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Dynamics and pathways of disposed sediments in the Borndiep Basin

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Author(s)
Marcio Boechat Albernaz
Edwin Elias

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Author(s)		
	Marcio Boechat Albernaz Edwin Elias	

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Samenvatting

Het programma *Kennis voor Beheer en Onderhoud Waddenzee* richt zich op het opbouwen van een solide kennisbasis over morfologie en sedimentdynamiek ter ondersteuning van de taken van Rijkswaterstaat op het gebied van waterveiligheid, bereikbaarheid, natuur en waterkwaliteit. Rijkswaterstaat is onder andere verantwoordelijk voor het onderhoud van vaargeulen en streeft naar het minimaliseren van baggerwerk om ecologische impact en kosten te beperken. Een belangrijk aandachtspunt is het optimaliseren van verspreidingsstrategieën van gebaggerd materiaal, zodat snelle opvulling van de vaargeul door recirculatie en additionele vertroebeling worden beperkt.

Het voornaamste doel van deze studie is te beoordelen of en hoe numerieke modellen en innovatieve technieken, zoals *Delft3D-FM* in combinatie met *SedTRAILS,* kunnen worden gebruikt om de locatie en effectiviteit van verspreidingslocaties evalueren, en uiteindelijk bijdragen aan een beter onderbouwd en duurzamer sedimentbeheer. In deze studie is het getijdebekken van Ameland gekozen als testcase.

Deze studie onderzoekt de sedimenttransportpaden die samenhangen met twee verspreidingslocaties: Zuiderspruit en Scheepsgat. De analyse is uitgevoerd met behulp van hydrodynamische simulaties in Delft3D-FM. Het model maakt gebruik van vereenvoudigde, representatieve randvoorwaarden voor getij en wind, en is doorgerekend met een hoge roosterresolutie. Deze resolutie blijkt essentieel om de complexe hydrodynamische en morfodynamische kenmerken van het bekken - zoals smalle geulen, drempelgebieden en zones van stromingsconvergentie en -divergentie - goed te kunnen weergeven. Dergelijke kenmerken hebben een sterke invloed op het sedimentgedrag en zijn bepalend voor de geschiktheid van verspreidingslocaties.

Een belangrijk hulpmiddel in dit onderzoek is *SedTRAILS (Sediment TRAnsport vIsualization & Lagrangian Simulator)*, een visualisatietool voor sedimenttransport, ontwikkeld in samenwerking met de TU Delft. Deze tool maakt het mogelijk om op basis van modelresultaten de paden van individuele sedimentdeeltjes (in dit geval zand) inzichtelijk te maken over grotere ruimte- en langere tijdschaal. Hierdoor ontstaat een gedetailleerd beeld van de verspreiding van deze sedimentfractie na verspreiding op de locaties Zuiderspruit en Scheepsgat binnen het getijdebekken van Ameland, maar ook een beeld van de langetermijn verplaatsing over het bekken.

Vanuit de verspreidingslocatie Scheepsgat wordt – volgens het model - onder gemiddelde omstandigheden het grootste deel van het zandige materiaal westwaarts getransporteerd, met beperkte recirculatie naar nabijgelegen platen. Zuiderspruit laat daarentegen een complexer verspreidingspatroon zien: ongeveer twee derde van het sediment beweegt westwaarts - deels richting beheerde vaargeulen - terwijl een derde oostwaarts wordt verplaatst en bijdraagt aan de sedimentatie nabij het wantij. Het uiteindelijke transport blijkt hier sterk afhankelijk van de exacte verspreidingspositie binnen het aangewezen gebied. Een oostwaartse verschuiving van de verspreidingslocatie resulteert in een grotere spreiding in oostelijke richting.

De in deze studie gebruikte aanpak levert veelbelovende inzichten in de sedimenttransportpaden en in de potentieel (on)gunstige effecten van verschillende verspreiding strategieën. Met behulp van deze techniek kan worden geëvalueerd of verspreidingslocaties in overeenstemming zijn met de huidige sedimentbeheerpraktijk, namelijk storten op locatie waar natuurlijke processen het sediment efficiënt door het gehele

systeem kunnen herverdelen. Naast het optimaliseren van de algemene ligging van de verspreidingslocaties, kan SedTRAILS meer gedetailleerde informatie geven over de transportpaden binnen één verspreidingslocatie, afhankelijk van de schaal, dominante processen en lokale morfologie.

Er zijn ook enkele belangrijke beperkingen en aannames in de gepresenteerde aanpak, welke leiden tot aanbevelingen voor vervolgonderzoek:

- De huidige simulaties zijn uitgevoerd onder gemiddelde getij- en windomstandigheden. Voor een vollediger beeld van sedimentgedrag, met name voor fijn sediment, is het nodig om ook extreme omstandigheden - zoals stormen en seizoensgebonden variaties, - mee te nemen. Dergelijke gebeurtenissen zijn van invloed zijn op de sedimentdynamiek op getijdeplaten en ondiepten, evenals op de uitwisseling van sediment met aangrenzende geulen en bekkens.
- De huidige implementatie van SedTRAILS is gevalideerd voor zandig sedimenttransport. Hoewel de huidige verspreidingslocaties in zandige locaties liggen, zijn er andere verspreidingslocaties waar fijn sediment dominant is. Om de potentiële terugkeer van fijn materiaal naar de baggergebieden beter te begrijpen, is het belangrijk om slibdynamiek expliciet te modelleren.
- SedTRAILS kan momenteel geen tijd- of ruimteschaal kwantificeren, maar richt zich op indicatieve transportpaden. Lopende ontwikkelingen binnen SedTRAILS zijn erop gericht deze aspecten te verbeteren.

Summary

The *Knowledge for Management and Maintenance of the Wadden Sea”* program focuses on building a solid knowledge base on morphology and sediment dynamics in the Dutch Wadden Sea. This knowledge supports Rijkswaterstaat in the fields of flood protection, accessibility, nature, and water quality. Rijkswaterstaat is responsible for the maintenance of navigation channels and aims to minimize dredging activities to limit ecological impact and costs. Optimization of sediment disposal strategies to reduce rapid infilling of navigation channels due to recirculation and additional turbidity is a key point of attention.

The primary objective of this study is to assess whether and how numerical models and innovative techniques such as *Delft3D-FM* in combination with *SedTRAILS*, can be used to evaluate disposal site location and effectiveness in terms of sediment spreading, and eventually can contribute to more robust and sustainable sediment management. In this study, the Ameland basin was chosen as a test case.

This study investigates sediment transport pathways associated with two disposal locations: Zuiderspruit and Scheepsgat. The analysis is based on hydrodynamic and sediment transport simulations using Delft3D-FM. The model uses simplified, representative boundary conditions for tide and wind and was run with a fine grid resolution. This resolution is essential to adequately represent the complex hydrodynamic and morphodynamic characteristics of the basin - such as narrow channels, shoal areas, and zones of flow convergence and divergence. These characteristics strongly influence sediment behavior and are key to assessing the suitability of spreading locations.

An important tool in this study is SedTRAILS (S*ediment TRAnsport vIsualization & Lagrangian Simulator)*, a sediment transport visualization tool developed in collaboration with TU Delft. This tool makes it possible to efficiently visualize the pathways of individual sediment particles (in this study limited to sand particles) over larger spatial and longer temporal scales, based on model results. This provides a detailed picture of the distribution of this sediment fraction following spreading at the Zuiderspruit and Scheepsgat locations within the Ameland tidal basin, as well as insight into long-term transport across the basin.

From the Scheepsgat disposal location, the model indicates that under average conditions most of the sandy material is transported westward, with limited recirculation towards nearby tidal flats. In contrast, Zuiderspruit shows a more complex spreading pattern: approximately two-thirds of the sediment is transported westward - partly towards managed navigation channels - while one-third is transported eastward and contributes to sedimentation near the watershed (*wantij*). The ultimate transport direction here strongly depends on the exact spreading position within the designated area. An eastward shift of the spreading location results in a greater eastward dispersion.

The approach used in this study provides promising insights into sediment transport pathways at disposal locations and the potential (un)favourable effects of different disposal strategies. Using this technique, it is possible to evaluate whether disposal locations are consistent with current sediment management practices, namely disposal at locations where natural processes can efficiently redistribute sediment throughout the system. In addition to optimising the overall placement of disposal locations, SedTRAILS can provide more detailed information on transport pathways within a single disposal site, depending on spatial scale, dominant processes, and local morphology.

There are also several important limitations and assumptions associated with the presented approach, which lead to recommendations for further research:

- The current simulations were carried out under average tidal and wind conditions. To obtain a more comprehensive understanding of sediment behaviour - particularly for fine sediments, it is necessary to also include extreme conditions, such as storms and seasonal variability. Such events influence sediment dynamics on tidal flats and shoals, as well as the exchange of sediment with adjacent channels and basins.
- The current implementation of SedTRAILS is validated for sandy sediment transport. Although the present disposal locations are situated in sandy environments, other disposal locations exist where fine sediment is dominant. To better understand the potential return of fine material to dredging areas, it is important to explicitly model silt dynamics.
- At present, SedTRAILS does not quantify transport time scales or spatial extents but instead focuses on indicative transport pathways. Ongoing developments within SedTRAILS aim to address these aspects.

Contents

1 Introduction

The program *Kennis voor Beheer en Onderhoud Waddenzee* (Knowledge for Management and Maintenance of the Wadden Sea) aims to build a robust knowledge base on morphology and sediment dynamics to support Rijkswaterstaat's responsibilities in the areas of accessibility, nature, water quality, and water safety.

Rijkswaterstaat is responsible for maintaining the navigation channels in terms of width and depth. In accordance with the Agenda for the Wadden 2050 and Natura 2000 management plans, the goal is to minimize dredging as much as possible, reducing both ecological impact and costs. Furthermore, the current sediment management practice aims to retain dredged sediment within the system, i.e. the tidal basin. In practice, sediment is disposed at locations where natural processes can redistribute it efficiently throughout the basin.

Having efficient dredging operations is key to reducing both ecological impacts and operational costs in the Wadden Sea. This involves two complementary strategies: on the one hand, optimizing dredging to minimize the volume of sediment removed; on the other, and more relevant to this research, enhancing sediment disposal strategies to reduce recirculation and minimize ecological impact.

To support this, numerical models such as Delft3D-FM in combination with SedTRAILS are being used to assess the sediment mobility and pathways from the current disposal sites. These models evaluate the location of sediment placement and the source-sink relations. By applying this modelling toolbox and integrating innovative techniques, new insights can be gained into how disposal strategies influence sediment dynamics, which in turn supports more sustainable management decisions. The core aim of this subproject is to improve understanding of what happens to dredged material after it is disposed: where does it go, how does it move, and what are the consequences for the morphology and ecological function of the system?

A key tool in this research is SedTRAILS, developed in close collaboration with the Delft University of Technology. SedTRAILS uses model simulations to visualize large-scale flow patterns and sediment transport pathways (Elias and Pearson, 2020). It has already been applied to study transport processes in tidal inlets (e.g. Lambregts, 2021) and for nourishments (Elias et al., 2020).

Problem definition & Objectives
Sediments dredged from the Holwerd–Ameland navigation channel are currently disposed of at designated locations, including the Zuiderspruit and Scheepsgat. Ideally, this material should recirculate within the Wadden Sea system or become part of the natural sediment dynamics, while avoiding redeposition in the dredged areas and navigation channel itself. However, the Wadden Sea's complex morphodynamics - an intricate network of tidal channels, shoals, and watersheds creates highly dynamic ebb–flood sediment transport patterns. This makes it challenging to predict the fate of dredged material and assess the long-term effectiveness of disposal strategies.

To support more sustainable sediment management, Rijkswaterstaat (RWS) is working to improve its understanding and tools to identify and quantify sediment transport pathways. Here the Borndiep system was chosen as a test case, specifically for the Zuiderspruit and Scheepsgat disposal sites (see Figure 1-1). The specific objective of this study is to explore how sandy sediments placed at these locations behave under simplified, representative boundary conditions for tide and wind. By tracing their movement within the Ameland basin, the study aims to provide valuable insights into how disposed sediments are redistributed within the tidal basin system and whether they ultimately contribute to or hinder the goals of efficient and ecologically sound sediment management.

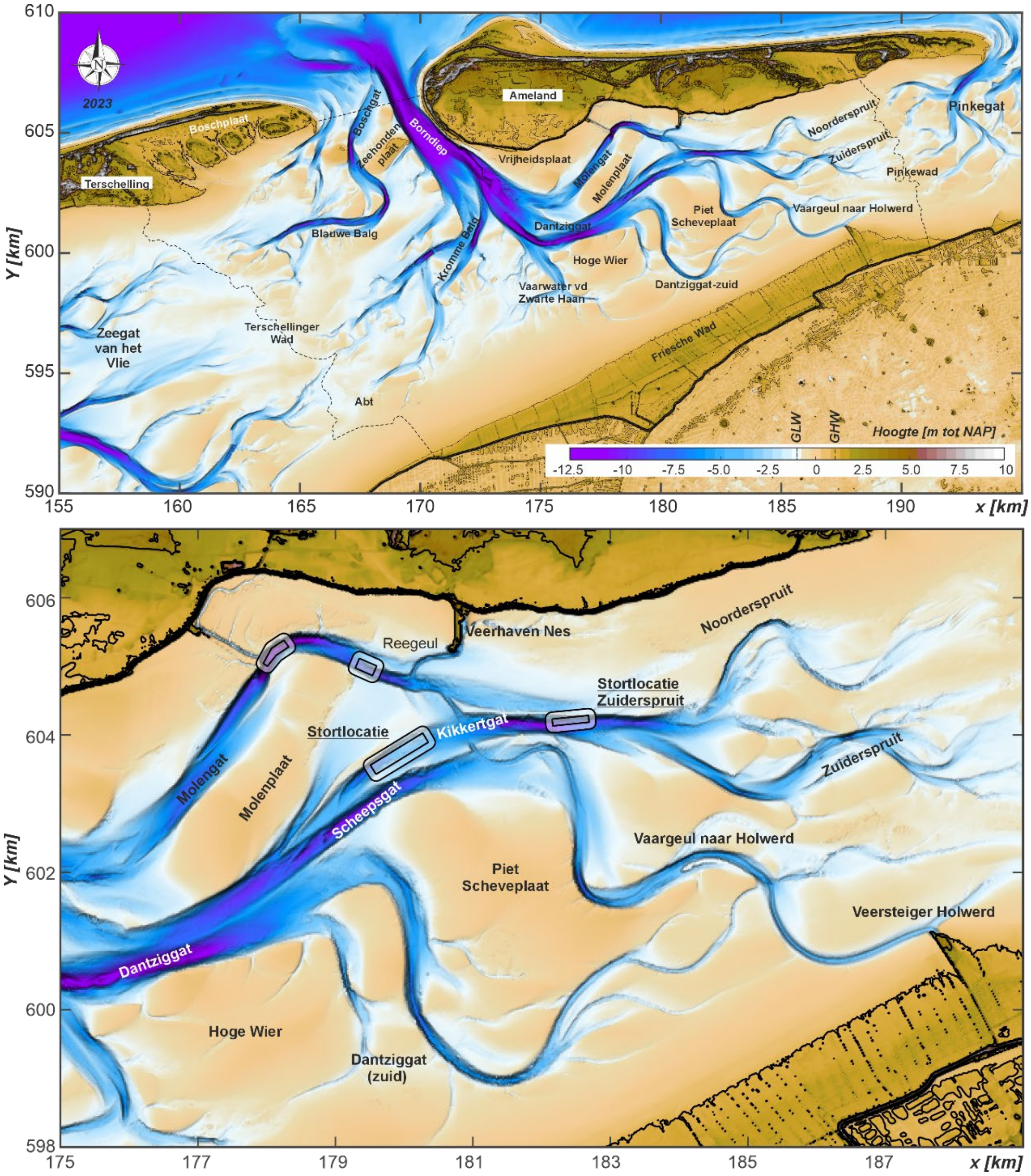

Figure 1-1: Overview of the main channels and shoals in the basin of Ameland Inlet (top panel) and location of the disposal areas (bottom).

2 Methods

A combination of Delft3D-FM and SedTRAILS was applied to simulate hydrodynamics and sediment transport within the Ameland tidal basin system, hereafter referred to as tidal basin, and to analyse sediment pathways from the disposal sites.
Delft3D-FM was used to compute the hydrodynamic conditions and the transport of sandy sediments within the model domain. The resulting flow fields and sediment transport vectors provided a detailed representation of the prevailing transport processes under average metocean conditions.

Subsequently, the SedTRAILS model was applied using the sediment transport output from Delft3D-FM. SedTRAILS was used to visualise and analyse the dominant sediment pathways originating from the Zuiderspruit and Scheepsgat disposal sites. This combined modelling approach allows for both a quantitative assessment of sediment transport and a qualitative interpretation of sediment dispersal patterns.

A brief description of each model is provided below, including the underlying assumptions and limitations of the modelling approach.

2.1 Delft3D-FM

Hydrodynamic and sediment transport simulations were conducted using a newly developed Delft3D-FM model (Elias and De Wilde, 2026) covering the entire Wadden Sea and adjacent North Sea, with model boundaries extending from IJmuiden in the south to east of the Ems-Dollard estuary in the north (Figure 2-1). A key feature of the model is its uniform and orthogonal grid design, which allows for local refinement within the Wadden Sea. An important lesson learned from this modelling is that high-resolution, local models are essential to obtain accurate results in the basin. For channel dimensions as the navigation channel, it is recommended to include the high-resolution multi-beam data in the bathymetric schematisation.

For the Ameland case study, high-resolution refinement was applied, achieving a spatial resolution of approximately 8 meters in the Ameland basin and Frisian Inlet. Sensitivity analyses confirmed that such high resolution is essential for accurately simulating water movement. However, in narrower channels like the Holwerd–Ameland navigation channel, the accuracy of bathymetric input data (soundings) becomes a limiting factor. Therefore, a resolution of 16 meters was selected for this study, focusing primarily on larger channels and basin-scale flow patterns.

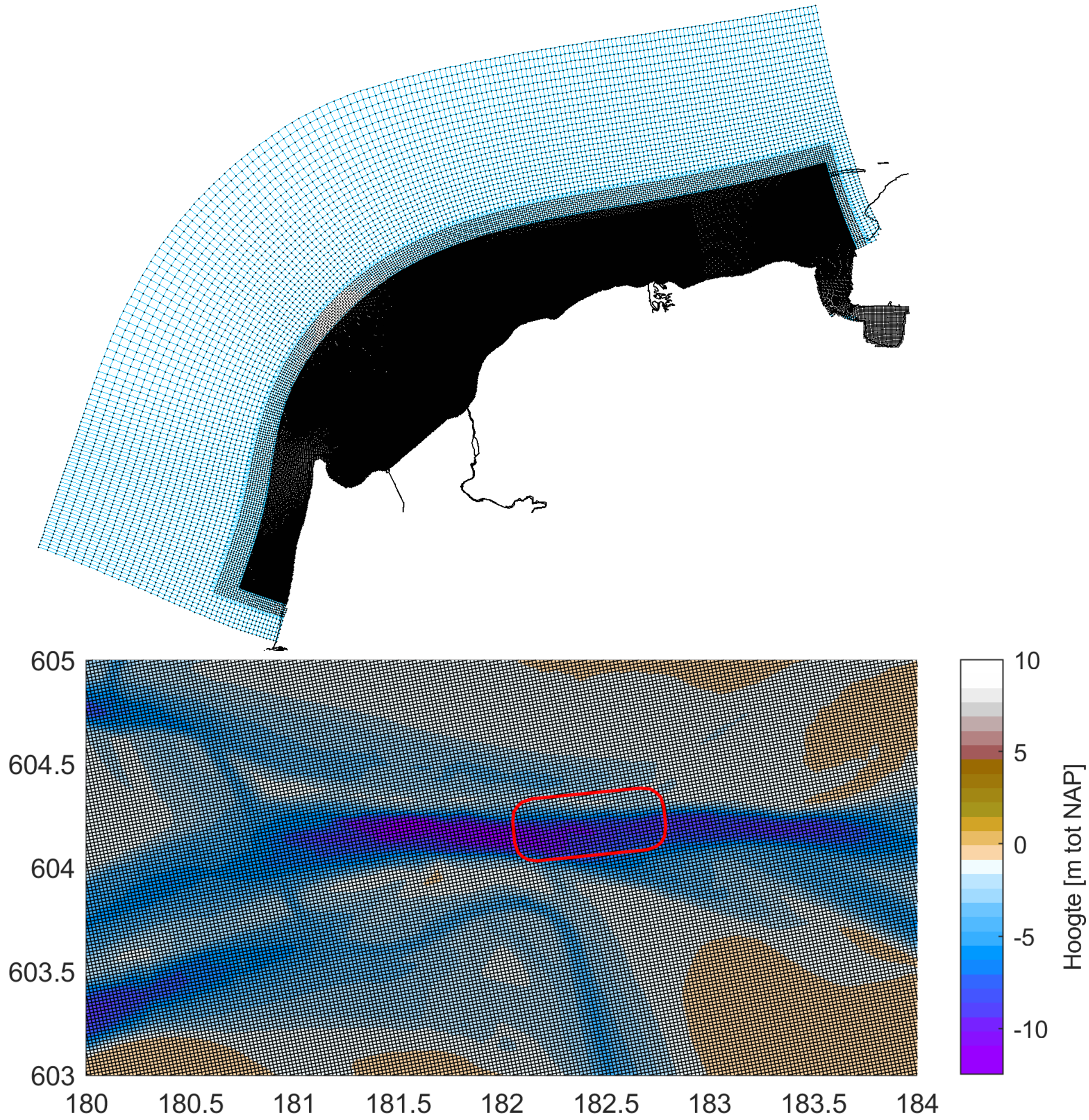

Figure 2-1: (Top) Delft3D-FM numerical grid domain covering the Wadden Sea from Noord-Holland to the Ems-Dollard estuary. Source: Elias and De Wilde (2026). (Bottom) Grid domain zoomed on the Zuiderspruit.

Hydrodynamics

Model simulations were performed using representative tidal forcing, derived from a 2017 simulation calibrated with measurements from that year. The period between 16 July 2017, 13:30 and 17 July 2017, 14:20 was selected as it provided the closest match to the annually averaged net discharge (Figure 2-2). This synthetic tide reflects average annual hydrodynamic conditions, based on:

- Tidal elevations at the inlet throat
- Ebb and flood discharges through the inlet
- Residual flows in the Ameland basin

This approach allows the dominant hydrodynamic and sediment transport regime - largely governed by water and sediment exchange through the inlet - to be captured, while remaining computationally feasible.

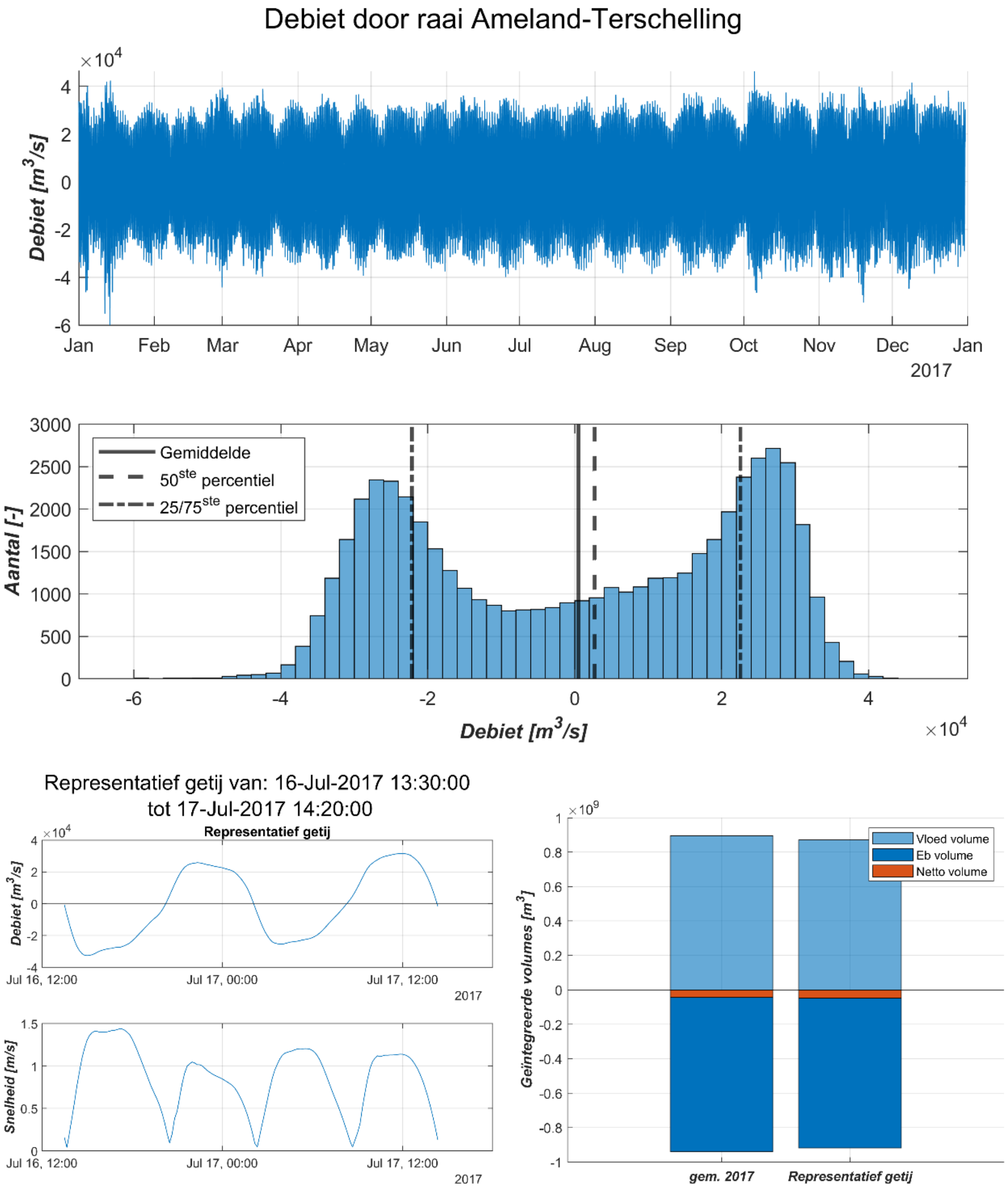

Figure 2-2: Selection of the representative tidal period based on Borndiep discharge. Top: Water discharge over the inlet along 2017. Bottom: Selected representative hydrodynamic period. Source: Elias and De Wilde (2026)

Wind forcing

To ensure that residual flow velocities within the basin were representative of long-term conditions, a spatially uniform and temporally constant wind forcing was applied during the selected 24-hour period. An average wind speed of 6.14 m/s from 214° was imposed. This wind forcing was chosen to reproduce residual flow patterns consistent with the annually averaged wind-driven circulation in the basin (Figure 2-3).

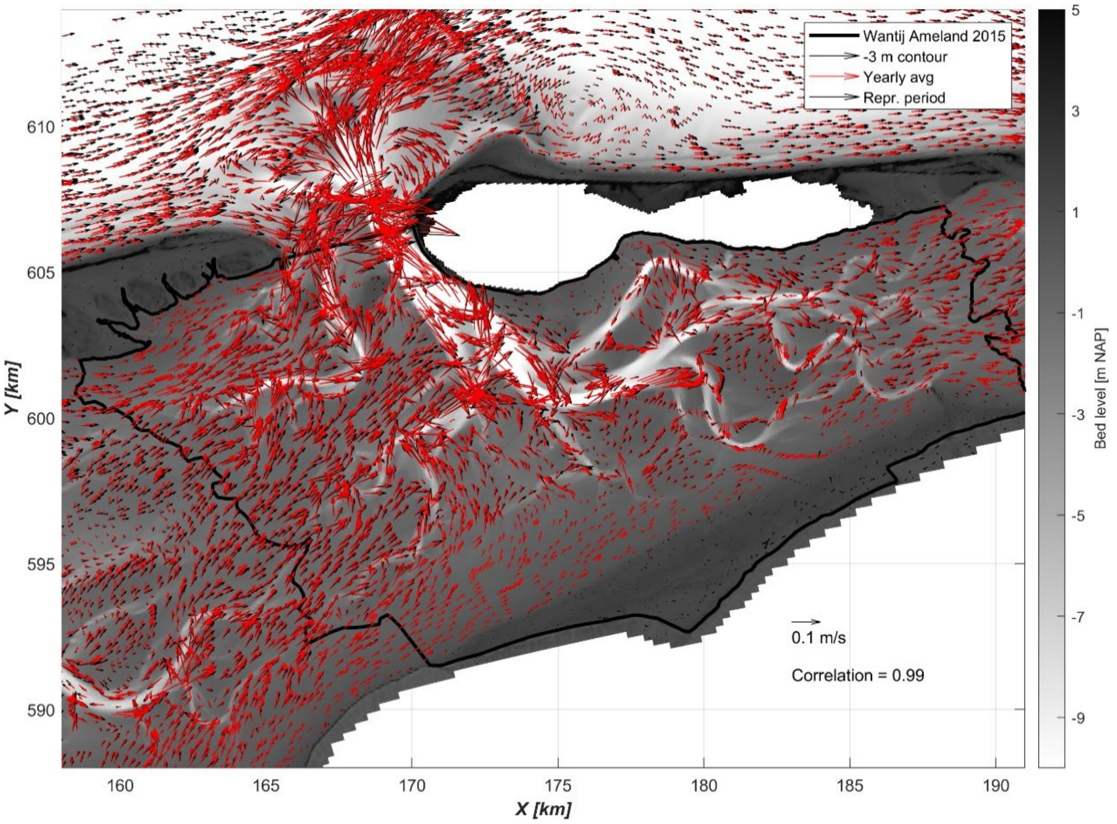

Figure 2-3: Comparison of residual flow velocities in the Ameland basin. Source: Elias and De Wilde (2026)

Sediment transport and bed levels
The bed levels were constructed using a combination of Vaklodingen and Beheerlodingen for the channels. Incorporating the higher-resolution bathymetric information, particularly within the channels, proved beneficial, as it significantly improved the model's performance with respect to water levels compared to using Vaklodingen data alone.

Sediment transport was computed using the Van Rijn (2004) transport formulation. The bed was schematised as a uniform sandy sediment with a representative median grain size (D_{50}) of 200 µm.

2.2 SedTRAILS: Visualizing Sediment Pathways

SedTRAILS (*Sediment TRAnsport vIsualization & Lagrangian Simulator*) was applied to visualize, identify, and analyse the pathways. Based on the Eulerian sediment transport vector fields derived from Delf3D-FM, SedTRAILS computes the Lagrangian pathways that idealized particles travel as they pass through a changing vector field (Figure 2-4). SedTRAILS was adapted from techniques described in Storlazzi et al. (2017) and employs a similar methodology to sediment particle tracking modules such as the particle tracking model PTM (MacDonald et al., 2006).

Unlike traditional particle tracking models - which often oversimplify sediment transport behaviour, SedTRAILS uses computed transport formulations for non-cohesive (sandy) sediment (van Rijn, 2007) and includes both bed load and suspended load. The tool converts mass fluxes into volumetric fluxes and then into effective particle transport velocities. A user-defined transport height scale (h_{tr}) controls the speed of the visualized particle motion, allowing for qualitative comparison of relative sediment mobility between different locations.

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Important: For a realistic approximation of particle motion, the length scale, h_{tr}, should be related to a representative height in the water column over which material is transported and varies depending on the mode of transport. Although, in theory this h_{tr} can be obtained by comparison with field data or model results, such validation datasets are not readily available. When we are interested in the maximum potential motion along a pathway for a particle in space, the timescale may be of secondary interest. In that case, for visualization purposes, this length scale factor, h_{tr}, can be adjusted to increase the rate of particle motion, since sediment transport rates are often very small in magnitude. The length scale factor can only be adjusted until the point where particle trajectories begin to diverge with changes to h_{tr}. This critical value can be obtained through sensitivity testing.

In the simulations performed for this research, the velocity of the sediment particle movement is not calibrated; it is not a sediment tracer. *SedTRAILS* was run to reproduce the sediment pathways in a computationally efficient manner. The timestep for particle velocity movement is based on numerical accuracy but does not represent the actual sediment particle velocity. Consequently, the length of the particle trajectory can therefore only be used qualitatively and must be interpreted as relative sediment mobility between source locations. Longer pathways indicate higher sediment mobility compared to shorter pathways. Implementation of a functionality to accurately reproduce the sediment particle velocity currently ongoing at Delft University of Technology and available for testing in February 2026.

Disposal areas; Zuiderspruit
Approximately 500 seed particles were released within each disposal area to represent the initial distribution of dredged material. The 500 seeds have enough coverage to represent the entire disposal polygons. The particles covered the entire disposal polygon and were released altogether once at the start of the simulation. Using the representative tidal conditions derived from the Delft3D simulations, SedTRAILS was employed in cyclic mode to simulate sediment dispersion over an extended period by repeatedly applying the selected tidal cycle. This approach allows the identification of dominant sediment transport pathways under average hydrodynamic conditions. It should be noted that the current methodology does not account for the time associated with particle travel or the timing of disposal. These and other limitations and assumptions are discussed further in Section 2.3.

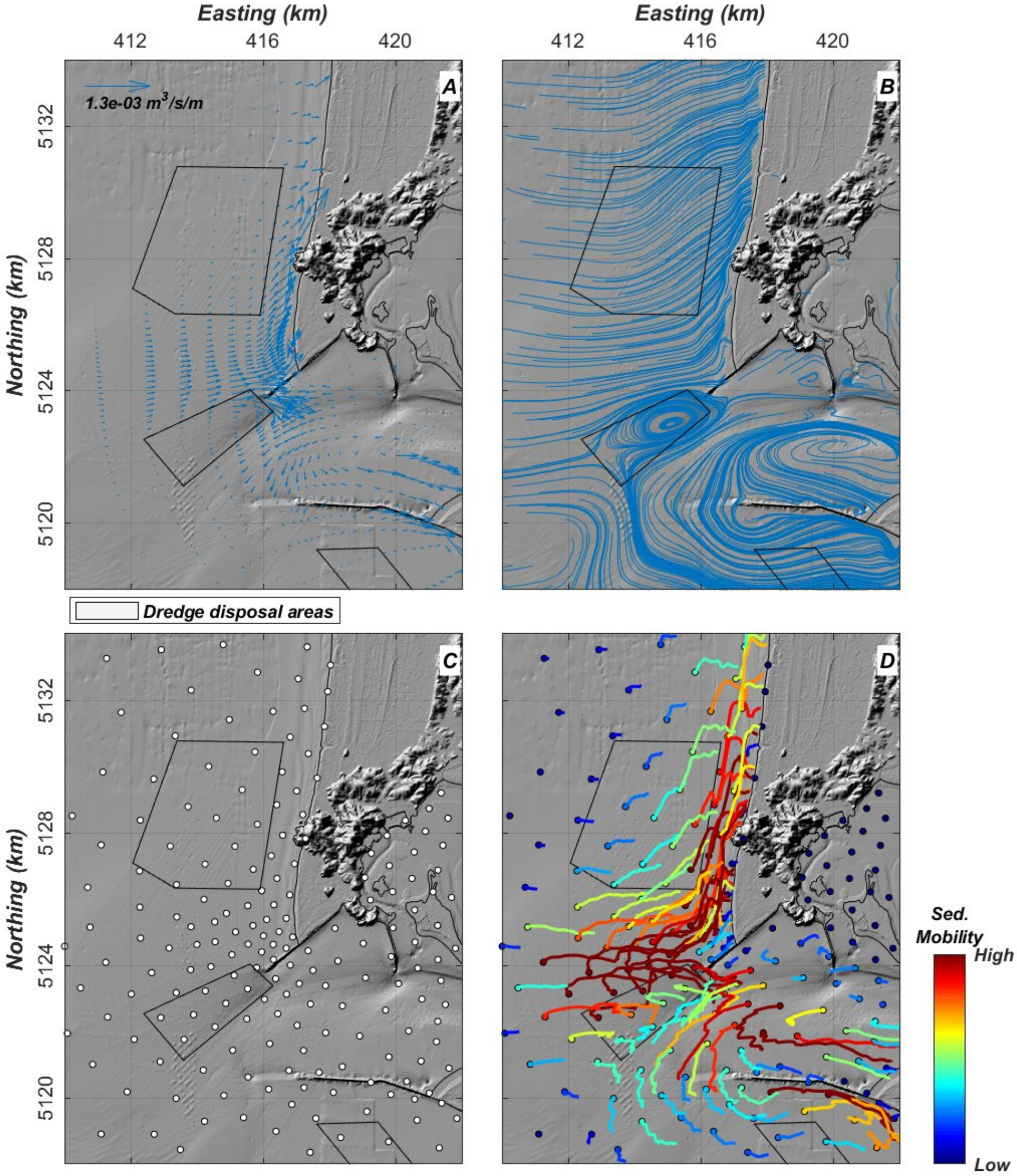


Figure 2-4 Example of a SedTrails visualization of lagrangian sediment transport pathways showing: A, a sediment vector field, B, streamlines representing the vector field, C, initial positions of the sediment sources, and D, sediment pathways derived from the SedTrails analysis. Sediment pathways in D are coloured by the relative mobility of the source. Note that in this example the goal was to identify the fate of dredge deposits in selected disposal areas indicated by the black polygons.

2.3 Key limitations from the modelling approach

The following assumptions and limitations apply to the modelling approach adopted in this study:

- **Representative hydrodynamic conditions**
  The simulations are based on a single, representative tidal period combined with an average wind forcing. As a result, only average (mean) hydrodynamic and sediment transport conditions are considered. Short-term variability and extreme events (e.g. storms or high-discharge conditions) are not explicitly accounted for.

- **Simplified sediment composition**
  Sediment dynamics are represented using a single sandy sediment fraction with a median grain size (D_{50}) of 200 µm. The presence and behaviour of finer sediments (silt and clay), including cohesive processes, are not included in the simulations.

- **Depth-averaged hydrodynamics (2DH)**
  The Delft3D-FM model is applied in depth-averaged (2DH) mode. Vertical flow structure and three-dimensional processes, such as stratification and baroclinic effects, are therefore not represented. This may influence sediment transport processes in areas where vertical gradients are relevant.

- **Qualitative nature of SedTRAILS results**
  SedTRAILS is used as a qualitative tool to illustrate dominant sediment transport pathways. The simulated travel times and distances of individual sediment particles are subject to uncertainty and are not considered reliable. Consequently, SedTRAILS results are interpreted in terms of pathway direction and connectivity only, and no quantitative conclusions regarding transport rates, distances, or timescales are drawn.

3 Hydrodynamics, sediment transport and pathways

3.1 Hydrodynamics

3.1.1 Hydrodynamics in the Ameland Basin

Tidal Propagation Overview

Figure 3-2 presents an overview of tidal propagation in the basin, based on the representative tide schematization. Tidal movement is illustrated in hourly intervals throughout the tidal cycle. The lower-right panels show time series of water levels and velocities at two locations: the inlet throat (grey dot in subplot 14) and the disposal area Zuiderspruit (red dot in subplot 14). These time series indicate an approximate one-hour delay in peak water level and velocity between the two sites.

Peak discharges through the inlet throat are -33,000 m^3/s (ebb) and +26,000 m^3/s (flood), with a total ebb volume of 440 million m^3 and a flood volume of 403 million m^3.

Ebb tides

At high tide in the inlet (timestep 1), flow velocities across the domain are limited. Ebb-dominant velocities occur in the Boschgat region (west side of the inlet), while flood-dominant flows are still present in Borndiep, extending into Dantziggat. On the shoals in the eastern basin, velocities are minimal or absent.

As the tide begins to fall (timesteps 2–3), velocities increase, reaching a peak of nearly 1.5 m/s in the Borndiep. This maximum is sustained for about two hours (timesteps 3–5), after which velocities gradually decline, reaching a minimum at timestep 8. The lowest velocity occurs roughly one hour after the lowest water level. The velocity rise phase (2 hours) is considerably shorter than the falling phase (3 hours).

In contrast, the Zuiderspruit location shows a very different evolution. Velocities increase gradually over a 4.5-hour period, peaking at over 1 m/s at timestep 6.5. A minimum is reached after only 2.25 hours of declining velocities.

Flow velocity maps reveal a contrast between the areas west and east of Borndiep. West of Borndiep, relatively high velocities are observed on shoals between channels during most timesteps, with no clear distinction between shoals and channels. In the eastern basin, however, higher shoals dominate, and flow velocities predominantly follow the channels.

At high tide in the inlet (timestep 1), velocities in the domain are limited. In the inlet, ebb-dominant velocities occur in the Boschgat region (westside of the inlet) while flood-dominant velocities occur in Borndiep and extend into Dantziggat. Velocities on the shoals in the eastern part are near absent.

Flood tides

Low tide in Borndiep occurs at timestep 7, with near-zero velocities reached at timestep 8. The rising tide is marked by a sharp increase in velocity between timesteps 8 and 9, followed by a smaller increase between timesteps 9 and 10. Peak flood velocities occur nearly three hours before the highest water level. Although the maximum flood velocity approaches that of the ebb phase, the strong ebb velocities persist for a much longer duration.

Velocities then gradually decrease between timesteps 10 and 12 and drop more rapidly thereafter, reaching a minimum at timestep 14.

At Zuiderspruit, a similarly short period (~1.5 hours) of increasing velocity is observed, followed by a two-stage decline. The maximum flood velocity (0.6 m/s) is considerably lower than the maximum ebb velocity (nearly 1.1 m/s), highlighting a strong ebb-dominant velocity asymmetry at this location.

Residual Currents
Residual currents (Figure 3-1) show ebb-dominant outflow in the Borndiep, with the strongest flow along the Ameland coast. Both Boschgat channels display flood-dominant behaviour. Although the seaward section of Borndiep (within the inlet throat) is mostly flood-dominant, a distinct division emerges within the basin: flood-dominant flow along the western side and ebb-dominant flow along the eastern side. The flood-dominant flow is directed toward the Kromme Balg lobe, where it converges with the ebb-dominant outflow from Kromme Balg. This convergence likely contributes to the formation of the large lobe in this region. The Kromme Balg channel itself is largely ebb-dominant.

South of the lobe, complex flow patterns arise within the Dantziggat area. Between Kromme Balg and Zwarte Haan, Dantziggat exhibits ebb dominance along its western side and flood dominance along the eastern side;a pattern reversed in the eastern part of Dantziggat. A shallow lobe just south of the Molengat shoal appears to result from flow convergence in this area.

In the southern section of the channel along Hoge Wier, flood-dominant (eastward-directed) flow increases, while the northern part remains ebb-dominant. Further detail on this pattern is provided in the next section.

It should be noted that applying a constant average wind field may lead to unrealistic residual flows over shallow shoal areas. These regions are more sensitive to wind-driven circulation than the deeper channel areas, and the simplified wind representation may therefore underestimate or misrepresent the local hydrodynamic response.

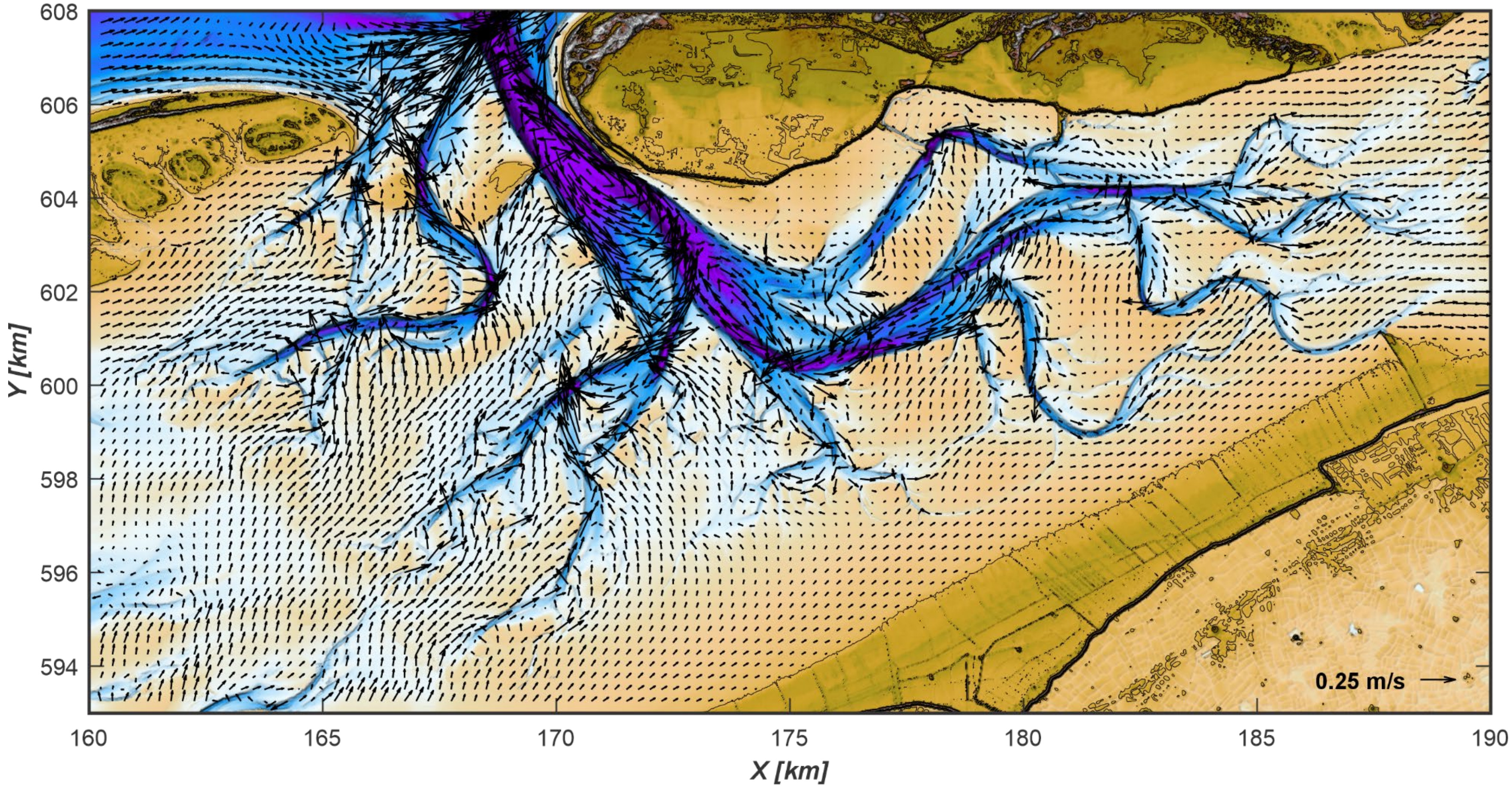


Figure 3-1: Residual flow pattern for the Ameland basin, based on a representative tide- and wind schematization.

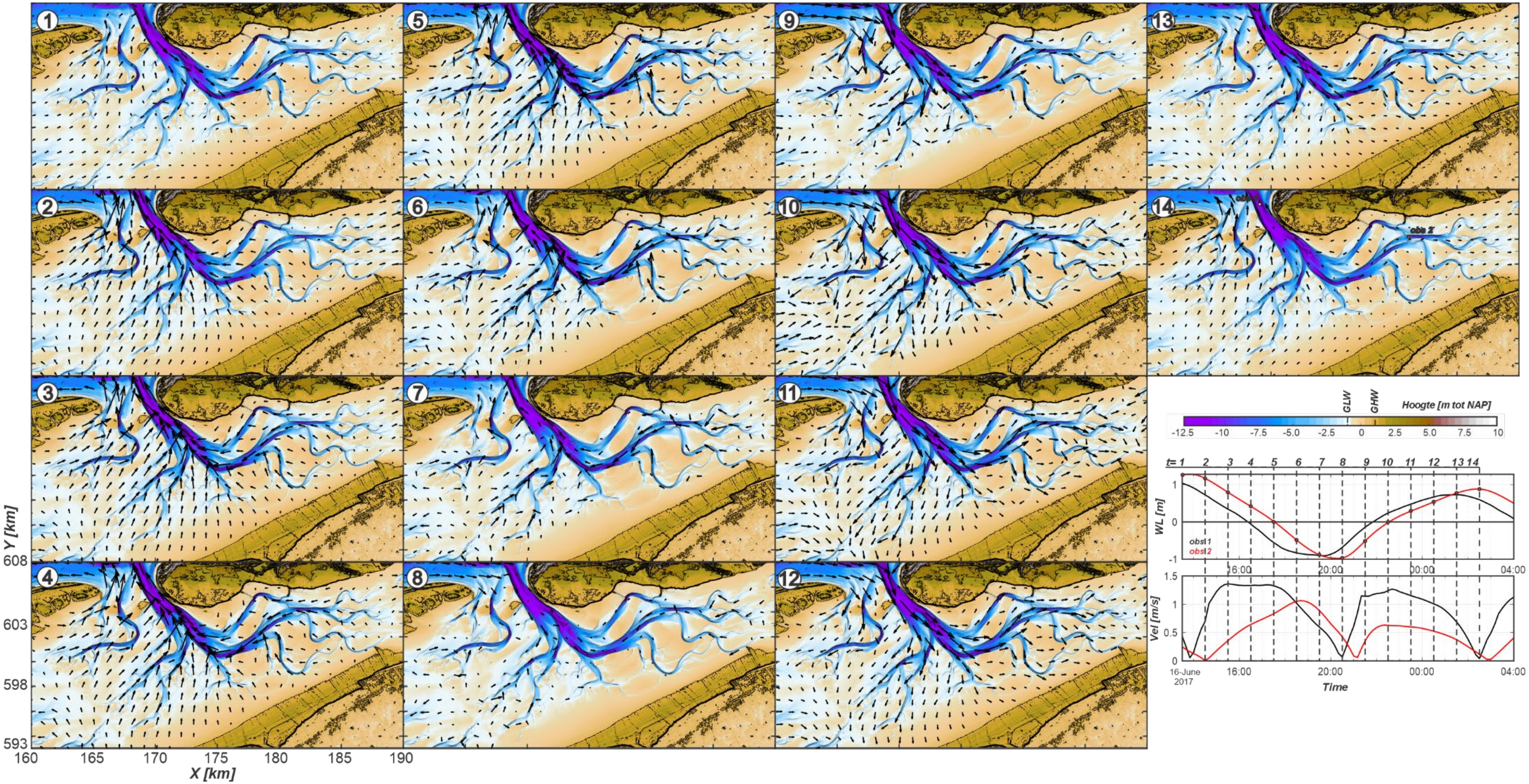


Figure 3-2: Overview of the tidal flow patterns in an hourly interval representative for the present-day flow in the Ameland basin. The subplot numbering 1-14 corresponds to the hours in the water level and flow velocity timeseries illustrated in the lower right panels. The locations of observation points for which the time series are plotted are indicated in subplot 14.

3.1.2 Hydrodynamics in the eastern-central part of Ameland basin

Figure 3-3 illustrates the complexity of residual tidal flow patterns in the central part of the basin. One of the most notable features is the spatial variation in ebb- and flood-dominant flow, which occurs not only along the channels but also across them. In the western part of Dantziggat (x-km 177–179), the northern side of the channel is predominantly ebb-dominant, while the southern side exhibits flood-dominant flow. This flood-dominant flow extends past Hoge Wier and continues onto Piet Scheve Plaat. In the Dantziggat (Zuid) channel, a similar pattern emerges: ebb-dominant flow occurs along the deeper western side, while the eastern side is distinctly flood-dominant.

3.1.3 Hydrodynamics at the Scheepsgat disposal side

At the Scheepsgat disposal site, a prominent sill (*drempel*) separates the northern and southern parts of the channel (Figure 3-3). North of the sill, the flow is strongly ebb-dominant. South of the sill, a divergence in flow direction is observed, with flood-dominant flow toward the east and ebb-dominant flow toward the west. The Scheepsgat disposal area lies north of the sill, within the ebb-dominant zone, suggesting that sediment deposited here is likely to be transported westward into the ebb-dominant section of Dantziggat.

A small channel connects the Scheepsgat outflow to Dantziggat, extending onto the Molengat shoal. Residual flow within this channel is directed toward the Molengat channel, facilitating cross-basin sediment movement. The navigation channel (Holwerd-Ameland) shows a similar cross-channel flow pattern, with ebb-dominant (northward-directed) flow along its western side and flood-dominant (southward-directed) flow along the eastern side. In the shallow lobe area at the northern end of Piet Scheve Plaat, residual flow is particularly complex due to the confluence of currents from Scheepsgat/Kikkertgat and the northward flow in the Holwerd-Ameland navigation channel. These converging flows likely contribute to the formation and dynamic behaviour of the lobe in this region.

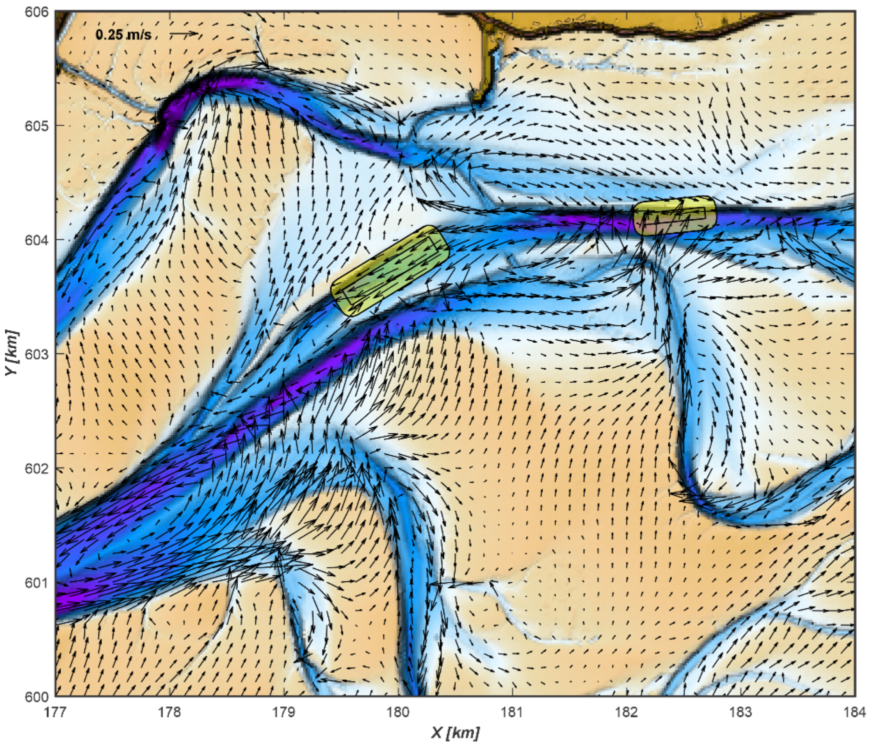


Figure 3-3: Details of the residual flow pattern in the eastern part of Ameland basin at the Zuiderspruit (eastern yellow box) and Scheepsgat (western yellow box) disposal locations. See Figure 3-4 for details of the tidal flow in hourly intervals.

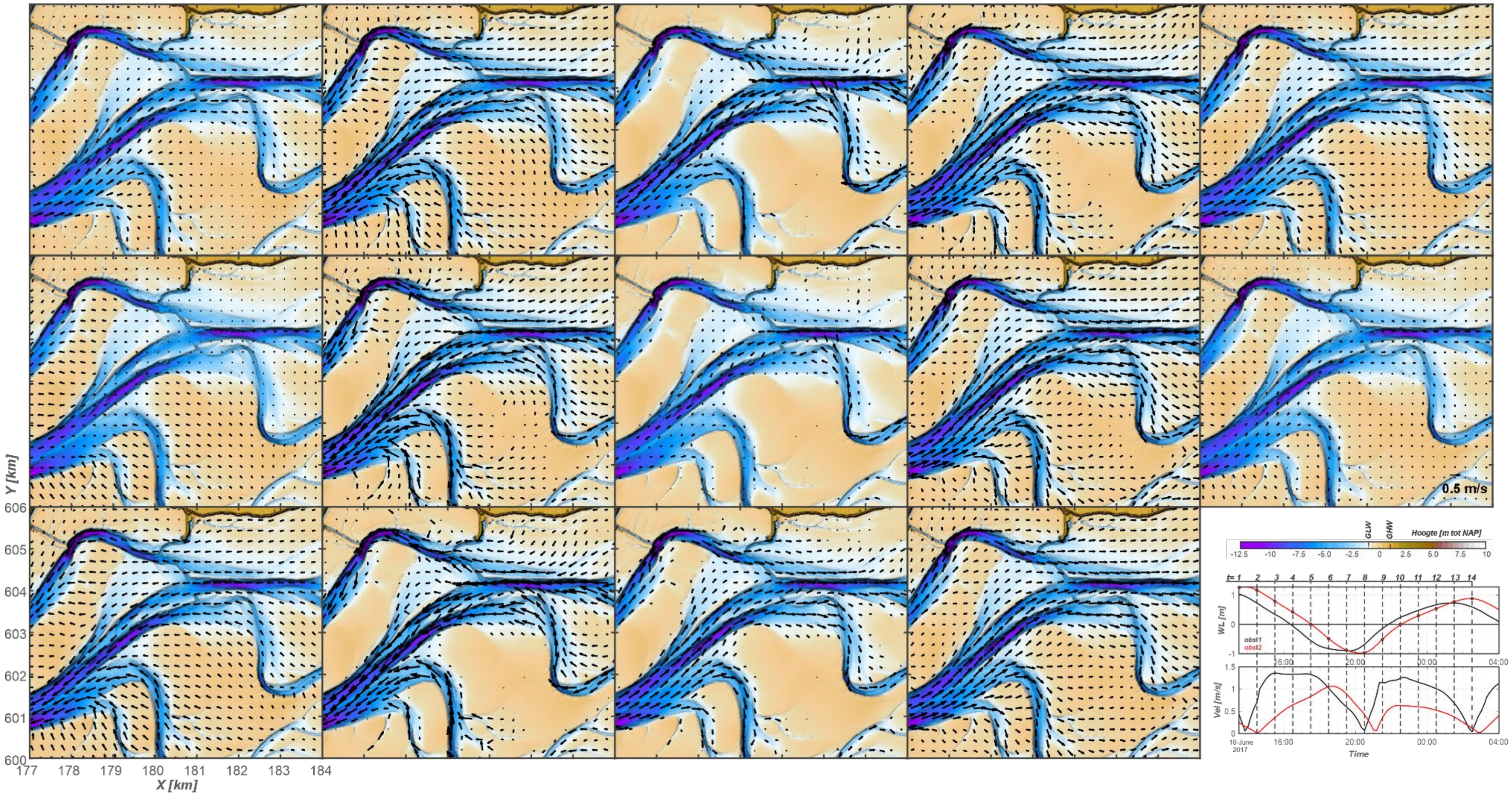


Figure 3-4: Details of the tidal flow patterns in an hourly interval representative for the present-day flow in the eastern part of Ameland basin. The subplot numbering 1-14 corresponds to the hours in the water level and velocity timeseries illustrated in the lower right panels. The locations of observation points for which the time series are plotted are indicated in subplot 14.

3.1.4 Hydrodynamics at the Zuiderspruit disposal side

Residual flow at the Zuiderspruit location is particularly complex (Figure 3-5). Most notable are the divergent residual flow vectors observed both within the channel and across the disposal site. In the northern and central parts of the disposal area, the residual flow is predominantly ebb-dominant, directed westward. In contrast, the southern part exhibits eastward residual flow, indicating localized flow reversal.

On the shoals and lobes to the north and south of the site, residual flow patterns are directed toward the central channel. This suggests that sediments disposed of in the area are unlikely to settle directly onto these adjacent shoals. Instead, they are more likely to be transported eastward or westward, depending on the exact location of disposal within the site.

To the east, the channels of Noorderspruit and Zuiderspruit display opposing residual flow directions. In Noorderspruit, the residual flow is directed eastward, toward the Ameland tidal divide (*wantij*). In contrast, flow in Zuiderspruit is ebb-dominant, directed westward toward Kikkertgat.

From Kikkertgat, most residual flow vectors continue westward into Dantziggat. However, along the northern flank of the channels, some vectors also veer northward into the navigation channel leading to Molengat. This indicates a potential residual flow connection between the Zuiderspruit disposal area and the Molengat navigation channel.

No direct connection is observed between the disposal site and the southern section of the navigation channel. Residual flow in this region remains strongly ebb-dominant, effectively limiting the potential for southward sediment transport from the disposal area. Furthermore, the hourly flow vectors displayed in Figure 3-6 do not indicate any significant exchange or linkage between these zones.

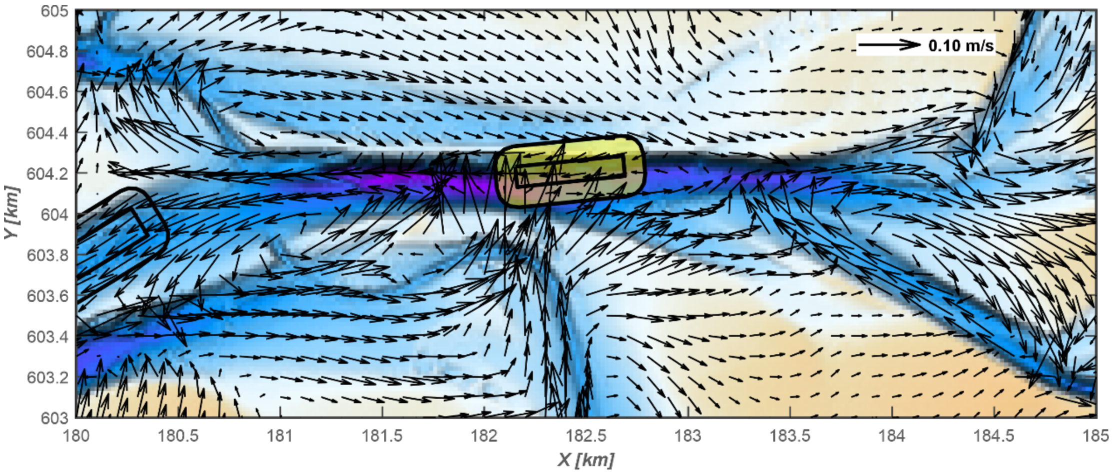


Figure 3-5: Details of the residual flow pattern at the Zuiderspruit disposal location. See Figure 3-6 *for details of the tidal flow in hourly intervals.*

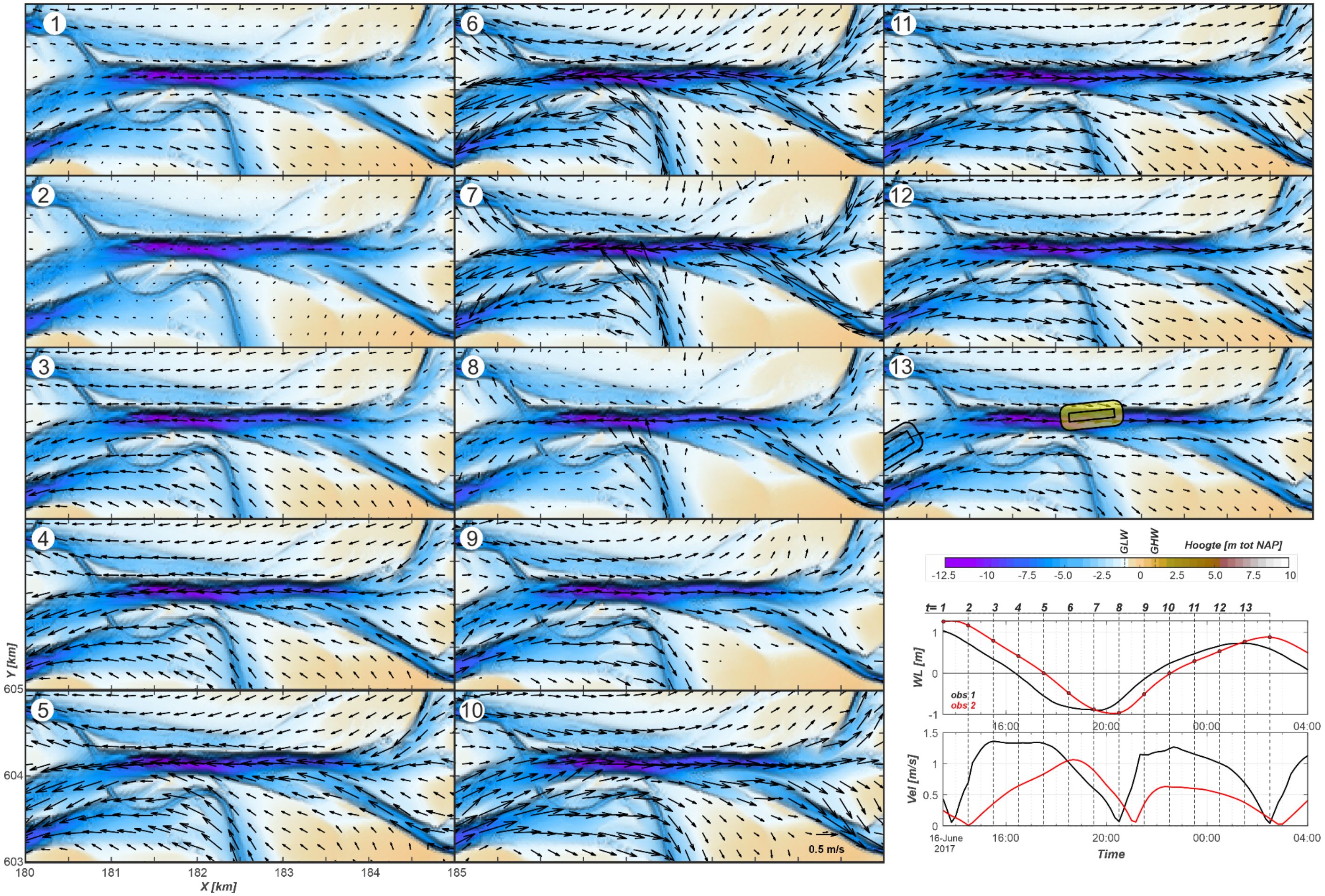


Figure 3-6: Details of the tidal flow patterns in an hourly interval representative for the present-day flow at the Zuiderspruit disposal location. The subplot numbering 1-13 corresponds to the hours in the water level and flow velocity time series illustrated in the lower right panels. The locations of observation points for which the time series are plotted are indicated in subplot 13.

3.2 Sediment transport

3.2.1 Basin-scale sediment transport patterns

The sediment transport patterns (Figure 3-8) display trends broadly similar to those of the residual flow (Figure 3-1) with both showing alternating ebb- and flood-dominant behaviour. While the direction of sediment transport generally aligns with the residual flow, the sediment patterns are less variable and more spatially coherent.

A key distinction lies in the spatial confinement of sediment transport, which occurs primarily within the channels – during the mild simulated conditions – where tidal velocities are highest. In contrast, transport across shoals is negligible, as the combined tidal and wind-driven forces rarely exceed the critical shear stress needed to mobilize sand-sized sediment.

The basin shows a clear division into ebb- and flood-dominated channels, with ebb dominance being more prevalent. Key observations include:

- **Borndiep channel** is mostly ebb-dominant toward the ebb-tidal delta. Within the basin, a distinct spatial separation occurs: ebb-dominant transport along the eastern side and flood-dominant transport along the western side.
- **West of Borndiep**, the channels are predominantly ebb-dominant.
- **Molengat** exhibits ebb-dominant transport toward Borndiep.
- **Dantziggat** shows ebb-dominant transport in the northern section, while a flood-dominant flow is observed along Hoge Wier toward southern Dantziggat and into Scheepsgat.
- **Kikkertgat** is generally ebb-dominant, though a transition zone from ebb- to flood-dominance is evident near the disposal location.
- **East of the disposal site**, flood-dominant transport occurs toward Noorderspruit.
- **In Zuiderspruit**, sediment transport remains strong and predominantly ebb-dominant.
- **Along the Ameland–Holwerd navigation channel**, alternating stretches of ebb- and flood-dominance are observed, with transport becoming increasingly flood-dominant closer to Holwerd.

Sediment transport pathways

An initial simulation using 500 particles, uniformly distributed across the eastern basin (Figure 3-7), illustrates tide-representative upscaled sediment transport pathways. In this figure, black dots represent final locations and orange lines trace particle movement. The results show that, under the simulated representative conditions, sediment activity is largely confined to channels. Particles on shoals and higher intertidal areas remain mostly immobile—expected to mobilize only under stormy, wind-wave conditions or during high water (surge) events.

Within the channels, sediment pathways display either ebb- or flood-dominant behaviour, consistent with the Delft3D-derived transport patterns described earlier. Most particles remain within the basin. A subset - primarily those seeded near the inlet, exhibits a net export trend toward the open sea. However, the majority remains confined to the eastern basin, illustrating limited exchange with the western part. Only a few particles move west of their original positions, and most settle on shallow shoals between Kromme Balg and Molenplaat. Very few reach Borndiep and are transported toward the inlet.

This suggests that the eastern part of the basin functions as an effective sediment trap under representative tide conditions: material entering this area is unlikely to be transported back to Borndiep or the ebb-tidal delta. However, it is important to note that storm surges and varying wind conditions can significantly influence sediment transport on the shoals. These effects were not examined in the present study.

Relation to dredging & dumping
The observed sediment transport on the basin-scale patterns supports the current sediment management practice. The current practice aims to retain dredged sediment within the system, i.e. the tidal basin. In practice, sediment is deposited at locations where natural processes can redistribute it efficiently throughout the basin.

The eastern portion of the basin functions as an effective sediment trap with limited exchange toward the ebb-tidal delta while intrinsic ebb-flood channels and sills towards the inlet have a complex pattern of sediment recirculation and even export towards the open coast. This spatial variability highlights the importance of sediment disposal strategies. Sediment transport is largely confined to channels and is predominantly ebb-dominant, especially near the inlet, suggesting that sediment export to the sea is limited under the simulated tide-representative conditions.

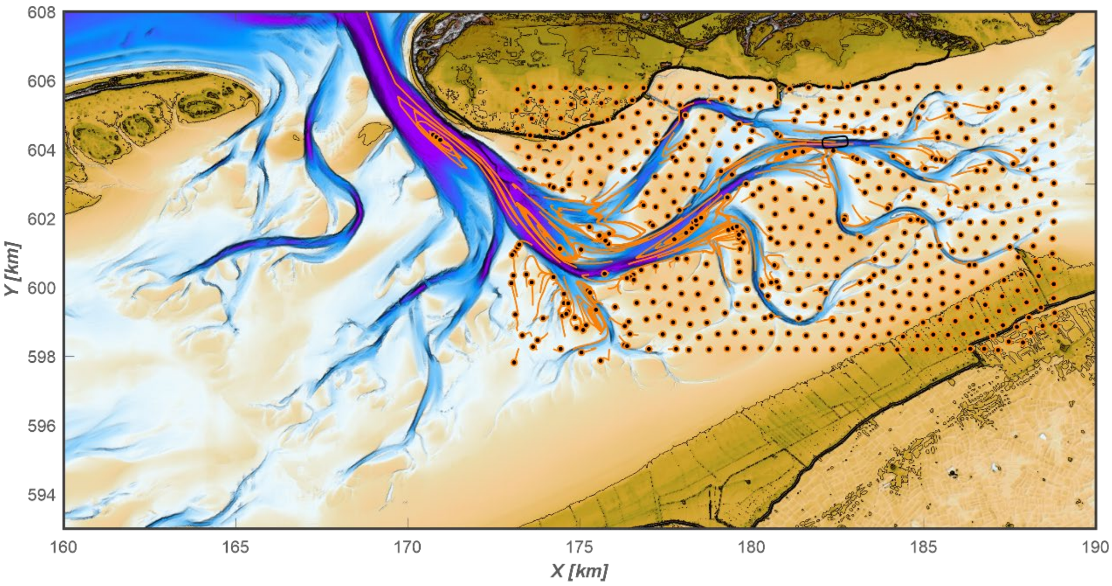


Figure 3-7: Basin-scale sediment pathways (orange lines) and underlaying bed levels. Black dots are the end locations after SedTrails runtime.

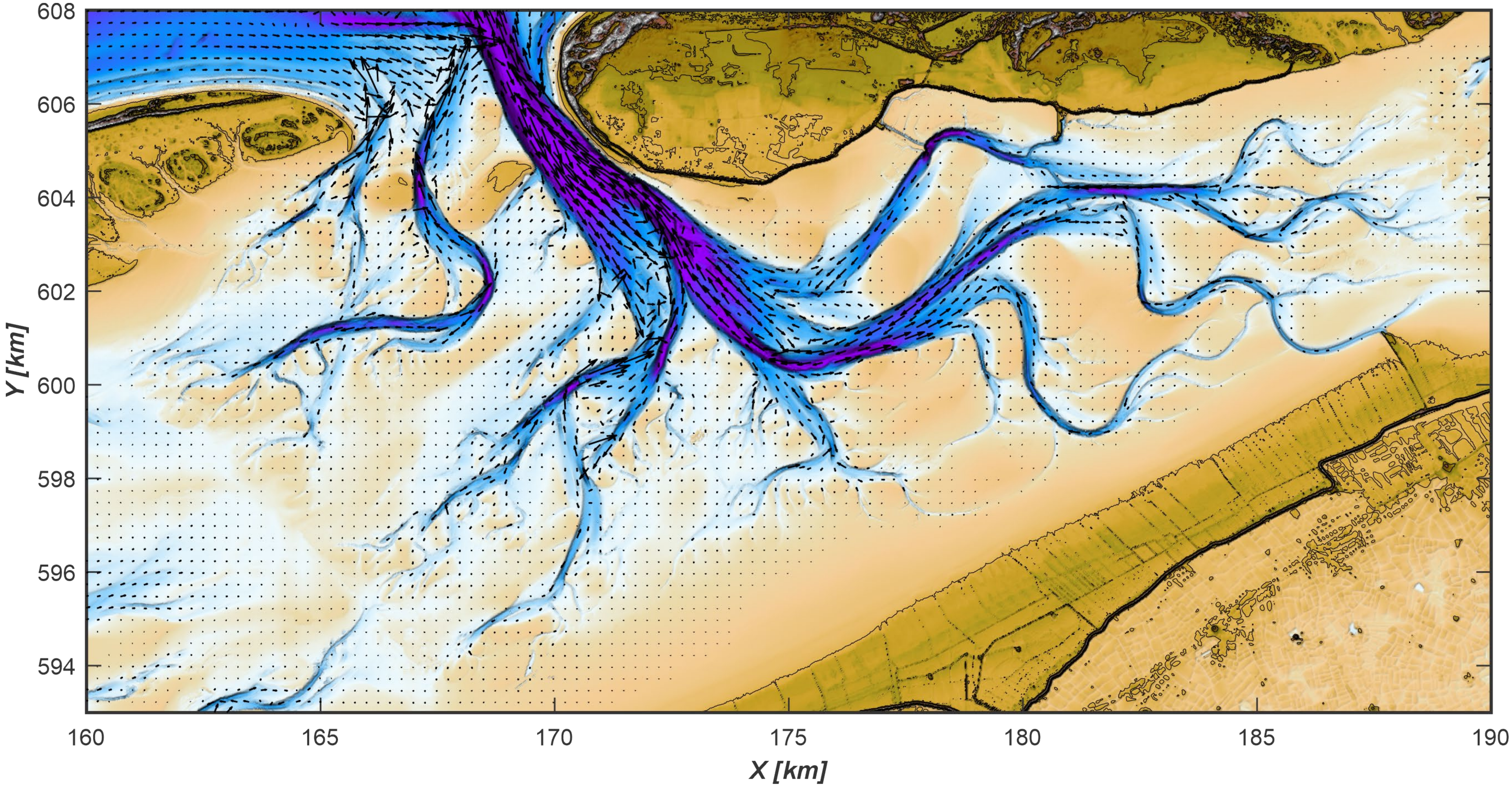


Figure 3-8: Patterns of the scaled annual sediment transport on the basin scale.

3.2.2 Disposal sites sediment transport patterns

Details of sediment transport patterns around the Zuiderspruit and Scheepsgat disposal locations are shown in Figure 3-9. In Dantziggat, sediment transport follows an eastward path along Hoge Wier toward Piet Scheve Plaat. These eastward transports converge with ebb-dominant (northward-directed) transport through the southern Dantziggat channel. This convergence zone explains the formation of the shoal in this area.

In contrast, the northern part of the Dantziggat channel is primarily ebb-dominant, with westward-directed sediment transport. However, just north of Piet Scheve Plaat, a distinct divergence point emerges. East of this point, sediment transport shifts direction and flows eastward, converging with northward transport from the Vaargeul Ameland–Holwerd channel. This additional convergence likely plays a key role in the development and maintenance of the shoal in this region. The Scheepsgat disposal site is located immediately adjacent to this divergence point.

The Scheepsgat disposal site lies within a zone of ebb-dominant transport, directed westward into the Dantziggat channel. However, exchange with the adjacent Molengat shoal appears limited, as transport rates onto the shoal remain low under modelled conditions.

The Zuiderspruit disposal location lies further east of Scheepsgat, in an area where sediment transport patterns become more complex. Just east of this site, a clear divergence zone develops, with opposing transport directions extending into the disposal area. While most of the sediment transport remains westward-directed, the southern boundary of the disposal location exhibits eastward transport. This internal variability suggests that sediment dynamics here are more sensitive to local hydrodynamic conditions.

The model results illustrate the proximity of the Scheepsgat and Zuiderspruit disposal sites to zones of converging and diverging sediment transport. For sand-sized materials, the transport figures alone do not indicate a direct (short-term) indication of recirculation back towards the dredge areas.

It is important to note that these interpretations of ebb–flood dominance apply specifically to the net transport of sand-sized sediments for the representative metocean. The basin also contains significant quantities of fine-grained material (mud), particularly near Holwerd, which are not explicitly represented in the current sediment transport simulations. Furthermore, variations in the metocean forces (e.g. wind direction) will alter or locally shift these patterns over time.

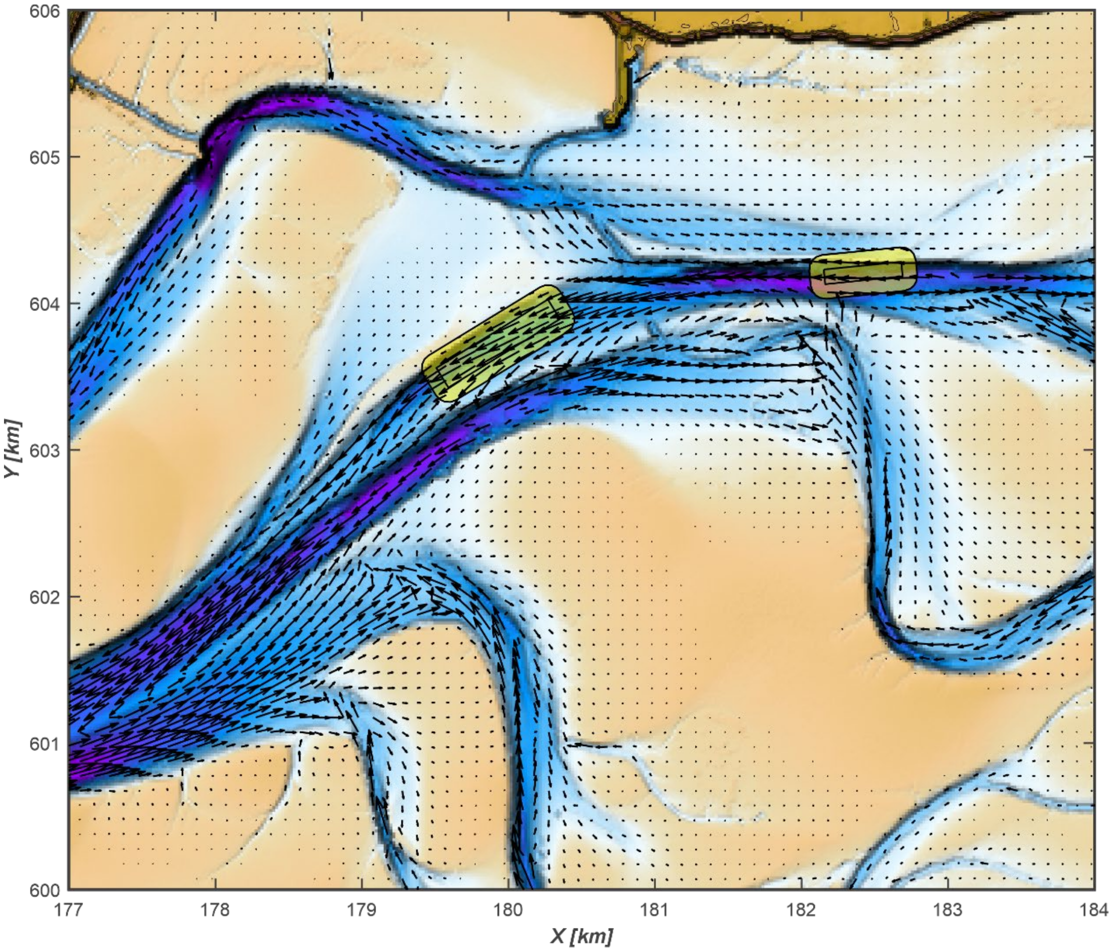


Figure 3-9: Patterns of the scaled annual sediment transport at both disposal locations.

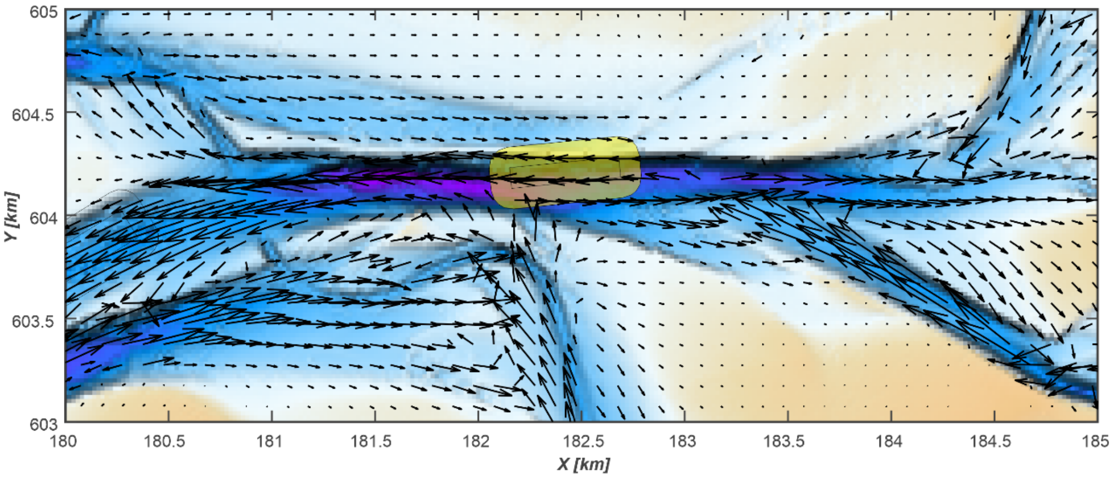


Figure 3-10: Details of the year-averaged sediment transport at the Zuiderspruit disposal area.

3.3 Pathways from the disposal sites

To investigate the potential recirculation of sand-sized sediment originating from the disposal sites, sediment transport pathway simulations were conducted using the SedTRAILS method. This analysis is particularly relevant given the complex transport dynamics observed near the Scheepsgat and Zuiderspruit disposal locations, where convergence and divergence zones may inhibit effective dispersal and promote localized sediment trapping.

By tracking particle pathways based on detailed sediment transport field (from Delft3D-FM), the SedTRAILS analysis provides insights into whether disposed sediments remain confined to the vicinity of the disposal sites, contribute to infill of nearby managed channels, or are successfully transported to other areas in or out of the basin.

3.3.1 Zuiderspruit

The pathways show both east (ebb) and westward (flood) dispersion (Figure 3-11), as expected. Most of the particles (*ca.* 63%) migrate westward towards Kikkertgat. A limited number of particles migrate onto the sill separating Kikkertgat and Molengat and attach to the shoals that are present here. These particles indicate that it is likely that some of the dispersed sediments will travel back into northern part of the navigation channel. From Kikkertgat some of the particles attach to the southeastern Molengat shoal, while other particles migrate further westward into Dantziggat. These particles end onto the sill area that forms the transition from Dantziggat and Borndiep. In potential these particles can then be picked up by the currents in Borndiep as was visible from Figure 3-7.

There is no sediment migration toward the southern section of the Ameland–Holwerd channel. This strict division is likely the result of the well-defined ebb- and flood dominant parts of the Dantziggat channel. It is also likely that the sill in between these two channel parts forms a physical barrier for sand sized sediment limiting the sediment transport into the flood-dominant part of the channel. This division is unlikely to exist for smaller grained material as these travel through the water column.

A smaller, but still substantial part of the particles (37%) travels eastward through Noorderspruit towards the Ameland tidal divide (*i.e. wantij*). A detailed analysis of the particle movement in the disposal area shows that a large variation in response is present in the disposal area (Figure 3-11 and Figure 3-12).

Sediment source-sink from the disposal area

Sediments released from the Zuiderspruit disposal site are transported in both flood and ebb directions. Particles originating from the southern boundary of the disposal polygon predominantly migrate eastward (i.e. flood directed), moving towards the water divide (*wantij*). In contrast, sediments released from the central and northern parts of the polygon mainly migrate westward (Figure 3-12).

For these westward-moving sediments, multiple transport pathways are identified. A portion of the material is captured by adjacent shoals, while another fraction is transported further towards the inlet. Additionally, part of the sediment recirculates in the direction of Ameland (see the green lines in Figure 3-12). This latter pathway is considered unfavourable, as it increases the likelihood of sediment deposition within the navigation channel.

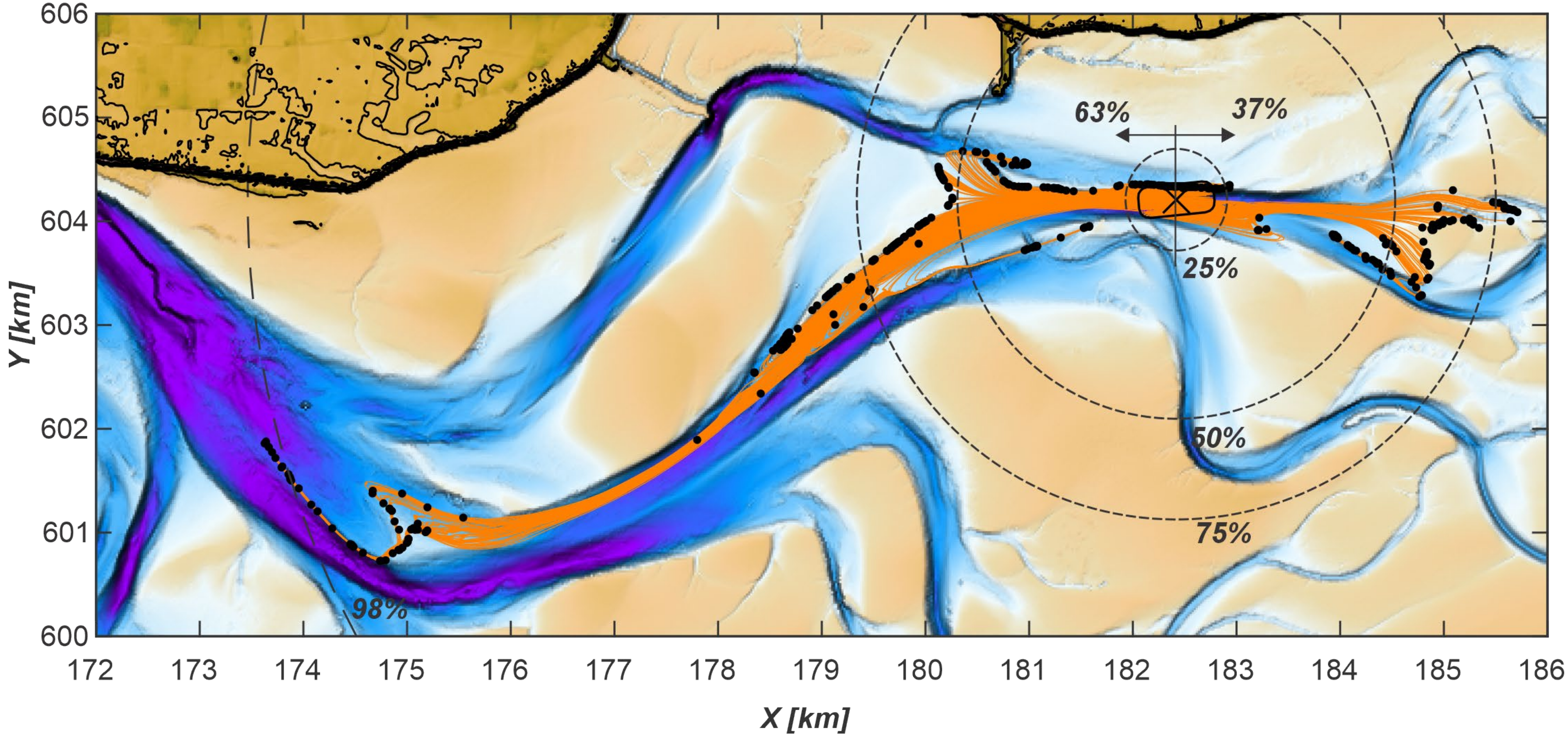


Figure 3-11: Sediment pathways from the Zuiderspruit.

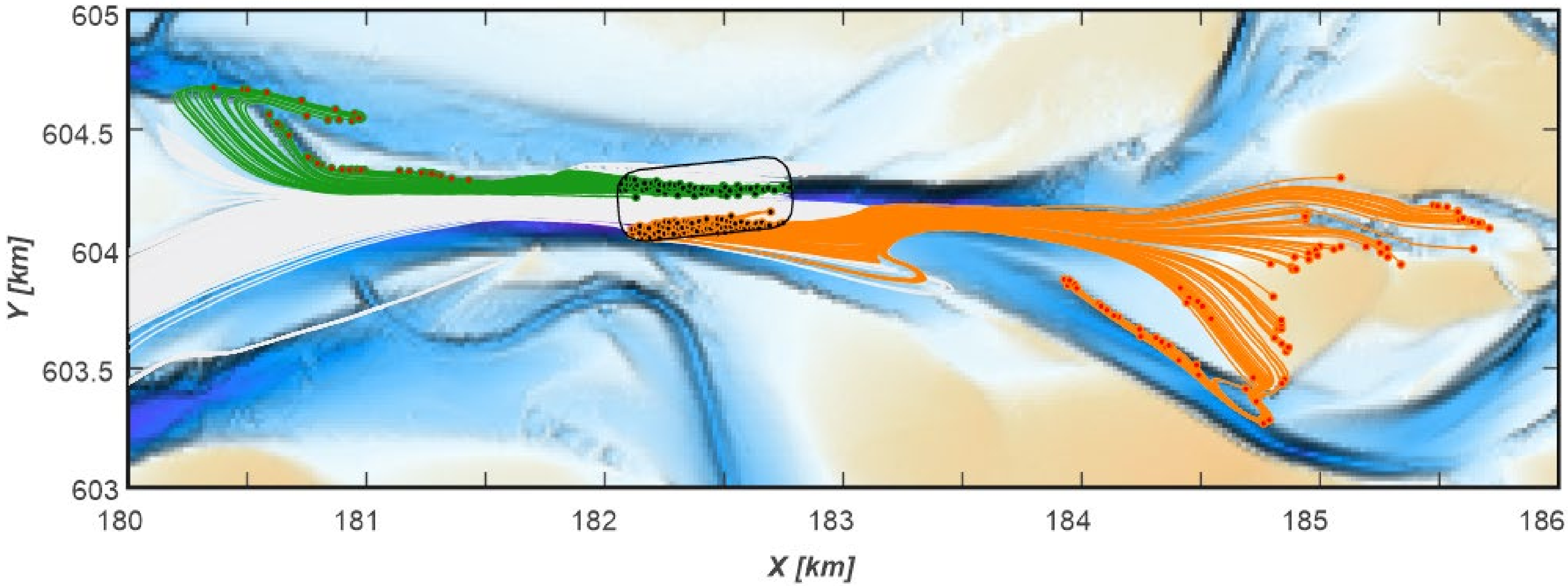
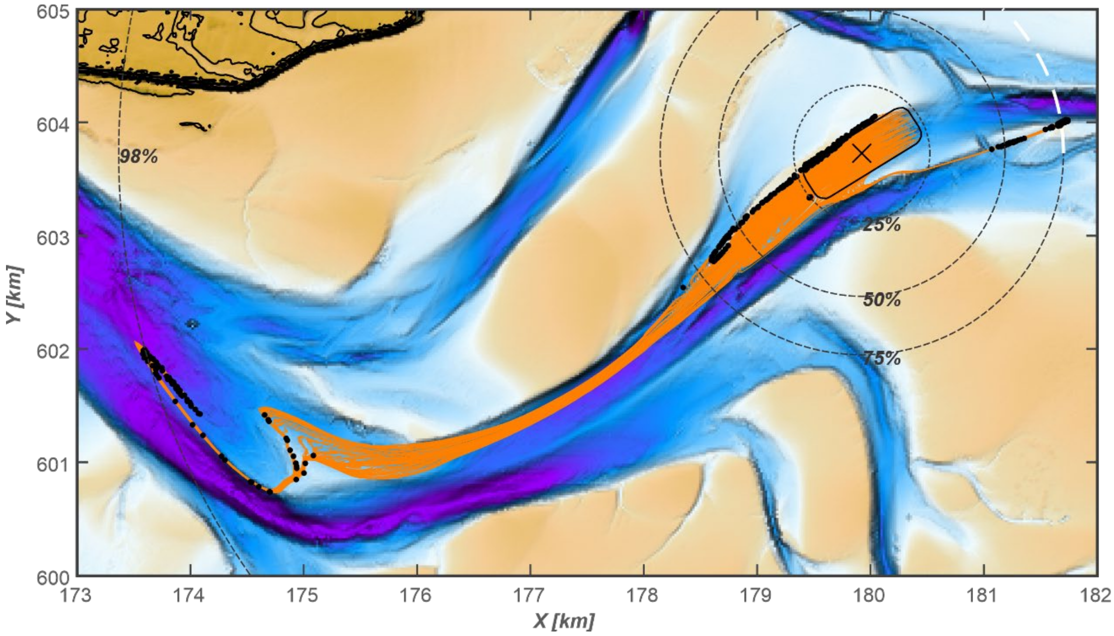


Figure 3-12: Sediment pathways highlighting the origin-destination of the sediments moving towards the water divide (orange) and towards Ameland (green). White tracks are the remaining pathways.

3.3.2 Scheepsgat

At the Scheepsgat, sediment transport is predominantly directed towards the west (*ca.* 67%). A fraction migrates towards the Ameland inlet (*ca.* 17%), while another portion of the sediments is deposited on the adjacent shoal (*ca.* 27%) or becomes trapped within a recirculation cell (*ca.*23%), over the sill, located near the disposal site. Eastward sediment transport amounts to ca. 23% and consist of sediments that crossed the sill and entered the flood-dominant part of the channel.

Figure 3-13 presents the detailed sediment pathways, with source-sink relationships distinguished by different colours. The recirculation cell is of particular interest (see blue lines in Figure 3-13), as sediments appear to remain trapped immediately adjacent to the disposal polygon (at the red dot). No significant return of sediments from this area to the navigation channel is observed.



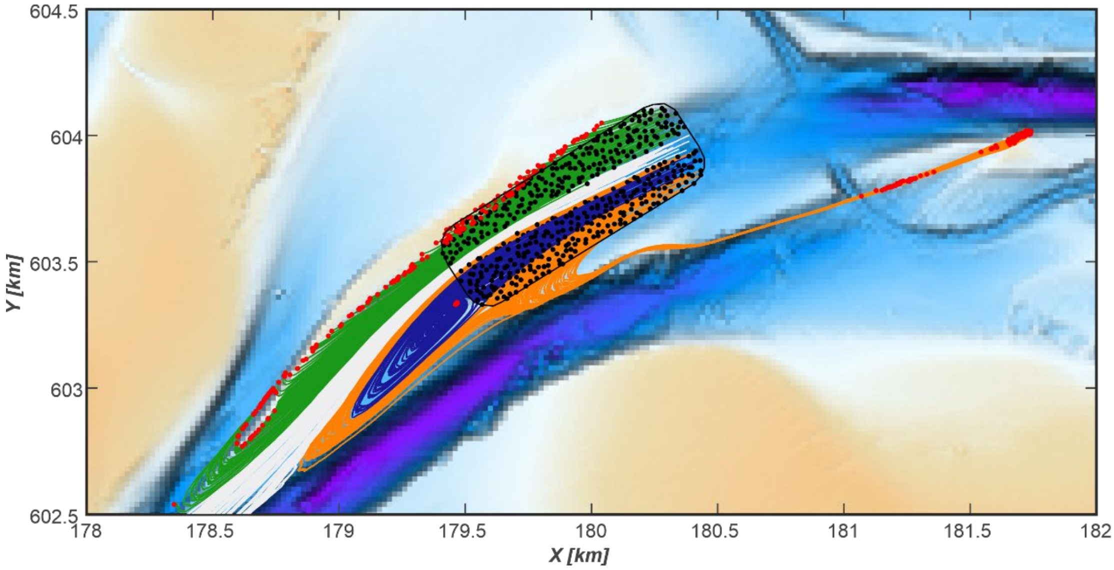


Figure 3-13: Sediment pathways from the Scheepsgat. (Top) overall sediment distribution; (bottom) highlights the origin-destination of the sediments moving towards the water divide (orange) and towards the inlet (green) and the local recirculation (blue). White tracks are the remaining pathways.

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3.3.3 The alternative Zuiderspruit

Due to the recirculation of sediments towards the navigation channel, RWS asked to investigate if an alternative location just adjacent to the current disposal site would improve the sediment dispersion away from the dredged channel. Here we performed SedTRAILS simulations with the disposal polygon shifted eastward towards the water divide.
The results (Figure 3-14) shows that a slight location shift results in predominant sediment dispersion towards the water divide, as expected.

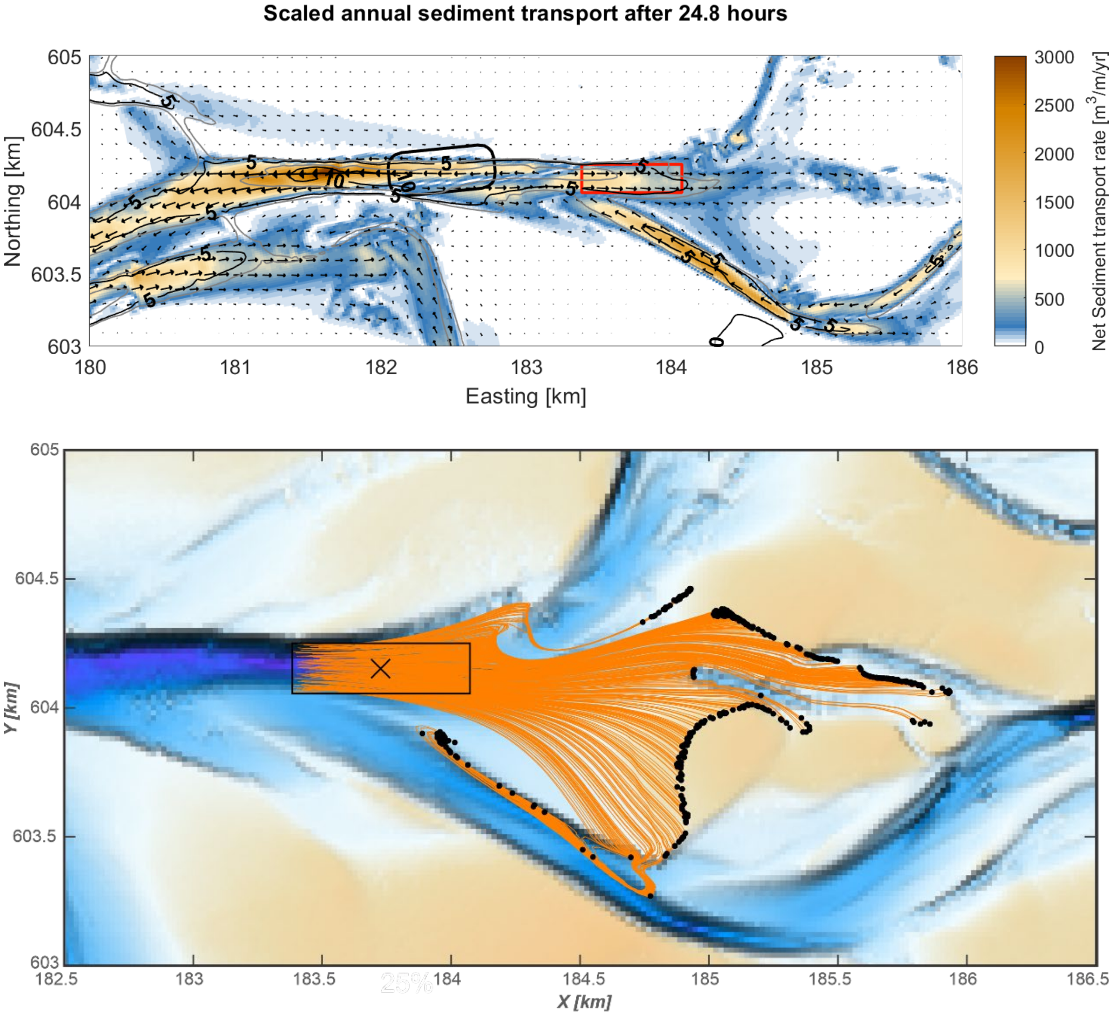

Figure 3-14: Sediment pathways from the alternative fictive Zuiderspruit disposal location. (Top) location of the Zuiderspruit alternative and the underlaying sediment transport pattern; (bottom) sediment pathways from the alternative Zuiderspruit.

This exercise, using the alternative (fictive) Zuiderspruit location, highlights the importance of micro-location in the selection of disposal sites. Owing to the complex channel morphology and the ebb–flood dominance in the system, even a relatively small spatial shift (i.e. in comparison with the basin scales) can substantially alter the resulting sediment pathways. The exercise also reinforces the strength of the current methodology, in which Delft3D and SedTRAILS are combined to support the optimization of disposal site selection.

4 Conclusions

The primary goal of the study is to assess if the numerical models, such as Delft3D-FM in combination with SedTRAILS, can be used to evaluate disposal site location and effectiveness in terms of sediment spreading, and eventually can contribute to more robust and sustainable sediment management. The combination of Delft3D-FM and SedTRAILS proved effective in efficiently mapping sediment pathways to support the assessment of sediment disposal. In this study, the -Ameland basin was chosen as a test case. The methodology was applied to two disposal sites: Scheepsgat and Zuiderspruit.

High-resolution Delft3D-FM hydrodynamic and sediment transport simulations, together with SedTRAILS sediment-pathway analysis, were applied with representative tidal and wind regimes while maintaining detailed spatial resolution across the model domain within feasible computational time. This approach enables an evaluation of how effectively these methods identify dominant sediment pathways, potential recirculation zones, and their implications for dredging and sediment disposal practices.

While larger-scale sediment transport patterns, such as the general ebb- and flood-dominant channel behaviour, can also be resolved with coarser models, the finer details that govern sediment dynamics near critical features like sills (*drempels*), channel junctions, and shoal edges require a much more refined grid. This is particularly important in areas near the disposal sites, where small-scale hydrodynamic structures significantly influence the direction and fate of sediment transport. The results shown here clearly illustrate that transport patterns are not uniformly distributed across or along channels. Instead, they exhibit pronounced spatial complexity, with sharp transitions, localized divergence and convergence zones, and asymmetries that would be lost in lower-resolution approaches. These fine-scale dynamics were crucial to understand in order to evaluate the potential for sediment trapping or recirculation - especially in relation to disposal locations.

Sediment pathways at Scheepsgat and Zuiderspruit
At Scheepsgat, the disposal area lies next to a major convergence zone near the sill (*drempel*) separating the northern and southern branches of Dantziggat. Although the site is situated within an ebb-dominated location, sediment passing over the sill can be entrained in an eastward, flood-directed transport corridor leading toward the Piet Scheve Plaat sill.
Our results show that, under average representative conditions, approximately:

- 23% of disposed sand recirculates toward the sill
- 17% is transported towards the inlet, and
- 23% is transported eastward
- 37% remain nearby and/or attach to nearby shoals

Most particles initially move westward toward Dantziggat and adjacent shoals, but the proximity to the sill means that relatively small hydrodynamic changes (storms, surges, morphological adjustments) could shift pathways.

At Zuiderspruit, the disposal site lies near a divergence in residual transport. As a result, sediment follows both:

- Westward pathways (~63%), moving toward Kikkertgat and sometimes the Holwerd-Ameland ferry channel (up to 13% of particles), potentially reintroducing material into managed navigation areas.
- Eastward pathways (~37%), primarily through Noorderspruit toward the Ameland water divide.

Transport direction depends strongly on the exact release location within the disposal polygon: southern releases favour eastward flood-dominated paths, while central and northern releases move predominantly westward. Shifting the disposal site eastward would likely enhance eastward transport towards the water divide (*wantij*) and reduce recirculation in the navigation channel.

Overall, the study demonstrates that sediment pathways in the Borndiep-Ameland basin are highly sensitive to local hydrodynamics and morphology. High-resolution Delft3D modelling combined with SedTRAILS effectively reveals these pathways and supports more site-specific sediment management aimed at minimizing recirculation and unwanted channel infill.

Applicability of SedTRAILS for evaluating sediment disposal locations
With SedTRAILS we can evaluate if the disposal locations fit within the current sediment management practice; retain dredged sediment within the tidal basin, by depositing sediment at locations where natural processes can redistribute it efficiently throughout the system. Also, we can check if the sediment will not (potentially) end up in undesirable locations, e.g. areas with ecological values or navigation channel.

Besides optimizing the overall location of the disposal site, the results here show that within the disposal location different sediment pathways can occur, depending on the size, dominant processes and local morphodynamics. With SedTRAILS we can provide more detailed information on such patterns and its implications for disposal strategies. However, in order to provide reliable information, a high-resolution, validated Delft3D-FM model is essential.

Limitations and assumptions
Although the approach presented in this report provides valuable insights into sediment pathways, some key limitations and underlying assumptions should be acknowledged.

First, the hydrodynamic forcing used in this study was based on representative tide and wind conditions. As a result, extreme events, such as storms, surges, and wind-wave conditions were not included in the simulations. These events are known to influence sediment dynamics on tidal flats and shoals, as well as sediment exchange with adjacent channels and basins. Consequently, the results do not account for the variability that may occur under more energetic or episodic conditions.

Second, the current implementation of SedTRAILS is validated to sandy sediment transport. The absence of fine-sediment dynamics should therefore be considered when interpreting the presented results.

Finally, SedTRAILS currently does not resolve transport timescales and associated distances, focusing instead on indicative pathways. Ongoing developments within SedTRAILS aim to address these aspects, but they were not yet available for application in this study.

Below we detail recommendations for future similar studies.

5 Recommendations

Maintain High-Resolution Spatial Modelling
Sediment transport in the Wadden Sea basins, such as the Ameland, is strongly influenced by small-scale (local) features, including divergence zones, residual flow structures, sills, and cross-channel asymmetries. Adequate spatial resolution is therefore essential to compute sediment pathways. Future studies should continue to apply high-resolution models capable of resolving these fine-scale patterns to support robust sediment management decisions.

Expanded Forcing Scenarios Including Seasonal and Episodic Variability
Future modelling should incorporate a wider range of hydrodynamic and meteorological conditions to capture both seasonal changes and episodic high-energy events. Calm periods promote deposition of sediments, while storms, surges, strong winds, and waves are key drivers of remobilization. These high-energy events are also essential for transporting sediment on higher grounds - such as shoals and tidal flats - that remain largely immobile/inactive under average conditions. Including this full spectrum of forcing is necessary for accurately representing sediment pathways but also sediment budgets, and long-term morphological development.

Include Cohesive Sediment Dynamics in Future Modelling
The current simulations consider only sand-sized material, limiting insight into the behaviour of fine sediments such as silt and clay. Despite the fact that the present disposal locations are mainly situated in sand-dominated areas, fine sediments are present and relevant in other parts of the basin, and therefore also present in the dredged disposal. Because fine sediments remain suspended longer and respond sensitively to small variations in flow velocity, duration of slack tides, and turbulence, they are prone to accumulate in low-energy environments (e.g., recirculation zones, intertidal flats, salt marshes, and near disposal sites). To accurately assess their fate and potential for recirculation, future modelling should incorporate cohesive sediments.

Combine scenarios towards sediment management
Given that sediment transport varies both in space and time, effective prediction of sediment pathways from the disposal sites requires the integration of high-resolution hydrodynamic modelling, and scenario-based simulations that include seasonal variability and storm conditions. The interpretation of the individual scenarios will enable more reliable assessment of sediment management practices, such as optimal locations and timing of disposal to avoid unintended sediment retention near disposal sites or increased sedimentation in sensitive ecological or navigational areas.

6 References

Elias, E.P.L., & Pearson, S.G. (2020). SedTRAILS: A Tool for Visualizing and Understanding Sediment Transport Pathways. Deltares report, in collaboration with Delft University of Technology.

Elias, E.P.L., Pearson, S.G., & De Ronde, J. (2020). Application of SedTRAILS in nourishment strategies. Deltares Report.

Elias, E.P.L. & De Wilde, T. (2026). Morfologische Analyse Centrale Waddenzee: Een verdiepende studie van het Amelander Zeegat. Deltares Report 11211571-003-ZKS-0001

Lambregts, S. (2021). Sediment dynamics in the Wadden Sea: Application of SedTRAILS in inlet systems. MSc Thesis, Delft University of Technology.

MacDonald, N.J., Davies, A.G., & McBride, R.A. (2006). The PTM: A sediment particle tracking model for estuarine and coastal environments. Journal of Coastal Research, SI(39), 1097–1101.

Storlazzi, C.D., Norris, B.K., & Rosenberger, K.J. (2017). The influence of grain size, grain size distribution, and bed slope on sediment transport on fringing coral reef flats. Continental Shelf Research, 133, 1–16.

Van Rijn, L.C. (2004). Sediment transport, morphology and computational modelling of aquatic systems. Aqua Publications.

Van Rijn, L.C. (2007). Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport. Journal of Hydraulic Engineering, 133(6), 649–667.

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