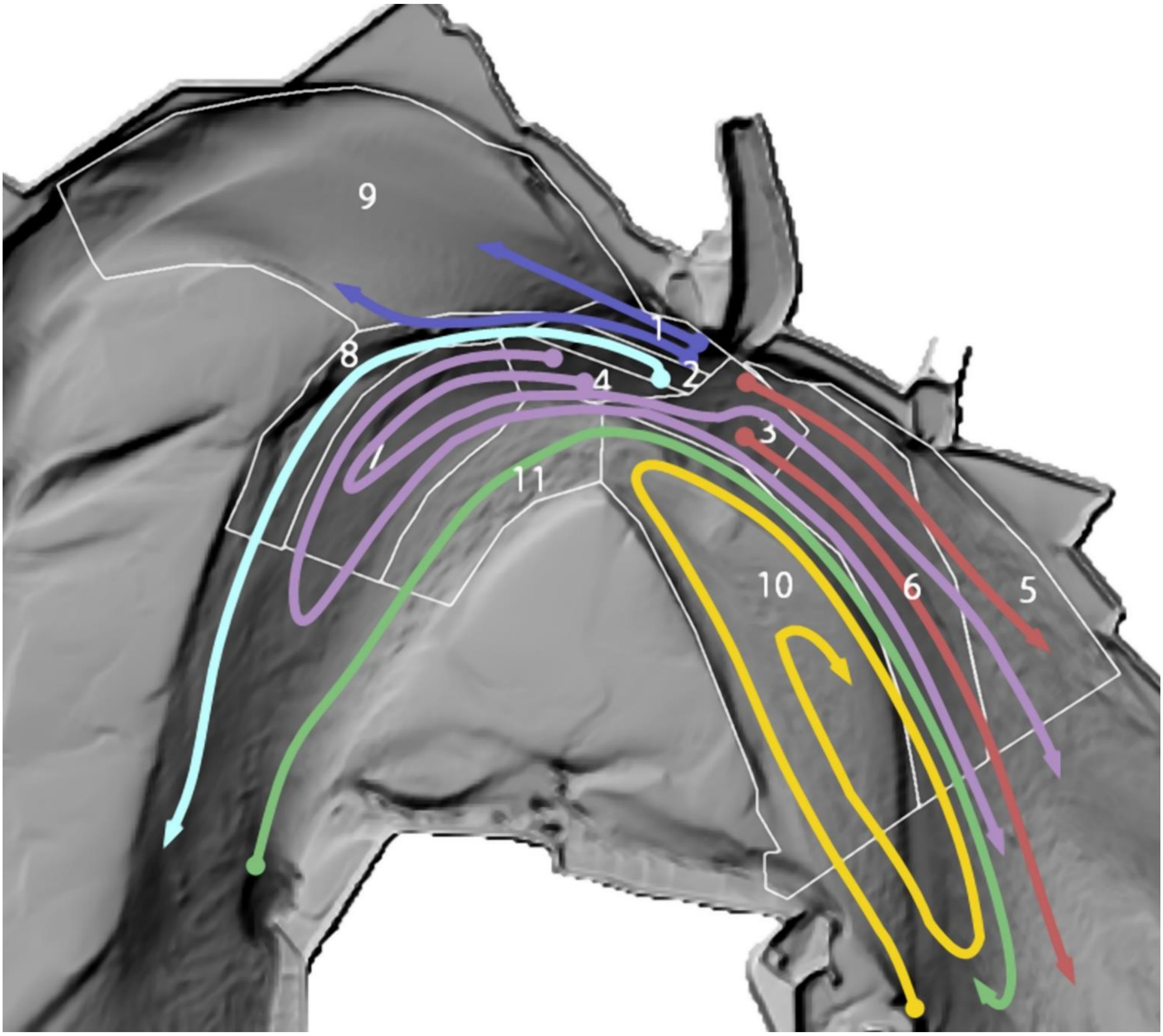
Investigation of Sediment Pathways in the Put Van Hansweert

Morphological effects of dumping in a deep pit of the Western Scheldt



Investigation of Sediment Pathways in the Put Van Hansweert
Morphological effects of dumping in a deep pit of the Western Scheldt

Author(s)
Edwin Elias
Floortje Roelvink
Stuart Pearson
Bas Huisman

Investigation of Sediment Pathways in the Put Van Hansweert
Morphological effects of dumping in a deep pit of the Western Scheldt

Client	Vlaams-Nederlandse Scheldecommissie
Contact	Frederik Roose
References	Email 13 en 17 januari 2020 “vraag met betrekking tot nadere analyse verspreiding zand in diepe putten”.
Keywords	Western Scheldt, Put van Hansweert, sand transport, dredging and dumping, SedTRAILS

Document control	
Version	1.0
Date	14-01-2021
Project nr.	1210301-001
Document ID	1210301-001-ZKS-0010
Pages	43
Status	final

Author(s)		
	Edwin Elias Floortje Roelvink Stuart Pearson Bas Huisman	

Doc. Version	**Author**	**Reviewer**	**Approver**	**Publish**
1.0	Edwin Elias	Ymkje Huismans	Toon Segeren	
	Floortje Roelvink			
	Stuart Pearson			
	Bas Huisman			

Samenvatting

Een aanzienlijke baggerinspanning is nodig om de vaargeul van de Westerschelde op diepte te houden. Het gebaggerde materiaal wordt teruggestort in het estuarium om er voor te zorgen dat de sedimentbalans niet veranderd én om de effecten op de omgeving te minimaliseren. Deltares is gevraagd door de ‘Vlaams Nederlandse Schelde Commissie’ (VNSC) om verschillende strategieën voor het storten van gebaggerd sediment te bestuderen. De Put van Hansweert is een locatie die is aangemerkt als mogelijke stortlocatie. Als onderdeel van dit onderzoek is in deze rapportage onderzoek gedaan naar de verspreidingsrichtingen van sediment vanuit de Put van Hansweert én de verbindingen die er morfologisch zijn met de omliggende gebieden. Zo kan verduidelijkt worden welke gebieden beïnvloedt kunnen worden door de stortingen in de Put van Hansweert. Ook draagt het bij aan het beter begrijpen van de verspreiding van gestort sediment in diepe putten.

De verbindingen van de Put van Hansweert naar omliggende gebieden zijn met het *SedTRAILS* model onderzocht. Dit model stelt de transportpaden samen op basis van de resultaten van moroflogische berekeningen met Delft3D. Een belangrijke conclusie is dat SedTRAILS een goede overeenkomst laat zien met het conceptuele kader dat door Huismans et al. (2021) geschetst is voor de morfodynamica van de Put van Hansweert. Bevindingen zijn verder:

- Het zuidelijke en centrale deel van de Put van Hansweert verspreiden sediment via de hoofdgeul met name naar de drempels. Opvallend is dat het via de hoofdgeul naar de Overloop van Hansweert getransporteerde sediment verder wordt vervoerd naar de binnenbocht (i.e. via een indirecte route). Dit zou de versterkte aanzanding op de binnenbocht kunnen verklaren die na de proefstortingen in de Put van Hansweert werd waargenomen.
- Een beperkte hoeveelheid sediment migreert van de noordwest-zijde van de Put van Hansweert naar het Middelgat. Het gaat om een klein volume dat op lange-termijn hierheen wordt vervoerd.
- Er is tijdens vloed een sterk noordoost gericht transport aanwezig op de westelijke rand van de Platen van Ossenisse. Dit verklaart de autonome geobserveerde aanzanding op de binnenbocht. Door de tijd heen wordt dit sediment van de noordrand van de Platen van Ossenisse in oostelijke richting getransporteerd naar de Drempel van Hansweert.
- Ter plaatse van de drempels is sprake van circulatie van sediment waardoor sediment ter plaatse vastgehouden wordt.
- De analyse van de sedimentpaden geeft geen indicatie dat er sprake zou zijn van aanzanding in de toegang van de haven van Hansweert.

Het wordt aanbevolen om SedTRAILS modellering ook toe te passen voor andere delen van de Westerschelde waar sediment wordt gestort. Het model kan daarnaast ook worden gebruikt voor optimalisatie van de stortlocaties (i.e. qua volume en ruimtelijke verdeling) én om de meer of minder morfologisch actieve gebieden van de Westerschelde te onderscheiden. Dit soort kennis kan dan worden gebruikt in kwalitatieve analyses (en mogelijk kwantitatief) om te beoordelen wat de levensduur van een storting per locatie zal zijn én in hoeverre de lokale capaciteit voor bergen van sediment wordt benut.

Summary

Considerable dredging efforts are needed to maintain the Western Scheldt's main navigation channel. The dredged material is dumped back into the estuary to balance its sediment budget and minimize effects on the estuarine processes. Deltares was requested by the 'Vlaams Nederlandse Schelde Commissie' (VNSC) to study various dredge-dump strategies. The Put van Hansweert is one of the main locations that is marked as a deposition area. As part of this research, this report studies the redistribution pathways of disposed sediment in the Put van Hansweert and the morphological connections to the neighbouring regions. Areas which may be affected by sediment disposal in the Put van Hansweert have been identified. The results of this study contribute to a better understanding of the morphological effects of sediment disposal in deep pits.

Sediment connectivity in the Put van Hansweert was studied using the *SedTRAILS* model, which constructs sediment pathways from Delft3D model results. An important conclusion is that the *SedTRAILS* results show good agreement with the conceptual framework of regional morphodynamics, that is presented in Huismans et al. (2021). Specific findings of the *SedTRAILS* modelling include:

- The southern and central part of the Put van Hansweert are actively dispersive and move sediment through the main channel to the sills. Noticeable is that along-channel redistribution of sediment to the Overloop van Hansweert is further transported to the inner bend (i.e. via an indirect route), which may explain the significant sedimentation that was observed on the inner bend after the pilot disposals at the Put van Hansweert.
- A limited amount of sediment migrates from the northwestern side of the Put van Hansweert into the Middelgat. This exchange is a long-term process with small migration rates.
- A strong northeast directed transport is present along the western shallow margin of the Platen van Ossenisse during flood, which explains the observed autonomous accretion at the inner bend. Over time this sediment, from the northern tip of the Platen van Ossenisse, will move eastward to the Drempel van Hansweert.
- Sediment gyres are present at the sills, which may trap sediment.
- The sediment pathway analysis does not indicate that sediment disposal may result in sedimentation in the harbour entrance of Hansweert.

It is recommended to apply *SedTRAILS* modelling also for the other regions in the Western Scheldt where sediment is dredged and dumped. The model can be used to optimize disposal locations and discern active versus less active regions of the Western Scheldt. Such knowledge can be used to qualitatively (or possibly quantitatively) judge the expected lifetime of disposal locations and their capacity to retain sediments.

Contents

1 Introduction

1.1 Background

The Western Scheldt provides access to the Harbour of Antwerp. Keeping the main navigation channel at depth to ensure unhampered ship access requires continuous, large dredging efforts. The dredged material is dumped back into the estuary to maintain its sediment budget and minimize effects on the estuarine processes. Deltares was requested by the ‘Vlaams Nederlandse Schelde Commissie’ (VNSC) to study various dredge-dump strategies. The aim of this report is to better understand the routes that sediment can take from the Put van Hansweert to the surrounding regions (i.e. main channel, inner bend, side slopes and secondary channels), which helps to better understand the morphological effects of sediment disposal in deep pits. This study is especially relevant for improving the definition of future sediment disposal in the Put van Hansweert, i.e. how and where.

1.2 Study Area

The Put van Hansweert is centrally located in the Westerschelde (Western Scheldt) Estuary (Figure 1.1). In total the Scheldt system is 350 km long and extends through the Netherlands, Belgium and France. Tidal influence extends roughly 160 km upstream to the weir at Gentbrugge. Upstream of the weir the channel is strictly fluvial. The downstream part can be subdivided in a single-channel part (between Gent and the Flemish-Dutch border), a multi-channel part that stretches between Vlissingen and the Flemish-Dutch border (the Westerschelde estuary), and the Vlakte van de Raan ebb-tidal delta west of Vlissingen. The Vlakte van de Raan shoal effectively shelters the estuary from the North-Sea waves. The water motion in the estuary is therefore dominated by tides and is forced by a semi-diurnal (progressive) tide in the North Sea. This tide travels from south to north along the Dutch coast and from west to east into the estuary. The tidal wave is amplified and distorted as it travels up the estuary; the mean tidal range increases from 3.8 m at Vlissingen to 5.2 m at Antwerp, 78 km upstream. Peak tidal velocities range between 1 and 1.5 m/s with maximum flood velocities consistently exceeding the maximum ebb velocities. Flood volumes reduce from an average of 1100 million m^3 at Vlissingen to 70 million m^3 at Antwerp (Gerritsen and De Jong, 1983; Claessens, 1988).

The Westerschelde estuary (Figure 1.1) is characterised by multiple channels, separated by shoal complexes. The largest of the channels is the ebb-channel, while the parallel subordinate channels are flood channels. The ebb- and flood channels tend to join in subtidal shoal areas. The general channel (and shoal) patterns has been described by Winterwerp (2001) as a series of six macro cells. The Put van Hansweert is located in macro cell 4. In Figure 1.1 (bottom panel) an overview of a recent bathymetry is presented based on 2017 bathymetric measurements. The Put van Hansweert is located between Hansweert and the large shoal complex Platen van Ossenisse to the South. With depths exceeding 35 m the Put is considerably deeper than the adjacent channel upstream (Drempel van Hansweert) and downstream (Overloop van Hansweert) channel. In the Put van Hansweert only a central main channel is present, but on both the upstream and downstream side secondary channels exist. On the downstream side the Put van Hansweert connects to the main channel and the secondary channel Middelgat. Middelgat is separated from the main channel by a large shoal complex. The southern end of this shoal is called Rug van Baarland and the northern part is Molengat. Between Molengat en Hansweert, a relative wide and shallow sill separates the Middelgat from the main channel. Upstream of the Put van Hansweert the main channel curves southward over the Drempel van Hansweert into Zuidergat. The large shoal area Plaat van Walsoorden separates the main channel from the secondary channel Schaar van Waarde.

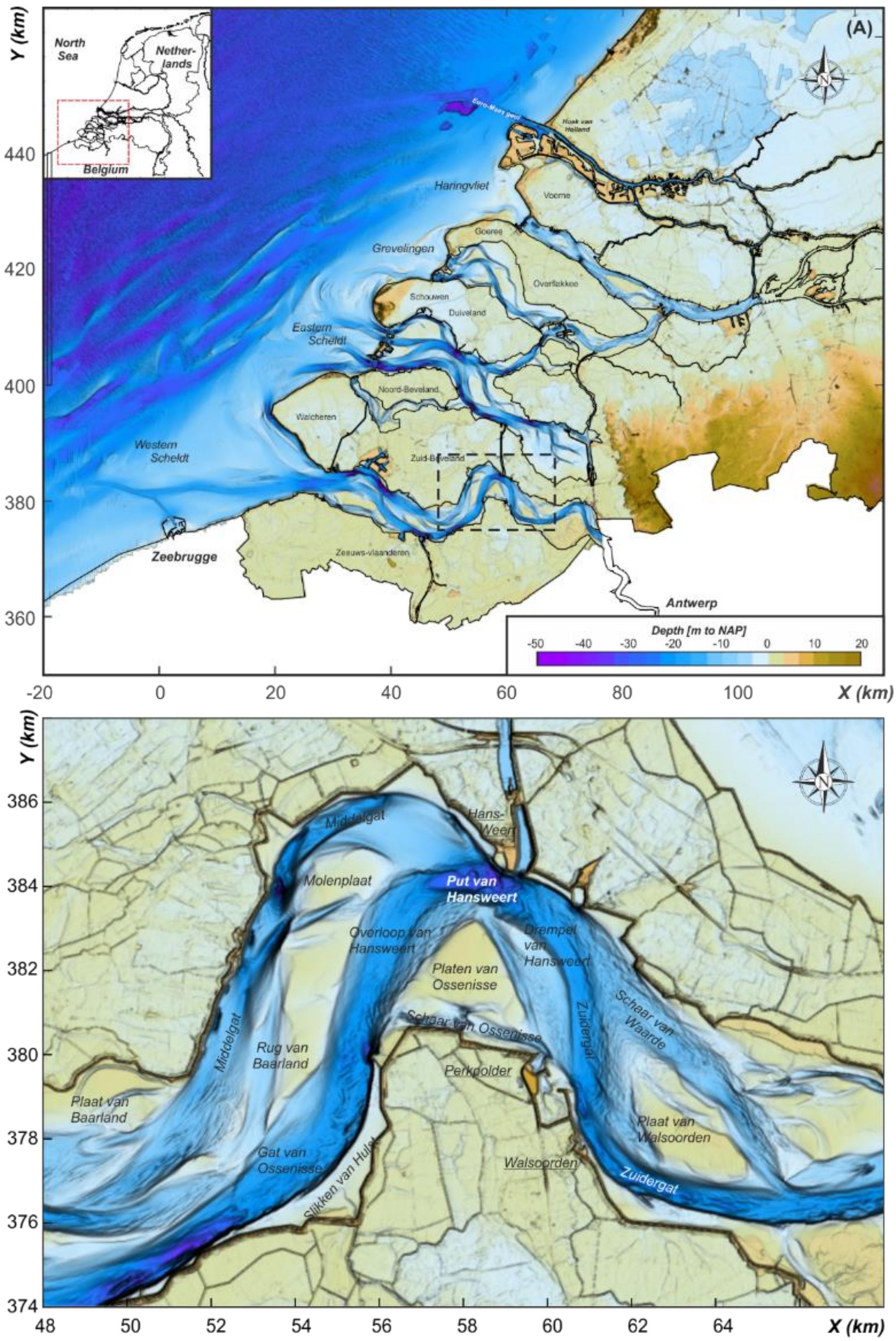


Figure 1.1: An overview of the morphological elements and geographical locations in the Bocht van Ossenisse (bottom panel) and its position in the Western Scheldt (top panel). Underlying DEM based on 2017 measurements. Note that we use the name Bocht van Ossenisse to describe the area between the Gat van Ossenisse/Plaat van Baarland and the Zuidergat/Plaat van Walsoorden.

1.3 A conceptual understanding of the Put van Hansweert

Deltares has carried out several studies to better understand and manage the dredging and dumping in the Western Scheldt. Van der Wegen et al. (2021) investigated the Western Scheldt hydrodynamics, focusing on local residual flow patterns in the deep pits of Hansweert and Borssele. Morphodynamic simulations for various dump scenarios and locations were carried out to analyze the impact on dredging volumes. Based on these simulations, Huisman et al. (2021) investigated the feasibility of dumping dredged sediments in deep channels of the Western Scheldt, focusing on residual transport to the dredging locations and impact on tidal characteristics of the Western Scheldt. This study was conducted through process-based modelling using Delft3D with various principal solutions for dredging and dumping scenarios around the deep Put van Hansweert. These authors showed that an increase in dredging volumes should be anticipated in the first years after disposal. The effects of disposal on the tides are expected to be small.

Other studies focussed on understanding the local spreading of sediment just after dumping in the deep pit. IMDC (2019) showed that dumped sediment falls towards the bed in a density plume, where it spreads over an area with a diameter of approximately 300 m. A considerable part (up to 50%) of the sediment could not be found a few weeks after the sediment disposal (Huisman et al., 2018). Plancke et al. (2019a) shows that especially the finer sand fractions could not be traced back.

Mesoscale morphological changes around this deep pit were studied by Plancke et al. (2019) and Huismans et al. (2021) through detailed analysis of well-monitored pilot placements in the Put van Hansweert (see Figure 1.2) complemented with some 2D and 3D simulations. The findings of these studies were summarized in a conceptual framework as summarized in Figure 1.2 (in Dutch).

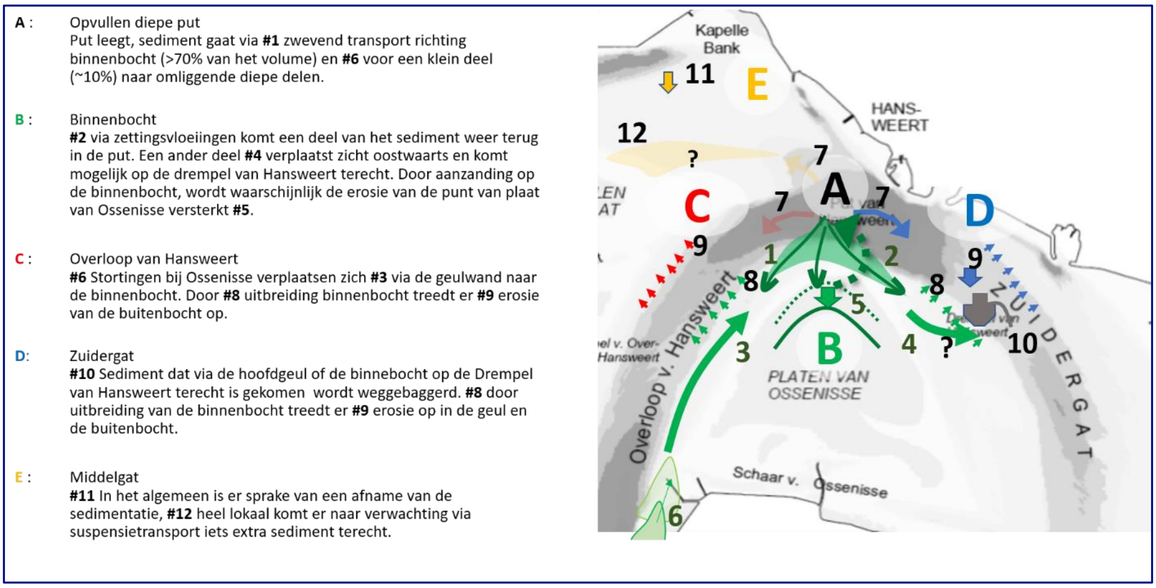


Figure 1.2: Conceptual model displaying the meso scale morphodynamics of the Put van Hansweert area (from Huismans et al. 2021, in Dutch).

Plancke et al. (2019), Huisman et al. (2021), and Huismans et al. (2021) conclude that most of the dumped deposits accrete on the inner bend of the Put van Hansweert (from the pit up to ~MSL -5m). A 70% increase in accretion of the inner bend was observed after dumping. According to Huismans et al. (2021) this increase suggests that a large part of the sediment is moved to the inner bend by suspended sediment transport. The steepening of the inner bend resulted a number of times in a collapse of the side wall (liquefaction), which moved sediment back into the Put van Hansweert.

The observed transport to the surrounding regions was relatively small (~10%), although it may have been difficult to trace such accretion as the main channel is dredged regularly. Considerable erosion was present at the Platen van Ossenisse (i.e. from ~MSL -5m and upward).

An important observation is also the strong northward transport of sediment that occurs along the eastern margin of the Platen van Ossenisse during flood. This transport moves sediment towards the western side of the Drempel van Hansweert.

An interesting observation for Middelgat is the reduced net accretion rate after disposal. The decrease in accretion rate compared to the period before disposal is rather unexpected. Enhanced erosion occurred at the north-eastern side of the Zuidergat, which is expected to be a result of the accretion of the inner bend. Similar erosion was observed at the north-western side of the Overloop van Hansweert, but this erosion was not affected substantially by the pilot disposals. In fact, the bend of the main channel is widening over time just East and West of the Put van Hansweert.

1.4 Objectives

The objective of this report is to better understand the morphological linkages or sediment pathways between the Put van Hansweert and the surrounding regions (i.e. main channel, inner bend, side slopes and secondary channels). Sediment disposal in the Put van Hansweert is more likely to influence the regions that have a morphological linkage. Identifying these linkages, also called connections or connectivity, contributes to a better understanding of the morphological effects of sediment disposal in the Put van Hansweert and to understanding sediment disposal in deep pits in general. Sediment connectivity can be used in the interpretation of morphological changes that were observed and allows us to test and improve the conceptual framework as discussed in Figure 1.1. In addition, understanding sediment connectivity can be used to improve the definition of future sediment disposals in the Put van Hansweert, i.e. how and where.

1.5 Reader

In addition to this introduction, this report consists of 4 chapters. Chapter 2 provides a brief introduction into the Delft3D 4 model. In this Chapter we also discuss SedTrails (***Sed****iment* ***TRA****nsport v****I****sualization &* ***L****agrangian* ***S****imulator*); a new tool that was developed as a postprocessing routine to enables visualization of the sediment pathways based on the sediment transports from traditional Delft3D simulations (see e.g. Stevens et al. 2020; Pearson et al. 2020 for examples). Chapter 3 provides an analysis of both the Delft3D model results and the *SedTRAILS* results. Firstly, we present a brief analysis of the velocity and sediment-transport fields that were computed with Delft3D in the Put van Hansweert. Secondly, we present sediment pathways computed with *SedTRAILS, a*nd present an analysis of the connectivity between various zones in the Put van Hansweert and the surrounding channels and shoals. A discussion of the results in relation to the conceptual model is given in Chapter 4. The final Chapter presents the conclusions and recommendations.

2 Model and Method

This Chapter describes the models and methods used to calculate sediment transport pathways. In the first section, the Delft3D base model that is used to compute the sediment transport vector fields is briefly described. The second section describes the computation of the sediment transport pathways using the *SedTRAILS* tool.

SedTRAILS is specifically developed to understand sediment transports in complex morphodynamic systems such as tidal inlets or estuaries. To investigate sediment transport processes such as sediment bypassing, in a traditional Delft3D modelling approach long-term morphodynamic simulations would be required. Such simulations are computationally expensive and as a result such simulations are often run in 2D setting, at reduced grid resolution or through model schematisations and acceleration techniques. It is not always clear if such models capture the underlying essential physics accurately.

The *SedTRAILS* tool can be applied as a post-processing routine on existing Delft3D models and allow us to address a whole new range of questions. Such as:

- Where do particles from a particular source travel?
- From which sources do particular receptors receive particles?
- What are the connected pathways between two points?
- Are there sources that contribute to exclusively to certain receptors?

The *SedTRAILS* approach was specifically developed to simulate sediment trajectories accurately and computationally efficient over long-time scales. Runtime efficiency is obtained from decoupling the sediment trajectory computation from the sediment transport vector computation. Sediment transports vectors are still resolved using the advanced flow and sediment transport equations that are present in Delft3D 4 or Delft3D FM. We use classic morphodynamic schematisation techniques to derive a morphodynamic tide and/or wave climate. A morphostatic Delft3D model is then run in high resolution over the morphological representative conditions. Since there is no morphodynamic feedback the sediment transport vector fields remain unchanged for repetitive tides. With a careful selection of a representative morphological tide, the Delft3D computation only needs to executed once. The resulting sediment transport vector fields can then be repeated to simulate particle motion over longer timescales (e.g. months to years) using *SedTRAILS*. The particle motion computations are efficient (fast) as the sediment transport vectors are already resolved. As a result, sediment pathways can be computed over long time-frames (months to years) so particle trajectories span the entire morphological system.

2.1 Delft3D model

The hydrodynamic and sediment transport calculations are based on the scaled-down NeVla model (see Figure 2.1) that was originally developed by Grasmeijer (2013). This model was applied to the Put van Hansweert by Huisman et al. (2018) to study the effect of various dredge-dump strategies. In this study, we use the so-called T00 model; a reference model that does not include any dredge and dump strategies. For long-term morphodynamic simulations, 3D simulations are usually not feasible given the long runtimes, therefore 2Dh results were used. A runtime limitation is not present in the *SedTRAILS* application as a short-term morphostatic computation is used as a base. In this study, we therefore use the 3D model results to best represent the hydrodynamic and sediment transport processes that occur in the Put.

The base grid is a subset of the NeVla model by Grasmeijer (2013). The original NeVla model was further optimized and applied in the studies of Vroom et al. (2015); Schrijvershof & Vroom, (2016).

The applied version of the NeVLa model has offshore boundaries far seaward on the North-Sea and a landward boundary near Kruibeke (south of Antwerp). The model domain consists of a structured, orthogonal, curvilinear grid with over 400,000 cells that covered the estuary and nearby open sea (Figure 2.1). The offshore domain has a maximum grid-size of 1 km^2 (200 x 500m) along its seaward boundaries. The grid resolution in the Western Scheldt estuary is 50 x 150 m. The grid was aligned with the dikes along the estuary to optimally cover the estuary domain. The grid-cell size of 50x150 m is considered sufficient to capture the main channels and shoals in the Bocht van Ossenisse (Figure 2.1, lower panels). Sixteen equally spaced vertical sigma layers were used to simulate 3D effects within the model domain. The underlying model bathymetry of the Western Scheldt is based on the 2013 bathymetric measurements.

Open sea boundaries of the model were forced using astronomic tidal constituents and a year-averaged discharge was applied to represent the river flow of the Scheldt and near Bath (35 m^3/s). Wind is included as a spatially uniform, but variable in time, field based on the 2014 measurements in Vlissingen (Schrijvershof & Vroom, 2016). The model was extensively validated and calibrated to accurately reproduce the tidal propagation from the open-sea into the estuary (Vroom et al., 2015).

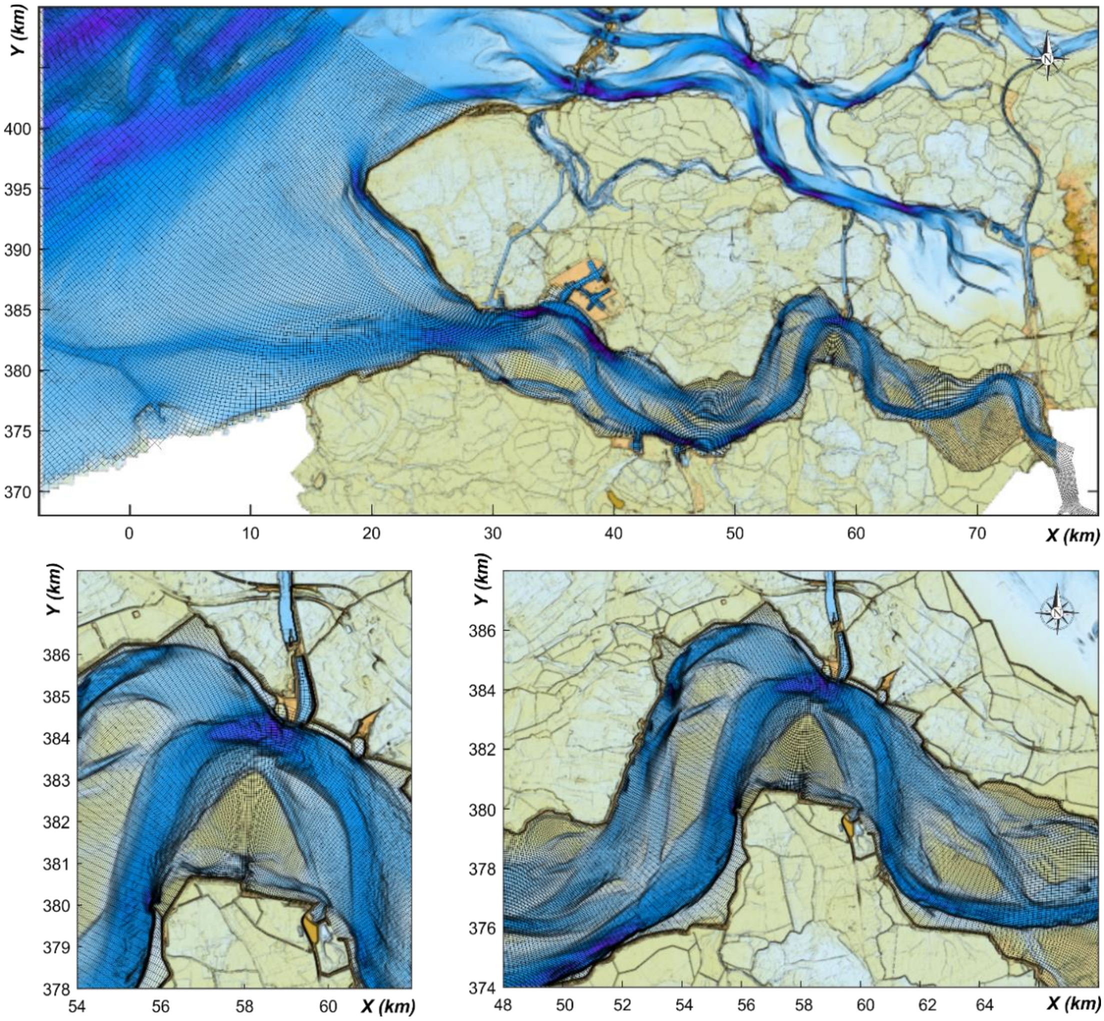


Figure 2.1: Overview of the NeVla Delft3D model (top panel factor 2 derefined for visualization) and details of the Put van Hansweert area (bottom panels).

The online morphology addition to Delft3D was used to simulate sediment transports in the flow domain at each computational time step (Lesser et al., 2004). The TRANSPOR2004 transport equations were used to model the movement of non-cohesive sand fractions and are implemented in the Delft3D flow solver. The Delft3D implementation of this formulation follows the principle description of Van Rijn (2007a,b,c), separating the sediment transport into suspended and bed-load components. Suspended sediment transport is computed by the advection–diffusion equation and includes the effect of sediment in suspension on the fluid density. Bed load transports represent the transport of sand particles in the wave boundary layer in close contact with the bed surface. The bed was schematized as a single sediment fraction using a median diameter (d_{50}) of 200 μm with non-erodible layers to armour specific channels and deep pits (based on TNO, 2003).

2.2 Basics of SedTRAILS

SedTRAILS (***Sed**iment **TRA**nsport v**I**sualization & **L**agrangian **S**imulator*) was applied to visualize, identify, and analyse the pathways along which sand-sized sediment was transported during the coupled hydrodynamic and sediment transport model simulations. Based on the Eulerian sediment transport vector fields, *SedTRAILS* computes the Lagrangian pathways that idealized particles travel as they pass through a changing vector field (Figure 2.2). *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).

Existing particle tracking approaches use velocity fields coupled with simplified formulas to govern sediment entrainment and settling thresholds based on critical shear stresses, often greatly simplifying the processes of sediment transport, as key behaviours like particle settling may be neglected. Trails uses the sediment transport vector fields derived from a transport formula that has been developed and rigorously tested for non-cohesive (sandy) sediment transport (van Rijn, 2007a,b,c) and computed at each computational time step in Delft3D. Mass fluxes of sediment calculated in a Delft3D simulation, S_m, are converted to an equivalent volume flux, S_v, by dividing by the bulk density, ρ_b, of the sediment:

$$S_v = \frac{S_m}{\rho_b} = \frac{\left[\frac{kg}{m \cdot s}\right]}{\left[\frac{kg}{m^3}\right]} = \left[\frac{m^3}{m \cdot s}\right] = \left[\frac{m^2}{s}\right]$$

The resulting flux is equivalent to that of the sand volume per unit width of a given grid cell face or transect, passing that point per second. The volumetric flux is converted into an effective velocity for transporting particles, u_{tr}, by means of division by a length scale, h_{tr}:

$$u_{tr} = \frac{S_v}{h_{tr}} = \frac{\left[\frac{m^2}{s}\right]}{[m]} = \left[\frac{m}{s}\right]$$

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. 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.

To capture temporal variations in sediment transport (for example, over the course of a tidal cycle), the 10-min mean total sediment transport (bed load plus suspended load) was calculated from the cumulative mean total transport from Delft3D simulations according to:

$$\overline{TT}(\Delta t_n) = \frac{\int TT(t_n) - \int TT(t_{n-1})}{(t_n - t_{n-1})} = \frac{\overline{TT}(t_n) \times (t_n - t_{n-1}) - \overline{TT}(t_{n-1}) \times (t_{n-1} - t_0)}{(t_n - t_{n-1})}$$

Where *TT* is the mean total transport and the overbar denotes an average at the bracketed interval, t_n is a given timestep, and t_0 represents the initial simulation timestep. One particle was released at each source location in the initial timestep. Although particle tracking models are often highly sensitive to the choice of initial timestep (for example, consider the release of a particle at the ebb versus flood stages of a tidal cycle), the effective particle velocities in this case (u_{tr}) were sufficiently small that the precise release time did not affect their ultimate trajectories. The use of the mean transport vector instead of the instantaneous transport vector has two advantages; Firstly, instabilities that may occur in the sediment transport field (for example in shallow areas) are averaged out over the selected interval. This averaging reduces instabilities and errors in the particle movement computation. Secondly, the number of output intervals is reduced. This reduces the amount of data that needs to be stored and particle computation time. The 10-minute averaging interval is small enough to not influence the accuracy of the particle computation.

Numerical accuracy was maintained using a 4th-order Runge-Kutta scheme with a computational timestep of 60 s. Particle positions were stored every hour to enable the tracking of particle positions on tidal timescales. A transport height scale, h_{tr}, of 0.1 m was chosen to increase the rate of particle motion in a given timestep. Note that this h_{tr} basically converts the sediment transport flux into a velocity that is 10 times the size of the flux. To account for the random motion of particles, a diffusion coefficient of 0.1 was applied. This corresponds to a random motion equal to 10% of the particle's travel distance in a given timestep.

Note that the velocity of the sediment particle movement is not yet calibrated in the *SedTRAILS*; it is not a sediment tracer. *SedTRAILS* was developed 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. 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 is recommended to also reproduce the time-scales of sediment movement and obtain estimates of volumetric changes.

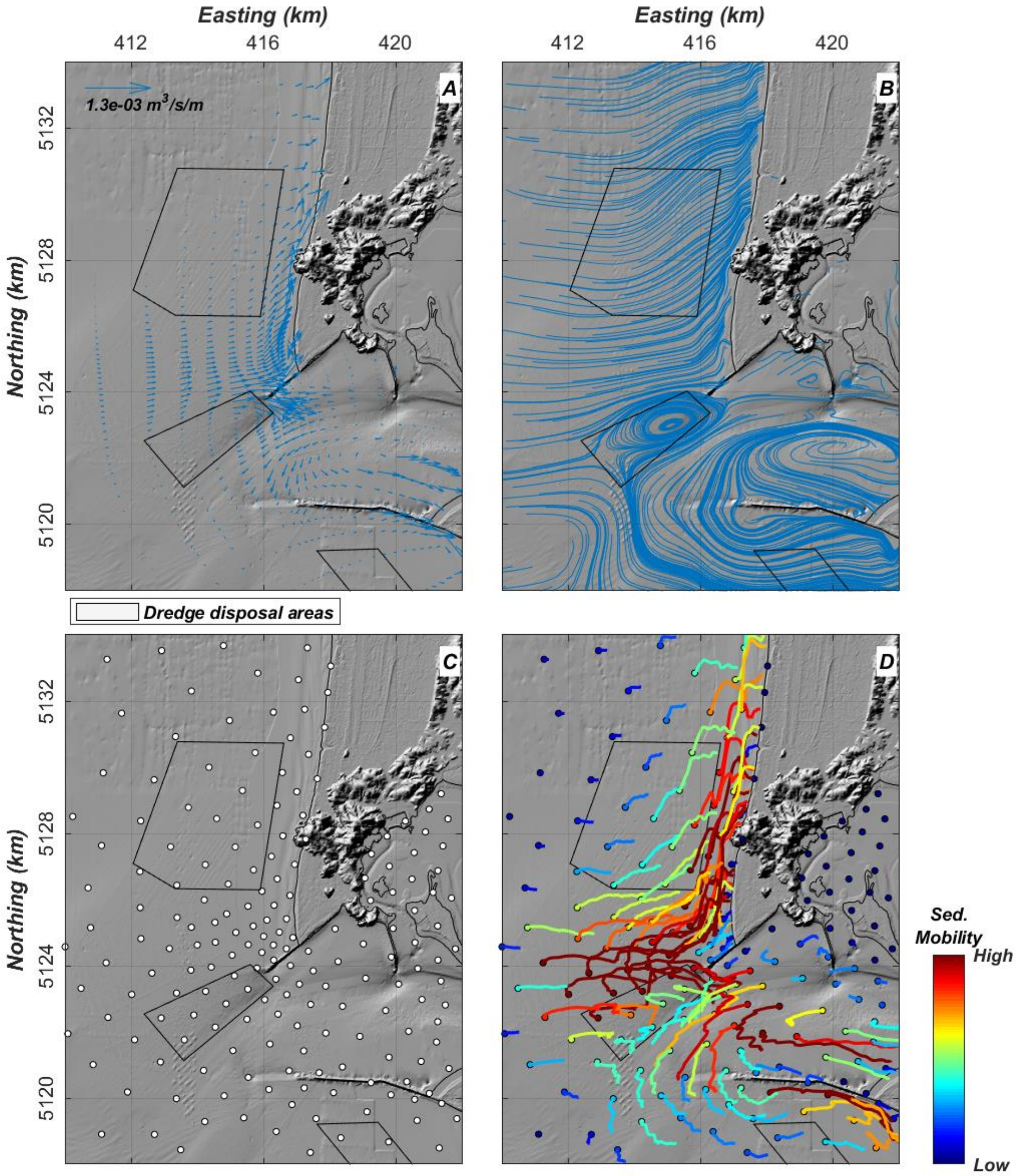


Figure 2.2: Example of a SedTrails visualization of lagrangian sediment transport pathways showing: A, a sediment vector field, B, streamlines representing the vector field, C, initial positions of the sediment sources, and D, sediment pathways derived from the SedTrails analysis. Sediment pathways in 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 *SedTRAILS* – Western Scheldt application

To assess the sediment pathways, a large number of possible particle trajectories from 1000 initial locations (or sources) distributed throughout the model domain are simulated simultaneously. The initial source locations are determined using k-means cluster analysis (Davis, 2002) based on a weighted combination of XY-coordinates and depth below mean sea level. This methodology results in a set of sources that is distributed throughout a model domain but provides finer detail in areas with greater bathymetric complexity, i.e. greater variations in depth over smaller distances. A first set of 500 sources was obtained based on cluster analysis of bathymetric datapoints in the Bocht van Ossenisse (Figure 2.3, top panel). The second set of 500 source locations is based on cluster analysis of bathymetric datapoints in the Put van Hansweert (Figure 2.3, top panel).

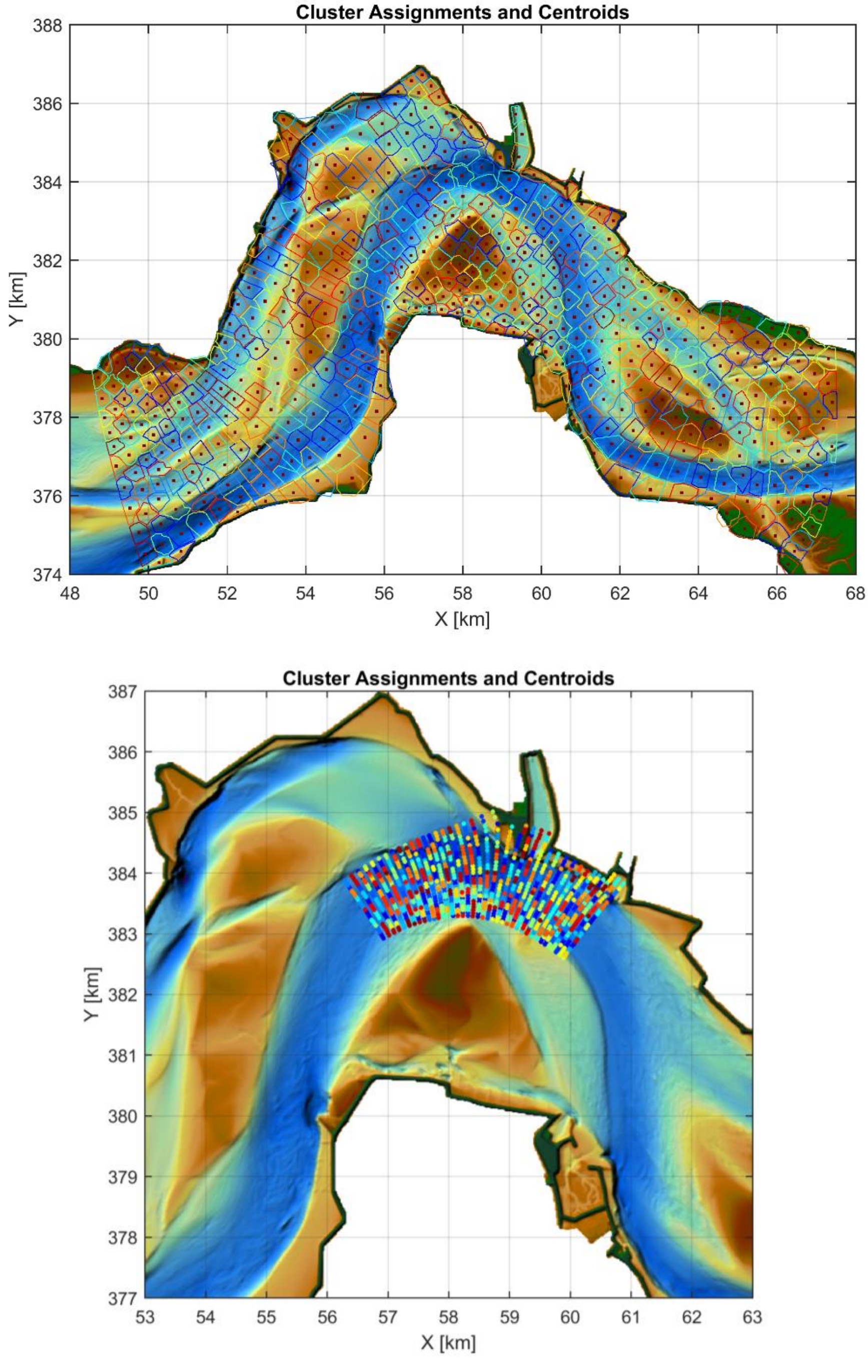


Figure 2.3: Locations of 500 particle sources derived from a cluster analysis on the bathymetric data of the Bocht van Ossenisse (top panel) and the Put van Hansweert (bottom panel).

To accelerate the sediment particle computations, *SedTRAILS* was run in cyclic mode using a morphological tide as basis. The objective of tidal input schematization with a morphological tide is to replace the complex timeseries of tidal water level and current fluctuations occurring in nature with a simplified tide or tides that reproduces the total residual signal (Lesser, 2009). A Delft3D model simulation forced by tides on the open-ocean boundary and the measured discharge in the Scheldt and Bath was performed over a 1-month timeframe. The results of a spatially explicit correlation analysis showed that a representative tide can be selected to accurately model sediment transport over a full spring-neap cycle, and accurately capture the sediment transport patterns at the Put van Hansweert (Figure 2.4). Sediment sources are advected according to the transport vector fields calculated by Delft3D for the chosen tidal period, that is repeated a user-specified number of times. In this study we ran SedTrails for 1-year. In Figure 2.5, the exact demarcation of the chosen tidal cycle is depicted, where boundaries are chosen such that velocities and hence sediment transport at the time boundaries are minimal, to prevent discrepancies at the transition between two consecutive tidal cycles.

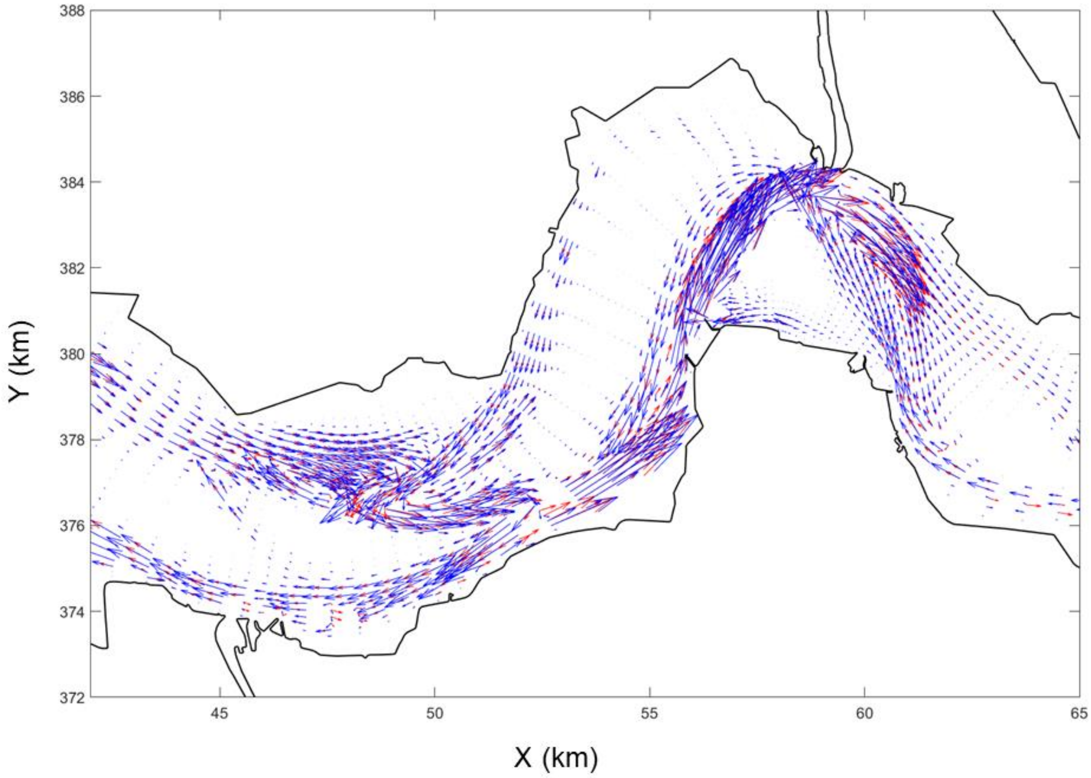


Figure 2.4: Month-averaged sediment transport (red) and tidally-averaged sediment transport (blue) for the seventh simulated tidal cycle, calculated with the NeVla Delft3D model

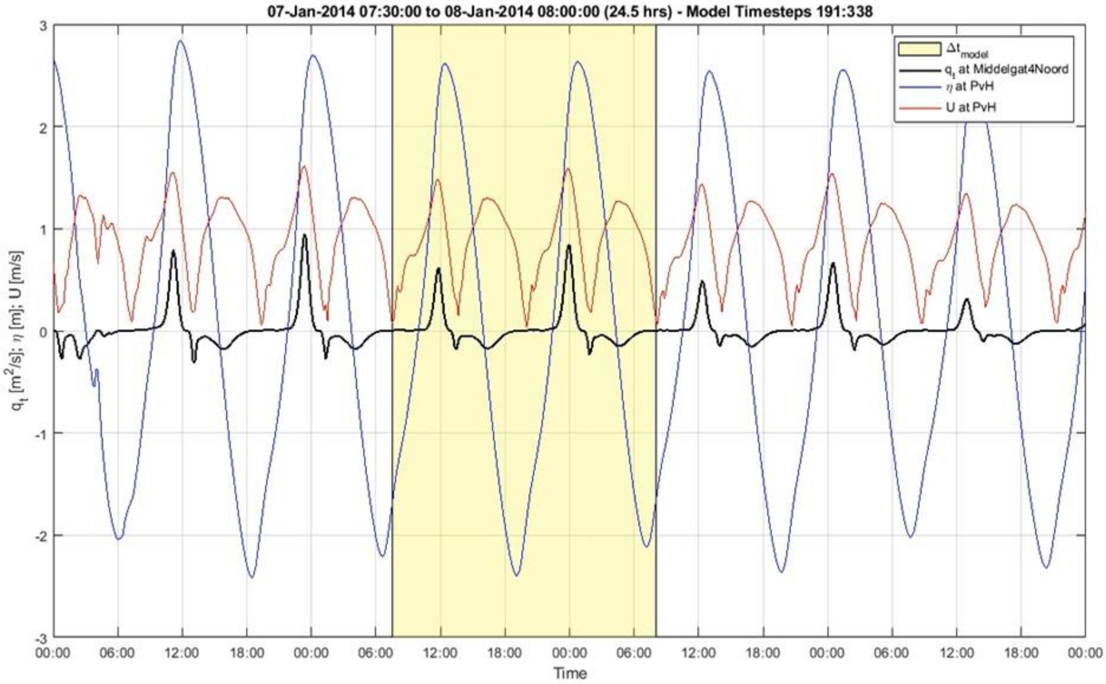


Figure 2.5: In yellow, the tidal period that is used for the SPIT calculations. Start and end time is chosen such that velocities (red line) and hence sediment transport (black line) are minimal at both boundaries.

3 Model Results

In this Chapter we present the Delft3D and *SedTRAILS* model results, aimed at understanding 1) the distribution of sediment from the pit to the surrounding areas and 2) the influence of the placement location on distribution patterns. In Section 3.1 the main characteristics of the Eulerian velocity and sediment transport fields that form the basis of the sediment pathways analysis are briefly described. In Section 3.2, *SedTRAILS* results are illustrated and analysed. These results provide insight into dominant sediment pathways in the Put van Hansweert and its interaction with the surrounding channels and shoals. The *SedTrails* results do not provide estimates of the volumetric changes but should be used to identify the connections between the Put van Hansweert and the surrounding areas. Understanding the connectivity and allows us to test and improve the conceptual framework as proposed by Huismans et al. (2021).

3.1 Delft3D

Model results of Delft3D simulations have been extensively analysed and reported in among others Huisman et al. (2018) and Huismans et al. (2021). Our analysis in this report is based on the results of the 3D model as the underlying hydrodynamics are considered most accurate in terms of reproducing the hydrodynamics and therefore the sediment transport rates in the Put van Hansweert, as also elaborated in Huismans et al. (2021). For long-term morphodynamic simulations it is computationally unfeasible to use the 3D model. However, for *Sedtrails* such limitation is not present as only 1 representative (double) tide is needed as a base. In this section, we present the main characteristics of the selected morphodynamic tide and the resulting sediment transports in the Bocht van Ossenisse and the Put van Hansweert. These transports were used in the *SedTRAILS* visualization and analysis.

3.1.1 Hydrodynamics

The modelled (depth-averaged) flow velocities in the Bocht van Ossenisse and in the Put van Hansweert are illustrated in Figure 3.1 and Figure 3.2. Averaged over the two tides, currents in the Western Scheldt are flood dominated, with larger peak velocities during flood tide compared to the ebb tide (see lower panel of Figure 3.1, at timesteps A and D). The maximum peak ebb and flood velocities in the Put van Hansweert exceed 2.0 m/s. The velocities in the main channel are significantly larger compared to the velocities in the secondary channels (Middelgat and Schaar van Waarde). In the main channel, maximum flood velocities are observed 50 minutes before high water (A) and minimal velocities 1 hour after high water (C). Noticeable in panel C are the relatively large velocities along the shoals and in the secondary channels when flow in the main channel is minimal.

During flood the majority of the flow enters the Put van Hansweert from the main channel, with only a minor contribution of flow from Middelgat (panels A, B and F in Figure 3.1 and Figure 3.2). From the Put van Hansweert flow is directed eastward onto the Drempel van Hansweert. The Plaat van Walsoorden separates the flow in two directions. Part of the flow is redirected to the south into the main channel (Zuidergat) and part of the flow is directed into the Schaar van Waarde. Roughly, equally high flow velocities are present in both channels. During ebb (C,D,E) velocities are directed from the Schaar van Waarde and Zuiderdiep westward. Large flow velocities occur along the eastern margin of the Platen van Ossenisse (see panel D). In this area the flood velocities were significantly smaller compared to the velocities in the main channel which illustrates a clear eb dominance. From the Put van Hansweert, the majority of the flow follows the main channel, with only small velocities into Middelgat. In downstream[1] direction, the velocities in the Middelgat increase.

[1] Downstream refers to flow and transport in western direction (towards the open sea). Upstream refers to directions towards Antwerpen.

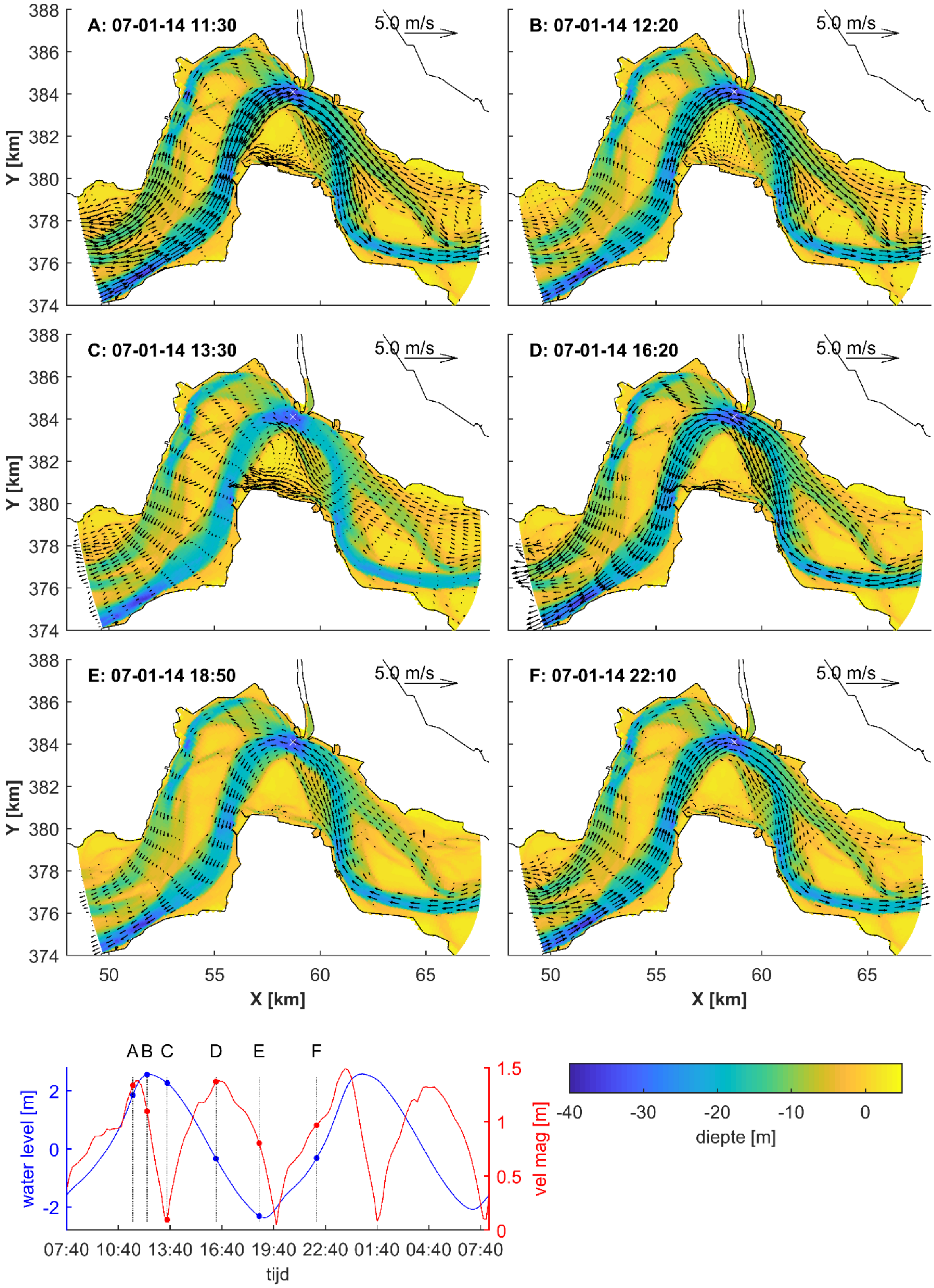


Figure 3.1: Depth-averaged velocities at 6 points in time (panel A to F) for larger Hansweert region. In the lower panel, corresponding water levels and velocities are depicted for the Put van Hansweert.

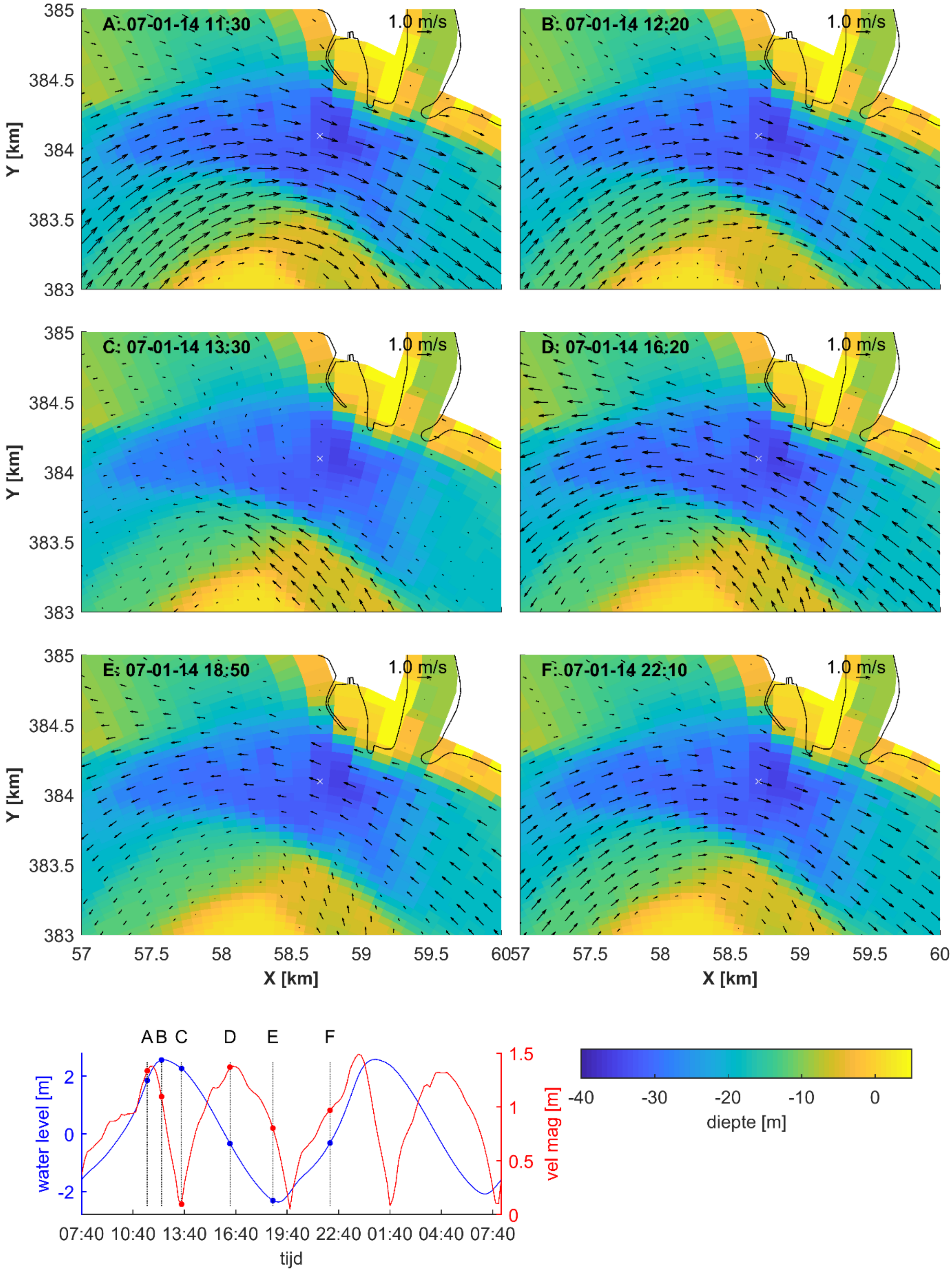


Figure 3.2: Depth-averaged velocities at 6 points in time (panel A to F) for the Put van Hansweert area. In the lower panel, corresponding water levels and velocities are depicted for the Put van Hansweert

3.1.2 Sediment transport patterns

Largest total-load sediment transports are observed in the main channel and in the western end of Middelgat (Figure 3.3 and Figure 3.4). Patterns show similar features compared to the flow. During flood, large sediment transports are observed in the main channel, from the Gat van Ossenisse (panels A, B) to the Overloop van Hansweert and into the Put van Hansweert. Maximum transports are observed along the western margin of the Platen van Ossenisse, while minimal transport occurs along the eastern margin of the shoal. The downstream transport direction along the eastern shoal margin forms a sediment gyre on the Drempel van Hansweert. From the Put van Hansweert transports are directed primarily into the Schaar van Waarde and to the Plaat van Walsoorden (panel B). In the main channel Zuiderdiep transports are small near Walsoorden, but these transports significantly increase in upstream direction.

During ebb, large sediment transports occur in the main channel Zuiderdiep (panel D), while transports in the Schaar van Waarde are minor. Transports from Zuiderdiep are directed along the eastern margin of the Platen van Ossenisse and into the Put van Hansweert. Transports in the adjacent central part of the channel are small. From the Put van Hansweert transports are directed into the main channel with maximum ebb transports along the western margin of the channel, towards Rug van Baarland. Along the western side of the Platen van Ossenisse, transports are smaller and opposite (upstream) directed. Transport vectors from the Put van Hansweert into Middelgat are relatively small. However, transports in Middelgat significantly increase in upstream direction.

The detailed sediment transport fields for the Put van Hansweert (Figure 3.4) illustrate the variation in sediment transport rates in the area. During flood, transports maximize along the southern side of the Put, while during ebb, transports are focused in the central part of the channel.

Averaging all transport maps over the morphological tide results in the residual sediment transport field as displayed in Figure 3.5 (the numbers in the section below correspond to the labels in this figure). Most noticeable features in the residual sediment transport patterns are:

- opposite convergent sediment directions along the Platen van Ossenisse, upstream (1) and downstream of Hansweert (2),
- opposite divergent transport directions along the southern (downstream, 3) and northern (upstream, 4) side of the main channel,
- sediment gyres (circular transports) on the Overloop van Hansweert (5) and on the Drempel van Hansweert (6).
- a net upstream transport from the Put into the Schaar van Waarde and towards the Plaat van Walsoorden (7),
- divergence of net transports upstream and downstream of Walsoorden (8),
- divergence of net transport upstream and downstream of Gat van Ossenisse (9),
- Net ebb-dominant transport in Middelgat (10) that increases in downstream direction.

.

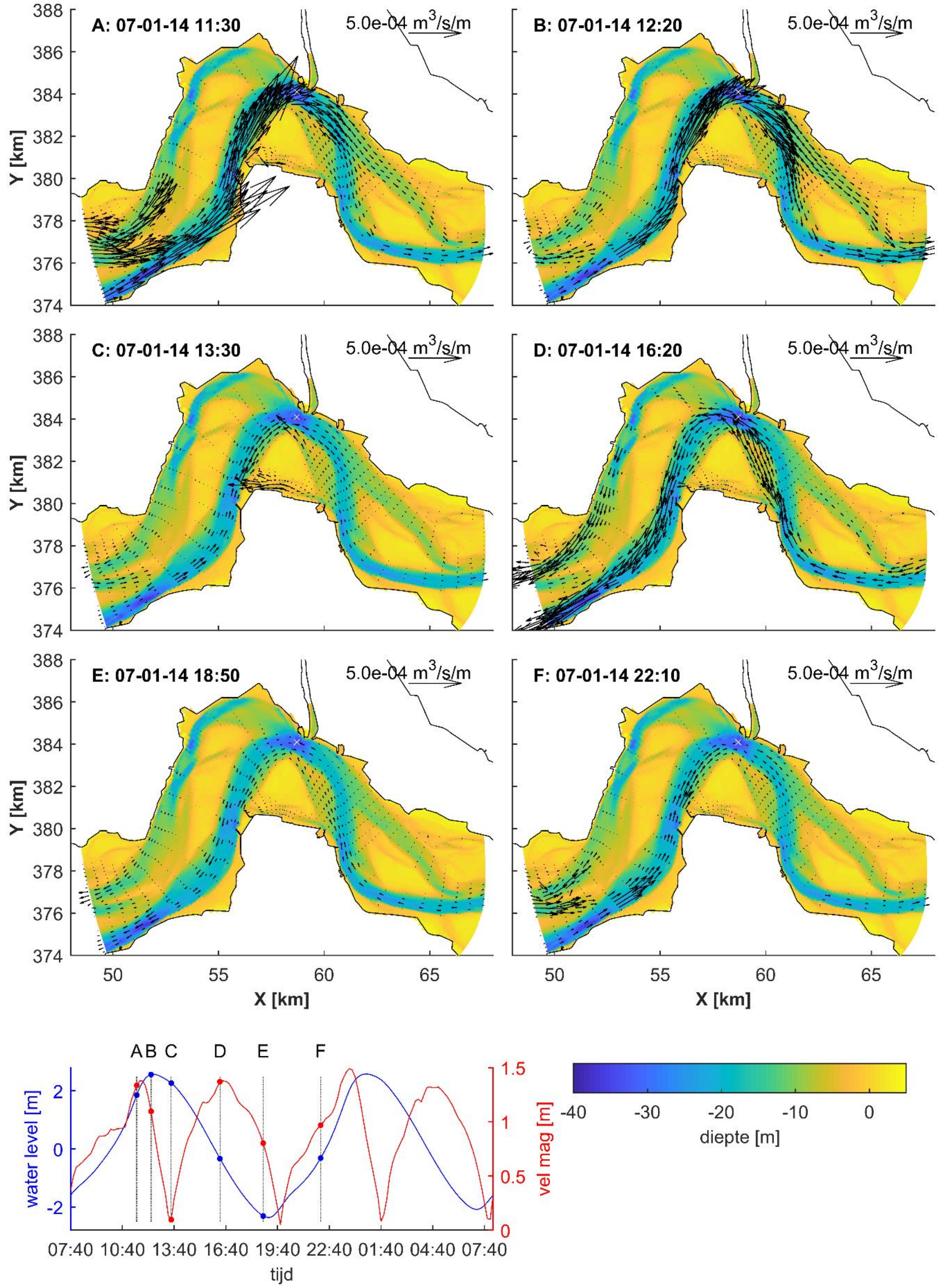


Figure 3.3: Total sediment transport vectors at 6 points in time (panel A to F) for larger Hansweert region. In the lower panel, corresponding water levels and velocities are depicted for the Put van Hansweert.

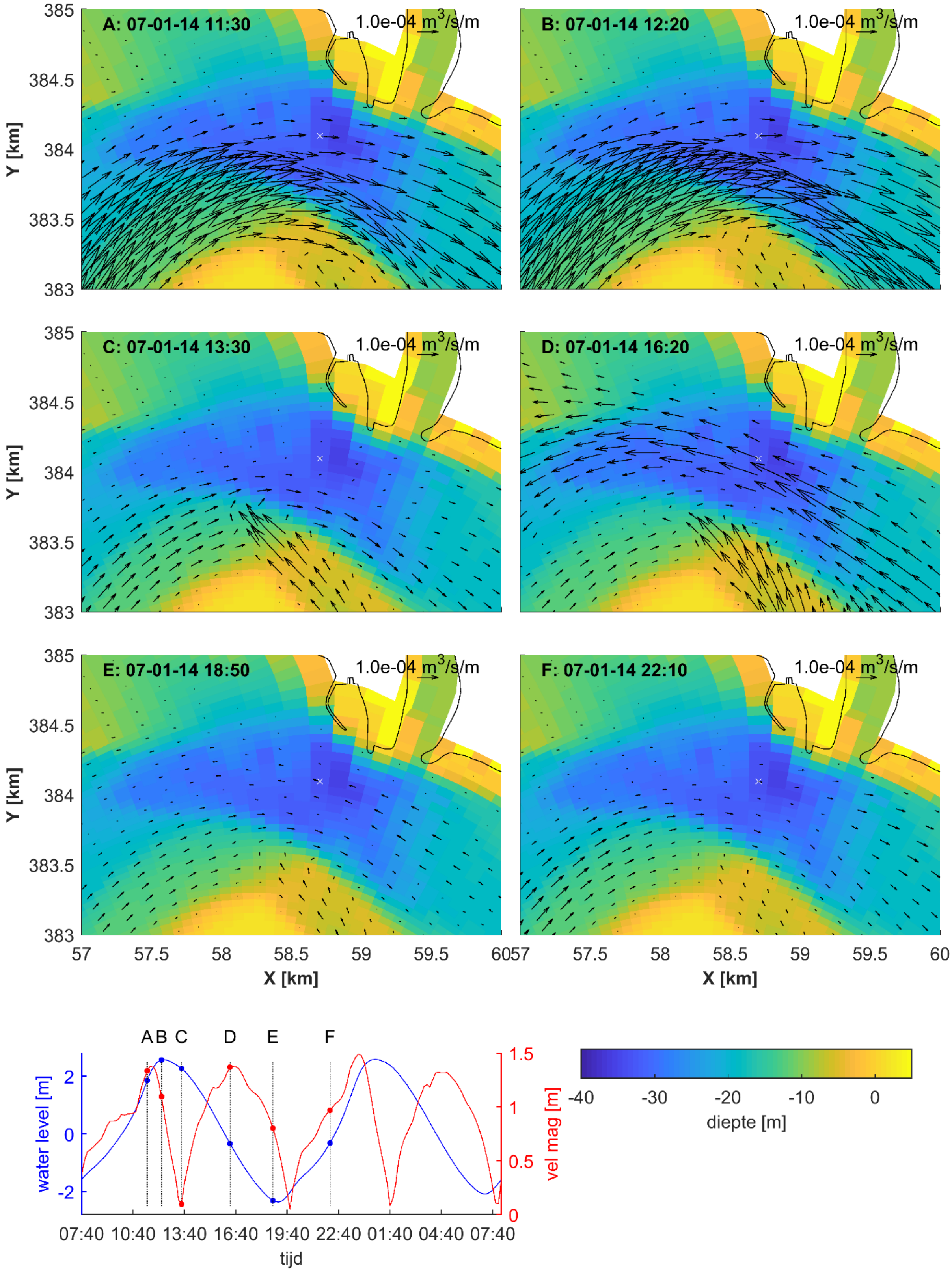


Figure 3.4: Total sediment transport vectors at 6 points in time (panel A to F) for the Put van Hansweert area. In the lower panel, corresponding water levels and velocities are depicted for the Put van Hansweert.

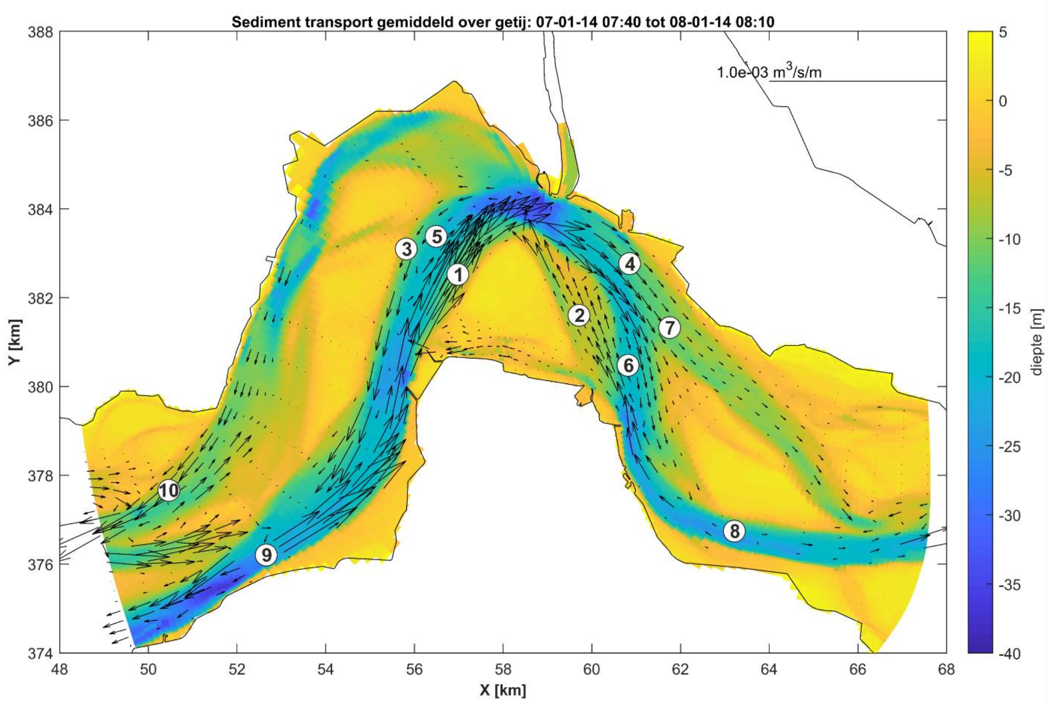


Figure 3.5: Tidally-averaged total sediment transport vectors in the Bocht van Ossenisse.

3.2 SedTrails

In this section, the results of the *SedTRAILS* model are presented and analyzed. The first section (3.2.1) focuses on the sediment trajectories and sedimentation patterns in the larger-scale Bocht van Ossenisse. Sections 3.2.2 and 3.2.3 specifically focusses on the trajectories that interact with or originate from the disposal area of the Put van Hansweert. A more detailed analysis of the computed trajectories is presented in Section 3.2.4 through the connectivity framework and network diagrams.

3.2.1 Large-scale sediment trajectories in the Bocht van Ossenisse.

The trajectories of sediment in the Bocht van Ossenisse and the Put van Hansweert are shown qualitatively in Figure 3.6. The sediment gyres that can be observed in the sediment transport vector field after thorough investigation, appear as clear circulation cells on both the upstream and downstream side of the Platen van Ossenisse from the *SedTRAILS* analysis (Figure 3.6, areas D and F). Noticeable are the limited number of trajectories that develop along the western margin of the Platen van Ossenisse and Slikken van Hulst. Along this area the largest (residual) transport rates were observed (Figure 3.5), which is also reflected in a high mobility of the particles (Figure 3.7). Particles placed along the Slikken van Hulst and along the western margin of the Platen van Ossenisse migrate at large sediment transport velocity upstream, and into the Put van Hansweert. As a result, these trajectories develop as single dashed lines.

In the Put van Hansweert, three dissimilar particle trajectories develop. Firstly, particles are redirected in downstream direction. These particles propagate downstream along the Platen van Ossenisse and Rug van Baarland (i.e. West of the Overloop van Hansweert), or they accumulate in a sediment gyre in the Overloop van Hansweert (D). Secondly, particles propagate from the Put van Hansweert to the Schaar van Waarde. A near linear trajectory develops with preferential upstream migration of the particles (C). Thirdly, a sediment gyre develops in the Zuidergat, on the Drempel van Hansweert (F), as particle movement on the channel's eastern side is upstream directed while on the western side, along Perkpolder and the Platen van Ossenisse, particles migrate downstream. From Zuidergat, a small number of particles interacts with the Schaar van Ossenisse.

No particles are redirected towards the western side of the Platen van Ossenisse, which explains that only a limited number of pathways develop here.

Sediment placed in the permit area (the *Vergunningspolygoon*, area delineated by the white polygon in Figure 3.6) of the Put van Hansweert is likely to be transported to either the Overloop van Hansweert (D) or Schaar van Waarde (C). Particles that are placed along the southern margin of the pit (along the tip of the Platen van Ossenisse) may interact with area C and area F. Particles placed in the northwestern tip of the permit area may be transported towards Middelgat / Molenplaat, although the rate of particle migration is limited here. A cluster of particles north of the permit polygon is placed on land or in the Kanaal van Hansweert, therefore these particles show no migration. The limited particle exchange from the Put van Hansweert towards the western side of the Platen van Ossenisse indicates that it is unlikely that disposal material will be transported from the Put towards this area.

The distances travelled by individual particles can be used to visualize transport rates or sediment mobility (Figure 3.7, top panel) while the spatial gradients in sediment mobility provide a proxy for sedimentation and erosion (Figure 3.7, bottom panel). The sediment mobility provides an important indicator for the behaviour of sediment at the dump side. Materials dumped in areas with high sediment mobility are more dispersive compared to the areas with low sediment mobility. The sediments locations indicated by 1 through 5 in Figure 3.7, show high mobility, which means that sediments dumped here are likely to be mobilzed and deposited elsewhere. Sediments dumped in areas 6 through 9 are less mobile and are likely to remain in the dump area over a longer time frame.

Sediment mobility is large along the western side of the Platen van Ossenisse and along the souther side of the Put van Hansweert (Figure 3.7, [1, 2]). Here the particles migrate upstream, due to the high mobility. Larger sediment mobility is also observed in the main channel towards the Gat van Ossenisse (Figure 3.7, [2]), and on the Drempel van Hansweert towards the the Schaar van Waarde (Figure 3.7, [4]). In the secondary channels such as the Schaar van Ossenisse and Middelgat (Figure 3.7, 6), only short paths and limited mobility is present. Under the selected tidal conditions, only limited particle movement occurs on the Platen van Ossenisse as the shoal remains mostly supra tidal.

A sedimentation-erosion plot (Figure 3.7, bottom panel) can be obtained from the spatial gradients in the sediment mobility. This sedimentation-erosion is slightly misleading as it does not show a volumetric change but either a negative (convergence) or positive (divergence) change in mobility. Areas with higher relative sedimantion or erosion values are more likely to show a morphological respons compared to areas with low values. In areas with large variation in rate such the Drempel van Hansweert (Figure 3.7, a,b) are likely to show dynamic or spatially complex morphodynamic repsonses.

Combining the insights from the trajectories (Figure 3.6), sediment mobility (Figure 3.7, top panel) and relative sedimenation-erosion (Figure 3.7, bottom) allows us to qualitatively describe the various dump locations in the Bocht van Ossenisse. Sediments dumped in the southern part of the Put van Hansweert (Figure 3.7, top panel [3]) are likely to be actively transported in upstream and downstream direction. In upstream direction they can contribute to accelerated accretion on the Drempel van Hansweert (Figure 3.7, bottom panel [a]) or contribute to a net transport towards the Schaar van Waarde [b]. The Schaar van Waarde is dispersive near Hansweert (Figure 3.7, top panel [4]) and sediments accumulate towards the Plaat van Walsoorden (Figure 3.7, top panel [9]). Sediments that propagate from the Put downstream are likely to show limited mobility. In the northern part of the Put sediment mobility is limited (Figure 3.7, top panel [7]). This indicates that, compared to the other parts of the Put, sediments are likely to remain present over a longer interval and only migrate slowly. Particle trajectories indicate movement into Middelgat (Figure 3.7, bottom panel [c]).

Sediments that propagate along the western Platen van Ossenisse will partly propagate downstream along the Rug van Baarland where a more active dispersion is likely (Figure 3.7, top panel [2]), while another part will get trapped on the western side of the Overloop van Hansweert (Figure 3.7, bottom panel [d]).

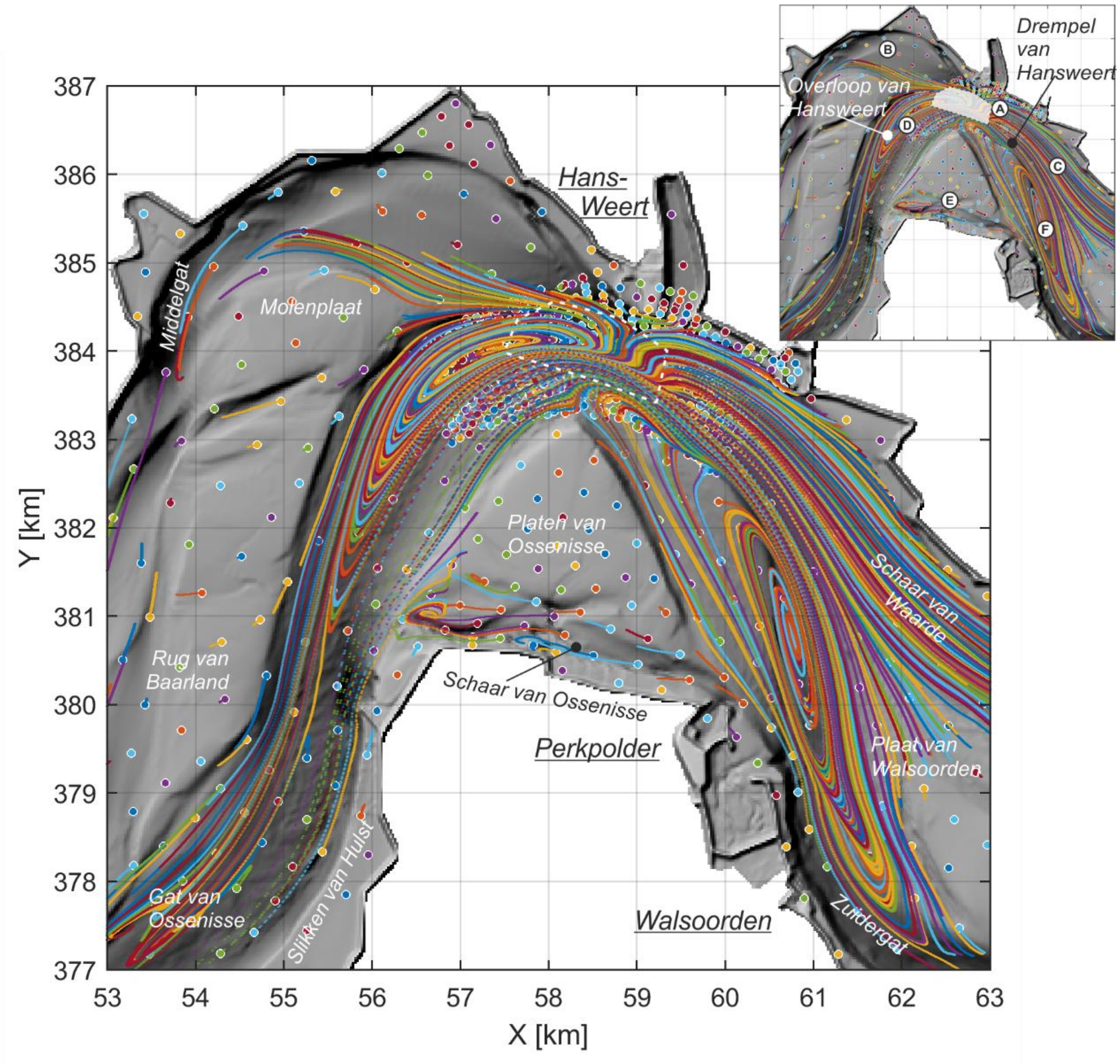


Figure 3.6: Sediment Pathways in the Bocht van Ossenisse. Dots indicate the starting particle source locations and lines illustrate the computed particle trajectories after 1 year of simulation. Colours are used to distinguish the various particle sources.

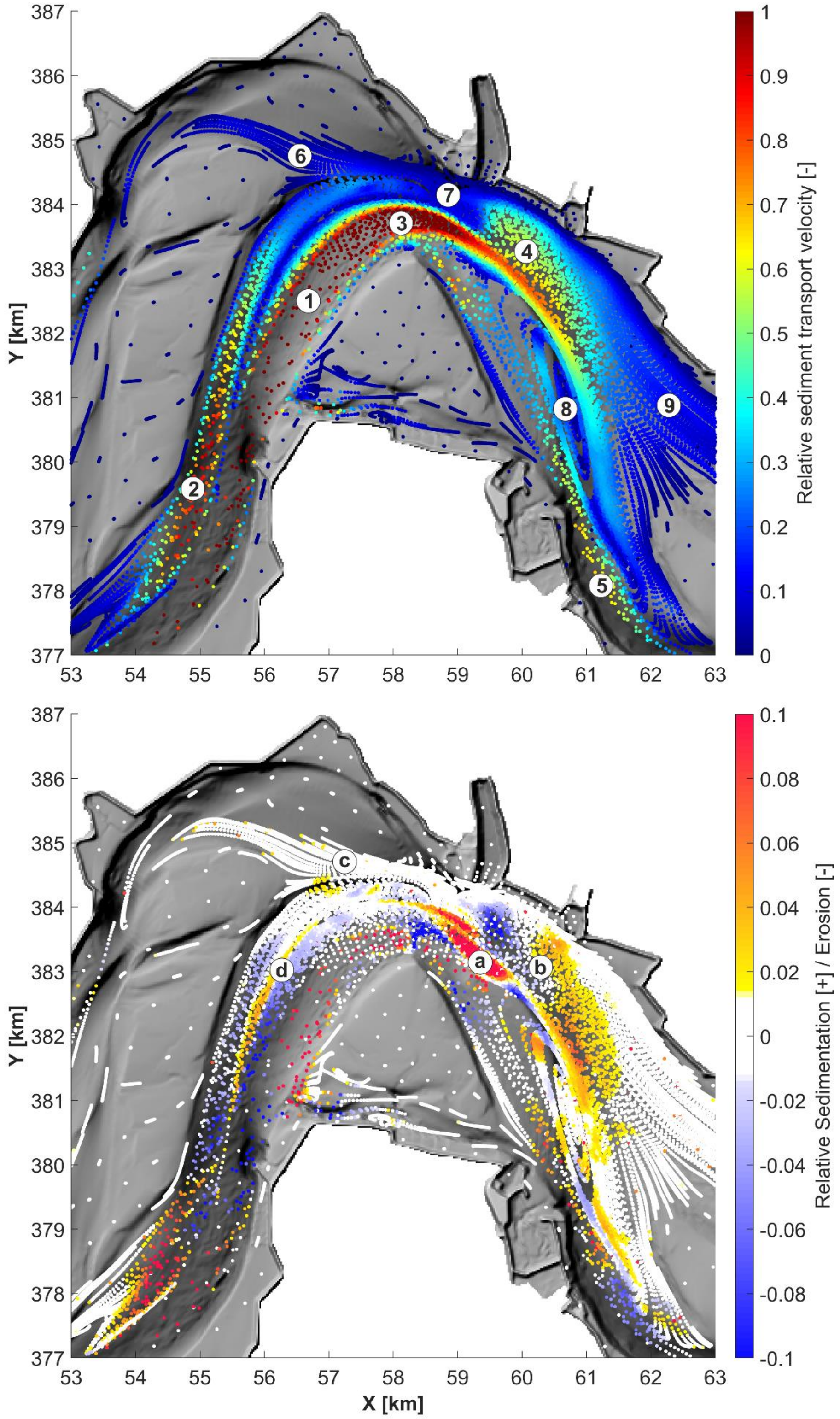


Figure 3.7 Top panel: Relative sediment transport velocity based on the distance travelled during a tidal cycle. Bottom panel: Prediction of relative sedimentation / erosion patterns, coloured according to the ratio of distance travelled during two consecutive tidal cycles.

3.2.2 Sediment interactions grouped by morphological zones

By plotting all particle trajectories, the main sediment pathways are clearly visualized, but the linkages between the various morphological elements are difficult to discern. Therefore, the sediment trajectories are grouped and coloured based on morphological zones (Figure 3.8). These zones are defined following Huismans et al. (2021). The colours indicate particle trajectories that interact with the morphological zones. These trajectories consist of particles that (1) originate from the selected area, (2) particles that propagate through the area and (3) particles that end in the selected area.

The trajectories from the Put van Hansweert (zone A) show that sediment diverges to the East and the West. Detailed results for the Put van Hansweert (zone A) are discussed in the Section 3.2.3. Sediment transport north of Molenplaat and into Middelgat (area B, white trajectories) is limited to the particles that are present in this region, or that originate from the northwestern side of the Put van Hansweert.

Various source zones interact with the Schaar van Waarde (C, purple/blue trajectories). The main interactions occur with the Drempel van Hansweert and the eastern section of the Put van Hansweert. A direct feedback between particles that are placed on the northeast side of the Put van Hansweert and the Schaar van Waarde is observed. These particles migrate near linearly into the Schaar van Waarde. Because of the central location and large bed dynamics of the Hoofdgeul Oost (zone D, light blue trajectories), many sediment trajectories from adjacent regions pass through this region. Eventually, the sediments at the South-Western side of zone D end up either in the Binnenbocht Oost (zone E) while sediment from the northeastern side of zone D and Put van Hansweert is transported towards the Schaar van Waarde (zone C). Additionally, sediment from the upstream (Zuiderdiep) and downstream regions (Gat van Ossenisse and Binnenbocht West) contributes to the sediment pathways at the Hoofdgeul Oost and Binnenbocht Oost (zones D and E, respectively light blue and yellow trajectories). The long trajectories show that migration rates are high. A sediment gyre is located at the Drempel van Hansweert (within zone E) which keeps sediment recirculating locally, and therefore may explain the local sedimentation.

Sediment from the eastern side of the Overloop van Hansweert or Binnenbocht West (zone F, green trajectories) is transported towards the North-East with the flood current to the Drempel van Hansweert (zone D and E). Sediment that moves through the Hoofdgeul West (zone G, red trajectories; i.e. either originating from this zone or from the Put van Hansweert) ends up in the sediment gyre West of the Put van Hansweert or travels further towards the East into the Binnenbocht Oost, Hoofdgeul Oost and even the Schaar van Waarde (zones C, D and E). The sediment at the eastern side of the Molenplaat (zone H, violet trajectories) is mainly directed towards the South with the ebb current. A small proportion of the sediment at the southern side of Molenplaat travels via the sediment gyre of the Overloop van Hansweert and Binnenbocht to the sediment gyre at the south-western side of the Drempel van Hansweert.

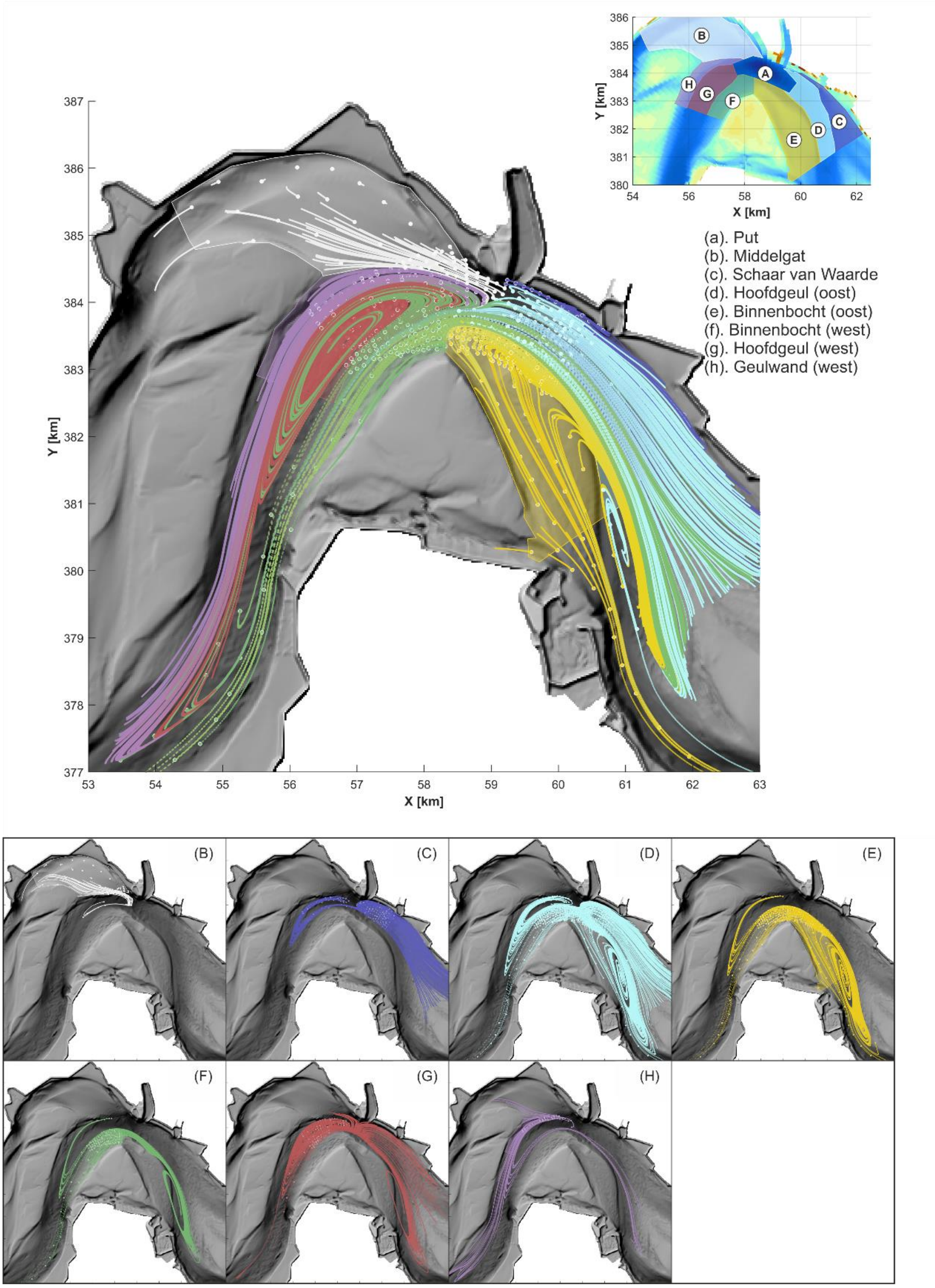


Figure 3.8: Particle trajectories for particles interacting with 7 source locations (individual source particles are grouped by colour) that represent the different morphological elements of the Bocht van Ossenisse (see upper panel). Lower panels; results for the individual areas. Results for sources that interact with Area (A), Put van Hansweert, are visualized in Figure 3.9*.*

3.2.3 Detailed analysis of sediment pathways in the Put van Hansweert

More insight into the transport of sediment from the Put van Hansweert to the adjacent regions can be obtained from an analysis of the particles that interact with the Put van Hansweert (*Figure 3.9*), and from the sources within the Put van Hansweert (Figure 3.10). In both figures the Put is subdivided in 3 zones based on the similarities in sediment trajectories.

Particles released on the northwestern side of the Put (Figure 3.10 A, dark blue colour) are all trajected towards Middelgat / Molenplaat. Compared to the other trajectories the pathways are short, indicating that sediment mobility is relatively low. Hence, the dumped deposit will only disperse and migrate slowly. Particles released in the northeastern corner (C, red color) are all directed towards the Schaar van Waarde. Particles released in the central and southern part of the Put (B) are advected into the main channel and migrate both in the upstream and downstream direction. In upstream direction they remain trapped near the Platen van Ossenisse and do not migrate further upstream. These sediments can contribute to the observed deposition at the tip of the eastern Platen of Ossenisse. Most of the particles that migrate in upstream direction are directed to the Schaar van Waarde, but some deposition may take place before particles arrive here. Particles. A few trajectories migrate along the southern margin of the Plaat van Walsoorden into the Zuiderdiep. These particles are eventually redirected into the gyre south of the Drempel van Hansweert.

The sediment pathways in *Figure 3.9* and Figure 3.10 show generally similar characteristics. Although a larger number of sources can actually interact with the Put van Hansweert. The largest differences are observed in subpolygon C. Material that originates from the area is likely to be transported upstream as no downstream trajectories develop. Downstream sources in the main channel are however likely to interact with this part of the Put.

The main conclusion from the analysis is that depending on the exact dump location in the Put van Hansweert, sediments can be directed differently. Sediments that are dumped in the central, western or southern part of the Put van Hansweert are most likely to remain or recirculate back into the main channel. Sediments dumped along the northern and along the north-eastern part of the Put are likely to be transported into the secondary channels Middelgat and Schaar van Waarde.

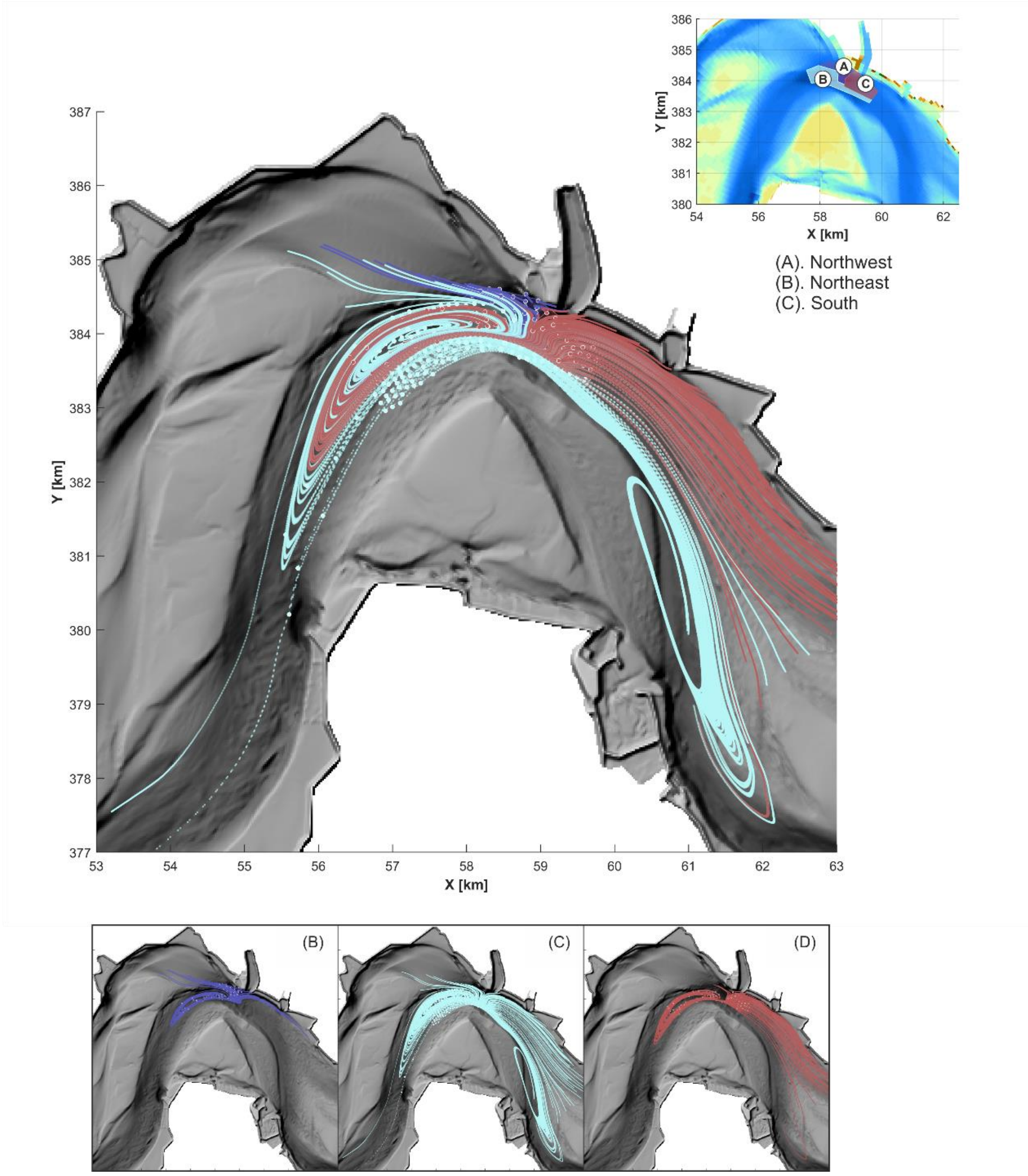


Figure 3.9: Particle trajectories from sources that interact with the Put van Hansweert (grouped in 3 sub-polygons).

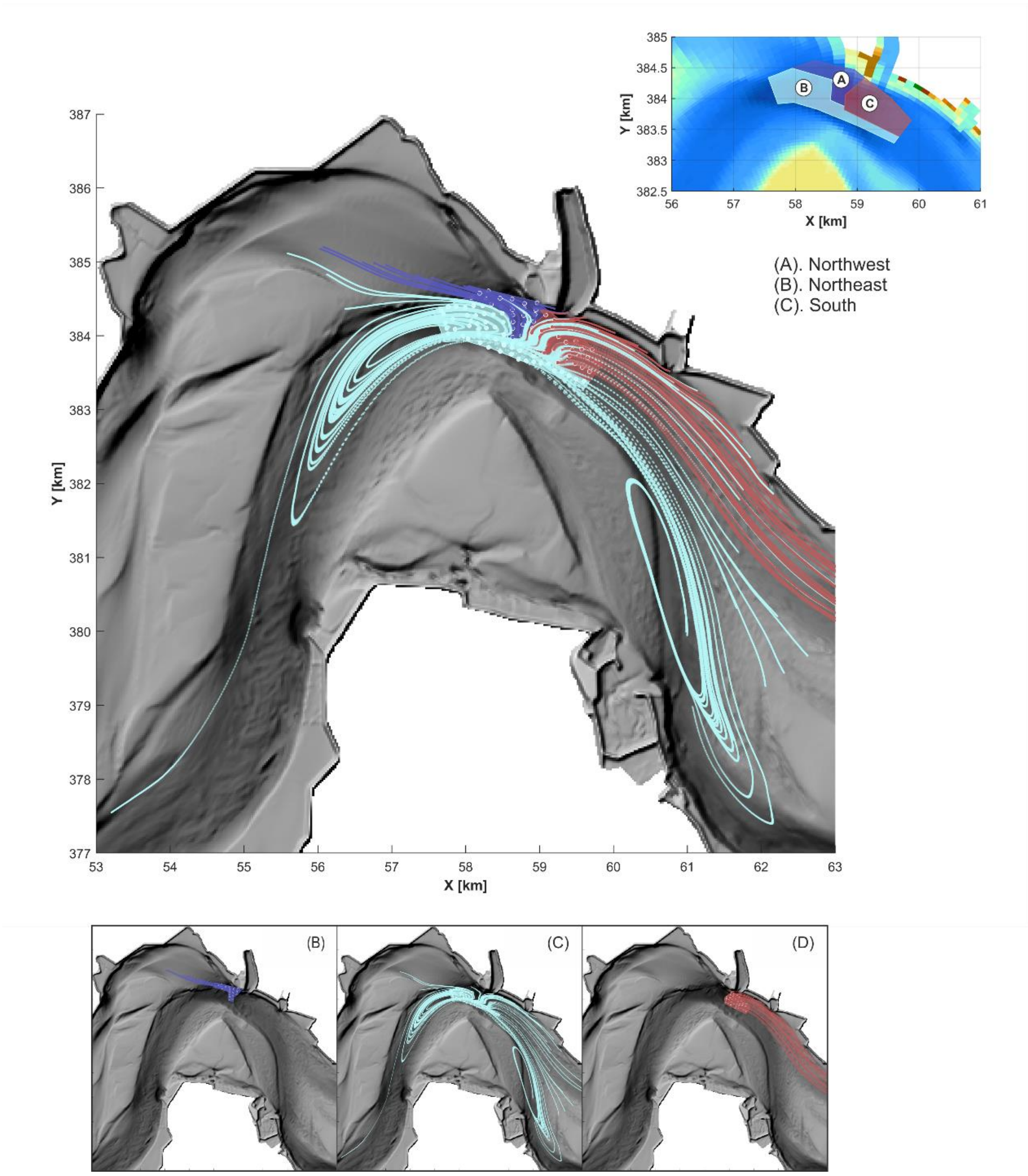


Figure 3.10: Particle trajectories from sources that originate from the Put van Hansweert (grouped in 3 sub-polygons)

3.2.4 Visualizing connectivity

Plotting the sediment trajectories results in visually appealing figures (Figure 3.6 through *Figure 3.9*). These trajectories illustrate the larger-scale pathways in the Put van Hansweert and in the Bocht van Ossenisse, but do not directly show the connections between the various morphological elements. These connections can be visualized by incorporation of techniques from graph theory and network analysis. The morphodynamic system is series of nodes (the various areas in the domain) and the links (sediment trajectories) between them.

Figure 3.10 illustrates a network visualizing the connections between the various zones (labelled 1-10) in real topographical space (top) or in abstract topological space (bottom). The thickness of the lines indicates the strength of the connections; thicker links correspond to larger sediment fluxes. Only the top 10% strongest connections are shown in the top panel in order to clarify the dominant patterns. In the bottom panel, the network diagram is conceptualized in abstract topological space, and all connections are shown in the thin lines. Thicker lines still indicate the dominant connections and correspond to the lines in the top panel. Including the thin lines (less important connections) allows for a convenient assessment of the succession of different pathways, linking nodes that may not be directly linked. This allows users to analyze all possible sources, and not just the obvious connections.When we consider not just the dispersal of sediment from a single point in the Put van Hansweert, but that point's role within a larger sediment-sharing network, we obtain a more holistic view of the system.

Zone 1 (northern part of Put van Hansweert)
The northern part of the Put van Hansweert (1) displays limited connectivity with its surrounding zones. The most prominent out-connection is with the Middelgat (8), as sediments migrate from zone 1 to zone 8, but the actual rate of transport is most-likely small given the relatively short paths that were computed here (Figure 3.9). An inward (sediment supply) connection is also present with the downstream main channel zone 6. Limited inward connections occur with zone 8. Exchange of sediment occurs with zone 2.

Zone 2 (central/southern part of Put van Hansweert)
Being in the central part of the main channel, the central part of the Put (2) is connect to all other nodes. However, significant interaction only occurs between node 2 and 6, as these two cells actively exchange sediments between each other. Sediments exchanges (import and export) between node 2 and nodes 1, 6, 7, and 10. Sediments are exported to zones 3, 4, 5, 8, 9

Zone 3 (eastern part of Put van Hansweert)
The eastern part of the Put van Hansweert is primarily connected to the upstream nodes 4 (export). Minor sediment exporting connections are also present with zone 1. The most significant connection occurs with zone 4 as sediments move from zone 3 to zone 4. Minor sediment imports occurs from zones 6 and 7, while minor export occurs to zones 1 and 5. Minor exchange of sediments occurs with zone 2.

It should be noted that a limitation of *SedTRAILS* is the representation of a physical time-scale, which is not yet possible. Hence, we can investigate pathways, but cannot verify whether particles travel along these pathways in several days or several years, making it difficult to identify volume distributions of deposited sediment. Moreover, connectivity metrics should be interpreted with care. These metrics highly depend on the delineation of network nodes and can therefore show values that do not necessarily represent physical phenomena.

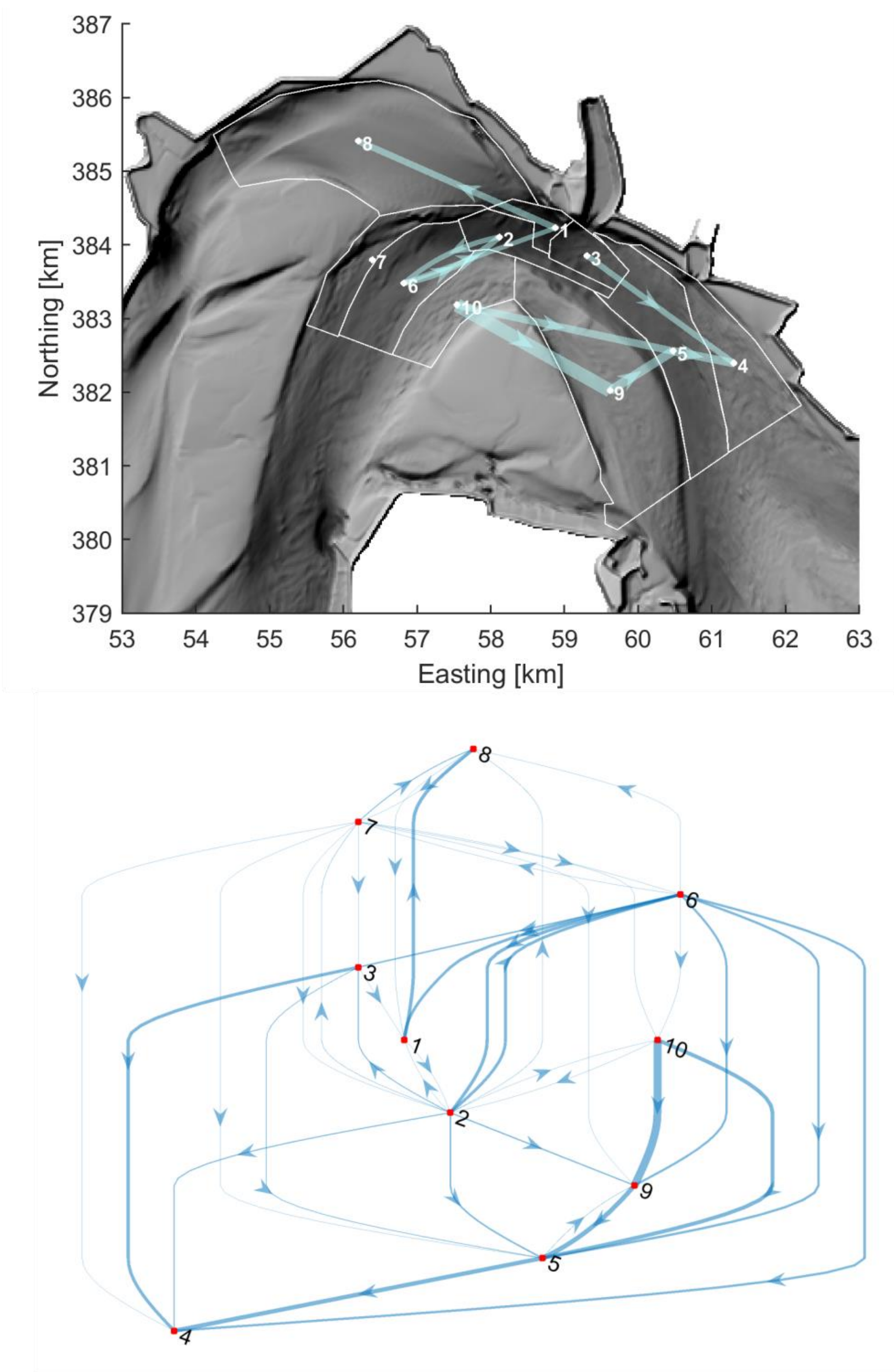


Figure 3.11 (Top panel): Network diagram for connections in the network in real topographic space, indicating only the top 10% strongest links. Bottom panel: Visualization of the network diagram in abstract topological space (height differences are for visualization purposes, they do not represent actual height differences). Blue lines indicate the connection between two nodes, with their thickness implying the strength of the connection, and the arrow indicating the direction.

4 Discussion

A summary overview of the dominant sediment transport pathways found in the current study is given in Figure 4.1 and discussed in relation to the findings from the bathymetric data during the pilot sediment disposals (Huismans et al., 2021). Characteristic features of the dominant transport pathways are presented for four regions within the Put van Hansweert, as well as for the adjacent regions in the main channel, on the inner bend and in the Middelgat. The results should be interpreted as the most logical connections between regions, but do most-often not show whether erosion or sedimentation will take place.

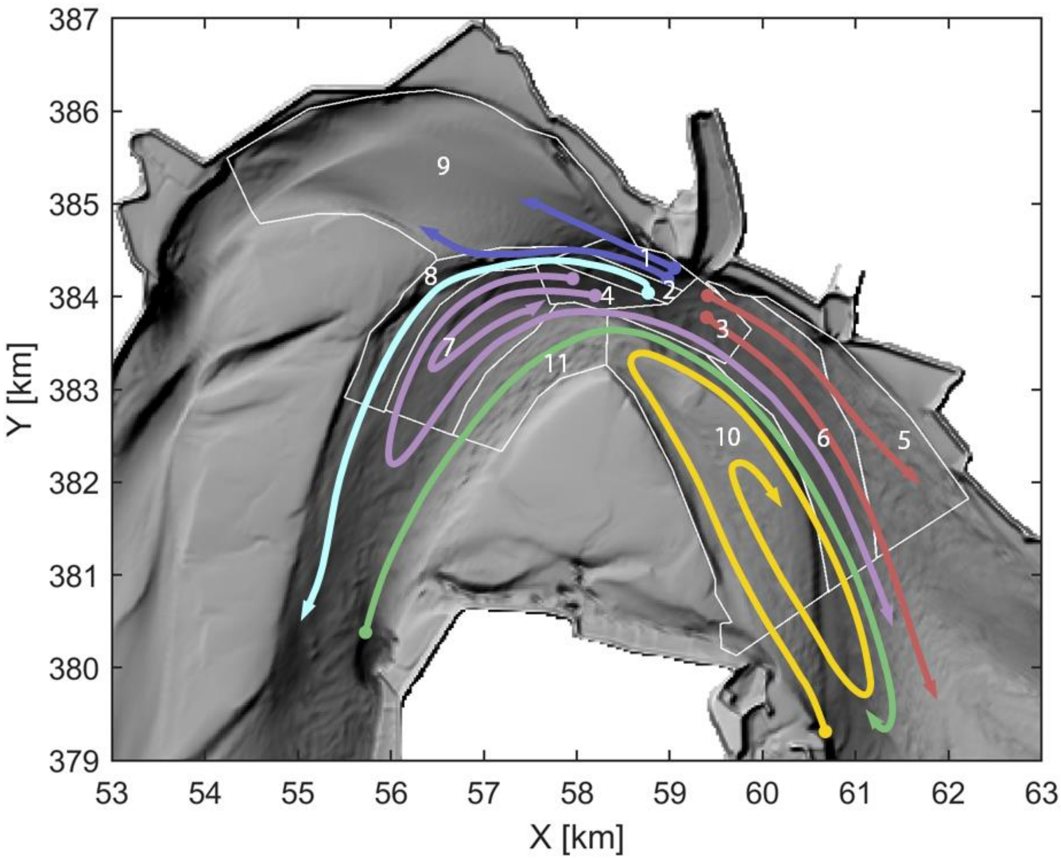


Figure 4.1: Overview of dominant sediment transport pathways in Put van Hansweert region.

Four distinct zones with dissimilar dominant trajectories have been identified for the Put van Hansweert (regions 1 to 4). All of these regions within the Put van Hansweert are actively dispersive (i.e. that sediment has the tendency to leave this area). This aligns with the quick erosion that was observed for the pilot sediment disposals in the Put van Hansweert (Huisman et al., 2018; Huismans et al., 2021).

According to the model, the sediments deposited in the Put van Hansweert are likely to travel in upstream or downstream direction, since the gross sediment transports in along-channel direction significantly exceed the computed across-channel transports. The sediment from the eastward region (3) is transported to the East, while sediments originating from the middle and south-westward sections of the Put (regions 2 and 4) are mainly advected westward through the main channel.

A direct path towards the inner bend, as suggested by Huismans et al. (2021) based on observed accretion during the pilot sediment disposals, is not directly apparent from the sediment pathway analysis. Although this seems to be contradictory this is not necessarily the case, as an indirect route to the inner bend is present for sediment originating from the south-westward section of the Put van Hansweert (region 4). Sediment is first transported towards the Overloop van Hansweert with the ebb current (i.e. from region 4 to 7) and then with the flood current towards the inner bend of the Put van Hansweert (region 11). This recirculation may significantly boost the sedimentation at the inner bend. The model therefore does include a mechanism which can bring sediment from the Put van Hansweert to the inner bend and further eastward. Still the very quick accretion of the inner bend as found in the data analysis of the pilot disposal sites suggests that the transport to the inner bend may in practice be much larger than computed by the model. There may be across-channel residual transport processes that are not resolved by the model, although this cannot be ascertained with the data or models. Based on the evidence from the monitoring of the pilot disposals, it is well possible that cross-channel transports redistribute sediment from the cells within the Put van Hansweert to the inner bend.

Trajectories of sediment particles that originate from the eastern section of the Put (region 3) are directed towards the Schaar van Waarde, and towards the Plaat van Walsoorden and Zuidergat. The current findings suggest that sediment originating from this zone may contribute to the sediment balance of these regions, although it cannot be pinpointed where accretion will take place. Some of the sediment mobilized from the eastern regions of the Put van Hansweert is likely to end up at the Drempel van Hansweert, where a circulation cell may trap the sediment. Pilot disposals were not carried out at eastward side of the Put van Hansweert, which could therefore not be used as a reference. Some enhanced erosion was, however, observed north-east of the Zuidergat at the lower section of the side slope (~MSL -15m) during the placement of the pilot sediment disposals (Huismans et al., 2021). This effect is, however, considered an indirect effect of the accretion of the inner bend, which pushes the flood and ebb current outward, thus increasing the radius of the bend of Hansweert. This indirect effect was not evaluated in the current study, as a static bathymetry was used. The current modelling is, however, an indication that eroded sediment from this region has moved sediment into the Schaar van Waarde.

The northern part of the Put van Hansweert (region 1) is considered a source for the Middelgat (region 9), although the exchange towards the Middelgat is considered a long-term process with relatively low transport rates. This aligns with the pilot nourishment in 2019 at the northwestern side of the Put van Hansweert, which did also show some accretion at the entrance of the Middelgat (Huismans et al., 2021), although the eroded material could only partially be traced back in this study. Noticeably, the pilot nourishment in 2019 at the northwestern side of the Put van Hansweert also showed enhanced accretion at the inner bend, which suggests a larger redistribution to the adjacent regions as predicted in the modelling. In practice, it is envisioned that a part of the sediment from the northwestern side of the Put van Hansweert can move to the other regions in the Put van Hansweert (regions 2 to 4) as a result of spatial spreading of the sediment directly after dumping over a circle with a diameter of about 300 m due to the impact of the density plume with the bed (Huisman et al., 2018; IMDC, 2019, Huismans et al 2021).

In general, the modelling suggests that sediments placed here have a higher likelihood of remaining in place than for the other regions of the Put van Hansweert, which is not in line with observations from the data analysis. In fact, a large transport towards the inner bend is suggested by Huismans et al. (2021). Therefore, the results in this region should be interpreted keeping in mind this discrepancy. In addition, it is uncertain how a change in the depth of the Put van Hansweert would affect the transports here, possibly increasing transports when a disposal of sediment is made. Furthermore, the dumped sediment may also rework the locally present sediment, bringing more in suspension. The modelling in this study is considered best-suited for the evaluation of the effect of the sediment that has settled at the bed, and to a lesser extent to the finer sediment that is transported during (or directly after) the dumping of the sediment.

Sediment pathways originating from the Gat van Ossenisse follow the eastern side slope of the Overloop van Hansweert with the flood current (i.e. from region 11), overshoot along the Put van Hansweert and travel into either the Zuidergat or towards the Plaat van Walsoorden. In addition, also sediment originating from the Zuidergat is transported northward along the eastern margin of the Platen van Ossenisse (i.e. from region 11) towards the northern tip of the shelf of the Platen van Ossenisse, which suggests that sediment accumulation can occur at the northern tip of the Platen van Ossenisse. A large share of this sediment will move eastward towards the Drempel van Hansweert. This aligns well with the findings from the data analysis of the pilot sediment disposals. Accreted sediment at the northern side of the shelf of the Platen van Ossenisse may eventually also induce underwater landslides (or liquefication of the slope) moving sand from the inner bend to the Put van Hansweert (Huisman et al., 2018 and Huismans et al 2021). These underwater slope collapses are very common in the Western Scheldt, but their frequency may be enhanced in this area. Sediment from the landslides may then be dispersed through the main channel towards the Overloop van Hansweert and Drempel van Hansweert or be transported back onto the inner bend, as the data-analysis suggest.

Our model schematization does not include processes that model the supratidal shoals of the Platen van Ossenisse. Sediment pathways do, however, illustrate potential mechanisms that explain the sediment losses of the Platen van Ossenisse. The relative sediment mobility at the eastern side of the Platen van Ossenisse increases in northward direction (Figure 3.7), which suggest an erosive gradient.

Similarly, to the findings of Huisman et al. (2021), the sediment trajectories do not indicate that sandy sediment will migrate into the Harbour of Hansweert. However, particle trajectories do travel directly along the entrance. It is possible that small-scale processes that determine the sediment exchange in the entrance are not resolved in the model. It can therefore not fully be excluded that some material will be trapped int this area.

5 Conclusions & Recommendations

5.1 Conclusions

Sediment connectivity in the Put van Hansweert was studied using the *SedTRAILS* model, which constructs sediment pathways from Delft3D model results. An important conclusion is that the *SedTRAILS* results show good agreement with the conceptual framework of regional morphodynamics, that is presented in Huismans et al. (2021).

Based on this study a large number of sediment pathways could be discerned in the Put van Hansweert and adjacent regions (i.e. Overloop van Hansweert, Drempel van Hansweert, Zuidergat, Schaar van Waarde, Middelgat and Platen van Ossenisse). Pathway visualizations show the likely destination of sediment from the Put van Hansweert, which provides an extension of the knowledge of the functioning of the Put van Hansweert that was discussed by Huisman et al. (2018) and Huismans et al. (2021). The conclusions on the transport patterns that were made based on the modelling are the following:

- The Put van Hansweert is actively dispersive, which means that sediment is eroded and transported away from the Put van Hansweert. This aligns with the observed erosion of pilot sediment disposals in earlier studies (e.g. Huisman et al., 2018; Plancke et al., 2019; Huismans et al., 2021).
- The modelling indicates that sediments deposited in the Put van Hansweert are transported through the main channel towards the sills, although part of the sediment from the southwest side of the Put van Hansweert may end up at the inner bend due to a recirculation south-west of the Put van Hansweert (i.e. an indirect route via the Overloop van Hansweert).
- A direct transport from the Put van Hansweert to the inner bend is not apparent from the sediment pathway analysis. Observations of enhanced accretion at the inner bend after pilot dumps in the Put van Hansweert (Huismans et al., 2021) do, however, suggest that across-channel transport to the inner bend can be considerably larger than modelled in this study.
- A limited amount of sediment migrates from the northwestern side of the Put van Hansweert into the Middelgat. This exchange is a long-term process as migration rates are small. The observation from the disposal here was that a strong accretion was found in the inner bend, which is not indicated by the modelling. In practice it is expected ebb and flood currents will move the initially loose sediment during the sediment dumping processes partially to adjacent regions, while the modelling is focused on the effect of the sediment that has settled at the bed.
- A strong north-east directed transport is present along the western shallow margin of the Platen van Ossenisse during flood, which then moves eastward from the most northern tip of the inner bend to the Drempel van Hansweert. This is in line with previously observed measured sediment transport rates and migration of bed forms (Plancke et al., 2018; Plancke et al., 2019b).
- Sediment gyres are present at the sills of the Overloop van Hansweert and Drempel van Hansweert, which may trap sediment.
- The model schematization does not include processes that model the supratidal shoals of the Platen van Ossenisse, but an erosion of especially the northeastern edge of the shoal is expected based on the gradient in the relative sediment mobility.
- An influence on the harbour entrance of Hansweert could not be discerned from the models.

Relevant for the dredging and disposal strategy for the Western Scheldt is that a working hypothesis can be made for the redistribution of the disposed dredge-sediment in the Put van Hansweert based on the modelling and data-analysis (as discussed above). A notion here is that transport pathways in the direction of the tidal currents are more certain (e.g. towards the Drempel van Hansweert, along the margins of the Platen van Ossenisse and to the Middelgat) while others are less well understood (e.g. transport from the Put van Hansweert towards the inner bend).

A practical conclusion is that the *SedTRAILS* model was relatively easy to apply, given that the numerical Nevla model (Delft3D) was already present.

5.2 Recommendations

Based on this study some recommendations can be formulated with respect to the sediment deposition strategy, the application of sediment transport pattern modelling in the Western Scheldt, and monitoring that can be used to further enhance our understanding of the physical system of the Western Scheldt.

- It is recommended to initially spread sediment that is disposed in the Put van Hansweert over the four earlier discussed regions to avoid a too strong impact at either the inner bend, Middelgat or towards the Drempel van Hansweert (and Schaar van Waarde). Based on the monitoring of the morphological change it may be decided to place more sand in the north-western and eastern side of the Put van Hansweert when accretion on the inner bend is considered too large. Similarly, less sediment may be placed at the north-western side when the impact on the Middelgat is considered too large.
- Monitoring of the bathymetric changes on the inner bend, Middelgat and around the Drempel van Hansweert is recommended to verify the effects of the disposal strategy.
- In order to get insight on how sediment spreads when disposed at other locations, *SedTRAILS* modelling can be used. Most insight will be gained if a site is chosen with different characteristics than the Put van Hansweert.
- An optimization of the location of disposal sites can be made even within meetings for the regions where a *SedTRAILS* model is available, as the potential (modelled) morphological influence on the surrounding area can be analyzed quickly when the computations have been prepared in advance. So, an analysis can be made during a meeting based on the suggestions of the people present at the workshop.
- Maps can be made of active and less active regions of the Western Scheldt (using the *SedTRAILS*) model to qualitatively (or possibly even quantitatively) judge the expected lifetime of disposal locations and their capacity to hold sediments.
- The current *SedTRAILS* modelling does not yet analyze the rate at which the changes take place. To have a better perspective on the actual time scale at which transports take place, it would be useful to make a proxy for the rate of transport (and interaction).
- The modelling of dredge dump scenarios in the deep pits of the Western Scheldt requires accurate representations of the local sediment transports and morphology. The most difficult processes are the influence of complex flow phenomena in the deep pits on the stability of the disposed sediment and the potential transport by residual transport mechanisms (e.g. to the inner bend). This will require a comparison of numerical models with detailed measurements of the currents and sediment concentrations, such as those by Plancke et al. (2017) for the Platen van Ossenisse and Plancke et al. (2019) for the Put van Hansweert.

References

Claessens, J., 1988. Het hydraulisch regime van de Schelde. Water 43, 163-169. (with English summary).

Cleveringa, J., 2013. Ontwikkeling mesoschaal Westerschelde (factsheets). Basisrapport kleinschalige ontwikkeling K-16. Project LTV veiligheid en toegankelijkheid; LTV V&T-rapport K-16. 30 augustus 2013. Rapport A2666. I/RA/11387/13.083/GVH.

Davis, J.C. 2002. Statistics and data analysis in geology, third edition: Wiley and Sons, New York, 638 p.

Gerritsen, F., De Jong, H., 1983. Stabiliteit en Doorstroomprofielen in de Westerschelde. Report WWKZ-83.VOO8, Rijkswaterstaat, Vlissingen, 38 pp.

Grasmeijer, B. 2013. Actualisatierapport Delft3D Schelde-estuarium. Achtergrondrapport A-27. LTV.

Huisman, B.J.A., Schrijvershof, R. Lanckriet, T., Van der Werf, J., 2018. Baggerdepositie in Diepe Geulen. Strategie Voor Het Plaatsen van Sediment in de Diepere Getijdegeulen van de Westerschelde. 1210301-000-ZKS-0027. Delft: Deltares. In opdracht van de Vlaams Nederlandse Schelde Commissie (VNSC).

Huisman, B.J.A., Huismans, Y., Vroom, J., 2021. Effecten van storten in diepe putten van de Westerschelde. Synthese van proefstortingen en modelanalyses. Deltares rapport 1210301-015-ZKS-0009. In opdracht van de Vlaams Nederlandse Schelde Commissie (VNSC).

Huismans, Y., van der Vegt, H., Huisman, B.J.A., Colina Alonso, A.C, 2021. Westerschelde: storten in diepe putten Technische rapportage: mesoschaal morfologische ontwikkelingen rond de Put van Hansweert. Deltares rapport 1210301-015-ZKS-0006. In opdracht van de Vlaams Nederlandse Schelde Commissie (VNSC).

IMDC, 2020. Report on CFD calculations disposal plumes. IMDC report for VNSC I/RA/12161/20.005/BDC/FKY. Auteurs: Foteini Kyrousi & Boudewijn Decrop.

Lesser, G.R., J.A. Roelvink, J.A.T.M. van Kester, and Stelling, G.S., 2004, Development and validation of a three-dimensional morphological model: Coastal Engineering, v. 51, p. 883–915.

Lesser, G.R., 2009, An approach to medium term coastal morphological modelling. PhD Dissertation, Delft Technical University, Delft, Netherlands, 239 p.

Menninga, P.J, Dam, G. 2013. LTV - Veiligheid en Toegankelijkheid. Simulaties met effectenanalyse op mesoschaal. Basisrapport kleinschalige ontwikkeling K-20, Consortium Deltares-IMDC-Svašek-Arcadis, Arcadis rapport 077010281:0.1

MacDonald, N.J., Davies, M.H., Zundel, A.K., Howlett, J.D., Demirbilek, Z., Gailani, J.Z., Lackey, T.C., Smith, J., 2006. PTM; Particle tracking model; Report 1; Model theory, implementation, and example applications: U.S. Army Corps of Enginneers Engineer Research and Development Center Technical Report ERDC/CHL TR-06-20, 169 p.

Pearson, S.G., van Prooijen, B., Elias, E., Vitousek, S., Wang, Z.B., 2020. Sediment Connectivity: A Framework for Analyzing Coastal Sediment Transport Pathways. Submitted to Journal of Geophysical Research, Earth Surfaces.

Plancke, Y., Claeys, S., Verwaest, T., & Mostaert, F., 2017. Overleg Flexibel Storten: Deelrapport 23 – Stroming- en sedimentmeting ter hoogte van de diepe put van Hansweert. Versie 3.0. WL Rapporten, 00_031_23. Waterbouwkundig Laboratorium: Antwerpen.

Plancke, Y., Meire, D., & Mostaert, F., 2018. Agenda voor de Toekomst Morfologie Mesoschaal: Deelrapport 14 – Bodemtransport nabij de Platen van Ossenisse op basis van een analyse van bodemvormen. Versie 3.0. WL Rapporten, 14_024_14. Waterbouwkundig Laboratorium: Antwerpen.

Plancke, Y., Meire, D., & Mostaert, F., 2019. Agenda voor de Toekomst - Sedimentstrategie Westerschelde: Syntheserapport. Versie 0.1. WL Rapporten, 13_122_1. Waterbouwkundig Laboratorium: Antwerpen.

Plancke, Y., Bastiaensen, E., & Mostaert, F. 2019a. Proefstortingen Westerschelde: Deelrapport 2 – Analyse beun- en boxcorerstalen bij de uitvoering van de stortproef 2019 in de diepe put van Hansweert. Versie 0.1. WL Rapporten, 19_079_2. Waterbouwkundig Laboratorium: Antwerpen.

Plancke, Y., Meire, D., & Mostaert, F., 2019b. Overleg Flexibel Storten: Deelrapport 31 – Stromings- en sedimenttransport metingen ter hoogte van de diepe put van Hansweert. Versie 3.0. WL Rapporten, 00_031_31. Waterbouwkundig Laboratorium: Antwerpen.

Schrijvershof, R. en Vroom, J., 2016. Effecten van realistische (extreme) stortstrategieën in de Westerschelde. Deltares rapport 1220094.

Stevens, A.W., Elias, E., Pearson S., Kaminsky, G.M, Ruggiero, P., Weiner, H.M., Gelfenbaum, G., (in press). Observations of Coastal Change and Numerical Modeling of Sediment Transport Pathways at the Mouth of the Columbia River. Open-file Report -, U.S. Geological Survey, Santa Cruz, CA.

Storlazzi, C.D., van Ormondt, M., Chen, Y-L., Elias, E.P.L., 2017. Modelling Fine-Scale Coral Larval Dispersal and Interisland Connectivity to Help Designate Mutually-Supporting Coral Reef Marine Protected Areas; Insights from Maui Nui, Hawaii: Frontiers in Marine Science, v. 4, p. 1-14.

TNO, 2003. Kartering moeilijk erodeerbare lagen in het Schelde estuarium, TNO rapport 03-213-B1208

Van Rijn, L.C., 2007a, Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport: Journal of Hydraulic Engineering, v. 133, p. 19.

Van Rijn, L.C., 2007b, Unified view of sediment transport by currents and waves. II: Suspended transport: Journal of Hydraulic Engineering, v. 133, p. 22.

Van Rijn, L.C., 2007c, Unified view of sediment transport by currents and waves. III: Graded beds: Journal of Hydraulic Engineering, v. 133, p. 15.

Vroom, J., De Vet, L., Van der Werf, J., 2015. Validatie Waterbeweging Delft3D-NeVla Model Westerscheldemonding. 1210301-001-ZKS-0001. Delft: Deltares.

Van der Wegen, M., Schrijvershof, R., Alonso, A.C., Broekema, Y., Kranenburg, W., & Huisman, B.J.A., 2021. Hydrodynamics in the Pits of Borssele and Hansweert - Data-Analysis and Delft3D-FM Modeling. Deltares report 1210301–015.

Watts, D. J., & Strogatz, S. H., 1998. Collective dynamics of ‘small-world’networks. *nature*, *393*(6684), 440.

Winterwerp, J.C., Z.B. Wang, M.J.F. Stive, A. Arends, C. Jeuken, C. Kuijper and P.M.C. Thoolen, 2001. A new morphological schematization of the Western Scheldt Estuary, The Netherlands, River, Coastal and Estuarine Morphodynamics Conference RCEM2001 (IAHR), Japan.

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.