Deltares

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A novel method to visualize and analyse sediment transport pathways

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Client	Rijkswaterstaat Water, Verkeer en Leefomgeving
Contact	S. Pluis
Reference	-
Keywords	Sediment transport, morphodynamics, Delft3D

Document control	
Version	0.1
Date	11-05-2020
Project nr.	11205236-003
Document ID	11205236-003-ZKS-0002
Pages	37
Status	final

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Doc. version	**Author**	**Reviewer**	**Approver**	**Publish**
0.1	Edwin Elias	Marcel Taal	Toon Segeren	
	Stuart Pearson			

Summary

This report forms part of the Dutch knowledge program KPP – BenO Kust and presents the SedTRAILS tool. SedTRAILS is a novel method that visualizes sediment transport pathways based on the sediment transports computed with Delft3D. SedTRAILS is not a sediment tracer, but a post-processing routine that uses high-resolution sediment transport vectors from Delft3D to compute sediment trajectories or pathways.

It was demonstrated through two case-studies for the Columbia River and for the Western Scheldt that sediment trajectories can be computed efficiently and robustly. Analysis of the sediment pathways provides a valuable new additional method of analysis that can greatly enhance our insights in the sediment transport process and help to better understand how complex morphodynamic systems such as tidal inlets and estuaries work.

An extended summary is provided in Dutch, that specifically focusses on the application of SedTRAILS for the KPP-BenO Kust program.

Uitgebreide samenvatting

Dit rapport is gemaakt binnen het kennisprogramma KPP BenOKust. Het heeft twee doelen, te weten (i) een introductie in SedTRAILS en de mogelijkheden ervan tonen voor een breder publiek van beheerders van morfologische systemen middels deze samenvatting (in het Nederlands) en (ii) het geven van inzicht in de werking van SedTRAILS door bespreking van twee case studies (in het Engels).

SedTRAILS is geen nieuwe simulatiesoftware, maar is ontwikkeld als een nabewerking op de resultaten van bestaande sedimenttransportmodellen (zoals Delft3D). Op basis van de berekende sedimenttransportvectoren worden transportpaden berekend. Deze paden illustreren hoe sediment zich verplaatst en stellen ons in staat fenomenen zichtbaar te maken als:

• Waar sediment van een bepaalde bron zich (allemaal) heen verspreidt;
• Vanwaar het sediment komt dat op bepaalde plekken accumuleert;
• Langs welke wegen het sediment reist tussen twee punten;
• Waar sedimentbronnen uniek of dominant zijn voor specifieke plaatsen.

Met reguliere Delft3D modellering zouden vragen hierover niet direct kunnen worden beantwoord. Er moeten dan aanvullende “particle-tracking” simulaties, met software, zoals Delft3D PART, worden gemaakt. Een nadeel van Delft3d PART is dat het niet de Van Rijn formules voor zandtransport bevat maar de Partheniades-Krone transportformule voor cohesief sediment gebruikt, hierdoor is een directe vergelijking met Delft3D resultaten voor zandtransport niet mogelijk. SedTRAILS maakt gebruik van de al in Delft3D berekende sedimenttransportvectoren en alleen de resulterende verplaatsing van de sedimentdeeltjes word berekend. Groot voordeel daarvan is dat er geen aanvullende modelsimulaties nodig zijn. Dit maakt de SedTRAILS methode snel en efficiënt.

Het is belangrijk te begrijpen dat SedTRAILS niet de verplaatsing van een individueel deeltje berekent (geen particle-tracking). SedTRAILS visualiseert hoe een deeltje zich (door een al berekend transportveld) zou verplaatsen en welke route het dan volgt. Uitwisseling met de bodem wordt niet meegenomen. Deze uitwisseling vormt in werkelijkheid wel een belangrijk onderdeel in de verplaatsingssnelheid van het sediment. In de huidige implementatie van SedTRAILS is de verplaatsingssnelheid niet gekalibreerd. Het berekende transportpad, de route die het sediment volgt, zal gelijk zijn aan die berekend wordt met een particle tracking model. Hoe lang het duurt om van begin tot eind van dat pad te reizen volgt niet uit SedTRAILS. De resultaten worden daarom uitgedrukt in termen van mobiliteit. Een lang transportpad betekent dat deeltjes sneller bewegen dan een kort transportpad.

SedTRAILS kan worden toegepast op de resultaten van elk proces-gebaseerd model voor sedimenttransport. De enige voorwaarde is dat de sedimenttransport-vectoren in voldoende detail worden weggeschreven. Het maakt dan niet uit of deze vectoren berekend zijn met bijv. Delft3D 4, XBeach, Delft3D FM, Mike, Finel of Telemac. Qua toepassing maakt het karakter van het systeem niet uit. Het werkt voor een rechte kust, maar b.v. ook bij een zeegat. Feit blijft wel dat SedTRAILS ontwikkeld is voor complexe morfologische systemen zoals zeegaten en estuaria. Dergelijke systemen zijn uitgestrekt en hebben lange tijdschalen van morfologische ontwikkeling.
Morfologische voorspellingen op de schaal van zulke complexe morfologische systemen zijn vaak rekenintensief. Dat maakt de systemen lastiger te bestuderen met proces-gebaseerde modellen. Er

zijn namelijk compromissen nodig tussen rekentijd, resolutie, data voor afregeling[1], een formulering voor sedimenttransport (bv. Van Rijn) en het aantal simulaties.
Als dieptegemiddelde modellen met beperkte resolutie gedraaid worden blijft (bij die complexe morfologische systemen zoals zeegaten) de vraag of zo'n model de onderliggende fysica op de schaal van kleinere morfologische elementen (geulen en platen) wel voldoende bevat om tot realistische voorspellingen te komen. Ook andere bestaande instrumenten, zoals algemene denkmodellen en empirische relaties geven niet het detail dat nodig is. In deze systemen heeft SedTRAILS een duidelijke toegevoegde waarde. In systemen met geringe complexiteit (bijv. een rechte kust) heeft de SedTRAILS aanpak waarschijnlijk minder toegevoegde waarde. Hier geven de sedimenttransport vectoren al voldoende inzicht.

In deze rapportage zijn twee casestudies uitgewerkt om toepassing van SedTRAILS inzichtelijk te maken: (1) de verspreiding van sediment nabij de monding van de Columbia River en (2) de sediment uitwisseling met de diepe Put van Hansweert in de Westerschelde, .

Bij de Columbia River is gekeken naar de optimale stortlocatie om het eroderende naastliggende strand te voeden. Rechtstreeks daar aanbrengen is kostentechnisch niet mogelijk. Met behulp van Delft3D modellering en SedTRAILS zijn ca 19.000 transportpaden berekend over een representatief getij- en golfklimaat, onder verschillende rivierafvoeren. De resultaten gaven inzicht in hoe gebieden onderling verbonden zijn en onder welke condities deze uitwisseling gebeurt. Duidelijk werd dat zand vanuit de voorgestelde stortgebieden slechts zeer beperkt bijdraagt aan de zandhuishouding van het eroderende strand. De uitwisseling tussen stortgebied en strand loopt via de aangrenzende buitendelta. De resultaten zijn gebruikt voor grotere groepen, om de complexiteit van het systeem te bespreken.

Voor de Put van Hansweert is SedTRAILS ingezet om een al opgesteld conceptueel model te toetsen. Daarnaast is de samenhang tussen morfologische elementen gevisualiseerd. Dat gebeurde via 'connectiviteit', waarmee het mogelijk was de samenhang statistisch te beschouwen. Connectiviteit is een van veel statistische instrumenten die beschikbaar zijn om de resultaten van SedTrails nader te duiden. Met behulp van deze instrumenten krijgt de beheerder inzicht in de werking van het morfologisch systeem.

Het aantal mogelijke toepassingen van SedTrails is breder dan deze twee case studies. De beste weg vooruit is om stap voor stap ervaring op te doen. Uit een eerste verkenning voor kustlijnzorg volgde de suggestie van een koppeling met de kustviewer. Zo'n koppeling kan RWS-interne discussies over (geplande en uitgevoerde) suppleties ondersteunen, maar ook ondersteuning bieden in de gesprekken met de omgeving. Voor het onderzoek naar het gedrag van morfologische systemen zijn de mogelijkheden van post-processing van resultaten van procesgebaseerde simulaties met SedTrails waarschijnlijk nog talrijker. Te denken valt aan het op andere wijze onderzoeken van het gedrag van sediment bij een hogere zeespiegel.

[1] Merk op dat de juistheid van instellingen afhankelijk is van beschikbare bodemdata. De beschikbaarheid van bodemdata is van een veel lagere resolutie in tijd en ruimte dan van waterbewegingsdata.

Contents

1 Introduction

In this report we describe a new modelling tool called ***SedTRAILS*** (***Sed****iment* ***TRA****nsport* *v****I****sualization &* ***L****agrangian* ***S****imulator*). SedTRAILS is a novel method that uses the results of a high-resolution Delft3D sediment transport computation as a base to calculate the pathways that idealized particles travel as they pass through a changing sediment transport vector field. These pathways allow us to visualize, and analyse, sediment transport pathways and identify the linkages between various morphological elements of the system such as the sediment bypassing processes (see Figure 1.1).

This report provides an introduction into the *SedTRAILS* tool in Chapter 2. Chapter 3 illustrates the application of *SedTRAILS* to study sediment dispersal in the Columbia River Estuary (USA) and in the Western Scheldt (Put of Hansweert). Chapter 4 summarizes our findings and provides an outlook into future development of the tool.

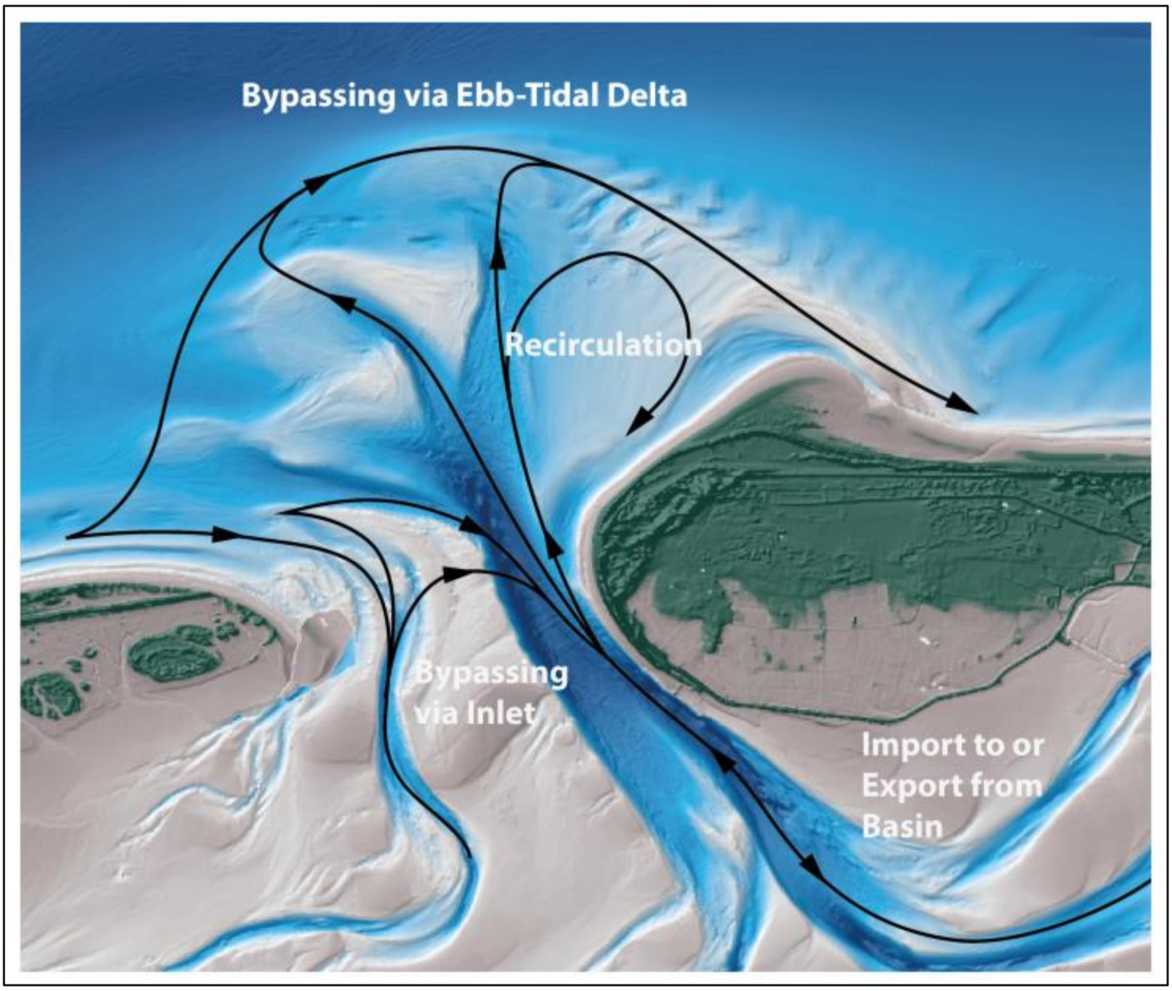

Figure 1.1 Conceptual diagrams identifying key questions regarding sediment transport pathways. 1. Where does sediment from a particular source (e.g. nourishment) travel? 2. Which sources contribute sediment to a particular receptor? 3. What is the most important sediment pathway connecting two points? 4. Which points have the greatest influence on the rest of the system? 5. How resilient is the system of sediment pathways to perturbations? These questions cannot be answered through field measurements or 'traditional'' process-based modelling alone.

2 *SedTRAILS* – Background and Method

In this Chapter we provide a brief background in the reasoning why *SedTRAILS* was developed (section 2.1), and briefly describe the Delft3D process-based model (section 2.2) and the *SedTRAILS* tool (section 2.3).

It is important to realize that SedTRAILS is not a sediment tracking model in a classic sense. SedTRAILS is a visualization of the sediment transport vector field that was computed by Delft3D. SedTRAILS allows us to construct the sediment pathways or trajectories; the routes that sediment will follow through the morphodynamic system based on the computed sediment transport vectors. These trajectories can be queried to analyse the morphodynamic connectivity between the various elements of the morphodynamic system and allows us to answer where sediment moves to or where sediment came from. Such analysis cannot be made directly from de Delft3D model results. Additional model simulations using dedicated particle tracking models such as Delft3D PART would be needed. Such simulations can only be made for cohesive sediments and are computationally expensive.

2.1 The need for a “different” model approach

Delft3D has been under development at Deltares (and its predecessor WL-Delft / Delft Hydraulics) since the early 1990’s and has been applied in complex morphological systems in the past, like tidal inlet systems (see e.g. Elias 2006; Lesser 2009; Van der Weegen 2009; Dastgheib 2012; Elias and Hansen 2012). These studies show that process-based model suites like Delft3D have reached the stage that they can be used successfully to investigate tidal inlet processes and greatly improve our fundamental understanding of the processes driving sediment transport and morphodynamic change.

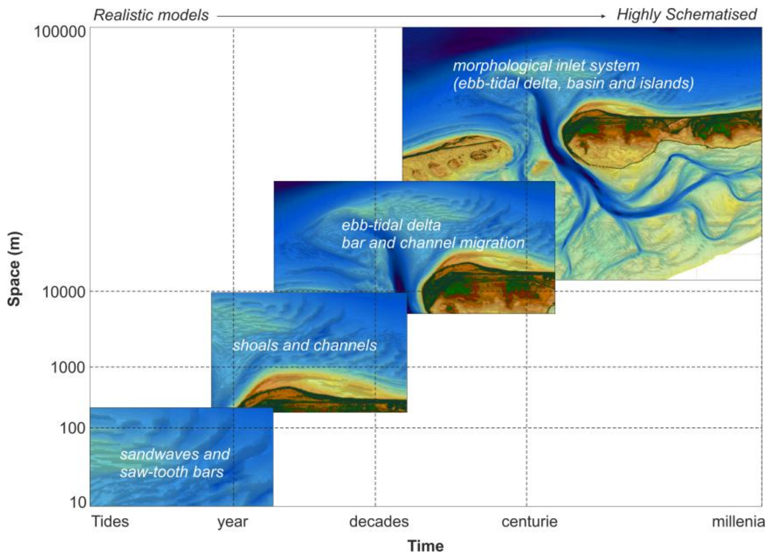

Figure 2.1: An example of a scale cascade describing various morphological elements in Ameland tidal inlet (the Netherlands). From Elias and Teske (2015).

Process-based models seem to perform particularly well at the end nodes of the scale cascade (Figure 2.1), on the short term (small scale) and on the long term (large scale). By using different assumptions and schematizations, simulations over the appropriate spatial and temporal scales can be made. Both short-term, quasi-realtime models (Elias 2006; Elias and Hansen 2012) and the long-term models (Van der Weegen 2009; Dastgheib 2012) seem to produce useful results. The quasi-realtime models (e.g. Elias 2006; Elias and Hansen 2012) have typically a high resolution in grid size and boundary forcing and use the most complex sediment transport equations to capture the dominant processes as accurately as possible. These models are typically run over short time frames (e.g. tides to spring-neap cycles). Long-term models (e.g. Van der Weegen 2009; Dastgheib 2012) are constrained by computational run time. Low-resolution grids, schematisations of boundary conditions, and morphodynamic acceleration techniques such as “MorFac” (see Lesser 2009 for a detailed explanation) are used to enable such simulations.

For medium term model simulations (timescales of years to decades see Figure 2.1) one can try to run the quasi-real time models over longer periods, but unless super-computers are employed, such efforts are still limited to one or at best a couple of years. To reach timescales of 5-25 years, it seems necessary to adopt the long-term model strategy, to improve understanding of the underlying concepts, and where possible reduce the schematizations applied. Typically, such morphodynamic model studies are cumbersome and time-consuming due to the long runtimes involved. Runtimes over a week (to weeks) are no exception. This imposes a major limitation on the amount of runs that can be made. Very often the model can only be run once or twice. Especially if model results deviate from what is expected (not uncommon in morphodynamic models), this leaves a lot of uncertainty in the interpretation of the results.

One of the major pitfalls in morphodynamic modelling is to assess the model skill (capacity of the model to reproduce reality) by only quantitatively comparing model results and measurements. A clear example is given in the study of Lesser (2009), but his conclusion is valid for most morphodynamic studies performed to date. Lesser demonstrated through agreement between modelled and measured morphodynamic behaviour of Willapa Bay, that a process-based numerical model could reproduce the most important physical processes in the coastal zone over medium-term (5 year) timescales. Most of the observed general patterns are reproduced, but the magnitude and/or precise location of these changes are not accurately predicted. In his case the Brier Skill Score, an objective score to measure the model performance results, is a negative value. Which in essence means that the model skill is worse than simply predicting that no morphological change occurs. Extensive tweaking of parameter settings, initial inputs, and boundary conditions to “custom fit” the model to the observations is an often used and accepted method to improve the model skill. With “tweaking” an optimal hind-cast result may be achieved, but in the process, you may have altered to underlying dynamics of the model to such an extent that these are no longer representative of the natural processes.

An important lesson learned from the Kustgenese 2 research project is the importance of small-scale processes even on the larger scale of the ebb-tidal delta. Small-scale shoal instabilities can trigger a new sediment-bypassing cycles and result in complete relocation of channels and shoals. These subtle dynamics are difficult, if not impossible, to capture in existing general conceptual models, empirical relationships and model schematizations. These differences are, however, essential for understanding tidal inlet and channel morphodynamics and hence coastal management along the adjacent island coastlines.

The realisation that we may not fully understand the subtle dynamics that underly ebb-tidal delta and inlet behaviour was a primary driver for the development of the *SedTRAILS* tool. *SedTRAILS* was developed to efficiently compute inlet-scale sediment transport without sacrificing model resolution and accuracy. With SedTRAILS we can run models that capture the processes on the smallest scales (tides) and show the morphodynamic connectivity on the scale of the entire inlet system.

2.2 Some basics of Delft3D Online Morphology and SedTRAILS

2.2.1 Basics

The sediment transports used in the *SedTRAILS* model are based on Delft3D Online Morphology. The main components of the Delft3D Online Morphology model are the coupled Delft3D-Wave and the Delft3D-Flow modules. Delft3D-Flow forms the core of the model system simulating water motion due to tidal and meteorological forcing by solving the unsteady shallow-water equations. These equations can be resolved on a structured grid (Delft3D 4) or unstructured mesh (Delft3D FM). Wave effects, such as enhanced bed shear stresses and wave forcing due to breaking, are integrated in the flow simulation by running the 3rd generation SWAN wave processor. The SWAN wave model is based on discrete spectral action balance equations, computing the evolution of random, short-crested waves (e.g. Booij et al., 1999). The results of the wave simulation, such as wave height, peak spectral period, and mass fluxes are stored on the computational flow grid and included in the flow calculations through additional driving terms near surface and bed, enhanced bed shear stress, mass flux and increased turbulence. Wave processes are resolved at the wave time-step, which is typically every 10 to 60 minutes.

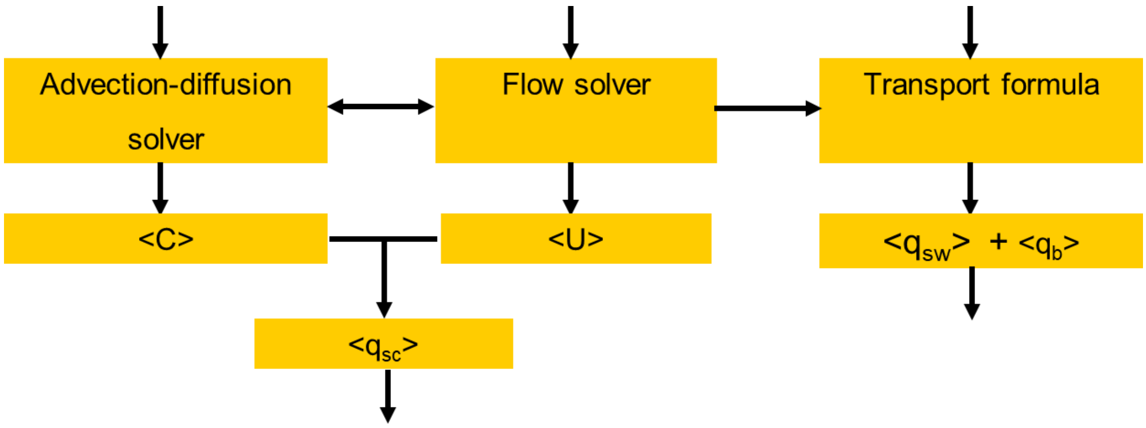

Figure 2.2: Schematic overview of the sediment transport equations in Delft3D 4.

Sediment transports and morphodynamic change are resolved at each flow timestep (Online Morphology). By default the sediment transport equations of Van Rijn are used (Van Rijn, 2007a,b,c). The Delft3D implementation of this formulation follows the principle description of Van Rijn (1993), separating suspended load (S_s) and bed load (S_b) components (see Figure 2.2). Bed load transports represent the transport of sand particles in the flow boundary layer in close contact with the bed surface. Suspended sediment transport is computed by the advection-diffusion solver. To describe sediment characteristics, additional formulations are included to account for: density effects of sediment in suspension, settling velocity, vertical diffusion coefficient for sediment, suspended sediment correction vector and sediment exchange with the bed. The elevation of the bed is dynamically updated at each computational time-step by calculating the change in mass of the bottom sediment resulting from the sediment transport gradients. A series of tuning parameters (such as f_{SUS}, f_{SUSW}, f_{BED}, f_{BEDW}), allows for the calibration of the individual contributions of the suspended load transports, the bed-load transports, and the wave-driven suspended and bed load transports before bed elevation updating.

Lesser (2004) provides a complete overview of model testing under a range of (simple) validation cases. These cases include:

- theoretical results, such as the development of sediment transport under flow conditions, the modelling of an equilibrium longitudinal bed slope from a plane bed, and the simple case of sediment settling from suspension.

- laboratory datasets, such as reproducing a flume experiment with downstream migrating trench, the formation of bars and channels in a curved flume with spiralling flow and reproducing sediment concentration profiles under the action of waves and currents.
- Case studies, such as the wave-driven deformation of a sediment hump, and tombolo formation behind an emergent shore-parallel breakwater.

2.2.2 Sediment Tracking in Delft3D

Tracking sediment to illustrate sediment pathways can in principle be performed with the standard Delft3D application. Delft3D will not compute the movement of individual particles, but Delft3D can compute the sediment transport of multiple fractions simultaneously and thereby follow the movement of each fraction. By using multiple sediment fractions with similar sediment characteristics and properties, the movement of each separate fraction can be followed. This approach has been used to track movement of larger scale morphologic features (such as nourishments) in the past. Bak (2017) provides a recent example, tracking the movement of the Ameland ebb-tidal delta nourishment. In this example the sediment of the nourishment was tagged as a separate sediment fraction compared to the sediment of the ebb-tidal delta (both fractions had similar characteristics). This method of sediment tracing has two major limitations. Firstly, these simulations are computationally expensive. To capture e.g. the sediment bypassing cycle, sediment movement from the updrift to the downdrift island, model simulations over longer time-spans of months to years would be needed. Such simulations may take weeks to months of runtime to complete. Secondly, Elias (2011) revealed that if initial tracer deposits are small compared to the total sediment volume, the exchange layer thickness becomes an important calibration parameter for the dispersal rate. Since sediments are assumed to be well-mixed within the bed layers, the ratio of tracer versus native sediment mass available determines the contribution of each sediment class to the sediment transport in subsequent time-steps.

Elias et al. (2011) resolved the latter limitation by adding a sediment tracking addition to the Delft3D code. Sediments tagged as "tracer" behave as normal sand fractions in the sediment transport equations, but are excluded from the bed updating, while keeping the normal sediment transports and bed level exchange unchanged. Since bed mixing and exchange are naturally occurring processes, the modeled tracer behavior is not physically accurate. The predicted tracer transport rates and magnitudes must be interpreted as maximum movement rates, and decay of tracer availability due to mixing, and lag effects due to burial and resurfacing of sediments are not accounted for. This code update did not resolve the computational runtime constraint, as a 10-month simulation for the Columbia River took over six weeks to complete. The need for a computationally more efficient method to study sediment dispersal was a second motivation to develop the *SedTRAILS* tool.

2.3 SedTRAILS

2.3.1 Introduction

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* 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 execute 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.

2.3.2 Method

SedTRAILS (***Sed**iment **TRA**nsport v**I**sualization & **L**agrangian **S**imulator*) was applied to visualize, identify, and analyze 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 2.3 provides an illustration of the mehod based on the Columbia River case study (see Chapter 3.1). *SedTRAILS* was adapted from techniques described in Storlazzi et al. (2017) and employs a similar methodology to sediment particle tracking modules such as PTM (MacDonald et al., 2006).

Existing particle tracking approaches (like Delft3D PART) 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 behaviour 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 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 dividing 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.

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.

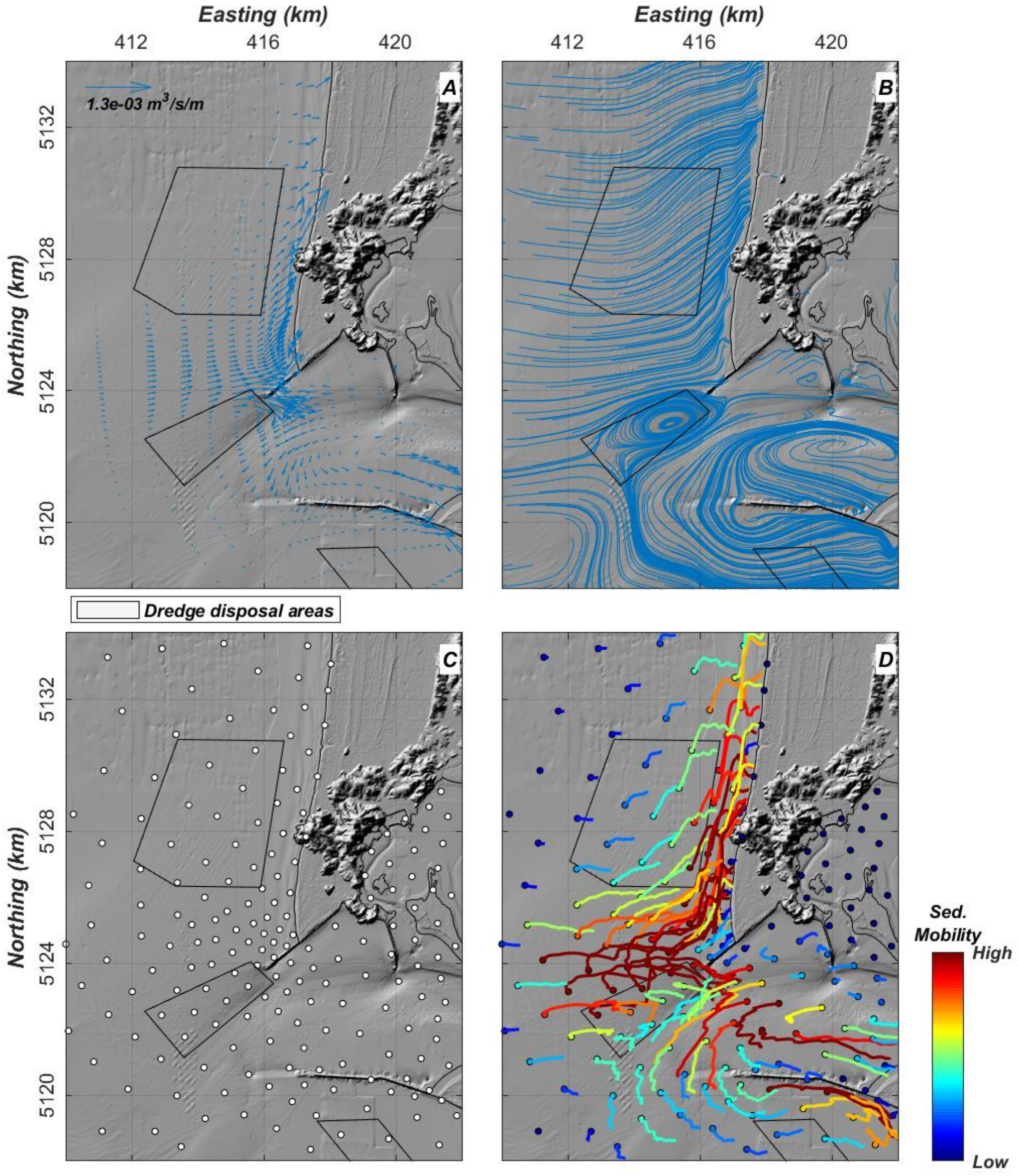

Figure 2.3: Example of a SedTRAILS visualization of lagrangian sediment transport pathways showing: A, a sediment vector field, B, streamlines representing the vector field, C, initial positions of the sediment sources, and D, sediment pathways derived from the SedTRAILS analysis. Sediment pathways in 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.

3 Case studies

In this section the use of *SedTRAILS* is demonstrated through two case studies. Firstly, the fate of dredge disposal at the North-Head disposal site located in the Mouth of the Columbia River (USA) is discussed (section 3.1). In this application the sediment linkages between the MCR and adjacent open coasts of the Long Beach Peninsula and Clatsop Plains are analysed. The results of this section are based on Stevens et al., (2020). Secondly, sediment dispersal in the Put of Hansweert (Westerschelde) is investigated (section 3.2) to assess the interaction dredge material with the adjacent channels and shoals. The results presented in this section are based on Elias et al. (2020)

3.1 Sediment dispersal at the Mouth of the Columbia River

3.1.1 Introduction

Hydrodynamic and sediment transport modelling at the Mouth of the Columbia River (MCR) is challenging due to the interaction of strong tidal currents and (highly-variable) density stratification, the importance of waves and wave-current interaction, tidal asymmetry and related mean flow in the system, and wetting and drying of large tidal flats and wetlands in the lower estuary. For this study, the hydrodynamic model application was adapted from Elias and others (2012). The model grid and boundary conditions were modified, and the sediment transport module was activated to simulate hydrodynamics and sediment transport. Through the analysis of the sediment transport pathways described below, we aim to understand the connectivity and linkages between the lower estuary, ebb delta, and adjacent shorelines to the MCR under variable wave-, tide-, and discharge conditions.

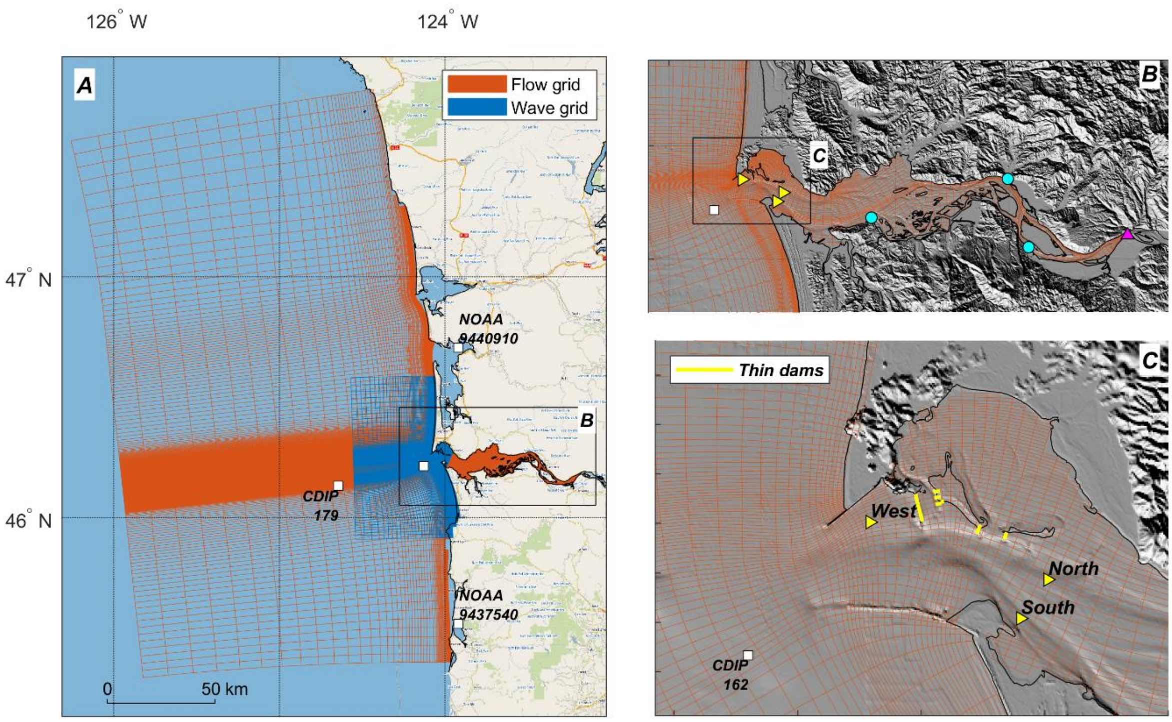

Figure 3.1 A, Hydrodynamic (red) and wave model grids (blue) used for model simulations. The hydrodynamic model grid is shown in detail for the Columbia River Estuary and MCR in B, and C, respectively. The grid resolution in B and C was reduced by a factor of 3 for display.

3.1.2 Model Simulations

Morphodynamic schematizations of boundary conditions were derived for wave, tidal, and fluvial forcing to reduce the number of conditions needed to represent long-term sediment transport patterns and magnitudes. Lesser (2009) provides a comprehensive description of input schematization techniques for the neighbouring Willapa Bay inlet and demonstrated that schematized model inputs can be used for medium term morphodynamic predictions. The wave climate schematization described in Lesser (2009) was based on a 5-year time-frame (1998-2003) of which the winter and summer seasons are grouped separately. A total of 19 wave classes were chosen to represent the morphological impact of all wave conditions that occur during a year. Willapa Bay and Columbia River are exposed to a similar wave climate from the north-eastern Pacific, and we therefore utilized the same wave climate schematization as described in Lesser (2009); see Table 3.1for details.

The objective of tidal input schematization with a morphological tide is to replace the complex time series of tidal water level and current fluctuations occurring in nature with a simplified tide or tides (Lesser, 2009). Gelfenbaum and others (2017) described the construction of morphological tides for the Columbia River for high (~10.000m^3/s inflow at Bonneville Dam) and low (3,000-5,000 m^3/s inflow) discharge regimes based on a spatially explicit correlation analysis. This analysis showed that a single representative tide can be selected to accurately model sediment transport over a full spring-neap cycle during both low and high river flow.

A total of 38 morphostatic simulations were performed to calculate the average annual sediment fluxes for high and low discharge scenarios. For each discharge scenario (2) and wave class in the wave schematization (19), a 50-hr simulation was performed. The transports from each wave class were scaled by their probability of occurrence and summed to yield the average annual sediment flux.

Sediment transport pathways from each simulation were computed over a time period of 365 days using *SedTRAILS* and total transport vector fields saved at 10-min intervals. Output from the 50-hr Delft3D simulations were looped cyclically over the 365-day duration of the *SedTRAILS* time frame. Figure 3.2 provides an example of typical sediment transport vectors and SPIT pathways for a number of selected wave events.

Table 3.1: Morphological wave climate schematization based on Lesser (2009) subdivided in winter and summer conditions.

Wave class	H_{sig} (m)	T_p (s)	Direction (deg.)	Wspeed (m/s])	Wdirection (deg)	Probability (percent)
			Winter conditions			
1	1.00	10.2	279	4.2	196	5.0
2	2.28	8.6	216	8.2	176	2.0
3	2.29	10.0	241	6.0	176	2.0
4	2.16	11.4	262	4.9	156	4.5
5	2.16	13.0	278	3.6	155	9.9
6	2.06	11.4	294	2.5	195	10.4
7	3.88	10.1	224	10.3	201	3.0
8	3.87	12.2	257	7.5	205	3.5
9	3.79	13.9	278	5.5	199	4.5
10	3.71	13.4	291	5.8	201	2.5
11	5.76	12.9	241	12.0	207	1.0
12	5.9	15.1	281	8.7	216	1.0
			Summer conditions			
13	0.7	9.8	271	2.94	343	3.0
14	1.67	8.4	221	5.8	198	2.5
15	1.58	9.9	259	2.88	284	6.0
16	1.64	10.4	281	3.66	329	14.1
17	1.53	8.6	300	5.02	334	16.6
18	3.5	10.7	241	8.56	190	3.5
19	3.38	13.2	284	4.06	267	5.0

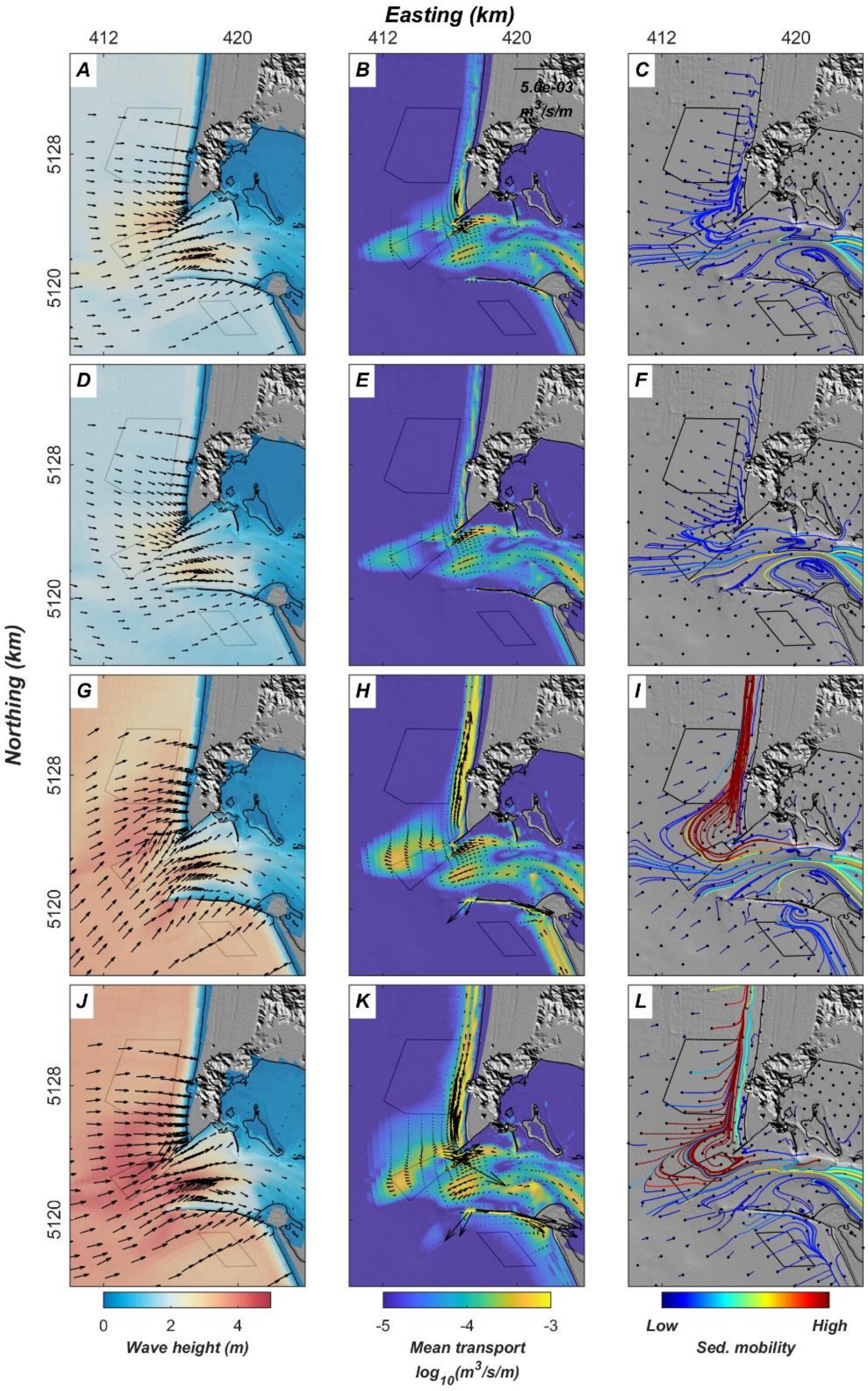

Figure 3.2 Examples of typical SedTRAILS results. Maps showing significant wave height (left panels), mean total sediment transport (middle panels), and sediment transport pathways (right panels) for a range of wave conditions. A-C Wave class 5, D-F, wave class 6, G-I, wave class 7, and J-L, wave class 8 during the low discharge scenario.

3.1.3 An analysis of the sediment pathways

The sediment pathways were computed similarly for the 19 individual wave conditions for high and low river discharge conditions as described in the Morphodynamic Schematization section. Examples of sediment transport pathways for 4 wave conditions during low- and high- river discharge conditions are shown in Figure 3.3. During low-wave conditions, the dominant sediment movement occurred in the estuary and mouth. Sediment pathways were predominantly directed offshore through the navigation channel and MCR. Some pathways along the northern channel indicated landward transport during low discharge conditions. Sediment mobility in the estuary increased during high-flow conditions and all transport pathways directed offshore (Figure 3.3A).

Enhanced shear stress due to waves generally increased the length of the pathways observed along the coasts under both high and low discharge scenarios. For moderate wave energy directed from the southwest with a significant wave height of 3.5 m and peak period of 10.7 s, northward pathways were observed along narrow surf zones both north and south of the inlet (Figure 3.3B). The relative mobility of sediment transported in the surf zone was much higher for sources on the north side of the inlet relative to the south. In addition, sediment sources originating within the MCR and ebb delta on the north side of the navigation channel, including several originating within the Shallow Water Site dredge placement area, were directed to the north and ultimately were incorporated into the surf zone pathways, suggesting a direct connection between MCR sediment and beaches to the north under these wave conditions. On the other hand, sediment transport pathways originating from sources to the south of the navigation channel within the MCR terminated along the South Jetty or were directed onshore towards Clatsop Spit, suggesting no connection between the MCR and adjacent beaches to the south under these conditions.

Southward littoral transport was observed for wave energy from the northwest, a wave height of 3.71 m and a peak wave period of 13.4 s (Figure 3.3C). Under low discharge conditions, sediment transport pathways from sources originating in shallow areas north of the inlet, including the North Head dredge disposal area, were directed onshore and incorporated into the surf zone. However, higher discharge conditions resulted in more complicated pathways north of the inlet, with some pathways originating within the North Head disposal site directed offshore. The North Jetty clearly separates the inlet from shallow sources to the north by interrupting southward directed littoral transport pathways under both high and low discharge conditions. Although most pathways originating within the inlet were directed offshore and terminated on the ebb-delta front, the moderate northwest directed wave energy resulted in some connectivity between the MCR and adjacent beaches. For instance, sediment transport pathways originating from sources within the MCR on the south side of the navigation channel were directed offshore and southward and incorporated into the littoral transport along Clatsop Plains beaches.

Large waves from the southwest resulted in high sediment mobility and northward transport pathways along a large portion of the ebb delta including the North Head and Shallow Water dredge placement areas (Figure 3.4D). Surprisingly, dispersal pathways in both north and south directions were enhanced with high wave energy from the southwest. While the sources originating on the north side of the inlet followed the dominant wave direction, pathways originating within the inlet and on the south side of the ebb delta took a circuitous route and were somewhat sensitive to discharge conditions along paths that ultimately were mostly directed to the south. Although the sediment mobility was relatively low, offshore directed pathways were observed for sources with relatively deep initial locations.

A total of 19,000 source pathways were computed with SPIT, with 19 wave classes, two discharge scenarios, and 500 sources per simulation. Interpretation and synthesis of the raw results was challenging due to the density of the sediment transport pathways and number of scenarios examined (Figure 3.4A). Results were simplified by examining sediment source regions within several polygons of interest including the North Head dredge disposal area, Benson Beach, and the maintained navigational channel. The pathways for high- and low- discharge scenarios were generally similar and only the results from the low discharge scenarios are described here. Sediment transport pathways from sources originating within the North Head dredge disposal area were directed onshore and northward for westerly and southwestly wave classes (Figure 3.4B). Northwesterly waves resulted in limited southward directed pathways from sources within the North Head dredge placement towards Benson Beach. No pathways originating within the North Head permit area interact with the inlet regardless of wave direction suggesting that dredge material placed within the North Head site is unlikely to contribute to shoaling in the navigational channel.

A primary objective of the placement of dredged material in the nearshore is to supplement the sediment budget and mitigate erosion of beaches and associated coastal change hazards in proximity to the inlet. Baseline monitoring of beach nearshore morphology reported that Benson Beach eroded approximately 2.1 Mm3 (420,000 m3/yr) between 2014 and 2019. Analysis of the sediment transport pathways was performed to identify source regions that can supply sediment to Benson Beach. Sources with pathways that intersected Benson Beach were located on the north side of the MCR, as well as throughout the northern ebb delta including both the Shallow Water Site and North Head dredge placement areas (Figure 3.4C). However, only wave conditions from the northwest produced sediment transport pathways between the North Head dredge placement area and Benson Beach, suggesting limited connectivity between these two areas. On the other hand, sediment transport pathways from sources originating within the Shallow Water Site as well as the ebb delta between the Shallow Water Site and North Head site intersected Benson Beach under a variety of wave conditions. The total probability, or percent of time, that sediment transport pathways from each source location interact with Benson Beach (Figure 3.5) suggests that areas along the ebb delta between the inlet and North Head placement area are more often connected to Benson Beach. The total probability of interaction for each source was computed by summing the number of wave classes with pathways that intersected Benson Beach multiplied by the wave class probability of occurrence. This analysis suggests that placement of dredge material in the region between the Shallow Water and North Head sites would more directly and efficiently enhance the sediment budget of Benson Beach.

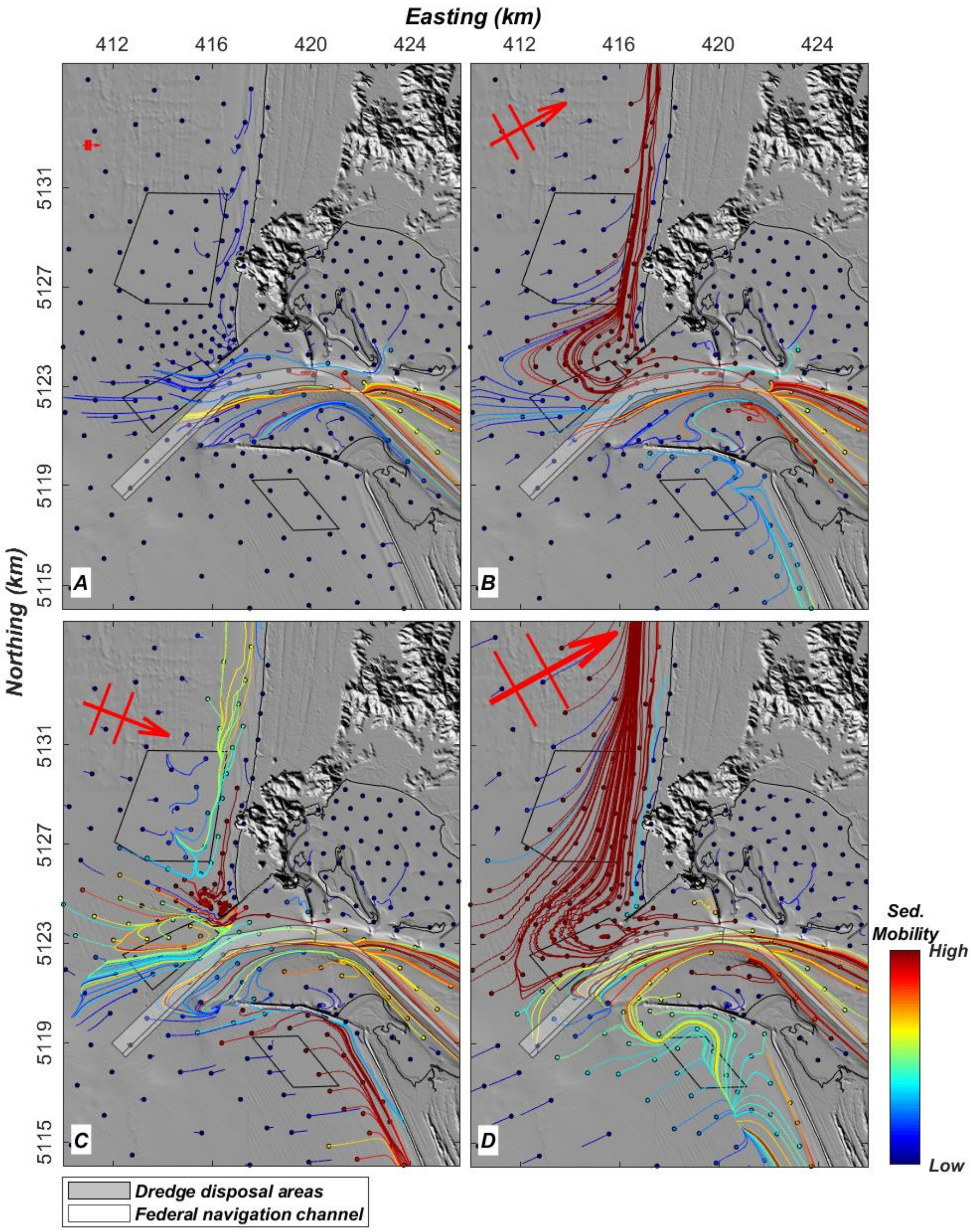

Figure 3.3 Sediment transport pathways derived from the application of SedTRAILS to schematized model simulations with high river discharge and constant wave forcing. Wave classes 13, 18, 10, and 11 are shown in panels A-D, respectively. See Table 5 for the definitions of each wave class.

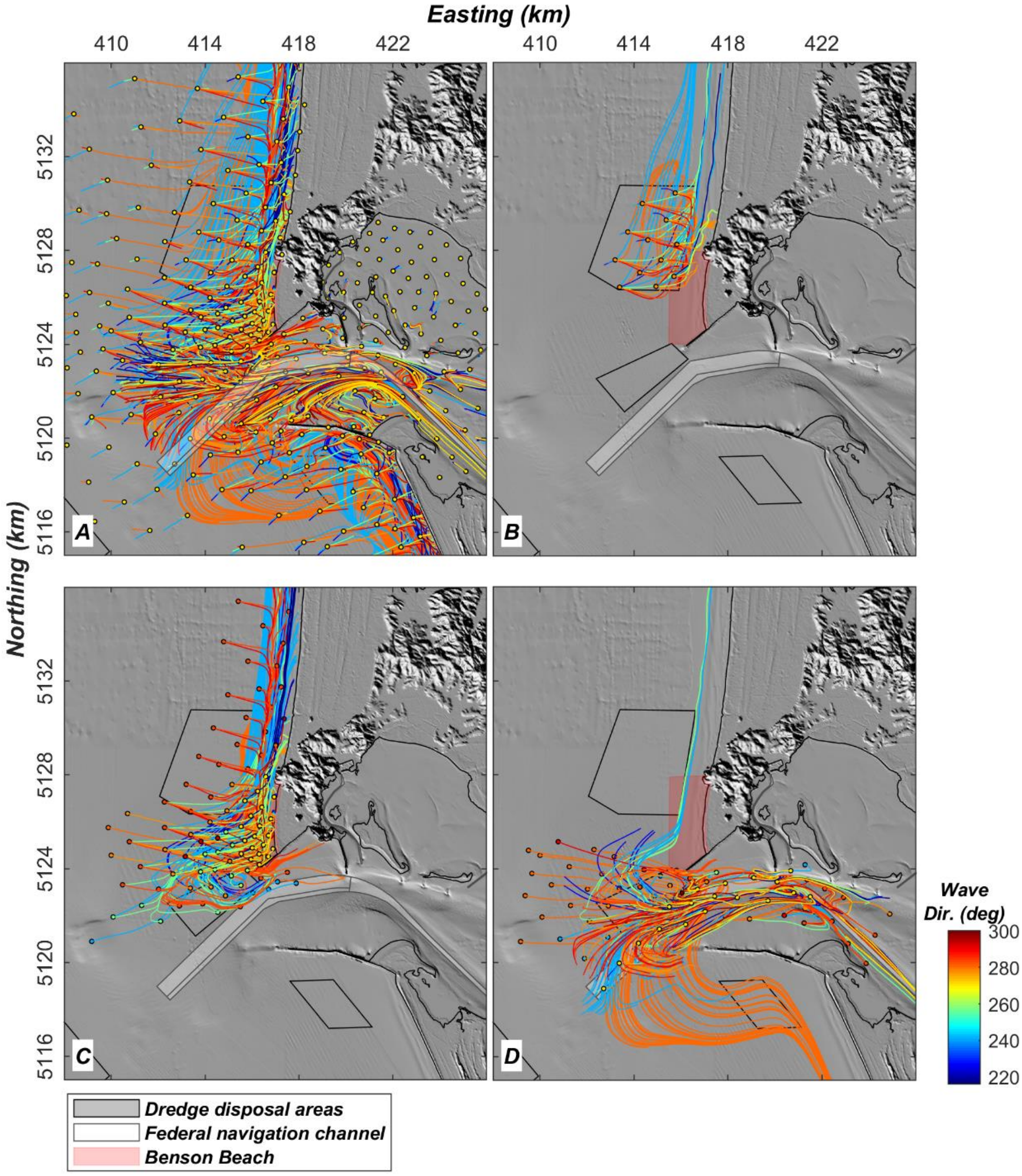

Figure 3.4 Sediment transport pathways computed for various source locations and polygons of interest for the high river discharge scenario including, A, all 500 sources and 19 wave classes, B, sources from all wave classes originating within the North Head dredge disposal area, C, sources and wave classes with pathways that interact with Benson Beach, and D, sources and wave classes with pathways that interact with the navigational channel.

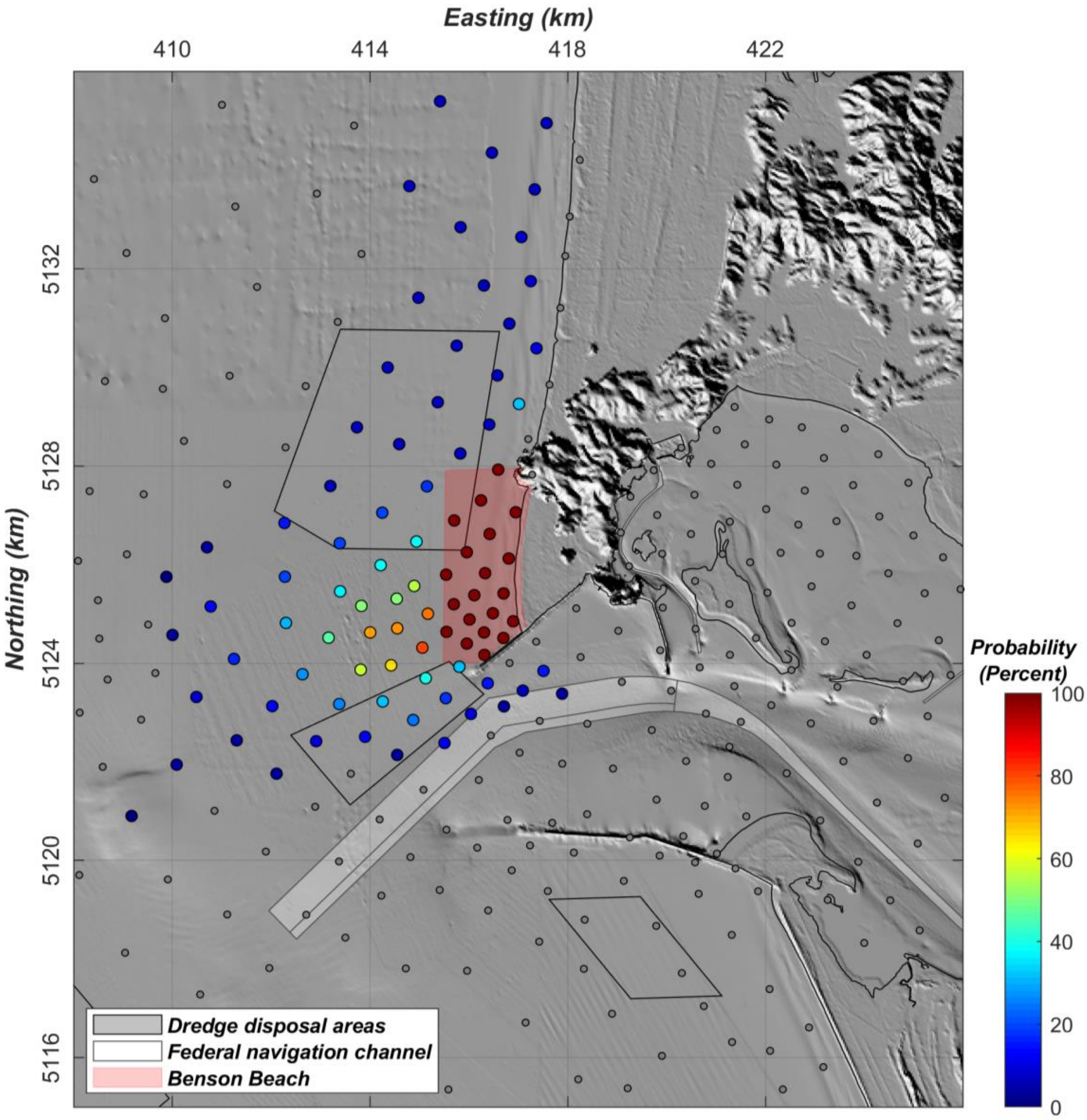

Figure 3.5 Probability of sediment transport pathway interaction between each source region and Benson Beach during low river discharge conditions. Source locations with zero probability of occurrence are shown in gray.

3.2 An analysis of sediment dispersal of the Put of Hansweert (the Western Scheldt, the Netherlands).

3.2.1 Introduction

The Western Scheldt provides access to the Harbor 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. Huisman et al. (2018) 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 of Hansweert (Figure 3.6) i.e. how and where.

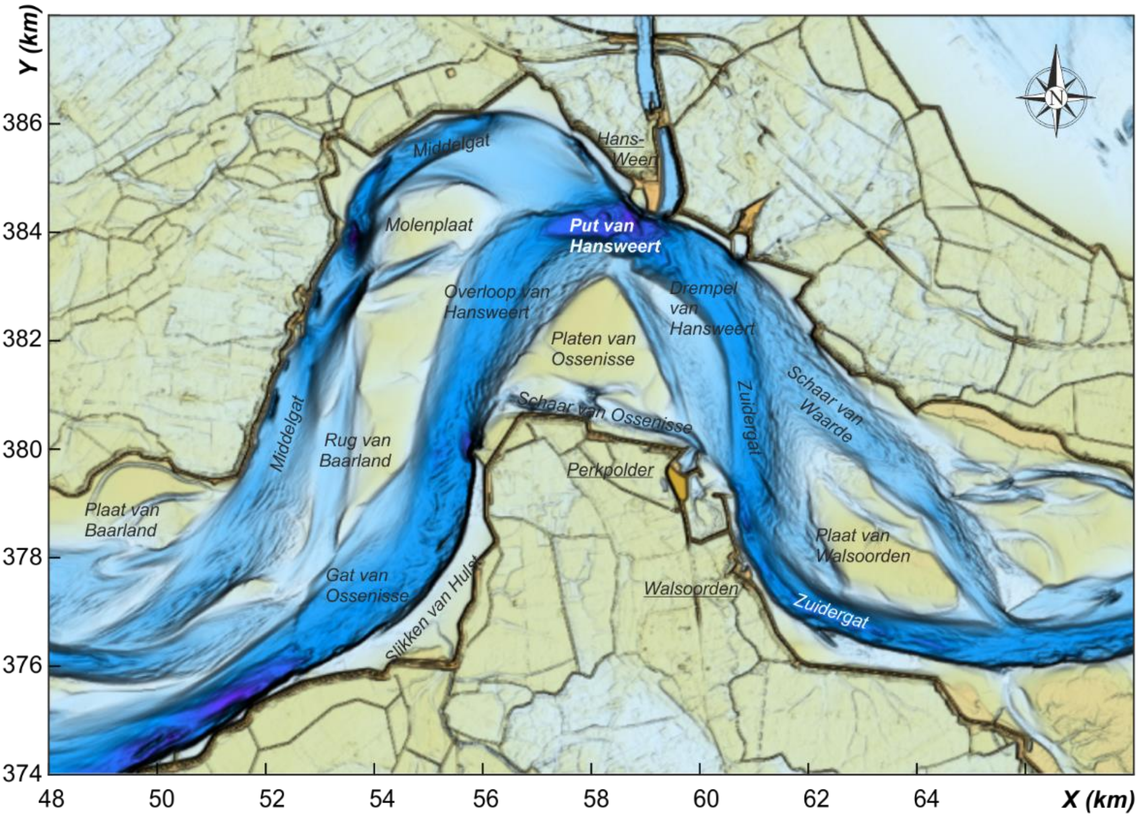

Figure 3.6: An overview of the morphological elements and geographical locations in the Bocht van Ossenisse (bottom panel) and its position in the Western Scheldt (top panel). Underlying DEM based on 2017 measurements. Note that we use the name Bocht van Ossenisse to describe the area between the Gat van Ossenisse/Plaat van Baarland and the Zuidergat/Plaat van Walsoorden.

3.2.2 Delft3D model results

The hydrodynamic and sediment transport calculations are based on the scaled-down NeVla model (Vroom et al, 2015). 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.

Model results of Delft3D simulations have been extensively analyzed and reported in among others Huisman et al. (2018, 2019). 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. 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. The sediment transport vector fields are saved in 10-minute intervals and used as a base for the *SedTRAILS* visualization and analysis.

Typically, analysis of the sediment transport fields would focus on the residual sediment transport field that is derived from averaging all transport maps over the morphological tide (Figure 3.7 (the numbers in the section below correspond to the labels in this figure). Most noticeable features in the net 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.

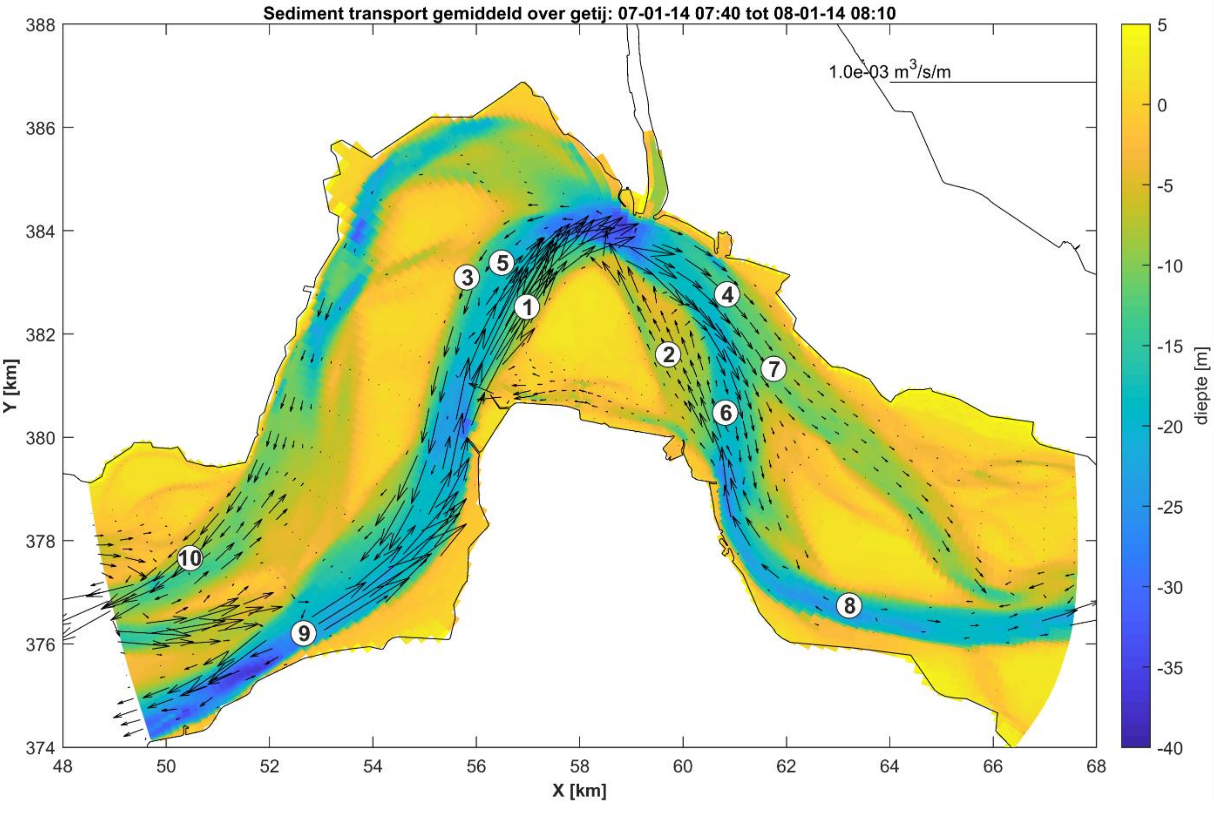

Figure 3.7: Tidally-averaged total sediment transport vectors in the Bocht van Ossenisse and Put of Hansweert.

3.2.3 *Application of SedTRAILS*

The objective of this SedTRAILS application 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 of 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 of 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 proposed by Huismans et al. (2020, in Dutch). 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.

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. A first set of 500 sources was obtained based on cluster analysis of bathymetric datapoints in the Bocht van Ossenisse. The second set of 500 source locations is based on cluster analysis of bathymetric datapoints in the Put van Hansweert (Figure 3.8).

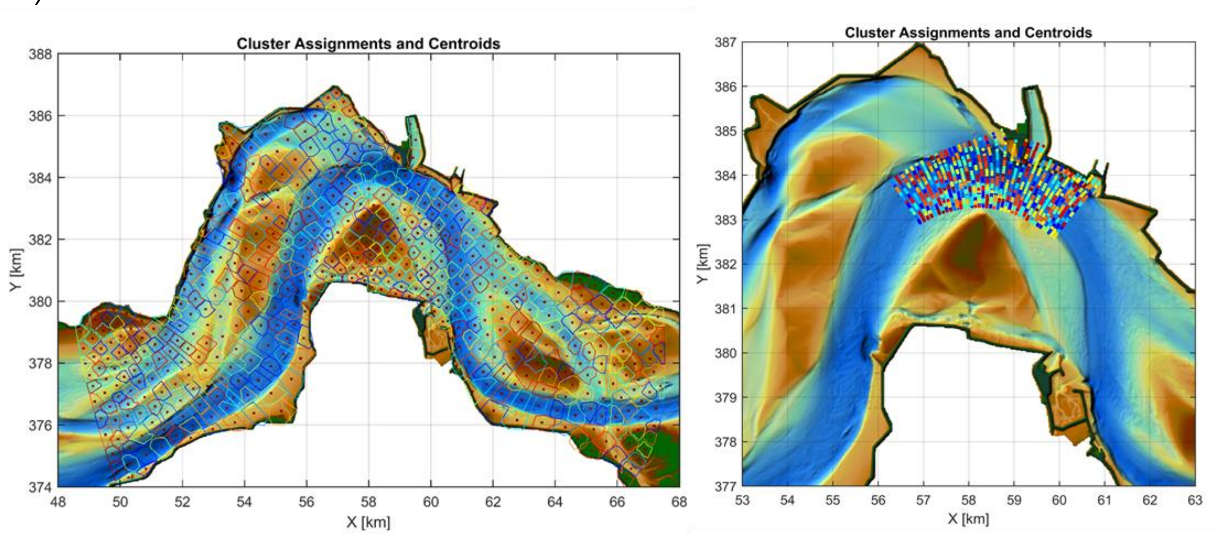

Figure 3.8: Locations of 500 particle sources derived from a cluster analysis on the bathymetric data of the Bocht van Ossenisse (left panel) and the Put van Hansweert (right panel).

The trajectories of sediment in the Bocht van Ossenisse and the Put van Hansweert are shown qualitatively in Figure 3.9. 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 3.9, 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 3.7), which is also reflected in a high mobility of the particles (Figure 3.10). 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 3.9) 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.

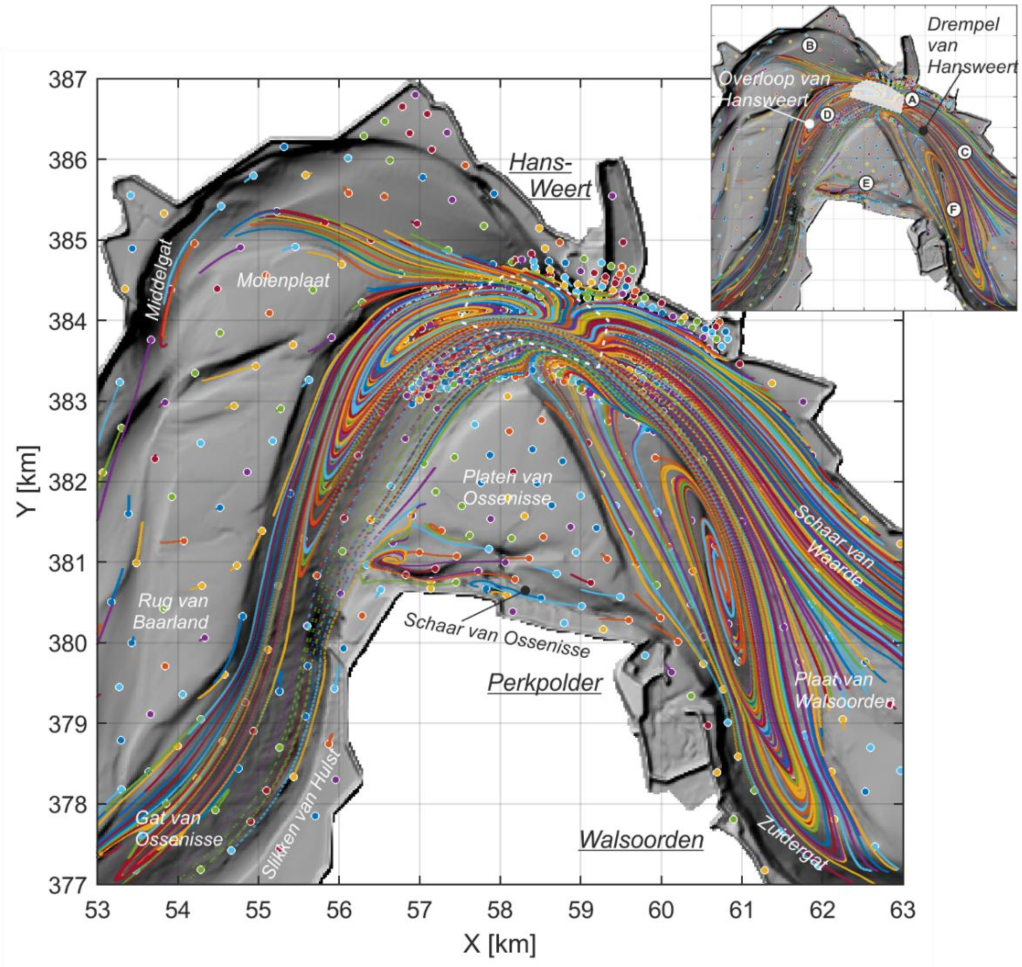

Figure 3.9: Sediment Pathways in the Bocht van Ossenisse. Dots indicate the starting particle source locations and lines illustrate the computed particle trajectories after 1 year of simulation. Colours are used to distinguish the various particle sources.

The distances travelled by individual particles can be used to visualize transport rates or sediment mobility (Figure 3.10, top panel) while the spatial gradients in sediment mobility provide a proxy for sedimentation and erosion (Figure 3.10, 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 3.10, 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 of Hansweert (Figure 3.10, [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 3.10, [2]), and on the Drempel van Hansweert towards the the Schaar van Waarde (Figure 3.10, [4]). In the secondary channels such as the Schaar van Ossenisse and Middelgat (Figure 3.10, 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 3.10, 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 3.10, a,b) are likely to show dynamic or spatially complex morphodynamic repsonses.

Combining the insights from the trajectories (Figure 3.9), sediment mobility (Figure 3.10, top panel) and relative sedimenation-erosion (Figure 3.10, 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 3.10, 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 3.10, bottom panel [a]) or contribute to a net transport towards the Schaar van Waarde [b]. The Schaar van Waarde is dispersive near Hansweert (Figure 3.10, top panel [4]) and sediments accumulate towards the Plaat van Walsoorden (Figure 3.10, 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 3.10, 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 3.10, 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 3.10, top panel [2]), while another part will get trapped on the western side of the Overloop van Hansweert (Figure 3.10, bottom panel [d]).

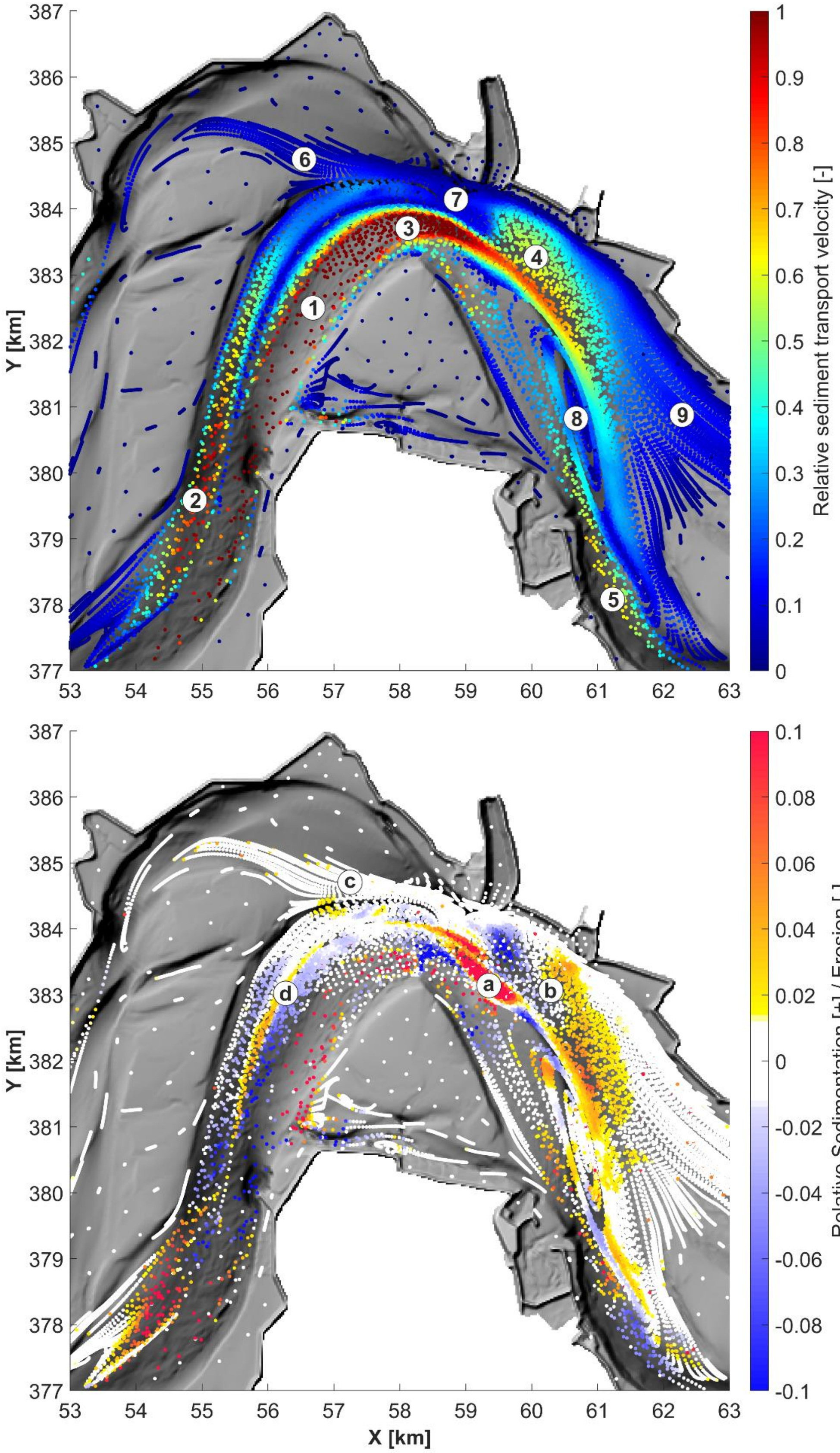

Figure 3.10 Top panel: Relative sediment transport velocity based on the distance travelled during a tidal cycle. Bottom panel: Prediction of relative sedimentation / erosion patterns, coloured according to the ratio of distance travelled during two consecutive tidal cycles.

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 3.11). These zones are defined following Huismans et al. (2020). 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. 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.

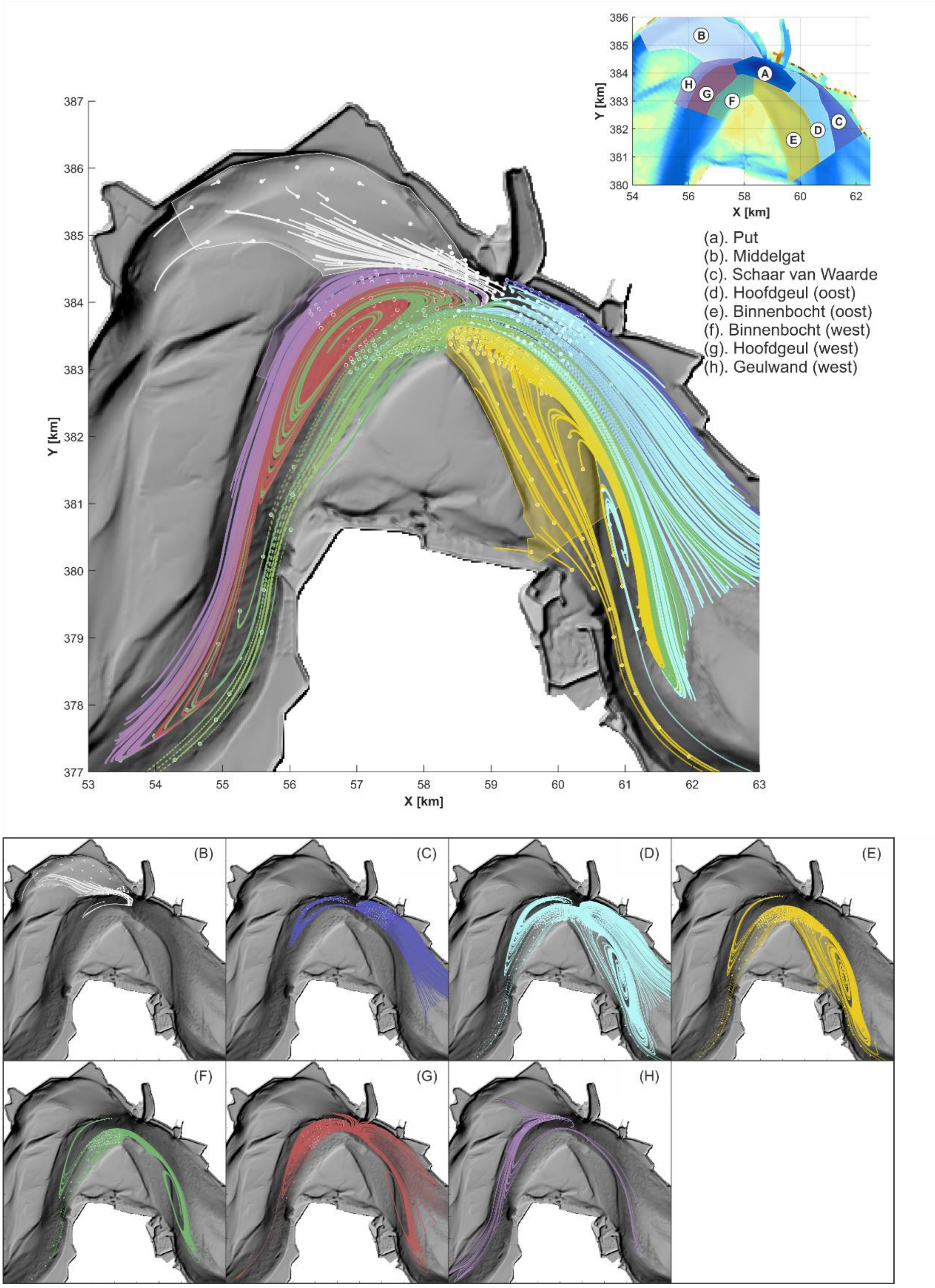

Figure 3.11: Particle trajectories for particles interacting with 7 source locations (individual source particles are grouped by colour) that represent the different morphological elements of the Bocht van Ossenisse (see upper panel). Lower panels; results for the individual areas.

3.2.4 Network diagrams and connectivity

Plotting the sediment trajectories results in visually appealing figures (Figure 3.9 through Figure 3.11). 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 3.12 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 occur from zones 6 and 7, while minor export occurs to zones 1 and 5. Minor exchange of sediments occur 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.

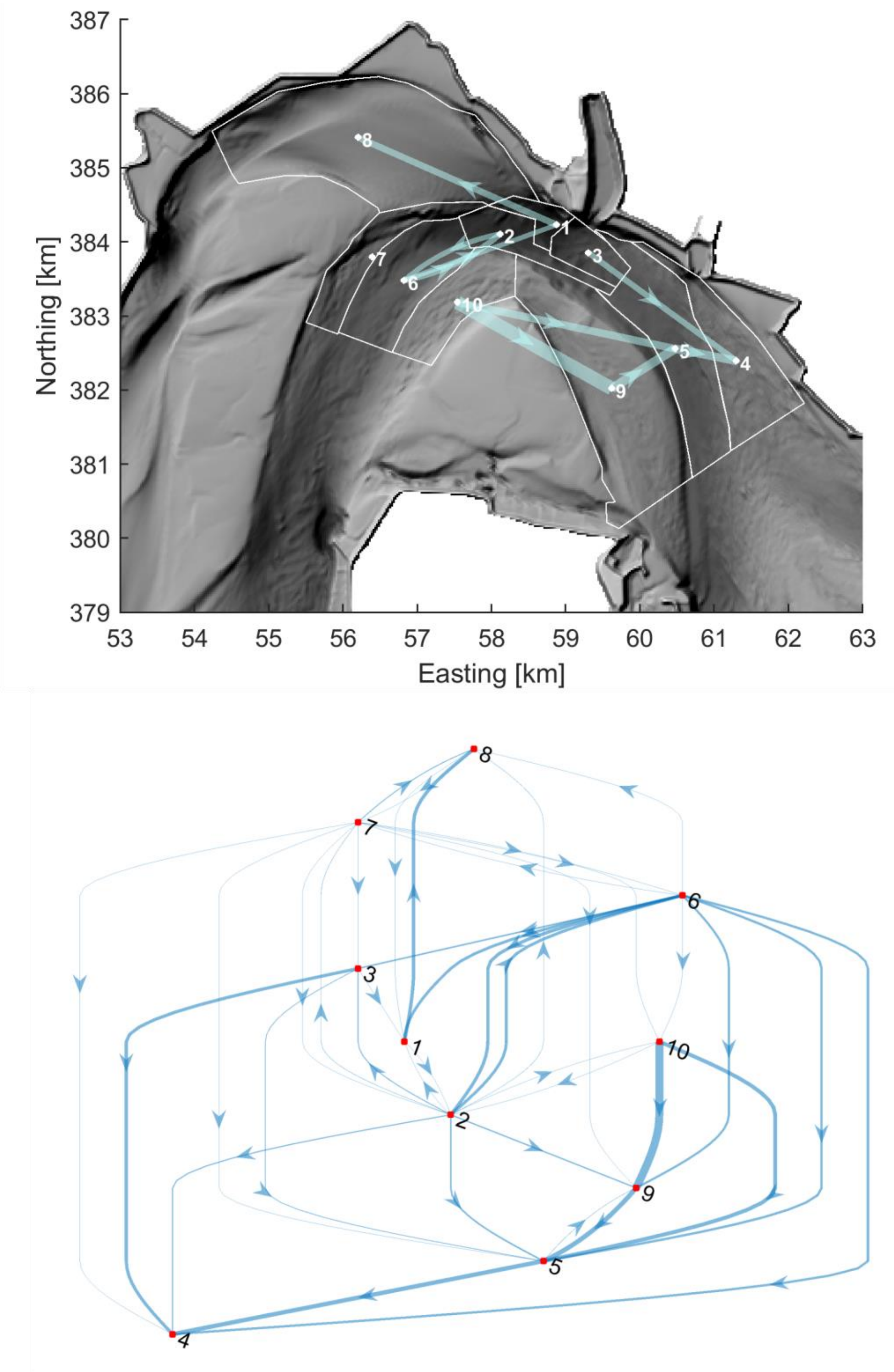

Figure 3.12 (Top panel): Network diagram for connections in the network in real topographic space, indicating only the top 10% strongest links. Bottom panel: Visualization of the network diagram in abstract topological space (height differences are for visualization purposes, they do not represent actual 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 Conclusions & Recommendations

4.1 Conclusions

A new method of analysing sediment transport pathways in complex morphodynamic systems was developed. SedTRAILS provides novel method that allows us to capture large-scale (inlet wide) sediment transports in a computationally efficient method. 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?

These questions, such could not be addressed through traditional model analysis. It was demonstrated through case-studies for the Columbia River and for the Western Scheldt that robust and computationally efficient sediment trajectories can be computed. Plotting these sediment trajectories already provides insights in the major sediment pathways and linkages between the various elements of the morphodynamic system. In addition, once the particle trajectories have been calculated, the results can be queried to answer various questions of interest:

Connectivity provides a structured framework for analyzing these sediment pathways, schematizing the system as a series of geomorphic cells or nodes, and the sediment fluxes between those nodes as links. Once organized in this fashion, the resulting network can be expressed algebraically as an adjacency matrix: sediment moving from a given source to different receptors. There is a wealth of pre-existing statistical tools and techniques that can be used to interpret the data once it is in this form, drawing on developments in other scientific disciplines.

4.2 Recommendations and Ongoing work

A major limitation of the presently used implementation of SedTRAILS is that the velocity of the sediment particle movement is not yet calibrated; 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 accurately reproduce the time-scales of sediment movement.

A secondary goal in the development of *SedTRAILS* is to visualise the functioning of complex morphodynamic systems such as tidal inlets. By converting sediment transport vectors into particle movement visually attractive and easy to understand visualisations of complex sediment transport processes can be made. Through the development of GUI's and analysis tools this functionality can be made available to both model experts and non-experts. Such tools could be coupled to e.g. the Kustviewer which would allow to illustrate sediment transport dynamics without complex modelling. Such tools can help coastal managers better plan coastal management strategies.

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