High-resolution data-based geomorphological analyses of the trilateral Wadden Sea

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ABSTRACT

The Wadden Sea is a geomorphologically complex system of tidal flats and creeks. It is not only an important habitat for a multitude of species but also a thriving economic and living environment. The Wadden sea developed under the sea level rise since the last ice age, yet whether it can withstand its predicted anthropogenically induced acceleration and how geomorphological properties might change is a core question of recent research.
To understand these geomorphological processes and their development, analyses and data-based approaches have become standard tools for coastal engineers, ecologists, and geologists. However, most studies focus on regional scales and usually restrict processing, analyses and publication of data to national or subnational scale. Natural processes do not adhere to these boundaries and thus a transnational approach to consistently process and provide data and results is imperative. As participants of the publicly funded joint project "Digital hydro-morphological twin of the Trilateral Wadden Sea" (TrilaWatt), we rise to this challenge and offer both a high-resolution morphological and sedimentological data base for the Wadden Sea as a whole and user-oriented analysis products in an open-access and citable environment for faster and easier decision making, supporting also those who do not necessarily possess the tools or resources for complex analyses themselves.
Within these parameters, we developed and implemented new ways of data-based, process-oriented interpolation methods for sedimentological sampling data of the surface and subsurface of the seabed in the framework of the Functional Seabed Model. The methodology and representative results are presented here.

KEYWORDS

Data-based modelling; geomorphology; sedimentology; Wadden Sea; trilateral; bathymetry

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1. INTRODUCTION

The Wadden Sea is a complex and geomorphologically highly active region. With intertidal flats, tidal creeks, fixed anthropogenic boundaries to the mainland, and barrier islands and tidal inlets seawards. To understand this system under the influence of sea level rise and its acceleration, climate change with intensifying storms, and increasing anthropogenic alterations a focus on both data- and process-based modeling approaches is needed.

The foundations of such model studies are primarily consistent high-resolution base data on the elevation, morphology, and other properties of the Wadden Sea. To provide an actual additional value to the research community, we – partners or stakeholders of the research project TrilaWatt (https://trilawatt.eu/, last accessed 20.04.2023) – aim to generate products under the FAIR principle (findable, accessible, interoperable, reusable) for the whole trilateral Wadden Sea with documented methodology, which is presented here.

This article will focus especially on the data based approach of generating a time-dependent continuous and consistent surface sedimentological model for the Wadden Sea in the framework of the Functional Seabed Model (Milbradt, 2012), or FSM for short.

2. BATHYMETRIC MODELLING

Bathymetric information, bound by physical reality, is typically collected as point clouds of an unstructured and spatially discrete nature via acoustic signals (McCaffrey, 1981). For purposes such as nautical charting or the study of marine ecosystems, geomorphological dynamics or also terrestrial disaster management, spatially continuous models are generally required (Schlurmann et al., 2010). This is achieved by applying different interpolation and approximation approaches to the respective input data sets, typical examples might be linear interpolation within triangulated meshes or averaging approaches in Voronoi tessellations (Sievers et al., 2021).

Combining these approaches in space (spatial interpolation) and time (temporal interpolation) within and between datasets achieves spatio-temporal interpolation and, depending on the input or base data, elevation information can be calculated at any point in space and time within the spatial and temporal extent of the base data to create a digital elevation model, short DEM, (Sievers et al., 2021), see Fig. 1.

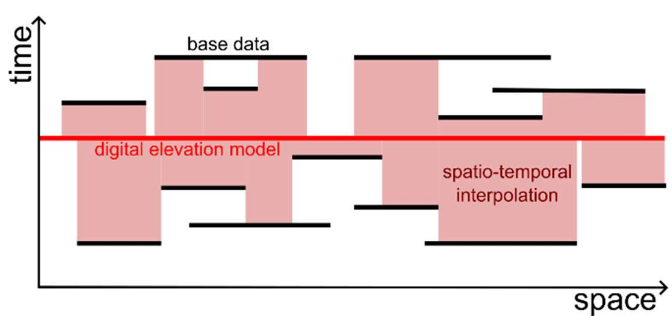

Fig. 1: Concept of spatio-temporal interpolation of base data to create a DEM.

The FSM has accumulated about 144,000 data sets with circa 370 billion survey points through several research projects and collaborations over two decades, and is able to perform spatio-temporal interpolation along the Wadden Sea, with a particularly high data density in the Netherlands and Germany (Pineda, 2023).

3. SURFACE SEDIMENTOLOGICAL MODELLING

Ecosystem analyses and hydro-numerical approaches require not only information on sea-floor elevation and its changes over time, but also surface properties such as roughness, permeability and erosion resistance (Hesse et al., 2019). These parameters are usually derived from sediment samples, whether by grabber or sonar. In the case of actual physical samples, a common representation is the cumulative grain size distribution function or GSD. As for example Colina Alonso et al. (2022) show, even using the GSD itself, analysis of spatially varying modalities of certain grain size fractions can provide insight into larger scale relationships that can be transferred and applied on a global scale to better understand sediment properties and coastal evolution.

1.1. Temporal extrapolation

To extend the capability of modelling and analyses further from the original sampling times of the samples themselves, an evolution equation was formulated and integrated into the FSM (Sievers, 2022). The solution of this equation constitutes an extrapolation function that is coupled to the bathymetric evolution as derived from the FSMs bathymetric component (see chapter 2) as well as hydrological indicators from external sources, see eq. 1,

$$\frac{\partial d_{50}(t)}{\partial t} = -\frac{\partial z(t)}{\partial t} * \frac{\lambda\big(z(t)\big)}{1+\big||\nabla z(t)|\big|} * \big(1-n(t)\big) * d_{50}(t) * \sigma_0 * \begin{cases} B_{sed} \\ B_{ero} \end{cases} + \begin{cases} S_{sed} \\ 0 \end{cases} \tag{1}$$

with $d_{50}(t)$ being the time-dependent median grain size [mm], $z(t)$ being time-dependent the elevation [m], $\lambda\big(z(t)\big)$ being an elevation-dependent depth uncertainty factor [-], $\big||\nabla z(t)|\big|$ being the magnitude of the gradient vector [-], $n(t)$ being the time-dependent porosity (shortened notation), see eq. 2, [-], σ_0 being the initial sorting of the GSD after Folk (1980) [-], B_{sed} and B_{ero} being logistic boundary conditions, see eq. 4 and eq. 5, and S_{sed} being a restriction term, see eq. 6. Note that there is no restriction term under eroding conditions, as it has so far not proven necessary.

The time-dependent porosity, see eq. 2,

$$n\Big(d_{50}(t), \sigma\big(d_{50}(t)\big)\Big) = n_{base}\big(d_{50}(t)\big) * \Big(1 + \sigma\big(d_{50}(t)\big) * \sqrt{w_c\big(d_{50}(t)\big)}\Big)^{-1} \tag{2}$$

is calculated by modifying a well-known $d_{50}(t)$-dependent base porosity $n_{base}\big(d_{50}(t)\big)$ [-], in our case Wilson (2018), with the sorting $\sigma\big(d_{50}(t)\big)$ (shortened notation) [-], see eq. 3, and the settling velocity $w_c(d_{50}(t))$, in our case Wu & Wang (2006), to account for the possibility of filling of pores by smaller grains within a coarser matrix and possible cohesive effects.

The time-dependent sorting is heuristically approximated as follows, see eq. 3,

$$\sigma(d_{50}(t), \sigma_0, d_{min}, d_{max}) = \sigma_0 * \left(1 - \frac{d_{50}(t)}{d_{max}}\right) * \left(1 - \frac{d_{min}}{d_{50}(t)}\right) \tag{3}$$

with d_{min} being the minimum and d_{max} being the maximum grain size in the surrounding sediment. When derived from sediment samples, we usually approximate these values by $d_{min} = d_5 * 0.5$ and $d_{max} = d_{95} * 2$.

The boundary conditions B_{sed}, see eq. 4, and B_{ero}, see eq. 5, are of a logistic nature to ensure a decreasing rate of change due to less potential when the extrapolation approaches them.

$$B_{sed} = \left(1 - \frac{d_{min}}{d_{50}(t)}\right) * \frac{1}{1 + \tau_b(t)} \tag{4}$$

$$B_{ero} = \left(1 - \frac{d_{50}(t)}{d_{max}}\right) * (1 + \tau_b(t)) \tag{5}$$

They utilize the time-dependent bottom shear stress $\tau_b(t)$ as can be derived location-variant from existing data products (Hagen et al., 2021). This has been prototypically combined with wave energy input, for a few years, since high-resolution results for wave simulations for longer periods were not available.

The hydrodynamic conditions during sedimentation, especially bottom shear stress values, can prevent the settlement of smaller grain sizes. This hydrodynamic restriction is taken into account with the restriction term S_{sed}, see eq. 6,

$$S_{sed} = \sigma_0 * \tau_b(t) * \max\left(0, d_{50}^{\tau}(t) - d_{50}(t)\right) * \left(1 - \frac{d_{50}(t)}{d_{max}}\right) \tag{6}$$

with $d_{50}^{\tau}(t)$ [mm] being a reference median grain size derived from an inverse Shields-function (Shields, 1936) using the bottom shear stress information to validate the calculated median grain size against and – if necessary – adjust according to their difference.

With this evolution equation, a median grain size can be calculated along a given bathymetric time series at the sampling point regardless of the temporal direction or step size from any initial starting time t_0, see Fig. 2 (Sievers, 2022).

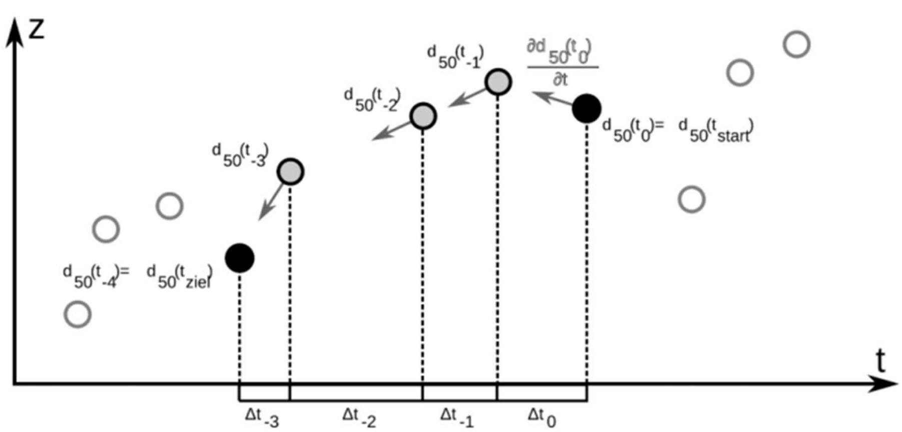

Fig. 2: Temporal development of median grain size along bathymetric time series with varying elevation values (z) over time (t).

The time-dependent skewness of the GSD can be approximated heuristically as in eq. 7.

$$Sk(d_{50}(t), d_{max}, d_{min}) = \frac{d_{max} + d_{min} - 2 * d_{50}(t)}{2 * (d_{max} - d_{min})} \tag{7}$$

Finally, for further analysis, a cumulative GSD function can be restored from selected scalar parameters by using an adapted approach from Tauber (1997) after Sievers (2021) as is shown in eq. 8,

$$F(\phi, \phi_{50}, \sigma, Sk) = 1 - \left(1 + e^{-1.7*(\phi-\phi_{50})*(\sigma - Sk*\tanh(\phi-\phi_{50}))}\right)^{-1} \tag{8}$$

with ϕ being the variable grain size in ϕ-notation (Krumbein, 1936; 1938) and ϕ_{50} being the median grain size in ϕ-notation.

1.2. Spatio-temporal interpolation

Especially with grabber sediment samples, extrapolation at sampling positions does not always provide the necessary information for further analysis, especially if the data base is locally or generally sparse. Fig. 3A exemplifies this by portraying an exemplary spatial data distribution in a what could be a intertidal flat with tidal creeks (Sievers, 2022). Some areas are vastly undersampled and especially regarding potentially differing sampling dates, the information is probably not usable for spatial analysis. Fig. 3B on the other hand shows the potential advantage of using the previously elaborated extrapolation technique not only at the sample positions, but arbitrarily chosen model points to properly cover relevant geomorphological properties.

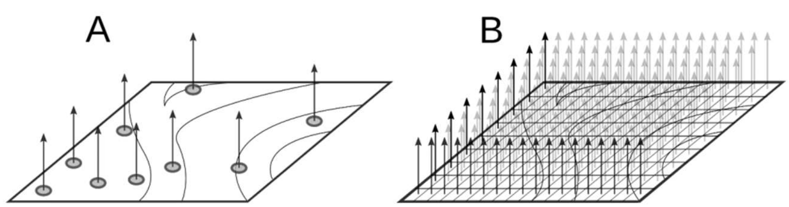

Fig. 3: Fictitious intertidal DEM with (A) inconvenient sample distribution and (B) virtual samples positions on a model structure. Arrows indicate extrapolation.

To facilitate this, the evolution equation eq. 1 is treated as an initial value problem, where the initial value is a spatially continuous and consistent high resolution "digital sediment model" (DSM) with one singular temporal validity. This initial condition is generated by extrapolating all samples from their specific sampling date back (or forward) to the initial DSM time stamp and creating one spatially consistent GSD model using expert knowledge, hydrological parameters and, if necessary, historical charts or other reference material. From this DSM on, the extrapolation is applied in user-specified time steps for the whole model area. Previous time-steps can be utilized as mixing material in case erosion takes place as a quasi-stratigraphic model. This can be extended by using a background core sample model.

Extrapolating from arbitrarily chosen model points in time will at some point either directly hit a sample or at least engage its close surroundings. To ensure that these spatial and temporal areas of influence (AoI) are properly represented in the model, in a first step their spatio-temporal boundaries are detected by geomorphological analyses (Sievers, 2022). In a second step, an influence function, in our case a modified normal distribution, is applied to calculate based on spatio-temporal distance of the extrapolated model point to the sample, how much the measured sample influences the closer area, see Fig. 4 (Sievers, 2022).

The closer the model point to the sample, the higher the influence factor, where it reaches one at the sample itself and zero at the boundaries.

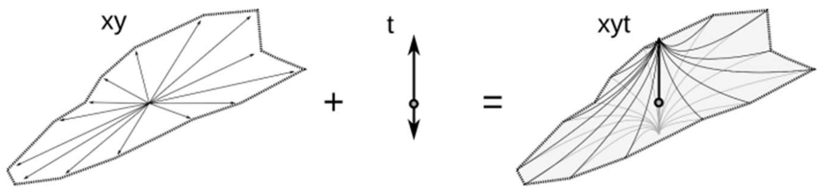

Fig. 4: Combining spatial (xy) and temporal (t) AoIs produce spatio-temporal AoI.

All previously mentioned components taken into account, the implemented procedure can be defined as a spatio-temporal evolution-based interpolation with sediment sample data assimilation, as input sediment sample information will be represented in full when a DSM model node coincides spatially and temporally with the sample.

4. PROTOTYPICAL RESULTS AND ANALYSES

The result of this procedure is a spatio-temporally continuous and consistent time-dependent data-based DSM that covers – due to the coupling to bathymetry – as much area and time as the FSMs bathymetric component can cover with DEMs.

For the Dutch part of the Wadden Sea we were able to generate annual DSMs from 1990 until 2021 in 10 m grids, for the German parts of the Wadden Sea we were able to generally annual DSMs from 1960 until 2020 in 10 m grids, for the Danish parts of the Wadden Sea no models could be generated based on a lack of publicly accessible data.

For prototypical analyses, we focus on the bilateral area of the greater Ems estuary and the surrounding back barrier tidal basis between 1990 and 2020, with exemplary scalar analyses shown in Fig. 5 with the median grain size d_{50} [mm] and in Fig. 6 the skewness Sk [-] after Folk (1980) extracted from the DSM of 2020.

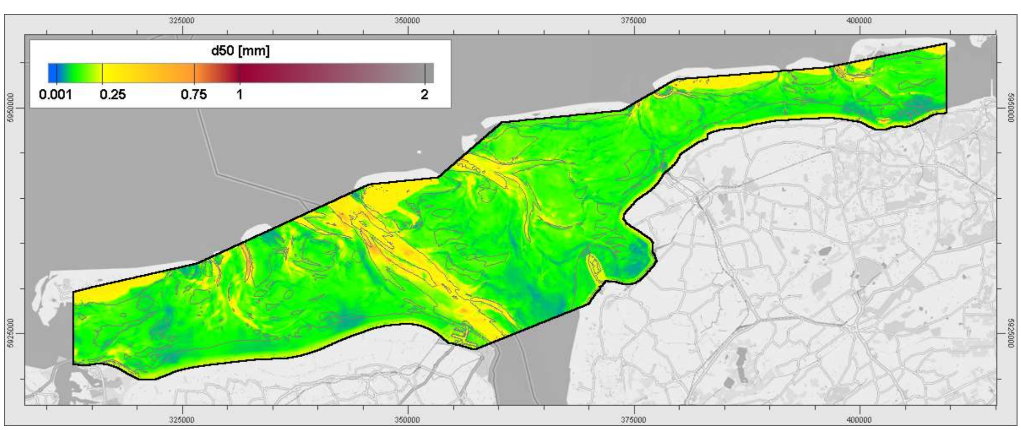

Fig. 5: DSM 2020 median grain size [mm], 10 m incremented isolines (grey), focus area boundary in black. Background map ©OpenStreetMap.

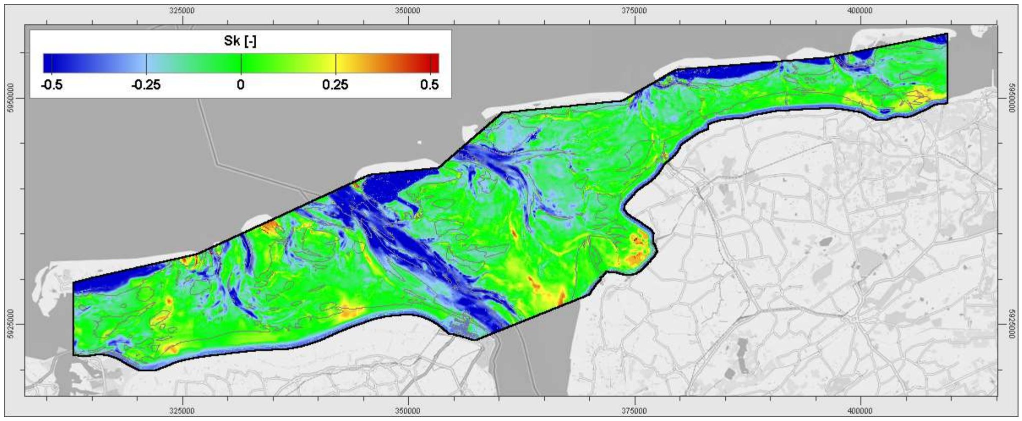

Fig. 6: DSM 2020 skewness [-], 10 m incremented isolines (grey), focus area boundary in black. Background map ©OpenStreetMap.

The presented methodology however offers more than just temporally static scalar analyses. Within the previously displayed focus area, the DSMs cumulative GSD functions of each model node can be analyzed each year to calculate a freely selectable parameter or grain size fraction percentage and for example calculate differences or create time series. This is illustrated in Fig. 7 and Fig. 8, with the sediment fraction of > 125 µm extracted and analyzed from the DSMs. These data can be further utilized by experts in the field to derive further information and, ideally, generate new insights and greater process understanding.

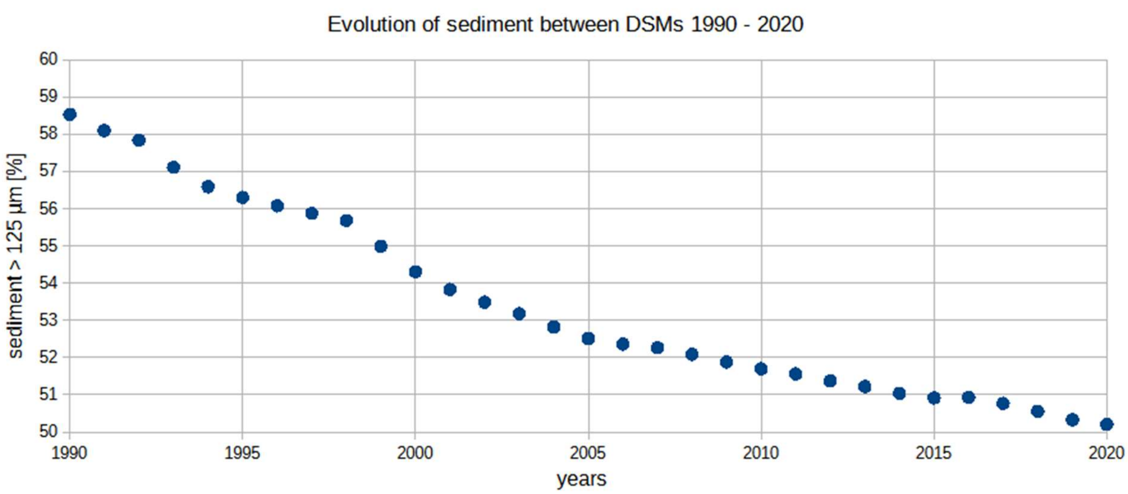

Fig. 7: Time series of sediment evolution > 125 µm of the greater Ems focus area as derived from the DSMs.

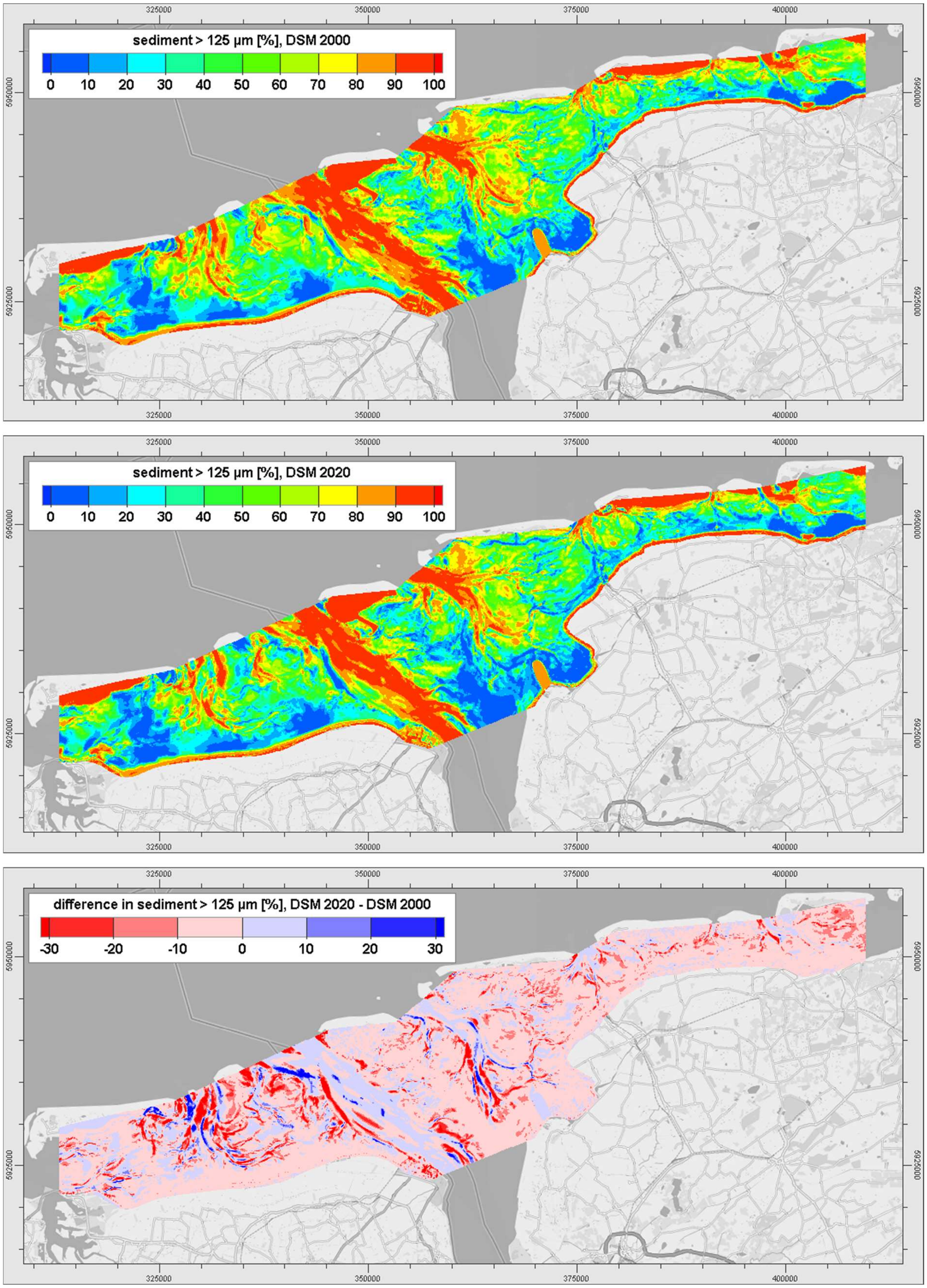

Fig. 8: Sediment fraction > 125 µm extracted from two DSMs and their difference. Background map ©OpenStreetMap.

5. CONCLUSION

The TrilaWatt (https://trilawatt.eu/, last accessed 20.04.2023) project aggregated research and product development expertise from multiple research projects. The methodology presented in this article will help to optimize hydro-numeric approaches of both project partners and external stakeholders alike.

Products provided and usable under the FAIR principle will include annual DEMs and DSMs for the Wadden Sea from 2000 to 2020, with the exact spatial extent still open and dependent on accessibility of Danish data.

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