Deltares

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Summary

Rijkswaterstaat-WVL requested Deltares to provide visualizations of sediment transport at the Dutch coast, which are presented in a web-based viewer (referred to as the 'Coastviewer'). The Process maps in the 'Coastviewer' act as a means for storing and sharing knowledge on sediment transport patterns at the shoreface of the Dutch coast and making this information accessible to users at Rijkswaterstaat. This report provides an overview of these maps (or 'Proceskaarten' in Dutch), as well as the methodology that was used for the creation of the maps. A number of maps have been made.

The first map that was included in the web-based viewer is an expert interpretation of the wave-driven transport patterns (and processes) at the Dutch coast, which is based on a sketch made by Van der Spek (2015). The sketch can be used to give a first impression of the Dutch coastal system to anyone that is new to the region, and can also be instrumental in stakeholder meetings to visually show the relevant local transport processes acting at coastal measures.

Other maps provide a more technical overview of the sediment transport patterns along the shoreface of the Dutch coast, as well as maps of the relative influence of processes on the transport patterns (e.g. as a result of tidal currents, wave-driven currents or the impact of a spring tidal cycle versus a neap tidal cycle). These plots can be used to better understand the physical system, which is important as effects of coastal measures can then be interpreted correctly. The current study also shows the current capabilities to predict coastal transports for different regions of the Dutch coast, which is relevant in-view of discussions on future research of the Dutch coast and model improvements.

A good representation of sediment transport patterns was achieved with the coastline models in shallow water (where wave-driven transport is dominant) and at the lower shoreface (where tidal currents and wave stirring play a role. This provides an opportunity to further improve the evaluation of the effectiveness of nourishments near to the coast, because coastline models can give information on transport that is not available from the bathymetric data. A logical first application of coastline models would be for the Wadden coast, where analyses of the observed volume changes of the coastline are available. For the lower shoreface of the Dutch coast the influence of tidal asymmetry needs to be explored, which seemed to play a role especially at the Holland coast.

Computed sediment transports in complex regions, such as the southwestern delta and tidal basins, could, however, not be aligned well with expert interpretation. A problem is that suitable models are not yet available for most of the tidal basins. It will be necessary to calibrate and validate the numerical models in these regions to be able to make robust predictions for these complex regions. Without the models it will, for example, be difficult to evaluate the impact of any future measures (e.g. sand nourishments or wind parks) near to ebb-delta's, while these regions are very important for shielding the headlands of the Dutch island coasts. A model validation needs to be made by means of a comparison of computed sediment transports (i.e. sediment going in and out of predefined regions) with the observed changes in bathymetric surveys.

Contents

1 Introduction

The Dutch coast consists of about 300 km of sandy beaches which are maintained with regular sand nourishments. The Dutch ministry of public works ('Ministerie van Infrastructuur en Waterstaat') is responsible for the monitoring and maintenance operations. This requires a good insight in the actual monitoring data and processes which are of relevance for the coastline changes. For this purpose, they have been using interactive visualizations of coastal data in a web-browser environment for a few years (the 'Coastviewer'). Visualizations were made of relevant monitoring data that are collected along the Dutch coast, such as the yearly bathymetric profile surveys near to the coast (JARKUS), offshore bathymetric datasets (Vaklodingen) and sediment data.

Last year, it was requested by Rijkswaterstaat Water, Verkeer en Leefomgeving (RWS-WVL) to also visualize the processes that move sediment along the Dutch coast in the Coastviewer (or otherwise referred to as the 'Proceskaart'). The area of interest is the sandy Dutch coastline (excluding the estuaries and tidal basins), which stretches from the Belgian to the German border. A coastal map with a principal overview of these transport patterns (Figure 1.1) has been sketched earlier by Van der Spek (2015). This map has been digitized and included in the CoastViewer, but in addition also information was added from sediment transport computations. For example, arrows indicating the directions in which sediment spread along the Dutch coast, or contour-plots showing the effect that waves and tides can have on the mobilization of sand. The Proceskaart is not only relevant to for understanding the driving mechanisms of sediment transport along the Dutch coast, but also a means to visually show how the system works to stakeholders in view of discussions on future coastal measures.

The objective of this memo is to describe the visualizations of (transport) processes at the Dutch coast that were made in this project as well as the applied methodology to make these visualizations. A combination of information sources (from separate wave, tide and transport models) was used in this study to make visualizations of relevant transport processes at the Dutch coast.

In Chapter 2 we present the methodology and data used for computing the relevant hydrodynamic forcing conditions and sediment transport rates. Section 3 shows the results obtained and incorporated in the Coastviewer as visual layers, which comprises 1) maps of the intensity of sediment transport due to either wave-driven currents or tidal currents (with wave stirring), 2) overviews of the computed net transport rates in shallow water due to the wave-driven current and at the shoreface outside the breaker zone and 3) visualizations of the enhancement of transport by wave stirring and for neap tides. Finally, Section 4 summarizes the findings and limitations of the approach presented here with a concise set of conclusions.

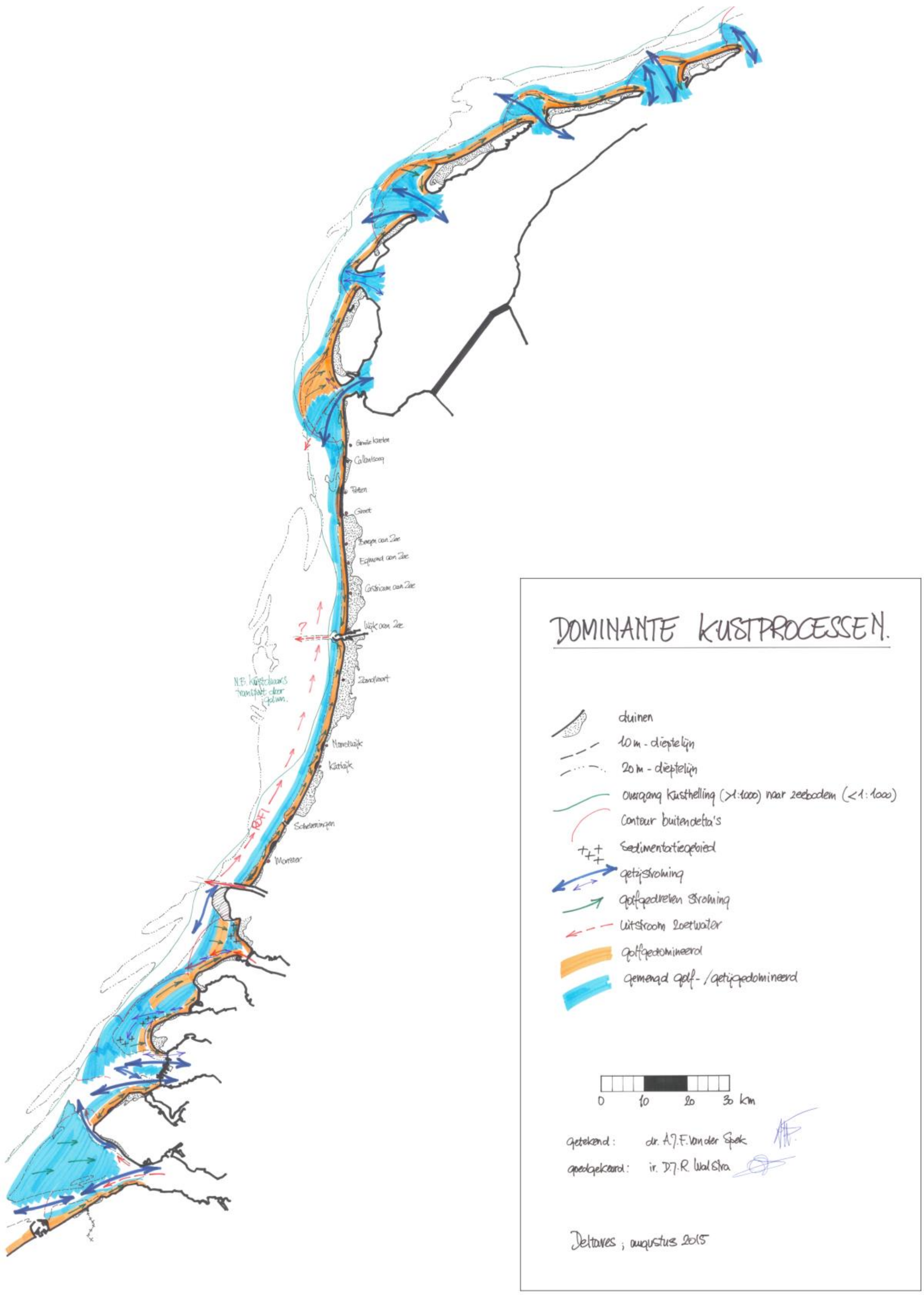

Figure 1.1 Sketch of principal transport processes at the Dutch coast by Van der Spek (2015)

2 Methodology

2.1 Forcing conditions

A primary goal of the study is to showcase the relevance of the principal forces that shape the coast. Changes of the coastal bathymetry (erosion and accretion) will take place when there is an imbalance of the incoming and outgoing transport of a coastal section, which means that the driving forces or local sediment composition are different. In order to correctly interpret the maps, it is relevant to have good overview of the principal transport processes. A summary is provided here of processes that act at the Dutch coastline, of which the ones that act at larger scales (kilometers or more) are accounted for in the ‘Proceskaart’ of the Coastviewer. The main driving processes / mechanisms are:

- Tidal currents
- Waves
  - suspension of sand by waves
  - obliquely incoming (normal) wave conditions driving a longshore transport
  - wave-orbital motions, inducing subtle net onshore movement of sand
  - wave-induced water-level setup, creating local offshore currents (rip currents)
  - (erosive) storm conditions, driving water level variations and offshore currents (undertow)
- Wind-driven currents
- Sea level rise (climate change)

Tidal currents play a role along the whole Dutch coast, but especially in tidal basins and, estuaries where these currents are large, and in deeper water where wave-driven currents are small. The tidal currents move suspended sand (i.e. sand that is lifted into the water column) over long distances as well as bed load material near to the bottom (especially for the tidal basins). An enhancement of the transport takes place when tidal currents coincide with waves, which stir up the sediment into the water column. So, wave stirring results in a considerable increase the suspended sediment concentrations (Figure 2.1). Furthermore, also the bed load transport is also enhanced by the stirring of the waves, which contributes to the transport capacity in tidal basins. This is the first role of the waves, basically making more sediment available for transport by currents. In fact, the wave stirring is extremely important for the transport in deeper water (at the lower shoreface) where currents cannot easily stir the sediment. In tidal basins the waves are smaller and especially important at the edges of the shoals.

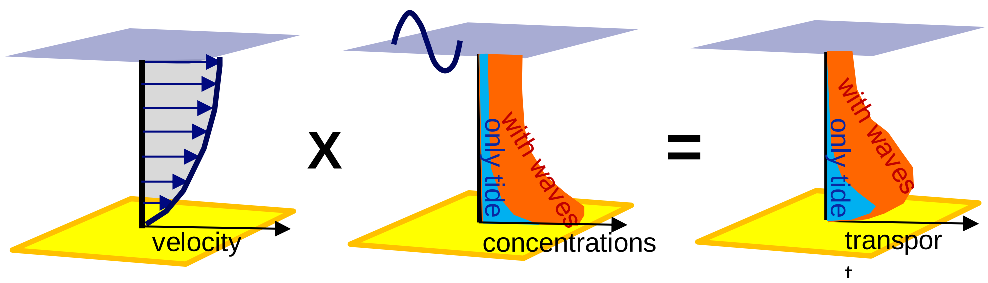

Figure 2.1 Sketch of the tidal current velocity, sediment concentration and transport rate for a situation with and without waves. The ‘blue plane’ indicates the water surface and ‘yellow plane’ the bed.

Waves can also induce currents in shallow water when they approach the coast under angle, as the incoming ‘momentum’ of the waves is transferred to an alongshore current when the waves are breaking. These wave-driven currents can be quite strong at about 0.2 to 0.5 m/s for regular conditions and reach large velocities up to 2 m/s during storms (for a short period of time). These longshore currents strongly affect the shallow regions of the uniform coastline sections (i.e. at the Holland coast or island beaches) as well as the shoals of the ebb-deltas of the south-western delta and Wadden coast. These longshore currents are often dominant for local morphology in shallow water, as they have much more impact than wind-forces and tidal currents.

Wave-orbital motions in shallow water can induce a slow (but steady) onshore transport of sand, as the return current of the wave motion is slightly smaller than the onshore orbital excursion of the wave. Typically, the effect on the transport is much smaller than the tide-driven and wave-driven current. Still this process is very relevant for the cross-shore profile shape of beaches and for shoreface nourishments, which over-time are pushed towards the coast by the waves (Figure 2.2). On a larger scale the waves can also push the remainders of ebb-deltas towards the coast (i.e. the underwater part of an estuary or tidal basin seaward of the inlet), which can take decades or even centuries. This is for example the case at the inlets of the Haringvliet and Grevelingen, which (as a result of the dams) lack the offshore tidal currents that can push the sand back to sea. On short-time scales these onshore transport processes (by wave-orbital motion) are, however, not very well visible and therefore not further visualized in this study, although they are included to some extent in the applied sediment transport formulations of Van Rijn (2007a,b).

Locally the breaking waves create a small water-level setup close to the shoreline at the sub-tidal bar (i.e. at a few meters depth) which can induce a strong local return current (referred to as a ‘rip current’ or ‘muistroom’ in Dutch). Typically, this return current is in offshore direction and located at a place where wave breaking is slightly smaller, which is often next to a groyne (‘strandhoofd’ in Dutch) or a discontinuity in the breaker bar. These currents are very relevant for swimmers and to some extent also for the local cross-shore distribution of sand (in shallow water), but are expected to have a rather small impact on the larger scale morphology (kilometers or more) as investigated in this study.

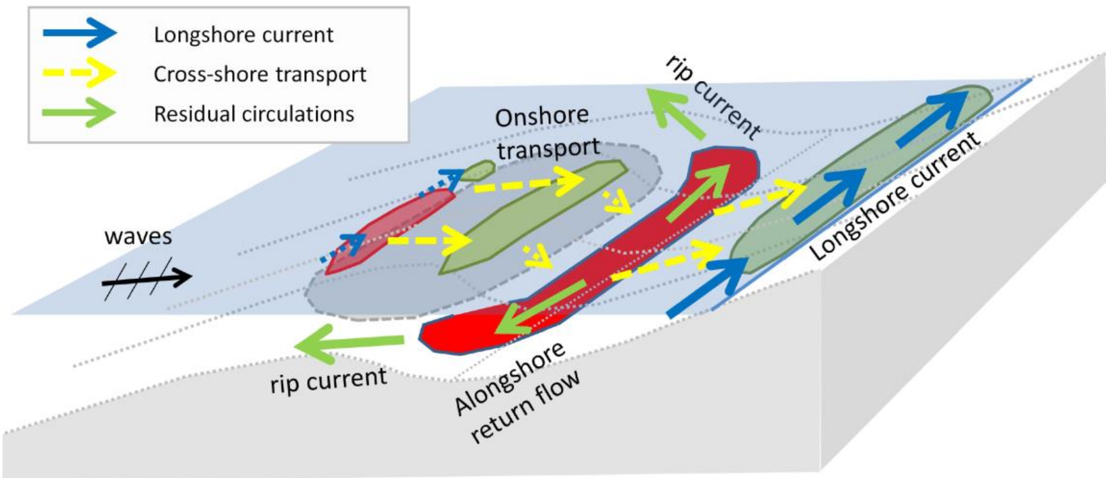

Figure 2.2 Illustration of the longshore current, onshore transport (due to skewness of the wave-orbital motion) and residual flows (due to water-level setup) at a shoreface nourishment (Huisman et al., 2019)

Storm waves do not only affect the longshore current and local rip currents, but typically also come with long period water-level variations (tens of seconds) which erode sand from the dune face (during high water. The eroded sand is then transported offshore by local return flow underneath the waves (undertow) near to the coast (in a few meters water depth). This can create large changes in the coastal morphology of the dunes, beach and nearshore zone.

However, over-time the beach and dunes will restore as a result of slow but steady onshore transport processes during quiet conditions (due to wind and waves). The effects are therefore not yet visualized in the Proceskaart.

Wind-driven currents may also play a role for longer beaches where a current can develop during conditions with coast-parallel winds. In general, the wind-driven current is strongest at the surface of the water (where the wind shear acts) which is, however, also the part of the profile with the smallest sediment concentrations. Over time (with persistent wind and long fetch) more of the water column will start to accelerate, thus creating also a current deeper in the water column. However, this is considered a rather local effect and is therefore not (yet) considered in the current studies.

Sea level rise or climate change in general are (in themselves) not additional transport mechanisms, but they can affect the transports due to above described processes. In the first place the sea level rise can affect the coastline as the higher water levels will enhance coastal erosion (i.e. more effect of storm waves), and thus contribute to cross-shore profile adaptation at alongshore-uniform coastlines. Secondly, the sea level rise can also affect the sediment import in tidal basins, which have more room to store the sediment. The effect is that the net tide-driven transport (with wave stirring) towards the basins will increase over time. Thirdly, small changes can take place in the incoming wave direction and wave height as a result of climate change, which can affect the longshore transport. However, these effects of sea level rise are not likely to be well-distinguishable at short to intermediate time scales (years) and therefore not (yet) included in the study.

2.2 Method of computing transports

Following from above description of the processes it is clear that a distinction can be made between regions with and without substantial wave-driven longshore currents. The region with a considerable influence of the wave-driven current is located in the shallow nearshore region of the open coast (mostly landward from the MSL -5m), while the tide dominated regions are in intermediate to deep water (MSL -10m to MSL-25m) of the lower shoreface of the Dutch coast. The current study therefore chooses a different approach for the lower and upper shoreface (see the methodology in Figure 2.3).

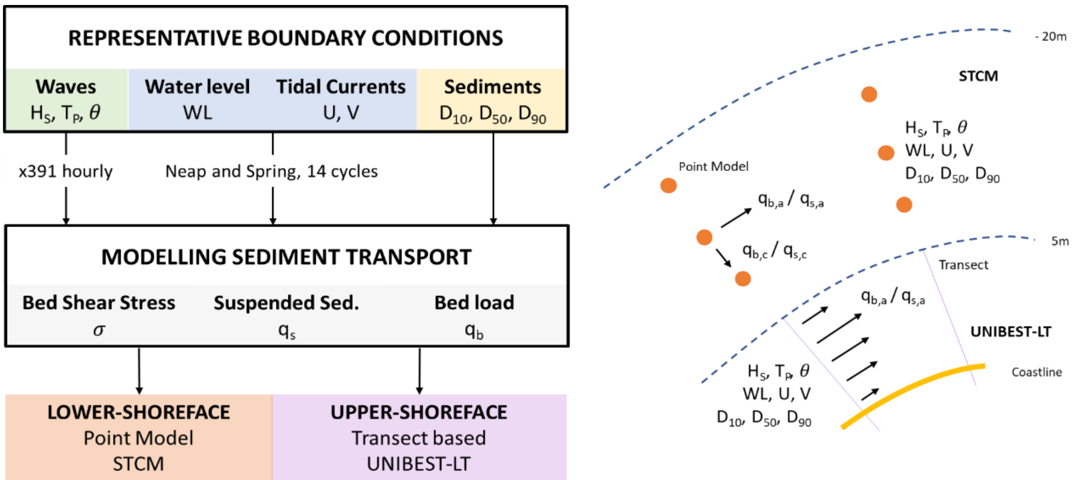

Figure 2.3 Methodology applied for computing representative sediment transport patterns. Left panel shows the workflow. The right schematic shows the two zones considered and resolved with slightly different approaches.

Sediment transport at the lower-shoreface of the Dutch coast has been computed with local point-models assuming that a combination of tidal currents and wave stirring can explain most of the transport. Delft3D models (see text below) were used to compute the water-levels, tidal velocities and wave-driven currents at the Dutch coast as input for the point model. In addition, these Delft3D models are also used to visualize the spatial distribution of the tide-driven and wave-driven sediment transports at the Dutch coast. A similar approach was applied by Grasmeijer et al. (2019) for the lower shoreface of the Holland coast.

For the nearshore region, an approach was used with a coastline model (UNIBEST-CL+), which computes the long-term averaged sediment transport rates in the nearshore region (landward of the depth-of-closure) of alongshore-uniform coastline sections. The longshore transport gradient in the nearshore (i.e. balance between incoming and outgoing transport) is considered the dominant factor for shoreline change at intermediate time scales (years to a decade).

Lower-shoreface modelling

Computations were made with a large-number of separate point-models (~2600) at predefined locations at the Dutch coast (at depths ranging from 5 to about 20 meter) using the Sandpit Transport Community Model (STCM). The individual model locations are shown in Figure 2.4. Runs were made with waves and tide foring, as well as a reference run with only tidal forcing. The resulting net yearly transports (along and across the coast) are shown in the Proceskaart, as well as the net aggregated transport over representative alongshore and cross-shore rays. The benefit of the approach with the point-models is that it is computationally inexpensive and allows to explore properly the tidal current and wave climate variability along the Dutch Coast.

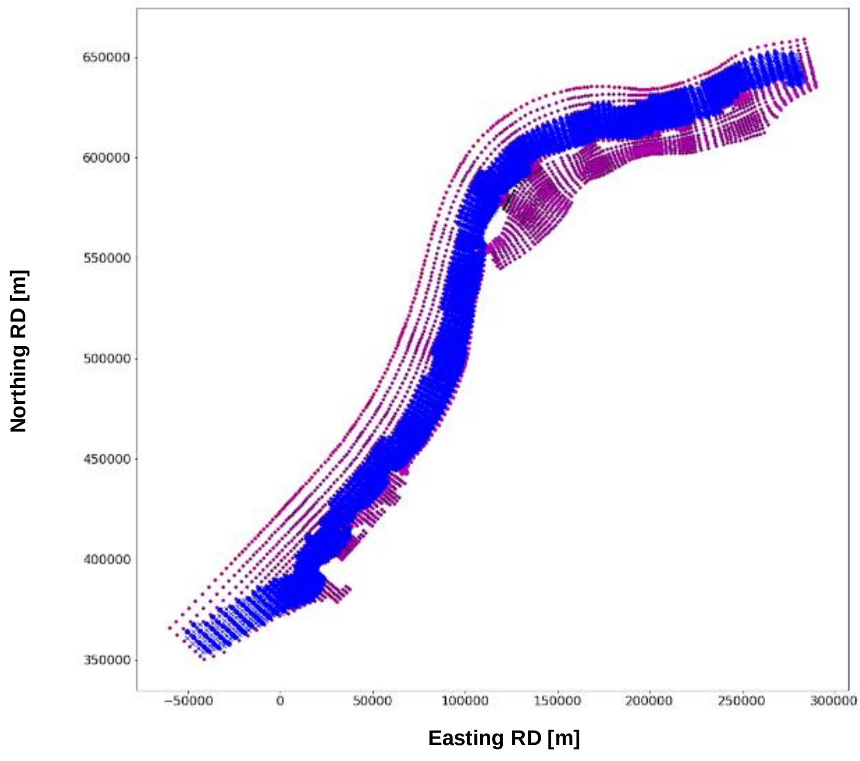

Figure 2.4 Hydrodynamic curvilinear grid (magenta nodes). Blue nodes define the lower-shoreface point models on each curvilinear grid node.

The bathymetry used for computing sediment transport patterns is static, which means that we use a unique recent bathymetry based on the Vaklodingen for the offshore regions and yearly coastline profile measurements (JARKUS) for the nearshore. This bathymetry is the same bathymetry as used for computing the wave nearshore transformation and tide propagation. In Figure 2.5 we show the bathymetry map and the 20 meter depth-contour.

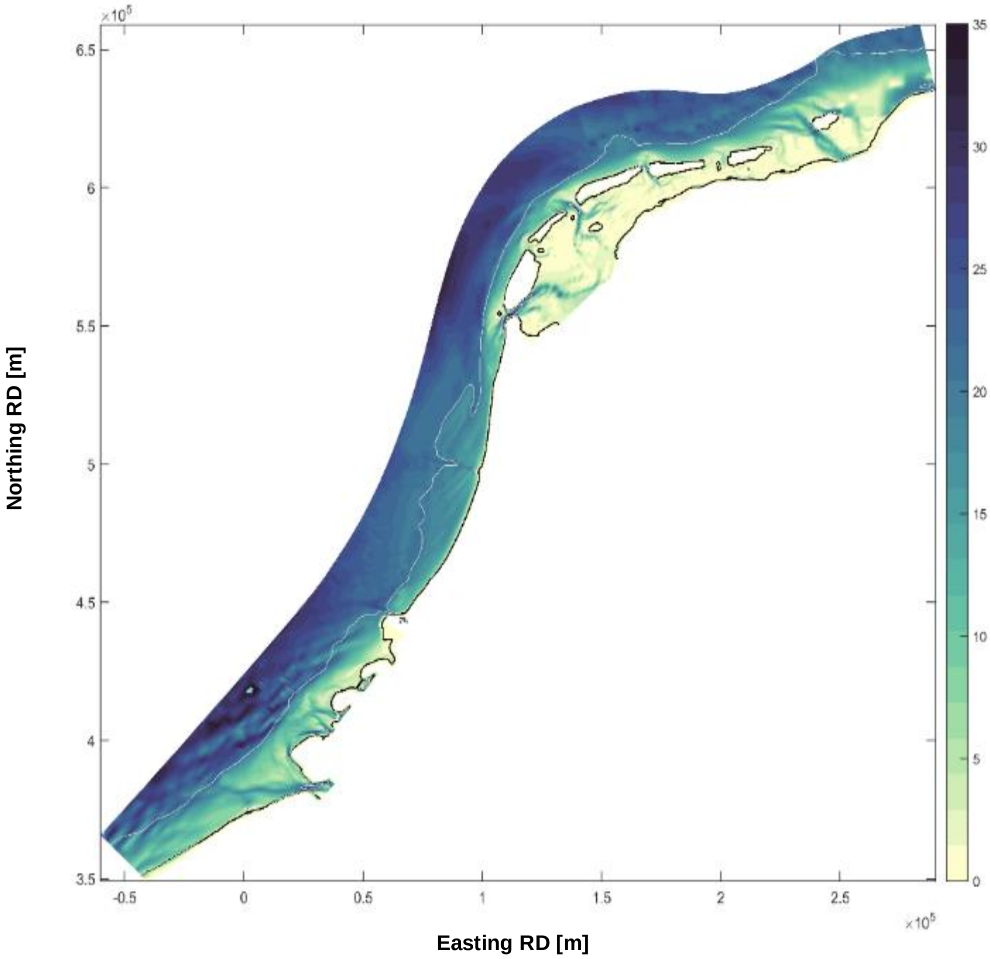

Figure 2.5 Bathymetry of the Netherlands used in this study. The colormap represents the water depth. The gray contour line corresponds to the 20m depth contour. The local coordinate system is RDnew [EPSG: 28992].

The hydrodynamic conditions (tidal currents and waves) were computed with Delft3D models spanning the whole Dutch coast (see Figure 2.6 for the waves and Figure 2.7 for the flow).

Each point-model is forced with a set of 391 representative hourly wave climate parameters (Significant wave height, peak wave period, and mean wave direction). The wave climate is defined by hourly significant wave height, mean and peak wave period, and mean wave direction observed in the offshore contours of the Dutch foundation at the Schiermnond (SCH), Ijmuiden (YM6), Eierlandse Gat (ELD), and Europlatform 3 (EUR) stations (see Figure 2.6). Measurement data used in this study, were collected for the period 1979-2018. These offshore-data are transformed to the nearshore using a look-up table procedure and a SWAN model set up on a curvilinear grid. Huisman et al. (2019) describes further details of the wave transformation procedure.

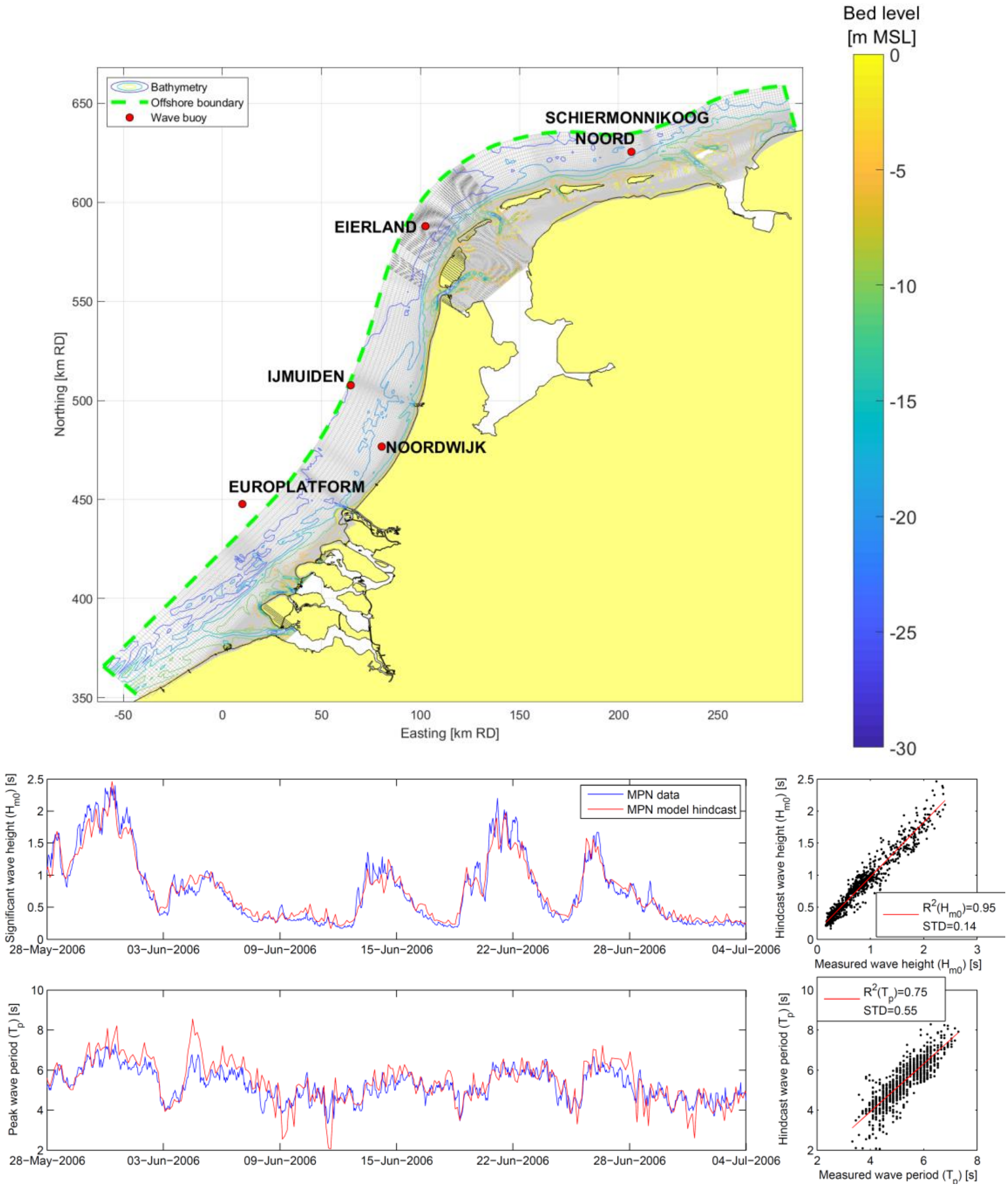

Figure 2.6 SWAN model domain used for the derivation of nearshore wave boundary conditions, which is an extended version of the wave model described in Huisman et al. (2019) and wave validation at Noordwijk Meetpost (MPN).

The tide velocities were derived from a modified version of the kuststrook-fijn model (Figure 2.7), which was used also in the Natuurlijk-Veilig project. The model extends from the Belgian-French coast to Northern-Frisia in Germany. Model boundary conditions were made based on the DCSM v6 astronomical forecast from Matroos for the period from July to August 2020 as well as for the periods May and December 2014 (Figure 2.7 lower panels). The differences between the kuststrook-fijn and DCSM-v6 are the residual of the fit with astronomical components. The periods in 2014 were used to check whether the astronomical components would also do well over a period of multiple years, which is the case. The nesting was successfully verified for some locations in the domain.

Each wave condition, as derived from the wave model, is simulated in combination with the water levels and tidal currents from the kuststrook-fijn model. A period of exactly 14 tidal cycles was simulated. In the current study we obtain data from the model run with just astronomical forcing. The representative period for the neap tides is defined by 14 cycles between 2019/06/23 10:00:00 and 2019/06/30 16:40:00. The representative period for spring tides is defined by 14 cycles tide between 2019/07/03 18:50:00 and 2019/07/11 01:00:00.

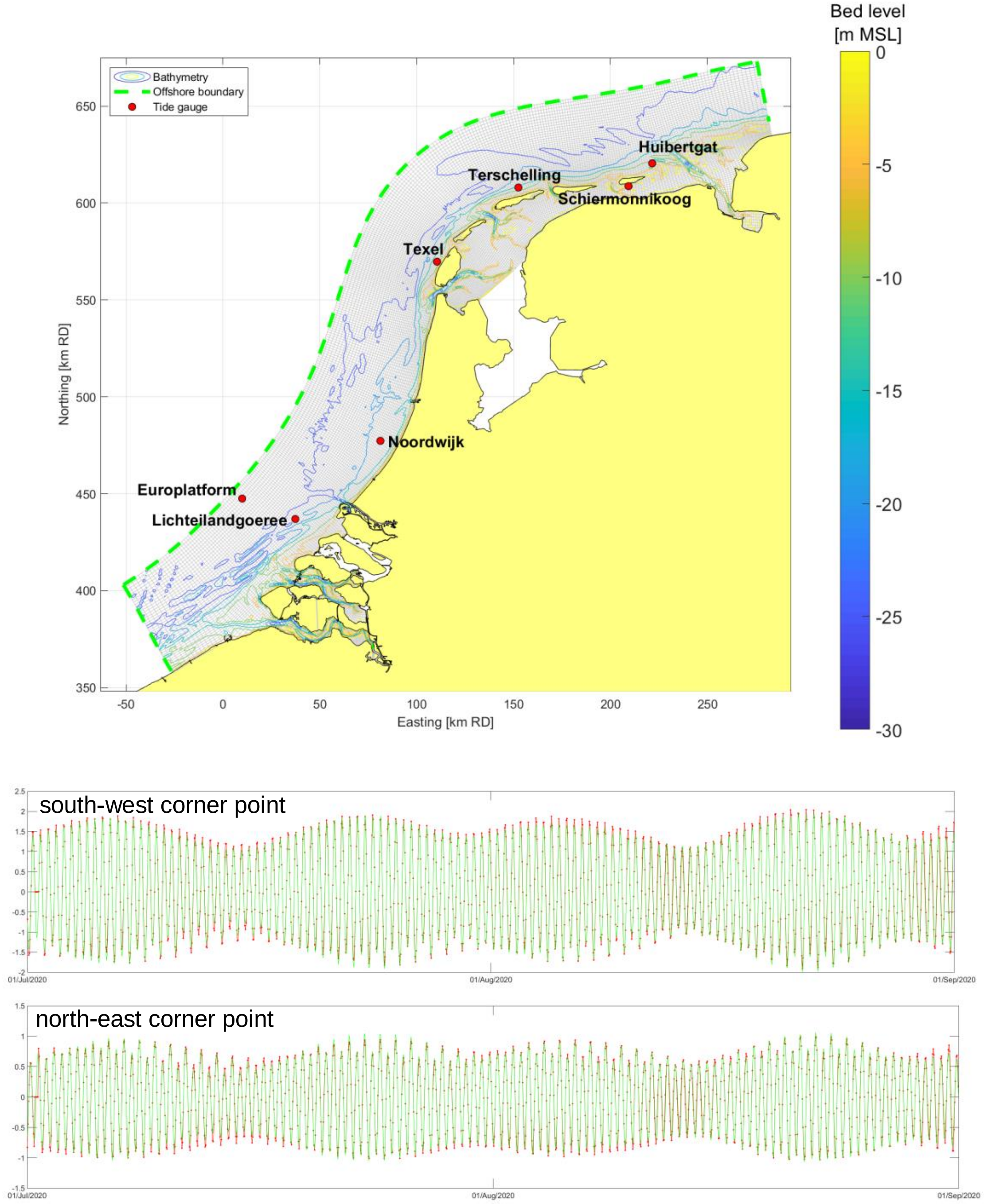

Figure 2.7 Modified kuststrook-fijn model used for the derivation of the astronomical tidal conditions. Lower panels : water-level conditions against DCSM v6 at the corner points of domain.

The Sandpit Transport Community Model (STCM) uses the same transport formulations as coded within Delft3D. Here we use the TRANSPOR2004 (Van Rijn, 2007a,b) formulation. The model accounts for wave-current interaction when computing the relative frequency of the waves in the presence of a current at a certain depth. Sediment transport patterns in the coastviewer are represented for the spring tide condition.

Hourly sediment transport is computed as well as the corresponding bed shear stresses. Sediment transport components (suspended sediment and bed load) and vectors are available. Note, that there is no feedback between sediment transport and bed level, we do not update bathymetric changes due to sand loss/gain. Sediment transport must therefore be treated as potential sediment transport. The total sediment transport is computed from the calculated transport fields for each of the wave conditions, taking into account the probability of occurrence of each wave condition.

Each point-model is set-up with the actual grain size distribution. In this study we use sediments from the TNO NCP entire Dutch Continental Shelf (DCS) grain size maps data (Maljers and Gunnink, 2008). This dataset was created as part of the EU project MESH. More than 7000 sample points in the DCS were used for smooth interpolation (with Kriging). We take $D_{10}/D_{50}/D_{90}$ considering only the sand fraction, excluding the mud and gravel fractions.

Upper-shoreface modelling

We assume that the wave-driven longshore transport is the dominant mechanism of sand transport in the upper-shoreface (defined as the area between the 5 meter depth and the shoreline). Cross-shore transports may be important for the seasonal distribution of sand over the cross-shore profile (Van Rijn et al, 2003), but are less relevant at longer time scales when seasonal fluctuations balance each other out. Reference is made to Tonnon et al. (2018), Stronkhorst et al. (2018) and Huisman et al. (2018) for more information on the use of the UNIBEST-CL+ coastline model for the Delfland coast.

The UNIBEST-CL+ model was used to compute the longshore wave-driven sediment transport at the Dutch coast. The model first computes the wave transformation for each of the 391 wave conditions for cross-shore profiles (Figure 2.8), which are spaced at a distance of about 1 km for the Holland coast and south-western delta and at about 3 km for the Wadden coast. The yearly coastal profile measurements (JARKUS) are used for the profiles.

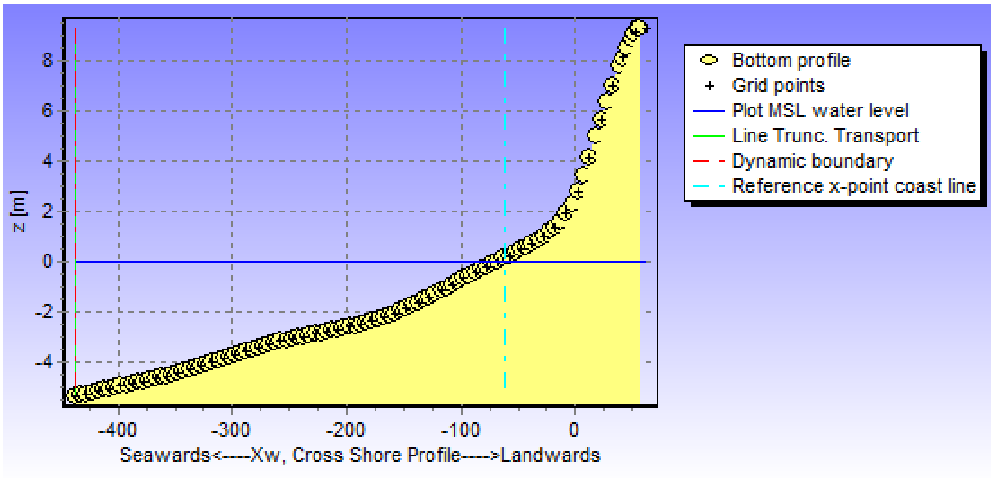

Figure 2.8 Example cross-shore profile for the Delfland coast (at x=5 km from Hoek van Holland)

A cross-shore distribution of the longshore current is then obtained for each of the wave conditions, and subsequently a longshore transport per condition using the TRANSPOR2004 formulations (Van Rijn, 2007a,b). The net transport is computed by weighing the contribution of all of the computed transports for each of the conditions (accounting for their duration). A median sediment grain size of 250 µm is used, which is representative for most beaches. The Holland coast model is shown as an example (Figure 2.9).

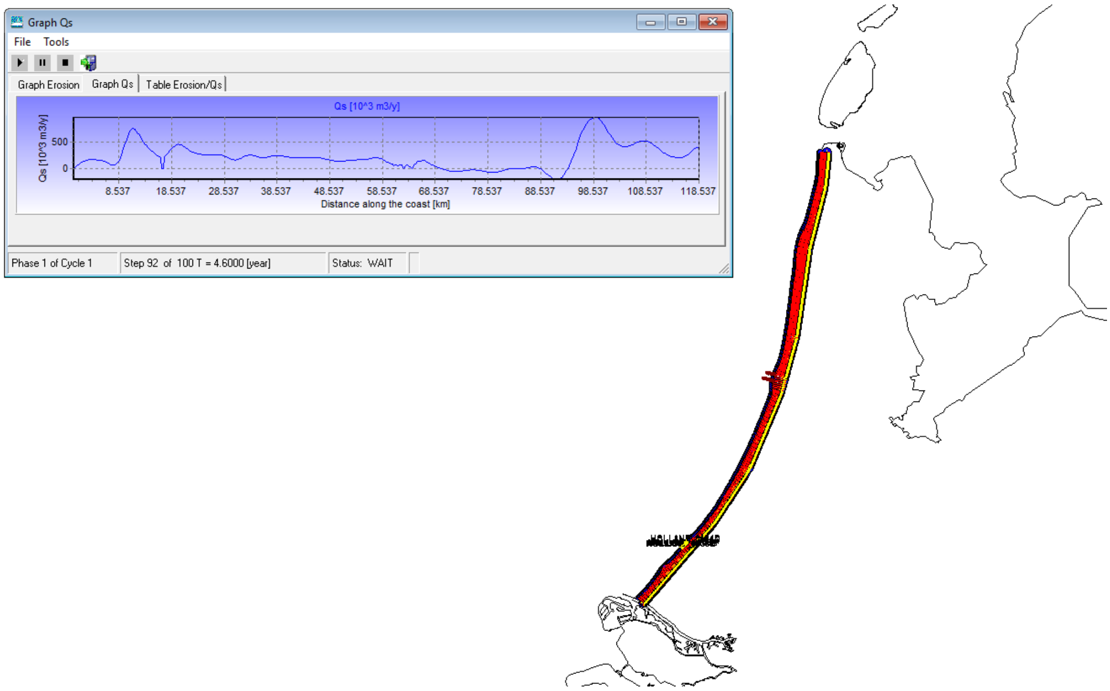

Figure 2.9 UNIBEST-CL+ model for the Holland coast, with the Sand Motor and Hondsbossche Duinen

A validation of the computed transport rates was made for the Delfland coast (Huisman et al., 2018), but not yet for other sections of the Dutch coast which was not feasible in the current project. A qualitative inspection has, however, been made. And results align with expert interpretation.

It is noted that the computed transport rates with UNIBEST-CL+ depend strongly on the shoreline orientation. We fix the shoreline orientation in the simulations, therefore we neglect shoreline rotation updates and their feedback on alongshore transport. In some places where the coast changes considerably over time (e.g. at the Sand Motor) this can have an impact on the transport rates. This holds especially for the magnitude of the transports, as the spatial pattern (determining the alongshore transport gradients) often remains quite similar.

3 Proceskaart

In this section we present the visualizations that are included in the Proceskaart of the Coastviewer. Each layer presented here is added and formatted into the datalayers.json file and linked with mapbox datasets.

3.1 Bathymetry of the Dutch coast

The bathymetry used for the sediment transport computations is added as a reference layer (Figure 3.1). It is very important to understand certain local results on highly dynamic environments, such as tidal inlets, where shoals can migrate in time and therefore change locally sediment transport patterns. Currently the bathymetry is static, but a time-variable bathymetry may as well be added in the future.

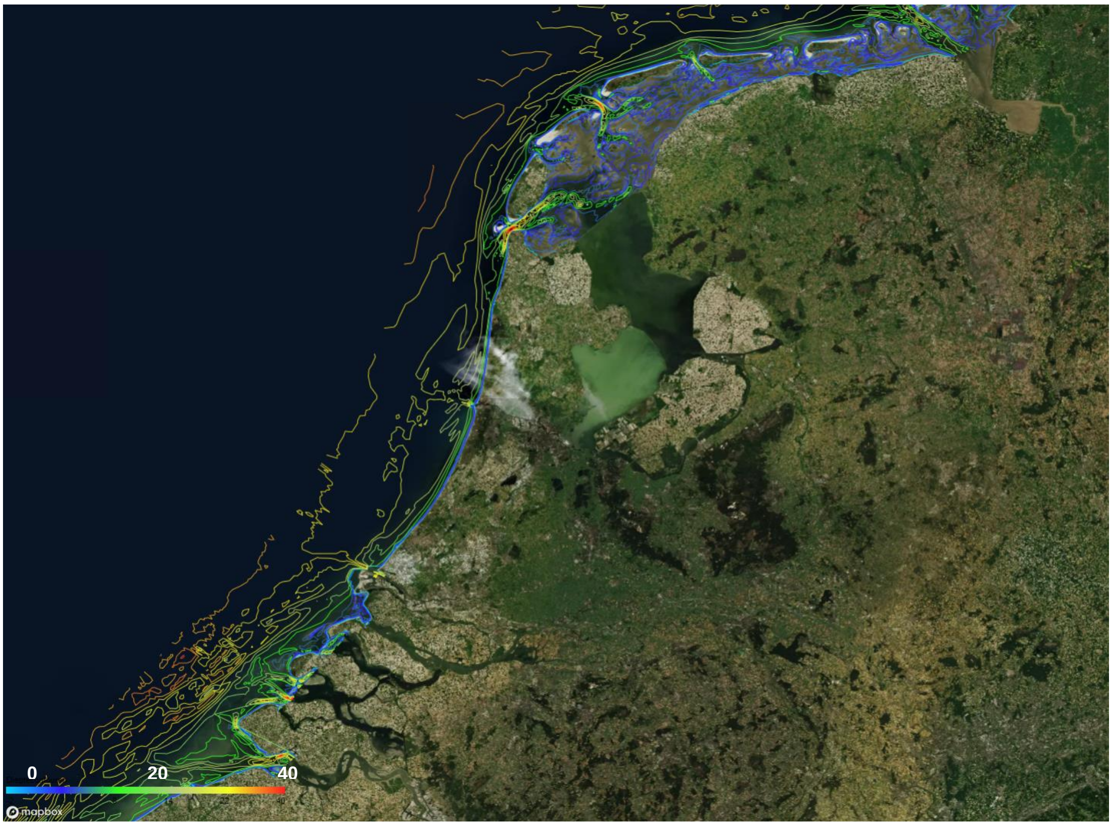

Figure 3.1. Bathymetry layer

3.2 Bed sediment

Three geospatial layers with D10, D50, and D90 sediment grain size are incorporated showing the TNO dataset for the Dutch North sea (Figure 3.2). It shows that the sediment at the sea bed is not uniform. Instead a coarser area can be seen seaward of Texel and Vlieland. Furthermore, the south-western section of the Dutch part of the North sea is relatively coarse, which is the result of the enhanced tidal conditions at the southwestern side of the Dutch North sea.

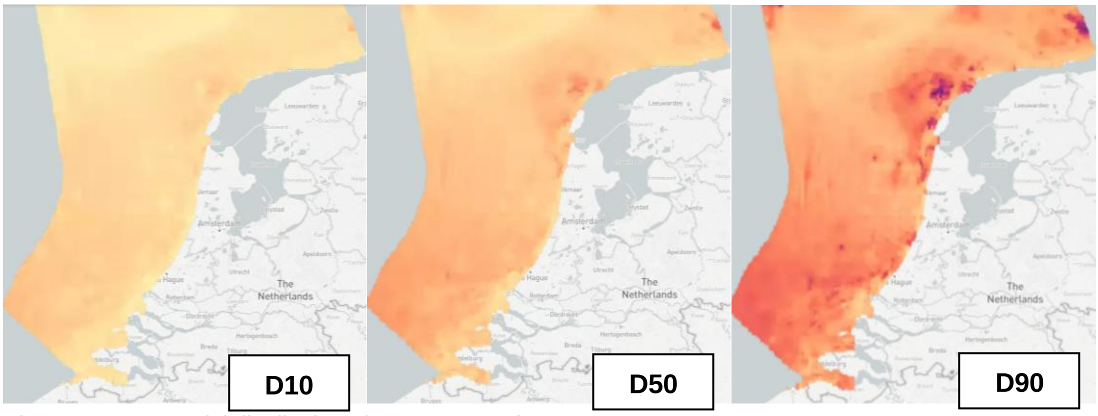

Figure 3.2. Geospatial distribution of D10, D50, and D90.

3.3 Sediment Transport at the shoreface

Sediment transport is presented in independent layers for the lower shoreface and the nearshore zone. For this purpose the net computed transports from the STCM model (for the lower-shoreface) and UNIBEST-CL+ model (for the shoreline) can be switched on. The net results of the STCM model are shown on a grid, which has been drawn along the coast taking into account the geographical features such as tidal channels and flats. The typical alongshore spacing is 4 to 20 km, while the different elements were defined also for different depth-ranges (5, 10, 15 and 20 meter depth). The size of the computed arrows is scaled logarithmically, as the transports in the tidal inlets are so much larger than for other areas. An interpretation of transport patterns has been given here with the white arrows. In general, it is noted that the results presented here are a first attempt to quantify net transport rates at the Dutch coast using numerical models. Detailed validated models will be needed to obtain confidence in the patterns, requiring a comparison to observed bathymetric changes.

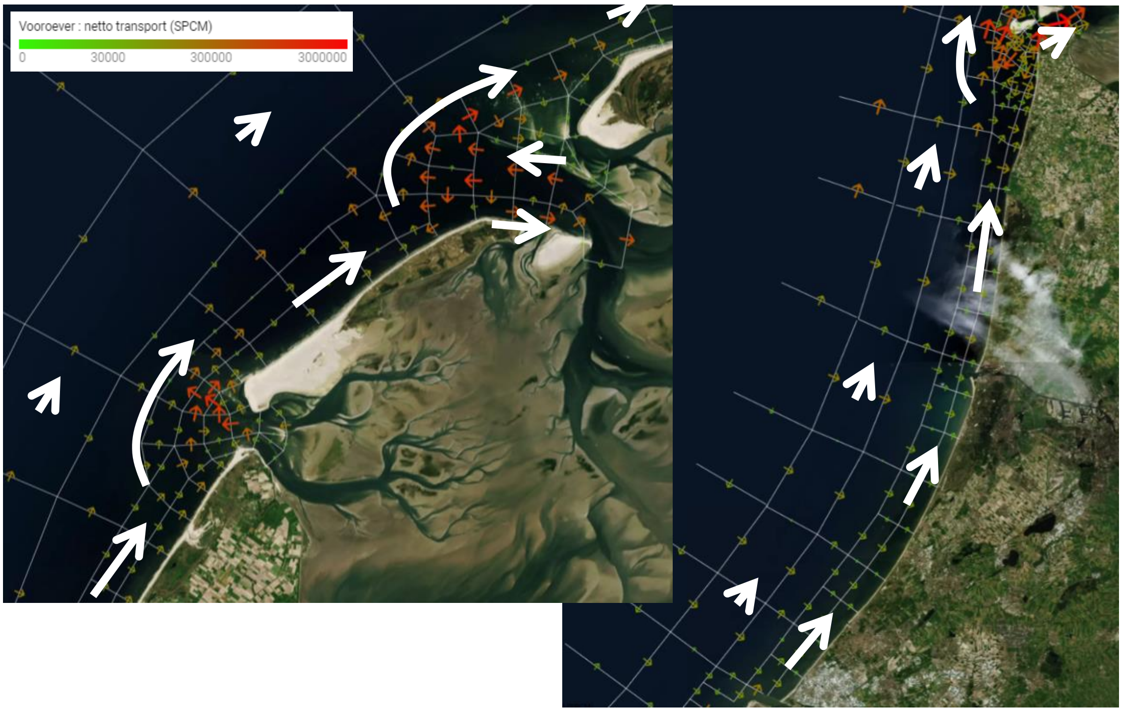

Figure 3.3. Illustrations of computed transports at the shoreface and tidal channels of the coasts of Holland and Vlieland (STCM model). White arrows were added to show the principal northward transport and bypass of the ebb-deltas. Results are based on current understanding and may change with new information.

An illustration of the transports at the Holland coast and Vlieland is shown in Figure 3.3. A net northward transport is shown along the coast, which aligns with the conceptual view by Van der Spek (2015). The net northward transport rates at the lower shoreface also increase towards the North on the Holland coast, as was also computed by Grasmeijer et al. (2019). A sediment bypass can be seen at the ebb-deltas of the Marsdiep, Eierlandse gat and Amelander Zeegat. Similar patterns are seen for Terschelling and Schiermonnikoog. Some of the tidal channels also import sediment, such as the Marsdiep and western channel of the Amelander Zeegat, which aligns with current knowledge on these systems. The model also shows onshore transport for most of the coastline, which may be present at some places but definitely not all over the coast. Onshore transport is therefore considered to be exaggerated to some extent by the model, while the overall patterns of transport towards the North and import into the basins are well represented. Furthermore, it is noted that largest gross transports are computed in the tidal channels, but the residual net transport (that are shown) are much smaller.

A strong onshore transport was computed at the Vlakte van de Raan, Eastern Scheldt ebb-delta, Bollen van de Ooster and Haringvliet monding (Figure 3.4), as was also sketched by Van der Spek (2015). Also the transport pattern from the channel North of Domburg to the Roompot, and from there through the ebb-channel to the northwest aligns with earlier studies (e.g. Huisman et al., 2009). However, at the same time a net southward transport was computed at the shoreface of the southwestern delta, while a net northward transport is suggested by Van der Spek (2015). In principal not much is known about the transport pattern in deep water, which may be southward, but the transports nearer to the coast (e.g. at the Bollen van de Ooster and at Goeree) are likely more inclined to the North as a result of the predominant wave conditions from the southwest.

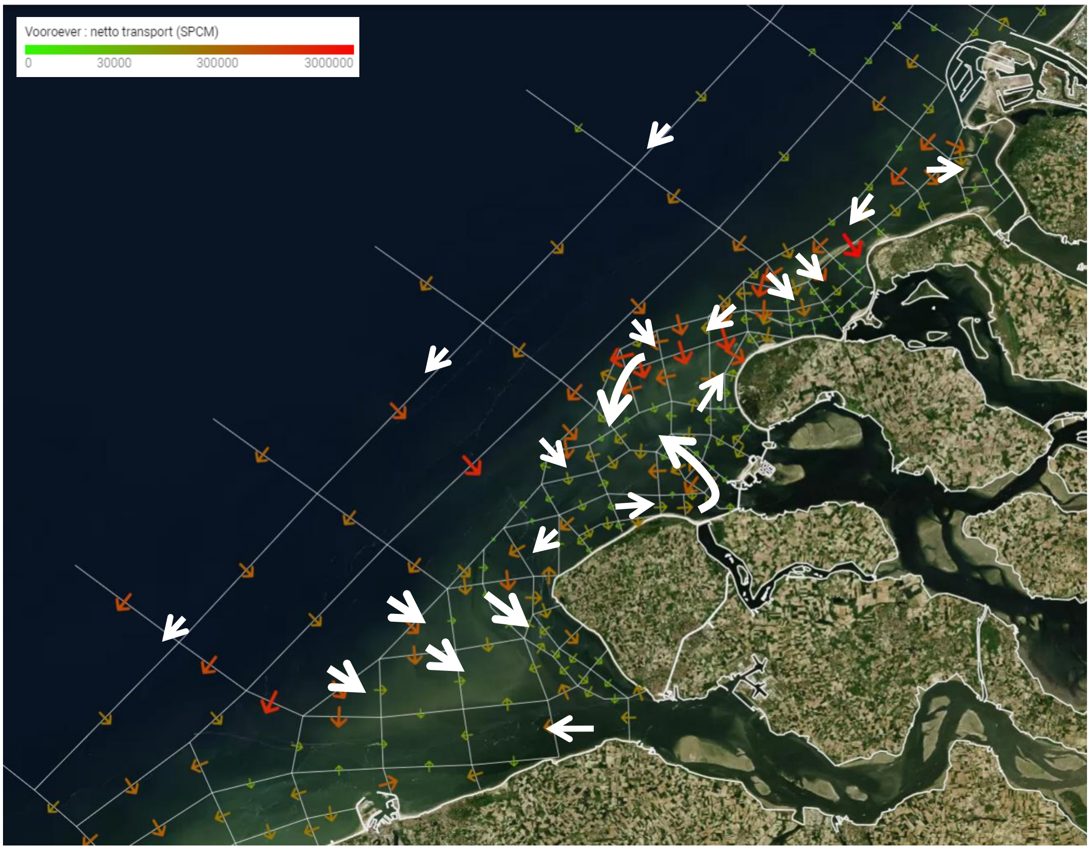

Figure 3.4. Illustrations of computed transports at the shoreface and tidal channels of the southwestern delta (STCM model). White arrows show the principal transports found. Results are based on current understanding and may change if new information becomes available from models or data.

Various attempts were made to investigate the cause of the difference (i.e. southward transport), for example by checking the tide conditions of the STCM point models in this region (i.e. whether they are exactly a fixed number of tidal cycles) and through a review of the computed astronomical tide conditions of the Kuststrook-fijn model. Tidal conditions did, however, seem to match with detailed models (e.g. DCSM v6), which are verified against water-level measurements. Furthermore, also the wave-driven current (as computed with Delft3D) was included in the STCM model, but this did not give a very substantial change in de moderately to deeper water that is under consideration. An open end here may be the wind forcing and subsequent wind-driven currents that can be generated, which may need to be investigated in future studies. In addition, it may also be needed to verify the asymmetry of the computed tidal currents at the southwestern delta with measurements, as a small difference may have a large impact on net transport. On the other hand, it may also be possible that net suspended transport is more southward directed (or less to the North) than expected from expert-judgment. This should be kept open as an option. In general, the onshore transport patterns at the shoal complexes and in the deeper channels seem to align with expert interpretations, but proper validation will be needed to verify the performance. Some reluctance should be taken into account when interpreting the southwest directed transports at the shoreface of the southwestern delta.

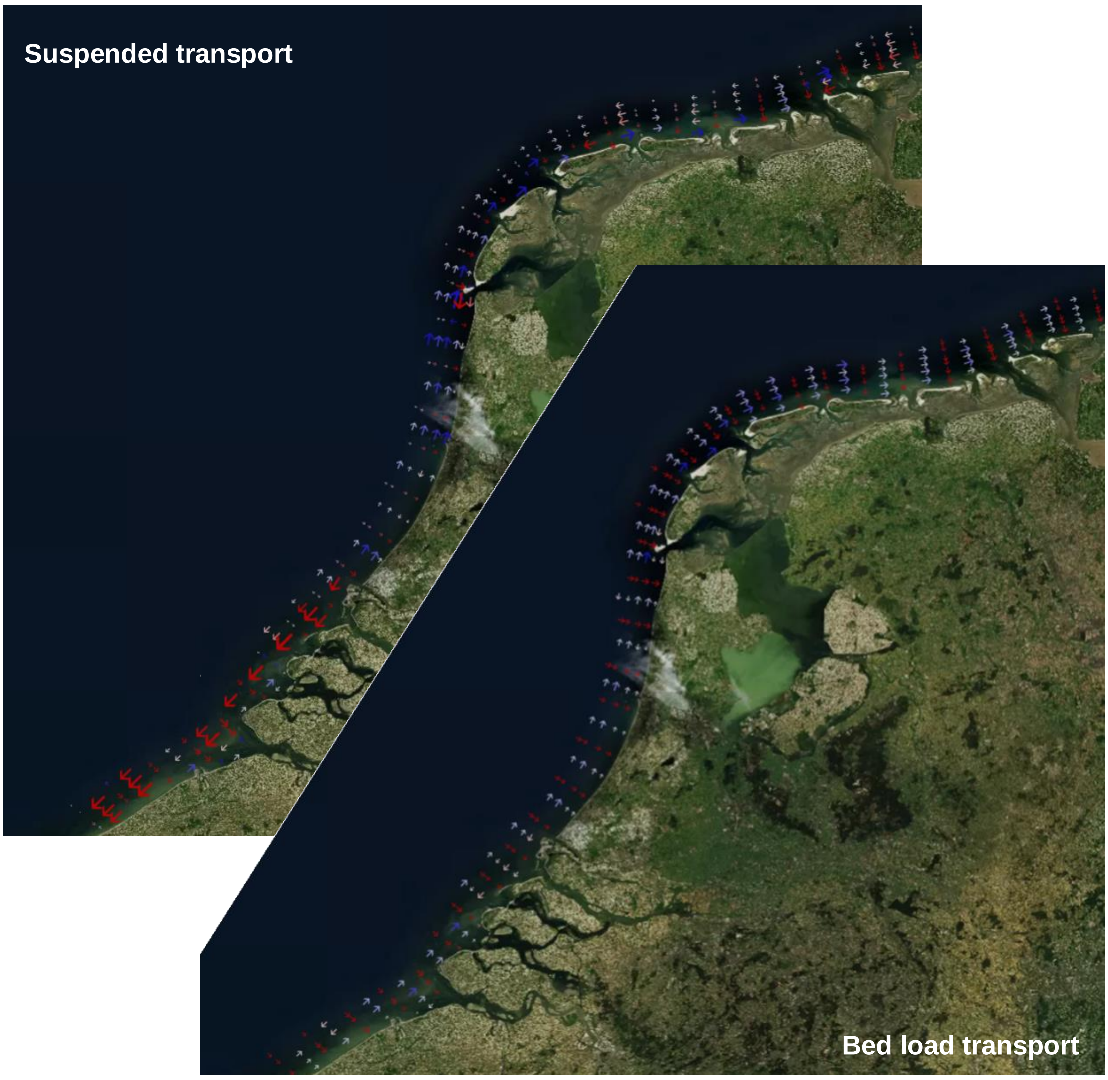

Figure 3.5. Suspended and bed load sediment transport at the lower shoreface of the Dutch coast. Results are based on current understanding and may change if better models or data are available.

An investigation of the bed load and suspended sediment transport shows that it is mainly the suspended transported that is southward directed (see Figure 3.5). These plots also provide a better overview of the transport patterns at a higher zoom level, as the results are presented differently at three zoom levels in the coastviewer (i.e. scale of the Netherlands, Province or region). This ensures that arrows do not clip at higher zoom levels, while sufficient details are shown when a detailed zoom is made into the map. In general, these aggregated plots are considered the best way to plot the modelling performed in this study.

3.4 Sediment Transport in the nearshore

The beaches and dunes are affected predominantly by the (gradients in the) wave-driven transport, which is typically located in shallow water close to the shoreline. Changes in the transport taking place further seaward (i.e. at more than a kilometer from the shoreline) are typically too far away to significantly influence the shallow nearshore area.

The UNIBEST-CL+ model was used to quantify these alongshore sediment transport rates at the Dutch alongshore uniform coastline sections (see Figure 3.6 and Figure 3.8). The magnitude and direction of the transport are shown with the arrows along the coast, where a red arrow represents a large transport and a green arrow a small transport.

Figure 3.6 Illustrations of computed transports in the nearshore due to wave-driven currents for the southwestern delta with a detailed zoom of Goeree (UNIBEST-CL+).

The transport rates at the southwestern delta transport align with expectations, as divergences of the longshore transport can be seen at the heads of the ‘islands’, where erosion is also taking place. Wave-driven transports are not very large and directed towards the estuaries (or the nowadays closed) tidal basins. The magnitude and pattern of transport at Walcheren and Schouwen align with computed wave-driven transport seaward of the Eastern Scheldt barrier in Huisman et al. (2009). A verification with actual coastline changes at the southwestern delta could, however, not be made in this study, and is suggested as future work. Models can then also be made useful for the evaluation of nourishment schemes.

The transport at the Holland coast is northward (Figure 3.7) as also shown by Van Rijn (1997). The magnitude of the transport rates goes up to a few hundred thousands m^3/yr, but insufficient time was available to validate this further against measurements. Noticeable are the local variations in sediment transport at the Sand Motor, where sediment is going southward on the southwestern side, while an enhanced northward transport is found on the northern side (Luijendijk et al., 2017; Tonnon et al., 2018; Huisman et al., 2018). Similarly, a divergence in transport is also found at the Hondsbossche and Pettemer Duinen where considerable erosion takes place of the nourishment protecting the local seawall. Earlier applications (e.g. Huisman et al., 2018) have shown that coastline models can be used to evaluate even larger ‘Sand motor’ type nourishments.

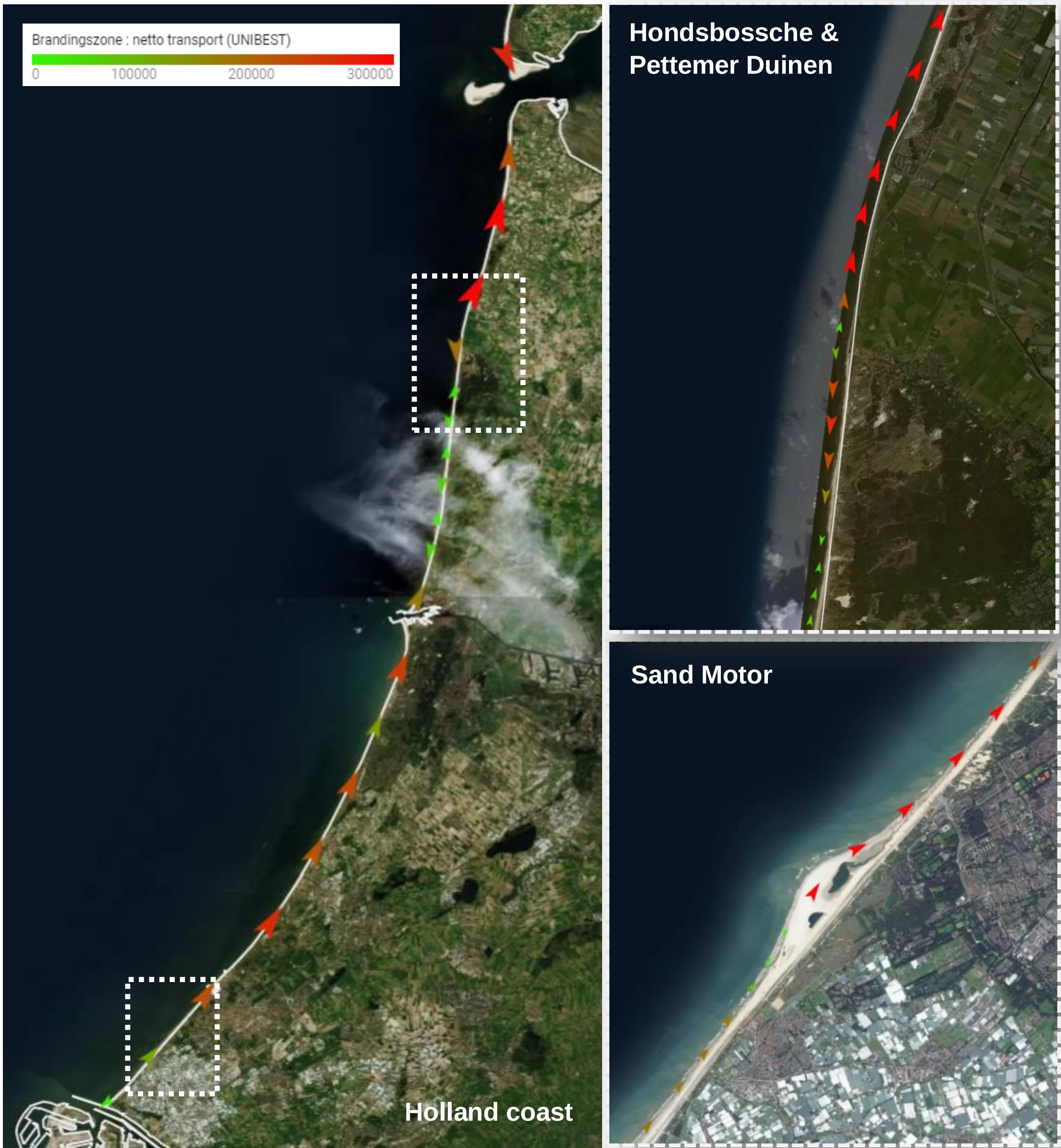

Figure 3.7 Illustrations of computed transports in the nearshore due to wave-driven currents at the Wadden coast with a detailed zoom of Texel (UNIBEST-CL+)

Sediment transport at the Wadden coast is predominantly towards the northeast (Figure 3.8), with the exception of the southern side of Texel and the heads of Terschelling and Ameland which have a considerably different shoreline orientation. The general patterns align well with the expert knowledge of the system. The coastline models are most-likely very useful for the evaluation of nourishments and obtaining understanding of the local coastal system. Further validation will, however, essential. It will improve the applicability and quality of the coastline model predictions.

Figure 3.8 Illustrations of computed transports in the nearshore due to wave-driven currents at the Wadden coast with a detailed zoom of Texel (UNIBEST-CL+)

3.5 Influence of waves and tide

3.5.1 Spatial overview of transport due to waves and tides

Tide is especially relevant inside the tidal basins and estuaries of the Dutch coast, which can be visualized from a Delft3D simulation for a spring-neap cycle with the modified Kuststrook-fijn model using only the astronomical forcing (Figure 3.9). The transport rates are plotted on a logarithmic scale which extends from 10^{-5} $m^3/m/s$ for the red color to 10^{-9} $m^3/m/s$ for the light-blue line.

The large transports in the tidal channels of the Waddenzee and southwestern delta (Figure 3.3 and Figure 3.4) can be explained from the tidal transports. Noticeable is that the tide-induced transport rates are relatively small at the uniform coastline sections (e.g. Holland coast and mid-sections of islands) and on the lower shoreface of the Dutch coast. Still the tide is expected to be dominant also at the lower-shoreface, because the influence of wave-driven currents will be negligible in deeper water (i.e. beyond a depth of about 10 m depth). In addition, the wave stirring is not accounted for in these 'tide only' plots, but can considerably enhance sediment transport in deep water (especially during storms) and is relevant for the mobility of sediments in tidal basins.

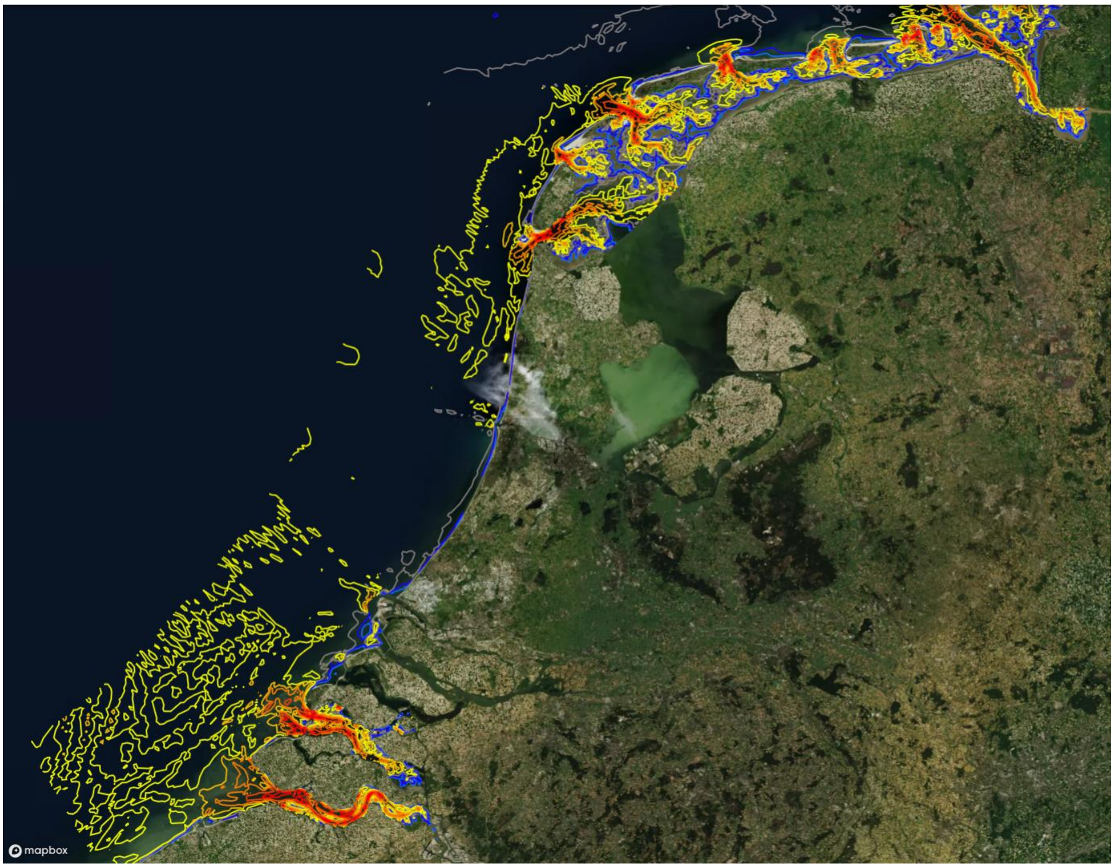

Figure 3.9 Computed average sediment transport for tide only during a spring neap cycle.

A current is generated when waves are breaking while they approach the coast under an angle. Typically, this current is directed along the coast for the uniform sandy coastal sections, but it can also be present at shoals in front of the coast (e.g. eb-delta) or in the Waddenzee.

Here an overview is provided of the locations where the wave-driven transport is present and the net magnitude of the longshore transport. For this purpose, the wave-driven transport was computed for each of the 391 wave conditions with the Delft3D model (for a model without tide). A water-level at MSL was applied in the model. Some more spatial spreading of the wave-driven transports will be present when water-level variation is included, but it will be difficult to see this on a map at the scale of the Netherlands. The average transport rates per condition were then multiplied with the duration of each of the conditions to obtain a net average long-term wave-driven transport (Figure 3.10). The transport rates are plotted on a logarithmic scale which extends from 10^{-5} $m^3/m/s$ for the red color to 10^{-9} $m^3/m/s$ for the light-blue line. It is noted that the model computes the region with wave-driven transport (due to breaking of obliquely incident waves), but the plot is not showing the effect of wave stirring.

Strongest transport rates are clearly present in shallow water at the Holland coast, which shows has a narrow strip with strong alongshore transports. Considerable wave-driven transport is also found at the south-western delta and ebb-delta of the Waddenzee. The plots suggest that bypassing around the ebb-delta takes place as a result of wave-driven transport (see Figure 3.3), which moves the sediment northeastward along the shoals of the ebb-delta. The magnitude of transport is considerable compared to tide only transport (i.e. at least an order of magnitude larger), suggesting that wave-driven current does play an important role on the ebb-delta. It will be needed to verify this using a model with combined tide and wave forcing as the combination of wave-stirring and tide will give a stronger transport than the tide-only situation.

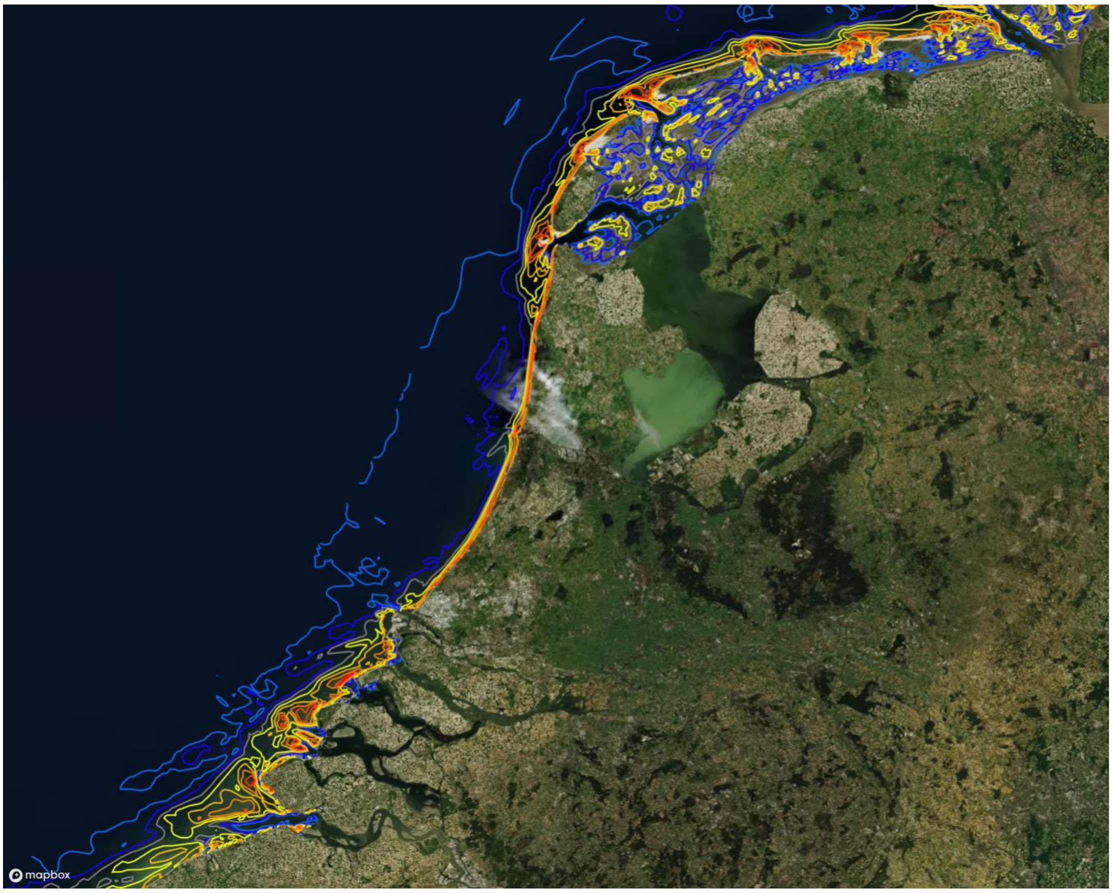

Figure 3.10 Computed average sediment transport due to wave-driven currents only (aggregate of 391 conditions).

3.5.2 Relative influence of spring tide versus neap tide on net transport

The relative influence of a spring versus a neap tide cycle has been explored with the STCM point-models for a situation with the 391 representative wave conditions and a period of 7 days of tidal velocties (Figure 3.11). An enhancement factor can be computed for the transport during spring tide. This enhancement factor has to be understood as how much the net sediment transport increases during the spring tide period. In both simulations we did include the same wave conditions. A red color is representative for regions where a much larger net transport is present during the spring tide, whereas the green areas show regions where neap and spring tide enforce a similar net transport. Yellow areas have some impact and are therefore considered mixed environments.

Noticeable is that the enhancement factor of the net transport for a spring tidal cycle versus the neap tidal cycle is highest (red) at the Holland coast, while the relative importance of the spring-neap tidal cycle is smaller at the southwestern delta and northern Wadden coast (green and yellow in Figure 3.11). This does not mean that the increase in tidal velocities during a spring tide is less for one region than for the other. The increase in the tidal velocities during a spring phase of the tide is present everywhere, also at the Wadden coast and southwestern delta. Instead it is expected that especially the asymmetry of the tide is differently influenced for a spring tide for these regions. The tidal asymmetry along the Holland coast and Texel is enhanced more during a spring-tide than for the other parts of the Netherlands. So, the tidal velocities remain much more symmetric in the northern Wadden coast and southwestern delta of the Netherlands.

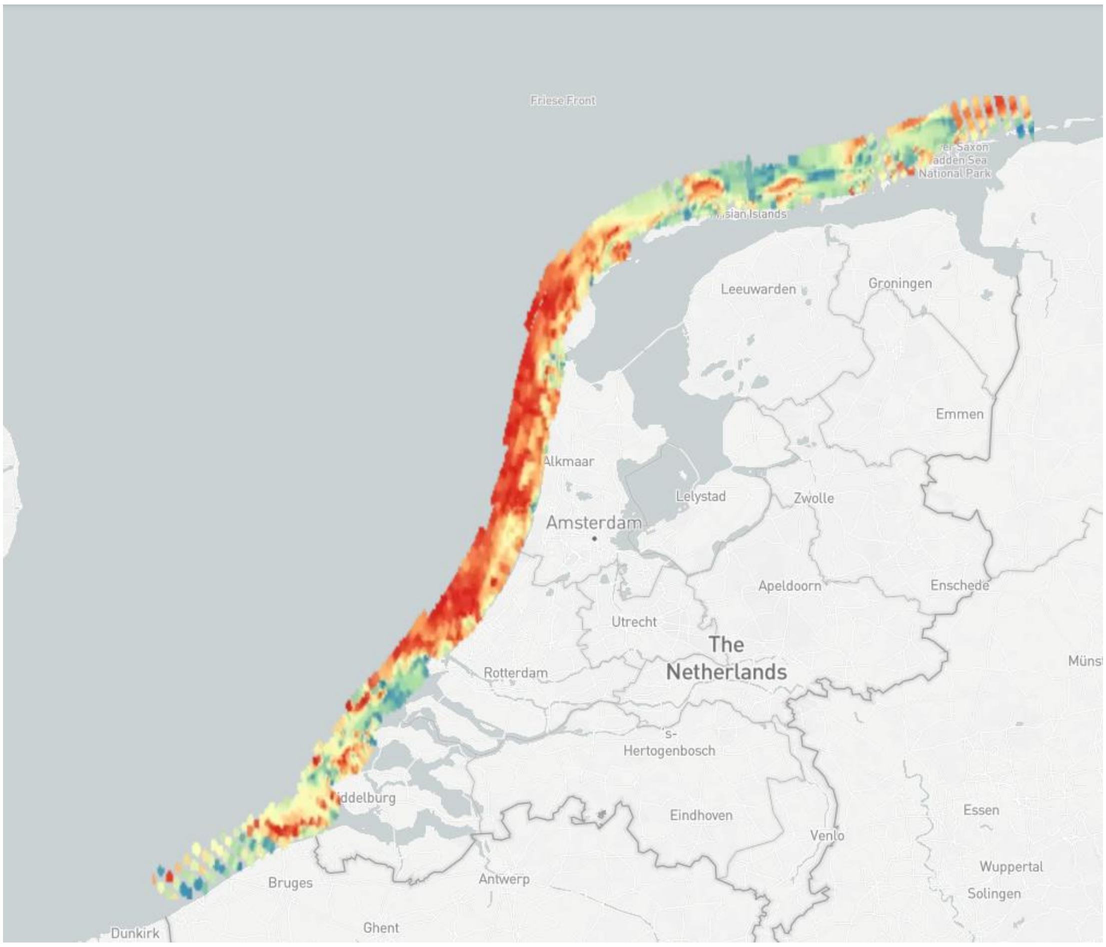

Figure 3.11 Enhancement factor of net transport rates along the Dutch coast for a spring tide with respect to a neap tide.

The above described enhancement factors show a very different influence of forcing conditions for the Holland coast versus the Wadden and southwestern delta coast, which interesting new finding. In this document an effort is made to explain these based on the supposed difference in tidal asymmetry during a spring tide at the Holland coast (versus the neap). This should, however, be considered as a rather preliminary finding for now, because the precise reasons for the differences in the effect of the forcing conditions could not be investigated in the framework of this study, and are also not known from literature. Further investigations will need to check the relevance of the water depth, sediment composition and type of tidal forcing which varies along the Dutch coast (e.g. the daily inequality) and possible other causes.

3.5.3 Conceptual overview

The computed transports in the current study provide a rather similar overview of the dominant directions of sediment redistribution as the sketches made by Van der Spek (2015). The conceptual overview as sketched by Van der Spek (2015) has therefore been included as it was in a Proceskaart of the Coastviewer (Figure 3.12).

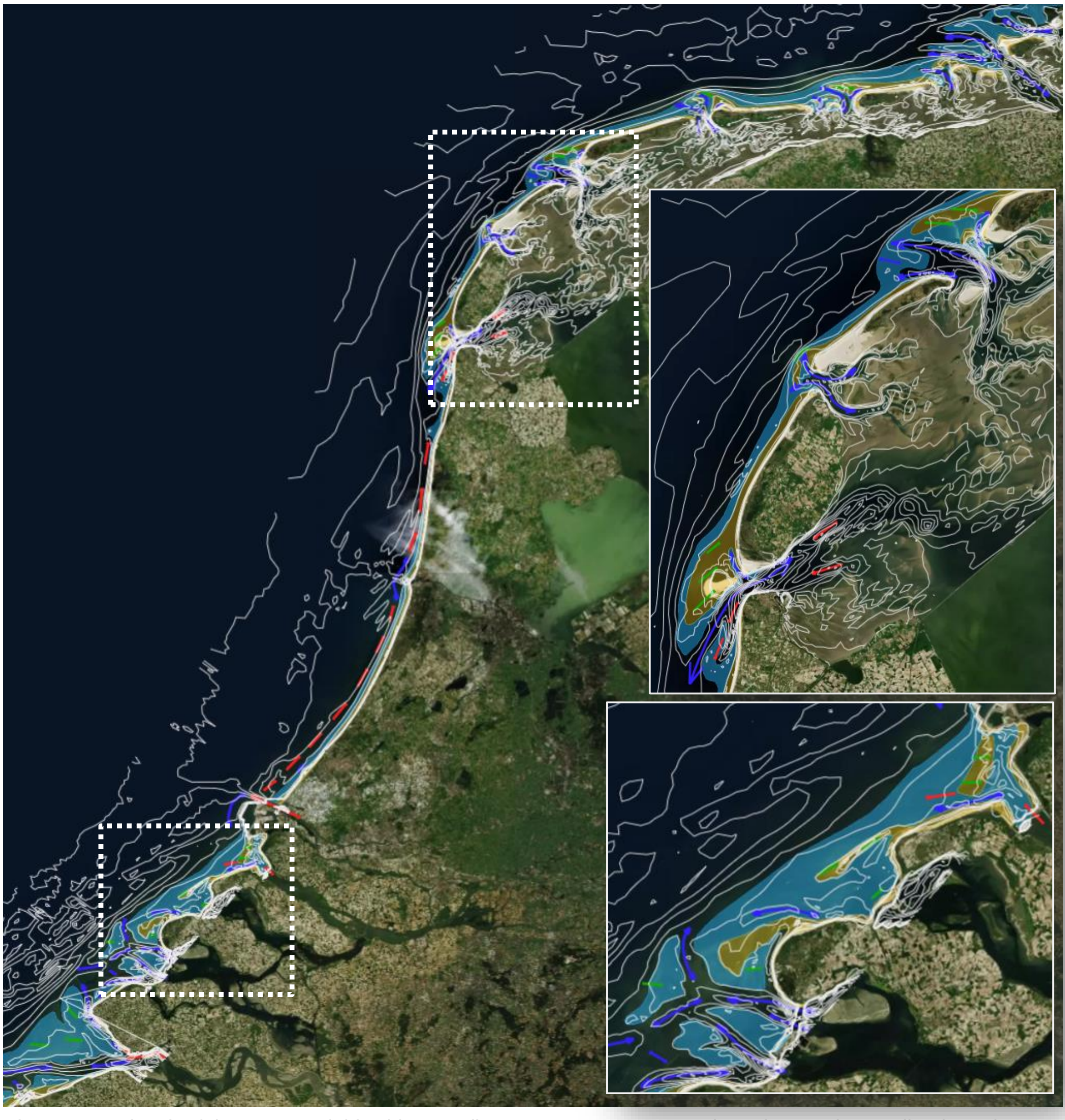

Figure 3.12 Sketch of the wave and tide-driven sediment transport patterns along the Dutch coastline based on expert judgment (Van der Spek, 2015).

4 Available maps and recommendations

Rijkswaterstaat-WVL requested Deltares to provide visualizations of sediment transport at the Dutch coast, which are presented in a web-based viewer (referred to as the ‘Coastviewer’). This report provides an overview of these maps (or ‘Proceskaarten’ in Dutch), as well as the methodology that was used for the creation of the maps. A number of maps have been made which have an applicability which is discussed below per type of ‘Proceskaart’. In addition, also the remarks are made on the maps and potential future research directions suggested.

- **Sketch of the coastal system**
  This process map provides an expert interpretation of the wave-driven transport patterns (and processes) at the Dutch coast, based on a sketch made by Van der Spek (2015). These sketches can be used to give a first impression of the Dutch coastal system to anyone that is new to the region, such as coastal managers, policy makes, foreign visitors and new researchers. The sketches can also be instrumental in stakeholder meetings to visually show the relevant local transport processes, and therewith also give a basis for measures that are proposed.
- **Sediment transport patterns at the shoreface**
  These process maps are used to show the patterns of sediment transport at the (lower) shoreface of the Dutch coast (beyond 5 meter depth), which basically is almost all of the Dutch coast. Results aligned well with expert interpretations of the processes acting at the shoreface of the Holland coast, and may even be used to illustrate the bypass of sediment around eb-delta’s of the Wadden coast, import of the tidal channels, landward transport at ebb-tidal shoals, as well as the net northward transports on the lower shoreface. That said, the results should also be interpreted with care when it comes to detailed patterns near to tidal basins, as some patterns do not align with expert interpretations. This holds especially for the southwestern delta, which shows southward transports that do not align well with current understanding. Validated models (with respect to observed bathymetric changes) for the tidal basins are needed to verify findings and/or come up with more accurate transport patterns, such models are now however not yet available for most of the tidal basins. The setup of validated models for the tidal basins and ebb-delta’s is therefore strongly recommended. In principal, the detailed transport patterns provide us with a measure of the current capabilities to predict large-scale coastal transports with models.
- **Nearshore wave-driven transport at the uniform beach sections**
  The computed transports along the beaches of the Netherlands give a good overview of the governing morphological processes close to the shoreline, which in-fact determine the shoreline changes at intermediate time scales (years to a decade). It is essential to further calibrate these UNIBEST-CL+ coastline models to be able to use these models for obtaining additional information on nourishment schemes and as an extension of coastal monitoring.
- **Maps of magnitude and relative influence of wave and tide-driven transport**
  The locations where wave-driven and tide-driven sediment transport processes play a role can be identified using maps with the transport intensity for wave-driven or tide-driven transport. In addition, also the enhancement of the transport as a result of spring-tide conditions (w.r.t. neap tide) is shown with the new visualizations. These maps are instrumental for gaining insight in the expected behaviour of the coastal system. The requirements for inclusion of particular physical transport processes can now be assessed better in advance even before a modelling assignment is started.

Recommendations from this study are to first make a validation of the nearshore transport rates (and gradients) at the uniform beach sections with respect to the observed coastline changes as presented in the kustlijnkaartenboek. A great opportunity will also be to use the new data collected at Ameland (and Wadden coast) as a reference for the model results, which also aligns the studies with other activities performed within B&O kust and Kustgenese. Secondly, it is strongly recommended to put the findings of the detailed transport patterns (at the ebb-deltas and tidal channels) next to validated numerical models and the observed changes in the bathymetry, as the transport patterns at the voordelta and tidal basins are still quite uncertain. Some of the tidal basins will still require the setup, calibration and validation of a morphological model. These models and data will be instrumental in obtaining a better understanding of the transports at the southwestern delta. An assessment of the potential influence of wind-driven currents on the hydrodynamics and net transport regime can, for example, be made.

In addition, maps of transport trajectories need to be added to the Proceskaart to be able to understand effects of nourishments in advance, for which the underlying paths can be created with the SedTrails model (which is in-fact a way of post-processing the Delft3D results). In this way the potential regions of influence of a sandy measure can be illustrated. Besides sand nourishments, one can also think of the potential trajectories of sediment from the dredged sediment disposals (e.g. at Loswal Noord). When such information is available, it will also be much easier to perform effective monitoring of projects as the major trajectories (and destination of the material) are better understood.

The current study focused on the intermediate time scale (years to a decade) transport processes that act at large scales (multiple kilometers), which are considered most relevant for coastal maintenance in the Netherlands. However, long-term processes will affect the availability of sediment on longer timeframes (decades to a century) and are therefore relevant to account for in future studies. Here one can think of illustrations of the potential coastline recession varying over time and per coastal section. In addition, also the effect of enhanced (or continued) sediment import on the ebb-delta's and surrounding coast is a relevant aspect to visualize in the near future.

Not only the sediment transport varies along the coast, but also the bed-shear stresses, sediment composition and other properties such as the habitat for marine species can vary considerably. In some locations of the coast, it will be important for assessments of environmental impacts to visualize the changes in bed-composition over time (e.g. near to a 'Sand Motor' or large structure) or to show the marine species (or habitat properties) in relation to a-biotic parameters such as the bed shear stresses. This will make it much easier to discuss findings and make sure that knowledge is not only available for experts and coastal managers but can be shared among more users / stakeholders.

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