functioning of the whole Delta21 infrastructure, is relevant to consider the pumping-power station (PPS) operating at the ESL, just down-drift from the new Tidal Inlet. As explained in Section 1.5, volumes of maximum 10,000 m³/s are expected to flow in and out the ESL through the PPS, in roughly a 24 hours cycle (12 hours filling and 12 hours emptying the lake). In reality, the filling-emptying of the ESL will depend on energy demand. For the purposes of this research a fixed 12x12 hour cycle, from 7:00 to 19:00 filling operations, generating through the turbines and from 19:00 to 07:00 pumping water volumes to empty the lake.

Figure 5.1 shows the schematized signal of the volume discharged by the PPS compared to the tidal signal (in the model) at a location ≈ 800 m from the PPS. Since the tide has a 12 hours 20 minutes period, both signals are out of phase, as can be depicted in the figure, disturbing the water level motion. Additionally, with the goal to schematized regular conditions, the discharged assumed to be pumped each cycle is assumed to be the lakes' storage volume (360 Mm³) in the 12 hour operation, resulting in a discharge of $\approx 8,100$ m³/s.

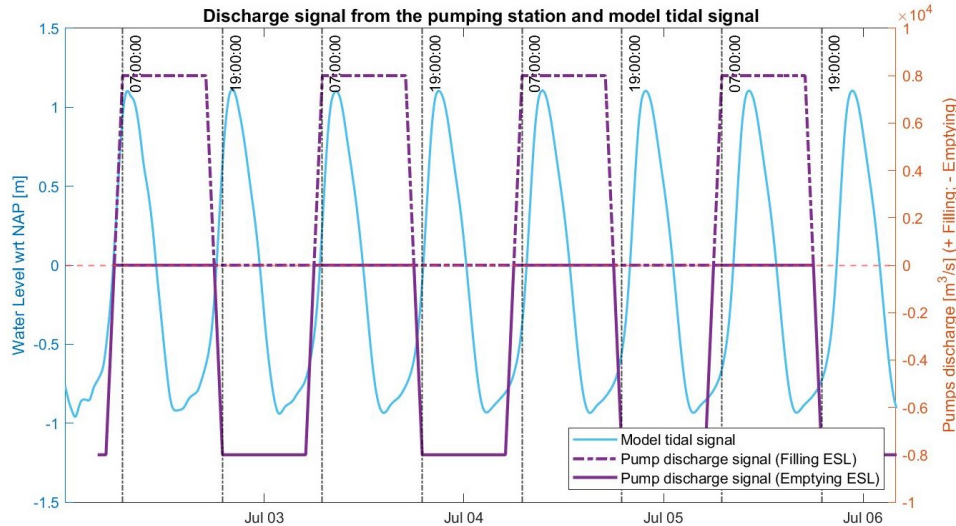


Figure 5.1: **Discharge signal from the pumping station at the ESL and tidal signals at a close location.** During the day period (7:00 to 19:00), the ESL will be filled, positive values of the purple plot. During the evening-night period (19:00 to 07:00), the lake will be emptied, negative values of the purple plot. The tidal signal with a period of 12 hours 20 minutes compared to the pumped discharge will be out of phase, causing a disturbance to the water level motion.

Another relevant feature is the realignment of the Slijkgat channel to guide the tidal currents and river flow through the new inlet. As the new barrier will be the only link with the sea, the entire water volume has to flow through this section. At the moment of this study, the section of the tidal inlet and the channel has not been designed. However, general considerations are done to schematize it in the model. Firstly, the current depth of the channel is at NAP -5.0 m, but with the Delta21 project in place,

a larger water volume will need to be discharged. As a recommendation from the Delta21 initiators, maximum current velocities in the Tidal Inlet of around 1.0 m/s should occur. The channel's width, according to the layout design, is proposed as 1,000 m (1,500 m at the barrier). Considering that the tidal prism before the closure of the estuary was in the order of 308 Mm³ (Van Wijngaarden et al. 2002), equivalent to $\approx 6,940 \text{ m}^3/\text{s}$, roughly the depth of the channel should be in the order of 7.0 m depth.

5.2. Model Set-up

Delft3D is a multidimensional hydrodynamic simulation program that computes non-steady flow and transport phenomena from tidal and meteorological forcing on rectilinear or curvilinear grids. It can be coupled with the WAVE- and SED-module to compute short wave propagation and cohesive/non-cohesive sediment transports, respectively (Deltares 2011a). The WAVE-module can be coupled "offline" or "online" with the FLOW-module; the present study will use the "online" utility of the software.

At the open boundaries, the forcing can be specified in the form of water levels (astronomical, harmonic, or time series), velocities, Neumann (water level gradients), or discharge (total or per grid cell). Delft3D applies a staggered grid, in which water levels and constituents are computed at the center of the grid cells. The velocity components are computed at the middle of the grid cell sides, and depth is computed at the grid cell corners. The computational grid should be large enough to prevent boundary disturbances from entering the area of interest, while the number of grid points should be limited to reduce computational times. Resolution in the area of interest should be fine enough to resolve the desired details. Bearing all these considerations in mind, the model is set-up, as explained in the following sections.

5.2.1. Grid and Bed schematization

The model is built upon 3 grids; one is used by the FLOW-module to compute water levels and currents, whereas the other two grids are used by the WAVE-module to compute the evolution of short waves towards the shore. The FLOW-grid extends from Noordwijk at the northern boundary to Nieuw Haarstede at the southern boundary in the long-shore direction and extends approximately 25 km offshore. It has an inland open boundary at the location of the Haringvliet Dam.

The original FLOW-grid was implemented in previous studies (i.e., Steijn et al. 2001; Holland 1997; De Vries 2007; Colina Alonso 2018). The present study aims to understand the development of the Haringvliet ETD once the Delta21 plan is implemented, which implies the returned tidal motion into the estuary through the sluices. To achieve the proper tidal motion propagating in and out the estuary, the FLOW-grid is extended 44 km upstream from the dam (see Figure 5.2a). The grid resolution is in the order of 90x90 m² at the ETD area, coarsening further offshore and towards the northern and southern boundaries with a maximum resolution in the order of 800x800 m². The resolution was maintained just upstream of the dam and coarsens towards the right bank and further upstream; the maximum grid cell size is approximately 550x300 m.

The WAVE-grids are depicted in Figure 5.2c and Figure 5.2b. The larger WAVE-grid covers the area of the North Sea with a resolution of 600x600 m² while the smaller grid covers the Haringvliet delta with a higher resolution (50x50 m²). The small grid is nested in the larger one. Together, they cover the entire FLOW-grid and even extend further at the southern boundary. The extension guarantees that the waves are fully developed once they enter the FLOW-grid domain (De Vries 2007).

In the coastal areas, the bathymetry is schematized with Vaklodingen datasets for the years 2012, 2015, and 2018. Rijkswaterstaat data for the estuary area is also available, representative of the year 2016 (Rijkswaterstaat 2020d). The depth measurements are triangularly interpolated, or grid-cell averaged to the curvilinear grid, and further smoothed to reduce small scale disturbances. The three data sets of bathymetry are shown in Section 3.4.1 in Figure 3.10.

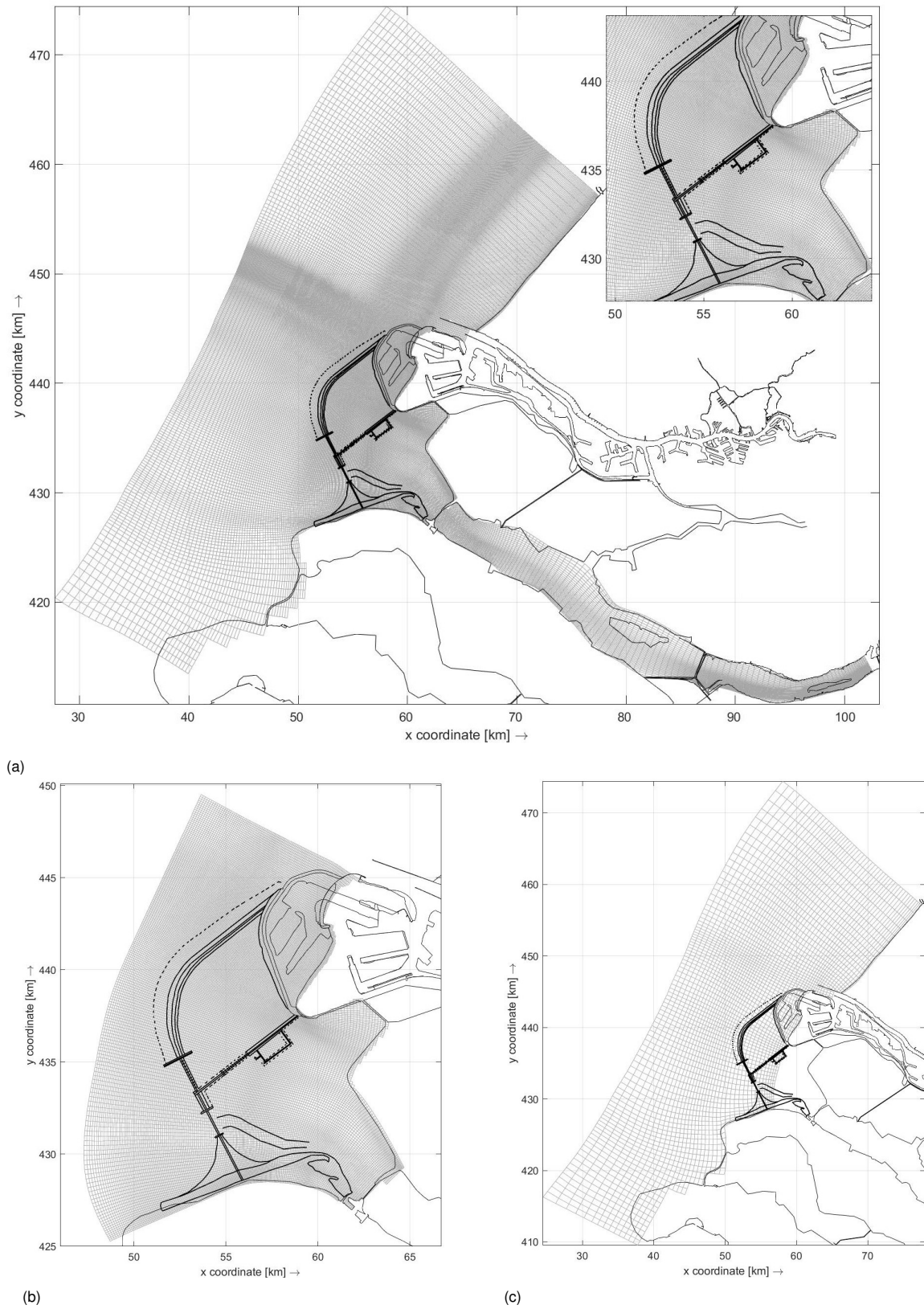


Figure 5.2: **Computational grids in the model** (a) FLOW-grid extended approximately 50 km upstream from the Haringvliet Dam, the insert to the right shows the resolution closer to the delta area where resolution is in the order of $90 \times 90 \text{ m}^2$. (b) Nested WAVE-grid, extended offshore to cover the Delta21 area, resolution in the order of $50 \times 50 \text{ m}^2$ (c) Original WAVE-grid with resolution in the order of $600 \times 600 \text{ m}^2$, together with the smaller one, cover the entire FLOW domain.

In previous studies, the bed material has been schematized by two sediment fractions: mud and sand (e.g., Steijn et al. 2001; Holland 1997; De Vries 2007). Mud was schematized by mud layers placed over part of the bathymetry, assumed to protect the sand layers below, which will not erode until all mud above has eroded. In the more recent study by Colina Alonso (2018), only the sand fraction was implemented. Both studies use a median grain size (D_{50}) of 160 μm .

At the Haringvliet mouth, mud content has increased while sediment grain size has decreased in the last years, due to less dynamic conditions (see Section 3.4.2). Even though Dam et al. (2006) show the importance of the silt content and cohesive transport in the model to accurately predict the morphological development of the Haringvliet mouth, to avoid complex modeling, a single grain class will be kept. This is especially true for the Rak van Scheelhoek channel's development. However, according to Figure 3.12a, at the seaward side of the ETD, sediment sizes between 150-200 μm predominate. Most of the material has a marine origin, and the morphological changes of interest are principally at the ETD and the seaward side (especially after Delta21 intervention); a $D_{50} = 160 \mu\text{m}$ is considered to be representative of the bed conditions.

5.2.2. Flow boundary conditions

Three different boundary conditions are prescribed at the model open boundaries. At the long-shore boundary, offshore harmonic water levels are prescribed. At the cross-shore boundaries, Neumann boundary conditions are set, and at the inland boundary, river discharges are applied.

Water level boundary conditions were derived and validated in previous studies (Holland 1997; Roelvink 1999). Later Steijn et al. (2001) calibrated and validated the model to predict the effects of the MV2. The model was improved by new Neumann boundary conditions for the southern and northern boundaries ((De Vries 2007)). In the present study, we derive new discharge boundary conditions at the new inland boundary based on discharge information at *Bovensluis* station located at (51° 41' 33.00"N, 4° 29' 36.24"E)². Wave conditions are prescribed in the wave model to run in parallel with the flow model. All modeling exercises are forced with the wave climate derived by De Vries (2007).

5.2.3. Tide boundary conditions

To reduce computational times, input reduction techniques become extremely relevant, especially for long period simulations. In tidal input reduction, the objective is to replace the complex varying time series of tidal water levels with a simplified (morphological) tide. The representative simpler is such that its morphological impact is as similar as possible to the average morphological changes (or residual sediment transports) occurring during an entire spring-neap cycle of real tides (Lesser 2009). The entire spring-neap cycle is reduced to a single cyclic signal (Moerman 2011), and the residual sediment transport generated by it is assumed to be representative of the long-term mean transport (Chu et al. 2015).

The morphological tide in the present study was previously used in the model with the work of De Vries (2007) and Colina Alonso (2018). It was originally derived by Holland (1997) using a nested model. The tidal signal is represented as the summation of harmonic components, obtained from harmonic analysis. It considers 8 components, M_2 and M_4 being the most important; daily components are neglected. The morphological tide is a cyclic constant tide of a 12 hour 24 minute period and has a tidal range 1.1 times bigger (1.91 m) than the average real tidal range (Holland 1997). Figure 5.3 compares the water level signals of tidal measurements and the morphological tide.

The resulting signal does not display the spring-neap cycle, generated by M_2 - S_2 interactions, nor daily inequality generated by interactions of diurnal components, e.g., K_1 or O_1 . In estuaries with deep channels and drying intertidal flats, this is an important limitation. The lack of maximal high waters or lowest low waters reduces the maximum current velocities in the channels (Holland 1997), causing smaller residual currents. The latter has an important implication in morphological evolution as residual

²It is assumed that the discharge regime derived from this data will be representative of the new situation even though it neglects the new discharge distribution between the Haringvliet and the Nieuwe Waterweg if the Haringvliet is reopened.

currents are the ones ultimately dictating the changes of the bed. Nevertheless, the variation of the spring-neap cycle through the year is filtered out in the cumulative transports (Holland 1997).

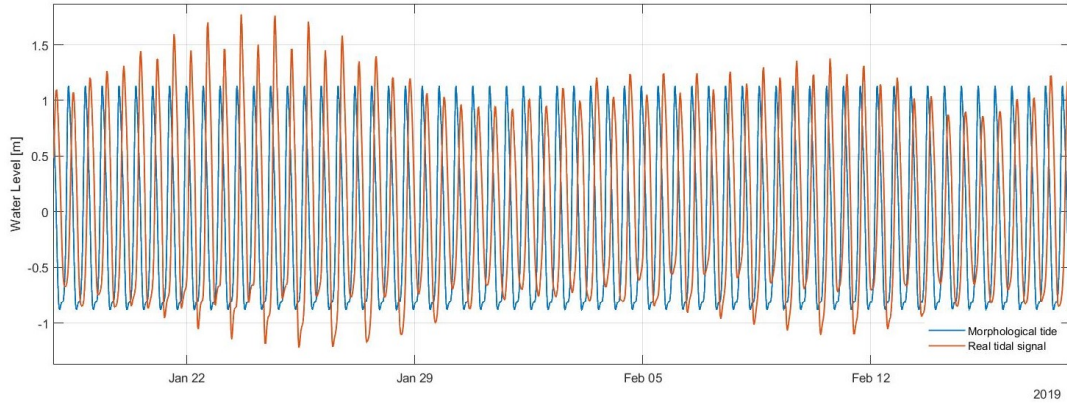


Figure 5.3: **Morphological tide and real tide signals for the spring-neap cycle.** Morphological tide is retrieved from the model at the location of the Hinder channel, and the real tidal signal is from the *Haringvliet 10* station from *Delft Dashboard* (Van Ormondt et al. 2020) for the year 2019. The spring-neap cycle and daily inequality are present in the tidal water level measurements but lost for the morphological tide.

According to Van de Kreeke et al. (1993), in estuarine environments with a small residual current, a morphological tide that considers the interaction between M_2 , M_4 and M_6 tidal components causes tide-induced long-term (several months) bed-load transports, representative of the full tidal signal. Interactions with S_2 cause sediment fluxes varying in time with the beat frequency (a period of around 14 days) and in the long-term (in the order of several months) their influence is averaged out. Triad interactions with diurnal components, i.e. M_2 with K_1 and O_1 , have a net contribution to residual sediment transports and depends on the phase angle difference between $K_1 + O_1$ and M_2 (Chu et al. 2015). However, its importance is minor if $2K_1O_1 < M_2M_4$ (Lesser 2009). When M_2 tide dominates, as assumed in this research,³ net contributions from semi-diurnal interactions are more relevant.

When residual currents are strong, i.e., in the presence of relatively high river discharges, the net sediment transport is underestimated, and contributions of the daily components K_1 and O_1 become important (Chu et al. 2015). Chu et al. (2015) presents a case where daily components are important with residual current velocities in the order of 0.3-0.5 m/s and an amplitude of the M_2 component of 1.2 m at the mouth. In the present study, current velocities are in the order of 0.2 m/s for regular discharge conditions, and the M_2 amplitude at the Haringvliet mouth is in the order of 0.95 m. It is concluded that the representative tide derived by Holland (1997) is still acceptable for reproducing reliable sediment transports in the simulations of the present study. The water level at the boundary is described by Equation 5.1 and implemented as a harmonic boundary condition.

$$\xi(t) = A_0 + \sum_{i=1}^n A_i \cos(2\pi f_i t - \varphi_i) \quad (5.1)$$

Where:

$\xi(t)$ water level elevation at the boundary at moment t .

A_0 mean water level over a certain period.

A_i local tidal amplitude of harmonic component i .

f_i frequency of the harmonic component i .

φ_i phase of harmonic component i .

The amplitude of the mean water level is determined by the surge level and should be computed for each wave condition as it depends on the related wind speed and direction. The surge level is not included in the present model.

³The relation is approximated from the tidal components available for *Haringvliet 10* station from **DDB** as $2K_1O_1 = 0.014 \ll M_2M_4 = 0.165$ (Van Ormondt et al. 2020).

5.2.4. Neumann boundary conditions

At the cross-shore boundaries, instead of a fixed water level, alongshore water level gradients are prescribed (Neumann boundary conditions) (Colina Alonso 2018). The water level gradients need to be derived for each tidal component, and they are also imposed as a harmonic boundary condition. For further detail, in their derivation, the reader is referred to the study by De Vries (2007).

5.2.5. Discharge

The river discharge schematization is based on the scenarios considered for the Delta21 plan in Table 5.1. The objective is to compute representative discharge regimes occurring along the Haringvliet, firstly, defining low, regular, and high regime conditions and secondly making a seasonal yearly schematization.

Figure 5.4 shows the probability analysis for 1997-2017 record of daily mean discharge measured at *Bovensluis* station, approximately 35 km upstream from the Haringvliet Dam, located at $51^{\circ} 41' 33.00''\text{N}$, $4^{\circ} 29' 36.24''\text{E}$ (for the full record see Figure D.3). The entire record was divided into bin classes of $250 \text{ m}^3/\text{s}$ width. Figure 5.4b clearly shows that discharges between $250 \text{ m}^3/\text{s}$ and $500 \text{ m}^3/\text{s}$ have the largest probability of occurrence (35%) and discharges of approximately $520 \text{ m}^3/\text{s}$ or less happen 50% of the time (Figure 5.4a).

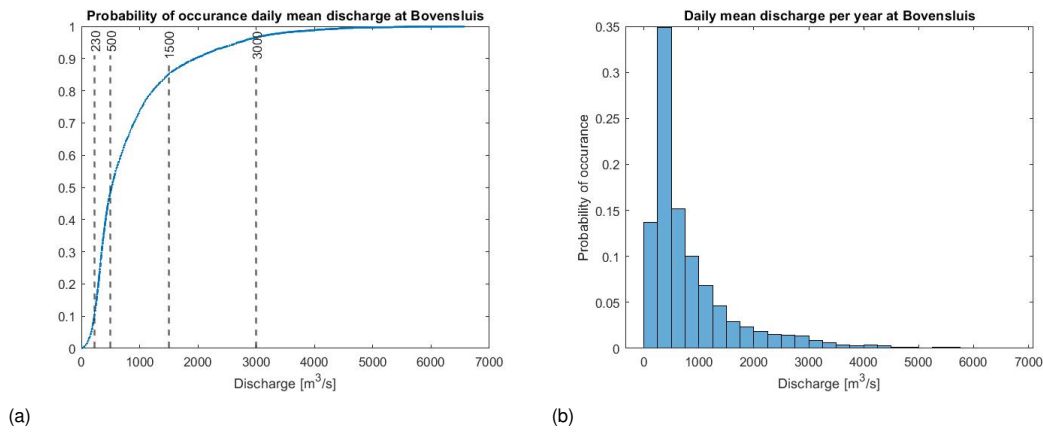


Figure 5.4: **Probability distribution of river discharge according to daily mean discharge measurements at *Bovensluis* Station.** *Bovensluis* station is located at $51^{\circ} 41' 33.00''\text{N}$, $4^{\circ} 29' 36.24''\text{E}$ and the analysis is done for data in the period 1997-2017 (a) Probability of Occurrence. Discharges lower than $3,000 \text{ m}^3/\text{s}$ have a 96.6% probability of occurrence and 50% of the time discharges of $518 \text{ m}^3/\text{s}$ or less occur. (b) PDF for bin classes of $250 \text{ m}^3/\text{s}$ width. The class with larger probability of occurrence ($\approx 35\%$) are discharges between $250\text{-}500 \text{ m}^3/\text{s}$.

Discharges greater than $4,000 \text{ m}^3/\text{s}$ hardly ever happen. In the record, the maximum mean daily discharge registered was $6,575 \text{ m}^3/\text{s}$ on January 6th, 2003. Before this period, an extreme mean daily discharge of $9,015 \text{ m}^3/\text{s}$ was computed in 1995 (Colina Alonso 2018). Because the mentioned extreme discharge is not included in the analyzed period, the class intervals derived for this schematization have as an upper bound of $7,000 \text{ m}^3/\text{s}$.

For a model simulation with a duration of several years, the seasonality of the forcing must be considered. Figure 5.5 shows the yearly distribution of the mean daily discharge data. From the data points, 2 seasons are identified: a winter season with discharges reaching more than $4,000 \text{ m}^3/\text{s}$ and an average of approximately $1,160 \text{ m}^3/\text{s}$ and between April and October, a summer season with average discharges of approximately $610 \text{ m}^3/\text{s}$.

Based on the probability distribution of the discharge at *Bovensluis* station (Figure 5.4b), during a long period of the year, discharges lie between 250 and $500 \text{ m}^3/\text{s}$, and discharges of less than $250 \text{ m}^3/\text{s}$ have a 13.7% of occurrence. When the discharge is less than $230 \text{ m}^3/\text{s}$, the Haringvliet sluices will be closed to avoid salt intrusion reaching the freshwater intakes upstream. The situation is not of interest since it will not generate morphological changes on the ETD. It is the first class-interval in Table 5.2.

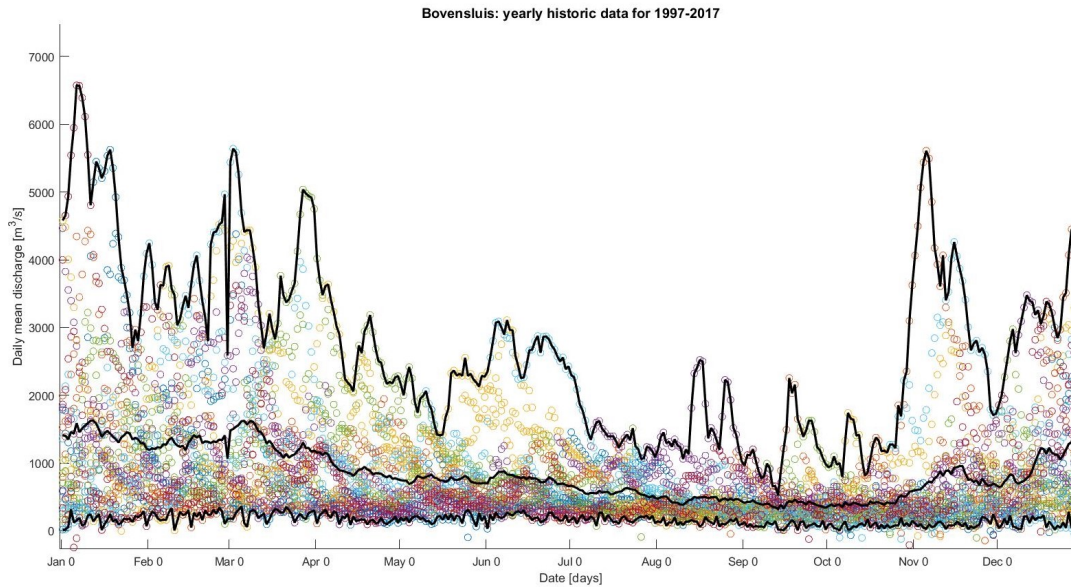


Figure 5.5: **Seasonal distribution of the mean daily discharge data at Bovensluis Station.** The measuring station is located 35 km upstream from the Haringvliet Dam. The data used for the analysis is retrieved for the period 1997-2017 (Rijkswaterstaat 2020c). Each color represents values of mean daily discharge for each year of the period analysed. From the observed distribution, summer season is defined from April 1st to October 31st and winter season from November 1st to March 31st.

The second class-interval is for discharges between 250 and 500 m³/s and has the highest probability of occurrence.

Table 5.2: **Discharge schematization in five discharge classes for the entire year and the seasons defined.** Each class shows the corresponding probability of occurrence in percentage and days of the year as well as the mean of each class. This analysis is made for the whole year and the summer and winter seasons defined.

Station	Bovensluis	Classes [m ³ /s]				
		I 0-230	II 230-500	III 500-1500	IV 1500-3000	V 3000-7000
All year	[%]	0.1110	0.3734	0.3641	0.1141	0.0338
	days/yr	40.52	136.38	133.00	41.67	12.33
	Mean	161.3	353.3	873.7	2126.0	3848.6
summer season	[%]	0.1284	0.4619	0.3429	0.0599	0.0042
	days/yr	27.48	98.86	73.38	12.81	0.90
	Mean	166.7	350.8	850.1	2030.8	3321.1
winter season	[%]	0.0836	0.2469	0.3944	0.1895	0.0755
	days/yr	12.71	37.52	59.95	28.81	11.48
	Mean	149.6	359.8	902.6	2168.3	3890.4

The next higher regime class is between 500 and 1,500 m³/s, being equally influential with a probability of occurrence of 36% of the time. The next class interval is chosen from those bins having similar probabilities of occurrence (between 1,500 and 3,000 m³/s). Finally, a class interval higher than 3,000 m³/s has a probability of occurrence of 3.38% and an upper bound of 7,000 m³/s (see Table 5.2).

The bins defined are applied to the data distinguishing between seasons, the values in Table 5.2 are presented for summer and winter seasons (see also Figure D.4). The summer season occurs during 213.43 days of the year and the winter season during 150.48 days.⁴ A more detailed analysis can be observed in Table D.2, where the probabilities of combined classes are also shown.

The discharge is further reduced into a representative discharge for the summer season and one for

⁴The total days considered do not sum up 365 days of the year since. During the analysis, days with no data were eliminated.

the winter season. It is considered that during a period of 7.238 days a year, no discharge will flow through the Haringvliet sluices, and for 35 days per year, the lower discharge class will occur (Class I). A weighted average of class 2-4, for each season, is computed, along with a high discharge of 3890.4 m³/s during 11.48 days/yr (see Table 5.3).

At the Nieuwe Waterweg, the original boundary condition is kept: harmonic boundary condition for regular and high discharge regime of 1,695 m³/s (see Table 3.1). No change is considered as the new operation of the sluices still aims to guarantee a minimum flow (1,500 m³/s) through the waterway to continue its operability (Van Wijngaarden et al. 2002).

Table 5.3: **Final seasonal discharge schematization.** The reduced and final schematization to be used in the long-term simulations include a discharge representative of summer and winter, a higher less probable discharge, and a really low. The schematization is representative of 98.28% of the year.

Discharge regime	Zero	Summer	Winter	High	Total
Probability [%]	0.0958	0.5085	0.3470	0.0315	0.9828
Probability [days/year]	35.0	185.0	126.3	11.5	357.8
Representative discharge [m ³ /s]	0.0(161.2) ⁵	575.2	855.7	3890.4	

5.2.6. Waves

Previous studies have derived representative sets of wave conditions, De Vries (2007) develops and calibrates a schematization of the wave conditions based on data at the *Europlatform* station (52.00° N, 3.28° E) for the years 1986-2000. The derived schematization is a set of 8 wave conditions representing 86.16% of the year and considers waves of maximum 4.75 m from north-westerly directions. Colina Alonso (2018) uses data from the same station for the period 1971-2001, reducing the wave climate into 6 wave-height classes, further detailed into 8 wave-direction classes. In this case, the wave conditions represent the full-wave climate and consider waves up to 6.5 m high.

In both studies, data from *Europlatform* station is used even though it lies outside the model domain (≈40 km offshore from the Haringvliet mouth). The records in that station present more complete data and include information on wind and wave directions for the entire analyzed periods. Wind conditions are frequently correlated to offshore wave conditions and also needs to be schematized for the model input (Lesser 2009).

The wave schematization derived by De Vries (2007) presents the corresponding peak period (1.2 times the average period of the waves in each class), wave direction, wind velocity, wind direction, and surge level for each wave condition. A total of 8 wave conditions (against a total of 46 by Colina Alonso (2018)) are obtained. Intending to reduce the input as much as possible, this schematization is, with some adaptations, chosen for simulations **S0** specified in Section 4.2.

The optimization of the wave schematization done by De Vries (2007) is based on the Opti procedure developed by Roelvink (2006), in which the target transport flux computed by the Bijker formula. The wave condition with the least contribution to the sediment transport is eliminated and new weight factors are computed each iteration. De Vries (2007) focused on transports along the Hinderplaat and Goeree coast, using a bathymetry of 1986. Even though the study uses a state that differs greatly from the one studied in the present research, the reproduced long-shore transports are assumed to still be accurate in the present situation. The original set of wave conditions is presented in Appendix D.3 and Table 5.4 shows the adjustments made in this study to relate the set of wave conditions to the discharge schematization derived in Section 5.2.5.

The weight factor was adjusted proportionally to obtain a total of 365 days a year for the wave conditions and be able to relate them to the discharge schematization. The probabilities of occurrence were further divided into summer and winter season based on the wave climate presented in Figure 3.8. Us-

⁵ 161.2 m³/s corresponds to the average discharge for the first class interval of the year schematization. Water will flow through the river, but the sluices at the Haringvlietdam will not allow it to flow into the Tidal Lake.

ing that information, the probability of occurrence per season was derived for the wave height classes presented in Table D.4. The modified weight factor is distributed into the summer and winter weights based on the wave height and correspondent probability for each season. The number of days/year for each wave condition per season is then computed.

Based on the number of days per year for each wave condition and taking into account that storm conditions hardly ever happen during high discharge periods, wave condition 40b is combined with the high discharge scenario. Similarly, the lowest discharge scenario is associated with a wave condition with a similar probability of occurrence.

Table 5.4: **Adjusted wave conditions for long-term simulations based on wave schematization by De Vries (2007).** Weight factors are adjusted proportionally to obtain a total of 365 days in a year and further distributed into summer and winter seasons. S: Summer, W: Winter, H: High discharge, ND: No discharge.

WC	Hs	Tp	Dir	Wind Velocity	Wind Dir	Weight	Days/ year	Weight		Days/ year		Discharge	
[-]	[m]	[s]	[°]	m/s	[°]	factor ⁶	[-]	Summer	Winter	Summer	Winter	[m ³ /s]	
8	0.48	4.45	292.90	4.20	240.00	0.47654	170.49	0.3325	0.1453	118.66	51.83	575.2	855.7
36	1.47	6.05	352.90	6.40	345.90	0.14740	52.73	0.0817	0.0660	29.17	23.57	575.2	855.7
40a	1.99	6.35	231.60	11.60	225.90	0.17388	62.21	0.0964	0.0779	34.41	27.80	575.2	855.7
40b	1.99	6.35	231.60	11.60	225.90	0.02601	9.30	-	-	-	-	3848.6	
43	1.99	6.35	277.40	10.80	271.20	0.08827	31.58	-	-	-	-	161.3	
64	2.98	7.77	231.60	15.20	225.60	0.03161	11.31	0.0110	0.0207	3.91	7.39	575.2	855.7
70	2.99	7.78	323.70	12.70	310.20	0.04565	16.33	0.0158	0.0299	5.65	10.68	575.2	855.7
89	3.98	8.98	247.50	18.10	253.00	0.00579	2.07	0.0014	0.0044	0.50	1.57	575.2	855.7
102	4.48	9.52	276.20	17.80	277.30	0.00228	0.81	0.0004	0.0019	0.15	0.66	575.2	855.7
Total						0.9974	356.84	0.54	0.35	192.45	123.51		

5.2.7. Wind and surge level

The wind conditions and surge level related to each of the wave conditions presented in Section 5.2.6 are computed based on the mean value of wind velocity, direction, or surge level, associated with all the waves that fall into the category of each of the selected wave conditions (De Vries 2007). The information is presented in Table 5.5 for each wave condition. Surge levels are not implemented in the model simulations.

Table 5.5: **Wind conditions and water level set-up related to the wave conditions.** Weight factors are adjusted accordingly with the computed factors for wave conditions, modified from De Vries (2007).

wc	Hs	Tp	Dir	Wind Velocity	Wind Dir	Water Level set-up	Weight factor
	[m]	[s]	[°]	m/s	[°]	[m]	[-]
8	0.48	4.45	292.9	4.2	240	0.02	0.476543
36	1.47	6.05	352.9	6.4	345.9	0.0018	0.147395
40a	1.99	6.35	231.6	11.6	225.9	0.0977	0.173875
40b	1.99	6.35	231.6	11.6	225.9	0.0977	0.026005
43	1.99	6.35	277.4	10.8	271.2	0.218	0.088266
64	2.98	7.77	231.6	15.2	225.6	0.1679	0.031605
70	2.99	7.78	323.7	12.7	310.2	0.4053	0.045652
89	3.98	8.98	247.5	18.1	253	0.3909	0.00579
102	4.48	9.52	276.2	17.8	277.3	0.6253	0.002278

5.2.8. Sediment transport schematization

The SED-module of Delft3D enables the computation of bed-load and suspended-load of cohesive (mud) and non-cohesive (sand) sediments. Suspended-load is solved by the advection-diffusion equation, whereas bed-load is computed by Van Rijn (2000) formulation (by default), which considers bed- and suspended-load for currents and waves.

The bed material in the model is schematized by a single sediment sand fraction of $D_{50} = 160 \mu m$, and no mud fraction is considered. Bed-load and suspended-load are computed by Van Rijn (2007a)

⁶Adjusted values from De Vries (2007) to obtain a total of 365 days, from which only 7.238 days/year discharges lower than $1,000 \text{ m}^3/\text{s}$ will occur at Lobith, the sluices at the Haringvliet Dam will have to close..

formulation. For bed-load transport, the formulation considers both the effect of flow and waves by using the concept of instantaneous bed-shear stress. This method has proven to work very well for particles larger than $200\ \mu\text{m}$, in combined steady and oscillatory flow over sandy beds. In the sand range, the bed-load transport is only weakly dependent on the grain size: increases slightly with increasing particle sizes with a factor of 2-3 for sizes between $62\ \mu\text{m}$ and $750\ \mu\text{m}$. The basic input for this model is the water depth, current velocity, significant wave height, peak wave period, the angle between wave and current direction, and sediment characteristics.

For particles smaller than $300\ \mu\text{m}$, grain size sensitivity computations by Van Rijn (2007a) showed that bed-load transport is generally much smaller than suspended load transport. The suspended sediment transport is computed by the advection-diffusion equation and computes the time-averaged (over the wave period) sand concentration profile for the combined effect of currents and waves. The effects of flocculation, hindering settling, and stratification are included by simple expressions (Van Rijn 2007b). The study analyses data for particle size classes from $60\ \mu\text{m}$ to $600\ \mu\text{m}$, concluding a strong dependence between suspended sand transport and particle size and current velocity. Transport of sand in suspension in the range between $0 - 400\ \mu\text{m}$ increases by a factor of 10 to 100 when waves are superimposed.

Since the selected schematization of the bed grain size is $160\ \mu\text{m}$ but is known from Koomans (2001) that finer material is present at the sheltered part of the Haringvliet mouth, applying smaller grain sizes in the model might vary the observed morphological evolution in the system, but is not performed in the present study.

At the inland open inflow boundary, concentration boundary conditions are necessary. A Neumann boundary condition is implemented, set to a zero concentration gradient, which has the effect of setting the sediment concentrations at the boundary equal to those just inside the model domain; a near-perfectly adapted flow enters the domain.

5.3. Model Calibration

Model results from previous studies showed that the erosion-sedimentation patterns were not predicted correctly at the Hinderplaat's shoreface. Holland (1997) and De Vries (2007) model results predicted sedimentation in the delta front and erosion at the inner side, whereas Vlakingingen data showed an opposite behavior. De Vries (2007) implemented the TRANSPORT2004 formulation for sediment transport, which includes the effect of transport by asymmetric waves. The author concluded that it leads to better reproduction of the morphological changes of the channels, sub-tidal areas, and flats.

Colina Alonso (2018) model results still showed the incorrect patterns for some forcing conditions. The correct representation of the mouth's evolution was reproduced only by low probable conditions. The author developed calibration exercises to improve the prediction qualities of the model. The calibration was done by increasing the wave impact on morphology through the parameters in the sediment transport formula. For all the results, no improvement in the incorrect pattern was observed. For details, the reader is referred to Colina Alonso (2018).

The model still reproduces the correct patterns at the Hinderplaat shoreface for wave conditions that generate south-directed sediment transports only. However, cross-shore transports by waves are almost absent in all simulations, which is an under-estimation of transport by asymmetric waves even with the implementation of the TRANSPORT2004 formula (also used in the present study) (Colina Alonso 2018).

5.4. Long term morphological run set-up

The input reduction was made by schematizing the forcing conditions such that they still represent the seasonal characteristic of waves, wind, and discharge (Section 5.2). To achieve a morphological simulation representative of years' development in realistic computational times, it is also required to

scale-up the bed level changes generated by the prevailing hydrodynamic forcing. The technique is to apply a morphological acceleration factor that enhances bed level changes each hydrodynamic time step (Roelvink 2006). The method is based on the assumption of linearity between the morphological changes and the hydrodynamics during that morphological time-step (Lesser 2009). The following section elaborates on the implementation of the morphological acceleration factor (MF) and the set-up of a long-term simulation with the selected forcing conditions.

5.4.1. Morphological Factor implementation

The MF approach multiplies the suspended sediment erosion and deposition fluxes and the gradients in the bed-load sediment transport vector components by a spatially-constant factor, the morphological acceleration factor (MF). The result is a bed elevation change MF times greater; it makes the morphological time-step MF times larger than the hydrodynamic time-step. This method allows the computation of long-term morphological simulations in a fraction of the required duration in terms of hydrodynamic time (Moerman 2011).

The main limitation of the MF approach is the assumption of linearity over the "lengthened" tidal cycle: bed level changes and sediment transport fluxes vary linearly with changing MF over a full sequence of MF times the number of tides. When oscillating forcing conditions are applied to the hydrodynamic model, it is essential to conceptually separate the hydrodynamic model from the morphological model (Lesser 2009). In this report, the hydrodynamics of the system predicted by the model will be presented in Section 6.2 and the morphological results on Section 6.3.

The fluctuations of the boundary conditions (tide, waves, discharge, and PPS discharges) are applied at a hydrodynamic time-scale. When using an MF, the fluctuations are enhanced by the factor before being applied to the morphological model. The selection of an appropriate factor remains a matter of the modeler's criteria. The validity of the linearity assumption can be easily tested by performing repeated simulations with different MF's and adjusting the hydrodynamic simulation time such that the morphological time is conserved.

In the present study, a sensitivity analysis of a constant MF is performed first (see Figure D.6) to determine the value over which bed level changes in the model will become unrealistic, despite the computational time saved. Then, the sensitivity of a variable MF is also evaluated.

We chose a variable MF to perform the long-term simulation because of the enhancing effect of the factor, especially in the presence of oscillating forcing in the model as the present case (Lesser 2009; Moerman 2011). Moreover, since the wave climate schematization is formed by variable wave conditions, from mild to strong in terms of the wave height, small MF values should be applied to high episodic events. Bigger MF's can be used for more constant conditions (Roelvink 2006).

Variable MF

The use of a variable MF makes the ratio between the morphodynamic and hydrodynamic time steps a function of the morphological time. However, Lesser (2009) warns about the implementation of a variable factor. Different values are used for different forcing conditions when the MF changes and sediment is in suspension, continuity of sediment mass is not conserved: the sediment in suspension effectively represents $MF \times \text{mass}$. If the factor changes while a (depth-integrated) mass of sediment S per m^2 of bed is in suspension, a sediment mass error of $S \times \Delta MF$ per m^2 of bed will occur. Lesser (2009) recommends performing the transition of MF's when suspended sediment concentrations are either relatively low or approximately equal.

A sufficiently long transition period between conditions can also help to minimize the sediment mass error during which an MF of zero is applied, and morphological changes are deactivated. Stark (2012) proposes an approach modified from Lesser (2009) that allows performing a simulation of a specific number of morphological years by adjusting the MF values related to each wave condition. Each wave condition has to run for entire morphological tides. The number of morphological tides over which each condition is simulated is such that the morphological duration corresponds to its probability of

occurrence. The number of morphological tides also ensures that the MF is kept under the desired value and is computed by Equation 5.2.

$$f_{MF} = \frac{p_c \times D_{\text{season}}}{nT_{\text{morph tide}}} \quad (5.2)$$

Where,

f_{MF} Morphological acceleration factor.

p_c Probability of occurrence of a specific wave conditions.

D_{season} Duration of the morphological simulation.

n Number of morphological tides over which the wave condition is simulated.

$T_{\text{morph tide}}$ Duration of a single morphological tide (740 minutes).

The sum of the weights of the wave conditions in terms of morphological tides determines the total duration of the simulation. The weights of the reduced wave climate should sum 1.0; if the sum is less than 1.0, the real morphological period is less than the one intended, but already represents the morphological development of the whole desired period.

First, a sensitivity analysis with constant MF's is performed to select the largest possible value of the factor that does not cause unrealistic bed level changes. The analysis can be consulted in Appendix D.4.1 where MF values of 1 (reference case), 5, and 30 are evaluated. Another sensitivity analysis is performed with a variable MF < 30 and < 50 for a year-long wave climate schematization applied to the morphological simulation (see Figure 5.6 for the whole analysis).

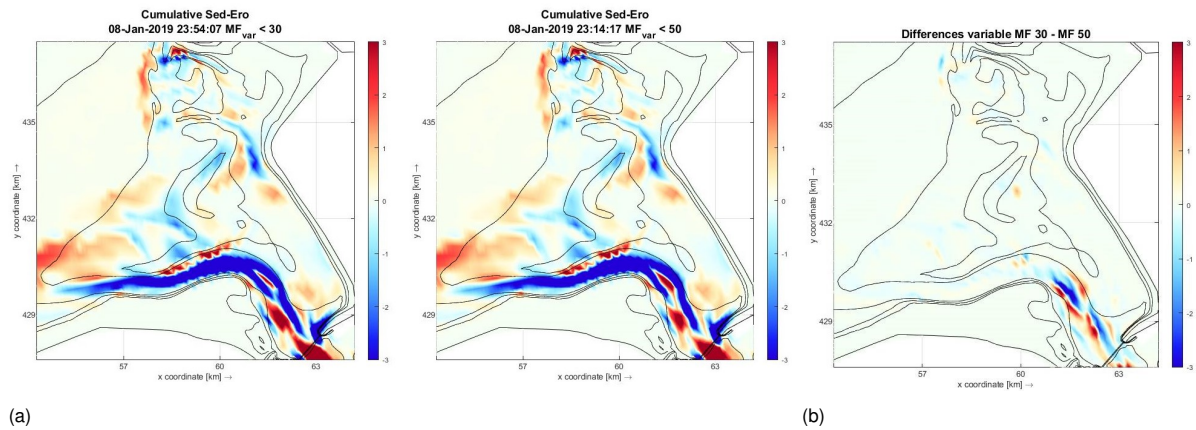


Figure 5.6: **Sensitivity of a variable MF for the model with an open estuary (scenario R1), 1 year morphological time.** (a) On the left the cumulative sedimentation-erosion patterns for variable MF values lower than 30 and on the right for MF values lower than 50. Both runs show similar patterns of sedimentation and erosion areas. Larger sedimentation is appreciated for the MF < 50 run at the Slikgat channel outside the Haringvliet Dam. (b) Differences between both runs, the larger deviations are specially noted at the Slikgat section just at the seaside of the Dam.

The sensitivity analysis studies the case with an open Haringvliet, but without the Delta21 intervention. The system's state already allows us to observe large bathymetric changes. From a general qualitative assessment, enhanced patterns for the MF < 50 run are observed. Larger sedimentation in the Slikgat is seen at the location of the Haringvliet Dam and to the east of Kwade Hoek for the MF < 50 run. The biggest differences are present in the first section of the Slikgat, where the Haringvliet Dam discharges into the sea.

Once the Delta21 plan is implemented, even a larger current concentration along the Slikgat and the new inlet will occur. Values MF > 50 will likely lead to unrealistic bed changes. A maximum MF of 30 is selected for the long-term simulations that include the Delta21 intervention, and in consequence, also for the validation runs for the 2012-2015 and 2015-2018 periods.

A wave schematization for 3 years of morphological time simulation is derived with the previously described procedure, for a variable $MF < 30$ (Table 5.6). The table shows the morphological factors and number of morphological tides for $MF = 30$ for 3 years wave climate. The climate is representative of 99.74% of the year. For 3-year evolution and $MF < 30$, a total of 75 morphological tides are necessary, and the average MF is 23.77, the total hydrodynamic simulation is scaled up 23.77 times.

The procedure followed in this research to implement the variable MF in the model, along with the different wave conditions, is the proposed modification by Stark (2012):

1. Set $MF = 0$ at the end of a harmonic cycle of the morphological tide (stops the morphological model).
2. Change the wave boundary condition instantly (no gradual shift towards the new wave conditions is necessary (Lesser 2009)).
3. Let the hydrodynamic and wave models stabilize and adjust to the new boundary conditions for a period of 100 minutes. After this transition period, the influence of the prior wave condition should be negligible.
4. Set the MF to the corresponding wave conditions value (restarting the morphological model).
5. Compute hydrodynamics, sediment transports, and accelerated morphological changes over a period of exactly one morphological tide (744 minutes) or a multiple.
6. Repeat the previous steps until all wave conditions are run for the number of morphological tides that are assigned to each of them, and the whole simulation time is covered.

Table 5.6: **Wave climate for long-term simulation with a 3-year duration.** Each wave condition is assigned several morphological tides to be run related to its probability of occurrence, and a variable morphological acceleration factor is assigned to each of them. MF values lower than 50 (Table D.5) and 30 are derived for the test simulations. The total hydrodynamic time in the model is 47 and 75 morphological tides, respectively. The climate implemented with this method is representative of 3 years of morphological evolution.

WC	H_s	T_p	Dir	Wind Velocity	Wind Dir	Weight factor	Duration (mor)	No. Mor. Tides	MF
[–]	[m]	[s]	[°]	m/s	[°]	[–]	[days/yr]		[–]
70	2.99	7.78	323.7	12.7	310.2	0.04565	50	4	24.1880
40b	1.99	6.35	231.6	11.6	225.9	0.02601	28	2	27.5573
102	4.48	9.52	276.2	17.8	277.3	0.00228	2	1	4.8276
89	3.98	8.98	247.5	18.1	253	0.00579	6	1	12.2700
43	1.99	6.35	277.4	10.8	271.2	0.08827	97	7	26.7239
8a	0.48	4.45	292.9	4.2	240	0.23827	261	17	29.7048
64	2.98	7.77	231.6	15.2	225.6	0.03161	35	3	22.3274
40a	1.99	6.35	231.6	11.6	225.9	0.17388	190	12	28.3464
8b	0.48	4.45	292.9	4.2	240	0.23827	261	17	29.7048
36	1.47	6.05	352.9	6.4	345.9	0.14740	161	11	28.3984
0.99741							1091	76	23.4049

To account for the stochastic character of waves, a random order of the wave conditions during the simulation time is implemented; wave condition 8 is divided into two periods (wc 8a and 8b) to avoid a too long continuous time of the less energetic condition. These conditions are combined with corresponding discharge and wind conditions derived in Section 5.2.

5.4.2. Validation periods results

To have an idea of the model's performance and the accuracy of its predictions, long-term simulations for 2 periods are conducted. Bathymetry data for years 2012, 2015, and 2018 is available for comparison in Section 3.4.1. Long-term simulations of 3 year periods are conducted to observe bed level differences. The model is forced with all processes, and the schematization presented in Table 5.6. The initial bathymetry in the model for each period is 2012 and 2015 taken from the Vakkolingen data

sets.

Figure D.8 shows the results for period 2012-2015 and Figure 5.7 for 2015-2018. The model results for both periods are qualitatively compared to the differences computed from the Vaklodingen data (left plot in Figure D.8a and Figure 5.7) to have a qualitative idea of the model's prediction regarding the real evolution of the system. The first difference between the model's prediction and the data, in both periods, is that the unpredicted sedimentation in the sheltered area and erosion seaward from the ETD. Instead, the seaward side is accreting, clearer for the period 2012-2015, where data shows larger sedimentation in the landward side than for 2015-2018.

Erosion in the shoreface is not correctly predicted. In the southern area of the ETD, erosion along the Slijkgat is seen in the data but with less clarity and to a lower extent than that predicted by the model runs for both MF values. At the bend where the channel turns around Kwade Hoek, also sedimentation is present for the model and the data, smaller area for the model. This is consistent with the locations where regular dredging along the Slijkgat needs to take place (De Groen 2014).

For the first period, the sensitivity of the variable MF is also performed, applying a variable $MF < 30$ and $MF < 50$. The results of both runs are compared, Figure D.8b displays the cumulative sedimentation-erosion patterns for both cases. The analysis is presented in Appendix D.4.3. Important to note for the 2012-2015 period, north from the Slijkgat, erosion in the Bokkegat is predicted by the model for both MF values, reopening this channel. In reality, this channel has been silting due to the reduced tidal currents, which have allowed the Hinderplaat and the former Garnalenplaat to merge into one mega-shoal (see Figure 3.10).

The results for the 2015-2018 period are shown in Figure 5.7, which shows slightly more accurate results from a qualitative point of view. To the south of the ETD, sedimentation-erosion patterns along the Slijkgat predicted by the model match the locations for regular dredging reported by De Groen (2014). At the Hinderplaat, data shows erosion at the delta front and sedimentation in the seaward side. The model, however, does not predict the erosion area entirely. The sedimentation appears to agree more, especially to the north-east of the shoal.

The least accurate prediction is at the north of the ETD. The model predicts a northward migration of the Kortsluitgeul. The data shows a similar trend but with lower magnitudes of sedimentation-erosion. In the Hindergat, however, the magnitude of sedimentation and erosion in the model is much higher than that shown in the data. The sedimentation at the seaward end of the Hindergat is further offshore in reality than where the model predicts it. The model shows the formation of features at the upper shore-face, offshore from the Hindergat with lobate forms. The data does not present these features.

Erosion due to water overflowing the northern shoal of the Hinderplaat is predicted, promoting the formation of a new channel at this location. In reality, this is still a complete shoal. In contrast, at the Bokkegat, the model correctly predicts sedimentation, and the channel feature is fading away, contrary to the model results for the period 2012-2015 (Figure D.8).

The system's state at the beginning of the simulation (2012) showed an evident channel feature: the Bokkegat. Since the model has demonstrated that transport due to tidal current processes have more influence over the morphological changes than transport due to waves in the cross-shore direction, the evolution for the 2012-2015 period enhances the presence of such channel. When this feature is milder, such as the 2015 initial bathymetry, the morphological changes predicted by the model are more accurate and the positive feedback for the growth of the channel is lower.

Qualitatively, a better prediction is observed for the 2015-2018 period, using a variable $MF < 30$ than for the 2012-2015 period. The qualitative accuracy of the model is evaluated visually through the agreement of sediment-erosion patterns. Grid-point comparison is not performed, nor the spatial variation, which could provide a quantitative reference of the skill of the model. Although a more scale selective method to compute the quality of the predictions could be more applicable in morphological studies such as the present (Bosboom 2019).

The qualitative agreement of the patterns provides confidence for the following forecast simulation exercises, as long as the practical implications are always considered. It is assumed that the results from the model will still predict a sufficiently accurate evolution of the system, and results can be used for this research while treated with care. Special attention needs to be taken towards results that show large erosion.

The following chapters present the results of the long- and short-term runs. An analysis is made of the hydrodynamics, the sediment transport patterns, and finally the bed level evolution.

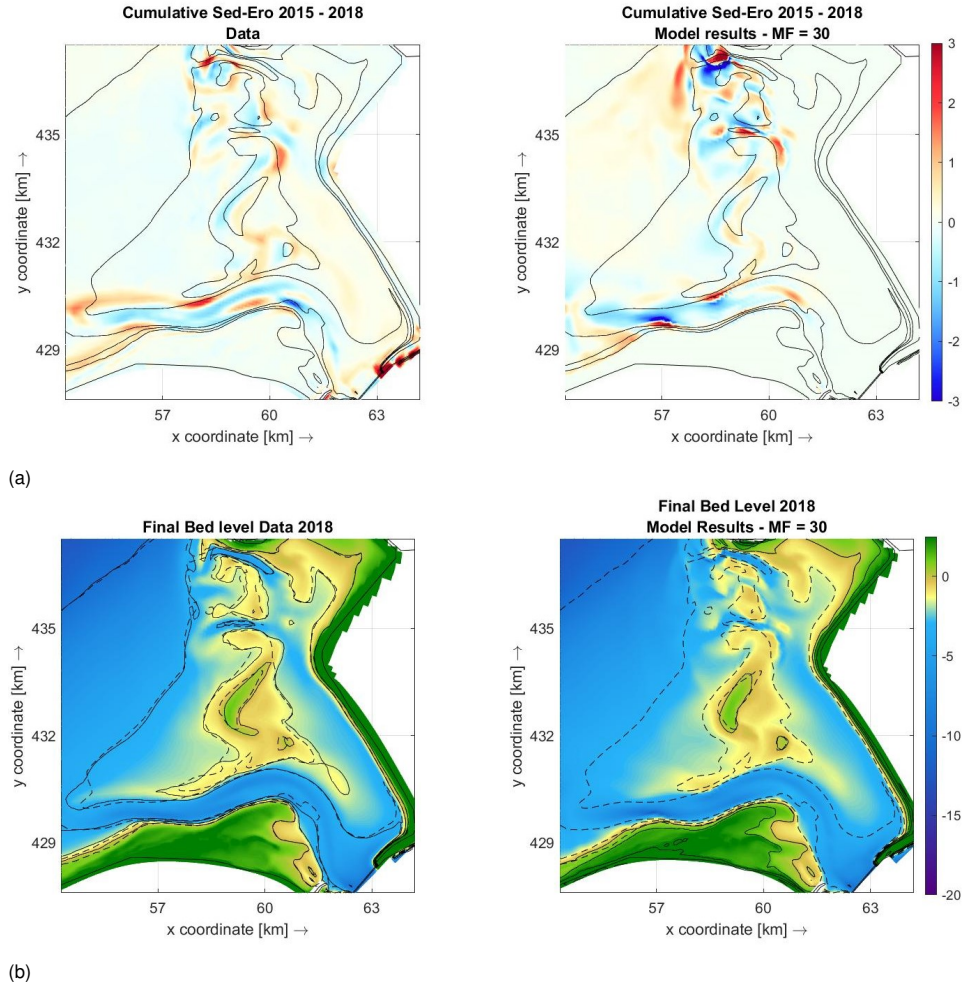


Figure 5.7: **Long-term validation results for the period 2015-2018, model with a closed basin (R0), for a MF value lower than 30.** (a) Cumulative sedimentation-erosion patterns for the assessed period showing differences for the Vaklodingen data (left), model results with $MF < 30$ (right). (b) Final bed level of the assessed period (2018) from Vaklodingen data (left), model results with $MF < 30$ (right). Dashed lines in (b) are the contours for 2015 and continuous lines are the contours for 2018.

6

Haringvliet response to D21 intervention

This chapter presents the first stage results of the modeling exercise, as described in Chapter 4. A short explanation of the tested scenarios and processes is made in Section 6.1. Section 6.2 shows the model's hydrodynamic results for the system before opening the Haringvliet Dam, when it is open, and when the whole Delta21 plan is implemented. The tidal range and tidal prism for the new situation are also predicted. Section 6.3 elaborates on the morphological changes in a 3-year time frame as a consequence of the net sediment transport patterns for the scenario D21 plan scenario.

6.1. Modelling Scenarios

The first stage of the simulation exercise is focused on modeling the long-term evolution of the study area. The objective of this simulation is to test whether the hypotheses stated in Section 4.1 are true or not. The various forcing processes are gradually included in the model.

Table 6.1 shows the system scenarios performed in the modeling study for this stage. Runs **A** only include tidal forcing, and discharge is added during runs **B**. Finally, runs **E** include waves and wind. The surge level is not included in the model. The available option is to account for a uniform surge level in the entire boundary. However, the water level gradients are not accounted for, which are the ones that might have a bigger impact on bed level changes in the shallow areas (Colina Alonso 2018). The goal is to reproduce the evolution in the long-term as a result of regular conditions at the Haringvliet estuary. We assume that the results from runs **E** reproduce the desired evolution.

Table 6.1: **Simulations depending on the processes and modeling scenarios.** Simulations A and B are used to assess the hydrodynamic behaviour for the present situation (R0), open estuary (R1) and D21 intervention (R2). Simulations E are compared to the previous simulations and to assess the initial and long-term morphological changes for the 3 scenarios.

Simulation	Processes				Scenarios		
	Tide	Discharge	Wind	Waves	Present situation (R0)	Open Estuary (R1)	D21 (R2)
A. Tidal forcing only	Yes	No	No	No	Yes	Yes	Yes
B. Tide and Q_{river} forcing	Yes	Yes (Q_{class3})	No	No	Yes	Yes	Yes
E. All processes	Yes	Yes (complete)	Yes (complete)	Yes (complete)	Yes	Yes	Yes
Simulations Comparison	A	A-B	A-E	A-E	R0	R0 - R1	R0 - R1 R1 - R2

Simulations **A** and **B** allow a preliminary understanding of the flow behavior in the present situation, how it will change with an open estuary, and even more with an intervention such as the Delta21 plan. These simulations are used for an initial assessment of the changes in the tidal cycle and currents (Section 6.2.1 to Section 6.2.3). Results from simulations **E**, a more realistic situation that includes all processes, are used to assess the initial and long-term behavior of the system once the Delta21 plan is executed. The final 3-year simulation, for a run with all the processes (**E**), is used to give a prediction of the system's evolution due to the intervention. The consequences of sediment transport and bed level changes are further elaborated in Section 6.3.

6.2. Hydrodynamic Results

6.2.1. Tidal cycle

According to Tönis et al. (2002), after the damming, the flow at the Haringvliet mouth showed a more circulating pattern due to the Haringvliet Dam blocking the flow into the estuary. The damming produced a large distortion of the previously clear 4-phased cycle, specifically in the 3 hours lag between horizontal and vertical tide (Tönis et al. 2002; Sha et al. 1993). The distorted tidal cycle is well predicted by the model. The results are presented, first for the only tide case and then accounting for all processes, for the scenarios **R0** (the present situation), **R1** (an open estuary), and **R2** (the Delta21 scenario).

Tidal forcing results

Scenario R0 was run for 2012 and 2018 bathymetries, the results for 2018 are in Figure E.2. The circulating pattern described by Tönis et al. (2002) can be observed. Although the Maasvlakte 2 (MV2) is included in the system, the altered tidal cycle after the closure of the estuary is maintained.

When the Haringvliet Dam is re-opened regularly, there is a clear change in the phases of the tidal cycle. Figure E.4 shows scenario **A** (only tide), in which the flow is allowed to go upstream through the sluices. The tidal cycle shows a more clear four-phased tidal cycle, similar to Tönis et al. (2002) descriptions of before the damming of the Haringvliet. The phases of the tidal cycle are defined based on the water levels at a location approximately 15 km offshore from the TL inlet with approximately 14 m depth; it is described as:

1. At high tide, currents offshore and inside the whole basin are in flood direction entering the estuary.
2. Approximately 3 hours later, currents offshore are still in flood direction while in some parts of the basin (outside the dam), they flow in an ebb direction. Inside the estuary, upstream from the dam, currents are still flood-directed. This phase is close to the high water slack.
3. At low tide, currents offshore and in the basin (outside and inside the dam) are in the ebb direction.
4. Approximately 3 hours later, currents offshore and in the basin (outside and inside the dam) are in the ebb direction. The low water slack is 1.5 hours after the defined phase 4.

The currents and water levels offshore and inside the basin are no longer in phase. High water offshore happens before offshore than in the rest of the locations. There is a lag between the water levels as the tidal wave propagates into the estuary upstream (see Figure E.4b). For the 4th phase of the cycle, a slightly different behavior than the one described by Tönis et al. (2002) is observed: flow reversal is predicted more than 3 hours after low water (see also Figure E.6).

The tide in offshore locations with relatively deep water shows the characteristic behavior of a progressive wave: water levels and velocities are almost in phase. As the tidal wave propagates into the basin, there is a phase difference between the vertical (water level) and horizontal (velocity) tide in each location. This phase difference increases the farther the tide propagates into the estuary until a phase difference of nearly $\phi = -90^\circ$ occurs at a location inside the estuary (pink plot); the rising period almost coincides with the flood period and the falling with the ebb period.

The tidal velocity is not in phase with the water surface elevation anymore, but with the negative water level gradient due to the increasing influence of the bed friction over the tidal wave propagation. Bed friction also induces a decreasing amplitude of the vertical tide as it propagates upstream. The vertical tide plot of Figure E.4b displays the deformation of the tide as it propagates into the estuary. As depths decrease, the flow becomes friction-dominated, introducing a diffusive effect into the flow and damping tidal amplitudes. A similar effect occurs on the horizontal tide. The exception is at the Slikgat channel, where velocity amplitudes are actually enhanced. An explanation is the flow concentration at this location. Water volumes mostly flow through the Slikgat as it is the main tidal channel.

When the Delta21 plan is implemented, the tidal cycle and its phases show further modifications. [Figure 6.1](#) shows the four-phased tidal cycle when the full Delta21 is in place (including the PPS), for run A. The tidal flow now must go through 3 width-constricted cross-sections: the new tidal inlet, along the Slikgat channel section, and the Haringvliet Dam (green, orange and pink dots respectively in the figure), to flow into the estuary. The tidal cycle based on water levels at the same offshore location shows the following phases:

1. At high water, tidal currents are in flood direction offshore and at all locations at the basin (Tidal lake and upstream the Haringvliet Dam).
2. Approximately 3 hours after high water offshore tidal currents are still in flood direction, but close to high water slack, while in all locations at the basin (TL and upstream from the dam), they are already ebb-directed.
3. At low water tidal currents offshore and in all locations at the basin (TL and upstream from the dam) are ebb-directed, close to maximum ebb velocities for the locations inside the basin.
4. Approximately 3 hours after low water, all currents are still in ebb direction, although close to low water slack. According to the model the 4th phase is 4.5 hours after low water ([Figure 6.1b](#)).

[Figure 6.1](#) also displays the flow patterns at the seaward side of the TL inlet, between it and the pumping power station (PPS) of the ESL. When the ESL is filling, and the flow is flood-directed offshore and in the basin (Phase 1), part of the flow is attracted to the new tidal inlet, and currents in the space between both lakes entrances are directed towards the TL inlet. When the flow leaves the TL, and the ESL is still filling, the flow is attracted to the PPS (Phase 2).

During Phase 3, all currents are ebb-directed, but the PPS is filling the ESL. A circulation is formed, currents flow from the TL inlet to the ESL entrance and small currents from the PPS to the TL inlet again. The milder current velocities may allow deposition between the entrances of both lakes. However, when the PPS discharge into the sea (the ESL) coincides with the flood period (ebb period), currents are directed towards (away) the new tidal inlet. Current velocities of about 1.0 m/s develop in this area, potentially entraining the sediment again.

The influence of the PPS can also be observed in the cycle of [Figure E.5](#), where the PPS operation is not included. A circulation cell between both entrances develops, caused by the flow separation generated by the structure in the downdrift side of the ESL. Velocities at the location between both entrances are around 0.93 m/s and show a uniform sinusoidal shape.

All processes results

When additional processes are considered apart from the tidal forcing, the cycle varies. When the discharge is included in the model, in scenario **R1**, the effect of the discharge during Phase 2 is to hinder the flood-directed tidal currents along the Slikgat and Rak van Scheelhoek channels. The effect is even more clear if all processes are included. [Figure E.6](#) displays the tidal phases for scenario and all processes (simulation **R1-E**). However, [Figure E.6a](#) shows the 4th phase for a moment 4.5 hours after low water. At this moment, all current velocities, offshore and inside the basin, are flood-directed again. During all the offshore ebb-period, current velocities inside the basin are also always ebb-directed ([Figure E.6b](#)). Flow reversal offshore always happens before it does inside the basin, and the ebb period offshore is longer than at locations inside.

The increasing tidal asymmetry as the tide propagates inland is clear in [Figure E.6b](#). The flood period becomes shorter, especially depicted in the Slikgat channel velocity signal. Flood velocities are larger than ebb velocities, i.e., high water propagates faster than low water, the water surface develops a vertical asymmetry with a steeper face. The effect is also recognized in the water elevation plot, from the shorter rising period than the falling period. This behavior is characteristic of a flood-dominated system, also concluded from the larger flood velocities (than ebb velocities) in [Table 6.2](#). Larger amplitudes for high water than for low water occur at all locations (case **E-R1**), showing a positive skewness of the vertical tide as well. This is further elaborated in Section 6.2.2.

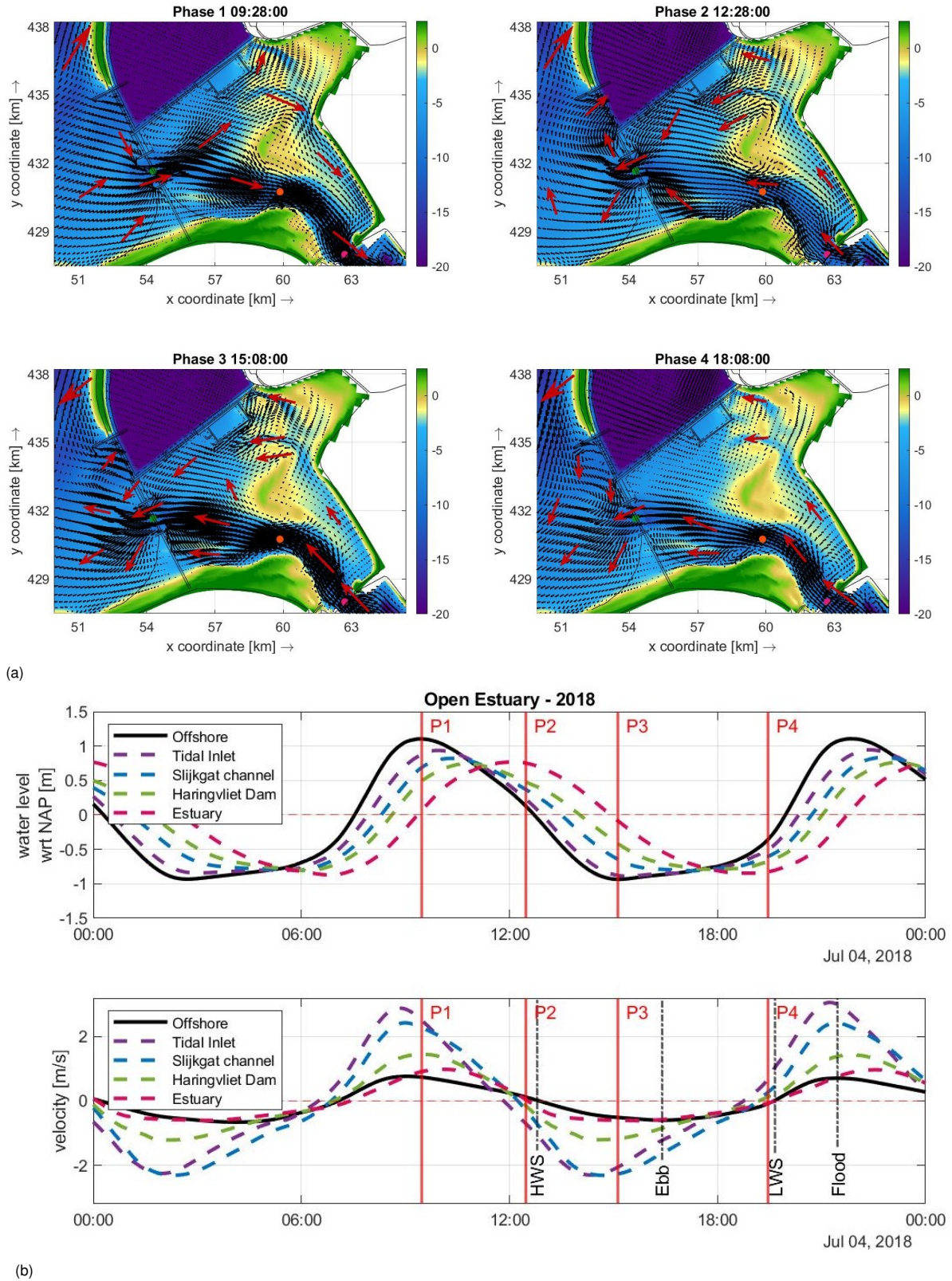


Figure 6.1: **Tidal cycle in the Haringvliet mouth showing 4 phases, for the only tide case A with an open estuary and D21 R3.** (a) Tidal cycle in the four phases defined by Tönis et al. (2002). The four phased cycle is not completely clear and the influence of the pumping station can be depicted. (b) Water level and velocity signals for different locations along the basin, dots in (a): tidal inlet in green, Slijkgat channel in orange and Haringvliet dam in pink. The estuary location is approximately 15 km upstream from the Haringvliet dam. Water levels are not the same in the whole basin anymore. Phases are defined based on water levels just offshore. Current velocities are clearly enhanced by the reduced cross-section at the new tidal inlet.

Once the Delta21 plan is implemented (**R2**), a further distorted cycle occurs, the flood-dominance is enhanced even more. The velocity signals show a longer low water slack, i.e., the flow reversal from ebb to flood is longer than from flood to ebb. The basin is flooded faster than it takes for it to reach low water levels again, another characteristic of flood dominated basins.

Figure 6.2 shows the results for the **R2** scenario with a run including all processes (**E**), which illustrates the tidal cycle and offshore-inlet current interactions. Phase 4 of the tidal cycle occurs approximately 4 hours after low water, closer to the low water slack. All phases show the same patterns as for case **A**. However, during the 4th phase, the flow is reversing offshore, while currents tend to enter the TL through the northern side of the inlet. Flow coming from the Haringvliet waterway is already ebb-directed. In the north part of the Hinderplaat, currents are also flood directed. This moment of the cycle coincides with discharge from the PPS into the sea, which produces an important flow from the PPS to the TL inlet despite the ebb-currents trying to flow out of the estuary.

The velocity and water level signals in Figure 6.2 show the characteristic tidal regime at the SW Dutch coast: the maximum long-shore flood- and ebb-directed tidal currents coincide with high and low water, respectively. The maximum ebb- and flood-directed currents at the inlet occur about half-way the high and low watermarks (Sha et al. 1993). Additionally, water levels at the new TL inlet and offshore are almost in phase. This tidal regime and the increase of the tidal prism would indicate that a more symmetric ETD should develop according to the model by Sha et al. (1993) models (Model E in Figure 2.2). However, the orientation of ebb-channels and the ETD also depends on the relative importance of tide-driven currents and the littoral drift.

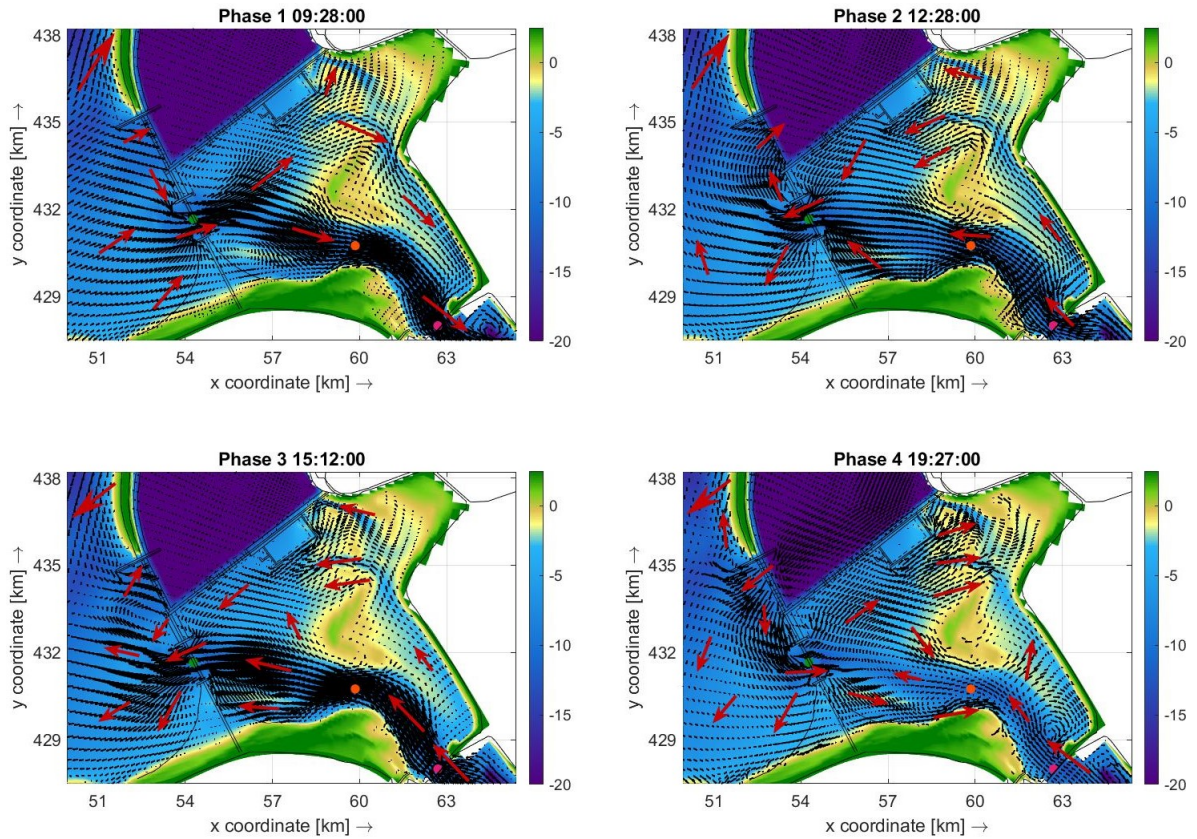
The layout of the D21 locates the new tidal inlet so that its cross-section is perpendicular to the long-shore tidal currents. A current concentration at the updrift side of the inlet during the ebb period is not particularly happening; on the contrary, currents deflect more downdrift. The dominant wave energy flux, responsible for the littoral drift to the north-east, promotes current directions and features downdrift-orientated. The results of the morphological evolution are elaborated in Section 6.3 and further discussed in Section 8.3.

6.2.2. Tidal prism, tidal range and velocities

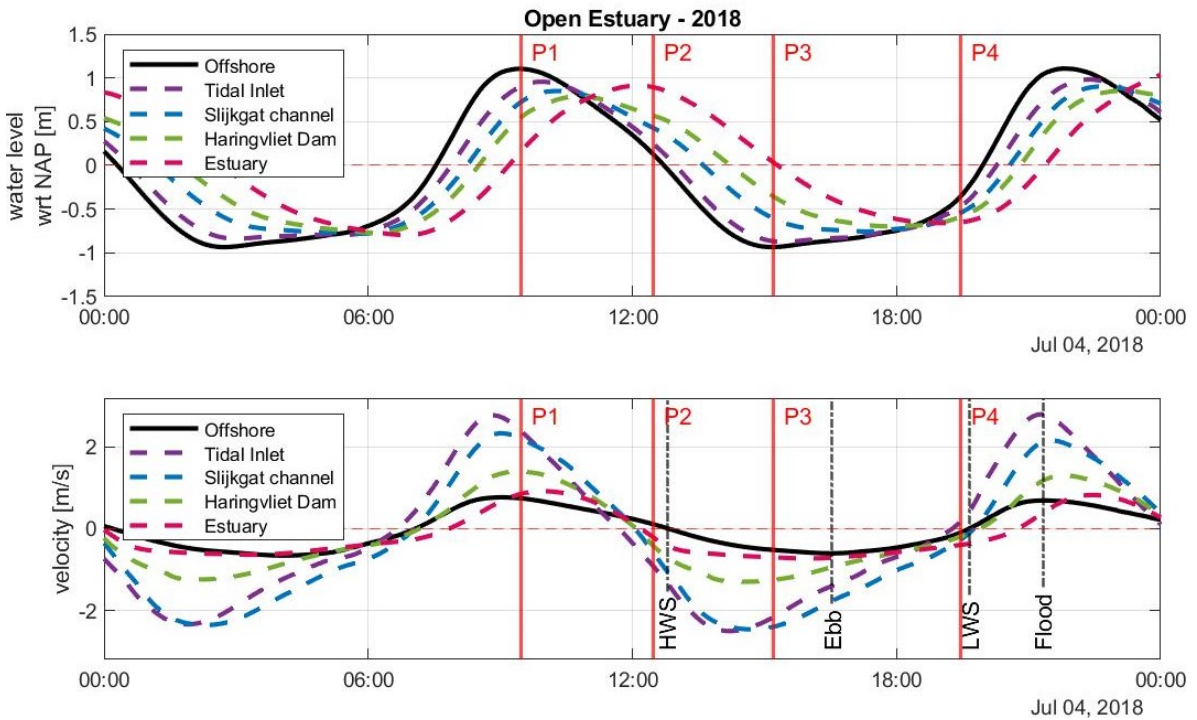
The simulations for the different scenarios and only forcing the model with water level boundary conditions, allows us to make predictions of the volume of water flowing in and out the basin each tidal cycle. The computation is performed to firstly validate the model predictions comparing them to expected volumes for the present situation (reported in the literature). Then, the tidal prism magnitude in the altered system is predicted. Before the damming of the Haringvliet, a tidal prism between 308 and 460 Mm³ was reported for the estuary. After the damming, the prism decreased to between 6 and 15 Mm³ (Louters et al. 1991; Van Wijngaarden et al. 2002).

The predictions are computed by the discharge flowing through different cross-sections in the basin. The most landward position is at the Haringvliet Dam and, in the seaward direction, the water volume flows through the Slijk gat and the Rak van Scheelhoek channels at the landward side of the Hinderplaat to then flow along a seaward stretch of the Slijk gat, the Kortsluitgeul, and the Hinder gat (see Table 6.3). In the outer side, during high tide, the water also overflows some parts of the Hinderplaat shoals. The computation includes two of those cross-sections. When the D21 is implemented, the cross-sections along the "new Slijk gat" before the location of the new TL barrier and at the barrier itself are also included. The tidal prism results are presented in Figure 6.3.

For the current situation (**A-R0**), the model predicts a tidal prism of ≈ 5 Mm³ at the landward side of the channels and ≈ 15 Mm³ at the seaward side. The values agree with those reported in the literature. The differences between the outer and inner cross-sections are due to the stored volume between them. As the tide propagates further inland into the basin, less water volume flows through the channels. The errors in Figure 6.3 can originate from the cross-sections used for the computations. During high water, there is an overflow at the shoals, the whole discharge flowing during the ebb-period is not accounted for, especially at the outer side of the channels.



(a)

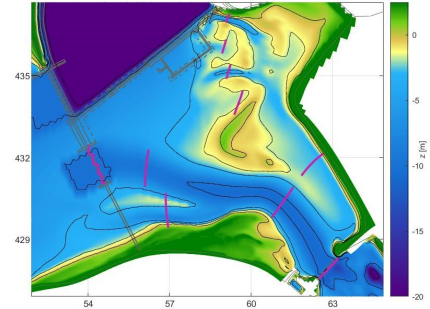


(b)

Figure 6.2: Tidal cycle in the Haringvliet mouth showing 4 phases, with all processes E and with an open estuary and D21 R2. (a) Tidal cycle in the four phases defined by Tönis et al. (2002). The four-phased cycle is not completely clear, and the influence of the pumping station can be depicted. (b) Water level and velocity signals for different locations along the basin, dots in (a): tidal inlet in green, Slijkgt channel in orange, and Haringvliet dam in pink. The estuary location is approximately 15 km upstream from the Haringvliet dam. Water levels are not the same in the whole basin anymore. Phases are defined based on water levels offshore. Current velocities are clearly enhanced by the reduced cross-section at the new tidal inlet. Phase 4 is shown for a moment approximately 4 hours after low water.

Figure 6.3: Tidal prism model computations for runs with the only tide (A) and all processes (E) for present situation (R0), opened estuary (R1), and D21 scenario (R2). The tidal prism is computed for the flood and ebb periods for each run and through the specified cross-sections from the Dam in the seaward direction: the Haringvliet Dam, at the inland side of the ETD through the Slijkat and Rak van Scheelhoek channels, at the seaward side of the ETD through the Slijkat, Kortsluitgeul, and the Hindergat channels, a cross-section before the TL inlet and along the Slijkat and finally at the TL barrier.

Run - Scenario Volumes [Mm ³]	A - R0			A - R1		
	Flood	Ebb	Error [%]	Flood	Ebb	Error [%]
Haringvliet Dam	0.12	-0.12	-4.5%	124.08	-123.54	0.4%
Inner channels (Slijkat + Rak van Scheelhoek)	5.21	-5.14	1.3%	123.84	-125.76	-1.6%
Outer channels	15.00	-14.64	2.4%	77.61	-114.46	-47.5%
Run - Scenario Volumes [Mm ³]	A - R2 no pumps			A - R2 pumps		
	Flood	Ebb	Error [%]	Flood	Ebb	Error [%]
Haringvliet Dam	190.63	-188.82	1.0%	188.76	-185.18	1.9%
Inner channels (Slijkat + Rak van Scheelhoek)	193.61	-192.95	0.3%	191.59	-189.15	1.3%
Outer channels	21.28	-45.65	-114.5%	8.75	-3.25	62.8%
Tidal Inlet (Slijkat)	176.47	-151.07	14.4%	176.88	-148.91	15.8%
Tidal Lake barrier	241.14	-237.74	1.4%	237.37	-231.38	2.5%



As expected, the tidal prism increases once the estuary is opened. Nevertheless, the model predicts a tidal prism still lower than reported in the literature before the damming with a magnitude of $\approx 124 \text{ Mm}^3$ flowing into the estuary through the Haringvliet Dam inland. The computed tidal prism is similar for the Haringvliet Dam and the one computed at the inner side of the channels since the location of both measurement cross-sections gives a small storage area between both. In the outer channels, the values computed between the flood and ebb periods show large differences (47.5% error). An explanation is that during the ebb-cycle, the volume flows through the selected cross-sections, but during the flood-cycle, the water also flows over the shoals and is not included in the computation.

The cross-section at the Haringvliet Dam is fixed, narrower than before the closure of the estuary, and unable to erode due to the bed protection¹, the cross-section will be unable to adapt and evolve towards its equilibrium area according to Escoffier (1940) model. This results in a constricted cross-section that will limit the volume flowing into the estuary and will never allow the conveyance of the original tidal prism.

Finally, when the D21 plan is implemented, without including the discharge from the PPS at the ESL, the TL provides additional storage area each tidal cycle, which results in a larger tidal prism. For this scenario, the inlet has shifted to the new barrier, at the entrance of the Tidal Lake. The volume flowing through the TL barrier's cross-section every tidal cycle represents the tidal prism for the new state. The model computes a value of approximately 240 Mm^3 , almost double the value of when only the Haringvliet sluices are re-opened. The volume computed at the outer side of the channels is minimal in this case. Most of the water flowing does not follow these channels anymore when filling and emptying the basin.

The tidal prisms computed at the TL barrier and the Haringvliet Dam, with the full implementation of the D21, are $\approx 237 \text{ Mm}^3$ and $\approx 188 \text{ Mm}^3$ respectively. Considering a flood period of 5.73 hours (taken from the horizontal tide plots in Section 6.2.1), it results in a discharge of approximately $11,500 \text{ m}^3/\text{s}$ and $9,100 \text{ m}^3/\text{s}$ respectively. The discharge magnitudes agree with the estimations of D21 developers.

To evaluate the influence of the PPS, the case with and without it is also evaluated. The general effect of the PPS on the hydrodynamics, is a slight reduction of the tidal prism at all the analyzed cross-sections. In the example illustrated, the filling operation of the ESL attracts currents towards the PPS instead of allowing them to flow into the TL. The tidal prisms are computed for a specific tidal cycle during the simulation, e.g., when the beginning of the flood cycle coincides with the emptying of the ESL. The discharge from the ESL generates a current directed to the TL entrance, which might also explain the higher tidal prisms computed during flood than during ebb for R2 in Figure 6.3.

¹ The bed protection is not actually schematized in the model.

Water levels and currents velocities are also computed at specific locations in the model. Table 6.2 shows the values predicted for the maximum and minimum water levels along with the tidal range. The maximum ebb and flood current velocities for the runs (A) and (E) are also presented in the table. All values are computed for the scenarios when the estuary is open (R1), and once the Delta21 intervention is in place (R2). The values allow a comparison between the offshore tidal characteristics and those inside the basin. The location *Offshore* is ≈ 15 km seawards from the Hinderplaat, with depths of around 14 m. The output at the *Slijkgt channel* is taken at the Slijkgt, mid-distance between the TL inlet, and the *Haringvliet Dam*. The *Estuary* results are from ≈ 15 km upstream from the *Haringvliet Dam* and the *Upstream boundary* output is exactly from inland boundary of the model.

In all locations, higher maximum flood velocities than ebb velocities are predicted. The highest velocity magnitude is at the Haringvliet Dam when the estuary is open (R1) and at the new tidal inlet location when D21 is implemented (R2). The horizontal and vertical tidal amplitudes damp as the tidal wave propagates inland and becomes friction-dominated. The decreased amplitudes are observed in Table 6.2 from *Offshore* in the landward direction (up-down in the table). The table also shows the tidal range for each location, values above 2.0 m are marked in bold.

Table 6.2: **Maximum and minimum water levels, tidal range, and maximum flood and ebb velocities for different simulations A and E for scenarios R1 and R2.** Simulations A are for the only tide case, and simulations E include all processes with the complete schematization. Values are shown for locations in the model from offshore in the landward direction until the upstream boundary. A decrease in tidal amplitude (for vertical and horizontal tide) is seen for all cases except for the Slijkgt channel's velocity, where currents are more constricted. The values of the tidal range above 2.0 m and flood/ebb velocities above 1.0 m/s are highlighted in bold.

Simulation	A-R1			A-R2			E-R1			E-R2		
Maximum wl	HW	LW	H _t	HW	LW	H _t	HW	LW	H _t	HW	LW	H _t
Unit	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]
<i>Offshore</i>	1.10	-0.93	2.03	1.10	-0.93	2.04	1.10	-0.93	2.03	1.10	-0.93	2.04
<i>Tidal Inlet</i>	1.08	-0.87	1.95	0.94	-0.89	1.83	1.08	-0.87	1.95	0.96	-0.87	1.83
<i>Slijkgt channel</i>	0.81	-0.59	1.41	0.82	-0.81	1.63	0.83	-0.44	1.27	0.85	-0.78	1.63
<i>Haringvliet Dam</i>	0.45	-0.48	0.94	0.74	-0.81	1.55	0.56	-0.22	0.78	0.79	-0.77	1.56
<i>Estuary</i>	0.54	-0.53	1.07	0.77	-0.85	1.61	0.68	-0.39	1.08	0.91	-0.66	1.57
<i>Upstream boundary</i>	0.69	-0.61	1.30	1.07	-0.93	2.01	0.95	-0.04	0.99	1.22	-0.47	1.70
Maximum velocity	Flood	Ebb		Flood	Ebb		Flood	Ebb		Flood	Ebb	
Unit	[m/s]	[m/s]		[m/s]	[m/s]		[m/s]	[m/s]		[m/s]	[m/s]	
<i>Offshore</i>	0.82	-0.70		0.71	-0.60		0.80	-0.69		0.69	-0.60	
<i>Tidal Inlet</i>	0.75	-0.44		3.06	-2.31		0.75	-0.39		2.80	-2.50	
<i>Slijkgt channel</i>	2.04	-2.05		2.43	-2.32		1.84	-2.31		2.16	-2.46	
<i>Haringvliet Dam</i>	0.97	-0.85		1.43	-1.21		1.03	-0.84		1.31	-1.30	
<i>Estuary</i>	0.71	-0.37		0.97	-0.61		-0.38	-0.38		0.83	-0.73	
<i>Upstream boundary</i>	0.00	0.00		-0.44	-0.44		-0.08	-0.08		-0.08	-0.08	

For all cases, velocities along the Slijkgt are higher than in the other locations, reaching around 2.0 m/s when the estuary is open (scenario A-R1) and 2.4 m/s when Delta21 is also implemented (A-R2), both in the case of flood-directed flow. For the R1 scenario, velocities at the Haringvliet Dam also exhibit larger flood velocity magnitudes reflecting the flood dominance of the estuary (for cases A and E). At the location of the new tidal inlet, also a flood dominance is detected for the R2 scenario. With the D21, current velocities at the location of the future tidal inlet increase considerably. They reach values of 3.06 m/s for the only tide run and 2.8 m/s for the run considering all processes. Velocities over 1.0 m/s are bold in Table 6.2.

The extreme large velocities observed along the channel and at the barriers' cross-sections can be the result of the concentrated flow through the constricted sections. Broekema (2020) explains high velocities over the scour holes at the Eastern Scheldt Storm Surge Barrier. There is a jet-like flow structure downstream of the barrier, the flow contracts due to the lateral non-uniformity of the flow upstream. The result is high horizontal velocity gradients and high (downward) velocities at the center of the jet². These mechanisms can be observed downdrift of both barriers during the ebb period. The

²The model in this study does not resolve the vertical structure of the flow but, the depth-averaged velocities can still reflect the large currents at the center of the cross-sections.

2D model predicts the flow concentration at the structures, and the largest magnitudes occur at the center of the cross-sections. The 2D flow structure at the Haringvliet Dam plotted at [Figure E.1](#).

Comparing case **E-R1** and **E-R2** in [Table 6.2](#), the effect of the D21 on the water levels is to increase the tidal range for locations inside the basin and to increase maximum flood/ebb velocities. A significant increase especially at the *Tidal Inlet* and the *Slijkgat channel* is observed. The numbers in the table represent the behavior of the higher flood velocity values at the *Tidal Inlet* location (case **R2**). There is a positive skewness of the horizontal tide that also indicates shorter flood periods.

Maximum flood and ebb velocities at the *Upstream boundary* are sufficiently small to assume that the effect of the boundary will not significantly impact the results. The velocity magnitudes show that the influence of D21 on the velocity signal does not reach this location as for both cases **E-R1** and **E-R2**, the computed result is the. Also relevant to notice is the fact that maximum flood and ebb-tidal velocities decrease $\approx 13\%$ at the *Offshore* location with D21. Its influence over the long-shore tidal currents reaches areas farther from the study area of this research.

6.2.3. Residual currents

When the tide approaches shallow water, it deforms: the horizontal and vertical tides become asymmetric due to non-linear components in the tidal signal. The system is flood-dominant because the horizontal tide in the study area is positively skewed. The net direction of the currents will be related to the net direction of the sediment transport and, consequently, to the bed level changes. The overall effect is accounted for by averaging the currents over a certain period, namely, the residual currents.

Residual currents in tidal inlets can be generated by different mechanisms, other than tidal asymmetry. The accelerated flow at the inlet produces eddies at both sides of the inlet gorge because of a flow separation mechanism resulting in residual current patterns. The phasing of vertical and horizontal tides might produce residual flows if more than half of the flood tide coincides with water levels above mean sea level. The inflow of water towards the basin needs to be compensated by a return flow. The resultant residual current is a consequence of this mechanism known as Stoke's drift. For the shoals, most of the flooded stage will be during flood tide resulting in flood-directed residual currents, while to compensate the inflow, the residual current in the channels should be ebb-directed (Bosboom et al. [2015](#); De Swart et al. [2009](#)).

Other mechanisms are bathymetry-driven. If a channel's cross-section consists of deep and shallow areas, the net direction in the deeper parts tends to be ebb-directed while in the shallows is flood-directed. The result is a horizontal circulation easily seen in a 2DH (depth-averaged 2D) simulation. From a 3D point of view, near shoals, a curvature-induced secondary flow develops. Similar to river bends, there is a small water level gradient in the cross-section balanced by a circular current perpendicular to the main flow direction. The upper part of the water column is directed away from the center of curvature and towards it in the lower part, thus contributing to the maintenance of the shoals (Bosboom et al. [2015](#)).

The resulting residual currents will generate a net sediment transport that will cause morphological changes. The interest of the study is to comprehend how the system will evolve when the D21 is present. It is important to understand the distribution of the residual current patterns. The results are presented in [Figure 6.4](#), and [subsection 6.2.4](#) elaborates on the derivation.

6.2.4. 14.5 days Pseudo-Spring-neap cycle

The computation of residual currents aims to observe their average direction over a certain period. Usually, the tidal cycle period is the one considered. However, when there are water level variations in a larger time scale, i.e., the spring-neap cycle, the calculation should be performed for that cycle. Otherwise, the residual currents will be biased either to the effect of spring or neap tide.

In this study, the numerical simulation performed is forced with a semi-diurnal cyclic morphological tide. The signal of morpho-tide is such that the daily inequality and spring-neap cycle are lost. Additionally,

the D21 implementation involves a discharge from the PPS of the ESL with a diurnal signal. The result of the interaction between the tidal boundary condition and the anthropogenic signal is a pseudo-spring-neap cycle of 14.5 days. To consider its effect on the modeled system, the residual currents are computed for this period. The considerations for this spring-neap cycle are addressed below.

The morphological tide forcing the model has a period of 12 hours 24 min, whereas the discharge from the PPS is schematized by a cyclic in/outflow repeated every 24 hours. The frequency difference between the tidal boundary condition and the anthropogenic discharge signal will produce a beating of the signals that might impact the water level amplitudes experienced in the area. The area of influence of this variation is unknown before the modeling exercise.

The case is similar to the generation of a spring-neap cycle; the cycle usually considered is the product of the interaction between either semi-diurnal components M_2 and S_2 or diurnal components K_1 and O_1 (Kvale 2006). In the present anthropogenic system, the resulting cycle is caused by a diurnal and a semi-diurnal component, similar to an M_2 and S_1 interaction.

The description of the tides is usually based on the tidal equilibrium theory. It relates the semi-diurnal tide to the phases of the moon or synodic month, producing spring (higher) tides every 14.76 days, during the new or full moon and neap (lower) tides during the first- and third-quarters. The total period is of 29.53 days. However, the tidal equilibrium theory fails to explain amphidromic circulation, the common occurrence of diurnal tides in low latitudes, or the existence of tide-dominated areas that are synchronized with the 27.32-day orbital cycle of the moon, namely the tropical month³. The latter is better explained with *Dynamic Tidal Theory*, which models each tidal constituent with certain amplitude, period, and phase angle, as the result of imaginary satellites with their own mass, and are derived from harmonic decomposition. The tidal wave moves around an amphidromic point at its own speed, the geometry of each basin determines which constituents are amplified. For details, the reader is referred to Kvale (2006).

Under these concepts, it is safe to assume that the "spring-neap" cycle for the present case will deviate from the normal synodically-driven spring-neap cycle characteristic of the North Sea, probably the case in the area just seaward and to the north of the new tidal inlet. The importance of considering the pseudo-spring-neap cycle is to account for the phasing between the tide entering and leaving the basin while the PPS is discharging in/out the ESL. The net effect of the currents will dictate if sediment is being transported in the area between the Tidal Lake entrance and the location of the PPS and if they will ultimately allow the deposition of material there. There could be implications for the evolution of new shoals near this area. Moreover, the accumulation of material in front of the PPS might compromise its operation if this is the prevailing situation.

6.2.5. Residual currents interpreted

The selected period for the computation of the residual current, for the 14.5-day cycle, has an initial date of 22-Jul-2018 06:00:00 (hydrodynamic time). The computation period is selected so that throughout the 28 morphological tides, the pumps from the PPS are discharging in/out of the ESL, to include the effect of the beating between the signals and capture the net effect.

The resulting residual currents in the system are presented in Figure 6.4. In the deeper areas, ebb-directed residual currents occur, specifically along the new Slijkpat channel from the north-eastern corner of Kwade Hoek towards the Tidal Lake barrier and the remaining stretch of the former Slijkpat. From the Haringvliet Dam to the corner of Kwade Hoek, almost no residual current is observed.

Along the former Slijkpat channel, ebb-directed residual currents follow the channel (a in Figure 6.4c). They encounter the new barrier, turning to the north and looking for a path to flow seaward through the new inlet. To the north of the former ETD (the Hinderplaat), along the Kortsluitgeul and the Hinderpat, also ebb-directed residual currents are found (c in Figure 6.4c). Only over the Hinderplaat

³The orbital cycle of the moon is the time that takes the moon to orbit from its maximum northerly declination to its maximum southerly declination and back.

flood-directed currents occur (**b** in [Figure 6.4c](#)). Along the Hindergat, currents eventually find their path obstructed by the structure between the ESL and TL, forming a small circulation between the structure and the northern Hinderplaat shoal, marked with No. 1 in the sketch of [Figure 6.4c](#).

[Figure 6.4b](#) shows a schematization of the model simulation representing the duration and periods of the pumping operation as an on-off switch (top red plot), the variable MF indicating the related wave condition (lower blue plot), and the period over which residual transports are computed (dashed black lines). The period over which the 14.5-day residual currents (and transports) are computed spans only over 3 wave conditions, *wc 64*, *40a* and *8b*.

The concentration of currents along the channels can be observed from the darker blue and larger velocity vectors in the plotted velocity field. From south-east to north-west, they are encountered at: east side of the Haringvliet Dam, before and after the structure; along the western bank of the Slijk gat channel along the stretch orientated north-south; along the Slijk gat west-east orientated larger residual currents are observed at both banks; along the former Slijk gat and parallel to the southern abutment, at the TL inlet in the northern side and just seaward from the barrier's bed protection.

The patterns of residual currents and their gradients provide an idea of where the transport capacity is higher due to larger current velocities eroding the bed. Once the current velocities decrease, transport capacity also decreases, and the sediment settles. It is particularly desired to identify erosion areas where existing and new structures are threatened. The residual currents parallel to the southern barrier's abutment inside the TL and at the inlet's bed protection are in the order of 0.5 m/s. The local velocities observed in the mentioned areas are plotted in [Figure 6.4d](#) and the maximum velocities are listed in [Table E.3](#).

Local velocities signals at the key locations, marked with red dots in [Figure 6.4a](#) are plotted in [Figure 6.4d](#). The plots show values higher than 1.0 m/s at the Haringvliet Dam and both locations along the new Slijk gat channel. At the Dam, there is a slight flood tendency, and the maximum velocity is in the order of 1.5 m/s. Along the channel next to Kwade Hoek, the local velocity is in the order of 1.24 m/s, increasing at the bend where the maximum velocity is in the order of 1.75 m/s in ebb direction. Similarly, the former Slijk gat still presents important velocity magnitudes in the order of 0.6 m/s. Along the southern abutment of the TL barrier, maximum local velocities are flood directed and almost reaching 1.0 m/s. On the northern side of the TL inlet cross-section, the maximum velocity is 1.56 m/s in the ebb direction. Finally, in the area between the ESL and the TL, velocity magnitudes are in the order of 0.82 m/s, the negative value indicates southern directions.

At the seaward side of the TL barrier, residual currents are also ebb-directed, stronger at the cross-section of the barrier, at the bed protection, and just seaward from it. Further seaward, the velocity vectors decrease and deflect to the north. Low magnitude residual velocity vectors turn toward the PPS and back southwards, forming circulation No. 6 in [Figure 6.4c](#). Some of the velocity vectors just seaward from the TL inlet deflect to the south, towards the coast of Goeree, and then describe a circulating pattern deflecting to the east again towards the inlet (circulation No.7). Further offshore, magnitudes decrease, promoting the deposition of material. Inside the TL, the ebb-directed velocity vectors at the Hindergat also form a circulation (No. 1).

Flood-directed residual currents are only found over the Hinderplaat just south of the Hindergat channel, at the coast of Kwade Hoek south of the former Slijk gat, and just eastward of the TL inlet. At the latter location, the residual current patterns deflect to the north towards the structure between the ESL and the TL, before flowing back through the tidal inlet, forming a circulation cell (No. 2 in [Figure 6.4c](#)). As the vectors deflect, they also decrease in magnitude. Another part of this flood-directed vectors deflects to the south, some immediately return to the main channel, and others continue further east, eventually flowing back to the main channel (No. 3).

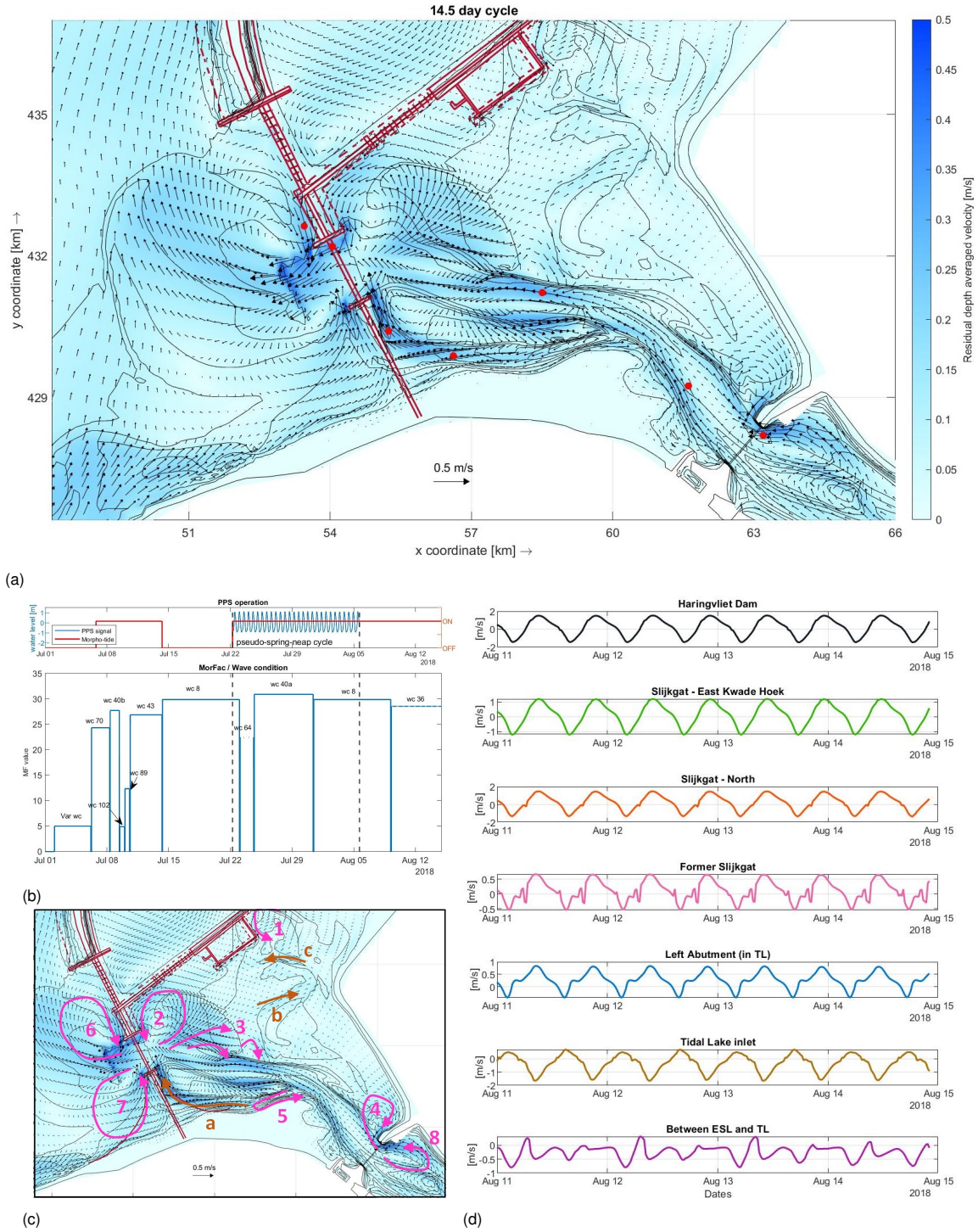


Figure 6.4: **Residual depth-averaged currents, computation, and velocity signal at specific locations in the model, for the D21 scenario and a run with all processes.** (a) The residual values are computed for a pseudo-spring-neap cycle of 14.5 days. Currents along the channels and over the developing ETD are ebb-directed. (b) The schematization of the model's forcing: the pumping operation (top red plot), the variable MF with the related wave condition (lower blue plot), and the period over which residual transports are computed (dashed black lines). The cyclic morphological tide is represented in the top plot for the period over which the residual currents are computed. (c) Circulation patterns are detected and indicated with pink arrows and by number over the velocity vectors. (1) At the outflow of the Hidergat; before exiting the TL at the northern bank of the Slikgat channel, residual flood-directed currents deflect to the left (2) and right (3), at the east side of the Haringvliet Dam inside the TL (4), to the northern edge of Kwade Hoek (5), ebb-directed residual currents exiting the inlet deflect to the north (6) and to the south (7) and upstream the Haringvliet Dam a flood-directed current deflects to the east. (d) Local velocities at key locations, marked with red dots in the map plot. Values higher than 1.0 m/s are found. Along the channel, next to Kwade Hoek, the local velocity is in the order of 1.24 m/s, increasing at the bend to 1.75 m/s where it is ebb-directed. The former Slikgat still presents important velocity magnitudes. At the northern side of the TL inlet cross-section, the maximum velocity is 1.56 m/s ebb-directed. In the area between the ESL and the TL, maximum velocities are in the order of 0.82 m/s; the negative values indicate southern directions.

The circulation patterns formed at the outflow from the Hindergat (No. 1) and at the north-western corner of the TL (No. 2) are produced as the flow meets the structure between the ESL and TL and looks for other paths, to finally flow into the sea. Contrarily, the circulation formed at the end of the new Slijkgat channel and to the south (No. 3) is probably produced by other mechanisms.

During the ebb period, currents mostly flow along the channels, along the Slijkgat towards the inlet and into the sea. However, during the flood period, the water will flow into the TL directly in a NE direction (perpendicular to the TL inlet). The flow will promote the formation of flood-delta features inside the TL, as will be explained in Section 6.3. The evolution of these features will reduce the water depth progressively, and a water level gradient between the back area of this feature and the adjacent channel will occur. The effect is a circulation pattern over the developing shoal, flowing back to the main channel in a clockwise direction (No. 3 in Figure 6.4c).

To the north of Kwade Hoek, between its coastline and the former path of the Slijkgat, a circulation is also formed, No. 5 in Figure 6.4c. As observed in Section 6.2.1, during the ebb period, water flows mostly through the new Slijkgat channel. However, during the flood period the water volume starts flowing over shallower areas and finds a path along the former Slijkgat, while currents along the main channel are still ebb-directed (see Phase 4 of the tidal cycle in Figure 6.2a). The preference of the flow to follow what was originally the main ebb-channel, along the coast of Goeree towards the north-eastern corner of Kwade Hoek, results in net currents directed to the east; while along the old Slijkgat channel the currents are west-directed. This mechanism might promote the deposition of material over this shoal.

Other observed circulation patterns are seen at the Haringvliet Dam to the east, upstream (No. 8), and downstream (No. 4); along with the circulation cells in No. 6 and No. 7 at the TL inlet, they are typical of a flow separation mechanism in the horizontal plane because of a sudden expansion of the cross-section. Only the circulation upstream from the Dam is the result of the flood-directed current; the rest are the consequence of the ebb-directed currents. The seaward circulation at the northern abutment of the TL inlet, flowing back to the TL inlet, shows larger vectors than the circulation at the southern TL inlet abutment. There is probably a reinforcement from the PPS currents flowing at the ESL. The currents will likely produce sedimentation patterns close to the PSS and its bed protection.

Along Goeree's coast, residual currents are directed to the east. If these currents produce net sediment transport, the presence of the abutment represents an interruption of the littoral drift, enhancing the accumulation of material. The location could be a low-dynamic area that allows the deposition of material and the growth of shallow areas. The potential development of a sandbank at this location is addressed in Chapter 7.

Since the model simulations are depth-averaged (2DH), the horizontal distribution of the current patterns are well predicted. In contrast, the vertical variations of the velocity profile are not resolved, e.g., due to bottom friction and wind-induced surface friction, which become important in the shallowest areas like the ones present inside the TL.

The results from the residual current analysis give a preliminary assessment of the locations where net sediment transport can be expected. The actual transport of material that will eventually produce bed level changes also depends on the upstream sediment supply from the estuary and the velocity magnitude. Only if the currents have enough transport capacity, i.e., velocities at the bed are higher than the critical velocity,⁴ the material move.

The hydrodynamic conditions are bathymetry-dependent, and their net action is responsible for bathymetric variations. Therefore, there is positive feedback between residual currents and morphological change. For these reasons, it is necessary to use a morphodynamic model that accounts for the feedback each time-step. The results of the fully morphodynamic model are presented in Section 6.3. The analysis of those results goes beyond the morphostatic analysis elaborated so far.

⁴The critical velocity of the particle is the velocity over which the balance between the friction and drag forces of the grain is lost.

6.3. Morphological changes

To evaluate the behavior of the system with the D21 implementation, a 3-year long-term simulation was conducted. Computational times needed to be kept realistic. For this purpose, a variable MF for a 3-year wave climate schematization was chosen (see Section 5.4.1 in Table 5.6).

As observed in Figure D.6 for a **R1** scenario (open estuary), if the initial bathymetry is not in equilibrium with the system, initial bed level changes can be considerably large. The enhancing effect of the MF produces unrealistic changes due to positive feedback between the flow and the morphology. Large bed level variations were already visible for $MF = 30$. Once D21 is present, the initial changes will probably be larger. To minimize unrealistic initial bed level changes and guarantee computational stability in the model, an adjustment period for bathymetric changes is applied, with a low MF value.

The 3-year simulation runs with variable morphological factors $MF < 30$, and the adjustment period is chosen of 12 morphological tides, with a constant value of $MF = 5$. In Section 5.4.1 it was proven that $MF = 5$ value produces low errors (Figure D.7). After the adjustment period the schematization presented in Table 5.6 is applied to the model.⁵

The use of a variable MF is also thought to be beneficial for the discrepancy of time scales between the morphology, and the PPS hydrodynamic forcing, which is in the time scale of the tidal forcing and waves. When oscillating signals are present in the model, they are also enhanced by the MF. The use of a variable MF allows the application of lower values to more energetic conditions and higher MF values to more regular conditions. It also guarantees the occurrence of each wave condition for entire morphological tides to account for the net effects of the entire tidal cycle. The same assumption is made for the pumping cycle.

This section presents first the net sediment transport patterns that will ultimately produce the observed morphological bed level changes and are elaborated in Section 6.3.2.

6.3.1. Sediment transport patterns

Sediment (sand) transport in tidal environments can be caused by numerous drivers (Section 2.2). It is the net effect of the tidally-averaged transport that interests us for understanding the causes and origins of bed level changes. The magnitude and direction of the net (residual) sediment transport hints on how the tidal environment will evolve. In this study, the bed material is schematized with a $D_{50} = 160\mu m$, in the range of fine sands. Therefore, the focus is on the net sediment transport of granular (coarse) sediment.

The analysis of residual sediment transport patterns is done by averaging the transports over the pseudo-spring-neap cycle derived in Section 6.2.3. The mean total transport of sand is computed at each grid cell in the model domain for each time-step, throughout the duration of the simulation. The values represent the mean transport during the whole simulation at the given time-step.

The residual patterns plotted in Figure 6.5a are computed from selecting an initial and final date to complete the 14.5 days of the chosen cycle. The corresponding values are then subtracted (Elias et al. 2020), and the resulting transport is the net transport for the 14.5-day period. For a plot with a finer resolution to observe the lowest magnitudes of the sediment transport pathways, the reader is referred to Figure E.7. The selected computation period for the net sediment transport patterns is the same as selected for the residual currents in Section 6.2.3, marked by vertical dashed-lines in Figure 6.4b. Figure 6.5b shows the main sediment transports directions that were identified.

The main directions observed for the sediment transport are at the two barriers, i.e., the Haringvliet Dam and the TL inlet barrier. In the first case, the patterns show a net sediment import upstream of the Haringvliet Dam, mostly concentrated at the eastern side of the sluices (marked with No. 7 in Figure 6.5b). At the TL inlet, the pattern shows a net export of material towards the seaward side and

⁵The period over which each wave condition is acting in the model and the corresponding MF can be consulted in Figure 6.4b.

in NW-directions (No. 1 in Figure 6.5b). Overall, the TL seems to be exporting material at both of its ends.

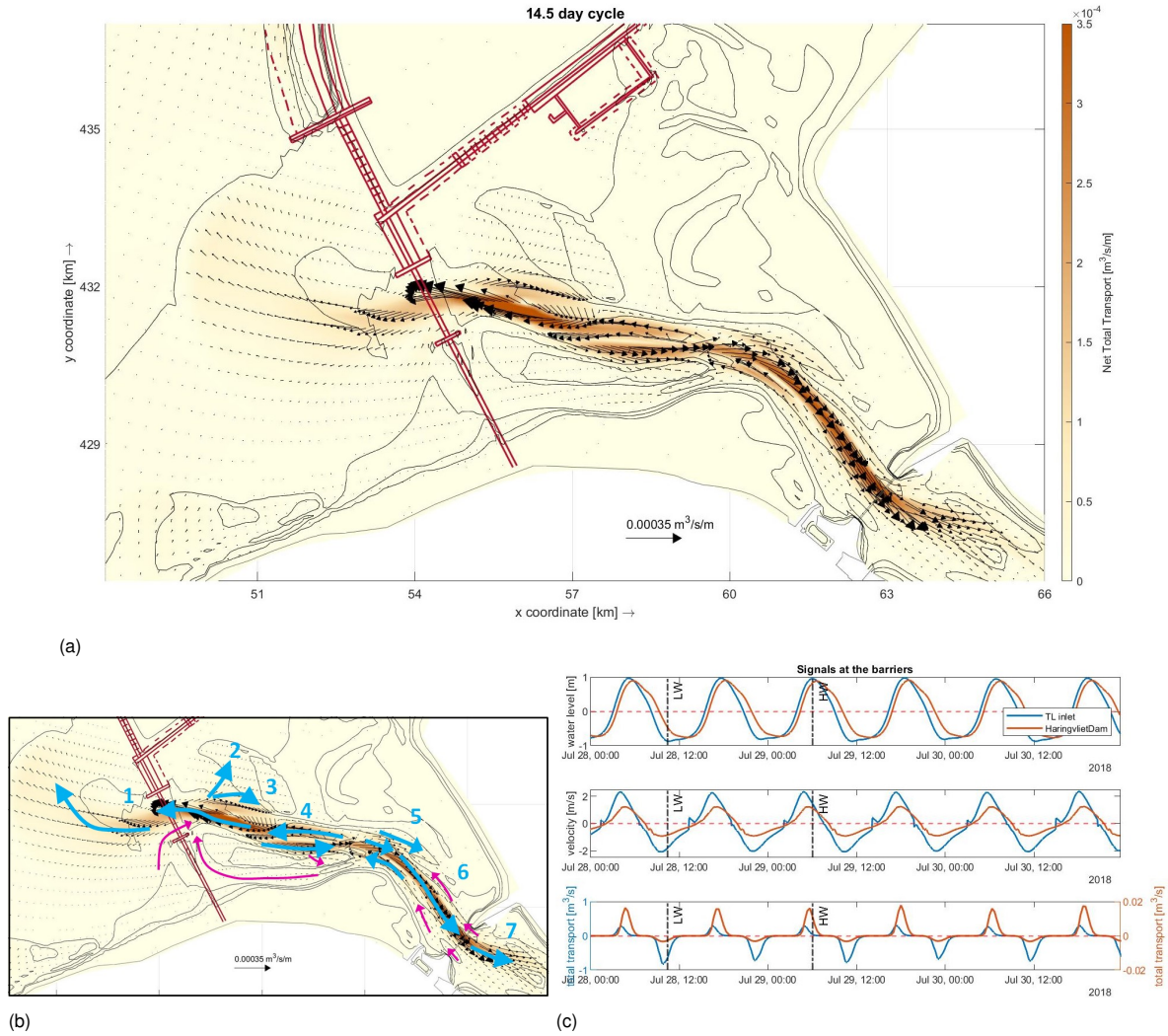


Figure 6.5: **Mean Total transport for the 19-days spring-neap cycle.** The mean transports are computed as the average total transport for the 38 morphological tides that constitute the pseudo-spring-neap cycle in the PPS-tidal inlet system. (a) Residual sediment patterns in the Haringvliet, the TL, and seaward from the structure are represented and mainly show flood-directed transports at the TL barrier and ebb-directed at the Haringvliet Dam. (b) Schematic view of the main pathways according to the net total transport vectors. In blue, the larger transports are indicated, and in pink, those of lower magnitudes. Specific areas are identified with numbers. (c) Water level, flow velocity, and total transport time series at the location of the TL inlet and the Haringvliet Dam. The flood dominant character of the basin is observed at both barriers for the water surface elevation and the current velocity. At the Haringvliet Dam, total flood-transports are larger than total ebb-transports. At the TL barrier, the opposite occurs. Negative values correspond to the ebb-period of the tidal cycle.

To better understand the behavior, the water surface elevation, current velocity, and total transport time series are plotted in Figure 6.5c, at the location of the TL inlet and the Haringvliet Dam. The flood dominant character of the basin is observed at both barriers in the water surface elevation and the current velocity plots. In contrast, the total transport at the TL inlet does not follow the velocity signal, as should be expected for the transport of coarse material.

At the Haringvliet Dam, flood-transports are larger than ebb-transports. The import of sediment upstream appears to be the result of horizontal tidal asymmetry. However, at the TL barrier, the opposite occurs. Other mechanisms should be producing the export of sediment at this cross-section. The instantaneous total transports during the tidal cycle show that during the flood-period, material mostly flows along the channel and into the Haringvliet waterway, probably advected from the main channel.

At the TL inlet, the flood-directed total transport is an order of magnitude lower. During the ebb-period, there is almost no transport at the Haringvliet Dam, but at the TL inlet, large total transports travel offshore. The material is probably put into motion along the channel and advected towards the inlet in the ebb-period. The total transport vector patterns follow those of the suspended sediment transport. Sediment transport is dominated by suspended load transport (not shown). The topic is further discussed in Chapter 8.

Despite the clear export trend at the TL barrier, expected due to the formation of an ETD in the seaward side of the TL, a transport pattern from the barrier in the flood direction is also identified (No. 2). The pattern is eastward-directed, with slightly larger magnitudes to the south and decreasing in the same direction. The main pathways are shown in Figure 6.5b and will be elaborated below. The net sediment transport patterns at the Hinderplaat and the sheltered area behind it are of a much lower order of magnitude and are not visible in the plot.

A closer look at the origin of the flood directed transports east of the TL inlet shows that they originate within the TL, just eastwards from the barrier. The transported material does not seem to be imported from offshore but entrained in the main channel, at its edge with the bed protection, generating a scour hole. The mechanism might be responsible for the growth of flood-delta features inside the TL.

Net flood-directed sediment transport occurs at the southern side of the TL inlet. The rather low transport is identified with a pink arrow in Figure 6.5b. The pattern follows Goeree's coast towards the TL, where it meets the ebb-directed transports. The material is transported seawards again, to be finally deposited offshore, building up the ETD. The pattern is typical of a bypass through the inlet (Herrling et al. 2018).

Immediately southwards of the flood-directed transport patterns in No.2, transport vectors deflecting further to the south towards the main channel appear (No. 3 in Figure 6.5b). These sediment transports are consistent with the residual currents observed in Figure 6.4a. Transports identified with No. 3 meet the ebb-directed transports along the right bank of the Slijk gat channel (seen in the direction of the sediment transport vectors), No. 4 in the figure. A circulation occurs, the material is transported eastwards inside the TL (No. 2), a fraction flows towards the channel (No. 3), and finally out of the TL (No. 4). Along the section No. 4 of the channel, the net sediment transport vectors increase in magnitude in the seaward direction, an indication of erosion.

The net flood directed sediment transport vectors extend along the Slijk gat channel, north of Kwade Hoek, parallel to Goeree coast (No. 4), towards the channel's bend (No. 5) and eventually into the Haringvliet waterway (No. 6 and 7). Only in the eastern coast at Kwade Hoek and between the Slijk gat and Rak van Scheelhoek, smaller transport patterns are detected in the ebb direction again (pink arrows in area No. 6), which ultimately meet flood-directed transports (No. 4) to the north of the NE corner of Kwade Hoek.

During the flood period, water levels are rising, and the shallowest parts are not covered yet. During the ebb period, water levels start falling, and the shoals are underwater. The ebb period is longer than the flood-period due to the flood-dominance of the basin. The resultant effect is residual currents and net sediment transports, averaged over a 14.5-day cycle, in ebb-direction direction. Finally, an area with really low transports is located at the meeting point between the main ebb channel Slijk gat and Rak van Scheelhoek (pink arrow at area No. 4 in Figure 6.5b), hinting of a place where the deposition will take place.

At the location marked with No. 4 in Figure 6.5b, a circulation cell also forms between the sediment transports to the northern and southern banks of the channel. On the northern(southern) bank, the net total transport is ebb-(flood-)directed. A fraction of the flood-directed sediment transports deflects to the south decreasing in magnitude (pink arrow in area No. 4). The east-directed transport will meet the ebb sediment transport vectors coming from the eastern coast of Kwade Hoek, developing an accretion zone.

Along the northern coast of Goeree inside the TL, net west-directed sediment transport occurs, a few orders of magnitude smaller than in the main channel. These vectors follow the coast until the new barrier and deflect northwards, where they encounter small flood-directed transports from the inlet (pink arrow in Figure 6.5b). A figure with a coarser vector field where the directions of the small magnitude transports are clearer can be consulted in Figure E.7.

In the areas marked with No. 6 and 7 in the figure, the transport vectors are mostly flood-directed. In No. 6, small flood-directed transport spreads to the east, wider than the main cross-section of the Slijkgat and over the shallowest parts. As they approach the Dam, they reach milder transport vectors in the ebb-direction. The meeting point shows almost zero magnitudes, indicating a deposition area. In stretch No. 7, the sediment transport vectors deflect slightly to the east and decrease in magnitude as they enter the Haringvliet waterway. There is a large magnitude difference between the vectors just crossing the Dam and those barely 2 km upstream, where large sedimentation is expected.

For a better insight of the order of magnitude of the material transported through the barrier's cross-sections, a computation of the net sediment transport is made firstly for the pseudo-spring-neap cycle and then for a tidal cycle during each acting wave condition. In Figure 6.4b, the 14.5-day pseudo-spring-neap cycle period was indicated with vertical dashed lines. The period over which the 14.5-day residual transports are computed spans over only 3 wave conditions. Therefore, it is decided to evaluate the sediment transport patterns that each wave condition produces. The pumps are off during the first period of wave condition *wc8*, during *wc 40b* and *wc 43*, the largest and lowest discharge regime in the model occur. The computed transports are presented in Table 6.3.

Table 6.3: **Mean total transport per wave condition through the barriers.** The net transport rates per wave condition are computed for a single tidal period (744 min). The net transport rates in the last row correspond to the average over a cycle of 14.5 days (28 morphological tides). The rates are computed for the model's total transport output and averaging for the selected period. Positive values indicate flood direction, whereas negative values correspond to ebb-directed net transport. At the Haringvliet Dam, the net total transport in all cases is flood-directed. At the TL inlet, the net total transports are ebb-directed except when *wc 70*, *102* and *89* are acting in the model. The rates over the spring-neap cycle at both barriers indicate a net export of material from the TL area.

WC	H _s	T _p	Dir	Wind Velocity	Wind Dir	Haringvliet Dam		Tidal barrier	
[-]	[m]	[s]	[°]	m/s	[°]	[m ³ /s]	mcm/yr ⁶	[m ³ /s]	mcm/yr
70	2.99	7.78	323.7	12.7	310.2	9.30E-02	2.933	6.3E-02	1.990
40b	1.99	6.35	231.6	11.6	225.9	3.33E-02	1.051	-1.4E-01	-4.484
102	4.48	9.52	276.2	17.8	277.3	1.98E-01	6.258	2.9E-01	9.067
89	3.98	8.98	247.5	18.1	253	8.59E-02	2.709	2.0E-02	0.639
43	1.99	6.35	277.4	10.8	271.2	1.08E-01	3.419	-3.4E-02	-1.081
8a	0.48	4.45	292.9	4.2	240	7.74E-02	2.440	-9.1E-02	-2.874
64	2.98	7.77	231.6	15.2	225.6	8.44E-02	2.661	-5.6E-02	-1.761
40a	1.99	6.35	231.6	11.6	225.9	8.67E-02	2.734	-8.3E-02	-2.615
8b	0.48	4.45	292.9	4.2	240	8.40E-02	2.648	-4.5E-02	-1.407
36	1.47	6.05	352.9	6.4	345.9	6.03E-02	1.903	-3.3E-02	-1.033
Net Transport Spring-Neap cycle						9.26E-02	2.919	-6.28E-02	-1.981

The results presented in the table confirm the net sediment transport patterns observed in Figure 6.5 for the pseudo-spring-neap period considered. At the Haringvliet Dam, the model predicts a volume of sand being transported upstream from the dam, in the order of 9.26×10^{-2} m³/s or 2.919 mcm/yr. Conversely, at the TL inlet cross-section, the model computes net sediment transport in the seaward (ebb) direction in the order of 6.28×10^{-2} m³/s or 1.981 mcm/yr.

The computed transports roughly show a net sediment loss for the TL, despite the large growth of a flood-delta shoal (see also Section 6.3). The material that generates the FTD might originate from inside the TL itself. Material from the TL is redistributed, promoting the growth of shoals inside the TL and, according to the net sediment transport pathways at the barriers, will also deposit in the seaward side, an ETD will also emerge. Upstream of the Haringvliet Dam, a shoal will grow.

⁶mcm: million of cubic meters.

The net sediment transport per wave condition for one tidal cycle is computed to understand if, during any of them, there is an important import of sediment towards the TL that might explain the growth of the FTD. The resulting transports show that for wave conditions 70, 102, and 89, there is a net import of sediment from the seaward side at the tidal barrier cross-section. For all the other wave conditions, net transports remain flood- and ebb-directed at the Haringvliet Dam and the TL barrier, respectively. Wave conditions 70, 102, and 89 are the most energetic conditions, i.e., they have the highest wave heights in the schematization with WSW to NNW directions.

Understanding the mechanisms behind the growth of the FTD will help to unravel the sediment pathways. This new feature represents the growth of the intertidal areas and therefore is valuable ecologically. This is further discussed in Section 7.2 and Section 8.6.1.

The last fact to stress from Table 6.3 is the difference in computed transports for wave condition 8. During the first period (wc 8a), net sediment transport magnitudes for a given tidal cycle is larger at the TL barrier and at the Haringvliet Dam than during the second period over which it acts. During wc 8a there is no in/out discharge from the PPS, whereas during wc 8b the pumps are in operation. The effect of the pumps is to hinder the export of sediment at the TL barrier cross-section (in the seaward direction), probably due to the residual current flowing from the PPS to the inlet (circulation marked with No. 6 in Figure 6.4). For the Haringvliet Dam case, the discharges from the PPS show an influence, also reducing the volume imported into the Haringvliet waterway through the sluices.

It seems that the overall effect of the PPS is to decrease the sediment transports along the main channel in both directions, and therefore through both control cross-sections. This could be related to the decreased water volume flowing through the TL inlet and Haringvliet Dam, Figure 6.3 showed that the tidal prism is smaller for the case with pumps than without pumps. Further evaluation of the PPS influence is necessary.

6.3.2. Bed level changes: an overview.

The previous section made a thorough analysis of the net sediment transport field to define sediment transport pathways and predict the bed level changes caused by the D21 implementation. The analysis was conducted top-down, starting with the general trends of sediment pathways. Then a more detailed analysis was done to explain specific developments (see also Chapter 7).

The resulting 3-year evolution of the study area is presented in Figure 6.6. The final bed level is the result of a long-term simulation where the model input is schematized through input reduction techniques (Chapter 5). The operation of the PPS at the ESL is also included during most of the simulation (see Figure 6.4b) to account for the phasing of the discharge signal and the morphological tide, producing a pseudo-spring-neap cycle of 14.5 days. Finally, the sediment fluxes and, consequently, bed level changes are enhanced by a morphological accelerator factor (Lesser 2009), variable in function of the acting wave condition, and its probability of occurrence (Stark 2012).

To understand the processes originating bed level changes, a top-down analysis was made. The starting point is the resulting bed evolution throughout the entire simulation. First, the bed level changes for the whole simulated 3-year period (Figure 6.7a) and then for the pseudo-spring-neap cycle (Figure 6.7b) are analysed. Afterward, the bed level evolution at specific time-steps are studied (Figure 6.9).

In both figures, the main accretion areas (red), from south-east to north-west are: between the Dam and ≈ 2 km upstream from the Haringvliet Dam, the area between the main channel (new Slijkgrat) and the Rak van Scheelhoek channel, north to Kwade Hoek between it and the channel, directly eastwards from the TL inlet, and finally at the seaward side around the NAP -10 m contour. On the seaward side, along Goeree's coast on the eastern side and just next to the abutment, there is accretion also. The accretion to the east from the inlet and inside the TL, as well as that at the seaward side of the TL inlet, are typical developments of a flood-tidal delta and ebb-tidal delta, respectively. They will be henceforth referred to as the developing FTD and ETD.

Similarly, the erosion areas (blue), from south-east to north-west, are: at the eastern side of the Haringvliet Dam, along the Slijkgtat channel east from Kwade Hoek, and to the north after the channel's bend. Further to the NE, just before the TL inlet and at the seaward side just seaward from the inlet, erosion is also observed. The erosion can be related to scour holes developing next to the bed protection in both directions. To the south-west of the study area, the landward side of the shoal known as Bollen van de Ooster also erodes.

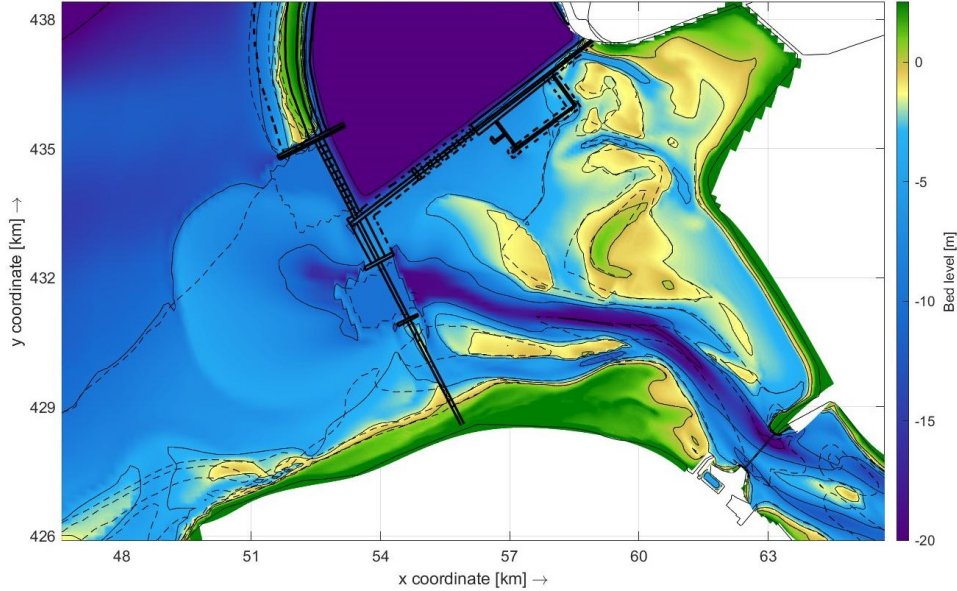


Figure 6.6: **Final bed level for the entire simulation representing the 3-year evolution of the system after implementing the D21 plan.** The presented result is obtained from a run where the complete schematization of waves, discharge, wind, and a morphological tide with $T = 740$ min is implemented to force the model. Additionally, the operation of the PPS at the ESL is implemented in the model. A variable morphological accelerator factor that depends on the acting wave condition enhances the sediment fluxes and bed level changes to reduce computational times (see Chapter 5). The dashed contour lines represent the original bathymetry and the solid lines the same contours after the simulation.

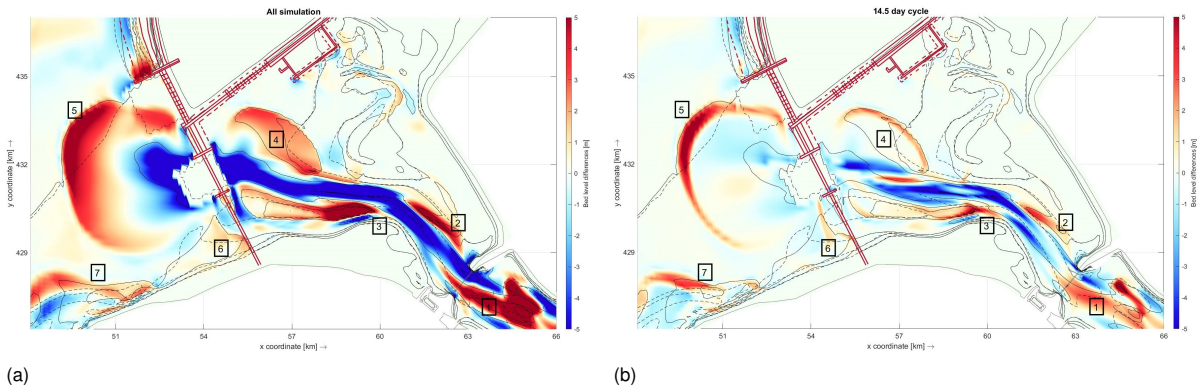


Figure 6.7: **Sedimentation-Erosion patterns from a simulation representing 3-year evolution after the D21 implementation.** Accretion is depicted in red and erosion in blue. The dashed lines are the contours for the initial bed level and the solid lines are the contours after the simulation. (a) Resulting patterns after the entire simulation time. Maximum sedimentation-erosion is in the order > 5 m along the main channel (erosion), and sedimentation inside the Haringvliet waterway, shoals to the east of the main channel and north of Kwade Hoek, and in the seaward side at the developing ETD. Sedimentation and erosion is also depicted at the former ETD (Hinderplaat) with magnitudes in the order of ± 1 m. (b) Resulting patterns for a 19-day spring-neap cycle. Sedimentation erosion patterns are similar for the entire simulation, although patterns at the former ETD are less visible.

For the entire simulation, the accretion is larger than 5 m, especially inside the Haringvliet waterway (No. 1) and at the most seaward edge of the developing ETD (No. 5). Between Kwade Hoek and the Slijkgtat channel (No. 3), and between the Slijkgtat and Rak van Scheelhoek channels (No. 2), deposition is also > 5 m. At the developing FTD (No. 4), the accretion is in the order of ≈ 3 m.

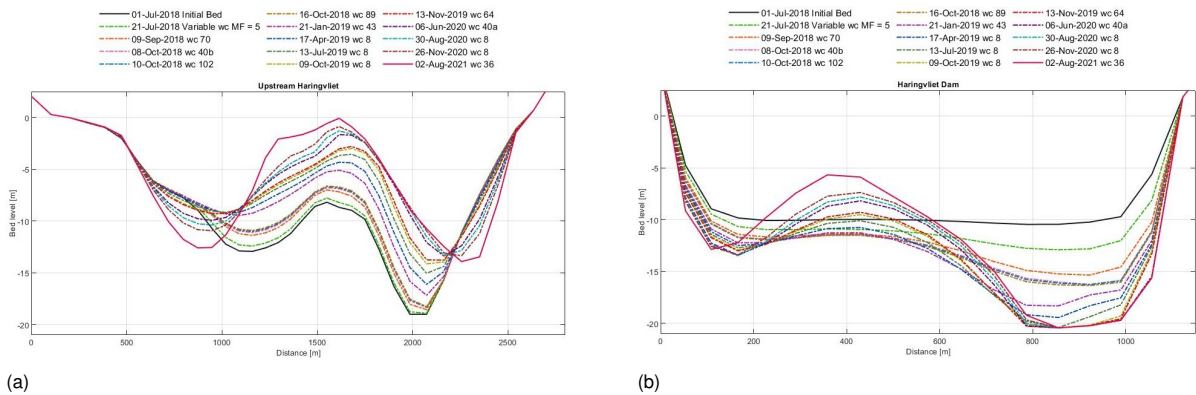
The patterns between [Figure 6.7a](#) and [Figure 6.7b](#) agree, only at lower order of magnitudes, such that patterns at the Hinderplaat are not visible for the pseudo-spring-neap cycle plot. The main sedimentation-erosion areas are accurately predicted by the net sediment transport patterns. Additionally, both figures show a deformed development of the ETD lobate shape, at the northern edge, in front of the PPS of the ESL. The lack of smoothness can be explained by the influence of the discharge from the PPS. When the PPS is emptying the ESL, the discharge into the sea generates large currents that will stir sediment up and push it southwards (see [Figure 6.2a](#)).

The discharge of the PPS has an influence mostly over the area between the ESL entrance and the TL inlet, on the offshore side. The effects inside the TL are of an order of magnitude lower (see [Figure E.10](#)). The influence on the bed level changes extends to the seaward area around the forming ETD, showing differences in the order of more than 1 m, considering a case with pump operation and a case without operation. The differences inside the TL, between both cases, are in the order of 0.2 m. The PPS operation produces larger erosion next to the structures, as expected, but also produces larger sedimentation over the bed protection.

The evolution of key cross-sections is evaluated for a better understanding of how the features grow. The cross-sections, from the Haringvliet waterway in the seaward direction, are located ≈ 2 km upstream from the Haringvliet Dam; at the Haringvliet Dam; inside the TL, four cross-sections are examined and, at the seaward side, two cross-sections more. [Figure 6.8](#) presents the evolution of each cross-section. The bed level at the beginning of the simulation is plotted with a solid black line and the final bed level with a solid-red line. The trends are explained from inland in the offshore direction.

Firstly, the large flood-directed transports through the Haringvliet Dam, decreasing upstream, produce the large sedimentation observe at the Haringvliet waterway (No. 1 in [Figure 6.7b](#)), covering an area upstream from the dam up to 2 km distance. At the Haringvliet Dam cross-section ([Figure 6.8b](#)) and upstream ([Figure 6.8a](#)), the increasing bed level elevation is clearly depicted. Upstream of the dam, a shoal emerges with the highest elevation reaching almost NAP 0 m, dividing the Haringvliet's waterway cross-section in two. The deepest part of the channel also accretes, from NAP -19.0 m to -14.0 m. At the dam, the bed level elevation reaches $\approx$ NAP -5.0 m in the shallowest section, but at the eastern side, the bed level decreases from NAP -10.0 m to $\approx$ -20.0 m. Here, the current streamlines concentrate on the east side of the Haringvliet Dam structure.

The bed level changes of area No. 1 represent a reduction in the waterway's cross-section under MSL of 47.6% from 20,894 m² to 14,159 m². Exactly at the Haringvliet Dam, the cross-sectional area increases 31%, from 7,518 m² to 10,892 m². These findings show that the cross-sectional area to convey the water volume is close to 11,000 m² as both cross-sections tend to a similar number, with a decreasing rate at the Haringvliet Dam; for the discharge regime in the model. Further analysis is necessary to determine what are the consequences, although it is out of the scope of the present research.



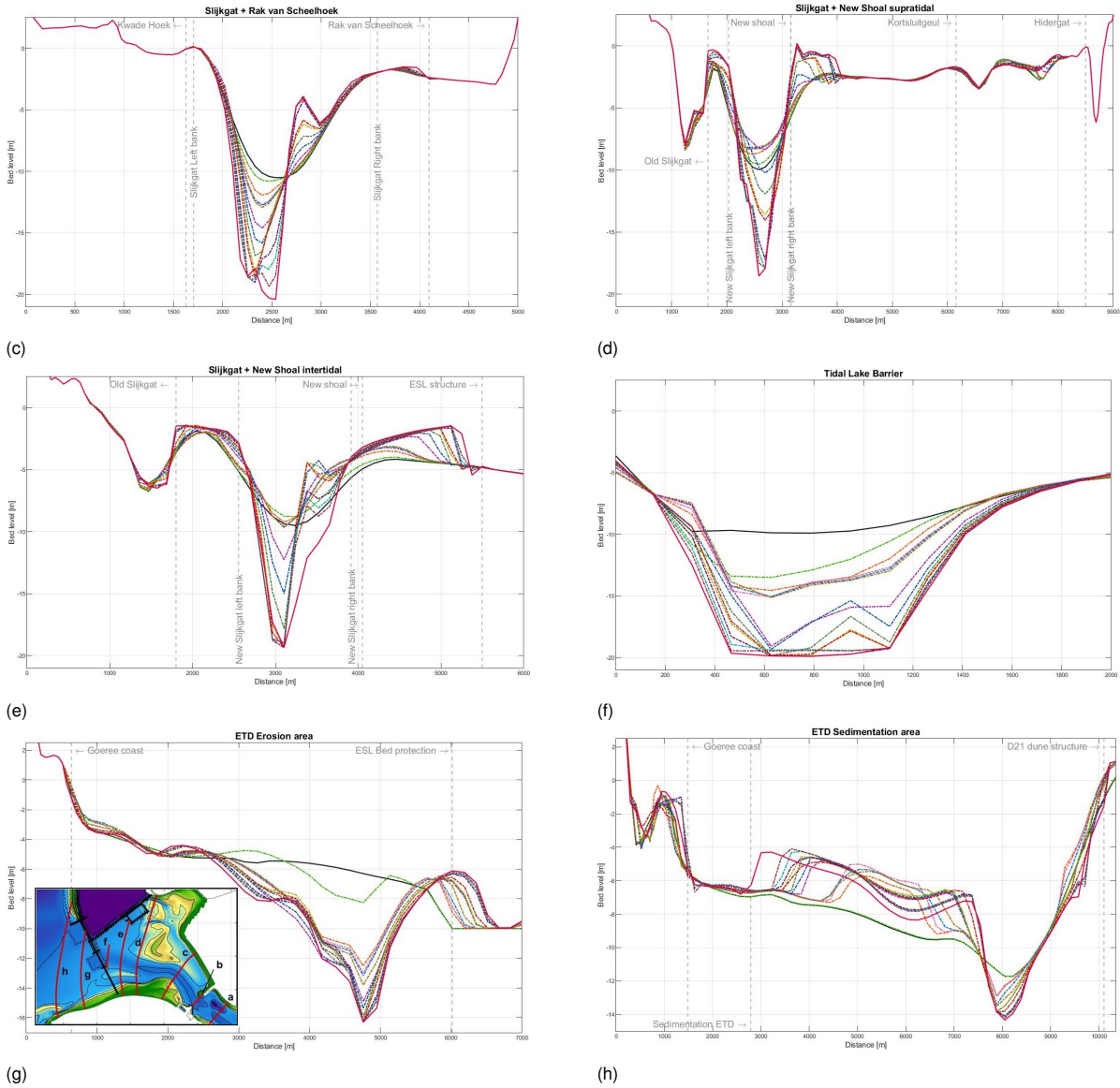


Figure 6.8: **Cross-sections evolution throughout the entire simulation, representative of 3 years of morphological changes.** The solid black lines represent the initial bed level in the model for the different cross-sections while the solid red lines represent the final bed level after the simulated period. The dashed lines are intermediate time-steps. (a) Haringvliet waterway, ≈ 2 km upstream from the dam. (b) Haringvliet Dam. (c) Cross-section just downstream from the Haringvliet Dam showing the Slijkgat and Rak van Scheelhoek cross-sections. (d) Cross-section inside the TL from Goeree to the MV2 corner, going through the Slijkgat-Kwade Hoek shoal, FTD, and the Hinderplaat and its channels. (e) Cross-section inside the TL from Goeree to the ESL structure, through the Slijkgat-Kwade Hoek shoal and FTD. (f) Slijkgat cross-section just inside the TL before the bed protection. (g) Cross-section just seaward from the inlet covering from Goeree's coast to the PPS of the ESL and through the eroded zone of the ETD. (h) Most offshore analyzed cross-section corresponding to the accretion zone of the developing ETD. Covers from Goeree coast to ESL dunes. The location of the cross-sections is shown in the small plot of panel (g).

The accretion marked with No. 2 in Figure 6.7, between the Slijkgat and the Rak van Scheelhoek channels, appears to originate from net flood-directed sediment transport along the main channel arriving at the bend. At this location, most of the material is forced to continue along the main channel, to the south-west. The main ebb-currents follow the channel as they flow seaward. In contrast, the flood-currents tend to flow over the shallows, not following the bend. This effect produces the spread of the transport vectors wider in the cross-section and decreasing in magnitude with increasing bed level.

The result is a bar formation at the end of a developing flood-channel. The emergence of this feature is depicted in the cross-section evolution of Figure 6.8c and also in the last 4 snapshots of Figure 6.9.

The cross-section changes also show the large erosion in the main channel, with depths increasing from ≈ -10.0 m to ≈ -20.0 m. On the eastern bank of the channel, the emergence of the bar is observed as the bed level increases. Further to the east(right in the plot), the formation of the flood-channel also becomes clear. Next to the Rak van Scheelhoek channel, a very mild bed level increase corresponds to the slight growth of the shallow area between both channels. At the Rak van Scheelhoek channel, no changes are depicted.

The sedimentation area between the north side of Kwade Hoek and the Slijkgat (No. 3 in [Figure 6.7](#)) appears to be the product of the lower transport capacity of the flow as a circulation area is formed here (see also [Figure 6.4a](#)), agreeing with the predictions in Section 6.3.1. The net ebb-directed transports meet flood-directed ones, ultimately settling at this location. The initial state of the bed already presented shallow depths, [Figure 6.8d](#) show the increasing bed level between the former and the new Slijkgat channels, from depths in the order of NAP -2.0 m to -0.5 m.

The growth of this shoal originates from material eroded along the east edge of Kwade Hoek, transported in the ebb-direction. Similarly, the flood-directed transports erode the northern side of the shoal itself and the northern bank of the main channel right next to it, redistributing the material towards the shoal. The cross-section evolution again shows the large erosion along the Slijkgat channel, reaching depths of ≈ -18.0 m. Finally, the shoal extends in the eastward direction, becoming wider at its western edge. The growth is enhanced during the action of *wc 8* and onward, from the snapshots in [Figure 6.9](#). In [Figure 6.8e](#), the western side of the shoal seems to stop increasing its height during the last part of the simulation, but it still grows in volume as it becomes wider.

Understanding the emergence and growth of the FTD (No. 4) and the ETD (No. 5) is an important part of the present study as they are features characteristic of tidal environments and key elements in the morphological evolution of basins. Furthermore, their progressive evolution is the result of hydrodynamic-morphological feedback and, in this specific study, the product of an anthropogenic intervention.

The emergence of the FTD becomes clear after 9 days of hydrodynamic simulation, in the 7th snapshot of [Figure 6.9](#), at the end of the period during which *wc 43* acts in the model. During the rest of the simulation, the feature grows consistently. According to the net sediment transports, the growth of the FTD is the product of material transported eastward from within the TL, when flood-currents enter the TL, not as the result of an import from offshore (see Section 8.6.1).

The growth of the FTD is also seen in [Figure 6.8e](#) and [Figure 6.8d](#). The former presents the cross-section evolution at the northern side of the feature, and the latter corresponds to the southern side of the FTD, where the highest elevations of the feature are found at the end of the simulation.

Both plots show the increasing bed level elevation. A turning moment is detected during *wc 8*. The dark blue plot in [Figure 6.8d](#) shows the accretion triggered during *wc 8*. Nevertheless, at the northern edge ([Figure 6.8e](#)), after *wc 70* acts, the bed level plot (orange) already shows the start of an accretion trend. After *wc 40a* the larger growth occurs. Especially in [Figure 6.8e](#), the eastward extension of the feature as time progresses is clearly represented; the material is spread farther but with a lower bed elevation increment. In [Figure 6.8d](#), the channel's right bank also shows a trend to accrete, reaching a maximum during *wc 8*, to erode again, while the FTD front extends to the east. This shows that there is a redistribution of the material.

The last observation of [Figure 6.8d](#) is the changes in the northern area of the Hinderplaat (right side of the plot). Although minor, the bed level shows a depth decrease at a channel between the Kortsluitgeul and the Hinderplat while both of these channels present almost no change. South of this channel, the shoal is eroding while the material is deposited inside the channel, smoothing out this feature.

[Figure 6.8f](#) and [Figure 6.8g](#) show the cross-sections immediately seaward and landwards from the TL inlet, respectively. Each cross-section represents the erosion produced by the flow as it enters and exits the TL. Because of the hard structure (bed protection at the barrier), this erosion was expected.

The bed level reaches NAP -20.0 m inside the TL and NAP -16.0 m at the sea-side; the erosion is in the order of 10 m for both cases and seems to stabilize by the end of the simulation.

On the right side of Figure 6.8g, the initial bed level shows where the bed protection elevation is. No erosion is allowed in the model, but an important accretion occurs. While *wc 8a* acts in the model, minor bed level changes occur, but during *wc 8b*, bed level elevation variations are larger. Probably the operation of the pumps during the second period has an influence. The sedimentation spreads further towards the PPS entrance increasing in height as well, with the largest increase during *wc 40a*.

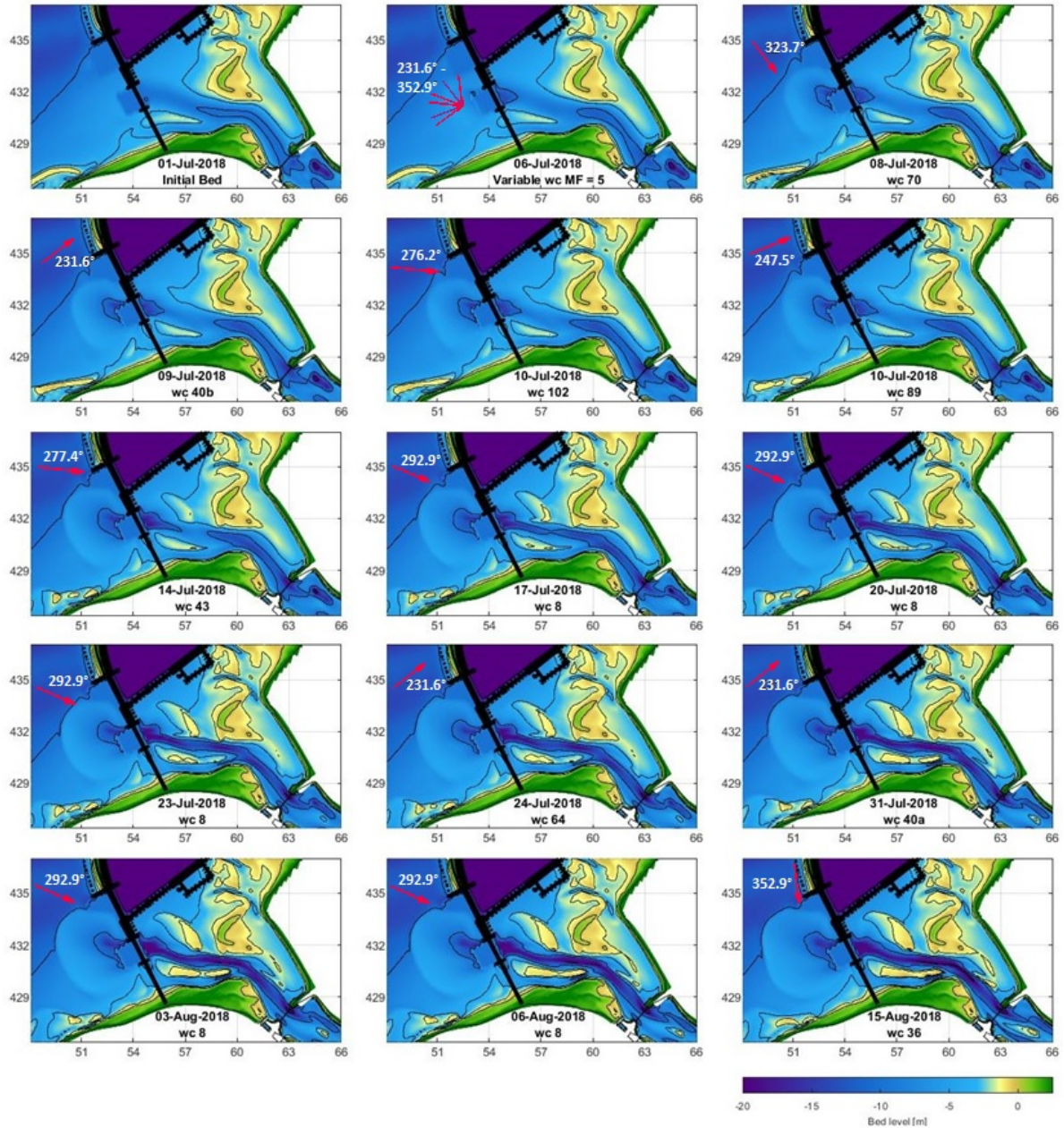


Figure 6.9: **Bed level evolution through the 3-year simulated period.** First snapshot is the initial bed level in the model. Each subsequent snapshot corresponds to the final time-step over which each wave condition acted in the model, representing the effect of it over the evolution of the bathymetry. The corresponding wave condition and date (time-step) are indicated at the bottom of each plot, and the red arrows denote the wave direction. Observe that in the second snapshot, an initial ETD-like feature is already visible, growing and extending seawards during the rest of the simulation. Firstly, it extends to the NW, then becomes more symmetric, and finally, another front grows to the WSW. The emergence of the FTD inside the TL is clear after *wc 43* acts in the model. Bollen van de Ooster breaches after *wc 70* acts and further divides into migrating shoals after *wc 89*. The growth of the shoal north to Kwade Hoek seems to be triggered during the action of *wc 8a*.

Contrarily to the evolution of the FTD, the emergence and growth of the ETD is already depicted in the 3rd snapshot of [Figure 6.9](#), i.e., after *wc 70* acts in the model. The shape of the delta's lobate feature indicates that its initial evolution is such that the most seaward edge is orientated to the north-west; erosion seaward of the bed protection is also depicted and elongates in the same direction. After the action of *wc 8*, the ETD starts to develop more symmetrically. In the last snapshot (last acting wave condition 64), the lobate shape shows two fronts extending seawards, the first and most developed one to the north-west and the second in a WSW direction.

The accretion corresponding to the growth of the ETD is better depicted in [Figure 6.8h](#). After the action of *wc 70*, the ETD starts to grow. The initial trend is to increase in height and become wider, spreading to the north (to the right in the figure). After the action of *wc 43*, the extension rate to the north decreases and shifts towards western directions (left in the plot), also occurring during the action of *wc 64*, *40a*, and *36*. The bed level decreases in height at the northern edge of the ETD. The shape observed at the end of the simulation (solid-red plot in the figure) is a wider and lower ETD than initially. A more detailed analysis per wave condition of the effect over the ETD will be elaborated in [Chapter 7](#).

Finally, along Goeree's coast, material settles close to the structure, due to longshore sediment transports. Part of the transported sediment might go into the TL and settle inside, or might be transported further inside. For certain wave conditions, some material might be transported from the most eastern side of Goeree's coast towards the downdrift side by ETD periphery bypassing (see [Figure E.9](#)). However, the transport of sediment further downdrift, toward the ESL dunes, is out of the scope of this research.

Additional material is also available from the Bollen van de Ooster shoal (ETD of the Grevelingen former estuary). After the action of *wc 70*, this shoal breaches, and due to the action of subsequent wave conditions, the eastern half of the shoal migrates eastwards, to the coast of Goeree. After *wc 89*, the shoal is further divided into 3 shoals that keep migrating downdrift. The shoals' sediment volume means huge nourishment for Goeree's coast. According to [Figure 6.4a](#) residual currents at the landward side of the shoal are ebb-directed and particularly larger at the breaching point. In [Figure 6.7](#), the erosion at the landward side of the shoal gives evidence of the breach. The causes of this breach are briefly discussed in [Chapter 8](#).

The conceptualization and interpretation of the results elaborated in this chapter are discussed in [Chapter 8](#) along with those of [Chapter 7](#).

Investigating the growth of intertidal areas.

This chapter presents the development and results of the modeling exercise for stage S1, as described in Chapter 4. Firstly, an overview of the results presented in the previous chapter and how they connect to the subsequent stage is elaborated in Section 7.1. Then an analysis of the bed level evolution is performed in Section 7.2 by evaluating the hypsometry and bed level changes. The analysis allows selecting the relevant wave conditions that could help or even enhance the stability of a sandbank at the seaward side of the TL, and other intertidal/subtidal features. Finally, the results of short-term simulations with the selected wave conditions are presented in Section 7.3, to assess the stability of a sandbank artificially added to the bathymetry at the area between Goeree and the TL inlet.

7.1. Summary of the bed level evolution

In the previous chapter, the evolution of the Haringvliet mouth under the D21 implementation was presented. The main objective of this study is to assess the stability of intertidal and subtidal areas, which are vital as natural habitats at the Haringvliet mouth. As seen in Figure 6.6 and progressively in Figure 6.9, new intertidal areas grow in the form of shoals and an FTD inside the TL and an ETD in the seaward side. For the ETD to grow such that typical sediment volumes in the order of several millions of cubic meters are stored in it (Elias et al. 2016; De Vries 2007), the system needs a larger time-span than the one simulated in the long-term exercise.

In this chapter, a thorough analysis is conducted to investigate the emergence of new shoals, the mechanisms behind their formation, and the source of material producing their growth. The intertidal zone is defined between the MLW and MHW are defined by the water levels at a location inside the TL as $MLW = -0.78\text{ m}$ and $MHW = 0.97\text{ m}$ wrt NAP (see Figure F.1). Certain features emerged after the action of specific wave conditions (e.g., FTD or Kwade Hoek-Slijkgat shoal) or their growth orientation varied (e.g., the case of the ETD). The present analysis is conducted to detect which wave conditions enhance and/or trigger the growth of shoals in general in the system. There is a special interest in the area between Goeree's coast and the updrift abutment of the TL barrier structure and inside the TL. These are where potentially intertidal and subtidal areas could be promoted on the seaward side.

For this stage of the study, firstly, it is necessary to detect how much of the intertidal and subtidal areas are growing inside and outside the TL. It is important to determine if the presented evolution is a loss or gain of the desired habitats. The analysis is conducted by computing the hypsometry for the total study area. The site is divided between the TL and the seaward area, where the ETD is developing. Additionally, the evolution of certain contours is evaluated.

Secondly, it is important to detect which wave conditions cause the growth of the features. For this analysis, the wave conditions producing the biggest bed level changes were identified, focusing on the specific changes each one promoted. The different wave conditions throughout the long-term simulation are also related to the dominant forcing acting in that period, according to the relatively larger influence of wave/tide/discharge. The dominance of each forcing condition is assumed as listed in Table 7.1 and will also support the conclusions regarding the contribution of each to the morphological changes.

Special attention is paid to the growth of the FTD and the ETD as valuable entities of the tidal environment and potentially valuable intertidal areas for natural enhancement. Additionally, the accretion at the updrift side of the inlet, between the barrier and Goeree coast outside the TL, is also of interest for the creation of additional shallow areas.

Table 7.1: **Dominant forcing in the model per period of acting wave condition in the long-term simulation.** This classification and the observed net sediment fluxes and bed level evolution, are used as a reference to define the dominant forces over the study site and distinguish the contribution of each to the morphological changes during the conceptualization stage. For example, the discharge influence in the study area can be observed from the period when *wc 40b* acts in the model.

WC [-]	Hs [m]	Weight factor [-]	Discharge [m ³ /s]		Dominant force(s)
			Summer	Winter	
70	2.99	0.04565	575.2	855.7	Waves
40b	1.99	0.02601	3890.4		Discharge
102	4.48	0.00228	575.2	855.7	Waves
89	3.98	0.00579	575.2	855.7	Waves
43	1.99	0.08827	161.2		Tide (in) / waves (out)
8	0.48	0.23827	575.2	855.7	Tide / discharge
64	2.98	0.03161	575.2	855.7	Waves
40a	1.99	0.17388	575.2	855.7	Tide-Waves-Discharge
8	0.48	0.23827	575.2	855.7	Tide-Discharge
36	1.47	0.14740	575.2	855.7	Tide-Discharge

7.2. Evolution of shallow areas

7.2.1. Hypsometry

The hypsometry of the study area is analyzed to observe the evolution of the bathymetry due to the D21 plan. According to the developments observed in the model, the area was divided in the TL basin, delimited by the Haringvliet Dam and the D21 structure surrounding the TL and a seaward area that extends from the TL barrier to the west until the end of Goeree's coast (≈ 6.4 km to the west) and to the north until the beginning of the ESL dunes (≈ 7.0 km offshore). The seaward area is further divided in 3, to the south from the coast to ≈ 2 km offshore, at the center extending ≈ 1.5 km further offshore, and to the north ≈ 3.5 km further offshore (see [Figure 7.1](#)).

The hypsometry is computed for of each area at 3 different moments: the original or present state **t0** (i.e., no intervention); the initial state once the D21 structure is in place **t1**, and accounts for the dredging at the main channel and bed protection structures; and the final state **t2**, after the simulated period representative of 3-year morphological evolution. The intertidal and subtidal areas for **t0** inside the TL correspond to the Hinderplaat and the Slikken van Voorne areas.

The hypsometry of the areas with the most relevant changes are presented from [Figure 7.2](#) to [Figure 7.3](#). The differences between each hypsometric curve are also shown as bar plots in the right panels. Blue bars represent negative differences, which means an eroding trend from one state to the other, and red bars represent accretion. The bars are computed for contours elevation every 0.5 m.

The hypsometric curve in [Figure 7.2](#), for the TL area, shows important differences between the 3 moments analyzed. From the original state (**t0**) to the initial bed level in the model (**t1**), a general decrease of bed level elevation for levels below the MLW. The trend agrees with the dredging operation performed on the Slijkgat channel, to a depth of NAP -10.0 m. The dredging reduced bed level elevations between NAP -1.5 m and -11 m (differences **t0-t1**). The path and width of the main channel, as considered in this implementation, require the removal of sediment from valuable shallow areas as well.

The changes from **t1** to **t2**, show two different trends. The areas below NAP -7.0 m become deeper while the areas above this contour become shallower (from red to yellow plot). The hypsometric curve

becomes steeper in the deeper areas (in 20% of the area) and approximately maintains the same slope for the shallower part. The behavior matches the observed erosion along the Slijkgat channel observed in Figure 6.8 from ≈ -10.0 to -20.0 m. Similarly, the bed level elevation increase from the NAP -7.0 m contour and shallower agrees with the large accretion observed inside the TL, especially in the FTD. The emergence of the shoals, as described in Section 6.3.2, is also represented in the increased levels of the yellow plot just below the MLW mark.

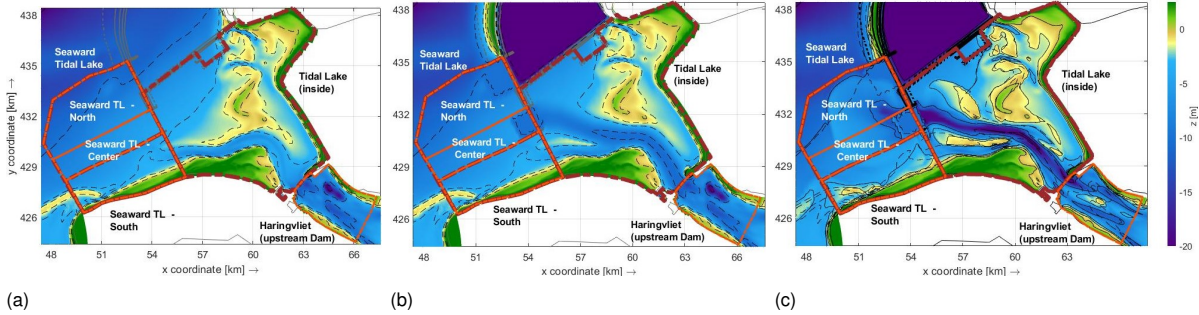


Figure 7.1: **Polygons delimiting the areas for the hypsometric analysis and the analyzed moments during the simulation.** (a) Original and present state of the system's bathymetry (2018). (b) The initial bathymetry in the model, once the D21 plan is implemented, includes the necessary dredging for the main channel and bed protection structures. (c) Final state after the 3-year simulation of morphological evolution. All figures show the polygons over which the hypsometry is computed. The study area is divided into the Haringvliet waterway area, up to 2 km upstream of the dam; area inside the TL delimited by the D21 structure and the Haringvliet Dam; the seaward area extending to the west until the end of Goeree's coast and to the north until where the ESL dunes start, further divided in north, center, and south.

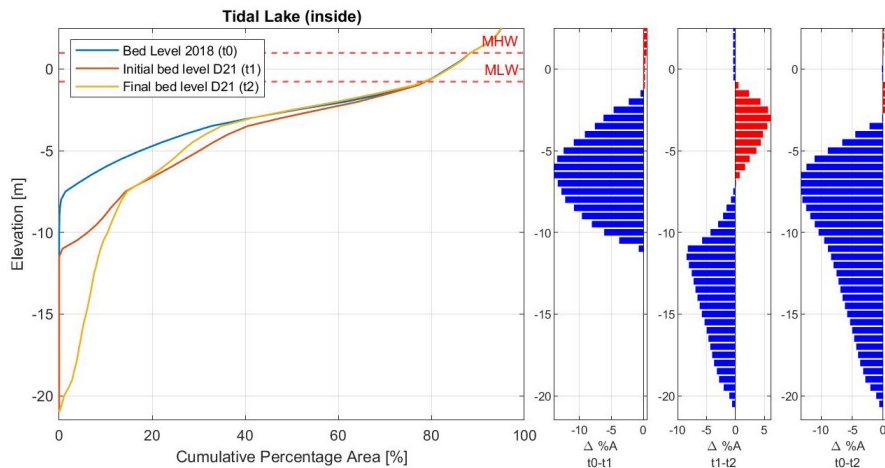


Figure 7.2: **Hypsometry corresponding to the Tidal Lake area for the original bed level, the initial bathymetry in the model and the resulting bed level elevation after 3-year simulation.** The right panel shows the hypsometric curve for the 3 states analyzed t0, t1, t2; the left panels present in bar plots are the hypsometry differences between one state and the other every 0.5 m contour. Between t0-t1 a general bed level elevation decrease is observed due to the original dredging of the Slijkgat channel. The evolution t1-t2 reveals erosion below NAP -7.0 m contour and deposition above it, with a larger bed level elevation increase around NAP -3.0 m. Between t0-t2, a similar trend is observed but showing a net increase of bed level elevation above -4.5 m, with the largest increase around NAP -1.5 m.

Comparing the original state **t0** and the resulting bed level after the implementation of the D21 plan, the trend is similar but at a different inflection point. For bed levels approximately below NAP -3.0 m, it decreases. Above NAP -3.0 m, the bed level increase is hardly visible. The hypsometric differences show a maximum bed level increase of 6.0% gain at the -3.0 m contour for **t1-t2**. However, comparing the gain to the original state reveals a maximum gain of 2.0% at NAP -1.5 m, because of the original dredged volumes. In general, there is an important gain of shallow areas above the -3.0 m contour with the biggest increase at NAP -1.5 m, which represents an important gain in the context of this study.

Just upstream of the Haringvliet Dam, large accretion was observed, specifically developing a shoal

≈2 km upstream from the dam (see Figure F.4b). Between **t1** and **t2**, the accretion between -8.5 to -1.5 m is clearly illustrated in the figure. The behavior outside the TL structure is also analyzed. Figure F.2 presents the hypsometry for the total area at the seaward side of the TL, as delimited in Figure 7.1. Figure 7.3 shows the hypsometry specifically for the southern part.

The hypsometric curves for the total seaward area show very mild differences, as the curves almost overlap. Considering the net effect, from **t0-t2**, there is accretion above NAP -11.5 m in the order of 4.0%, the largest between NAP -11.5 and -10.0 m. The accretion (red in Figure F.2) can be divided into those below and above the NAP -5.0 m contour. Below it, the bed level elevation increase is associated with the development of the ETD since the original elevation around the ETD was between NAP -10.0 and -7.00 m (see Figure 6.8h). Above the NAP -5.0 m contour, the accretion is mostly associated with the bed level elevation increase along the coast of Goeree; the original bed level elevations are around these contours.

To analyze more closely the changes in the seaward side, the hypsometry for the southern area, covering Goeree's coast, the center part just to the west of the TL entrance, and the northern area to the west of the ESL entrance were also computed. The most relevant results are at Goeree's coast (see Figure 7.3). In the central and northern areas, a general steepening of the hypsometric curve occurs, with inflection points at NAP -5.5 m and -12.5 m, respectively (**t1-t2** comparison). At the central area, erosion dominates between NAP -6.0 and -10.0 m, corresponding to the scours holes developed seaward of the bed protection. In the northern area, sedimentation dominates between ≈ NAP -7.0 and -11.5 m corresponding to the ETD development. This evolution is related to contours deeper than the intertidal area of interest in this study; for the hypsometry, the reader is referred to Figure F.3b and Figure F.4a.

Figure 7.3 displays the hypsometry specifically for the southern area that includes Goeree's coast. Around MSL, no differences are shown between **t0-t1** states since the bathymetry was not altered for the model input. Consequently, changes **t1-t2** and **t0-t2** are the same. The erosion in the first bar panel is negligible. For **t1-t2**, there is a general accretion trend, larger above NAP -4.0 m and also seen in the curves. A general bed level increase happens between the 40 and 90% of the areas. The largest bed elevation increase is between NAP -4.0 m and -1.0 m in the order of 8.0% increase. Around MSL (± 1.0 m), the accretion is in the order of 1.0% increase, although expected to continue as the material accumulates in the area, brought by the long-shore currents settling at the southern TL barrier structure.

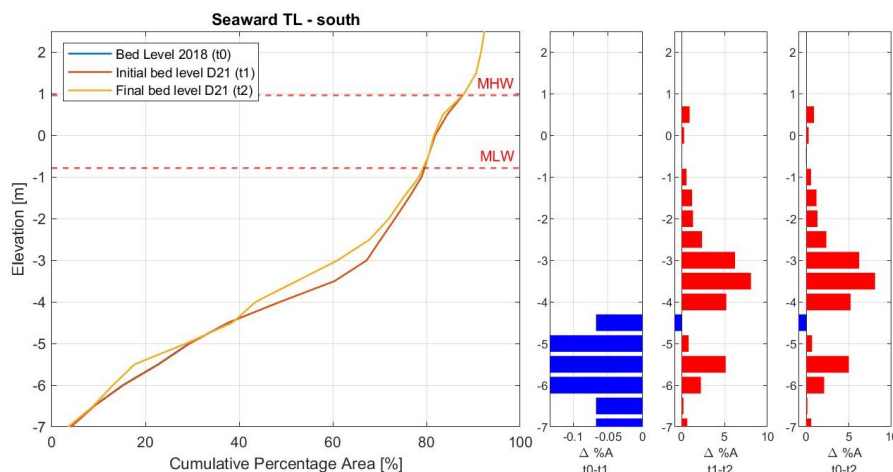


Figure 7.3: **Hypsometry corresponding to the southern seaward side of the Tidal Lake for the original bed level, the initial bathymetry in the model and the resulting bed level elevation after 3-year simulation.** The right panel shows the hypsometric curve, zoomed between NAP -5.00 and +2.50 m, for the 3 states analyzed **t0**, **t1**, **t2**; left panels present in bar plots the hypsometry differences between one state and the other, every 0.5 m contour. The hypsometric curve shows a general bed level elevation increase above NAP -4.5 m, larger below MLW and very mild around the intertidal zone.

Knowing the key bed levels where most accreting trends will occur, the evolution of the intertidal

area is also evaluated through the analysis of the evolution of the contours throughout the simulation. The contour evolution for bed levels NAP -7.0, -5.0, -3.5 and -0.8 is presented in Figure 7.4 and the evolution for contours NAP -10.0 m and 0.0 m is presented in Figure F.5.

From the NAP -10.0 m contour evolution (Figure F.5c), seaward, in the NW direction, the ETD edge feature is depicted as the NAP -10.0 m contour extends offshore into deeper waters. In Figure 7.4a, the NAP -7.0 m contour displays larger changes, showing a complete feature of the ETD. The fact that the ETD develops around -10.0 to -7.0 m depth is confirmed. Inside the TL, between the Slijkgat and Rak van Scheelhoek channels, the NAP -7.0 m contour migrates to the west, which is representative of the accretion between both channels, narrowing the main channel.

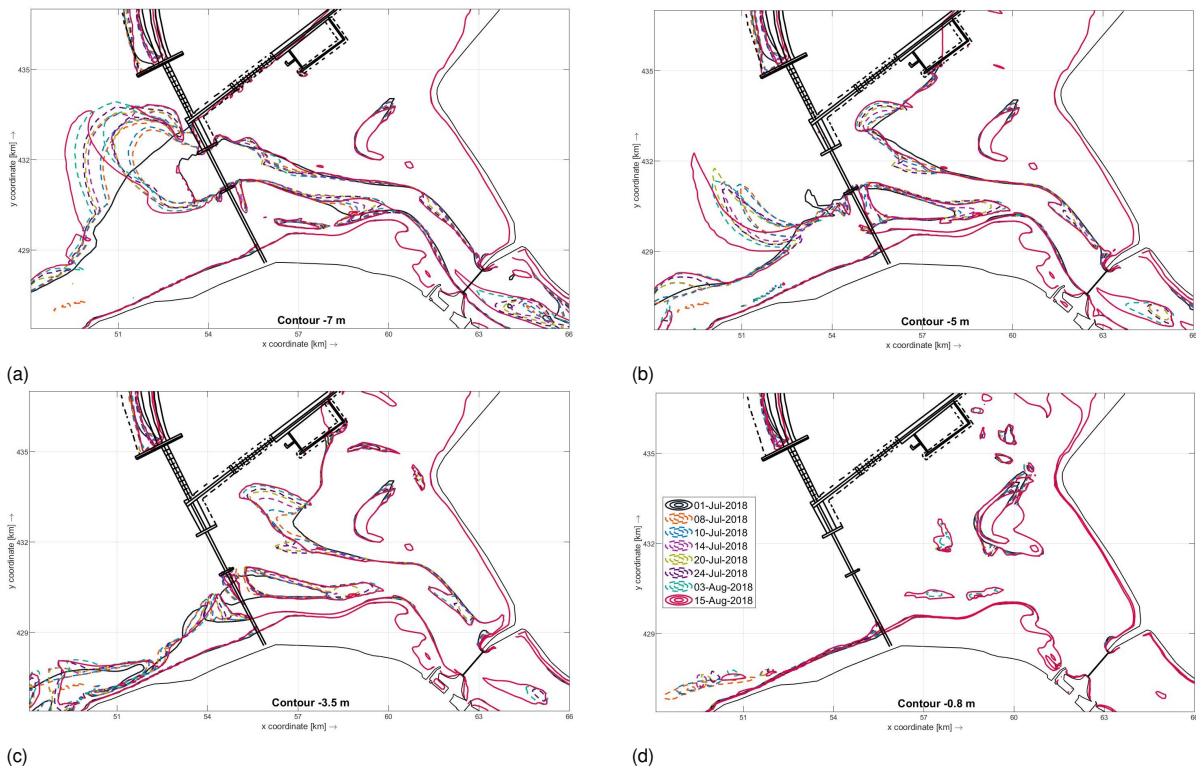


Figure 7.4: **Contours evolution throughout the simulation.** Contours for different time-steps, the initial contour is plotted in black-solid lines and the final contour in red-solid lines. Intermediate time-steps are plotted in dashed lines. (a) NAP -7.0 m shows the offshore edge of the ETD feature. (b) NAP -5.0 m contours depict the western extension of the ETD feature closer to the coast and the growth of the FTD and the Kwade-Hoek-Slijkgat shoal inside the TL (c) NAP -3.5 m presents the most dynamic behavior in the further growth of the FTD and Kwade-Hoek-Slijkgat shoal inside the TL at shallower depths, the formation of a flood-channel between the Slijkgat and Rak van Scheelhoek; in the seaward side the migration of most of the features in the eastern direction before encountering the TL southern abutment and (d) NAP -0.8 m (MLW) portrays the evolution of the Hinderplaat, the growth of shallower parts of the FTD and the shoal to the south inside the TL; in the seaward side the breach of Bollen van de Ooster and the eastward migration of the material stored in it in the form of shoals.

The evolution of the -5.0 m contour in Figure 7.4b is almost parallel to Goeree's coast and with a seaward limit at the southern edge of the inlet. In this figure, the western edge of the lobate ETD feature is depicted, expanding in shallower waters too. The feature at this depth is progressively migrating to the west. At the south-western edge of the plot, a progradation of the bed level is observed. Inside the TL, the growth of the FTD and the shoal between Slijkgat and Kwade Hoek is more visible.

According to Figure 7.4c, the NAP -3.5 m contour is very dynamic in the near-shore area. The figure displays important changes inside the TL and along Goeree's coast. Inside the TL, the Kortsluitgeul elongates; the formation of the flood channel between the Slijkgat and Rak van Scheelhoek is clear; the growth and widening of the FTD, and the longitudinal growth of the Kwade Hoek-Slijkgat shoal are portrayed as well. Between this shoal and the barrier's structure, a channel forms to convey the volume flowing through the former Slijkgat towards the inlet.

Along Goeree's coast, a diamond-shaped feature, protruding from the coast towards the sea, is observed. The contour evolution shows how the feature is pushed eastwards, towards the southern abutment of the TL, with a decreasing trend by the last period of the simulation. Currents parallel to the structure and towards the inlet occur (Section 6.2.3), preventing material from settling and pushing the sediment further eastward. At the south-western edge of Goeree, the breach of the Grevelingen ETD (Bollen van de Ooster) is also visible. The eastern side of the breached shoal is pushed to the east until the shoal at NAP -3.5 m depths merges with the coast (final red plot).

Investigating the contour changes for the intertidal lower bound, i.e., NAP -0.80 m, the changes observed are milder but still relevant. Inside the TL, the Hinderplaat only erodes at its south-western corner. The highest part of the emerged FTD is visible, extending to the east and widening. The Kwade Hoek-Slijkgat shoal develops in two parts that ultimately merge in the final stage of the simulation and at deeper contours (see Figure F.5 NAP -1.5 m). The seaward side, along Goeree, presents less dynamic behavior. An important development is an accretion between the southern abutment of the TL structure and the coast, typical of in groynes interrupting long-shore sediment transport in coasts. An interesting process is the migration of the shoal Bollen van de Ooster to the west after it breaches. Interestingly, the feature is first pushed as an entire entity, and then it is divided into three shoals that continue migrating until at least one of them merges with the coast (see also Figure F.5 NAP -1.5 m).

A final interpretation of the intertidal and subtidal areas resulting from the system's evolution under the influence of D21 is plotted in Figure 7.5. The figure presents a colored map showing depths between NAP ± 3.5 m. In this representation, the channel (depths below -3.5 m) are dark blue, and the intertidal area is represented approximately between cyan and orange colors with the depths around MSL in yellow. The shoals that emerged inside the TL are mostly around NAP -1.5 m but reach elevations at MSL in small areas. The small areas in yellow for these shoals explain the very mild difference in the hypsometric curves of Figure 7.2. A relatively mild increase in the bed level elevation of the whole TL area is the result of important features emerging.

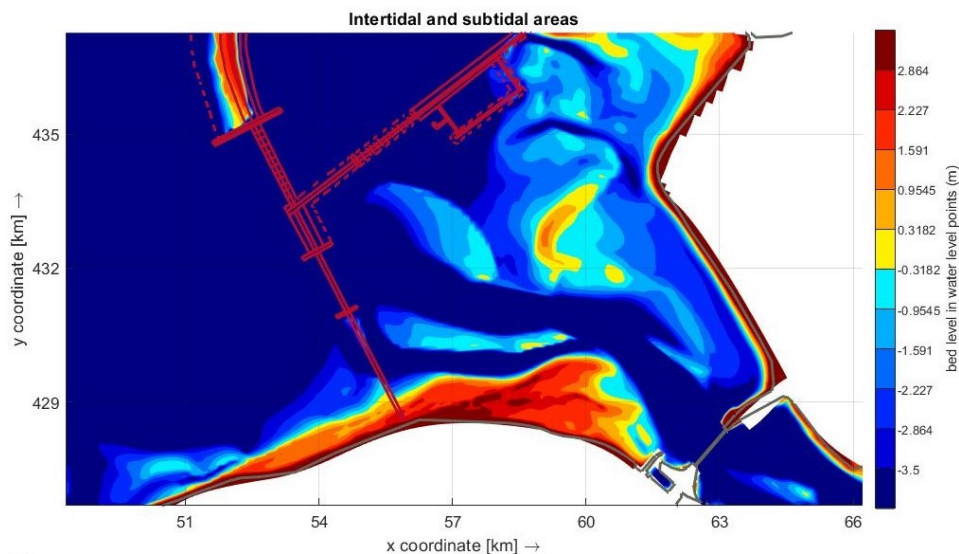


Figure 7.5: **Intertidal and subtidal areas map.** Colored map showing depths between NAP ± 3.5 m. In this representation, the channels (depths below -3.5 m) are dark blue, and areas higher than 3.5 m are dark red. The shoals and shallow coast range between blue and red patches. The intertidal area is represented approximately between cyan and orange colors with the depths around MSL in yellow. The shoals inside the TL reach elevations around MSL at very small areas. The larger part of them is close to -1.5 m contour.

7.2.2. Bed level changes per wave condition

The principal interest areas that add natural value and are potentially prone to grow further are the FTD area and Goeree's coast. Their growth is studied based on the acting wave condition in the model to

detect which will guarantee the stability of the shallowest areas, i.e., intertidal and subtidal areas. The analysis also serves to determine if the trends change toward the degradation of these environments. The effects over the ETD and the area upstream of the Haringvliet Dam are also considered, although to a lower extent.

The increase of intertidal areas compared to the present state of the system is almost negligible. The impact of the D21 over the shallow parts is canceled out. However, the FTD might represent an obstruction for the discharge through the siphon, and therefore maintenance dredging might be desired. Other shallows will be needed as nature compensation. First, it is important to determine where is the best area to create new shoals as compensation.

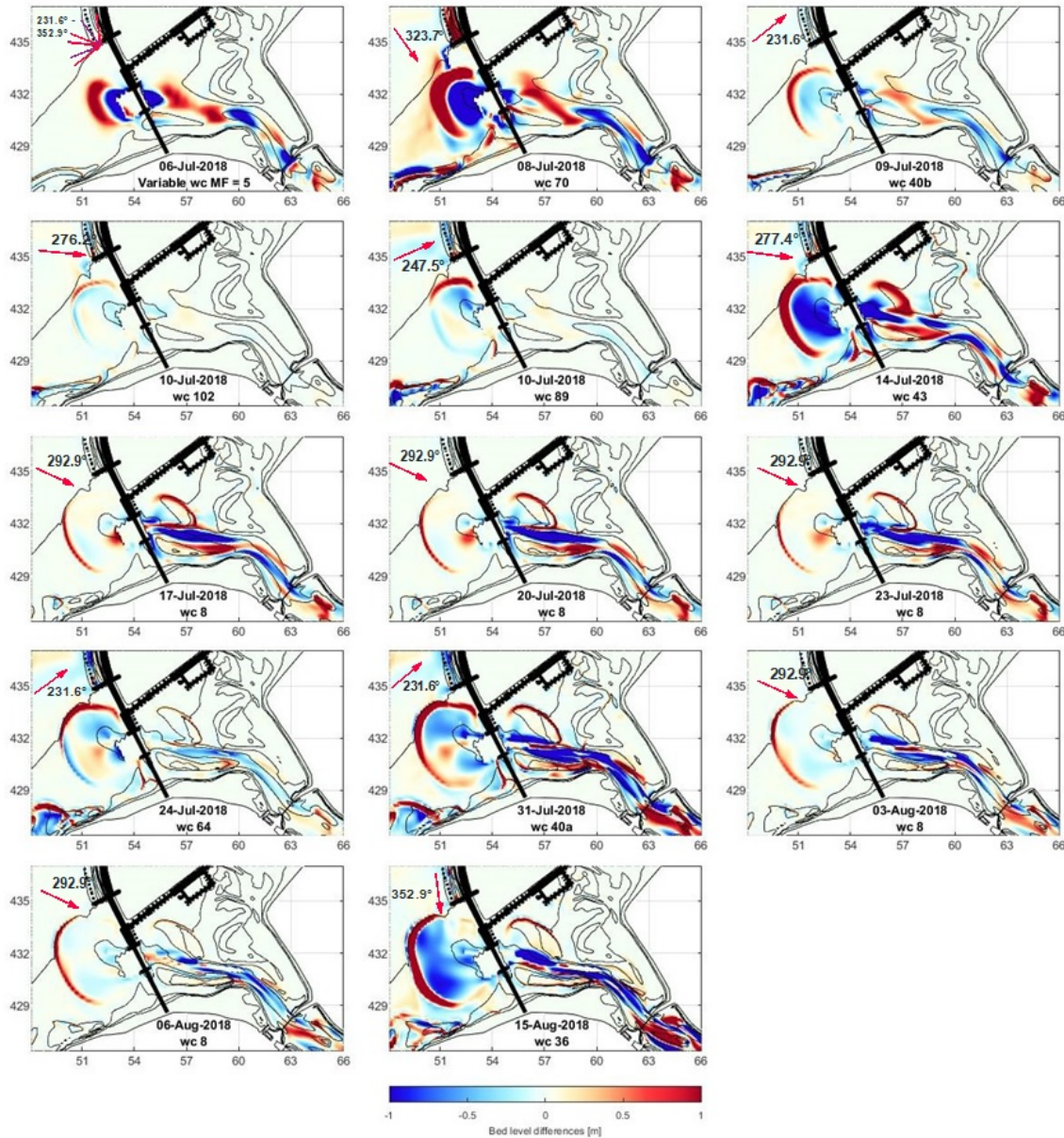


Figure 7.6: **Bed level differences through the 3-year simulated period.** Each snapshot corresponds to the bed level differences between the sequence of moments presented in Figure 6.9, relative to the previous time-step presented in the series. The differences show the effect that each wave condition has over the bed level changes throughout the simulation. The corresponding wave condition and date (time-step) are indicated at the bottom of each plot, and with red arrows, the direction of each wave condition is represented. Observe that wave conditions wc70, wc43, wc40a, and wc36 show the biggest changes. The emergence of the flood-delta features inside the TL after wc43 is also observed as large sedimentation. Bollen van de Ooster breach after wc70 is also observed from the erosion at the landward side of the shoal. Under wave conditions with $H_s > 1.40$ m large bed level changes are observed upstream the Haringvliet Dam.

Figure 7.6 presents the bed level changes specific for each wave condition. Each snapshot is the bed difference between the states presented in Figure 6.9, i.e., the bed level difference after each wave condition acts on the model. The bed level changes correspond to the evolution described in Section 6.3.2. The largest changes are observed after *wc 70*, *43*, *40a* and *36* act on the model. Additionally, throughout *wc 8a* (first period), important and consistent changes are clear. The erosion along the Slikgat channel is present for all conditions, with higher magnitudes for the mentioned ones.

A detailed analysis per wave condition and interest feature is elaborated in Table 7.2. It describes the net sediment transport patterns (Figure E.9) and the bed level change produced per wave condition and for each feature. The wave conditions presented are the selected according to their larger influence in terms of high sediment transports and high bed level changes. The purpose is to select those wave conditions that produce the emergence and maintenance of the shallow areas of interest, namely the FTD and Goeree coast. Most of them also produce growth in the ETD. The wave conditions selected produce the desired effect for more than one of the features¹. The wave conditions selected are used to conduct the short-term simulations (12 tidal cycles), to assess the stability of a sandbank located between Goeree and the southern abutment.

Table 7.2: **Development of morphological features as a function of the acting wave condition in the model.** The description elaborates on the net total sediment transport patterns and the bed level change after the action of each wave condition. The bold descriptions point out the wave condition that produces the biggest influence in terms of high sediment transports and higher bed level changes. The wave conditions in bold and italics are the wave conditions selected as those that produce the emergence and maintenance of the shallow areas of interest, namely the FTD and Goeree coast; most of them also produce the growth of the ETD.

Wave Condition				Feature Development ²			
WC	Hs	Dir	Weight factor	Flood-tidal delta	Ebb-tidal delta	Updrift accretion	Haringvliet waterway accretion
[-]	[m]	[degree]	[-]				
70	2.99	323.7	0.0457	-Very small flood-directed transports. -Accretion in the order of > 1.0 m.	-Large ebb-directed transports in a W to NW direction, decreasing offshore. -Accretion much larger than 1.0 m.	-Large along-shore transports at Goeree coast, eastward and into the TL. -Accretion in the order of >1.0 m.	-Small flood-directed transports, decreasing upstream. -Accretion in the order of 1.0 m.
102	4.48	276.2	0.0023	-Regular to large flood directed transports. -Very light accretion observed.	-Regular to large ebb-directed transports in a NNW direction, decreasing offshore. -Accretion in the order of 1.0 m to the NNW of the delta.	-Regular to large eastern along-shore transports at Goeree coast. -Very light accretion observed.	-Regular flood-directed transports, decreasing upstream. -Very light accretion observed.
43	1.99	277.4	0.0883	-Small flood-directed transports. -Large accretion in the order of > 1.0 m.	-Small flood-directed transport. -Large accretion in the order of > 1.0 m.	-Very small along-shore transport towards the east at Goeree coast. -Large accretion in the order of > 1.0 m.	-Regular flood-directed transports, decreasing upstream. -Accretion in the order of 1.0 m.
8a	0.48	292.9	0.2383	-Small to very small flood-directed transports originated inside TL. -Accretion in the order of 1.0 m at the most landward edge.	-Small ebb-directed transport to the WSW, decreasing offshore. -Accretion in the order of 1.0 m at the most seaward edge and west from the inlet next to bed protection.	-Almost no along-shore transport detected at Goeree coast. -No accretion or erosion detected.	-Small flood-directed transports, decreasing upstream. -Accretion in the order of 1.0 m.
40a	1.99	231.6	0.1739	-Very small flood-directed transport originated inside TL. -Accretion > 1.0 m at the most landward edge.	-Small ebb-directed transports in a W direction and towards the PPS, decreasing offshore. -Accretion in the order of > 1.0 m to the N seaward edge of the delta and in front of the PPS. <1.0 m to the WSW of the delta.	-Almost no along-shore transport detected at Goeree coast. -Small area with accretion in the order of > 1.0 m.	-Regular flood-directed transports, decreasing upstream. -Accretion in the order of >1.0 m.

Under *wc 70*, the initial bed level change towards the formation of the ETD and FTD is explicit. The FTD is more apparent after *wc 43* acts in the model, corresponding to the lowest discharge regime. Inside the TL, tidal currents are dominant (see also Table 7.1). Under the rest of the wave conditions, the FTD feature spreads further to the east. During the action of *wc 8a*³ the feature appears to continue growing progressively whereas during *wc 8b*⁴ the sedimentation is milder.

During the action of most wave conditions, the extension of the ETD is directed to the N-NW. A growth to the W occurs under the action of *wc 40a* and *36*, and in smaller magnitudes during *wc 8a* and *8b*.

¹ *wc 102* was selected based on the net sediment transport patterns as they show large magnitudes and are directed inwards the TL to the FTD (see Figure 8.5a and Figure E.9c)

² **Large:** approximately an order of magnitude larger than $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

Regular: approximately the same order of magnitude as $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

Small: an order of magnitude smaller than $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

³ PPS operation is off.

⁴ PPS operation is on.

At the beginning of the simulation, the accretion forming the ETD is large, but, by the last period, the accretion is mostly depicted at the most offshore edge of the delta and erodes at its landward side. This behavior explains the observations in [Figure 6.8h](#), the ETD first increases in height and then spreads wider at the expense of some of its own material, becoming lower.

The largest accretion upstream of the Haringvliet Dam happens during *wc 43* and *40a*. Assuming that the effect of waves inside the TL and further upstream is minimal, the growth during *wc 43* is purely the effect of tidal-driven currents in the basin. For *wc 40a*, the larger bed level changes are caused by the long period the wave condition acts on the model. It is the second most probable condition (see also [Figure 6.4b](#)).

Finally, the largest changes along Goeree are detected after *wc 70*, promoting the migration of the bed contours to the west. After *wc 43* and *wc 40a*, an accretion trend occurs to the west of the diamond-shaped feature, milder for *40a*. It is concluded that the area that is most likely to shelter a shallow sandbank is at Goeree coast, next to the southern abutment of the TL.

7.3. Sandbank Stability

The results presented in Chapter 6, a low dynamic area was detected at the corner between the coast of Goeree and the southern abutment of the TL structure. In [Section 6.2.3](#) and [Section 6.3.1](#) showed low residual currents and net total transports at the most eastward point. The material mostly deposits as the longshore sediment transport is now interrupted by the structure. Features in the subtidal zone migrate to the east to finally be blocked by the structure.

In [Section 7.2.1](#), it is concluded that the area at the coast of Goeree and to approximately 2 km offshore shows the larger bed level growth in the seaward area (see [Figure 7.3](#)). For this reason, the area is chosen to implement a sandbank in the intertidal range by nourishing the coast. The sandbank is built as a continuation of the coast that extends the intertidal zone and creates new resting and nourishing areas for the species in the Haringvliet mouth.

However, [Figure 6.7](#) presented erosion parallel to the abutment's structure (see also [Figure 8.1a](#)). This localized behavior originates from the currents converging near the structure. The circulation current pattern observed at the southern edge of the TL inlet and then deflecting to the south-east eventually meets along-shore currents, both converging at this point. The enlarged currents have an increased transport capacity that erodes the bed next to the structure. In an attempt to reduce the large currents at this location, the proposed sandbanks extend from the coastline to this area. Two versions of the sandbank are evaluated, **v1** is larger extending from the structure to ≈ 2.8 km to the west, **v2** extends only ≈ 1.2 km.

Both sandbanks have a triangular shape, formed between the structure's entire length and Goeree's coast. The configuration of the sandbanks is presented in [Figure 7.7](#), the polygon of the southern-seaward area analyzed in the hypsometry is included. The size of sandbank **v2** is smaller to assess whether the growth of the feature can be triggered, minimizing the initial nourishment. By creating a shallow area in the intertidal range, a less dynamic environment is promoted. Long-shore sediment transport patterns are directed to this area, and with the lower dynamics, deposition of material is expected. The sandbanks are added in the model with a bed level around MSL. Sandbank **v1** has an area of ≈ 261.7 ha, and sandbank **v2** of ≈ 110.6 ha.

To evaluate the benefit the sandbanks bring to the subtidal and intertidal areas, the hypsometry of the southern-seaward area is computed again and compared to the present state (2018 bathymetry), and the final result from the long-term simulation; [Figure 7.8](#) shows the results. In both cases, a general increase of the bed level in 40% of the area occurs, from the NAP -4.5 m to NAP +1.0 m contours.

The implementation of sandbank **v1** to the bathymetry means an additional increase in the bed levels of 7.1% at NAP -3.5 m contour (16.9% referred to 2018's bathymetry) and a maximum of 11.6% at the -2.0 m contour. Around the intertidal zone, the bed elevations increase in the order of 7.0%. Referred

to the original state, there is a total increase in the intertidal zone between 8.5% to 12.3%. The case of sandbank **v2** shows that the bed elevation increase of the areas around the NAP -3.5 contour is of 6.3% and a maximum of 9.0% for areas around the NAP -2.5 contour. This is equivalent to a maximum increase around the NAP -3.5 contour of 15.6%, referred to 2018's bathymetry. In the intertidal zone, the increase is between 5.8% and 9.8%. The second option means a lower increase of the subtidal and intertidal zone but a lower volume to nourish. Figure 7.8a and Figure 7.8b present the hypsometry of sandbank **v1** and **v1**, respectively.

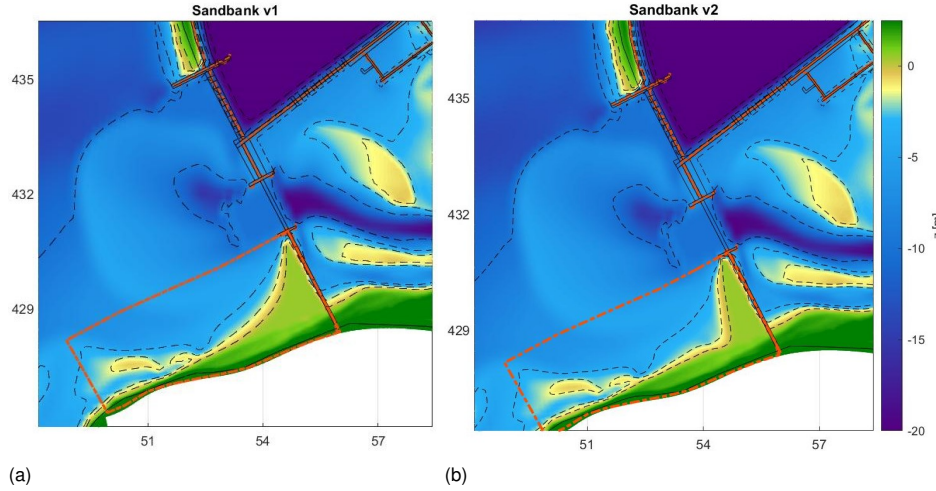


Figure 7.7: **Initial bed level of proposed sandbanks.** (a) Sandbank v1. Extends from the TL southern abutment structure to the west ≈ 2.8 km and $A \approx 261.7$ ha. (b) Sandbank v2. Extends from the TL southern abutment structure to the west ≈ 1.2 km and $A \approx 110.6$ ha. Both nourishing are proposed in a triangular shape between the structure and Goeree's coast. The plots also show the southern-seaward polygon used to compute the hypsometry.

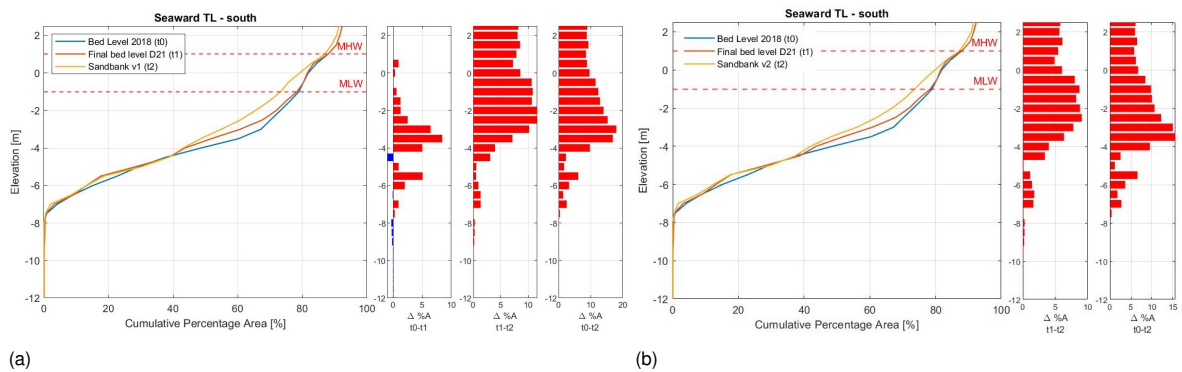


Figure 7.8: **Hypsometry for the proposed sandbanks.** Both cases show a general increase of the bed level in 40% of the area, from the NAP -4.5 m contour to the NAP +1.0 m contour. The maximum bed level increase is of 8.4% around the NAP -3.5 m contour. (a) Hypsometry sandbank **v1**: increase in bed levels of 7.1% around NAP -3.5 m contour (16.9% referred to 2018's bathymetry) and a maximum of 11.6% at the -2.0 m contour. (b) Hypsometry sandbank **v2**: increase in bed elevation of areas around the NAP -3.5 contour of 6.3% (15.6% referred to 2018's bathymetry) and a maximum of 9.0% for areas around the NAP -2.5 contour.

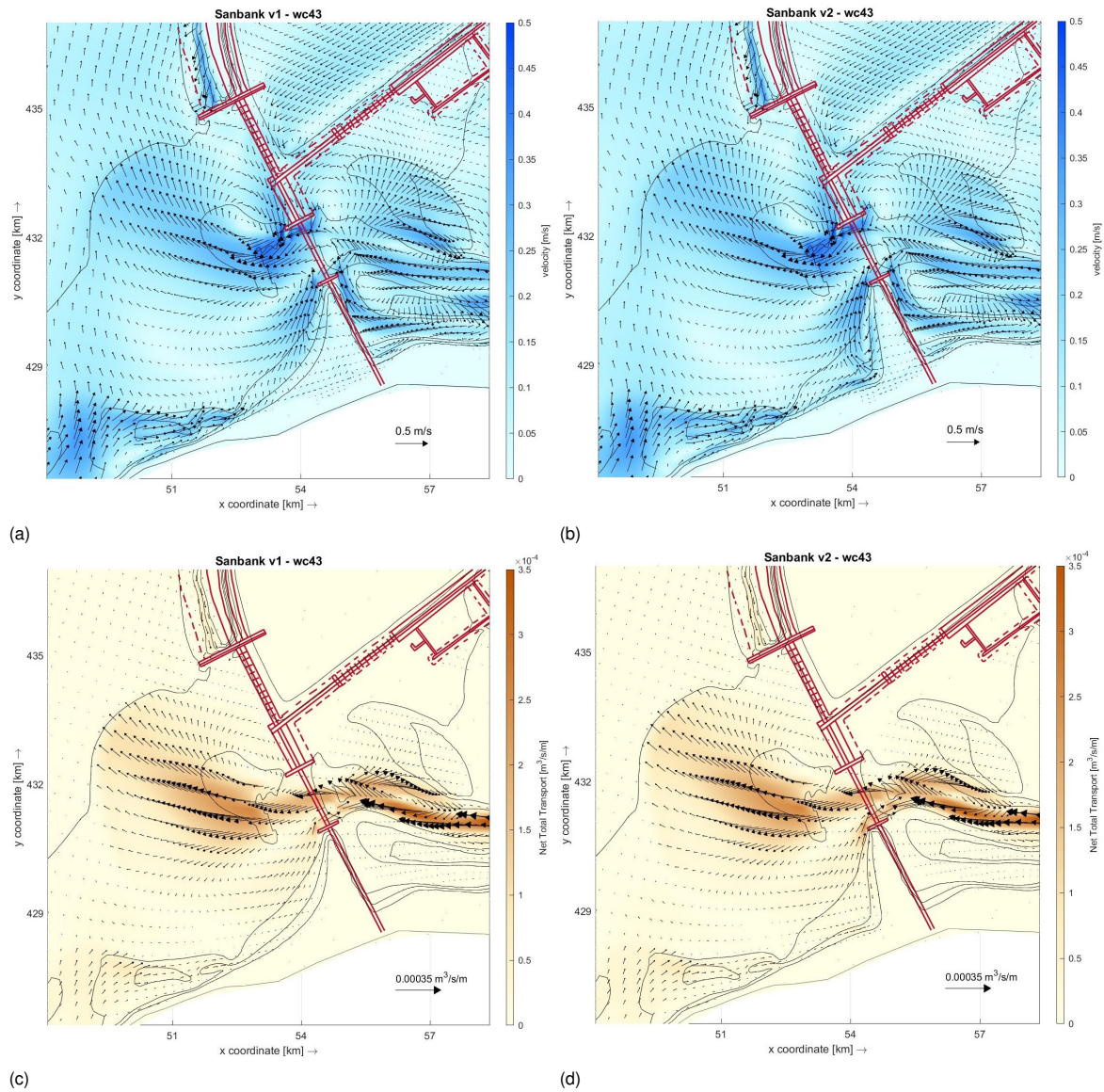
Both options are evaluated with short-term simulations, for the wave conditions selected in Table 7.2 and a regular discharge regime. The results presented in this chapter are representative of the general observations for the different simulations performed. For the run with wc 43, Figure 7.9 shows the results for residual currents, net sediment transports and bed level changes for sandbank v1 and sandbank v2 (left and right panels respectively). The currents and net transports are averaged over 4 tidal cycles, and the bed level changes are those of such period.

The residual currents in Figure 7.9a and Figure 7.9b show the same patterns inside the TL and similar to those observed during the long term simulation in Chapter 6. Over the ETD, in both cases, currents

are orientated to the north. At the western side of the ETD, they deflect to the south and returning towards the inlet, forming a circulation cell. Along the sandbanks, currents are east-directed and towards the TL inlet. The currents converge and increase as they approach the inlet in its southern edge.

At the shallowest part of the sandbanks, small currents are west-directed, forming a small circulation that could produce accretion. This behavior is more visible in the case of sandbank **v2**. The circulation cell at the north-seaward side of the TL inlet between the PPS and the inlet is also observed in these simulations. The circulation to the south is not totally clear. The strongest residual currents are observed at the sandbanks in the area closest to the inlet. Along the coast, to the west of the sandbanks, residual currents are larger and decrease to the east before increasing again at the sandbanks.

The net sediment transports are presented in Figure 7.9c and Figure 7.9. They show the same directions as the currents, with almost no differences between both versions of the sandbank. Only at the southern edge of the TL inlet net transports are larger for sandbank **v2**. The transport over the ETD is directed to the NNW, increases seawards from the bed protection offshore, and decreases again further offshore, behavior also observed in the previous chapter. Along the sandbanks, there is an east-directed long-shore net sediment transport. Over the shallowest parts, some transports are west directed, almost not visible for the sandbank **v1** but with larger magnitudes for sandbank **v2**. The currents and transport gradients hint of a larger erosive behavior in sandbank **v2**.



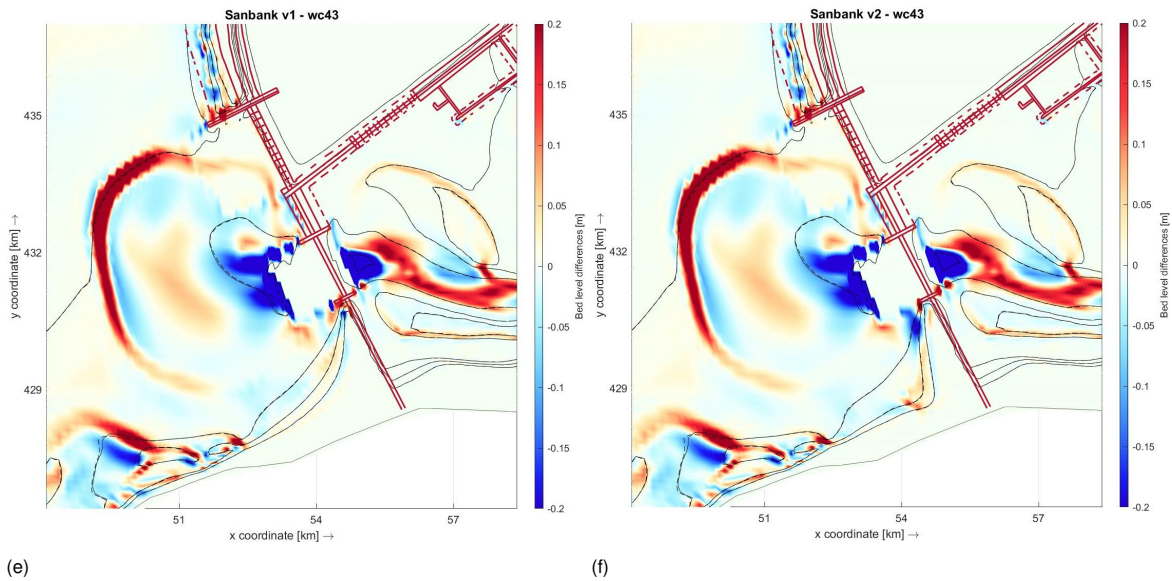


Figure 7.9: **Short-term simulation for *wc 43* for the response of sandbank *v1* and *v2*.** The results are shown for 4 tidal cycles, plots on the left correspond to the sandbank *v1* and plots on the right to the sandbank *v2*. (a)-(b) Residual currents. They show the same patterns inside the TL and over the ETD, where they are NNW-orientated. Along the sandbank, currents are east-directed and towards the TL inlet and west-directed at the shallowest parts, forming a circulation. The effect is enhanced for sandbank *v2*. (c)-(d) Net sediment transports. The sediment transport patterns show the same directions as the currents; magnitudes are larger for sandbank *v2*. (e)-(f) Bed level changes. The sedimentation-erosion patterns inside the TL and over the ETD are the same for both runs. Along the sandbanks, important erosion areas are detected at the northern side of the sandbanks, right next to the structure, larger for sandbank *v2*.

Finally, bed level changes produced by the net sediment transports are shown in [Figure 7.9e](#) and [Figure 7.9f](#), for sandbanks *v1* and *v2* respectively. Bed level changes are still important inside the TL and over the ETD, scour holes show erosion larger than 0.2 m, for a run representing ≈ 25 days. The sedimentation-erosion patterns are similar for both sandbanks. The main channel accretes in the area between the FTD and the Slijkgat-Kwade Hoek shoal. Sedimentation at the eastward edge of the FTD shows that the eastward extension of the feature continues. There is also some erosion at the northern bank of the channel in the border with the FTD, product of east-directed transports at the FTD, deflecting to the south, towards the channel.

The ETD shows a growth towards the NW and W, with some erosion at its front in the NW edge. In the southern area, along the coast of Goeree and the sandbanks, there is material depositing due to the currents circulation patterns. The circulation decreases the transport capacity of the current, allowing the material to settle. In contrast, large erosion is detected at the northern side of the sandbanks, exactly next to the TL abutment's structure. The erosion is larger and concentrated in the northern tip of the sandbank for the *v2* case. For sandbank *v1*, the erosion occurs only in two small points. There is also material settling along the sandbanks, due to material brought by the littoral drift; larger sedimentation for case *v2*.

The results of runs with forcing wave conditions *wc 8* and *40a*, are similar as those described for *wc 43*, specially inside the TL. For the mildest wave condition (*wc 8*), net sediment transports and bed level changes are of a lower order of magnitude, as can be expected. The circulation at the south-seaward side of the inlet is more visible in the residual currents for this wave condition. Results for *wc 40a* are very similar to those of *wc 43*, and along Goeree's coast, less activity is shown and almost none along the sandbanks (see [Figure F.7](#)).

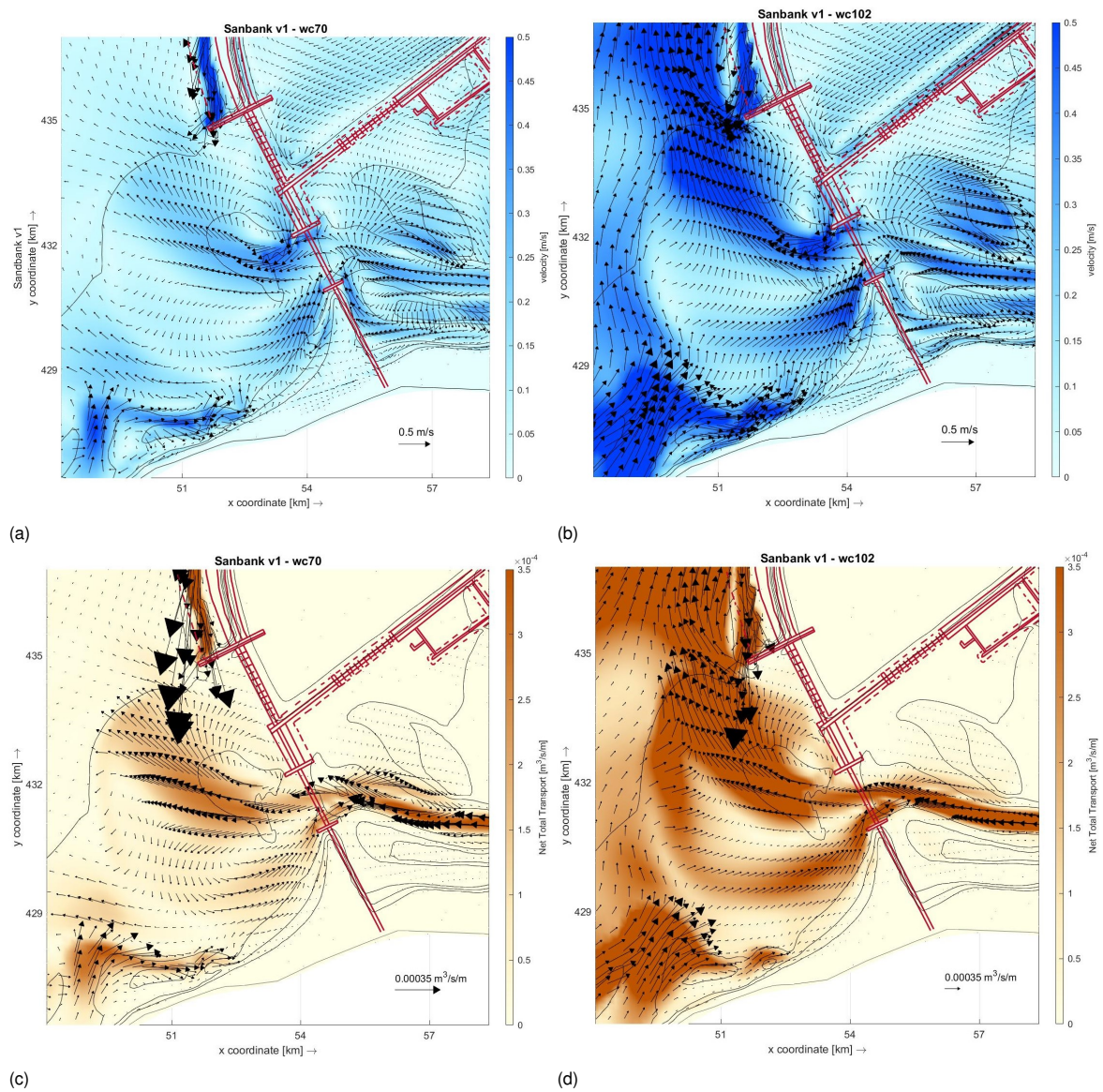
The results described so far are related to wave conditions between 0.48 m and 1.99 m wave height. Wave conditions with larger wave heights cause similar bed level changes, with larger erosion for sandbank *v2*. Its geometry makes currents converge at the corner between the original coast and the sandbank. The currents have enough transport capacity to generate larger net sediment transport at the northern area of the sandbank that will ultimately result in its erosion. For this reason, the following

results will focus on sandbank **v1**, for the other results the reader is referred to Appendix F.2.

When more energetic conditions occur, variations from Figure 7.9 are observed. Figure 7.10 shows the results for *wc 70* and *102* ($H_s = 2.99$ m and $H_s = 4.48$ m respectively), for sandbank **v1**. The residual currents plots (Figure 7.10a and Figure 7.10b), show that as the larger wave height increases the eastward currents along Goeree and the sandbank.

The ebb-directed residual current leaving the TL inlet deflects sooner to the NNW-N. The residual currents in the southern area, directed to the inlet, are present, but the circulation is almost not visible for *wc 70* and gone for *wc 102*. This reveals that in the balance between wave-driven currents and tide-(discharge-)driven currents, waves are winning.

The net sediment transports in Figure 7.10c and Figure 7.10d show the results for *wc 70* and *102*. The net transport vectors replicate the currents patterns, with larger magnitudes for *wc 102*. In both cases, after the material leaves the TL inlet seawards, the net sediment transport increases offshore of the bed protection and decreases again further offshore with NNW to N directions. In both cases, large east-directed net sediment transports occur along the sandbank, as well as over the shoals that conformed the Bollen van de Ooster. Sedimentation close to Goeree's coast is expected, with a source from the mentioned shoal.



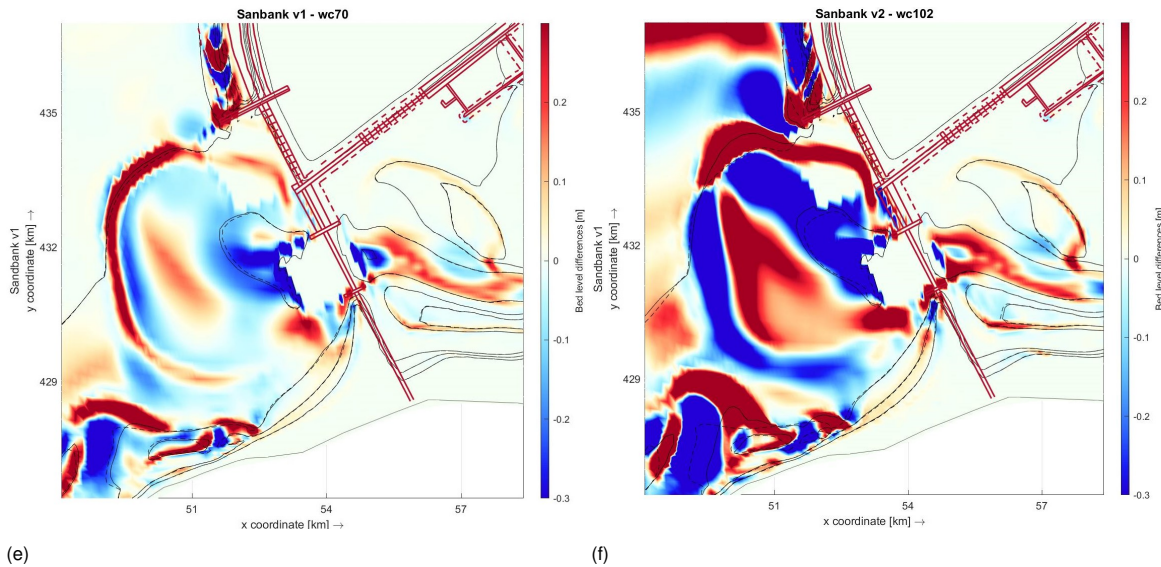


Figure 7.10: **Short-term simulations for wc 70 and wc 102, for sandbank v1.** The results are shown for 4 tidal cycles, plots on the left correspond to wc 70 and plots on the right to wc 102. (a)-(b) Residual currents. Patterns inside the TL are similar for both runs with larger magnitudes for wc 102. Over the ETD they are orientated to the NNW for wc 70 and to the N for wc 102. Along the sandbank, currents are east-directed and towards the TL inlet. At the shallowest part of the sandbanks, currents are slightly west-directed, forming a circulation. Important currents around the ETD seaward edge occur for wc 102. (c)-(d) Net sediment transports. The sediment transport patterns show the same directions as the currents; magnitudes are larger for sandbank wc 102. In both cases, an import of material occurs at the southern side of the inlet to the TL. Eastward transports occur over the seaward edge of the ETD for wc 102. (e)-(f) Bed level changes. The sedimentation-erosion patterns inside the TL are similar for both runs, with larger sedimentation for wc 102. Along the sandbanks, important erosion areas are detected at the northern side of the sandbanks, right next to the structure.

At the sandbank, accretion can be anticipated at the area closer to the original coast, and then erosion in the area closer to the structure. This is due to a negative net sediment transport gradient at the feature. Then the gradient is positive again, right before the structure. For wc 102, at the ETD front, there are east-directed transports that decrease landwards. Along the periphery of the ETD, sediment transport is directed from Goeree's coast to the north, towards the ESL dunes.

Figure 7.10e and Figure 7.10f present the bed level difference results for wc 70 and 102, respectively. The patterns inside the TL are very similar, although with larger sedimentation for wc 102. Because of the more energetic wave condition, there is a wave-induced water level increase (surge level). The increased water depths allow more material to settle. In the seaward side, sedimentation-erosion patterns are very different, especially at the ETD. For wc 70, the ETD grows to the NW and W, whereas for wc 102, it grows exclusively to the north and erodes at its western front with material settling landwards. The bed level changes in the ETD for wc 102 agree with the eastward sediment transports at its western edge.

Along the sandbank, trends are similar for both runs, sedimentation along the stretch closer to the original coast and erosion closer to the structure. The erosion near the abutment is more localized for wc 102. The sedimentation at the south-western corner of the bed protection for both runs develops because of the circulation observed in this area, larger for wc 102 also because of the larger surge levels.

The developments in the seaward area seem to be controlled by the acting wave condition in the model, as bed level changes vary from one run to the other. In contrast, the sedimentation-erosion patterns within the TL do not vary with the acting wave. The TL is dominated by the tide- and discharge-driven currents. The patterns observed and mechanisms acting in the area are typical of mixed-energy tidal inlet environments. A conceptualization of the results is further discussed in section 8.2, focusing on the developments in the seaward area and related to the nourishment.

8

Discussion

This chapter presents a deeper analysis of the results presented in Chapter 6 and Chapter 7. Firstly, a conceptualization of the observed behavior as a response to D21 implementation is made and explained in Section 8.1 whereas the conceptualization of the stability of intertidal areas is elaborated in Section 8.2. The hydrodynamics of the model are addressed in Section 8.4, observations during the long-term evolution of the system (Section 8.5) and the development of intertidal and subtidal areas (Section 8.6) are also commented. Finally, the limitations of the model related to the implemented modelling techniques are discussed in Section 8.7.

8.1. Conceptualizing the general response to the D21 plan

8.1.1. Hypotheses verification

Derived from the findings throughout Chapter 6 and Chapter 7, it is possible to state if the behavior as proposed in Section 4.1 is in fact observed in the system. The hypotheses are addressed in the order as they were originally presented.

Hypothesis 1: River discharge will hinder flood currents and bring sediment towards the TL. Siltation of the TL will occur.

Hypothesis No. 1 is partly verified. Usually, the opposite behavior is observed. The regular discharge regime, flowing out the estuary through the Haringvliet sluices, is not strong enough to hinder the flood currents flowing upstream into the estuary. According to the model, forced by regular conditions¹, it is only during larger discharge regimes that the net currents are flood-directed, consequently the net sediment transport too. From Figure 6.4 and Figure 6.5, it is concluded that the residual currents and the net sediment transport are flood-directed, importing sediment inside the Haringvliet waterway. Material from the river does not seem to arrive at the TL.

Hypothesis 2: Flood currents flowing along the Slijk gat channel will look for the easiest path.

This hypothesis is partly verified. As observed in Section 6.2.1 in Figure 6.2a, during the flood period, the currents follow two directions: along the Slijk gat channel and directly to the NE, normal to the TL inlet cross-section. The former is opposite to the original hypothesis. It can be explained by the fact that the channel's given depth promotes the conveyance of most of the flow through it. In contrast, the NE direction reflects what the hypothesis proposed, the preference of the flow for easier paths. Ultimately, flood currents indeed reach upstream of the Haringvliet waterway, shown in the tidal signal at locations more than 15 km upstream from the dam (see Figure 6.2b).

Hypothesis 3: Ebb-induced sediment transport will promote transport of material from the Hinderplaat in the offshore direction.

Hypothesis No. 3 is falsified. As it was easily expected, ebb-directed net sediment transport results at the TL inlet (see Figure 6.5a). However, it was bold to predict the origin of the material. The accretion

¹"Regular conditions" for waves/wind and discharge are defined as the general schematization for all forces as derived in Chapter 5. It corresponds to a representative situation that occurs more than 86.16% of the time (wave climate) with discharges of 575.2 m³/s and 855.7 m³/s during summer and winter, respectively. Wave conditions with $H_s > 4.5$ m are neglected.

originating an ETD offshore from the TL inlet mostly originates from the material eroded along the Slijkpat channel, specifically from the stretch just north of Kwade Hoek and not the Hinderplaat (see Section 6.3.1). The Hinderplaat shows minor changes, and the material eroded at its south-western corner is deposited just at the channel bank south of its origin (Figure 6.7).

Hypothesis 4: SW to NW wave condition will become more important for sediment transport in the outer delta.

Hypothesis 4 is verified. The wave schematization is formed by wave conditions from SW to NNW directions, most of them show large to regular net sediment transport ² over the ETD in the ebb direction. They contribute to the growth and seaward extension of the feature (see Figure E.8), except for *wc 40a*, which has the most shore-normal wave direction regarding the ETD front, and the generated transport fluxes are the smallest ³. The larger the incoming wave angle with the shoals, the larger the sediment transport fluxes (Bosboom et al. 2015). This is elaborated in Chapter 7 based on the short-term simulations for the different wave conditions.

Hypothesis 5: New flood delta features will emerge inside the TL.

This hypothesis is verified. Throughout Section 6.3, the development of an FTD inside the TL, was addressed. The analysis also describes the origin of the material that originates it and the mechanisms that trigger its formation. The FTD's growth was predicted, although at a location closer to the Slijkpat bend (Figure 4.1). Its growth is the product of the eroded material along the Slijkpat, specifically eastward from the bed protection; only under the least probable *wc 102* material from offshore is imported (see Figure 6.9 and Figure 8.5). Also, flood features are depicted at the bend, in the form of a flood channel that ends on a bar, between the Slijkpat and the Rak van Scheelhoek channels.

Hypothesis 6: Slijkpat orientation will adjust looking for an efficient path to the east, eroding Kwade Hoek north-eastern corner.

Hypothesis No. 6 is falsified. As it can be observed in Figure 6.9 and Figure 7.6, the growth of the ETD is in W to NW directions. During a low discharge regime ($161.2 \text{ m}^3/\text{s}$), the channel develops to the NW, and the growth of the ETD exhibits the same orientation (see Figure E.9e). The relatively larger wave-driven forces erode the ETD front, and it migrates to the NW. During high discharge regimes ($3,890 \text{ m}^3/\text{s}$), the growth of the delta is the result of west-directed net sediment transport from the TL inlet (see Figure E.9h); wave-driven currents are relatively smaller than the outflow of the inlet. The west-oriented growth is also observed during regular discharge regimes; it can be assumed that under such conditions, tidal-driven sediment transports are larger than the wave-driven sediment fluxes.

The growth of the ETD, its orientation as well as that of the seaward ebb-channel, are controlled by the wave-driven momentum fluxes. For the channel to show a shifting in the eastward direction due to shoal formations in the updrift side, comparable to Fitzgerald et al. (2000) bypassing processes models, larger volumes of sand must be deposited between Goeree's coastline and the TL inlet.

However, we observe the adjustment of the Slijkpat path inside the TL. In Figure 6.7 and more specifically in Figure 7.6, erosion (in blue) around the bend right at the north-eastern corner of Kwade Hoek is depicted. Settling of this material is observed to the north of this corner. There is a reorientation of the Slijkpat channel at the bend, making the bend milder.

Hypothesis 7: A terminal lobe will be formed between Goeree and the ESL, with a symmetric ETD's geometry.

This hypothesis was partially verified. As it was easily expected, the development of an ETD feature forming a lobate shape between Goeree's coastline and the ESL entrance indeed emerged (Figure 6.6). However, the symmetry of the ETD shows a downdrift orientation contrary to the original

²**Large:** approximately an order of magnitude larger than $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

Regular: approximately the same order of magnitude as $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

Small: an order of magnitude smaller than $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

³The behavior for *wc 40b* is different because it is associated with the largest river discharge, responsible of the high flood-directed sediment transports in Figure E.9h

state. The shift can be associated with the increase in the tidal prism and the coupling of the offshore and inland tidal signal, which are no longer in phase. As elaborated in the previous hypothesis, the orientation of the ETD and ebb-channel is controlled by wave energy. The littoral drift also enhances this trend in NW direction and the seaward ebb channels tend to the downdrift side (model E in [Figure 2.1](#) (Sha et al. 1993)). Nevertheless, this cannot be entirely represented by Sha et al. (1993) model; his models are based on a straight coastline. In the present study, the tidal inlet is located at a corner, with longshore wave-driven currents normally-directed towards the inlet. The ETD feature develops two fronts, i.e. two orientations of the ebb channel, controlled by the relative importance of wave- and discharge/tide-driven currents driving net sediment fluxes.

Hypothesis 8: Eastward littoral drift will produce accretion at Goeree available for bypassing down-drift (in the form of shoals).

Hypothesis No. 8 is partially verified. Bypassing mechanisms by shoal migration is not observed in the model prediction. As explained by Ridderinkhof et al. (2016), over the ETD waves stir-up material in the shallowest part of the shoals leading to converging wave-driven net sediment transport on the ETD, landward directed. This is observed under relatively more important wave-driven forces (see [Figure E.9e](#)). Sedimentation along the coast of Goeree is indeed happening but at a very small rate ([Figure 6.7](#)). The time frame of the simulation is too short to allow a sufficient build-up of material at the updrift edge of the west-orientated ebb-channel that could trigger the migration of features (Kana et al. 1999). A sufficiently large imbalance in the seaward side, produced either by a distortion in the bathymetry or an incidental highly energetic wave condition, that would trigger the formation of shoals in the ETD does not happen in the model (Ridderinkhof et al. 2016)⁴.

Other bypassing mechanisms are detected. Bypassing processes through the main channel and around the ETD periphery occur, depending on the acting wave condition⁵. This reinforces Herrling et al. (2014) findings regarding sediment transport patterns bypassing the tidal inlet in a mixed-energy system. Circulation cells towards the inlet observed during most acting wave conditions are formed only under fair-weather conditions. The circulation cell is lost for storm conditions like the net sediment transport patterns observed for *wc 102*. Some shoal migration is detected from the breached Bollen van de Ooster towards the coast of Goeree that might eventually produce large sediment build up updrift, that will ultimately bypass downdrift (see [Figure 7.4](#)).

Hypothesis 9: The area between ESL and TL will be a sheltered area promoting sediment deposition.

This hypothesis is falsified. The latest update of the D21 plan layout locates the PPS of the ESL just north of the TL inlet. The discharge from the PPS induces southern-directed currents that will influence the material deposited downdrift from the inlet (see [Figure E.10](#)). When no pumping discharges are considered, the final bed level shows a smoother lobate ETD feature that is not influenced by the pumps, which push sediment back seawards and generate a residual current to the south towards the TL inlet (see also [Figure 6.4](#)).

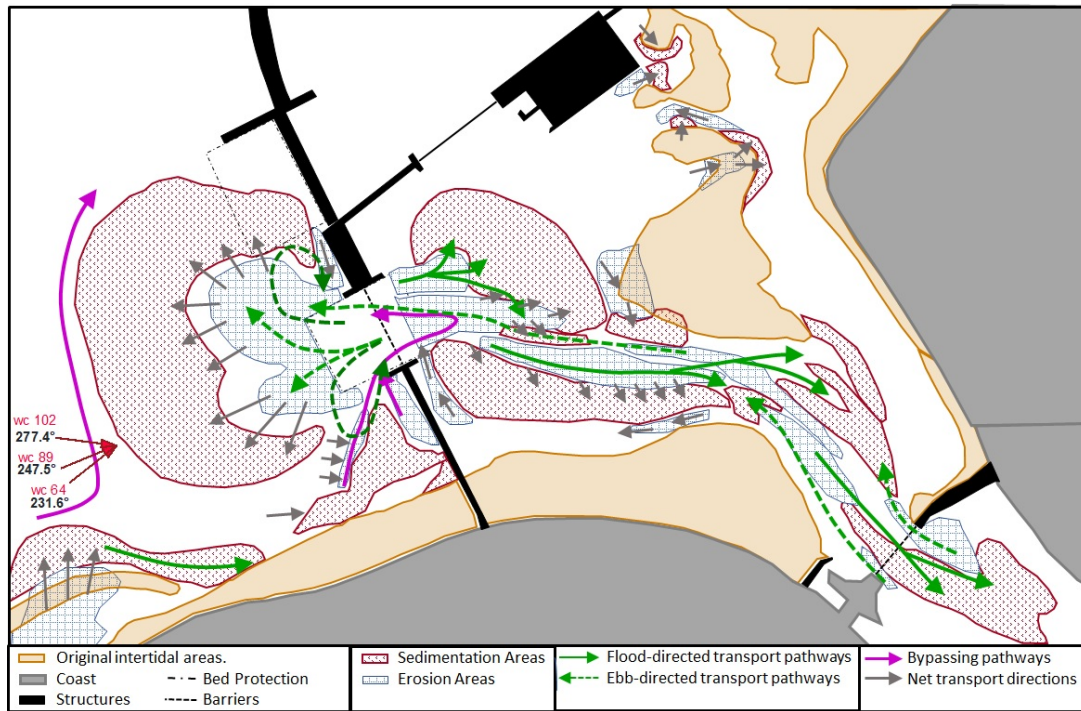
8.1.2. Conceptual model

A conceptual model is used to schematize the evolution of the system in the presence of the D21 plan; it follows the answered hypotheses. The conceptual model presented in [Figure 8.1](#) shows the principal sediment transport pathways and the most important erosion-accretion areas ([Figure 8.1a](#)), as well as the emergence, growth, and migration of the intertidal and subtidal features ([Figure 8.1b](#)).

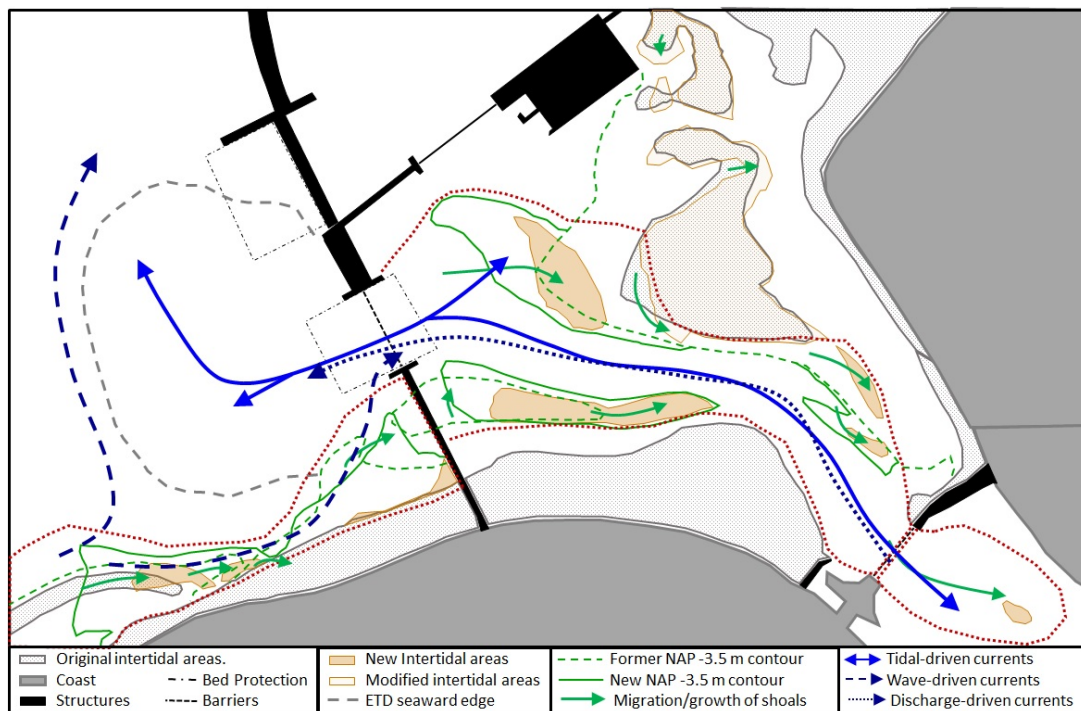
From the transport patterns analysed in Section 6.3.1, it is concluded that the emergence of most features is a redistribution of the available material inside the TL. The material inside the TL is also the source for most of the ETD and upstream shoal growth, at the seaward side and inside the Haringvliet waterway respectively.

⁴It is assumed that a storm condition is represented by *wc 102*. Such *wc* is not energetic enough to generate an imbalance with the bathymetry that would form shoals as described in the study by Ridderinkhof et al. (2016).

⁵See [Figure E.8](#): *wc 70*, *102* and *89* show bypass through the main channel, whereas *wc 102* and *89* show ETD periphery bypassing, according to the mechanisms described by Herrling et al. (2018)



(a)



(b)

Figure 8.1: **System's response to D21 implementation: Conceptual Model of net sediment transports, sedimentation-erosion patterns and growth of shallows.** (a) Conceptualization of net sediment transport and accretion-erosion patterns. Sediment transport through the barriers show a net export of sediment from the TL. Most of the material producing the emergence and growth of shallow areas comes from the eroded main channel. Two types of bypassing mechanisms are detected, through the main channel and ETD periphery (under certain wave conditions). Mechanism identified by the gray arrows in represent lateral transport patterns or those that not necessarily follow long pathways. (b) Conceptualization of the growth and migration of main features. Emergence of new shoals and intertidal areas are shown in orange while the original features are depicted in gray. Most activity is detected for the NAP -3.5 contour and the ETD is presented with a dashed gray line.

Tidal Lake: Sediment transport patterns as drivers of bed level changes

Figure 8.1a shows the principal accretion-erosion areas (red-blue). The main transport pathways are marked with green arrows, flood(ebb)-directed transports with solid(dashed) arrows. The main source of the accretion presented inside the Haringvliet waterway is product of the eroded area along the Slijkgat to the east of Kwade Hoek. Both edges of the dam, show erosion due to the increased transport capacity of the concentrated flow. The material eventually deposits inside the TL at the north-eastern corner of Kwade Hoek and between the channels Slijkgat and Rak van Scheelhoek. The growth of the shoal between the Slijkgat and Kwade Hoek is mainly due to material eroded in the main channel and immediately deposited at the southern bank (grey arrows on Figure 8.1a).

The stretch of the channel east-west orientated also erodes. At the southern bank, part of the material is carried by the flow towards the north-eastern corner of Kwade Hoek. Another part of the sediment travels eastwards, crosses the channel, and deposits at the eastern bank, between the Slijkgat and Rak van Scheelhoek channels. The currents transport capacity decreases and forms a flood channel with a growing bar at its end. Along the northern bank, the net transport is flood-directed and ultimately leaves the TL towards the sea and contributes to the emergence of the ETD.

Just east from the TL inlet, the scour hole developing at the edge of the bed protection is the principal source of material forming the FTD feature. As the tide-driven sediment transports wash over the forming shoal, the FTD progressively extends to the east. Some of the sediment also deflects to the south, returns to the main channel, and possibly travels again offshore towards the ETD.

Offshore evolution controlled by wave energy

The ETD grows due to material transported offshore from within the TL, in the WNW to N and SSW to WSW directions. The grey arrows in Figure 8.1a represent the material eroded just seaward from the bed protection and later deposited further offshore as the transport capacity decreases.

The seaward area is dominated by wave-driven forces. The orientation of the ETD front, as well as the seaward ebb-channel, are controlled by the wave energy. Breaking waves erode the ETD front and generate a shore-directed component of the radiation stress gradients that is not compensated by the pressure gradient in the momentum balance. The water level set-up spreads towards the TL and the inlet. The mechanism results in the landward migration of the shoal (Bertin et al. 2009). This "bull-dozer" effect causes south-westerly to westerly waves to push the ETD in NW directions. In contrast, tide- and discharge-driven currents replenish the ETD for its western extension (see Figure 8.5 and Figure 7.6). This behavior, typical of mixed-energy tidal environments, confirms the known theory of how ETD grows in a balance between the tide- and wave-driven forces (Herrling et al. 2014).

Along Goeree's coastline, net eastward-directed long-shore sediment transport occurs. After Bollen van de Ooster breaches, it migrates eastwards in the form of shoals until part of it merges with the coast. Further east, the eastward littoral drift causes accretion next to the TL southern abutment.

The subtidal diamond-shaped feature along Goeree's coastline migrates to the east. Waves breaking along the shoal stir-up sediment that is transported by eastward-directed wave-driven currents. The net sediment transport pathway describes a circulation that enters the TL through the inlet and travels towards the ETD with ebb-directed currents. This bypass mechanism is comparable to those described by (Herrling et al. 2018) and is schematized in Figure 8.1a by a pink arrow. Another observed bypassing mechanism is around the ETD periphery. This mechanism is only observed under the action of *wc 102*, the most energetic wave condition, and with directions from SW to WNW.

Two circulation cells form at the seaward side of the TL inlet to the updrift and downdrift sides (darker green arrows). These circulation cells are predicted in mixed-energy tidal inlet systems, generally at the downdrift side, and enhanced by the long-shore wave-driven currents (Herrling et al. 2014). In this case, high energetic wave fluxes generate strong eastward wave-driven currents along Goeree that can overcome western ebb-directed tidal(discharge)-currents and hinder the updrift circulation cell. During the most energetic wave conditions, large wave-driven sediment transports enter the TL.

The main current directions are represented in Figure 8.1b with blue arrows. Wave-driven currents control changes in the seaward side: along Goeree's coastline towards the southern side of the inlet as well as around the ETD edge, limiting the extension of the delta and reshaping it. Tidal currents (solid arrows) have influence over the FTD and ETD and along the whole channel, upstream from the Dam, as long as the river discharges are sufficiently low. Discharge-driven currents are important along the whole channel, and they decrease as soon as they reach the seaward side, discharging directly to the west.

Emergence of shoals in the intertidal and subtidal zones

The described net sediment transport patterns generate new features that emerge in the intertidal and subtidal zones. Figure 8.1b present the original intertidal/subtidal areas (gray-hatched patterns), the original intertidal/subtidal zones that suffered changes (light-orange), and the areas that emerged after the D21 implementation (orange). The changes around NAP -3.5 m clearly show the eastward migration of the features in the seaward side along Goeree and the evolution of the shoals inside the TL.

One of the main concerns of D21 implementation is the environmental impacts, especially to the protected Natura2000 area at the Haringvliet mouth that includes intertidal and subtidal environments at the Hinderplaat and Slikken van Voorne (see Section 1.5). As observed in the results presented throughout Chapter 6 and Chapter 7, the Hinderplaat shows minor bed level changes, mostly at its south-west side. At Slikken van Voorne practically no change is observed.

The south-western corner of the Hinderplaat erodes, and its front elongates to the south. The NAP -3.5 m contour around the Hinderplaat extends to the NW as the FTD is formed and merges with it. The shoal between the former and new Slijkgat accretes and extends to the east as it increases its height. Between the Slijkgat and Rak van Scheelhoek, the formation of a flood channel with a bar at its end is clear. The red dashed line suggests the active areas inside and outside the TL, and the gray dashed line marks the resulting edge of the ETD at the end of the long-term simulation.

Furthermore, the emergence of new shoals adds value to the intertidal and subtidal natural environments. The features detected are shoals and an FTD inside the TL. An ETD also emerges offshore, although at a slower rate. Finally, the accretion area detected at the updrift side of the inlet between the barrier and Goeree's coast shows low accretion rates. Nevertheless, it could potentially be enhanced by nourishments, decreasing the dynamics to promote further deposition. To understand how these intertidal and subtidal areas are growing and evolving along with the mechanisms behind them, a deeper analysis was conducted in Chapter 7.

8.2. Conceptualizing the stability of intertidal areas

To summarize the behavior observed in Chapter 7, a conceptualization is made and presented in Figure 8.2 according to the studied wave conditions for two configurations of a seaward sandbank. Figure 8.2a presents the conceptualization of the currents and Figure 8.2b shows the sediment transport patterns and key accretion-erosion areas.

For all wave conditions selected to force the model in short-term simulations, the currents and net sediment transport patterns were constant inside the TL, ultimately producing bed level changes that are independent of the acting wave boundary condition. These results reveal that tidal- and discharge-driven forces dominate the TL.

The sediment transport patterns for *wc* 43, with the lowest discharge regime ($161.2 \text{ m}^3/\text{s}$), showed similar patterns inside the TL as those observed in the short term simulations for all the wave conditions tested. It is concluded that the net sediment transport patterns observed are a consequence of tidal-driven currents. The largest growth of the FTD is observed during the lowest river discharge (see the light green arrows in Figure 8.2b and Figure 7.6). For a more detailed definition of the different physical forces' dominance, further modeling analysis should be performed. The present results only allow us to conclude that the area $\approx 3.6 \text{ km}$ inside the TL from the inlet, comprehending the FTD and the Slijkgat-Kwade Hoek shoal, is dominated by the tide.

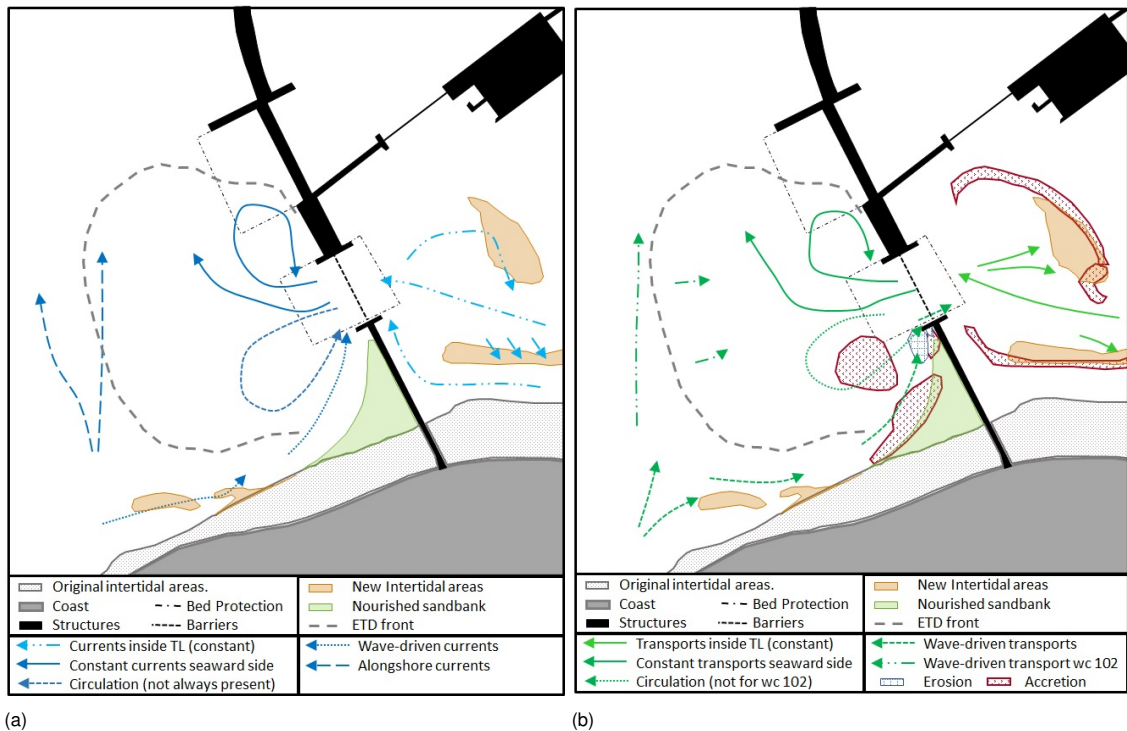


Figure 8.2: **Conceptualization of currents, net transports and bed level changes for evaluating the stability of intertidal areas.** (a) Conceptualization of currents. (b) Conceptualization of transports and key accretion-erosion areas. Current patterns and net sediment pathways inside the TL are constant, independent from the wave condition. In the seaward side, ebb-directed currents are mostly directed to the NNW as well as the main sediment pathway leaving the inlet. To the south of the inlet a circulation is generally formed that produces accretion at the south-western corner of the bed protection. Wave-driven transports usually occur along the coast and the sandbank, joining the circulating patterns before entering the TL. The material is generally directed offshore again towards the ETD in a bypass pathway through the main channel. Other bypass mechanism detected is around the ETD front from Goeree towards the ESL dunes.

In the seaward area, residual currents flow to the NNW-N for all the modeled wave conditions. A 2DH circulation cell between the TL inlet and Goeree is always present. It forms as the ebb-directed currents leave the inlet, but it disappears under the most energetic wave condition (*wc 102*). The effect of *wc 102* is to increase wave-driven radiation stresses along the coast, generating strong eastward currents and hindering the tide-driven ebb-directed flow (see the different patterns in Figure 8.2a).

The net sediment transport patterns agree with the currents directions (Figure 8.2b). The sediment circulation cell is not detected for *wc 102* either. Under this wave condition, the transports are mostly east-directed, increasing as they approach the structure. The net effect is an import of material towards the TL through the inlet. The material will probably return seawards with the ebb-directed currents and directed towards the ETD. This import at the TL inlet was already observed in Chapter 6, but once the sandbank is added, it also occurs under milder wave conditions.

The wave dominance in the seaward side is detected again. Wave-driven currents cause east-directed net transport of sand that pushes shoal features (e.g. the former Bollen van the Ooster shoal) to the east and closer to the coast. The sediment transport decreases next to the original coastline and increases again along the sandbank, favoring the import of material at the southern edge of the inlet.

For all the wave conditions studied, the sediment transport gradients cause accretion along the sandbank shallowest parts, closest to the original coastline. At the northernmost part of the shoal, where the flow enters the TL inlet, scour localized areas are detected. The shape of the sandbank covering the entire length of the abutment meant to reduce converging currents, decreasing the dynamic character of the flow with shallower water depths. The large erosion is still seen for both studied configurations of the sandbank. A higher bed level would be necessary, i.e. a larger nourishment⁶.

⁶The stability of the structure will not be endangered as it will include bed protection to avoid scouring next to it.

Finally, offshore from the ETD front, the residual currents are directed to the north (flood-direction). Assuming that the new coastline is determined by the D21 layout, the currents correspond to shore-parallel flood-dominant tidal currents. Only when *wc 102* is forcing the model, important sediment transports occur further offshore. The larger waves stir-up sediment at deeper water, making it available for transport. The net transport pathway is directed to the north and generates a bypass of material around the ETD front from Goeree's coastline to the downdrift side, towards the ESL dunes.

The area between Goeree's coast and the TL southern barrier structure is prone to deposition, but relevant for a longer time-span than the simulation of this study (decades). The shallowest contours will continue to accrete and ultimately merge with the western ETD development. Under such conditions, the mechanisms of growth and migration of shoals in typical ETD could still be used as a reference to enhance the development of shallow areas in the intertidal/subtidal zone (Herrling et al. 2014; Ridderinkhof et al. 2016). However, a specific study of these mechanisms lies out of the scope of the present research.

8.3. The D21 in the Haringvliet mouth: a mixed-energy tidal inlet system.

There are few studies for mixed-energy tidal inlets that distinguish the influence of interacting tide- and wave-driven processes on morphological evolution (Herrling et al. 2014). The present study improves the understanding of how intertidal and subtidal features emerge and grow under the influence of tides, waves, and discharge, e.g., the emergence of an ETD despite the flood-dominant character of the flow.

A new condition studied is the emergence of the features as a consequence of a shift in the basin's tidal inlet position. The former ETD is now sheltered from wave-driven processes by the TL structure. The new intertidal and subtidal features emerge about the new inlet.

The results of this research allow us to distinguish the contribution of the different forces involved in the development of the main shoals that form a typical tidal basin (see the model by Boothroyd (1985) in Figure 2.1), based on the net sediment transport pathways in the basin and through the shifted inlet. In this mixed-energy system, the contribution of the discharge is also considered. After the Haringvliet was dammed, the system shifted from a mixed-energy to a wave-dominated basin (Davis et al. 1984; R. De Winter 2008). With the reopening of the Haringvliet sluices and the D21 intervention, the Haringvliet mouth returns to a mixed-energy environment.

During the modeling exercises, three forces were considered: tides, waves, and discharge. The TL structure limits the waves' area of influence. On the seaward side, the largest bed level changes depend on the acting wave condition. The action of tidal-driven currents generating net sediment transports causes the largest bed level changes inside the TL.

The observations of the Haringvliet mouth's evolution, under the new configuration, are consistent with the typical behavior of mixed-energy tidal inlets. Ebb-directed sediment transports constantly nourish the ETD under regular tide-dominated conditions, and during episodic storm events, the ETD erodes at its most seaward edge (Herrling et al. 2014).

The balance between the eroding force of waves and the building force of the tide (Z. B. Wang et al. 2009) is recognized throughout the emergence of the ETD and FTD. During a period of relatively larger tide-dominance (*wc 43, 8 or 36*)⁷, the ETD and FTD growth is larger. When relatively larger wave-dominant conditions occur (*wc 102, 89 or 64*), the wave energy is focused on the shallowest parts of the ETD where it dissipates by breaking waves. Material easily stirs-up under higher waves and travels in NNW directions due to the long-shore momentum flux generated by obliquely incident waves.

In the configuration forced by the D21 layout, the long-shore littoral drift is east-west oriented and has to deflect northwards when it meets the structure. The result is a cornered ETD. Based on the observations in section 6.2, the tidal regime characteristic of the SW Dutch coast still occurs. The tidal

⁷Table 7.1 presents a summary of the model's periods associated to the relatively larger importance of waves/tide/discharge.

regime considering the new location of the inlet is schematized in Figure 8.3. The figure shows the four phases defined by Tönis et al. (2002) based on the results in Figure 6.2.

The scheme shows a regime similar to that described by Sha et al. (1993) for the estuaries in the SW Dutch Voordelta. With the increased tidal prism, a more symmetric evolution of the ETD was expected. However, westerly waves limit its growth to the east and push the shoals in NW directions, whereas north-westerly waves allow the extension of the ETD to the west. The red arrows in Figure 8.3 indicate the net effect of the offshore-inlet current interactions. During Phase 2 and 4, currents are concentrated in the downdrift side, whereas during Phase 1 and 3 are parallel to Goeree's coast. The latter is forced due to the perpendicular position of the TL inlet relative to the updrift coast. Both trends are consistent with the preferred growth orientations of the ETD: to the NNW and West.

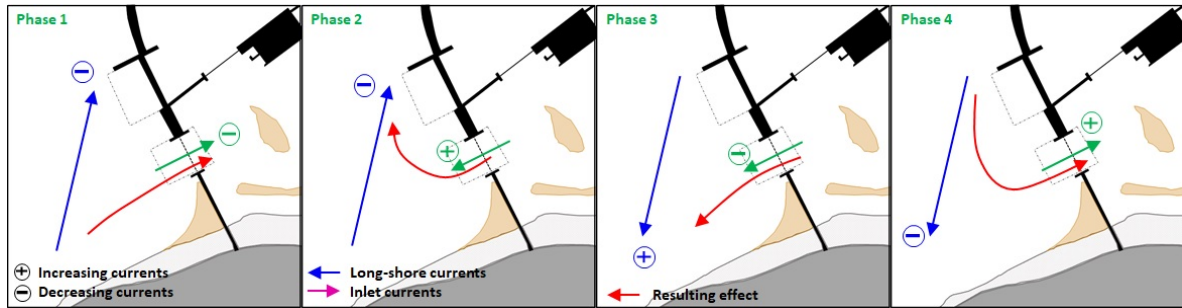


Figure 8.3: **Schematization of the tidal regime at the new location of the inlet.** The four phases as described by Tönis et al. (2002) are represented in the figure. Blue and green arrows represent long-shore and inlet tidal currents. The positive and negative signs indicate if the currents are increasing or decreasing during each phase, respectively. The red arrow represent the net effect of the offshore-inlet current interaction. The currents concentrate to the downdrift side during Phase 2 and 4 whereas they are west-orientated during Phase 1 and 3. These orientations match the growth observed in the ETD. Phase 4 occurs during a short period of the tidal cycle (also see Figure 6.2).

The relative importance of wave- over tidal-driven forces seems to control the geometry of the ETD. The observed evolution is more consistent with plot F in Figure 2.2, corresponding to small tidal prisms and eastward-directed wave-driven currents. This case can also be interpreted as that related to a relatively larger influence of wave forces than those of the tide. We can assume that in the presence of this large scale intervention, Sha et al. (1993) model is still valid.

In the scale of the D21 structure, long-shore processes adjust in a W-NE orientation of the coastline, from Goeree to the ESL dunes. The similarities between the present study results and those of typical mixed-energy tidal inlets allow us to assume that the sediment transport patterns and bed level changes detected also apply for other mixed-energy tidal inlet systems. The observations not only compare to those observed in nature in mixed-energy systems⁸ but also, despite the anthropogenic influence, the behavior resembles that observed in natural systems and broadly studied models of tidal inlets (Kana et al. 1999; Sha et al. 1993; Herrling et al. 2014).

To the author's knowledge, this is one of the first morphological study to evaluate the consequences of an intervention of the D21's magnitude on an estuary where the position of the tidal inlet is shifted in the offshore direction and simultaneously observes the emergence of features typical of tidal basin environments (Boothroyd 1985; De Swart et al. 2009) in an existing tidal estuary.

8.4. Evaluating the hydrodynamics

The hydrodynamic model was qualitatively validated comparing the model's tidal cycle for **R0** (present state) and **R1** (open estuary) scenarios. The results are comparable to the tidal cycle reported by Tönis et al. (2002) for a short basin (**R0**) and a long basin (**R1**). Tönis et al. (2002) included the Haringvliet sluices discharge during low tide, whereas the model did not implement this scenario. However, the

⁸The cited studies focus on mixed-energy barrier island tidal inlets. However, the sediment pathways discussed in those studies are very similar to the observations of the present results and therefore assumed to be comparable.

results for **R0** and **R1** still matched the observations from the literature. The hydrodynamic model was then extrapolated for a forecast simulation when implementing D21 (**R2**). Despite the simplification, the results for the **R2** scenario are assumed to be representative and realistic.

The analyzed tidal cycle was extracted from the initial period of the long term simulation in a morpho-static analysis. However, the progressive evolution of the bed is the result of hydrodynamic and morphological feedback. A fully morphodynamic model allows the bed level to update after each time-step as the result of the hydrodynamic forcing. An analysis of the tidal cycle with the final bed level is recommended to observe possible changes in the hydrodynamics.

8.4.1. Pseudo-spring-neap cycle

This research paid special attention to the derivation of a pseudo-spring-neap cycle as a result of the frequency difference between the semi-diurnal morphological tide forcing the model and a diurnal anthropogenic signal from the PPS operation. The 14.5-day cycle generated by the phasing of these signals becomes important since the main tidal motion through the TL inlet is extremely close to the in-/outflow from the PPS. In [Figure 6.2a](#), during Phase 4 of the tidal cycle, flood-currents coincide with the ESL emptying operation. The currents generated from the PPS are attracted to the TL inlet producing strong currents between both lakes. If the ESL is filling as in Phase 1, the flood-directed currents inside the TL are milder. A detailed analysis of these interactions was not performed.

The present study focuses on the long-term influence of the main forcings in the study area. The PPS signal schematization is as simple as possible; at the moment of the study, the exact operation of this facility was still unknown. The PPS influence was only evaluated through the bed level changes, comparing the cases with and without the PPS operation. The consequences extend up to the Haringvliet Dam, but the largest differences are in the seaward side ([Figure E.10](#)).

This research provides an original approach to consider the interaction between natural forcing conditions and an anthropogenic boundary condition in a long-term morphodynamic simulation. The forecasting of large-scale interventions in sensible systems, such as tidal estuaries, will be increasingly relevant in the future as further interventions against SLR become necessary. Reliable prediction models that account for these combined effects in the long-term become essential during conceptual project stages.

8.5. Evaluating the long term evolution

8.5.1. Net export of sediment at the TL inlet

As presented in [Section 6.3.1](#), the net effect on the sediment transports is an export of material of the TL, i.e., export into the Haringvliet waterway through the Dam and at the TL inlet towards the seaward side. The first case is easily explained by the transport of coarse material associated with tidal asymmetry. The basin is flood-dominant, observed at both cross-sections ([Figure 6.2b](#) and [Table 6.2](#)). This net transport agrees with the known theory: coarse material responds instantaneously to the flow following the same directions. The tidal asymmetry produces a flood-dominant flow causing a net flood-directed transport at the Haringvliet Dam.

At the TL inlet, the opposite occurs. There is net ebb-directed sediment transport despite the flood-dominant currents. [Figure 6.5c](#) presented the velocity and total transport signal for the TL inlet cross-section. There is a lower total sediment transport during the larger flood velocities than during the lower ebb velocities.

It is hypothesized that the net seaward export of material at the inlet is a consequence of larger sediment supply in the ebb-direction than in the flood-direction. The instantaneous transport vector field showed that during the flood period, sediment transport patterns just offshore from the inlet are smaller than just inside the TL. In contrast, during the ebb period, large velocities along the channel entrain the material and the material is advected offshore until it finds a less dynamic environment: seaward

from the inlet. There is a larger supply of sediment along the Slijk gat channel in a net ebb-direction than there is offshore to be transported into the TL.

The total transport vector field mostly agreed with the suspended transport vector patterns indicating that the sediment transport in the model is dominated by the suspended load transport (not shown). Sediment is mostly advected from the upstream cross-section. Figure 8.4 presents the depth-averaged suspended sediment signal for the same period as plotted in Figure 6.5c and for a location just inside the TL and just offshore (close to the ETD). The time series clearly reflects larger quantities of sediment in suspension during ebb-directed currents just inside the TL. In contrast, there is almost no material in the water column during the flood period at a location just seawards the TL inlet. The net effect can also be related to the slack-periods, however, it is not assessed in the present study.

Two main things can be concluded. Firstly, the prevailing mode of transport through the TL inlet is suspended load, in accordance with the fine fraction implemented ($D_{50} = 160\mu m$)⁹. Secondly, the findings regarding the origin of the material forming the FTD are also confirmed. During the flood period, the sediment in the water column largely increases from a point seaward of the bed protection to a point just eastwards (inside) of the bed protection. The bed protection will not supply any material. Therefore the sediment in suspension has to come from the channel itself.

The exact mechanisms driving the export of material at the inlet despite the flood-dominant flow are not fully explained. A thorough analysis of how the tide velocity signal varies in the scale of the TL inlet and the near field area could be useful to determine the magnitudes of material in suspension around the slack-periods and evaluate if this is the cause. Nevertheless, morphological changes depend on the sediment supply to the flow not only on the flow characteristics, as was observed in the present case.

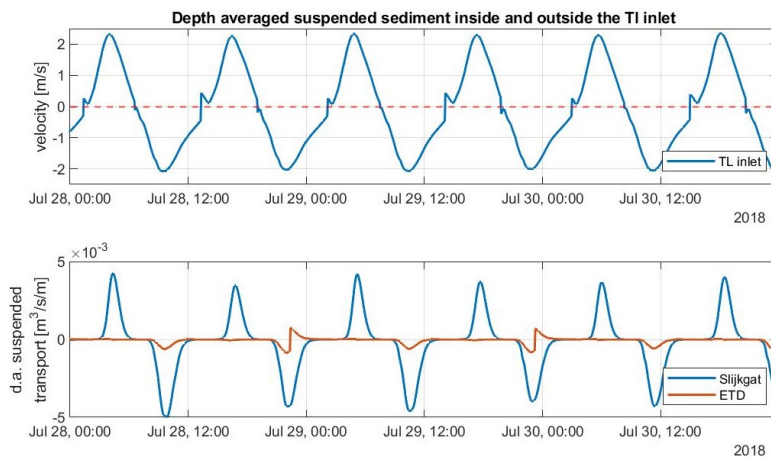


Figure 8.4: **Depth averaged suspended sediment transport at locations just inside and outside the TL inlet.** (a) Velocity signal at the TL inlet. The flood-dominance of the flow is clear in the signal. (b) Depth-averaged suspended transport signal just inside the TL (Slijk gat) and just offshore, close to the ETD. The suspended load during the entire tidal cycle is an order of magnitude lower in the seaward side than it is in the Slijk gat. For the location inside the TL, the suspended load is larger during ebb-directed currents than during flood-directed currents, agreeing with the net ebb-directed transport computed previously. The material transported in the ebb-direction is advected from upstream cross-sections along the channel.

8.5.2. Bypassing mechanisms observed

The modeling exercises in stages **S0** and **S1** allowed us to analyze bypassing mechanisms per wave condition. Two main bypassing processes are detected: through the main channel and along the ETD periphery. The mechanisms described by Fitzgerald et al. (2000) in Figure 2.4 would need longer (than 3-year morphological evolution) to develop.

⁹The dominance of suspended sediment transport load is also verified by the net sediment transport vector field. The suspended transport vectors agree with those of the total sediment transport. The mechanism is also expected, as the model is schematized with very fine sand

The area outside the TL and along Goeree accretes at low rates. To observed sufficiently volumes accumulated at the updrift side, an evolution in the order of decades is necessary. Such accretion might force the main channel's outflow to deflect to the north (now happening only for certain wave conditions) and produce a progressive northward shifting of the channel like the models of [Figure 2.4](#). A longer morphological run is necessary. For the present model and input schematization, it meant unrealistic computational times.

Shoal migration was only detected as a product of the breach and eastward migration of the Bollen van de Ooster shoal. The shoal is degraded into smaller ones that approach Goeree's coast, at least one of them eventually merges with it. If this development is real, the shoals will be huge nourishment for Goeree at the expense of the Bollen van de Ooster, also an important habitat within the Natura2000 area. It is important to determine if the breach of the Grevenlingen ETD is realistic or a model's artifact.

8.5.3. Slijk gat channel evolution

The results showed that the growth of shoals inside the TL is the result of the sediment redistribution within the TL, which originates at the Slijk gat channel. The large erosion rates along the channel indicate that the cross-sectional area has not reached equilibrium entirely.

The channel deepens while it also narrows. During the validation modeling exercises, we detected that the model favors erosion, especially along the channel. The behavior agrees with Y. Wang et al. (2016) study, which aims to reduce the unrealistic channel's incision in decadal morphodynamic modeling of tidal inlet systems. This is further elaborated in [Section 8.7](#).

An important source of sediment for the shoals growing at both sides of the Slijk gat is the erosion areas at both edges of the Haringvliet Dam. In reality, the Dam's bed protection would not allow this erosion. However, a non-erodible layer was not implemented in the model at the Haringvliet Dam. Nevertheless, the shoals will still grow, also fed by another eroding stretch of the channel.

Finally, the long-term simulation applies an initial Slijk gat channel of NAP -10.0 m depth and 1,000 m width in the bathymetry. The cross-section should be larger to convey the water volume flowing through the Dam regularly. The design of the main channel was not available at the moment of the present study. Variation of the initial depth and width of the Slijk gat should be tested to observe its influence on bed level changes inside the TL.

8.6. Investigating the growth of intertidal areas and shoals

8.6.1. Growth of the FTD

In [Section 6.3.2](#), we observed the growth of an FTD-like feature. Understanding the origin of the material responsible for its growth became key for the research as the shoal represents a gain for the intertidal/subtidal areas in the TL.

Under the action of *wc 102*, *89* and *70*, there is a net flood-directed sediment transport at the TL inlet cross-section (see [Section 6.3.1](#)). According to [Table 6.3](#), the largest import rate is during wave condition *102*, which is the strongest of the set, although the least probable one.

If the material transported during the action of these wave conditions overcomes the ebb-flow along the main channel and crosses towards the flood-delta feature, it would explain the large growth of the shoal. To analyze the sediment pathways followed by the material closer and find the mechanism that might trigger the growth of the flood-delta, the net sediment transport field at the TL inlet, during the 3 wave conditions are plotted in [Figure 8.5](#). The net total transport vector fields for *wc 102*, *89* and *70* are computed for one tidal cycle during the action of each wave condition in the simulation¹⁰.

¹⁰The average over a single tidal cycle was chosen to compare the transport fields since *wc 102* and *89* only act in the model during one tidal period according to their probability of occurrence

When *wc 102* acts on the model (Figure 8.5a, sediment transport through the TL inlet is essentially flood directed and is concentrated at the southern side of the TL inlet. The material travels from the updrift side, just offshore from Goeree's coast. The sediment transport is directed into the TL, a part of it turns to the seaward side but, most continues to the east, crossing the main channel towards the flood-tidal delta without any opposition from ebb-directed transports(currents).

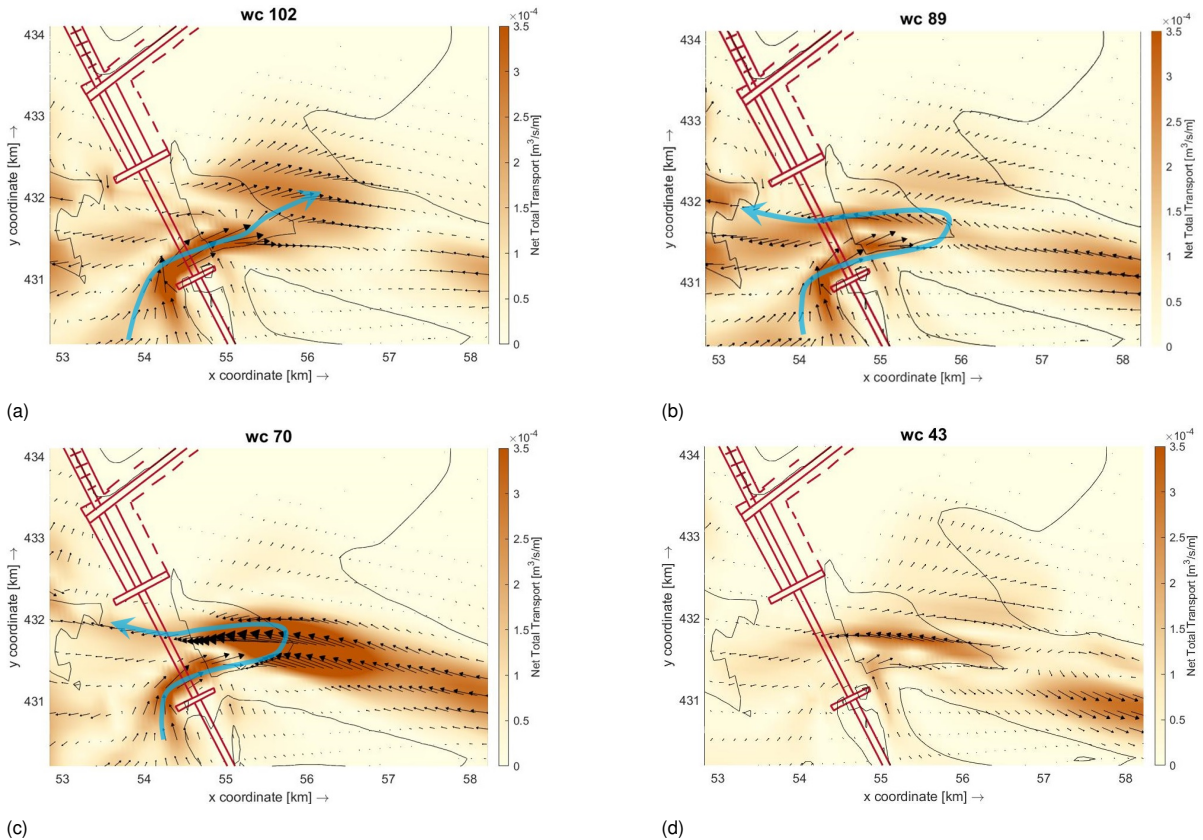


Figure 8.5: **Mean total transport averaged over a complete morphological tide, for wave conditions showing flood-directed net sediment transports at the TL inlet cross-section.** The area in the figure is a close-up to the TL inlet and where the FTD develops. The net sediment transport is computed over a single tidal cycle ($T = 744$ min). The sediment bypassing pathways are indicated with blue arrows. (a) Net total sediment transport for *wc 102*. Sediment transport through the TL inlet cross-section is mainly flood-directed and concentrated in the south. Sediment travels from the updrift side towards the inlet, part of it towards the area where the FTD grows. (b) Net total sediment transport for *wc 89*. Net flood-directed sediment transport is concentrated at the southern edge of the inlet, whereas it is mainly ebb-directed at the center. A circulation pattern is depicted carrying the material back to the sea. (c) Net total sediment transport for *wc 70*. The transport flowing through the cross-section has larger magnitudes in the flood direction at the southern abutment, whereas the ebb-directed transport decreases just before flowing through the inlet. (d) Net total sediment transport for *wc 43*; the largest sedimentation observed in the FTD is during this wave condition; net transports towards the FTD are originated within the TL.

Figure 8.5b presents the net sediment transport field during the forcing of *wc 89*. It shows that the net flood-directed sediment transport is also concentrated at the right side of the inlet whereas through the center it is mainly ebb-directed, showing similar order of magnitudes. A circulation pathway followed by the sediment is depicted immediately inside the TL where the material entering meets ebb-directed transports and turns to be carried back to the sea. The material entering the TL is probably not reaching the flood-tidal delta, but bypassing to the ETD through the channel (see blue arrow in the figure). The net transport directed towards the flood-delta features is mostly carrying material available at the area where the channel meets the structure of the TL barrier (bed protection).

During *wc 70*, the transport crossing the TL inlet cross-section has larger magnitudes in the flood direction and is concentrated at the southern abutment. The ebb-directed transports are concentrated in the middle of the main channel and are larger just before going through the inlet, decreasing sea-

wards. There is a negative sediment transport gradient. The material transported into the TL meets the ebb-currents(-transports) and flows out of the basin or settles at the inlet without reaching the FTD.

Finally, we observed that after the action of *wc 43*, the FTD has the largest sedimentation (see [Figure 7.6](#)). [Figure 8.5d](#) displays the net total transport field at the TL inlet for this wave condition. The transport vectors show that the net transport directed towards this feature originates within the TL channel, just east from the bed protection (see [Appendix E.2.1](#) for the complete set of net transport fields for all wave conditions).

Only under the influence of the most energetic wave condition *102*, the import of material into the TL is actually promoted. The material is transported from the seaward side, specifically and according to the pathways observed, from the sediment transported along Goeree's coast, accumulating at the updrift barrier of the TL and then imported into the TL. The contribution of *wc 102* to the FTD growth is minimal since it is the least probable condition. Despite the import of material for the mentioned wave conditions, the net transport averaged over the pseudo-spring-neap cycle of 14.5-days at the TL inlet is a net ebb-directed sediment transport. The growth of the FTD is mostly the product of erosion from the main channel just eastward from the bed protection, as during *wc 43* in [Figure 8.5d](#).

The FTD grows in an area between the main Slijkgat channel and the siphon located at **c1** in [Figure 1.3](#). Under extremely high river discharges, the D21 operation dictates that the TL inlet's barrier must close, and the excess volume flows into the ESL through the siphon. For the discharge to be able to flow in that direction, the area between the Slijkgat and the siphon should not be obstructed. The growth of this shoal might not be beneficial for the D21 operation despite its value for natural enhancement. Maintenance dredging will probably be desired. The gain in intertidal areas due to the FTD emergence will probably not occur.

An adjustment of the D21 layout, locating the barrier between the TL and the sea further offshore and with a more oblique angle with the coast, might shift the location of the FTD also further offshore. A larger plan area would be available within the TL to accommodate the growth of the flood-delta and a branch of the Slijkgat directed towards the siphon behind it. This design means a more extensive intervention and further sheltering of Goeree's coast ¹¹, which will need another morphological study and discussion with the stakeholders.

8.7. Modelling implementation and limitations

8.7.1. Grain size schematization

The grain size in the study site was schematized with a single sediment fraction in the range of fine sands ($D_{50} = 160\mu m$). In reality, the Haringvliet mouth has silted in the last years, especially due to the progressive sheltering of the area by the Port's land reclamations (MV1 and MV2). [Figure 3.12](#) showed mud contents along the Slijkgat pathway in the order of 60-80%. Similarly, Koomans (2001) reported a bed material grain size smaller than $75\mu m$ for most of the new Slijkgat.

The model revealed large erosion along the main channel as the result of the transport of coarse material. In reality, the large mud content would cause milder erosion trends; these results should be treated with care. As proven by Dam et al. (2006), the evolution of the Slijkgat and Rak van Scheelhoek channels is better predicted if combined sand and silt transport are considered in the model. They use a bed schematization of two sediment fractions reflecting more realistic conditions of the bed composition.

For the present situation, a more realistic schematization should include the silt content in the bed and the transport of cohesive material, which would eventually result in less erosion along the Slijkgat. This type of analysis implies a more complex model with at least two sediment fractions and different trans-

¹¹Wave energy shaping this coastline will not reach the area anymore. According to the present study, there is no important sedimentation in the stretch of the coast behind the barrier. However, considering the small sediment fractions available in the Haringvliet mouth (Koomans 2001), siltation might occur in reality, unattractive for touristic purposes.

port mechanisms with larger computational times. The calibration of the transport parameters (either for sand or mud transport) will be necessary. It can be done by reproducing known bathymetries during the period of increasing siltation at the Haringvliet mouth, i.e., after the construction of MV1 and MV2.

A morphological study by Herrling et al. (2014) in ETD at the Wadden Sea, considered several sediment fractions and proved that despite the specific analysis, finer fractions always followed the sediment transport patterns of the suspended transport load while coarser followed those of the bed load transport. In the model, because of the fine sediment size implemented, the transport detected was predominantly as suspended load (Van Rijn 2007b). The bed at the study area is composed by material ranging from fine sands to mud. We assumed that the although mud fractions are not included in the predictive model simulations, the current study with fine sand fractions still provides a reliable forecast of the system's evolution.

8.7.2. Variable MF and Input reduction

The enhancing effect of the morphological acceleration factor, especially in the presence of oscillating forcings, leads us to implement a variable MF (Lesser 2009; Moerman 2011). The approach also helped to couple MF values to the variable wave conditions. Small MFs must be applied under high episodic events, whereas bigger MFs can be used under more regular conditions Roelvink (2006).

To reduce computational times, the model implements input reduction techniques to schematized water level variations, wave climate, and the discharge regime. The input reduction accounts for yearly seasonality, aiming to reproduce constant conditions and to observe a regular evolution. Wave conditions above $H_s = 4.5$ m were neglected, and the maximum discharge regime acting in the model is $3,890.4 \text{ m}^3/\text{s}$. For this reason, the study does not predict the effects of extreme river discharges or extremely energetic wave conditions. The siphon between the ESL and the TL and a conveying channel were not included in the model. The effect over the TL bathymetry due to currents converging towards this location is unknown.

Finally, the discharge regimes were derived from water levels registered at a measuring station ≈ 35 km upstream from the Haringvliet Dam (*Bovensluis*). We assumed that the registered discharges in this station are representative of the flow conveyed in the Haringvliet waterway, even when the sluices remain open. In reality, if the sluices are regularly open, a redistribution of the Rhine and Meuse discharges between the northern and southern branches, the Nieuwe waterway and the Haringvliet, will occur. The discharge regime under such conditions should be taken into account in future studies.

8.7.3. Erosion in the model

The model predicts large erosion rates along the Slikgat channel. Some causes have been addressed in Section 8.5.3 and Section 8.7.1. The decreasing erosion rate during the last period of the simulation was initially assumed to be the stabilization of the bathymetry in response to the hydrodynamics. However, it could also be an unrealistic prediction. A key problem in long-term morphodynamic modeling in tidal inlet systems is the evolution of an unrealistic channel incision (Y. Wang et al. 2016).

The available sediment for transport is taken from an erodible layer defined in the model by a constant thickness (10 m). When the layer becomes too thin, Delft3D decreases the rate under which it is eroded (Deltares 2011b). Most of the erosion along the channel is in the order of 10 m. The decreasing erosion rates are probably due to a program setting than a trend towards equilibrium.

If the model could erode deeper, the erosion at the channel would be larger but unrealistic. It should show a more cohesive behavior, with milder erosion due to the high mud content. An approach to tackle the channel's incision in decadal morphodynamic modeling of sandy tidal inlet channels is by introducing a bedform roughness predictor or coarser bed sediments in the channel. The decrease in the channel's current velocity is inversely proportional to the bed drag coefficient, dominated by the bedforms (dunes). The channel's incision is further controlled if both effects are coupled, coarse material can promote the formation of dunes within the deep channels (Y. Wang et al. 2016).

8.7.4. Bollen van de Ooster (BvdO) breach

The model results for the long-term evolution showed that close to the beginning of the simulation, the Grevelingen ETD (Bollen van de Ooster shoal) breaches. The material store in the ETD spreads and reshapes into shoals that migrate to the east due to wave-driven currents. The model results show large residual currents behind the BvdO in the seaward direction that eventually produces the breach. If this behavior is real, and the shoals eventually merge with the coast, it means huge nourishment for Goeree's coast, but also a large loss in intertidal habitats at the Grevelingen.

Close to the location of the breach, there are shallow bed levels in the Vaklodingen source data (2018). However, probably not enough to produce a breach. Another explanation is the interpolation of this data into the model. The shoal lays further east from the area of interest. The computational grids at this location are coarser than closer to the TL structure. The feature is narrow, in the order of a couple of grid cells. When the data is interpolated to the grid, the bed levels at this location might be underestimated. The local bathymetry in the model shallower than in reality and unable to withstand the currents induced by the water level gradient behind the shoal.

More extensive analysis for the development of the BvdO shoal should be performed and is out of the scope of the present study. The results presented in this study are still open to interpretation.

8.7.5. Flow grid orientation

The modeling study was performed using as a starting point an existing model of the Haringvliet mouth (Holland 1997; De Vries 2007; Colina Alonso 2018) that does not include the area upstream from the Haringvliet Dam. For the present research, the model was extended ≈ 50 km upstream and used to assess the influences of the D21 plan in the local bathymetry.

The model gave satisfactory results. However, there is room for improvement. A general recommendation is that the grid orientation follows the main direction of the flow. In a scenario without any intervention, the flow mainly follows the grid orientation. When the D21 plan is implemented, the flow is forced to follow a path that is not parallel to the grid lines anymore. The most evident case is at the TL inlet, where the output cross-section is not a straight line but a zig-zag. The NNW directions of currents and sediment transport vectors seem to be favored by the grid itself. The sediment transport vectors and orientation of the ETD growth follow this direction for most wave conditions.

Models that allow the use of unstructured grids, e.g., Delft3D Flexible mesh, might be useful to model the complex geometries and sudden flow direction variations originated by the D21 layout characteristics.

8.7.6. Model's validation

For greater confidence in the model prediction, skill score measures could be computed. Generally used methods are based on grid-point quantitative comparison to a reference prediction or spatial validation techniques. A recently proposed methodology by Bosboom (2019) could be a useful tool for evaluating the model's predictions. The method is scale-selective and provides maps of prediction quality at the chosen scales. It allows the computation of skill patterns over the model domain, enabling the scoring of highly variable small features and the aggregated prediction.

In the present study, the approach by Bosboom (2019) could provide a quantitative measure of the model's prediction quality at the scale of the whole model domain, but also at that of the larger features, i.e., the ETD and FTD. The methodology asks for a reference prediction that could be provided by computational simulations with the smallest MF tested (MF = 5). This reference simulation implies extremely long computational times and lays out the scope of the present research. The results are assumed to be qualitatively acceptable based on a visual comparison of sedimentation-erosion patterns, as presented in subsection 5.4.2.

9

Conclusions

The conclusions of the present research are addressed through the research questions formulated in Chapter 1 in the same top-down chronology and consistent with the order of the results presented. The conclusions derived from the long-term response are related to the first four research questions (Section 9.1), and those derived from the investigation of the intertidal area's evolution are presented in Section 9.2.

9.1. Haringvliet response to D21 implementation

1. How has the hydrodynamics of the Haringvliet mouth evolved since the Maasvlakte 2 was built?

The presence of the Maasvlakte 2, although it has led to concentrated tidal long-shore currents at the Maasvlakte 2, does not further distort the existing tidal cycle.

After the damming of the Haringvliet estuary, there was a clear alteration in the tidal cycle. The basin shifted from a long-basin to a short basin behavior. Velocities inside the basin and offshore became almost in-phase, and the vertical tide led the horizontal tide by 90° . The cross-shore tidal currents decreased, and the long-shore tidal currents became relatively more important. These dynamics only considered the presence of the Maasvlakte 1 land reclamation (2002).

The protruded layout of the Maasvlakte 2 caused the long-shore tidal currents to concentrate next to it (De Groen 2014). The concentrated currents have also contributed to the scouring next to the MV2 Figure 3.10 (Van den Berg 2007). A hydrodynamic simulation for an only tide run, including the MV2 in the system and the present state (R0), showed that regarding the tidal cycle, it still follows the model presented by Tönis et al. (2002), despite the discharge at the sluices, is not included in the model.

The tidal currents form a circulation entering at the south of the basin during the flood period and leaving the basin at the north. During the ebb period, they enter through the northern channels and exit at the south. The long-shore tidal currents are still relatively more important than the cross-shore tidal currents (see model results in Section 6.2). This behavior has implications for the net sediment transports and the morphological changes that will be addressed below.

2. How have the morphological features of the Haringvliet mouth evolved since the MV2 was built?

The landward migration and spreading of the Haringvliet ebb-tidal delta (the Hinderplaat) due to the relative increase of wave-driven over tidal-driven forces and the decreased importance of the cross-shore tide has continued after the construction of the Maasvlakte 2.

The bathymetric data evaluated for the years 2012, 2015, and more recently in 2018, showed that the behavior at the Haringvliet mouth as described by Elias et al. (2016) since the closure of the estuary has continued. Long-shore tidal-driven transports are relatively more important than cross-shore processes. The material is set into motion by breaking waves in the shallowest parts, eroding the ETD front. The waves act like a bulldozer, pushing the material in the landwards. The less dynamic sheltered area behind the shoals has continued silting. The trends persist for the periods 2012-2015 and 2015-2018 (see Figure 3.10).

Along the channels, the Slijk gat (main ebb-channel), the Hindergat, and Kortsluithgeul, the tendency is to erode. In the Slijk gat channel, accretion areas to the north and east of the Kwade Hoek corner agree De Groen (2014) reports. At the MV2 coastline, there is erosion in the most offshore part of the reclamation for the 2012-2018 period, consistent with the increasingly concentrated tidal currents around the protrusion of the MV2 (Van den Berg 2007).

3. What will the overall expected behavior of the Haringvliet mouth be in the presence of Delta21 and how will the water motion be affected?

The Haringvliet mouth shifts back to a long-basin tidal regime under the presence of the Delta21 plan. The tidal prism increases significantly without reaching the magnitude from before the closure. The seaward area is controlled by wave-driven currents and the TL and main channel by the tide and discharge, depending on their relative importance.

Just the reopening of the estuary at the Haringvliet Dam showed the returned of the 4-phased tidal cycle as described by Tönis et al. (2002) for before the damming. There is again an interaction between the long-shore tidal currents and the returned cross-shore tidal current. Currents in the basin and offshore are no longer in phase. The tidal prism increases to 124 Mm³ each tidal cycle, consistent with the order of magnitude of the tidal prism reported before the damming (Louters et al. 1991; Van Wijngaarden et al. 2002), although, without reaching the magnitude from before the closure, limited by the fixed cross-sections at the new inlet and the Haringvliet Dam.

Once the D21 plan is implemented, the fourth phase of the cycle, during which currents offshore are ebb-directed, and currents in the basin (TL and upstream estuary) are flood-directed, is detected close to 4.5 hours after low water and the interaction lasts a short period of time. The tidal prism for the D21 scenario is larger (237.37 Mm³) than with only the reopening. The discharge of the PPS has an influence mostly over the area between the ESL entrance and the TL inlet, and the seaward area. Effects inside the TL are of an order of magnitude lower (see also Figure E.10b). The ESL PPS attracts an important water volume, and a lower tidal prism enters the estuary (for a scenario without operating pumps, the tidal prism is 4 Mm³ larger).

At the inlet, important currents develop in combination with the in/out-flow of the ESL. The effect extends to the seaward area around the forming ETD and even inside the TL (but milder). The importance of considering the interaction of the semi-diurnal morphological tide and the diurnal anthropogenic signal from the PPS lies in the net effect of their phasing (see Section 6.2.3).

The study area is roughly divided by the influence of hydrodynamic forces. Tidal-driven currents control the areas just offshore and onshore from the TL inlet. The main channel is also dominated by tidal-driven currents as long as the discharge is low. For regular to high discharge regimes, the channel is dominated by the discharge currents. Wave driven currents control the seaward area in a long-shore direction, east-west orientated Goeree's coast and from Goeree to the north around the ETD front.

4. What will the dominant sediment transport patterns be and its related effect on the morphology?

The net sediment transport pathways indicate that the emergence of the ETD, the FTD, and shoals inside the TL are a result of the redistribution of the material from the TL. The TL shows a net export of sediment, offshore, and into the Haringvliet waterway. The evolution of the bathymetry is consistent with mixed-energy tidal inlet systems.

The net sediment transport patterns evidence that the emergence of most features is the result of the material redistribution from within the TL, also the source for most of the growth of the ETD, the FTD, and the shoal inside the Haringvliet waterway (Section 6.3.1). The material entering the Haringvliet waterway and nourishing the shoal inside comes mostly from the Slijk gat east of Kwade Hoek. The cross-section tends to an equilibrium cross-section. Ebb-directed transports along the north-south orientated channel and flood-directed transports along the east-west orientated channel feed the developing shoals between the Slijk gat and Rak van Scheelhoek and between Kwade Hoek and the Slijk gat. The main channel erodes in the benefit of the shoals inside the TL.

According to the net sediment transport pathways, there is a net export of material for the TL. At the Haringvliet Dam, sediment travels upstream from the Dam to the waterway, and at the TL inlet, it flows offshore. The export rates agree with the orders of magnitude of the sand balance between ETD in the Voordelta (Elias et al. 2019). Tidal asymmetry driven transport causes the export at the Haringvliet Dam. The export of sediment at the TL inlet is related to the dominance of the suspended load over the total transport and could be related to the relation of transport of the suspended load and the duration of the slack-periods. Most of the sediment flowing offshore is advected from upstream. The trend opposes the flood-dominant currents. The exact mechanism driving this behavior was not fully explained and is still open to interpretation.

The seaward shift of the tidal inlet in the new estuary's configuration causes the emergence of an ETD in the seaward side and, despite the net export of sediment, an FTD inside the TL. The sediment pathways indicate that the source of the material forming the FTD is from the scour landward from the inlet's bed protection. Only during highly dynamic wave conditions (least probable), sediment from Goeree's coast is imported into the TL, reaching the FTD only during *wc 102*. This contribution is minimal.

The southern structure of the TL barrier is an interruption for the eastward-directed littoral drift, which pushes most of the subtidal and intertidal features along Goeree's coast to the east. Only when large volumes are settled in the corner between the structure and the coast, more constant rates of sediment enter the TL through the inlet. The material ultimately reaches the ETD transported by ebb-directed currents. The material along Goeree's coast bypasses the new inlet by this mechanism or by the ETD periphery during highly dynamic wave conditions. The second mechanism induces the sediment to reach the ESL dunes.

Wave forces control the evolution of the seaward area. The emergence and growth of the ETD is the result of the balance between the wave eroding force and the tide building force. Despite the anthropogenic intervention, the shift of the tidal inlet generates the emergence of new features typical of tidal environments. The ETD grows asymmetrically in W to NNW direction, downdrift side, because of the prevailing relative larger influence of wave- than tidal-driven currents in the seaward side. Under the tidal regime in the system, the ETD growth still matches with Sha et al. (1993) model of ETD geometry.

The sediment transport processes generating bed level changes are typical of a mixed-energy system (Herrling et al. 2014; Herrling et al. 2018; Sha et al. 1993), and it is assumed that the results can be extrapolated and related to other mixed-energy systems with similar hydrodynamic conditions, e.g., with predominantly westerly wave climates. The trends are expected to continue, although at a lower rate unless an alteration is forced.

9.2. Investigating the growth of intertidal areas

5. How will the intertidal and subtidal zone at the Haringvliet mouth behave under the D21 influence?

The changes in the original intertidal and subtidal areas under the D21 influence is minimal. The growth of new intertidal/subtidal areas inside the TL compensate for the initial dredging due to D21 implementation but might compromise its operation.

The original intertidal/subtidal areas, mostly inside the TL after the intervention, revealed minimal changes due to the structure. After the D21 implementation, there is a clear increase in intertidal and subtidal areas inside the TL. The FTD and Kwade Hoek-Slijkpat shoal emerge as the result of material redistributed from the main channel (see Figure 7.5).

In reality, the gain of intertidal areas inside the TL is only relevant when comparing to the initial state of the bed at the beginning of the simulation. If compared to the present bathymetry (2018), the gain is much lower. The initial dredging to implement the D21 plan removes material from the shallow areas next to the Hinderplaat, with a decrease of 7.6% or less from the NAP -3.5 m contour and shallower (see the hypsometry in Section 7.2.1). The loss of shallow areas, caused by the D21 construction, is canceled out by the growth of new features.

However, the FTD might represent an obstruction for the flow under an extreme discharge scenario when the operation of the siphon is necessary. Maintenance dredging might be sought to avoid obstruction in the FTD area. The naturally generated shoal will not develop, and another natural compensation for the lost intertidal and subtidal areas will be required.

In the seaward side, the increase of intertidal and subtidal areas is minimal; the largest gain occurs along the area approximately 2 km offshore Goeree's coastline and is associated with the accretion of the NAP -5.0 m contour and shallower. The NAP -3.5 contour is the most dynamic one showing the shoals along Goeree migrating to the east, towards the TL's structure. The largest bed level changes in the intertidal/subtidal features occurred under the influence of *wc 43*, *8a*, and *40a*, very constant conditions.

6. How will an artificially nourished sandbank located at the seaward side of the Tidal Lake behave under the new conditions?

A new sandbank as natural compensation to the intertidal/subtidal habitats, located in the seaward side, is more stable when it has a smooth geometry with the original coastline. The growth is promoted at a very mild rates.

Two configurations of sandbanks were evaluated at the area between Goeree and the southern structure of the TL. The first version (sandbank **v1**) was selected as a better option, with milder erosion along its most seaward contour for most of the wave conditions analyzed. The feature resembles a continuation of the coastline itself with a smoother transition than a sandbank **v2** (see Figure 7.7). The implementation of sandbank **v1** to the bathymetry means an additional increase in the bed levels of 7.1% at NAP -3.5 m contour and a maximum of 11.6% at the -2.0 m contour. Around the intertidal zone, the bed elevations increase in the order of 7.0%.

The plan geometry of both sandbanks, forming a triangular shape with the coastline and the structure, allows a continuation of the littoral drift that enhances the net transport of sediment into the TL. Sedimentation is promoted along the edges of the feature (at very mild rates), and erosion only occurs closest to the structure. The geometry of the feature also increases the import rates to the TL from Goeree's (sandbank) coast. The configuration of the sandbank, attached to the shore, facilitates the attraction of sediment towards the area. However, it represents an extension of Goeree's beaches and might be used as recreation rather than guaranteeing the conservation of the habitat.

7. Will the configuration of a nourished sandbank help trigger its own growth by taking advantage of tidal inlets' sediment accumulation processes (bypassing)?

The nourishment of a sandbank in the area between Goeree's coast and the TL barrier promotes the settlement of sediment on the deepest contours of the feature. Its growth is triggered by the interruption of the littoral drift rather than by the formation of shoals accumulating updrift from the inlet. Material bypassing the inlet, either through it or around the ETD seaward edge, will benefit deeper areas like the ETD and the ESL dunes.

The objective of a sandbank with a smaller horizontal area was to study the possibility of triggering a large sediment build up under energetic wave conditions, to minimize the initial volume to nourish. The observations allowed to establish the most stable configuration from the 2 sandbanks studied (sandbank **v1**). However, to trigger the growth of shoals in the ETD area, first, a large imbalance between the hydrodynamics and the bathymetry must be present (Ridderinkhof et al. 2016). Secondly, a more developed ETD seems necessary.

The area between Goeree's coast and the TL southern barrier structure is prone to deposition, and in a longer time-span than the simulation of this study (decades), the material will be likely to build up there. The shallowest contours will continue to accrete and ultimately merge with the western ETD development. Under such conditions, the mechanisms of growth and migration of shoals in typical ETD could still be used as a reference to enhance the development of shallow areas in the intertidal/subtidal zone (Herrling et al. 2014; Ridderinkhof et al. 2016). However, a specific study of these mechanisms lies out of the scope of the present research.

Recommendations

Based on the findings of the present study, we make recommendations for future research and practical applications related, firstly to the Delta21 plan development regarding morphological implications, secondly, related to important considerations specifically at the Haringvliet mouth and in general for silted environments. Finally, we make some recommendations for studies related to mixed-energy tidal environments under interventions.

9.3. D21 implications for morphology

This study answered many questions regarding the morphological evolution of the Haringvliet mouth if the D21 plan was implemented. However, it also raised several additional questions derived from the observed trends and because of the simplifications made in the present modeling exercise.

1. Adjust the D21 layout to accommodate the beneficial growth of the FTD and a conveyance channel towards the siphon at the ESL.

The increase of intertidal areas in the form of an FTD compensates for the loss due to the D21-related dredging. Therefore, it is important to allow its growth. To prevent maintenance dredging, and therefore high maintenance costs, an adjustment in the D21 layout that allows the growth of the FTD the conveyance of the excess water volume during extreme discharge events can guarantee the existence of both requirements. The adjustment would need a larger area for the TL and further sheltering of Goeree's coast. The evaluation of the proposition through morphological modeling is necessary, in addition to the agreement of the stakeholders involved.

2. Reassess the location of the additional compensation for the intertidal/subtidal zone.

The accreting characteristic of the chosen location to develop a sandbank as compensation and its potential to accumulate large sediment volumes such that positive feedbacks can be promoted makes the area interesting for such development; future research in this sense is encouraged. However, the sandbank attachment to Goeree's coastline might compromise the conservation of the habitat if its preferably used as a recreational area. The model results showed a natural growth of shoals inside the TL. This sheltered area, closer to the original ETD shoals, could represent a better location for an intertidal/subtidal habitat compensation development.

3. Develop a D21 specific morphological model and include additional processes

The model used in the present research has a series of limitations. One of the most noticeable is the lack of agreement between the D21 layout and the flow path induced by it, with the model's grid. An improvement of the orientations of the grid cells in the near-area of the D21 would be important to increase the accuracy of the evolution observed; unstructured grid models could be useful (e.g., Delft3D flexible mesh).

Additionally, the present model highly schematized the site conditions to decrease the computational times. Storm surge levels, extreme discharge regimes, and SLR were not included in the model, and the wave climate only considered westerly conditions. Storm surge levels and extreme discharges will have an influence in an episodic time-scale but drive bed level changes that will push the equilibrium trends to a certain condition. SLR will influence the long-term (in the scale of decades) development of the emerging tidal system, known to be sensitive to large SLR rates (Dissanayake et al. 2012).

The PPS operation was also highly schematized but its influence was proven to be significant in the seaward side. A clearer picture of the PPS operation would enable a more specific evaluation of the influence the phasing of their discharge with the tide, has over the bathymetry changes; important

to avoid erosion trends over important shallow features and accretion close to the PPS that might compromise its operation (Figure 6.7).

4. Study of revealed processes: Bypassing mechanisms, scouring and BvdO breach

The results revealed other processes that produce positive and not desired outcomes. Considering beneficial processes, the two bypassing mechanisms detected promote the maintenance of other features. Bypass through the main channel nourishes the ETD and bypasses around the ETD seaward edge could benefit the ESL dunes, mechanisms worth analyzing further. The undesired observed processes are related to the breach of the Bollen van de Ooster shoal due to wave-driven forces and the large scouring next to the bed protection. The development of the scour holes next to the TL inlet bed protection can reach large depths and must be considered in the design of the bed protection; the flow structure can be strongly influenced by this development similar to the developments in the Eastern Scheldt Storm surge barrier (Broekema 2020). The breach of the BvdO must be taken with care. Other than a physical phenomenon, it could also be an artifact in the model related to underestimated bathymetric data. The BvdO is a valuable intertidal shoal, and its stability under the D21 influence should also be thoroughly evaluated.

9.4. The Haringvliet mouth, a mixed-energy tidal inlet system

5. Improve modeling studies in the Haringvliet and in general in mixed-energy tidal inlet systems, by including different grain sizes and the transport of sand and mud.

The low dynamic back area in tidal inlet environments is usually characterized by a bed composition of fine grain sizes. The increasing sheltering of the Haringvliet mouth has produced the fining of the area, particle sizes $<63\mu$ (mud) have been reported behind the Hinderplaat (Koomans 2001). A more realistic schematization of the Haringvliet mouth should include the silt content in the bed and the transport of cohesive material. The approach will produce more realistically represent the mud layers in the channels, reducing the and probably the morphological changes (Dam et al. 2006).

The schematization of the bed composition by different grain sizes and even sand and mud fractions enables a more realistic evolution of morphological simulations in tidal environments. Sediment transport pathways are also dependent on the grain size, and morphological variations of tidal features can also be the result of erosion-sedimentation of different sediment fractions. The inclusion of such processes in morphological studies at the scale of tidal features is important in predicting and hindcasting the morphological evolution of mixed-energy tidal inlet systems, as the case presented in this research (Herrling et al. 2014; Herrling et al. 2018).

9.5. Interventions in tidal environments

6. Consider anthropogenic influences as part of model schematizations in modeling studies

The present challenges derived from climate change force us to intervene in coastal systems in an attempt to fight against erosion and SLR. Despite the efforts for sustainable interventions, e.g., Building with Nature approaches, natural systems are always sensitive to alien factors. The inclusion of these anthropogenic influences in forecasting models is extremely relevant in the accurate prediction of the system's response. The factors to include in the model schematization, besides structures, are boundary conditions of water levels, currents, and constituents that should also be extrapolated in the long-term (in the scale of decades) predictions.

7. Conduct further long-term forecasting of intervened tidal inlet systems under SLR.

There is an important development of long-term forecasting in tidal basin systems. However, most studies are focused on the prediction of the system's response to SLR under the present circumstances. To tackle the challenges due to climate change, faster action is needed. Forecasting the decadal morphological evolution of coastal systems and tidal basins under measures taken to prevent their degradation due to SLR, is a powerful tool for decision-making regarding interventions in these valuable natural systems.

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A

Additional Theory

A.1. Tidal basins dynamic equilibrium relations

Dynamic equilibrium implies that the morphology is in balance with the physical processes (Van der Spek et al. 2015). The stability of tidal inlets is then determined by the competing force tidal- and wave-driven currents, the former moving the material deposited at the tidal inlet by the littoral drift, brought by the latter, the wave-driven currents (Van de Kreeke 1992). The relations presented in this appendix are mentioned in Chapter 2.

The inlet velocity has to satisfy the hydraulic conditions, i.e., the maximum velocity of the inlet is a function of the cross-sectional area. Under the dynamic equilibrium assumption, empirical relations have been derived for the relationship between the equilibrium cross-sectional area in the inlet and the tidal prism. The relation derived by (O'Brien et al. 1972) (Equation A.1), is an integral part of the stability analysis and is derived from the assumptions underlying Escoffier's analysis for equilibrium cross-section (Van de Kreeke 1992).

$$A_{eq} = C * P^q \quad (A.1)$$

$$u_e = \frac{\pi P}{A_e T} \quad (A.2)$$

Where,

A_{eq} minimum equilibrium cross-section in the throat, measured below MSL.

u_e maximum velocity at the throat for a given cross-sectional area A_e at the same location, ≈ 1 m/s (Escoffier 1940).

T tidal period.

P (spring) tidal prism.

q empirical coefficient, ≈ 1 assuming $u_{eq} = 0.9$ m/s ((Escoffier 1940)).

C empirical coefficient, $\approx 7.8 * 10^{-5}$ assuming $u_{eq} = 0.9$ m/s ((Escoffier 1940)).

Empirical expressions for the relationship between the tidal prism and the sand volume in the outer delta and water volume in the channels have also been derived. The water volume corresponding to the channels was derived through the empirical relation by (Eysink, 1990) shown in Equation A.3 and applies when the flood-delta spans the whole basin.

$$V_c = C_V P^{\frac{3}{2}} \quad (A.3)$$

Where,

V_c equilibrium total channel volume below MSL.

P tidal prism.

C_V empirical coefficient, e.g. $73 - 80 * 10^{-6} \text{ m}^{-\frac{3}{2}}$ for the Eastern Scheldt and Grevelingen.

From Equation A.3 a relationship between tidal flat area and total basin area can be found, this is depicted in Equation A.4

$$\begin{aligned} A_f &= A_b - A_c \\ &= A_b - \frac{V_c}{D_c} \approx A_b - \beta \frac{H_m A_b^{\frac{3}{2}}}{D_c} \end{aligned} \quad (\text{A.4})$$

Where,

A_f flats' area, above MSL.

$A_c h$ horizontal area covered by the channels.

D_c characteristic channel depth.

H_m mean tidal range.

β constants for proportionality.

Finally, the volume store in the ETD was derived empirically by Walton and Adams (1977) as shown in Equation A.5.

$$V_{od} = C_{od} P^{1.23} \quad (\text{A.5})$$

Where,

V_{od} sand volume stored in the outer delta.

C_{od} empirical coefficient related to the wave climate.

P tidal prism.

A.2. Model of bar formation in tidal channels

There are two general modes for the build-up of sills at the end of flood-channels, forking and sidetrack (Stive et al. 2003). The channel-shoal interaction is still unsolved problem and the flooding and drying of the shoal parts is still a modelling challenge (Z. B. Wang et al. 2012).

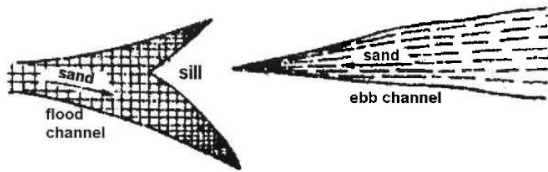


Figure A.1: Van Veen (1950) alternating ebb and flood channel models. Sill creation at the end of flood channels in a forking mode. (Retrieved from Stive et al. (2003)).



Figure A.2: Van Veen (1950) alternating ebb and flood channel models. Sill creation at the end of flood channels in a side track mode. (Retrieved from Stive et al. (2003)).

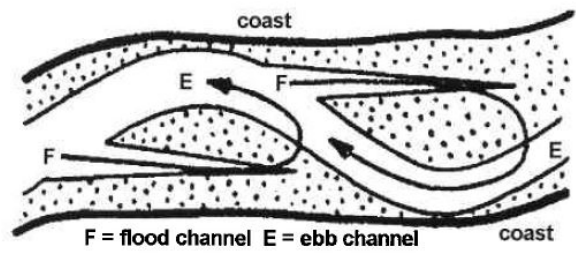


Figure A.3: Van Veen (1950) alternating ebb and flood channel models. Horizontal circulation between flood and ebb channels during the tidal cycle. (Retrieved from Stive et al. (2003)).

B

Study Area

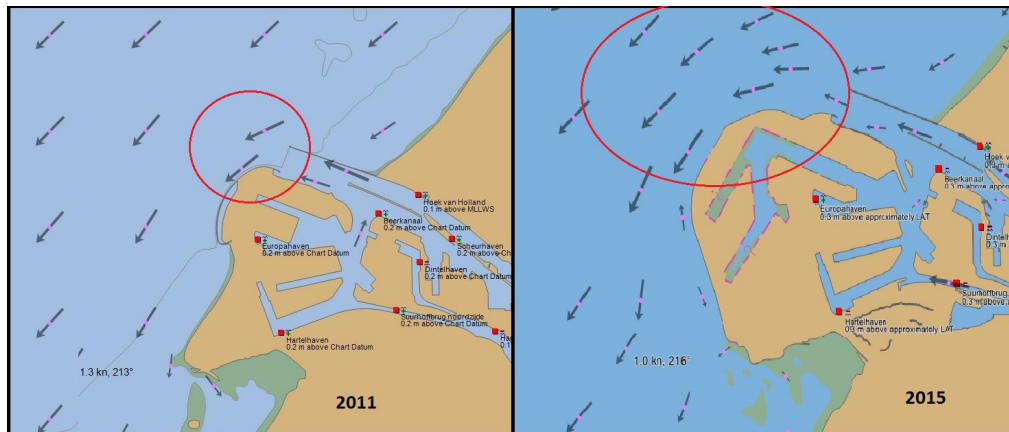


Figure B.1: **Overview of tidal currents before and after the Maasvlakte 2 construction.** Before the construction of the MV2 (2011) in the left figure, the coastline already protruded due to the Maasvlakte 1, producing small current concentration at the tip of the landreclamation (red circle). The tidal currents concentration was further increased due to the MV2 as it protrudes even further from the adjacent coastline as can be observed in the right figure for the year 2015 (red circle). (Retrieved from De Groen 2014)

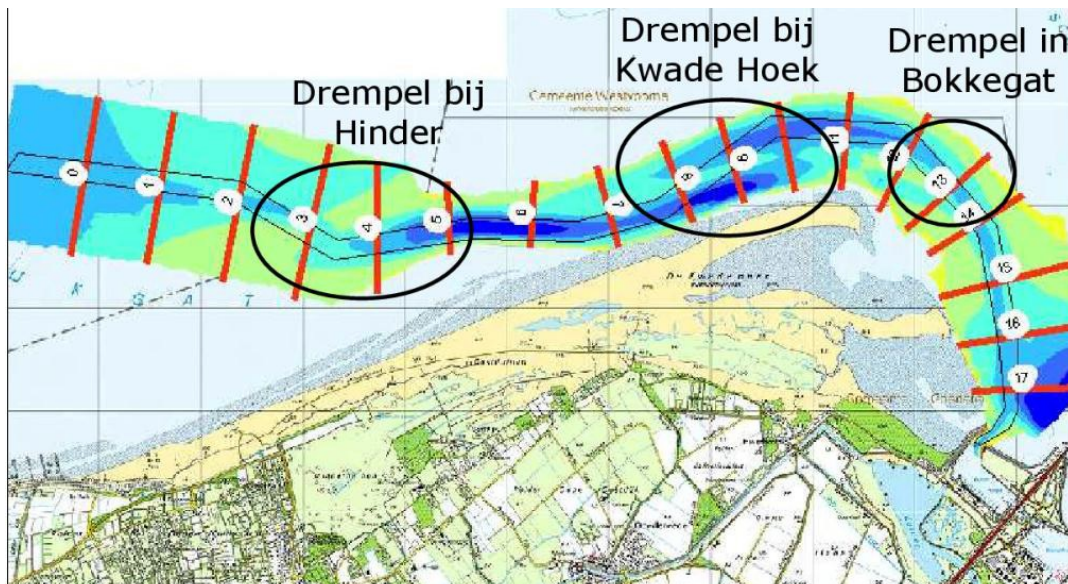


Figure B.2: **Slijkgtat channel plan view of the dredging problematic areas.** The areas marked by the black circles indicate the zones where more intensive dredging activities are needed to maintain the shipping access to Stellendam harbour. The Dutch words drempel bij means interference at. The first area from east to west, is located just before the bend where the Slijkgtat turns around Kwade Hoek, the second area is where a sill is formed where ebb- and flood-currents meet and the last area is further offshore, where the Slijkgtat meets the sea. (Retrieved from De Groen 2014).

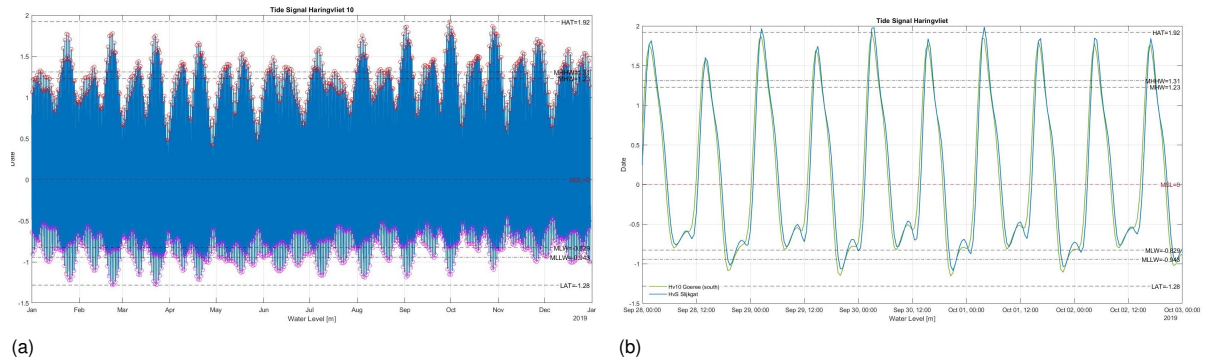


Figure B.3: **Tidal signal at the Haringvliet mouth for different time periods.** The tidal signal is retrieved from *Delft Dashboard* (Van Ormondt et al. 2020) for the year 2019 at Xtide Tidal Station *Haringvliet 10* (51°52'0.12" N, 3°52'0.12" E). (a) Comparison of tidal signals between Xtide station *Haringvlietsluizen* and *Haringvliet 10* for a week record, the daily inequality can be observed. (b) Tidal signal of a 2 month period with clear variations in the spring-neap cycles.

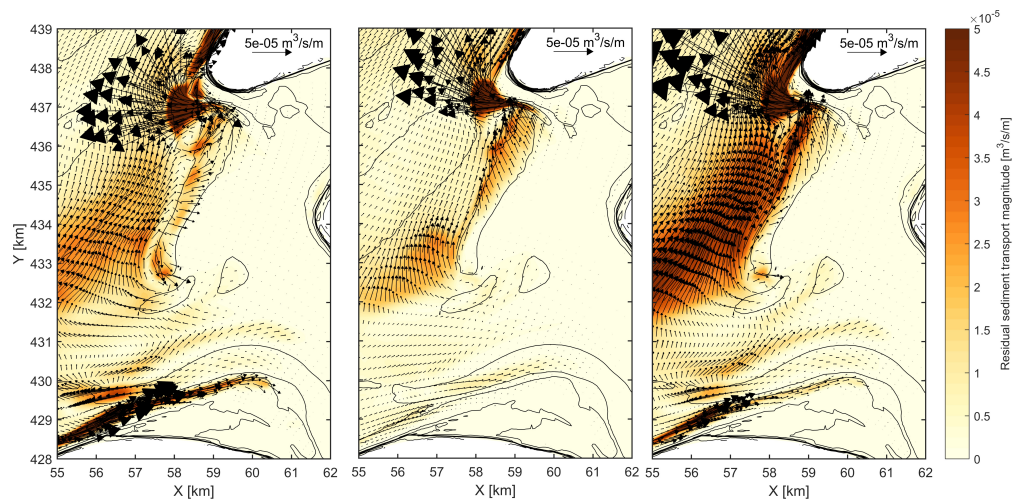


Figure B.4: **Modelled residual sediment transports for different wave and wind conditions of medium strength ($H_s \approx 2.4$ m).** From left to right the figure shows WNW, SSW and WSW conditions. WNW condition produces high transport rates along the coast of Goeree towards the Haringvliet mouth. In a similar but milder magnitude, transport along Goeree can also be seen for WSW conditions, while this condition also produces higher transport rates along the ETD front. For SSW conditions transport along Goeree coast and the ETD front are smaller. (Modified from Colina Alonso 2018)

C

Methodology

Table C.1: **Summary of modelling scenarios for assessing the stability of a sandbank south of the ESL.** Stage 0 corresponds to the long-term modeling exercise that is used to evaluate the response of the Haringvliet mouth to the D21 intervention and the changes in the dynamics of the system. Stage 1 refers to modeling exercises to assess the stability of a possible sandbank as compensation for lost intertidal/subtidal areas.

Code	Modelling Scenarios	Related Research question
S0	Long term morphodynamic simulation with Delta21 plan (no sandbank)	3. Overall expected behavior
S0	Long term morphodynamic simulation with Delta21 plan (no sandbank)	4. Changes in hydrodynamics
S0	Long term morphodynamic simulation with Delta21 plan (no sandbank)	5. Changes in sediment transports and morphology
S1.1	Simulations for currents and sediment transport (with sandbank)	6. Stability of sandbank
S1.2	Simulations for initial bed level changes (with sandbank)	6. Stability of sandbank

D

Model Set-up

D.1. Discharge Relation between Lobith and Bovenluis

Under the Delta21 plan the objective is to maintain the Haringvliet sluices open as the regular situation. Nevertheless, it is established that when discharges at Lobith¹ are lower than 1,000 m³/s the discharge further downstream at the sluices is so small that the tide propagation and salt intrusion will reach the new fresh water intakes at Strijensas and Roode Vaart (Lavooij et al. 2019). Under such situation the Haringvliet sluices must be closed and to tidal currents enter the estuary and no river flow is discharged into the Tidal Lake.

For the purpose of this study, the condition at Lobith needs to be translated to a discharge condition at the boundary of the model domain, at the Bovenluis Station. Figure D.1 shows the daily mean discharge for the period 1997-2017 at the location of both stations, and is already noticeable that the discharge at Lobith has a relation with the resulting discharge at Bovenluis. The flow along the Haringvliet is the result of contributions of the rivers Rijn and Meuse and according to Van Wijngaarden et al. (2002), the Rijn river has the biggest influence. Figure D.2 shows the probability of occurrence of the discharge at Lobith in Figure D.2a and Figure D.2b shows the correlation of discharges at both stations for the analysed period, resulting in a $R = 0.9245$.

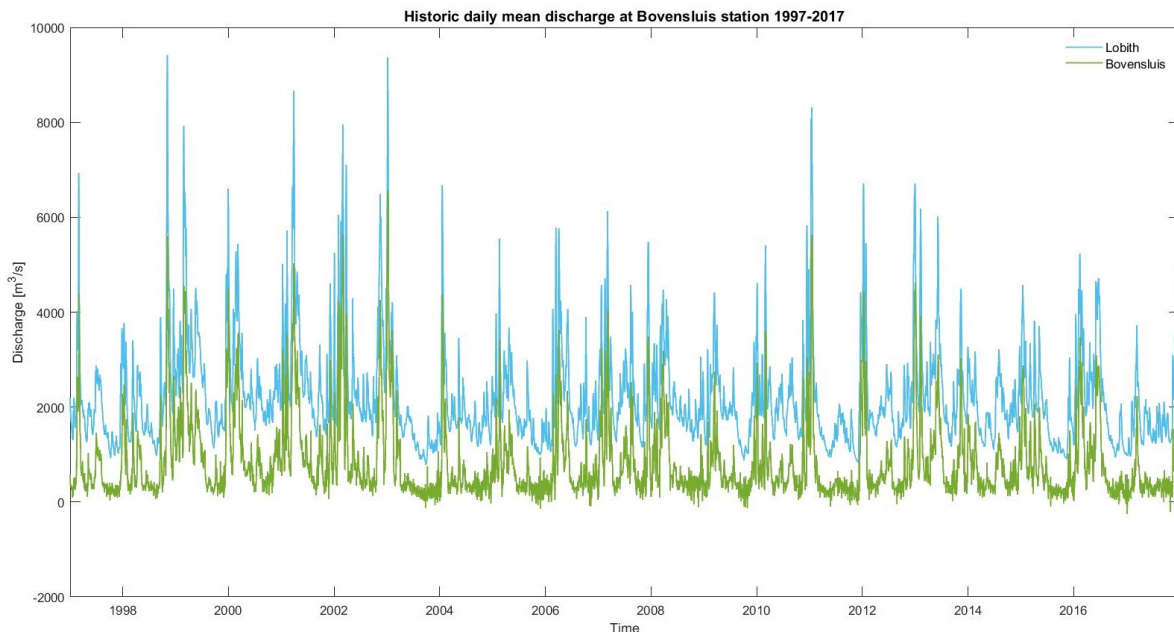


Figure D.1: **Mean daily discharge for Lobith and Bovenluis stations for the period 1997-2017.** The stations are located at 51° 51' 1.44"N, 6° 6' 12.96"E and 51° 41' 33.00"N, 4° 29' 36.24"E, respectively. The closure of the Haringvliet sluices under the D21 operation will depend on the discharges registered at *Lobith*, low discharges in this branch of the river Rhine will cause low discharges at the Haringvliet as well and the intrusion of the salt wedge further upstream than desired.

¹Lobith station is at the border between Germany and The Netherlands, where the River Rijn enters The Netherlands.

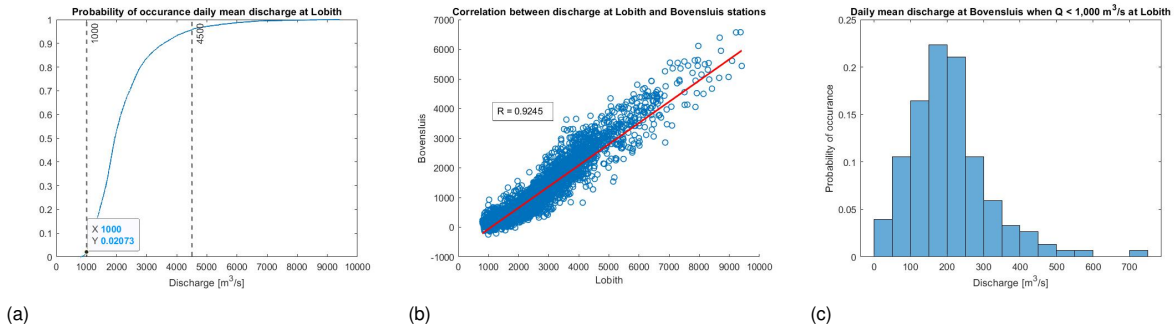


Figure D.2: **Analysis of the discharge relation between discharge at Lobith and Bovensluis stations for the period 1997-2017.** (a) Probability distribution of discharges at Lobith (b) Correlation between Lobith and Bovensluis discharges (c) PDF for discharges at Bovensluis when $Q_{Lobith} < 1,000 \text{ m}^3/\text{s}$ for bin classes of $250 \text{ m}^3/\text{s}$.

The probability of a discharge at Lobith $Q_{Lobith} < 1,000 \text{ m}^3/\text{s}$ is of approximately 2.0% (around 7 days a year) as shown in Figure D.2a. To determine what will the condition at Bovensluis is during this situation, discharges at Bovensluis during the days when $Q_{Lobith} < 1,000 \text{ m}^3/\text{s}$ were analysed; Figure D.2c shows the PDF for such days. The figure shows that the discharge at Bovensluis is between 150 and 250 m^3/s 43.4% of the time with this conditions. A weighted average for all the discharges at Bovensluis when $Q_{Lobith} < 1,000 \text{ m}^3/\text{s}$ to determine the first class interval of the discharge schematization for the model, scenario in which the Haringvliet sluices will be closed. This analysis resulted in an average of 230 m^3/s , this value will be used as the lower bound for the considered discharges during the simulations (see Table D.1).

This analysis is the starting point for the discharge schematization derived in subsection 5.2.5.

Table D.1: **Weighted average of discharges at Bovensluis when $Q_{Lobith} < 1,000 \text{ m}^3/\text{s}$.** The discharge at Lobith determines the closure of the Haringvliet sluices. The condition is extrapolated to discharges at the Bovensluis station to determine the probability of occurrence of these really low discharges and the possible closure of the Dam.

Initial [m³/s]	Final [m³/s]	Occurrence $Q_{Lobith} < 1,000 \text{ m}^3/\text{s}$ [%]	Occurrence entire year [%]	Weighted average [m³/s]
0	50	0.0395	0.0008	1.97
50	100	0.1053	0.0021	10.53
100	150	0.1645	0.0033	24.67
150	200	0.2237	0.0044	44.74
200	250	0.2105	0.0042	52.63
250	300	0.1053	0.0021	31.58
300	350	0.0592	0.0012	20.72
350	400	0.0329	0.0007	13.16
400	450	0.0263	0.0005	11.84
450	500	0.0132	0.0003	6.58
500	550	0.0066	0.0001	3.62
550	600	0.0066	0.0001	3.95
600	650	0.0000	0.0000	0.00
650	700	0.0000	0.0000	0.00
700	750	0.0066	0.0001	4.93
Total probability of occurrence [%]			0.0198	230.92
Total probability of occurrence [days/yr]			7.238	

D.2. Discharge at Bovensluis

The time series of the period analysed is shown in Figure D.3 and the probability distribution function for the discharges is shown in section D.2 in bin classes of $250 \text{ m}^3/\text{s}$. It is observed that during the analysed period discharges hardly exceed discharges of $5,000 \text{ m}^3/\text{s}$. From the PDF it is observed that discharges between $250 \text{ m}^3/\text{s}$ and $500 \text{ m}^3/\text{s}$ have the highest probability of occurrence (35%). This interval is chosen as the next interval class of interest to derive representative conditions in the river.

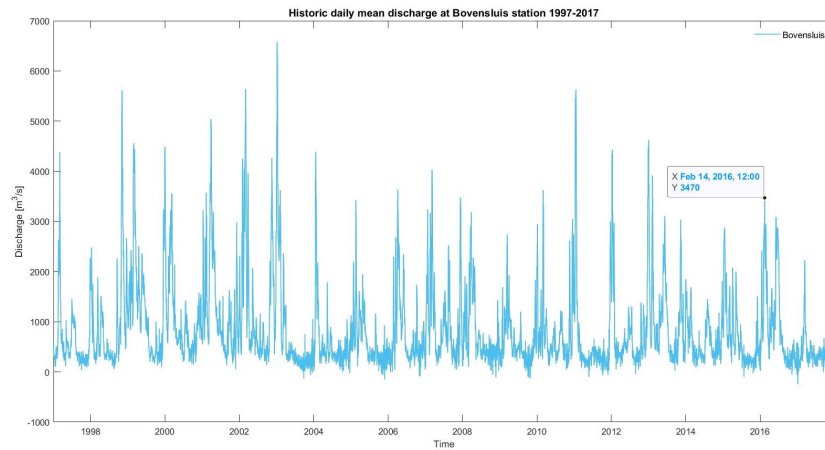


Figure D.3: **Historic discharge at Bovensluis station for mean daily discharge measurements for the period 1997-2017.** This record is used to derive the discharge classes in the probability analysis to select the representative discharges in the model (Rijkswaterstaat [2020c](#))

From the figure it is also clear that discharges greater than $1,500 \text{ m}^3/\text{s}$ have probabilities of occurrence of around 5%. The next interval class is then chosen between 500 and $1,500 \text{ m}^3/\text{s}$. Additionally, discharges greater than $3,000 \text{ m}^3/\text{s}$ occur approximately 3% of the time. The last class interval chosen representing the highest discharges in the river is between $3,000 \text{ m}^3/\text{s}$ and $7,000 \text{ m}^3/\text{s}$.

In the record the maximum mean daily discharge registered is $6,575 \text{ m}^3/\text{s}$ on January 6th, 2003. Before this period, an extreme mean daily discharge reaching $9,015 \text{ m}^3/\text{s}$ was computed in 1995 and can be observed in (Colina Alonso [2018](#)). Because the mentioned extreme discharge is not included in the analysed period in the current study, the class intervals derived for the schematization have an upper bound of $7,000 \text{ m}^3/\text{s}$.

The detailed probabilities of occurrence for each class is shown in [Table D.1](#) for data of the entire year as well as for data of the wet and dry season defined in [subsection 5.2.5](#). The table shows that the dominant discharges are represented by the second and third class (regular conditions defined in D2 scenario of [Table 5.1](#)). The 4th and 5th classes have lower probabilities of occurrence and show to be more important during the wet season. [Table D.2](#) also shows the combined probabilities of occurrence with a weighted average considering the 5 classes (column 5C), the 4 classes with discharges higher than $230 \text{ m}^3/\text{s}$ (column 4C), the classes representing discharges between 230 and $3,000 \text{ m}^3/\text{s}$ (column 3C) and for the "regular" and "high" scenarios.

Table D.2: **Derivation of discharge classes for model schematization.** The derivation is based on measurements of mean daily discharge at Bovensluis Station. 5 classes are derived for summer, winter and the entire year. The classes are then (weighted-)averaged to derive a representative discharge under regular conditions, high discharge regime, per season and yearly.

Station	Bovensluis	Classes [m^3/s]					Combined classes				
		0-230	230-500	500-1500	1500-3000	3000-7000	5C	4C	3C	Regular	High
P_{occ}	[%]	0.1110	0.3734	0.3641	0.1141	0.0338	0.9964	0.8854	0.8516	0.7375	0.1479
	days/yr	40.52	136.38	133.00	41.67	12.33	363.90	323.38	311.05	269.38	54.00
All year	Min	3.0	231.0	501.0	1502.0	3002.0					
	Mean	161.3	353.3	873.7	2126.0	3848.6	840.6	822.7	692.6	450.0	372.7
	Max	230.0	500.0	1499.0	3000.0	6575.0					
P_{occ}	[%]	0.1284	0.4619	0.3429	0.0599	0.0042	0.9973	0.8689	0.8647	0.8048	0.0641
	days/yr	27.48	98.86	73.38	12.81	0.90	213.43	185.95	185.05	172.24	13.71
Dry season	Min	3.0	231.0	501.0	1502.0	3003.0					
	Mean	166.7	350.8	850.1	2030.8	3321.1	610.5	589.1	575.2	453.5	135.6
	Max	230.0	500.0	1495.0	2995.0	4017.0					
P_{occ}	[%]	0.0836	0.2469	0.3944	0.1895	0.0755	0.9899	0.9063	0.8308	0.6413	0.265
	days/yr	12.71	37.52	59.95	28.81	11.48	150.48	137.76	126.29	97.48	40.29
Wet season	Min	5.0	231.0	501.0	1502.0	3002.0					
	Mean	149.6	359.8	902.6	2168.3	3890.4	1161.9	1149.4	855.7	444.8	704.6
	Max	230.0	500.0	1499.0	3000.0	6575.0					

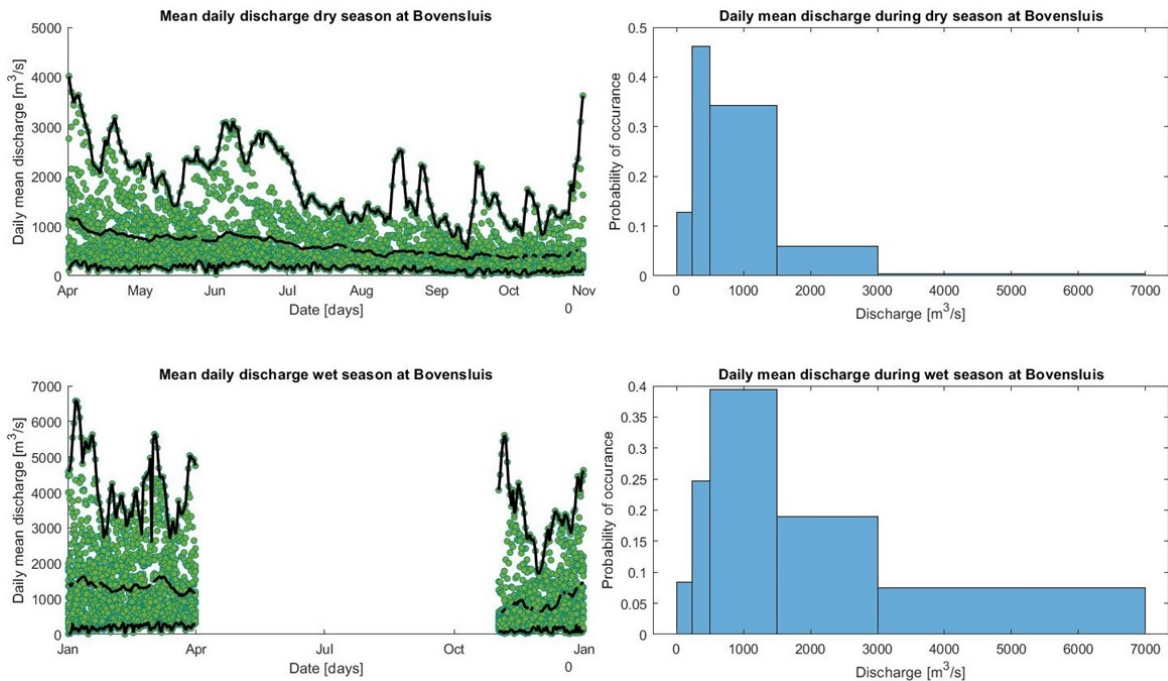


Figure D.4: **Probability analysis of discharge classes for each season of the year previously defined.** The left plots show the distribution of the data over the two different seasons along the discharge values, reaching larger discharges during winter season. Right plots show the pdf with the discharge classes for the separated seasons. Clearly larger discharge classes are more relevant for the winter period being the Class III the most probable one. For summer season the higher probability of occurrence corresponds to Class II.

The discharge is then further reduced into a representative discharge for the summer season and one for the winter season, considering a period of 7.238 days a year where no discharge will flow through the Haringvliet sluices and 32 in which the lower discharge class will occur (Class I). A weighted average of class 2-4, one for winter and one for summer seasons, is computed. Additionally, a high discharge of 3890.4 m^3/s during 11.48 days/yr is included (see Table 5.3).

D.3. Wave conditions

lower	upper	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.5	9.7	12.4	16.3	22	20.8	22.3	28.3	27.3	19.8	11	8.3	10.1
0.5	1	19.7	23.6	28.8	36.7	37.1	38.8	35.3	34.3	33	28.9	26.2	19.3
1	1.5	22.9	23.5	23.3	22.3	24.8	24.1	22.9	21	22.1	25.8	23.6	20.8
1.5	2	17.6	17	13.8	11.5	11.3	9.9	9.2	11.2	12.4	16	17.8	19.2
2	2.5	13.7	10.4	10.1	4.9	4.5	3.1	3.1	4	7.3	9.7	12.2	14.5
2.5	3	8.8	6.9	4.5	1.7	1.2	1	0.7	1.4	3.1	5.1	7	8.6
3	3.5	4.6	3.4	2.3	0.5	0.4	0.7	0.2	0.6	1.2	2	3	5.1
3.5	4	1.9	1.7	0.7	0.3	0	0.1	0.1	0.1	0.8	1	1	1.6
4	4.5	0.6	0.7	0.2	0.1	0	0	0	0.1	0.3	0.3	0.6	0.6
4.5	5	0.5	0.2	0	0	0	0	0	0	0	0.1	0.3	0.2
5	5.5	0.1	0	0	0	0	0	0	0	0	0	0.1	0
5.5	6	0	0	0	0	0	0	0	0	0	0	0	0
6	6.5	0	0	0	0	0	0	0	0	0	0	0	0
6.5	7	0	0	0	0	0	0	0	0	0	0	0	0
total		100	100	100	100	100	100	100	100	100	100	100	100

Figure D.5: **Yearly wave climate retrieved from the location of the Europlatform station.** The station is located at 52.00° N, 3.28° E. This data is normalized in [Figure 3.8](#) (Argoss 2020)

Table D.3: **Original wave conditions derived by De Vries (2007)** This schematization was used for the modeling exercise by adjusting the weight factors to the days per year, included in the schematization of this study.

wc	H_s [m]	T_p [s]	Direction [°]	Wind Velocity [m/s]	Wind Direction [°]	Weight factor [-]	Days/ year	Factor discharge [-]	Discharge implemented [m ³ /s]
8	0.48	4.45	292.9	4.2	240	0.5021	183.27	1.75	897
36	1.47	6.05	352.9	6.4	345.9	0.1553	56.68	0.08	41
40a	1.99	6.35	231.6	11.6	225.9	0.1832	66.87	0.08	41
40b	1.99	6.35	231.6	11.6	225.9	0.0274	10	9.84	5045
43	1.99	6.35	277.4	10.8	271.2	0.093	33.95	0.08	41
64	2.98	7.77	231.6	15.2	225.6	0.0333	12.15	0.08	41
70	2.99	7.78	323.7	12.7	310.2	0.0481	17.56	0.08	41
89	3.98	8.98	247.5	18.1	253	0.0061	2.23	0.08	41
102	4.48	9.52	276.2	17.8	277.3	0.0024	0.88	0.08	41

Table D.4: **Adjusted weight factors for the wave conditions of De Vries (2007) based on the seasonal distribution over the year.** Probabilities of the wave schematization for each season are distributed based on the wave climate from Argoss (2020) where summer and winter are as defined previously.

Hs [m]		Probability of occurrence		
lower	upper	Year	Summer	Winter
0	1	0.47539	0.33086	0.14453
1	2	0.36994	0.20461	0.16533
2	3	0.12284	0.04252	0.08032
3	4	0.02769	0.00669	0.02100
4	5	0.00397	0.00075	0.00322
5	6	0.00017	0.00000	0.00017
6	7	0.00000	0.00000	0.00000

D.4. Morphological Factor implementation

D.4.1. Constant MorFac

A sensitivity analysis of the model to varying the value of a constant MorFac is performed by simulating 20 days of morphological time and using MorFac values of 1, 5 and 30. The test was performed for the model with the extended domain towards the Haringvliet and allowing the tide to enter the estuary again (scenario R1) with the complete schematization of the forcing conditions. The final bed level changes for each run are shown in [Figure D.6](#). Taking the MF = 1 as the reference case, the lower

plots in the figure show the difference in results between the reference run and the runs for $MF = 5$ and $MF = 30$, left and right respectively.

The patterns of the bed level changes on the three simulations are extremely similar. With an open

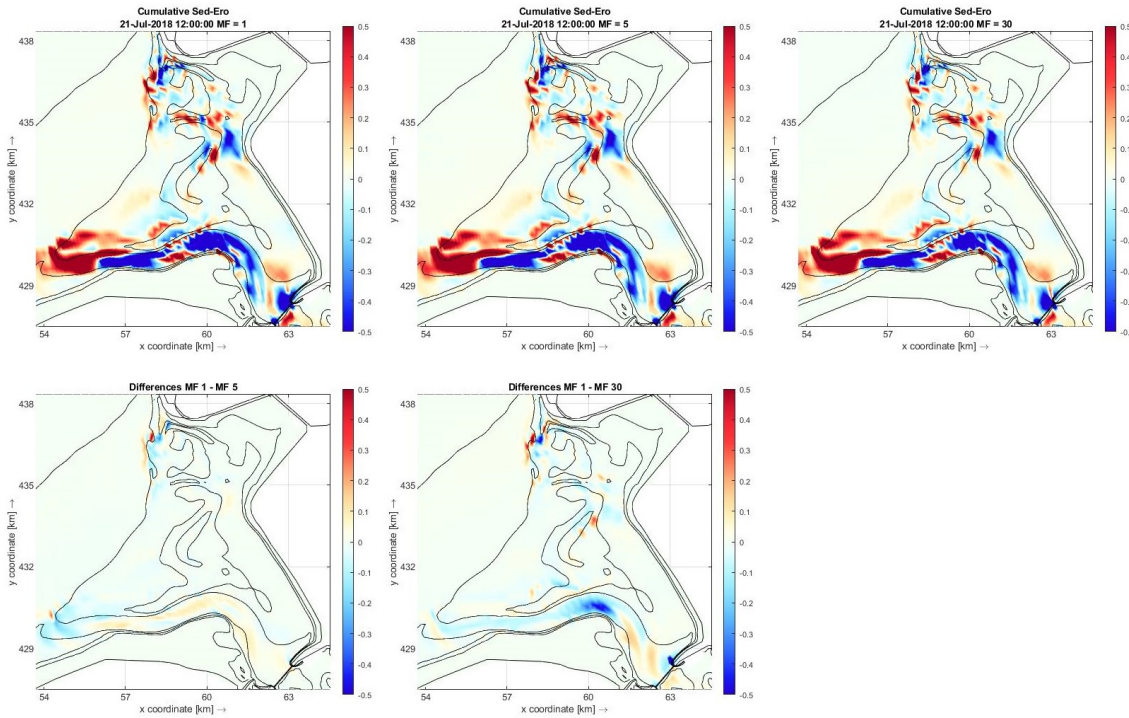


Figure D.6: **Sensitivity of a constant MorFac in the model with an open estuary (R1 scenario).** Simulations of 20 days morphological time are run to assess the MorFac influence in the bed level changes. The reference case is with $MF = 1$ presented in the first top plot. $MF = 5$ is shown in the middle top plot and $MF = 30$ in the left top plot. General patterns are similar for the 3 runs with more noticeable differences for the $MF = 30$ run specially in the Slijkgat channel. Bottom plots show differences for $MF = 5$ and $MF = 30$ with the reference case. The former show differences of an order of magnitude lower while the latter has important differences in large erosion areas just outside and east of the dam and at the Slijkgat channel bend surrounding the Kwade Hoek.

The three models predict erosion along the Slijkgat channel due to an increased flow volume through the Haringvliet Dam. Deposition is observed to the north-east and greater to the north of Kwade Hoek, at the locations reported by De Groen (2014) as the critical dredging areas along the Slijkgat. Also consistent with the real reported behavior of the system, sedimentation is shown at the outflow of the Slijkgat, where it meets with larger depths and current velocities decrease.

With a first general assessment only a slightly different pattern is appreciated at the outflow of the Hindergat channel, to the north of the ETD next to the Slufter coast. From these results it is also observed that the model is predicting erosion along the other channels and some more at the delta front while sedimentation patterns are presented in the sheltered side and at the ends of the channels in a greater extent. This can be explained as mentioned by Colina Alonso (Colina Alonso 2018), as an underestimation of sediment transport by the model due to asymmetric waves. Instead, residual transports and bed level changes appear to be mainly the result of current patterns along channels.

The differences in results shown in the lower plots are many order of magnitudes lower than the bed level changes for both cases, lower error for the run with $MF = 5$. Both runs show a slight overestimation of sedimentation patterns at the end of the Slijkgat channel and the Hindergat channel. However, the erosion patterns where the Slijkgat surround Kwade Hoek is underestimated by the $MF = 5$ run and overestimated by the $MF = 30$ run. Similar behavior is observed at the erosion pit formed to the north-east just outside of the Haringvliet Dam. This is an indication of the violation of the linearity assumption and has to be taken into account for the final long-term simulation. Especially for the R2 scenario, as the presence of Delta21 will most probably trigger big morphological changes at

the beginning of the simulation that might be unrealistically enhanced by large MorFac's.

To assess this further, a comparison of the bed level evolution at the detected locations is made for the three runs of constant MorFac's. Figure D.7 shows the comparison for this and two additional locations where sedimentation-erosion patterns seem to be consistent for the three cases.

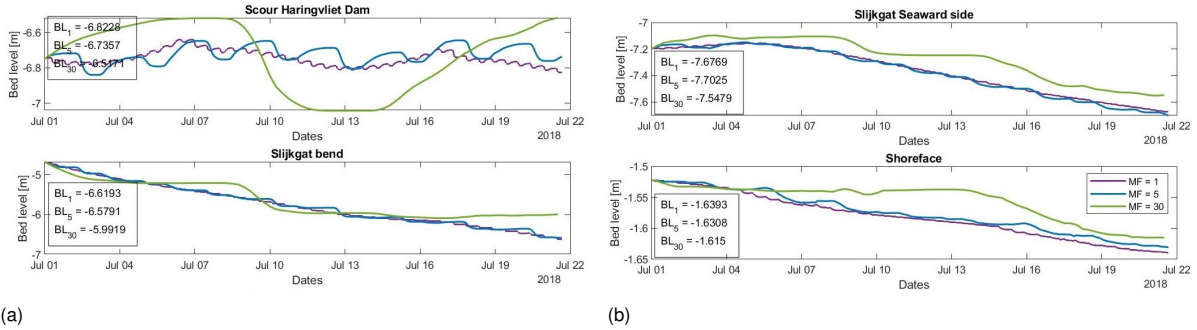


Figure D.7: **Bed level evolution at specific grid cells in the model domain.** Comparison is made of the model results for the applied constant values of the morphological acceleration factor 1, 5 and 30. The locations analysed are those that showed large differences with the reference case (MF= 1) and are shown in (a) the two left plots: Scour Haringvliet Dam and Slijkgtat bend; and (b) the two right plots: random locations in the model that does not show large discrepancies in the map of Figure D.6

Large discrepancies are observed for the location of the scour hole developed just outside the Haringvliet Dam, in the order of 30 cm for minimal bed level change (7 cm). This irregularity is probably due to accelerated currents in this area due to the contraction of the cross-section at the location of the Dam. At the erosion area located in the Slijkgtat bend, differences are in the order of 60 cm for a bed level change of 1.94 m. At the other plotted locations differences between MF= 1 and MF= 30 are in the order of 10 cm and 2.5 cm for a bed level change of 50 cm and 12 cm respectively. This shows that the implementation of a MorFac can produce important errors in areas that present large mismatches between the prevailing hydrodynamics and the present morphology. For the larger MorFac value the model is actually underestimating the erosion in general, and only produces instabilities at the specific location at the corner of the Haringvliet Dam. In contrast, MF= 5 results show consistency and a smaller error.

From the results it is concluded that both MorFac's provide an acceptable prediction for the bed level changes, the error introduced is out-weighted by the simulation time reduction (reduction of 70% of the computation time). However, since the long-term final simulations will be performed by a variable MorFac to account for the variability of the imposed forcing conditions a sensitivity analysis of that approach needs to be performed as well. The adopted approach is similar to that followed by Moerman (2011) and Stark (2012).

D.4.2. Variable MorFac

A wave schematization for 3 years of morphological time simulation is derived with the procedure described previously for a variable $MF < 30$ and is shown in Table 5.6. The table shows the morphological factors and tides for MF= 30 for 3 years wave climate. The climate is representative of 99.74% of the year. For 3 years evolution and $MF < 50$ a total of 47 morphological tides are necessary with an average MorFac of 36.69, meaning the total hydrodynamic simulation is scaled up 36.69 times. For $MF < 30$ a total of 75 morphological tides are necessary and an average MorFac of 23.77 is obtained.

D.4.3. Validation periods

In the first period, a sensitivity of the variable MF is also performed, applying a variable $MF < 30$ and $MF < 50$. Comparing the results for both MF's, Figure D.8b presents the cumulative sedimentation-erosion patterns for both cases. Patterns in the southern side of the ETD are similar, but show stronger sedimentation and erosion for the $MF < 30$ run in the most eastward section of the Slijkgtat. The patterns are explained by the concentrated tidal currents along the channel that will produce erosion.

Table D.5: **Wave climate for long-term simulation with 1 year duration.** Each wave condition is assigned a number of morphological tides to be run related to its probability of occurrence and a variable morphological acceleration factor is assigned to each of them. MorFac's lower than 50 and 30 are derived for the test simulations. The total hydrodynamic time in the model is 21 and 30 morphological tides respectively and the climate implemented with this method is representative of 1 year of morphological evolution.

WC	Hs	Tp	Dir	Wind Velocity	Wind Dir	Weight factor	Duration (mor)	MorFac < 50		MorFac < 30	
[-]	[m]	[s]	[degree]	m/s	[degree]	[-]	[days/year]	No. Mor. Tides	MorFac	No. Mor. Tides	MorFac
70	2.99	7.78	323.7	12.7	310.2	0.045652	17	1	32.42505	2	16.21253
40b	1.99	6.35	231.6	11.6	225.9	0.026005	9	1	18.47082	1	18.47082
102	4.48	9.52	276.2	17.8	277.3	0.002278	1	1	1.617882	1	1.617882
89	3.98	8.98	247.5	18.1	253	0.00579	2	1	4.112117	1	4.112117
43	1.99	6.35	277.4	10.8	271.2	0.088266	32	2	31.34646	3	20.89764
8	0.48	4.45	292.9	4.2	240	0.238272	87	4	42.3093	6	28.2062
64	2.98	7.77	231.6	15.2	225.6	0.031605	12	1	22.44811	1	22.44811
40a	1.99	6.35	231.6	11.6	225.9	0.173875	63	3	41.16611	4	30.87458
8	0.48	4.45	292.9	4.2	240	0.238272	87	4	42.3093	6	28.2062
36	1.47	6.05	352.9	6.4	345.9	0.147395	54	3	34.89682	5	20.93809
						0.997409	364	21	27.1102	30	19.19842

When the flow with the transported sediment reaches the end of it, at larger depths and wider cross-sections, the current velocities decrease allowing the material to settle.

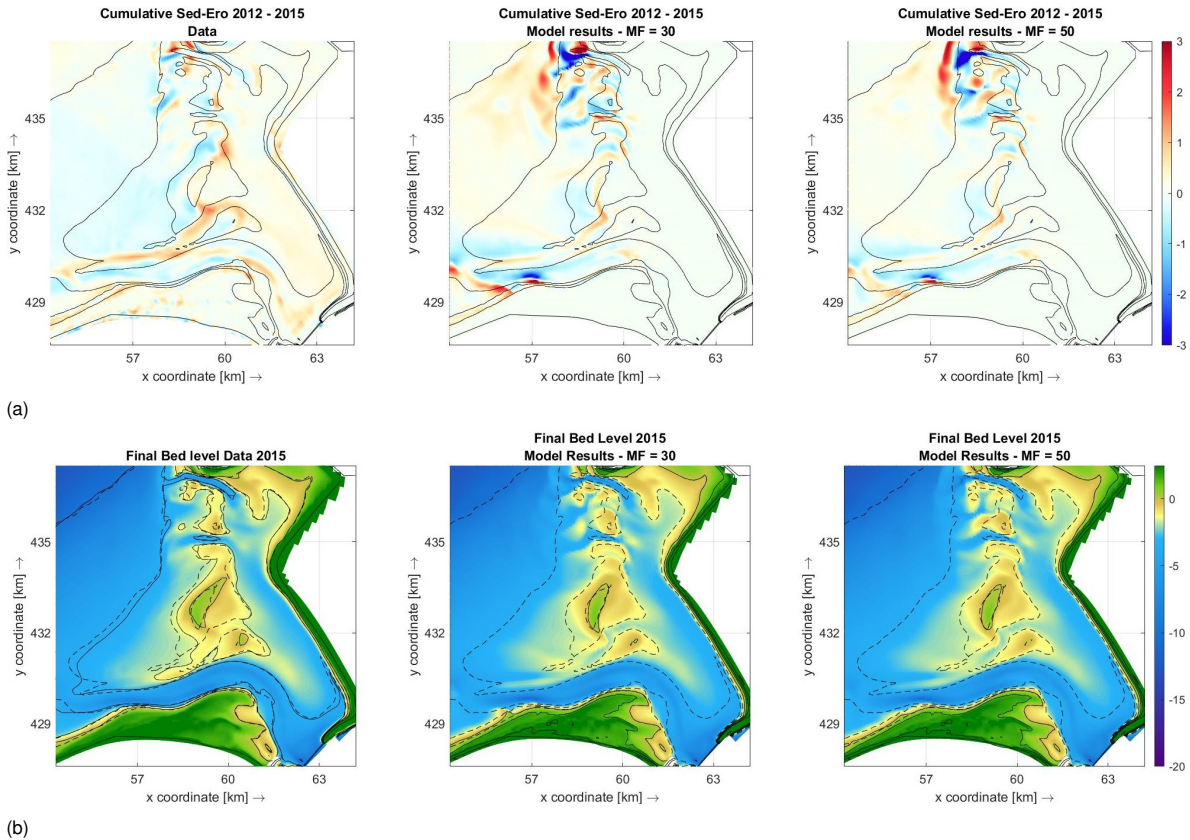


Figure D.8: **Long-term validation results for the period 2012-2015, model with a closed basin (R0), for MorFac values lower than 30 and 50.** (a) Cumulative sedimentation-erosion patterns for the assessed period showing differences for the Vaklodigen data (left), model results with MF < 30 (middle) and model results with MF < 50 (right). (b) Final bed level of the assessed period (2015) from Vaklodigen data (left), model results with MF < 30 (middle) and model results with MF < 50 (right). Dashed lines in (b) are the contours for 2012 and continuous lines are the contours for 2015.

For the 2012-2015 period, north from the Slijkgat, erosion in the Bokkegat is predicted by the model

for both MF values, reopening this channel. This is also observed in [Figure D.8b](#), where the channel feature is already clear. In reality this channel has been siltating due to the reduced tidal currents which has allowed the Hinderplaat and the former Garnalenplaat to merge into one mega-shoal (see [Figure 3.10](#)). Further analysis for this period is elaborated in [Appendix D.4.3](#).

For [Figure D.8](#), results at the north side of the ETD have larger differences. Erosion is visible also along the channels (Hindergat and Kortsluitgeul) and over the shallower parts of the Hinderplaat that are covered during high tide. Sedimentation is then seen at the end of these channels. The sedimentation patterns are very different for each run. At the seaward side of the Hindergat for $MF < 30$ the erosion patterns appear to be forming 2 channels, one turning to the north and one to the south. Each of them develop a lobate feature further offshore where the sediment deposits. Run for $MF < 50$ in contrast does not show this channel formation and the sedimentation feature offshore is more uniform and elongated southwards of the delta front. This could be explained by the counteracting force of the waves in the cross-shore direction which limits the lobate formations pushing material back in the landward direction. However, it was said that the model might be underestimating cross-shore transport due to waves. The reasons for this behavior needs to be further analysed.

The least accurate prediction is shown at the north of the ETD, at the upper shoreface. The patterns of the features as well as the magnitudes deviate considerably. Sedimentation at the end of the channels is indeed present in the data but to a lower extent and covering a smaller area. A large sedimentation area is predicted by the model at the seaward section of the Hindergat while according to the data sedimentation only occurs at the end of the channel and right next to the Slufter coast. The erosion in the shallow areas of the Hinderplaat where water overflows during high tide is not clearly observed in the data.

Additional results: Stage S0

E.1. Hydrodynamic results

This section shows the additional figures and tables to support the analysis made in Chapter 6. This includes results of the tidal regime and tidal prism.

According to Tönis et al. (Tönis et al. 2002), after the damming the flow at the Haringvliet mouth showed a more circulating pattern due to the Haringvliet Dam blocking the flow into the estuary. This behavior is well predicted by the model for the present situation as can be observed in Figure E.2 for 2018 bathymetry. The figures show that:

1. At high tide, currents offshore are in flood direction entering the basin from the south and coming out from the north.
2. Approximately 3 hours later, currents in the basin are in ebb direction while offshore are still in flood direction.
3. At low tide, currents offshore are in ebb direction, entering the basing from the north and leaving from the south of the basin.
4. Approximately 3 hours later, currents in the basin are already in flood direction while offshore are still ebb-directed.

Table E.1: **Tidal prism computation for runs with tidal and discharge boundary conditions.** Values are computed for the ebb and flood cycle for different cross-sections. Scenario **R2** includes the cross-sections at the TL inlet and inside the estuary since the tide travels upstream.

Run - Scenario Volumes	B - R0			B - R1			B - R2		
	Flood	Ebb	Error [%]	Flood	Ebb	Error [%]	Flood	Ebb	Error [%]
Haringvliet Dam	-17.77	-20.82	17.2%	104.34	-142.18	-36.3%	169.99	-205.21	-20.7%
Inner channels (Slijkgat + Rak van Scheelhoek)	-11.36	-25.84	127.4%	105.19	-143.59	-36.5%	173.75	-208.73	-20.1%
Outer channels	5.75	-33.39	-481.0%	66.50	-128.67	-93.5%	14.30	-46.91	-228.0%
Tidal Inlet (Slijkgat)	0.00	0.00	0.0%	0.00	0.00	0.0%	164.28	-164.43	-0.1%
Tidal Lake barrier	0.00	0.00	0.0%	0.00	0.00	0.0%	219.43	-252.35	-15.0%
Haringvliet Bridge	0.00	0.00	0.0%	0.00	0.00	0.0%	46.79	-84.45	-80.5%

Table E.2: **Tidal prism computation for runs with all processes.** Values are computed for the ebb and flood cycle for different cross-sections. Scenario **R2** includes the cross-sections at the TL inlet and inside the estuary since the tide travels upstream.

Run - Scenario Volumes	E - R0			E - R1			E - R2		
	Flood	Ebb	Error [%]	Flood	Ebb	Error [%]	Flood	Ebb	Error [%]
Haringvliet Dam	-64.62	-55.99	13.3%	68.77	-160.22	-133.0%	133.12	-230.01	-72.8%
Inner channels (Slijkgat + Rak van Scheelhoek)	-54.20	-59.90	-10.5%	72.12	-160.17	-122.1%	138.31	-232.80	-68.3%
Outer channels	-25.14	-63.16	-151.3%	48.00	-141.68	-195.2%	13.44	-53.28	-296.3%
Tidal Inlet (Slijkgat)	0.00	0.00	0.0%	0.00	0.00	0.0%	135.53	-179.25	-32.3%
Tidal Lake barrier	0.00	0.00	0.0%	0.00	0.00	0.0%	186.60	-277.58	-48.8%
Haringvliet Bridge	0.00	0.00	0.0%	-87.45	-23.50	126.9%	-0.02	-112.54	-

Table E.3: **Maximum current velocities observed at the locations where concentrated residual currents are identified.** Local velocities at the shown key locations are higher than 1.0 m/s at the Haringvliet Dam and at both locations along the new Slijk gat channel. The former Slijk gat channel still presents important velocity magnitudes. Local velocities next to the structures of the TL are also important with magnitudes higher than 0.5 m/s and at the area between the lakes are always flood directed.

<i>Location</i>	Maximum Flood	Maximum Ebb
	[m/s]	[m/s]
<i>Haringvliet Dam</i>	1.53	-1.47
<i>Slijk gat - East Kwade Hoek</i>	1.24	-1.24
<i>Slijk gat - Bend</i>	1.60	-1.74
<i>Former Slijk gat</i>	0.60	-0.57
<i>Left Abutment (in TL)</i>	0.97	-0.50
<i>Tidal Lake inlet</i>	0.78	-1.56
<i>Between ESL and TL</i>	0.36	0.82

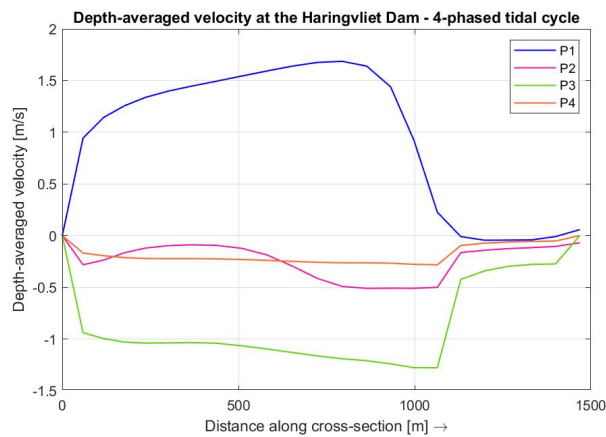


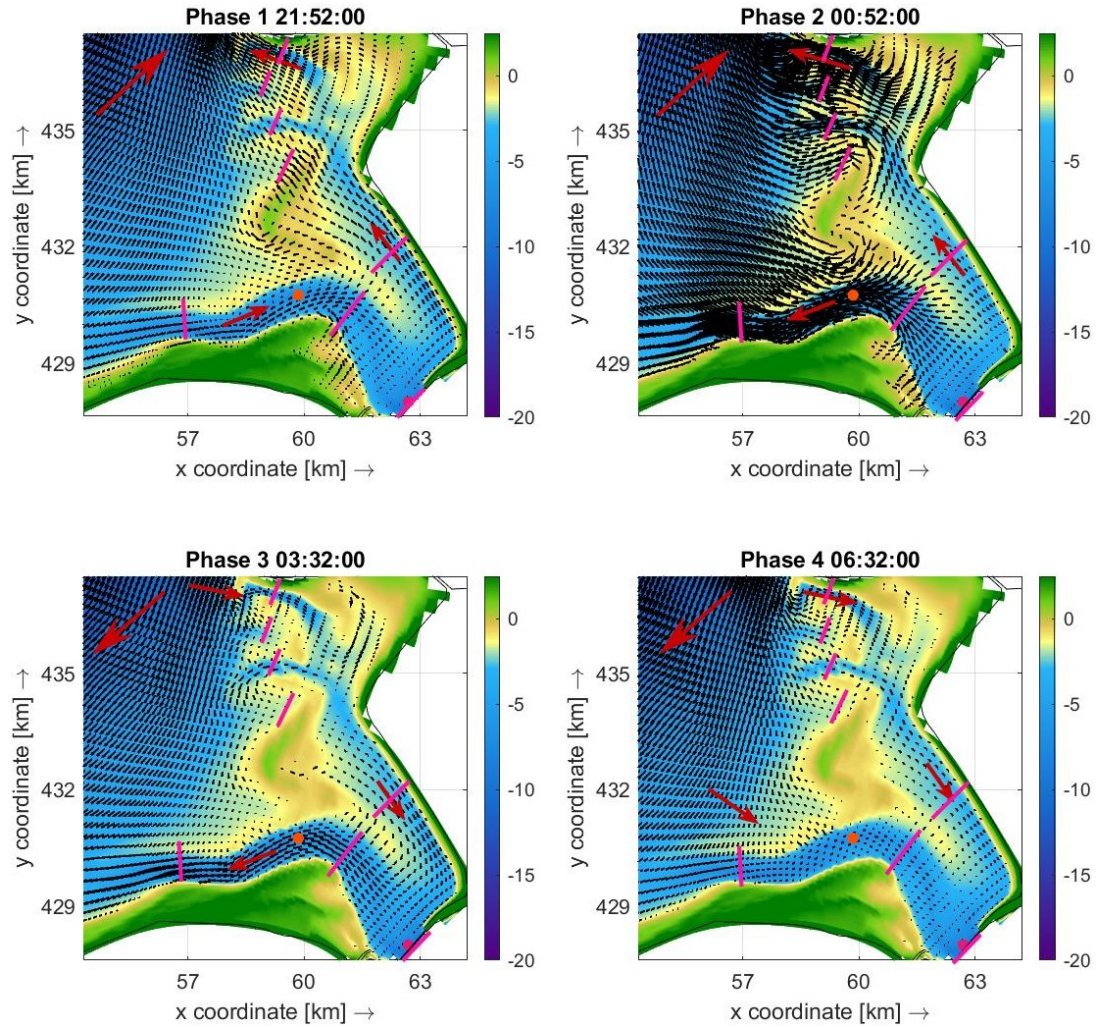
Figure E.1: **Depth-averaged velocity at the Haringvliet Dam cross-section for the 4 phases of the tidal cycle.** During phase P1 and P3 the depth-averaged velocity are maximum, showing large gradients from the edges (close to the structure) to the center of the cross-section.

The cycle can also be seen in [Figure E.4b](#), during Phase 1 velocities in all locations are in flood direction (positive). Phase 2 is close to high water slack in all locations, but happens first offshore and then inside the basin. As expected, currents and water levels offshore and inside the basin are no longer in phase. High water offshore happens before than in the rest of the locations; the plot shows the lag between levels as the tidal wave propagates into the estuary upstream.

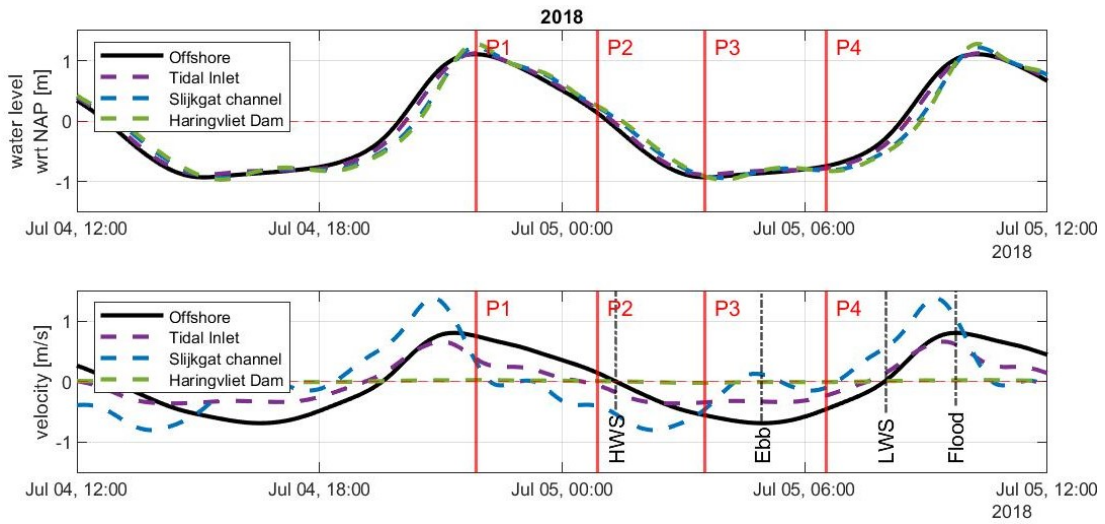
During Phase 3 low water happens offshore and at the location of the TL inlet simultaneously. Further inside the basin water levels are still decreasing and velocities ebb-directed for all cases. In Phase 4, as defined by Tönis et al. (2002), currents are ebb-directed in all locations plotted and water levels are also still decreasing. A slightly different behavior than the one described by Tönis et al. (2002) is observed: flow reversal is predicted more than 3 hours after low water (see also [Figure E.6](#)).

For further details of how the tidal regime changes with the intervention, the reader is referred to the main text.

Finally, [Table E.1](#) and [Table E.2](#) show the results for the tidal prism computations considering the discharge and all processes, respectively. These results showed larger error than the only tide case. However, the results presented in the main text associated to the **A** runs are assumed to be a better measure of the tidal prism volumes as no contribution of the discharge is included.



(a)



(b)

Figure E.2: **Tidal cycle in the Haringvliet mouth showing 4 phases, for the only tide case A with a closed estuary R0 (year 2018).** (a) Tidal cycle in the four phases defined by Tönis et al. (2002). The current patterns show the last four-phased cycle as stated by the author (b) Water level and velocity signals for different locations along the basin, dots in (a): Slikgat channel in orange and Haringvliet dam in pink. Water levels are in phase in the whole basin. Phases of the cycle are defined based on water levels just offshore.

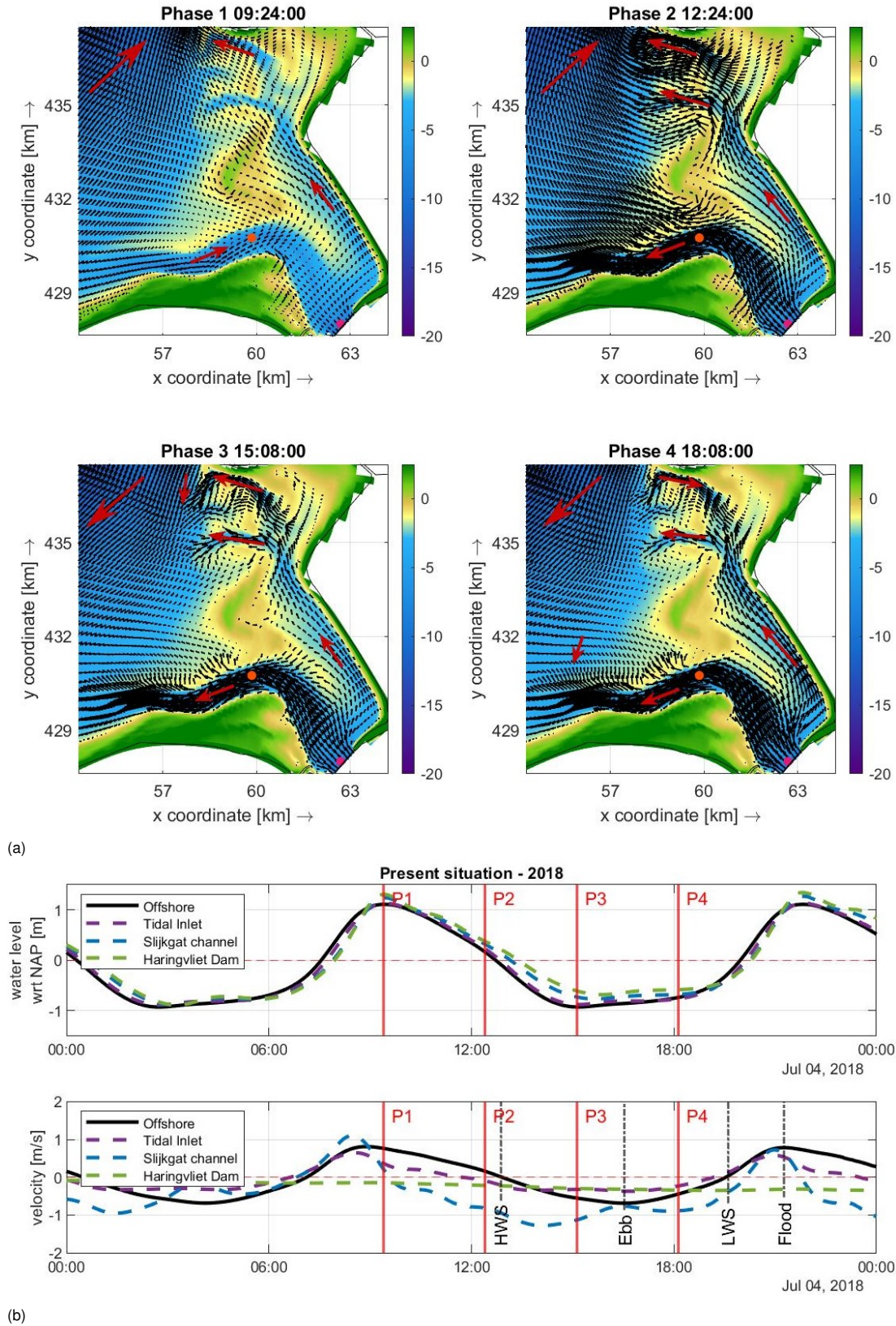
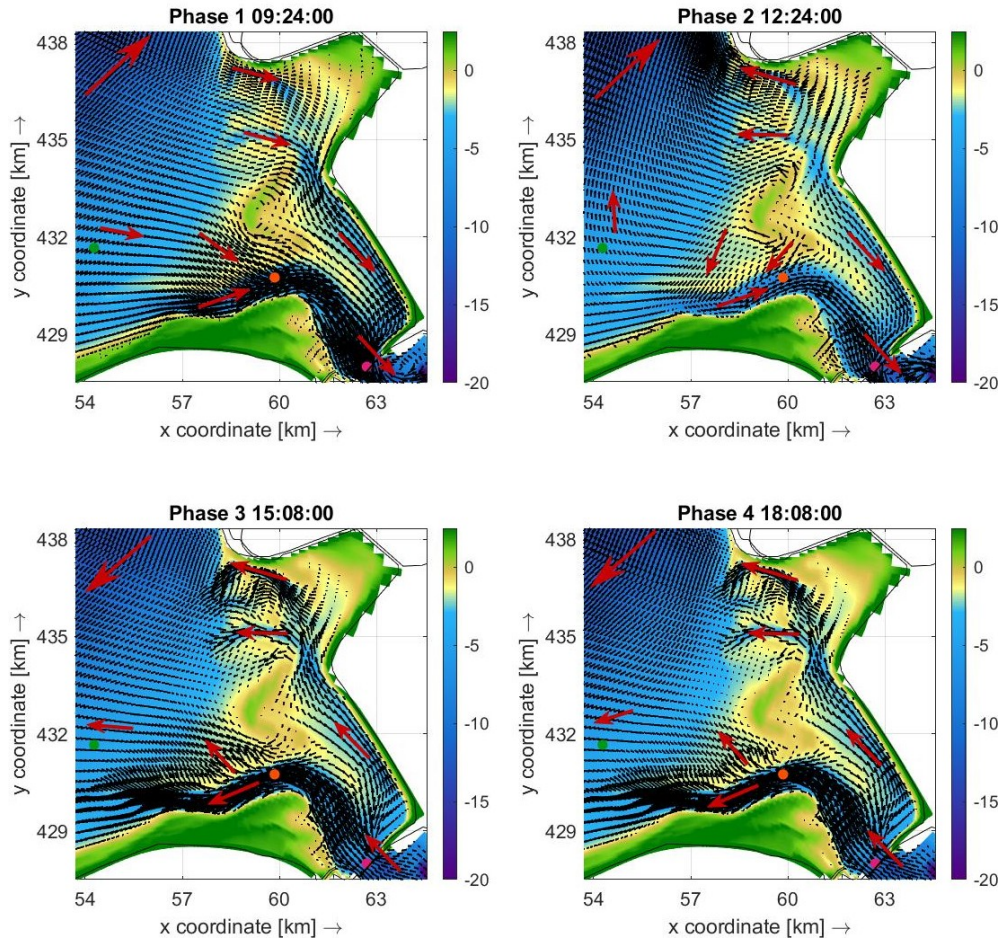
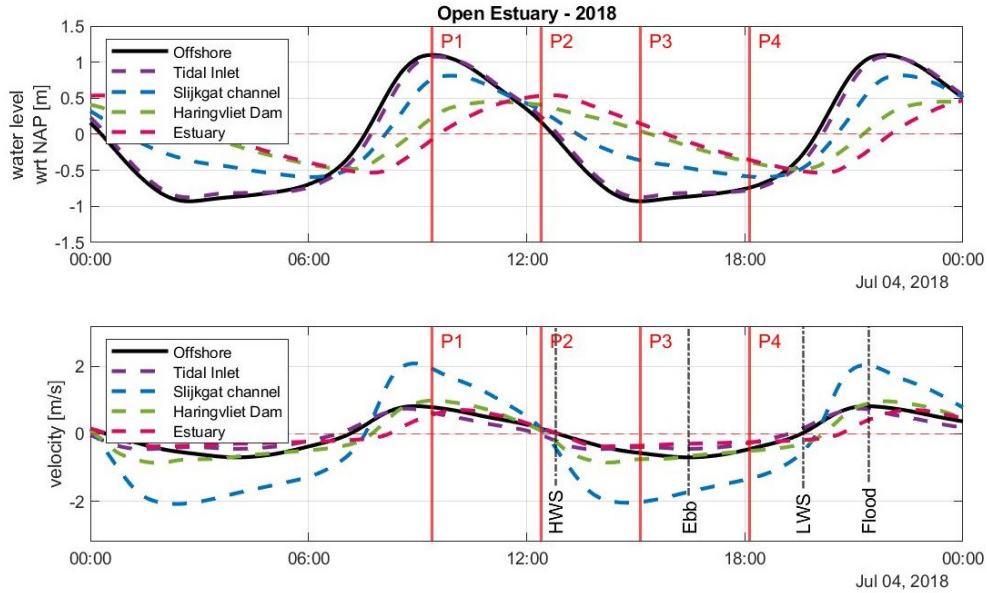


Figure E.3: **Tidal cycle in the Haringvliet mouth showing 4 phases, with all processes E for a closed estuary R0 (year 2018).** (a) Tidal cycle in the four phases defined by Tönis et al. (2002). The current patterns show the lost four-phased cycle as stated by the author (b) Water level and velocity signals for different locations along the basin, dots in (a): Slikgat channel in orange and Haringvliet dam in pink. Water levels are in phase in the whole basin. Phases of the cycle are defined based on water levels just offshore.

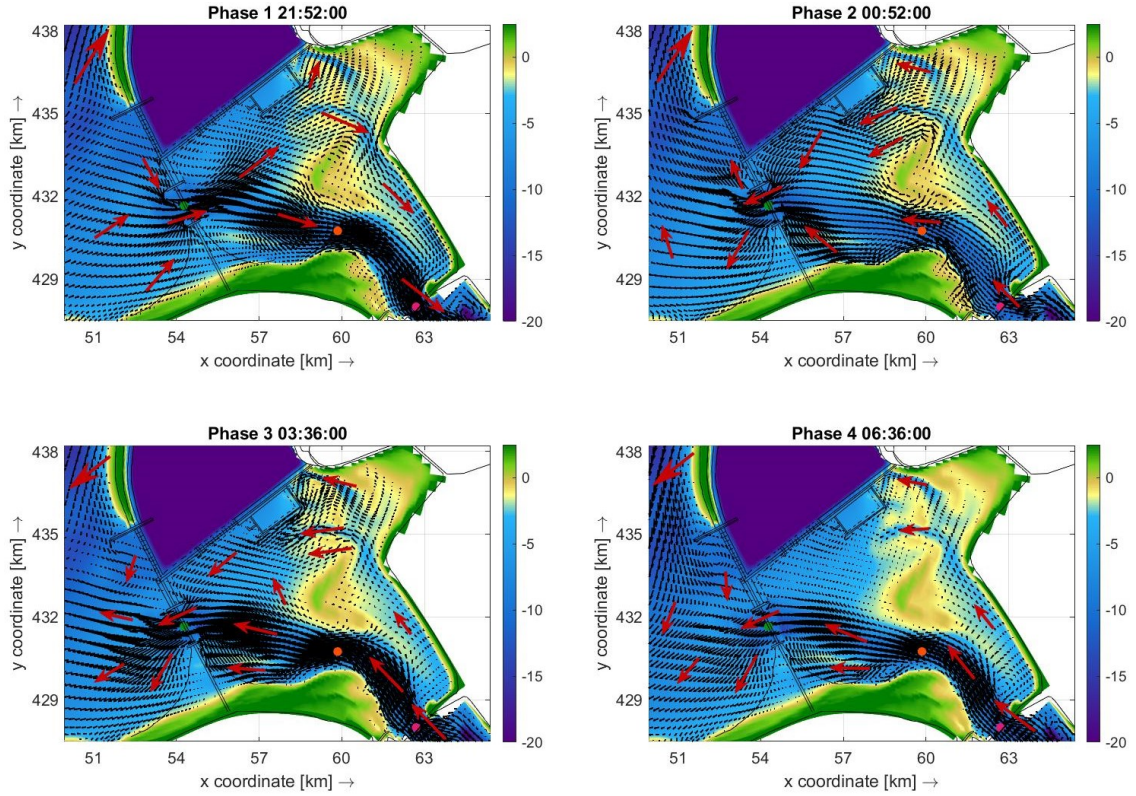


(a)

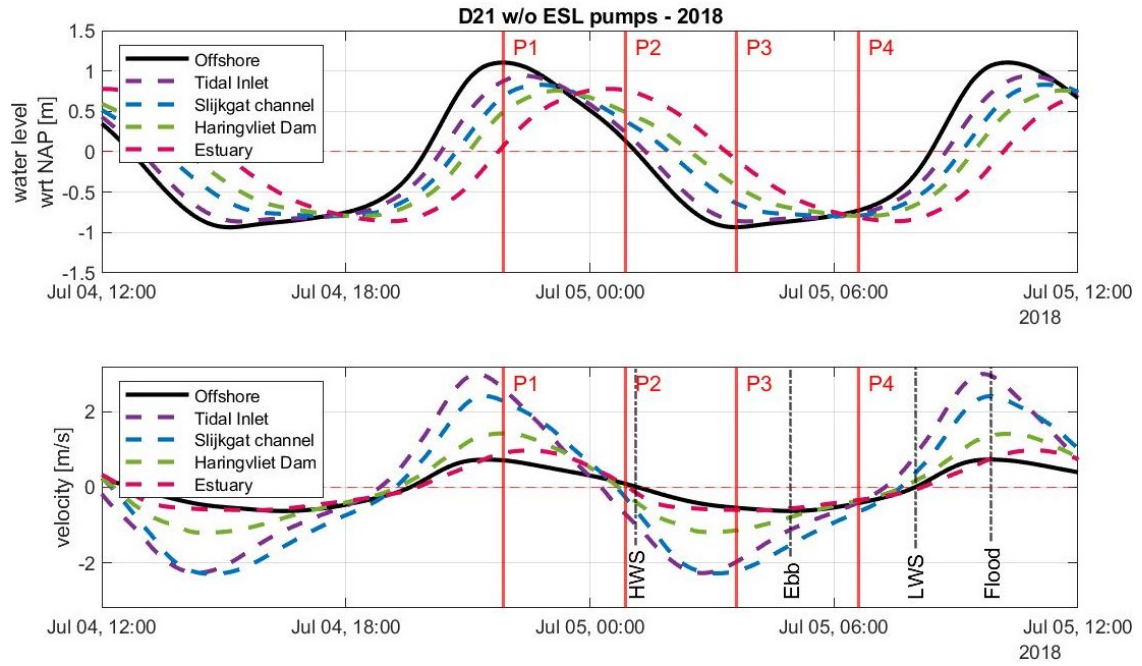


(b)

Figure E.4: **Tidal cycle in the Haringvliet mouth showing 4 phases, for the only tide case A with an open estuary R1.** (a) Tidal cycle in the four phases defined by Tönis et al. (2002). A more defined four phased cycle can be depicted again, similar to the case before the damming. (b) Water level and velocity signals for different locations along the basin, dots in (a): tidal inlet in green, Slijk gat channel in orange and Haringvliet dam in pink. The estuary location is approximately 15 km upstream from the Haringvliet Dam. Water levels are not the same in the whole basin anymore. Phases are defined based on water levels just offshore.



(a)



(b)

Figure E.5: **Tidal cycle in the Haringvliet mouth showing 4 phases, for the only tide case A with an open estuary and D21 (without pumping station) R2.** (a) Tidal cycle in the four phases defined by Tönis et al. (2002). The current patterns show a lost four-phased cycle influenced by the constant river discharge at the sluices and the presence of D21. (b) Water level and velocity signals for different locations along the basin, dots in (a): tidal inlet in green, Slikgat channel in orange and Haringvliet dam in pink. Water levels are not the same in the whole basin anymore. Phases are defined based on water levels just offshore. Velocities at the new tidal inlet and the Slikgat are enhanced by the concentration of water volume in those cross-sections.

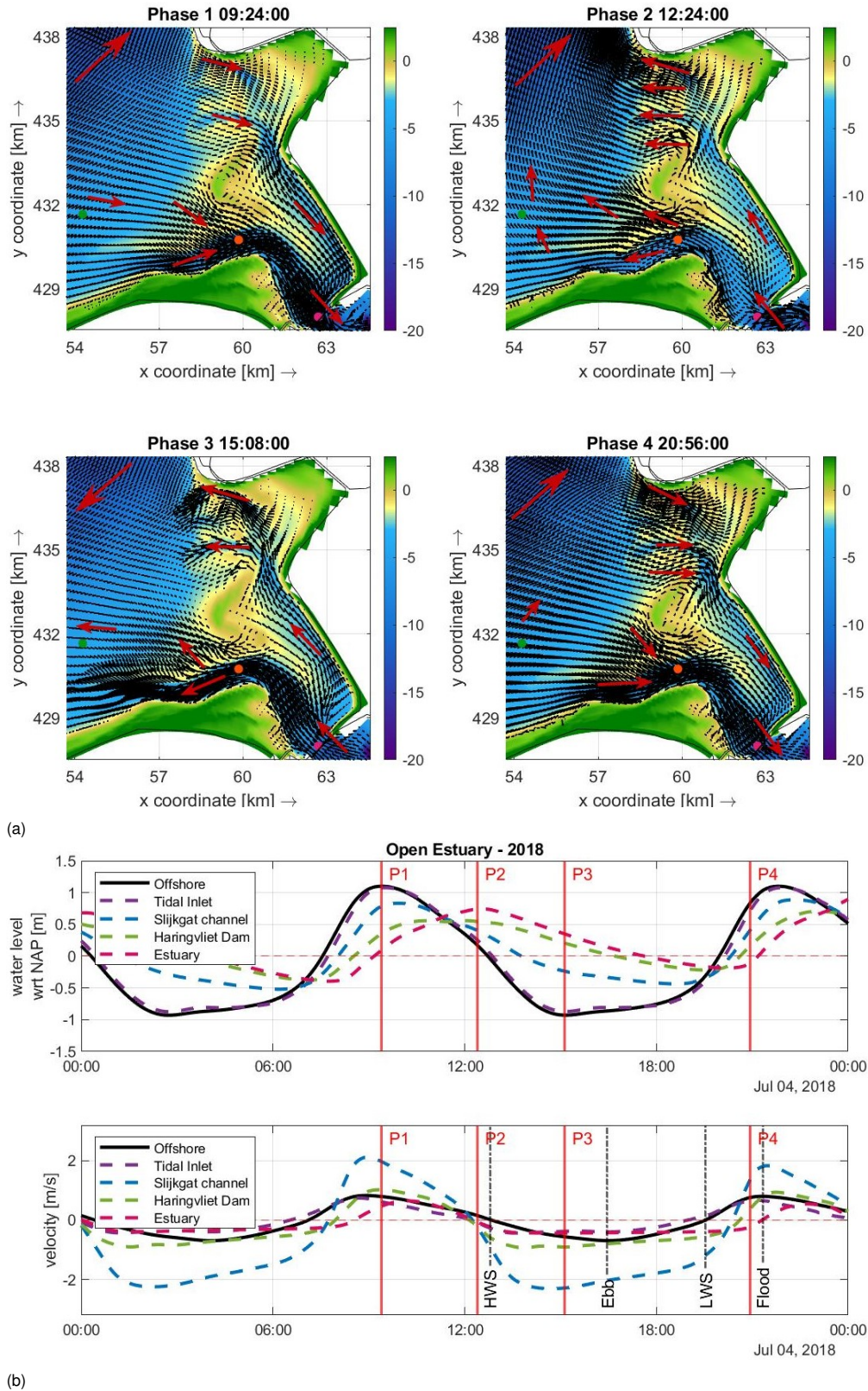


Figure E.6: **Tidal cycle in the Haringvliet mouth showing 4 phases, with all processes E and with an open estuary R1.** (a) Tidal cycle in the four phases defined by Tönis et al. (2002). A more defined four phased cycle can be depicted again, similar to the case before the damming. (b) Water level and velocity signals for different locations along the basin, dots in (a): tidal inlet in green, Slijk gat channel in orange and Haringvliet dam in pink. Water levels are not the same in the whole basin anymore. Phases are defined based on water levels just offshore. Currents entering the estuary are depicted until 5 hours after low water offshore (phase 4).

E.2. Morphological changes

In the process of analysis of the results, the results were investigated starting from the residual currents in the system for a spring-neap cycle of 19 days as described in [subsection 6.2.3](#); these currents will ultimately produce net sediment transports responsible of sedimentation-erosion trends that will produce bed level changes and result in the observed evolution of the system by the model. [subsection E.2.1](#) presents further results from the net total sediment transports in the study area and [section E.2](#) additional results of the bed level evolution.

E.2.1. Sediment transport patterns

In [subsection 6.3.1](#) the net total transport field was presented for the whole study area; [Figure 6.5a](#) shows the vector field such that the vector directions are appreciable, however due to the averaging between grid cells, the resolution is reduced and some information might be lost or not entirely clear. [Figure E.7](#) presents the net total transport vector field for all the model grid-cells; in this case the areas with finer grid overlaps the vectors and is less clear.

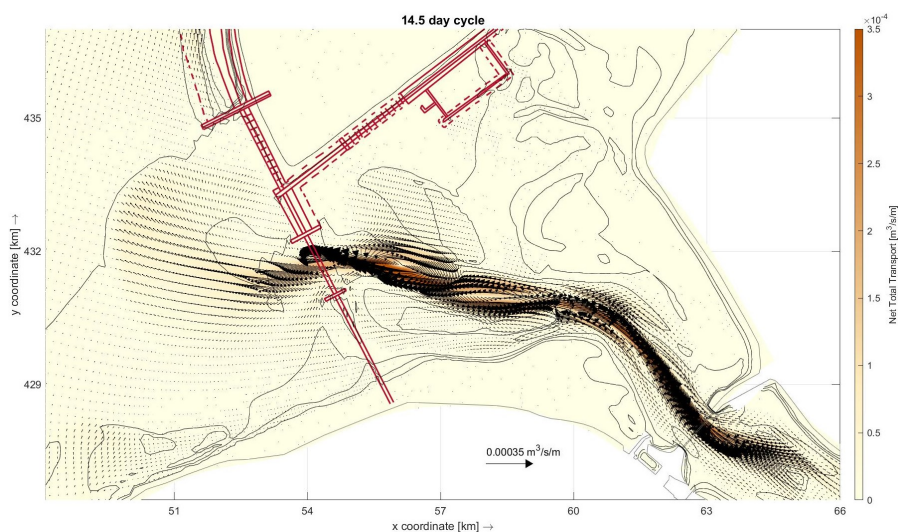


Figure E.7: **Mean Total transport for the 14.5-days spring-neap cycle.** This plot is the same as [Figure 6.5a](#) with a finer resolution for the observation of sediment transport patterns of the lowest magnitudes, marked in [Figure 6.5b](#) with pink arrows.

The net sediment transport described in [subsection 6.3.1](#) are computed for the spring-neap cycle for a selected period as shown in [Figure 6.4b](#) of 19 days, where all forcing are acting on the model, including the discharge from the PPS. However, it is clear from the schematic that the result might be bias by the acting wave conditions during such period, only wave conditions 8, 64, 40a, 8, 36 are considered in such computation. Despite this influenced result, when the net total transport vector field of sand is computed for the entire simulation the sediment transport patterns are the same as those described on [subsection 6.3.1](#), therefore concluding that the behavior described is representative of the whole development of the observed features at the end of the simulation ([Figure E.8](#)).

When the net transport through the barrier is computed, differences are detected depending on the acting wave condition. [Figure E.9](#) show the mean total transport field for one tidal cycle during the action of each wave condition of the schematic wave climate. The observations are as described in [section 7.1](#) which is the base to select the wave conditions to use for further analysis of the sandbank stability outside the TL. The wave conditions that seem to promote the transport of material towards the flood-delta features inside the TL and its consequent deposition are 102, 43, and 8a. Conversely, those that contribute to net ebb-directed sediment transports and the development of an ETD are wave conditions 70, 40b, 102, 89, 64 and 36. Finally, the wave conditions that show large magnitude of along-shore sediment transport along the Goeree coast and that might eventually promote the growth of intertidal areas at the updrift side of the inlet are wc 70, wc 102, and wc 89. These trends are easily observe in the series of plots in [Figure E.9](#).

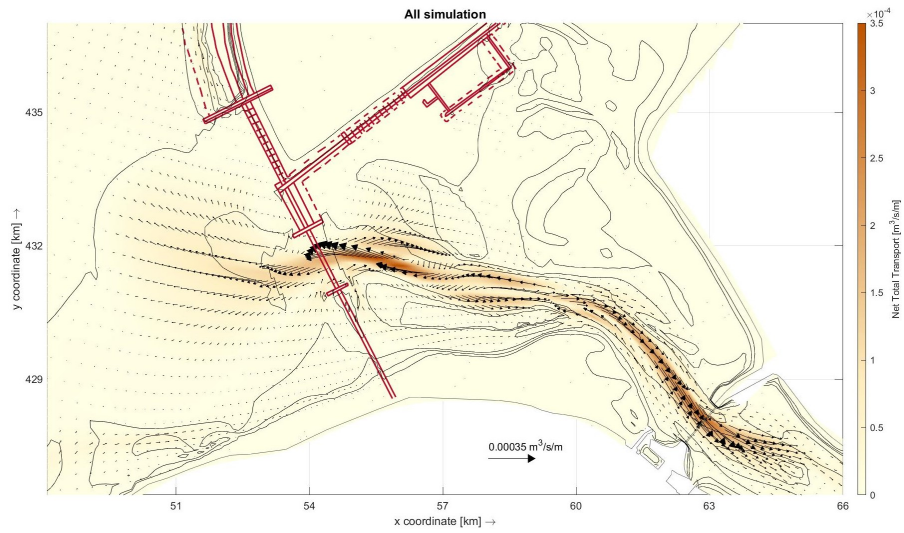
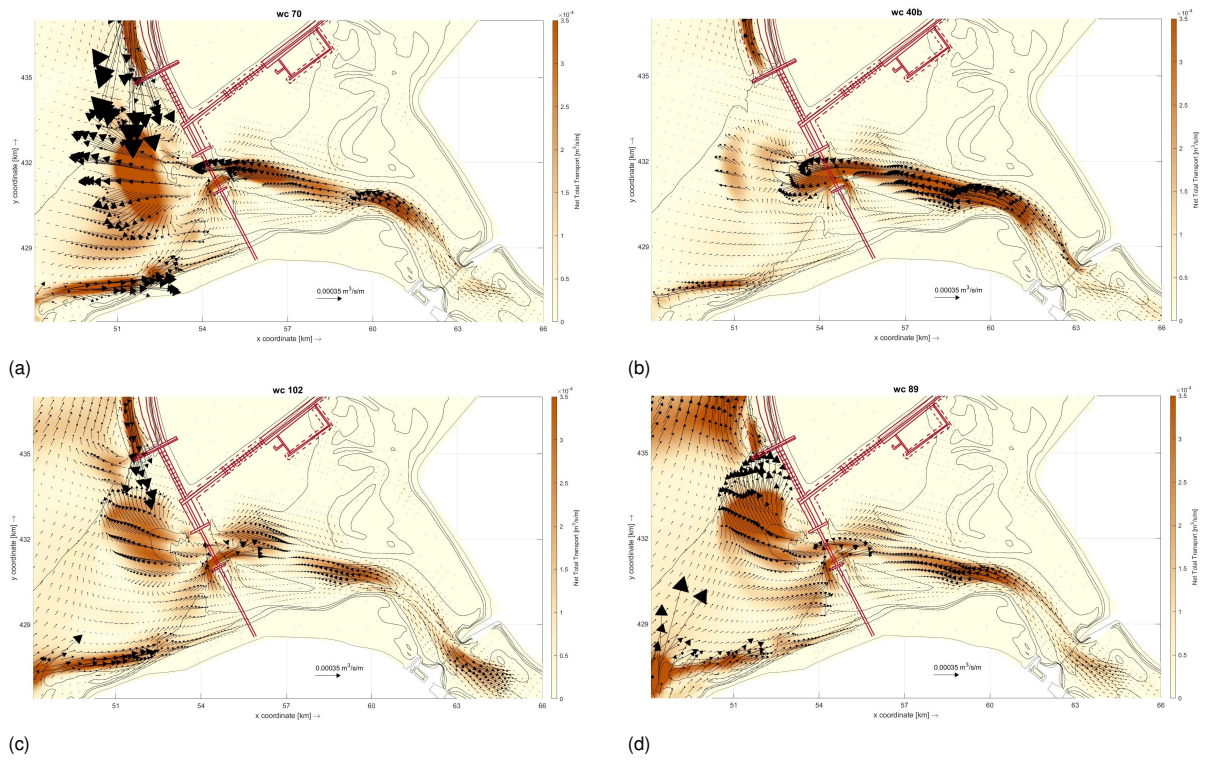


Figure E.8: **Mean Total transport field for the entire simulation period reflecting 3-year evolution morphological time.** Observed trends are the same as the ones described for the spring-neap cycle calculation.



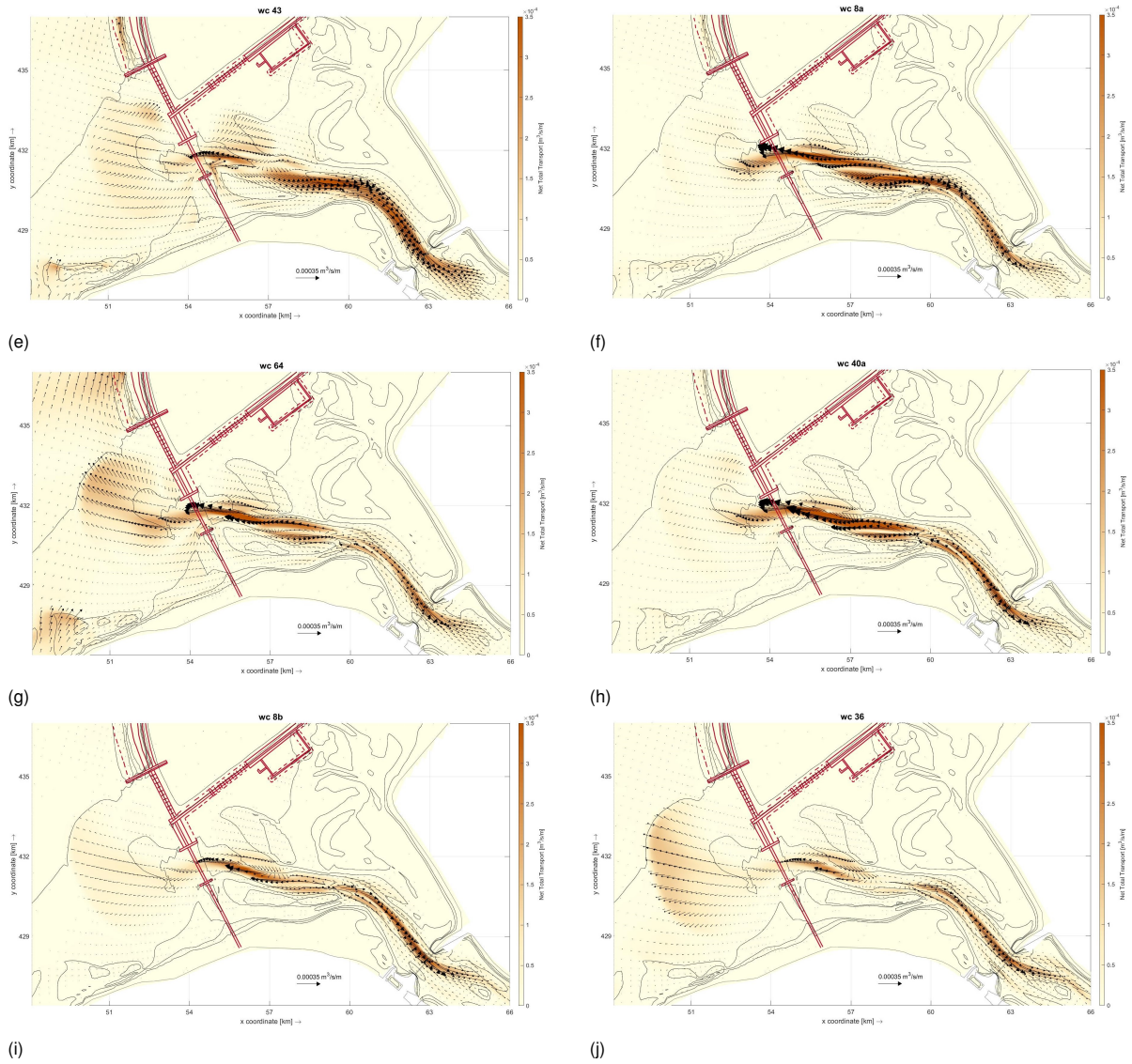


Figure E.9: **Mean total transport computed separately during each acting wave condition.** The presented net total transport vectors are computed for each grid cell during an entire morphological tide of $T = 744$ min time during which each wave condition is acting in the model. The net sediment transport vectors vary in directions offshore and magnitude depending on the acting wave conditions and the influences of other processes (see also [Table 7.1](#)).

E.2.2. Bed Level Changes

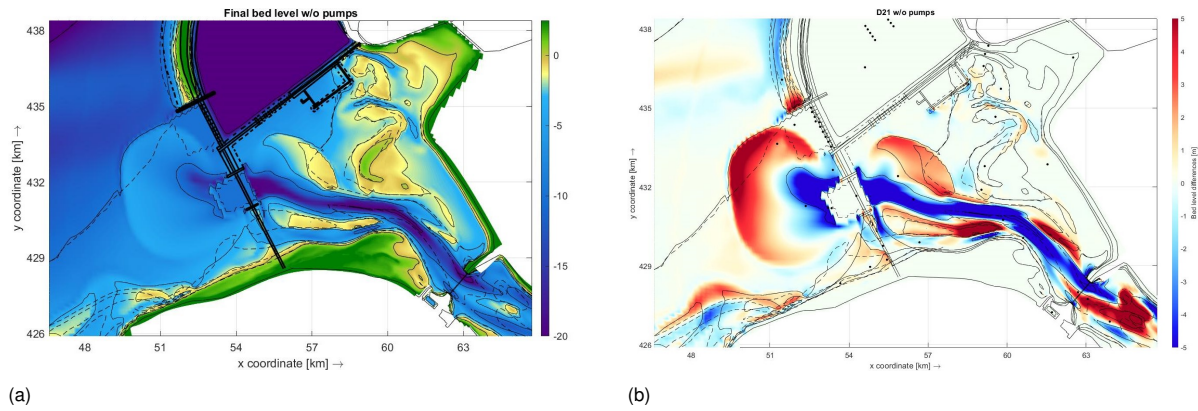


Figure E.10: **Bed level results for a run with out discharge from the PPS.** (a) Final bed level. (b) Bed level changes. The lobate shape of the ETD close to the PPS is smoother than when the PPS operation is included in the model.

Investigating the growth of intertidal areas.

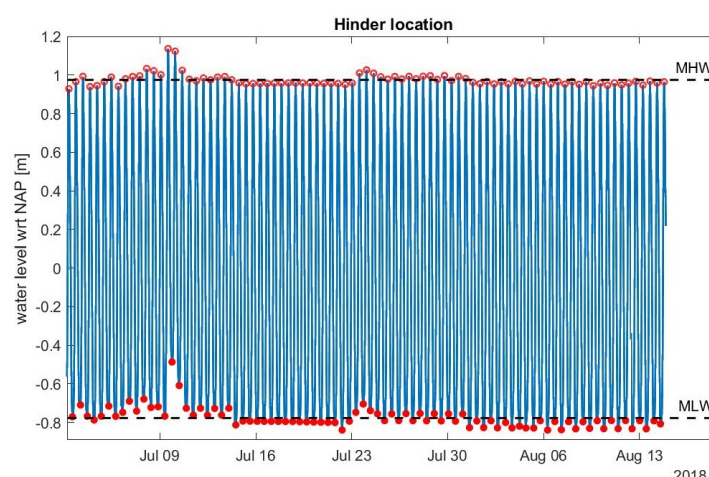


Figure F.1: **Definition of the intertidal zone.** Water levels at a location inside the TL and next to the Hinderplat are plotted to define the Mean Low Water (MLW) and Mean High Water (MHW) to establish the bounds of the intertidal zone in the shallow areas. These levels are assumed to apply to all the evaluated shallows.

F.1. Hypsometry

The hypsometric curves for the total seaward area show very mild differences, as the curves almost overlap. In the right panels, the bar plots show that between **t0-t1**, general accretion occurs above NAP -11.5 m, associated with the changes performed in the bathymetry in the model input. From **t1-t2**, the trends only show accretion between NAP -11.5 and -10.5 m while the remaining contours are eroded. If the net effect is considered, from **t0-t2**, there is accretion above NAP -11.5 m in the order of 4.0%; the highest between NAP -11.5 and -10.0 m. The erosion trends are associated with the scour just seaward of the TL barrier's bed protection, as it is present for bed levels below $\approx$ NAP -12.0 m, the original depth at this area. The accretion (red in Figure F.2) for **t0-t2** comparison can be divided in those below and above the NAP -5.0 m contour. Below this contour, the bed level elevation increase is associated with the development of the ETD since the original elevation around the ETD is between NAP -10.0 and -7.00 m (see Figure 6.8h). Above the NAP -5.0 m contour, the accretion is mostly associated with the bed level elevation increase along the coast of Goeree; the original bed level elevations are around these contours.

In the central and northern areas, a general steepening of the hypsometric curve occurs, with inflection points at NAP -5.5 m and -12.5 m, respectively (**t1-t2** comparison). At the central area, erosion dominates between NAP -6.0 and -10.0 m, corresponding to the scours holes developed seaward of the bed protection. In the northern area, sedimentation dominates between $\approx$ NAP -7.0 and -11.5 m corresponding to the ETD development.

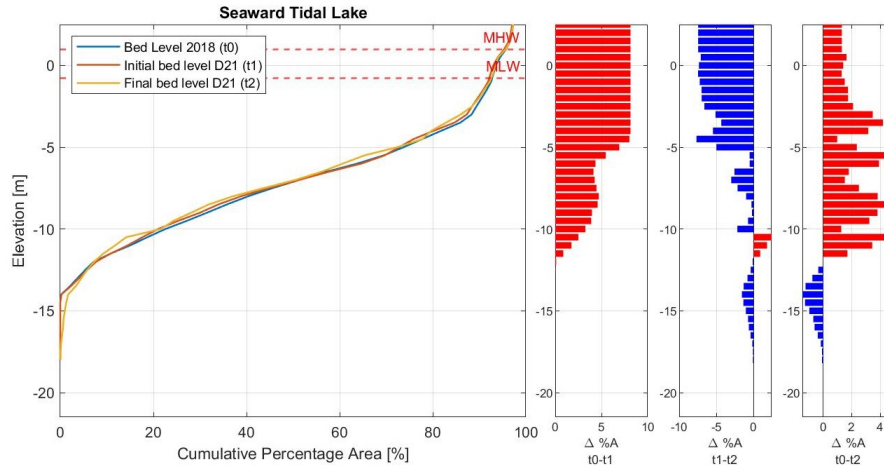


Figure F.2: **Hypsometry of the total seaward side of the Tidal Lake for the original bed level, the initial bathymetry in the model and the resulting bed level elevation after 3-year simulation.** The right panel shows the hypsometric curve for the 3 states analyzed t0, t1, t2; left panels present in bar plots the hypsometry differences between one state and the other every 0.5 m contour. The hypsometric curves in the left are almost overlapping, showing very small changes in the bed level elevation of the area. Between t0-t1 only accretion is shown, t1-t2 evolution is dominated by erosion for all the contour classes and t0-t2 is dominated by accretion. The t0-t2 accretion is associated with the growth of the ETD for deeper contours and to the accretion along Goeree for the shallower contours.

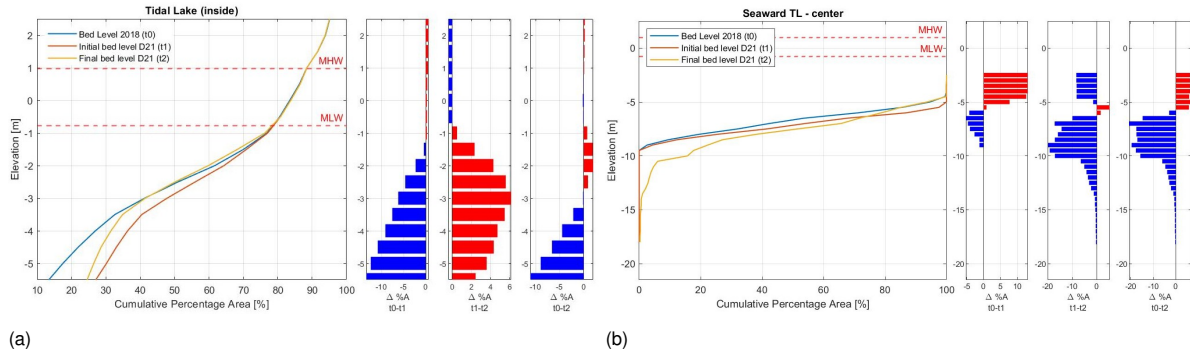


Figure F.3: **Hypsometry of the TL and the center seaward side for the original bed level, the initial bathymetry in the model and the resulting bed level elevation after 3-year simulation.** The right panel shows the hypsometric curve for the 3 states analyzed t0, t1, t2; left panels present in bar plots the hypsometry differences between one state and the other every 0.5 m contour. The TL area shows a the curve between NAP -5.00 and +2.5 m contours for a closer look to the intertidal zone. The seaward side, center, shows bed levels around NAP -5.00 m and lower.

Just upstream of the Haringvliet Dam, large accretion was observed, specifically developing a shoal ≈ 2 km upstream from the dam. The hypsometry clearly shows the bed level elevation increase from **t0** to **t2**, with the highest increase between the contours NAP -8.5 m and -1.5 m. The hypsometric curve is presented in [Figure F.4b](#). The hypsometric curve differences between **t0** and **t1** show some erosion (blue) below NAP -2.5 m in the order of 2% difference. Between **t1** and **t2**, the accretion between -8.5 to -1.5 m is again clearly illustrated.

From the NAP -10.0 m contour evolution ([Figure F.5c](#)), the erosion along the Slijkgt is clear as the contour lines narrow. Seaward of the TL inlet's bed protection, the seaward spread of the contour class is a synonym of the scouring. Further seaward, in the NW direction, the ETD edge feature is depicted as the NAP -10.0 m contour extends offshore into deeper waters. In [Figure 7.4a](#), the NAP -7.0 m contour displays larger changes, showing a complete feature of the ETD. The fact that the ETD develops around -10.0 to -7.0 m depth is confirmed. Inside the TL, the emergence of the Kwade Hoek-Slijkgt shoal starts to be visible. Between the Slijkgt and Rak van Scheelhoek channels, the NAP -7.0 m contour migrates to the west, which is representative of the accretion between both channels, narrowing the main channel.

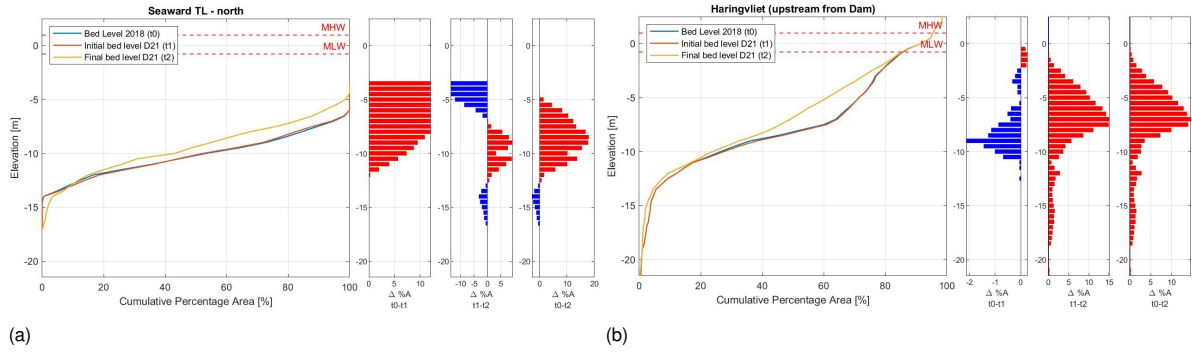


Figure F.4: **Hypsometry of the TL and the center seaward side for the original bed level, the initial bathymetry in the model and the resulting bed level elevation after 3-year simulation.** The right panel shows the hypsometric curve for the 3 states analyzed t0, t1, t2; left panels present in bar plots the hypsometry differences between one state and the other every 0.5 m contour. Considering t1-t2, the northern seaward side, shows bed levels around NAP -5.00 m and lower with an increase between NAP -10.00 and -5.00 m contours associated to the ETD growth. The Haringvliet hypsometry shows a large grow from NAP -1.5 m to -8.5 m contours associated to the shoal in the bathymetry.

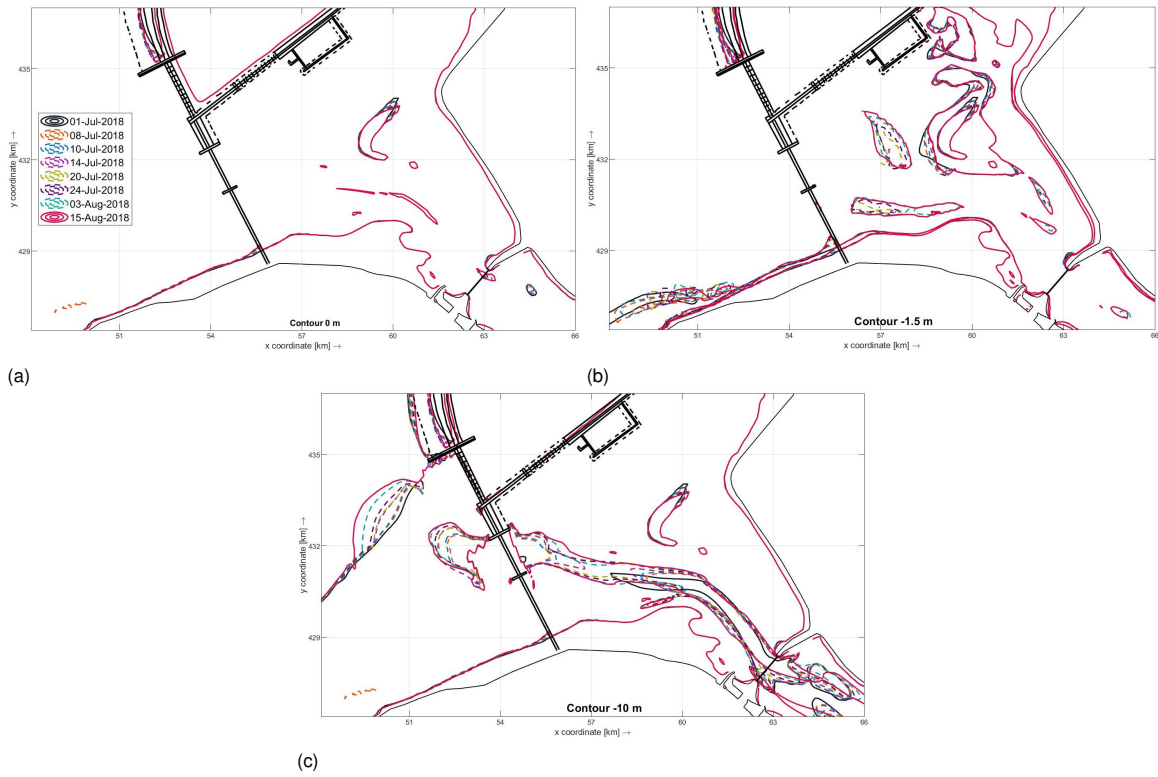


Figure F.5: **Contours evolution along the simulation.** Contours for different time-steps, initial contour is plotted in black-solid lines and the final contour in red-solid lines. Intermediate time-steps are plotted in dashed lines. (a) NAP 0.0 m shows the changes around MSL (b) NAP -10.0 m contours depict most offshore edge evolution of the ETD. (c) NAP -1.5 m contours, shows the merge of the growing shoals inside the TL at this depth.

F.2. Sandbank Stability

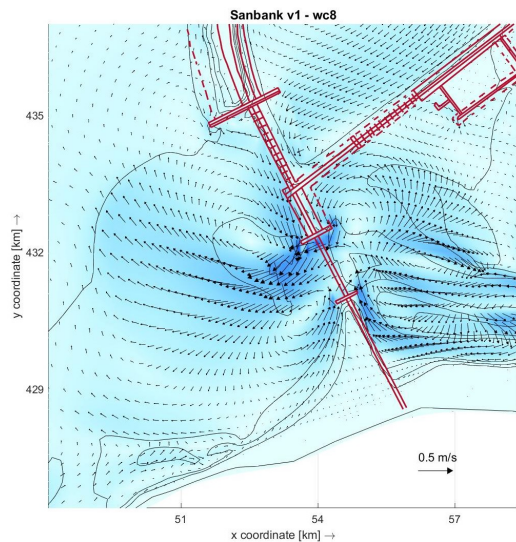
¹**Large:** approximately an order of magnitude larger than $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

Regular: approximately the same order of magnitude as $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

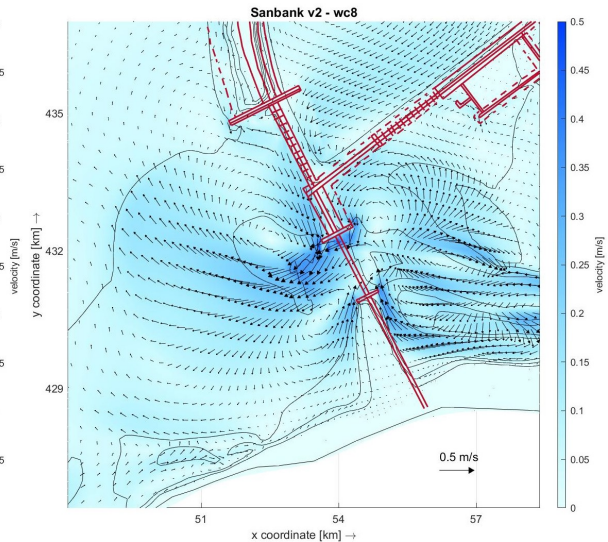
Small: an order of magnitude smaller than $3.5\text{e-}4 \text{ m}^3/\text{s/m}$.

Table F.1: **Development of morphological features as a function of the acting wave condition in the model.** The description elaborates on the net total sediment transport patterns and the bed level change after the action of each wave condition. The bold descriptions point out the wave condition that produces the biggest influence in terms of high sediment transports and higher bed level changes. The wave conditions in bold and italics are the wave conditions selected as those that produce the emergence and maintenance of the shallow areas of interest, namely the FTD and Goeree coast; most of them also produce the growth of the ETD.

Wave Condition				Feature Development ¹			
WC [-]	Hs [m]	Dir [degree]	Weight factor [-]	Flood-tidal delta	Ebb-tidal delta	Updrift accretion	Haringvliet waterway accretion
70	2.99	323.7	0.0457	-Very small flood-directed transports. -Accretion in the order of > 1.0 m.	-Large ebb-directed transports in a W to NW direction, decreasing offshore. -Accretion much larger than 1.0 m.	-Large along-shore transports at Goeree coast, eastward and into the TL. -Accretion in the order of >1.0 m.	-Small flood-directed transports, decreasing upstream. -Accretion in the order of 1.0 m.
40b	1.99	231.6	0.0260	-Small flood-directed transports. -Accretion < 1.0 m.	-Regular ebb-directed transports in a WNW direction, decreasing offshore. Some are flood-directed -Accretion in the order of 1.0 m.	-Along-shore transports at Goeree coast are west-directed. -Observed mild erosion.	-Small flood-directed transport decreasing upstream. -Mild accretion inside the Haringvliet.
102	4.48	276.2	0.0023	-Regular to large flood directed transports. -Very light accretion observed.	-Regular to large ebb-directed transports in a NNW direction, decreasing offshore. -Accretion in the order of 1.0 m to the NNW of the delta.	-Regular to large eastern along-shore transports at Goeree coast. -Very light accretion observed.	-Regular flood-directed transports, decreasing upstream. -Very light accretion observed.
89	3.98	247.5	0.0058	-Regular flood directed transports. -Very light accretion depicted.	-Regular ebb-directed transports in a N direction, decreasing offshore. Also directed towards the PPS. -Accretion in the order of 1.0 m to the N of the delta.	-Regular along-shore transport at Goeree coast to the east. Going inside TL and meeting ebb-transport. Large at Bollen van de Ooster. -Small area with accretion in the order of 1.0 m.	-Regular to small flood-directed transport, decreasing upstream. -Almost no accretion observed.
43	1.99	277.4	0.0883	-Small flood-directed transports. -Large accretion in the order of > 1.0 m.	-Small flood-directed transport. -Large accretion in the order of > 1.0 m.	-Very small along-shore transport towards the east at Goeree coast. -Large accretion in the order of > 1.0 m.	-Regular flood-directed transports, decreasing upstream. -Accretion in the order of 1.0 m.
8a	0.48	292.9	0.2383	-Small to very small flood-directed transports originated inside TL. -Accretion in the order of 1.0 m at the most landward edge.	-Small ebb-directed transport to the WSW, decreasing offshore. -Accretion in the order of 1.0 m at the most seaward edge and west from the inlet next to bed protection.	-Almost no along-shore transport detected at Goeree coast. -No accretion or erosion detected.	-Small flood-directed transports, decreasing upstream. -Accretion in the order of 1.0 m.
64	2.98	231.6	0.0316	-Small flood-directed transports originated inside TL. -Almost no accretion observed.	-Regular ebb-directed transports in a W-NW direction, decreasing offshore. -Accretion in the order of > 1.0 m to the N seaward edge of the delta and < 1.0 m to the west of the delta.	-Small along-shore transport towards the east at Goeree coast. Directed towards the TL inlet. -Accretion in the order of < 1.0 m.	-Regular flood-directed transports, decreasing upstream. -Accretion in the order of <1.0 m.
40a	1.99	231.6	0.1739	-Very small flood-directed transport originated inside TL. -Accretion > 1.0 m at the most landward edge.	-Small ebb-directed transports in a W direction and towards the PPS, decreasing offshore. -Accretion in the order of > 1.0 m to the N seaward edge of the delta and in front of the PPS. <1.0 m to the WSW of the delta.	-Almost no along-shore transport detected at Goeree coast. -Small area with accretion in the order of > 1.0 m.	-Regular flood-directed transports, decreasing upstream. -Accretion in the order of >1.0 m.
8b	0.48	292.9	0.2383	-Very small flood-directed transports originated inside TL. -Almost no accretion depicted.	-Small ebb-directed transport to the WSW-WNW, decreasing offshore. -Accretion in the order of 1.0 m at the most seaward edge in a W direction.	-Almost no along-shore transport detected at Goeree coast. -No accretion or erosion detected.	-Regular flood-directed transports, decreasing upstream. -Accretion in the order of <1.0 m.
36	1.47	352.9	0.1474	-Very small flood-directed transports originated inside TL. -Accretion > 1.0 m at the most landward edge.	-Small ebb-directed transport to the W, decreasing offshore. -Large accretion much larger than 1.0 m at the most seaward edge in a W direction.	-Almost no along-shore transport detected at Goeree coast. -Very mild accretion observed	-Regular flood-directed transports, decreasing upstream. -Large accretion much larger than 1.0 m.



(a)



(b)

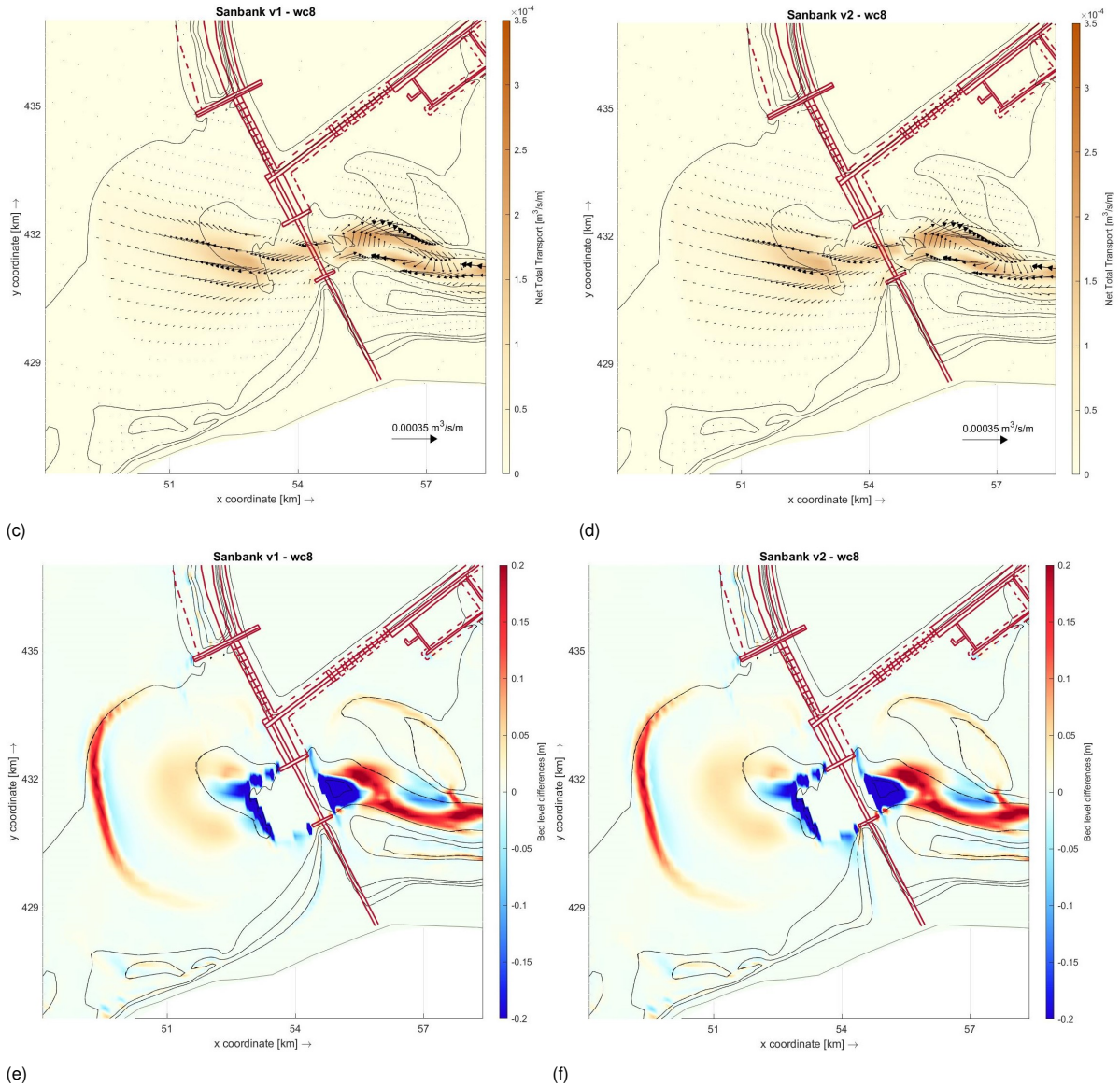


Figure F.6: **Short-term simulation for wc 8 for the response of the proposed sandbanks.** The results are shown for 4 tidal cycles, plots on the left correspond to the sandbank v1 and plots on the right to the sandbank v2. (a)-(b) Residual currents. (c)-(d) Net sediment transports. (e)-(f) Bed level changes. The residual currents over sandbank 2 are slightly larger, no difference is visible for the net sediment transports, but the erosion is larger sandbank v2. General trends are similar to those described by simulation with wc 43.

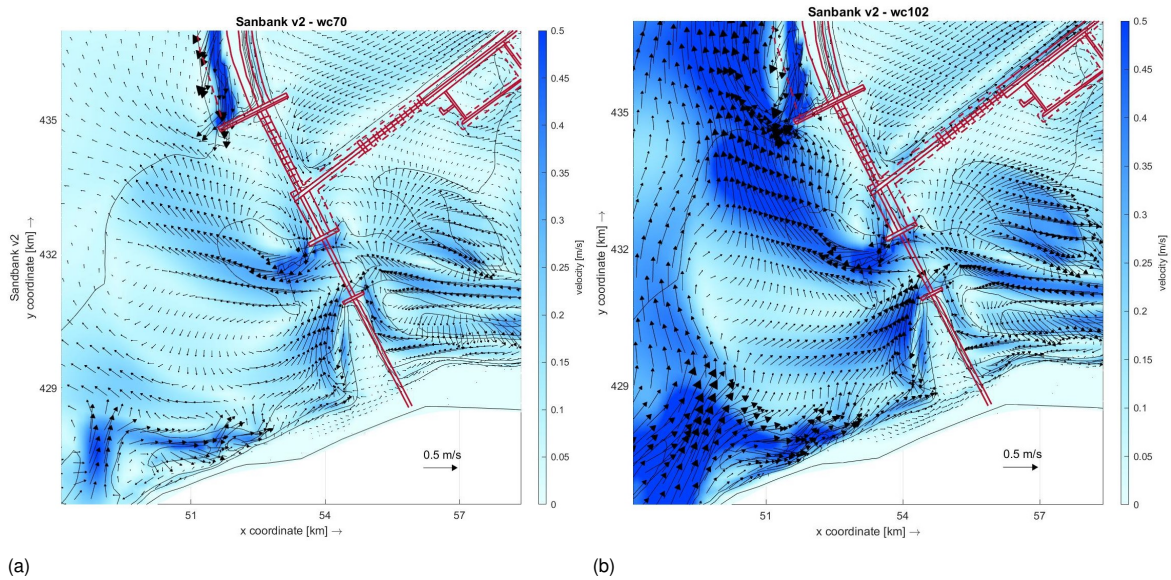
Bed level changes over such period are also presented. The residual currents in [Figure 7.10a](#) and [Figure F.8a](#) show the same patterns inside the TL and over the ETD where they are orientated to the NNW. At the western side of the ETD they are directed to the south and tend to return towards the inlet producing a circulation. Along the sandbanks, currents are east-directed and towards the TL inlet. However, at the shallowest part of the sandbanks currents are west-directed forming a circulation pattern that might produce accretion. The circulation at the north-seaward side of the TL inlet, towards the PPS of the ESL is present as well, as it was observed in [subsection 6.2.3](#). However, the circulation to the south is not present as part of the current is entering the TL through the southern side of the inlet.

The net sediment transports are presented in [Figure 7.10c](#) and [Figure F.8c](#). The sediment transport patterns show the same directions as the currents with no differences for both versions of the sandbank inside the TL. The transport over the ETD is directed to the NNW and increases seawards from the bed protection and decreases again further offshore. Along the sandbanks, transports are mostly directed

to the east towards the TL inlet as the currents. Over the shallowest stretches there are some transport west directed. The magnitudes are clearly larger for sandbank v2, specially once they reach the inlet.

When the bed level changes produced by the net sediment transports are analysed, we observed still important changes inside the TL and over the ETD. [Figure 7.10e](#) and [Figure F.8e](#) present the results of the runs with sandbanks v1 and v2 respectively. The sedimentation-erosion patterns inside the TL and over the ETD are the same for both runs; the main channel is accreting in the section observed in the plots and some sedimentation at the eastward edge of the FTD can be identified. The ETD shows an extension towards the NNW and to the W. In the southern area, along the coast of Goeree and the sandbanks, we can observe material depositing due to the circulation of currents in this area. The circulation decreases the transport capacity of the current around these areas enhancing the deposition. Additionally, important erosion is detected at the northern side of the sandbanks, right next to the TL structure. The erosion is larger and concentrated in the northern tip of the sandbank for the v2 case.

In [Figure 7.10e](#) the accretion along the sandbank shows that this configuration might promote the attraction of more material for the growth of the sandbank. The erosion at the north tip is in the order ≈ 15 cm and is related to the concentration of the flow when approaching the TL during the flood period. The changes for this version of the sandbank are of lower magnitudes and with more constant patterns than in [Figure F.8e](#).



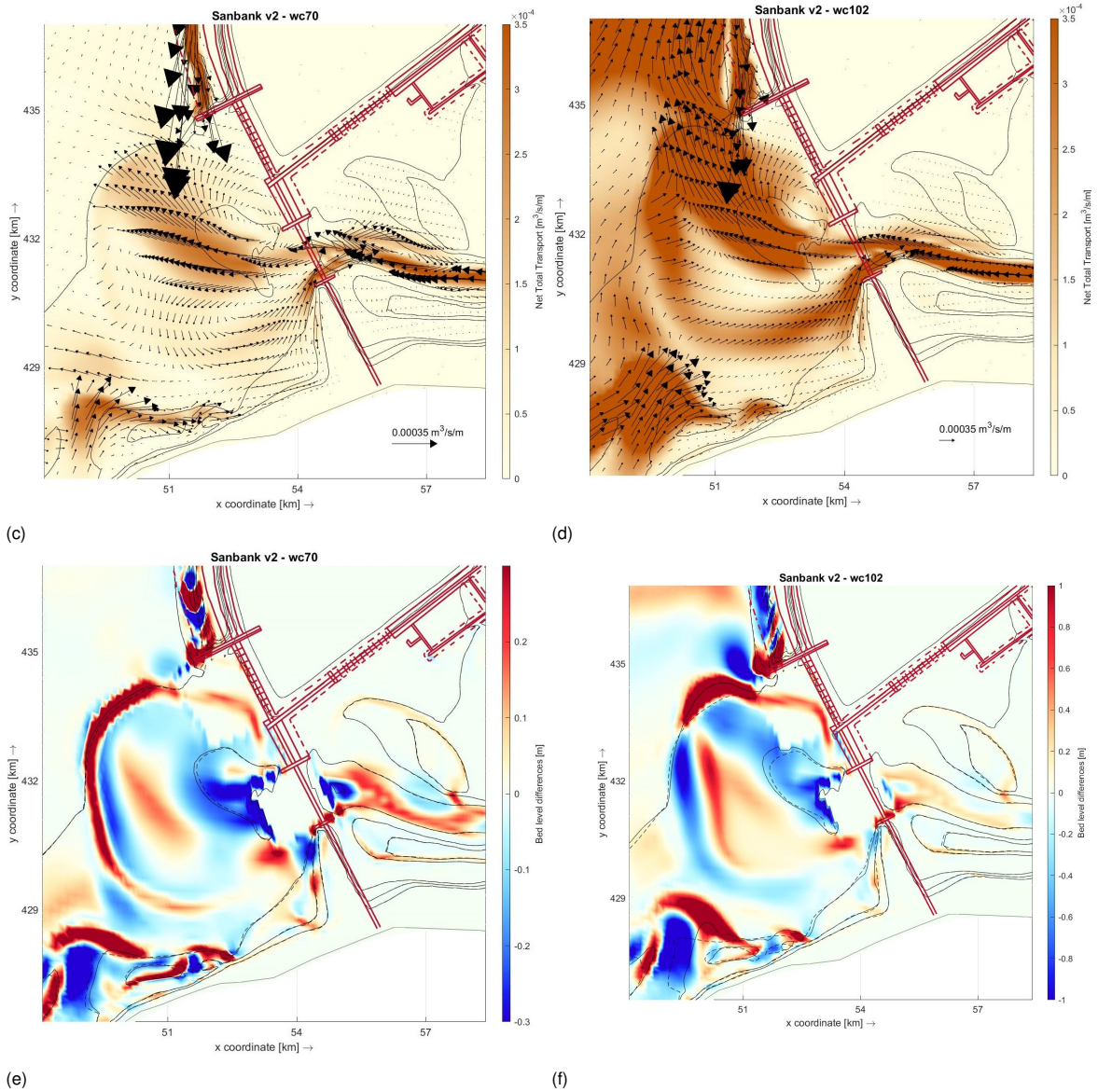


Figure F.8: **Short-term simulations for *wc 70* and *wc 102*, for sandbank v2.** The results are shown for 4 tidal cycles, plots on the left correspond to *wc 70* and plots on the right to *wc 102*. (a)-(b) Residual currents. Patterns inside the TL are similar for both runs with larger magnitudes for *wc 102*. Over the ETD they are orientated to the NNW for *wc 70* and to the N for *wc 102*. Along the sandbank, currents are east-directed and towards the TL inlet. At the shallowest part of the sandbanks, currents are slightly west-directed, forming a circulation. Important currents around the ETD seaward edge occur for *wc 102*. (c)-(d) Net sediment transports. The sediment transport patterns show the same directions as the currents; magnitudes are larger for sandbank *wc 102*. In both cases, an import of material occurs at the southern side of the inlet to the TL. Eastward transports occur over the seaward edge of the ETD for *wc 102*. (e)-(f) Bed level changes. The sedimentation-erosion patterns inside the TL are similar for both runs, with larger sedimentation for *wc 102*. Along the sandbanks, important erosion areas are detected at the northern side of the sandbanks, right next to the structure.

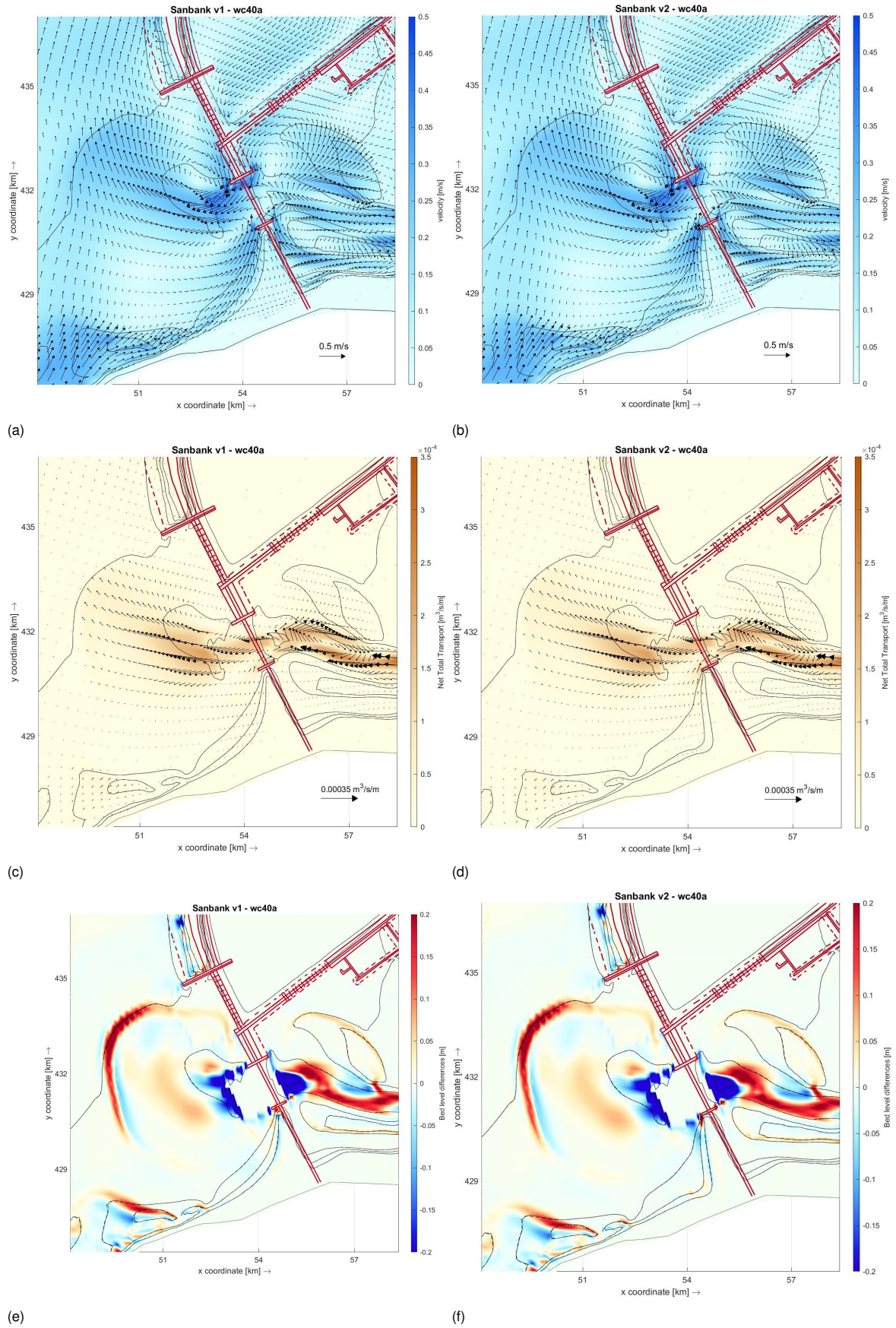


Figure F.7: **Short-term simulation for *wc 40a* for the response of the proposed sandbanks.** The results are shown for 4 tidal cycles, plots on the left correspond to the sandbank v1 and plots on the right to the sandbank v2. (a)-(b) Residual currents. (c)-(d) Net sediment transports. (e)-(f) Bed level changes. The residual currents over sandbank 2 are slightly larger, almost no difference is visible for the net sediment transports, but the erosion is larger sandbank v2. Sandbank v1 shows more sedimentation along its deepest contours. General trends are similar to those described by simulation with *wc 43*.