Memo

Aan
Jurre de Vries / Martijn Klein Obbink

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Onderwerp
data analysis Holwerd-Ferwerd 2024

Data analysis turbidity monitoring Holwerd – Ferwerd (update 2024)

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Samenvatting

In de geulen bij Holwerd en Ferwerd zijn in juli 2022 twee meetframes geplaatst om de troebelheid te meten gedurende een periode van meerdere jaren. Dit is gedaan voor een beter begrip van de natuurlijke dynamiek van de troebelheid onder invloed van getijstroming, wind, golven etc., maar ook om de mogelijke invloed van menselijke factoren op de troebelheid te kwantificeren, zoals de veerboot naar Ameland en baggeronderhoud in de vaargeul naar Holwerd. Het meetpunt bij Ferwerd (in het uiteinde van het Dantziggat) dient hierbij als ongestoorde referentie, omdat hier geen veerverbinding is en er geen onderhoud aan de vaargeul wordt uitgevoerd.

Dit memo van december 2024 is een vervolg op een eerder memo van december 2023 dat de eerste data-analyse beschreef. Ten opzichte van dit eerdere memo is er een extra jaar aan meetdata gebruikt om te analyseren. De volledige analyseperiode is nu juli 2022 – oktober 2024. Met name de data bij Ferwerd is nu completer dan vorig jaar omdat de uitvoering van de metingen is aangepast n.a.v. de eerdere bevindingen. Tevens is voor de interpretatie van de meetdata nu meer gebruik gemaakt van omgevingsdata, zoals de windcondities in het waddengebied en de MWTL metingen voor concentraties zwevende stof.

Uit de nieuwe analyse wordt onder meer het volgende geconcludeerd:
- Natuurlijk gedrag: op beide locaties worden de slibconcentratie (en dus troebelheid) op korte termijn (binnen een 14-daagse getijcyclus) sterk gestuurd door de lokale stroomsnelheid. Op langere termijn spelen ook andere aspecten een rol zoals het aanbod (o.a. door wind en golven) en de eigenschappen van slib. Deze ondervinden een seizoensdynamiek (zoals ook blijkt uit de chlorofyl-concentratie), waardoor op momenten met gelijke getijfase en stroomsnelheid de slibconcentratie heel anders kan zijn. Deze conclusie is niet veranderd t.o.v. de analyse vorig jaar. In oktober 2023 is er een atypische periode geweest met een sterke en persistente oostenwind, die vermoedelijk slib van het wantij terug naar de geulen heeft getransporteerd. Dit is een mogelijke verklaring voor de verhoogde concentraties in de wintermaanden hierna.
- Verschil Holwerd-Ferwerd: In tegenstelling tot de analyse van 2023 is de slibconcentratie bij Holwerd hoger dan die bij Ferwerd (gemiddeld over de hele analyseperiode). Dit komt

door een verbeterde calibratiecurve van de troebelheidssensoren. Deze bleek bij Ferwerd eerder niet betrouwbaar te zijn.
- Invloed van baggerwerk bij Holwerd: In tegenstelling tot de analyse van 2023 is er nu wel een duidelijke invloed gevonden van baggerwerk op de troebelheid. Indien de volledige dataset wordt opgesplitst in periodes met en zonder baggerwerk, is de slibconcentratie in de gestoorde periode 60% hoger dan in de ongestoorde periode. De toename is in de winter groter dan in de zomer. Bij een concentratie groter dan 2 g/l is er kans op zuurstofloosheid (dit treedt m.n. in de winter soms op). Bij referentiestation Ferwerd treedt er geen concentratieverschil op tussen gestoorde en ongestoorde periodes. Een belangrijk verschil met de eerdere analyse is dat toen al het baggerwerk in de wijde omgeving is gelabeld als verstorend, terwijl voor de huidige analyse alleen baggerwerk in het uiteinde van de vaargeul is gelabeld als verstorend.
- De invloed van de veerboot op de troebelheid is niet zichtbaar in de meetreeks.

Dit leidt tot de volgende aanbevelingen:
- Het zou goed zijn de metingen nog een jaar voort te zetten op beide huidige locaties met consistente instellingen. Hiervoor zijn twee argumenten. Ten eerste, de variaties van windsnelheid en -richting over de seizoenen kunnen van jaar tot jaar sterk verschillen waardoor ook de slibdynamiek van jaar tot jaar verschilt. Een lange tijdreeks is nodig voor voldoende representativiteit. En ten tweede de homogeniteit van de dataset. De afgelopen twee jaar zijn nog instellingen en posities van sensoren gewijzigd zodat er hierdoor trendbreuken kunnen optreden in de data.
- Meet naast slibconcentratie ook slibeigenschappen zoals vlokgrootte, valsnelheid en organisch gehalte om meer grip te krijgen op de oorzaken voor de sterke seizoensdynamiek.
- De meetreeks is uitstekend bruikbaar voor modelvalidatie en indien nodig kalibratie. Voor de opschaling van lokale metingen naar grootschalig systeemgedrag is het KRW-model beschikbaar. Voor de optimalisatie van het beheer en onderhoud aan de vaargeul tussen Holwerd en Ameland is een variant met lokale roosterverfijning beter bruikbaar. Omdat de kracht en beperkingen van metingen en modellen op een ander vlak liggen, is een gecombineerde inzet aanbevolen zodat ze elkaar versterken bij de analyse.
- Voer (mits praktisch haalbaar) een proef uit door een langere periode niet te baggeren (1 – 3 maanden) en te verspreiden vanaf de huidige locatie. Hierdoor leren we meer uit de meetdata over de afstand en duur van de invloed van het baggerwerk op de troebelheid.

1 Introduction

In the navigation channel near Holwerd and in Dantziggat near Ferwerd two monitoring stations have been installed to measure local flow and turbidity. The first analysis of these data has been carried out in 2023 and has been reported in memo (Bi and Van Kessel, 2023). Since then, the monitoring has continued.

The objective of the present memo is to extend the previous analysis by using longer time series of reprocessed data and including ambient hydro-sedimentary data.
The analysis aims at:
- a better understanding of mud dynamics in the tidal basin of Ameland and locally near Holwerd and Ferwerd;
- to quantify the local impact of dredging on turbidity.

The analysis is first and foremost based on the frame data from Holwerd and Dantziggat, but is also supported by additional data sources such as MWTL suspended particulate matter (SPM) measurements, SIBES bed sediment sampling, meteorological measurements, and the logging of dredging and disposal works in the fairway.

The setup of this memo is as follows. In Section 2 follows a factual description of the data. Section 3 presents the data analysis. Section 4 includes conclusions and recommendations on further monitoring and data analysis.

2 Data description

This analysis is focused on the data that is collected at the measurement stations at Holwerd (X_{RD} = 182 200 m, Y_{RD} = 599 400 m) and Dantziggat (X_{RD} = 187 580 m, Y_{RD} = 601 400 m). In addition, several other datasets are used to investigate the role of ambient conditions and sediment availability. Figure 2.1 shows the locations of the measurement stations.

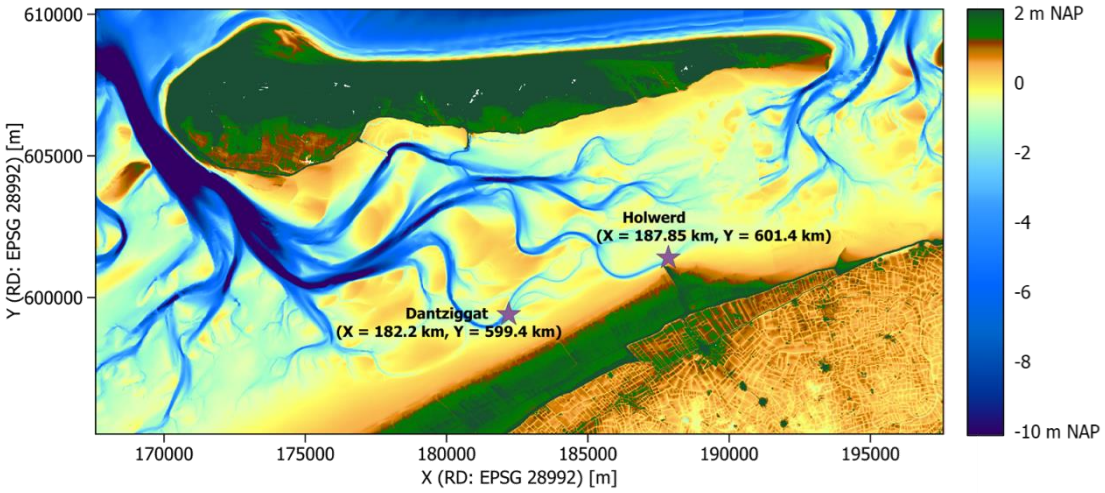

Figure 2.1: Location of measurement stations Holwerd and Dantziggat in the Wadden Sea, south of Ameland.

2.1 Observation points Holwerd and Dantziggat

2.1.1 Available data

The measurement stations at Holwerd and Dantziggat are operational since July 2022. Both measurement stations contain an ADCP, an MPP, and an STB instrument, and a second MPP sensor is installed at Dantziggat. The ADCP instrument measures flow velocities and flow directions at different heights. The MPP instruments measure conductivity, concentration chlorophyll-a, turbidity, water temperature, concentration oxygen, and saturation level oxygen. The STB instrument is used for records of the water level and the wave conditions (i.e., wave height and period). Bi & Van Kessel (2023) provide a more detailed description of the quantities that are measured with these instruments.

In the current analysis, we work with the data collected between July 2022 and October 2024. The data for the period between July 2022 and May 2023 was already part of the analysis in 2023 (Bi & Van Kessel, 2023). Improvements in the processing of the raw data have caused changes in the dataset compared to the data that was reported in 2023. Most notably is a change in the procedure by which the velocity data in the ADCP bins above the water surface are removed. The updated data is downloaded from an online server with the help of Rijkswaterstaat-CIV.

The height of the MPP instrument at Holwerd and the height of the STB instrument at Dantziggat have changed in June 2023. The height of the MPP instrument at Holwerd was changed from –1.16 m NAP to –1.81 m NAP. This implies that the conductivity, concentration

chlorophyll-a, turbidity, water temperature, concentration oxygen, and saturation level oxygen are measured at a different height after June 2023. The height of the STB instrument at Dantziggat was changed from −2.19 to −2.56 m NAP.

The turbidity measurements are converted into timeseries of the suspended sediment concentration (SSC) by a calibration curve that is developed by an extensive calibration procedure by Rijkswaterstaat-CIV. Over 20 sediment samples were collected per measurement location during 6 different days in 2023 and 2024. The concentrations sand, mud and total suspended matter are determined for these samples, and compared to the turbidity measurements by the MPP sensor. The resulting calibrations curves are shown in Figure 2.2. These illustrate that the SSC at Holwerd follows from multiplying the measured turbidity by 1.8225, and the SSC at Dantziggat follows from multiplying the measured turbidity by 1.9016. Note that these calibration curves have changed compared to the previous study in 2023, such that according to the current calibration the SSC at Dantziggat was overestimated in the study in 2023.

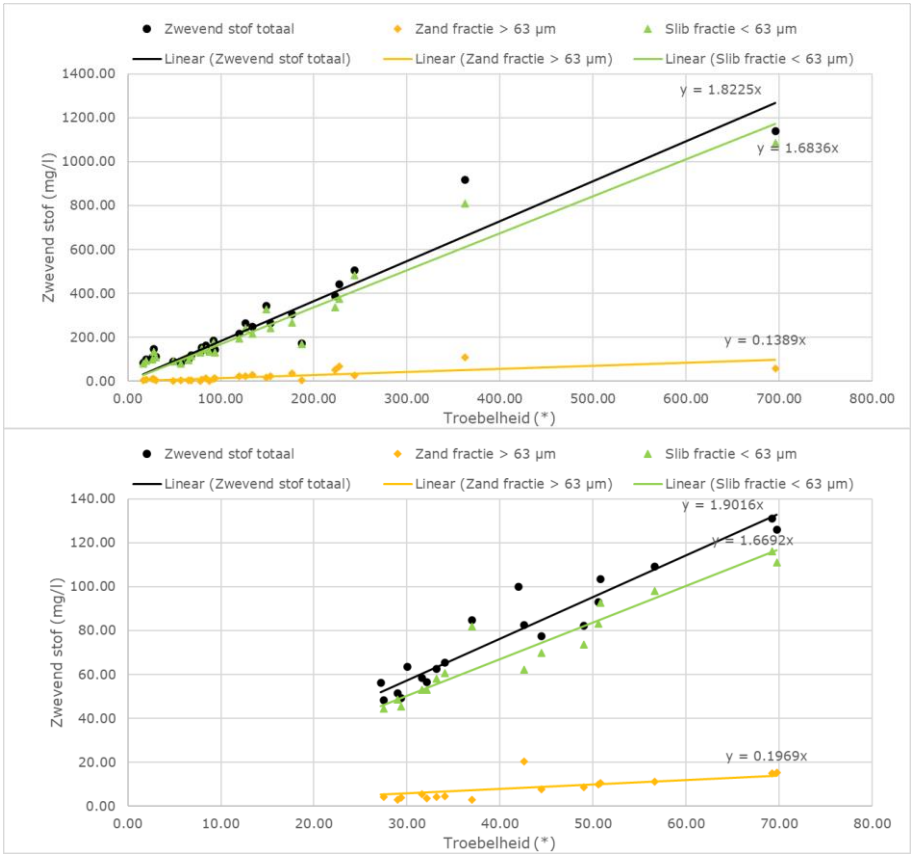

Figure 2.2: Calibration curve for the turbidity sensors at Holwerd (upper window) and Dantziggat (lower window). These calibration curves are used to convert the measured turbidity into SSC.

2.1.2 Data processing

Two different algorithms have been used to remove outliers in the data. The first algorithm is the Interquartile Range (IQR) method, which is effective in removing the outliers in cyclical data, such as in tidal current velocities (see Figure 2.3 for an example). The IQR method is a commonly used method in data processing. The main idea is to remove the data points that exceed the predetermined lower and upper bounds, that are determined from:

$$Lower\ Bound: Q1 - k \times IQR$$
$$Upper\ Bound: Q3 + k \times IQR$$
$$IQR = Q3 - Q1$$

where Q1 and Q3 are the first and the third quartile, respectively, and k is a user defined parameter that can control the lower and upper bounds, for which the default value is 1.5.

Another algorithm that is used in the processing of the data focuses on evaluating each data point based on its changes relative to neighbouring points. If the changes exceed a certain threshold, the data point is marked as an outlier. The underlying assumption of this approach is that natural processes often evolve gradually, and significant deviations from this pattern are likely to be anomalies. To be adaptive to the local characteristic of the data, a rolling window is utilized, the threshold for identifying outliers is computed each time using either the z-score (i.e. the number of standard deviations above of below the mean value) or IQR method. After initial evaluation, an additional check is performed, in which a small amount of 'floating' data points is removed. These 'floating' data points are disconnected from the rest of timeseries because their neighbours are identified as outliers in the previous steps. An example of data processing can be found in Figure 2.4. To process the data, the outlier-removing algorithms are applied with consideration of the temporal patterns of the original variables. The measurements with the MPP sensors show signs of biofouling (also discussed in Bi & Van Kessel, 2023).The data in those periods are also removed during the processing steps.

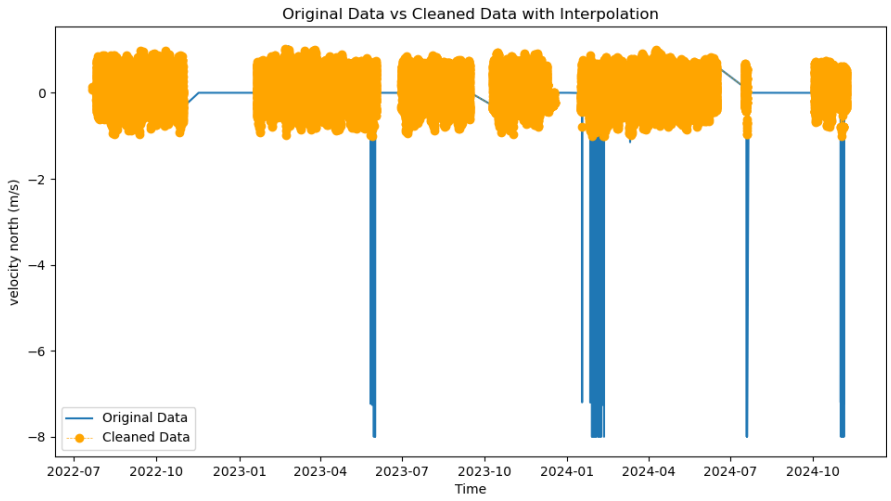

Figure 2.3. An example of applying the IQR method to the measured northward velocity at Holwerd.

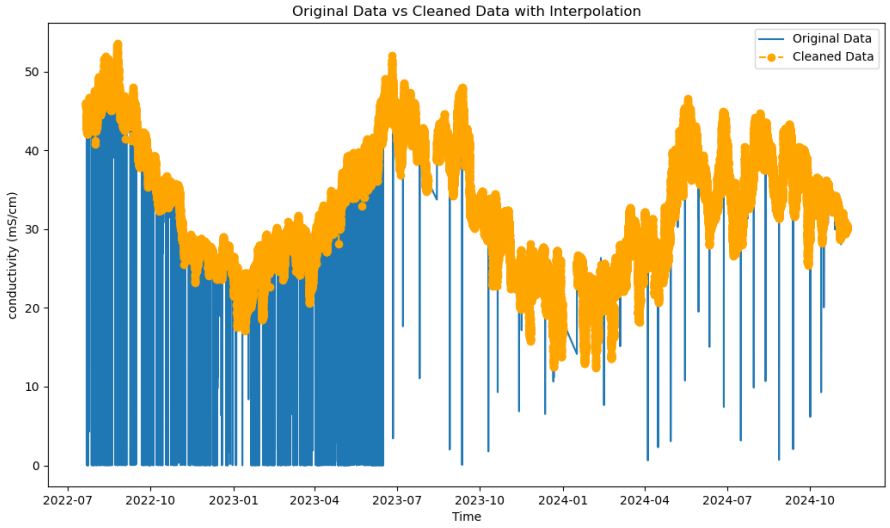

Figure 2.4. An example of applying the algorithm based on evaluating neighbouring data points with adaptive threshold.

2.2 Additional datasets

Several other datasets than the measurements at Holwerd and Dantziggat are used for the analysis of these measurements. These datasets are briefly introduced in this section.

Ambient conditions

Part of the data analysis focuses on variations with meteorological conditions, such as the wind speed and direction, for which we use KNMI observations at Hoorn, Terschelling. The meteorological data is downloaded from the data portal of KNMI (https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens). Figure 2.5 shows wind roses for measured wind conditions in 2022, 2023 and in Jan-Oct 2024. The wind roses illustrate the dominant southwestern wind direction. In 2022, winds were relatively often from the south. In 2023, an exceptional storm from the east occurred in October. 2024 is so far characterised as a year with relatively frequent winds from the dominant southwestern wind direction, but also winds from the east-northeast were measured relatively frequently.

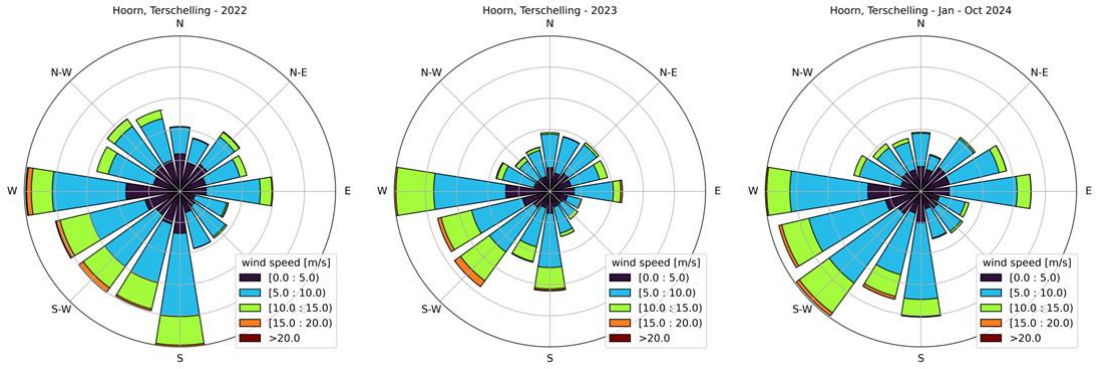

Figure 2.5: Wind roses for measured wind conditions at KNMI station Hoorn, Terschelling for the periods 2022 (left window), 2023 (middle window) and Jan-Oct 2024 (right window).

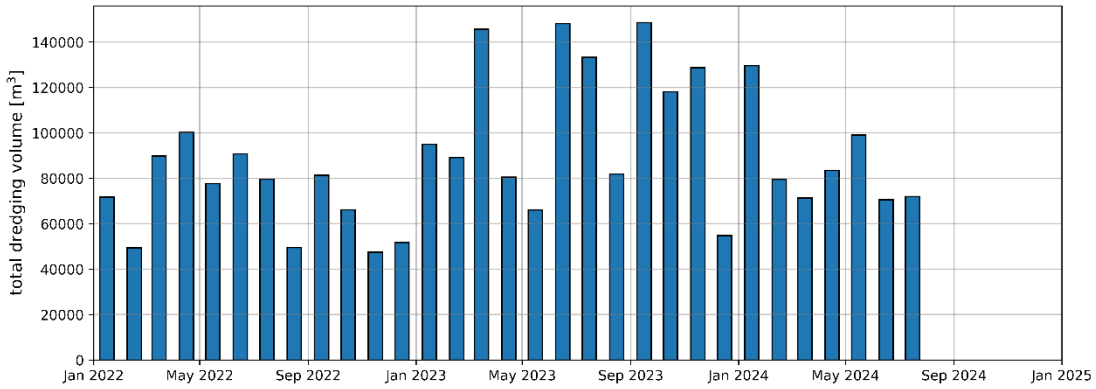

Figure 2.6: Histogram of dredging volumes in the areas 'Westkant' (Baggervak: 1.7.3.1.4.3), 'Rijkssteiger' (Baggervak: 1.7.3.1.4.2), 'Veerdienst deel' (Baggervak: 1.7.3.1.4.1) and 'Holwerd - VA33 (KP) ' (Baggervak: 1.7.3.1.1) from January 2022 until July 2024.

Maintenance of the fairway

The dimensions of the fairway between Holwerd and Ameland are maintained by means of maintenance dredging. The moments and locations of dredging and disposal are, together with the related sediment volumes, retrieved from the Reizen database. This database is maintained and provided by Rijkswaterstaat-NN. Since January 2022, the dredging volumes have been particularly high in March, June, July, September, October and November 2023, and in January 2024 (Figure 2.6).

Ferry crossings

We investigate the role of ferry crossings on the turbidity at Holwerd and Dantziggat based on the AIS data of the different ferries that are connecting Holwerd and Nes, Ameland. The AIS data is provided by Informatiepunt WVL of Rijkswaterstaat.

Bed sediment composition

The composition of the sediment bed in intertidal areas in the Wadden Sea is determined as part of the SIBES monitoring (Bijleveld et al., 2012). The SIBES sampling is carried out yearly since 2008. The most recent data on the bed composition that is currently available is based on sampling in 2023. The SIBES data is provided for this study by NIOZ with reference SIBES-2024-08.

Figure 2.7 shows the mud fraction in the top layer of the sediment bed in the years 2018-2023. These maps suggest that the amount of mud in the bed in 2022 and 2023 is lower than in previous years. This is particularly clear at the intertidal areas along the Frisian coast, where the mud content is around 20% in the sampling of 2022 and 2023, but around 40% in the sampling of 2018-2021.

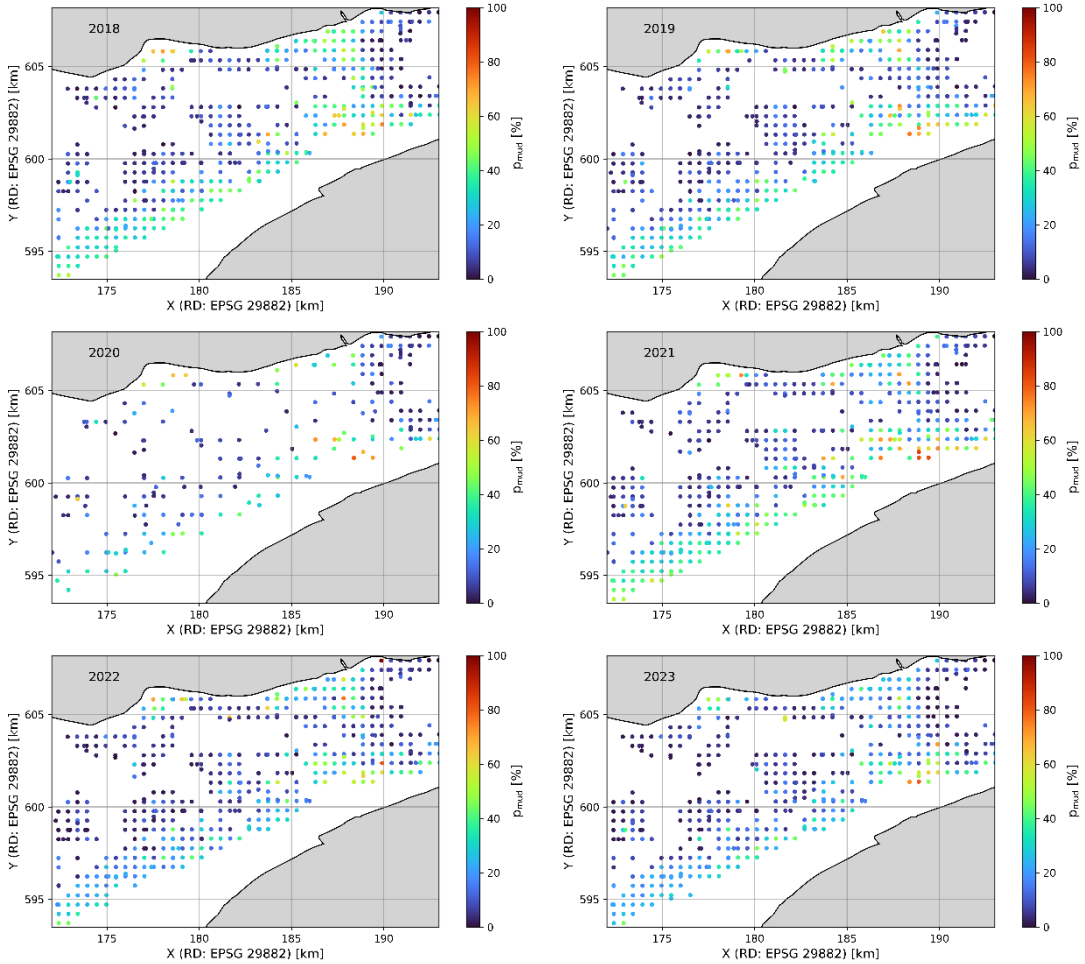

Figure 2.7: SIBES data of the mud fraction in the top layer of the sediment bed (p_{mud}) in the part of the Wadden Sea south of Ameland for the years 2018-2023.

MWTL measurements

The MWTL measurements of suspended particulate matter (SPM) provide a consistent dataset for the long-term SPM concentration (i.e. SSC) variations at several stations in the Wadden Sea since 1989. Sampling is carried out every 2 to 4 weeks, at approximately the same moment in the tidal cycle. The MWTL measurements provide insights into long-term trends in SPM in the Wadden Sea, for which we refer to Herman et al. (2018). The MWTL measurement station DANTZGT is located in the Dantziggat channel, close to the measurement station Dantziggat that is installed in 2022. The MWTL data is downloaded from https://waterinfo.rws.nl/ using the ddlpy API (see https://github.com/Deltares/ddlpy).

Figure 2.8 shows the SPM measurements at DANTZGT since 1989. In 2022, which is the first years of permanent measurements at measurement stations Holwerd and Dantziggat, the yearly mean SPM at DANTZGT was relatively low compared to previous years, in particular compared to the relatively high SPM in 2021. The mean SPM in 2023 is similar to the mean SPM over the last +/- 10 years.

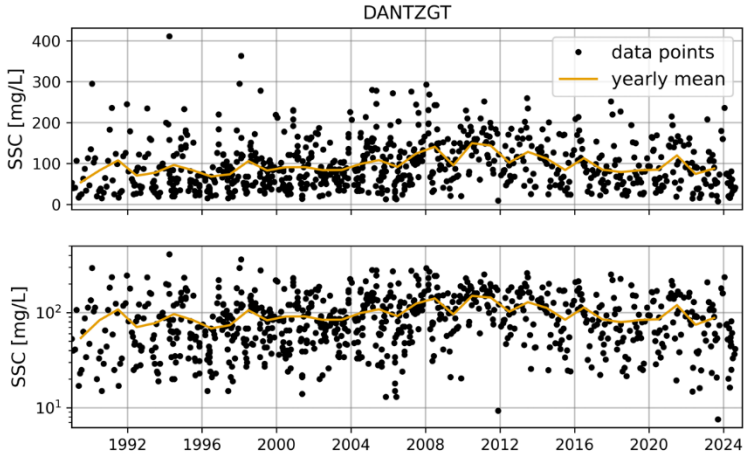

Figure 2.8: MWTL measurements of suspended particulate matter (SPM) at station DANTZGT since 1989. The black dots show the individual measurements and the orange line connects the yearly mean between years. The bottom panel shows the same data as the top panel, but on a logarithmic instead of on a linear scale.

3 Analysis of data

3.1 Observed SPM dynamics

At short timescales (i.e., during tidal periods), the turbidity at Holwerd and Dantziggat is largely governed by the tidal currents at the respective locations. The turbidity signal generally peaks at peak flood velocity and at peak ebb velocity, as illustrated in Figure 3.1. At Holwerd, the flood current is directed to the east-northeast and the ebb current is directed to the west-southwest. At Dantziggat, the orientation of the channel causes the flood current to be directed to the north-northeast and the ebb current to the south-southwest. The orientation of the flood- and ebb current varies slightly with the wind conditions, such that the current turns in downwind direction (not illustrated). The measured flow velocities at Holwerd are slightly higher than at Dantziggat. Measured turbidity peaks at Holwerd are typically about two times as high as measured turbidity peaks at Dantziggat (note the different scales of colorbars in Figure 3.1), although the ratio varies between different seasons in the measurement period.

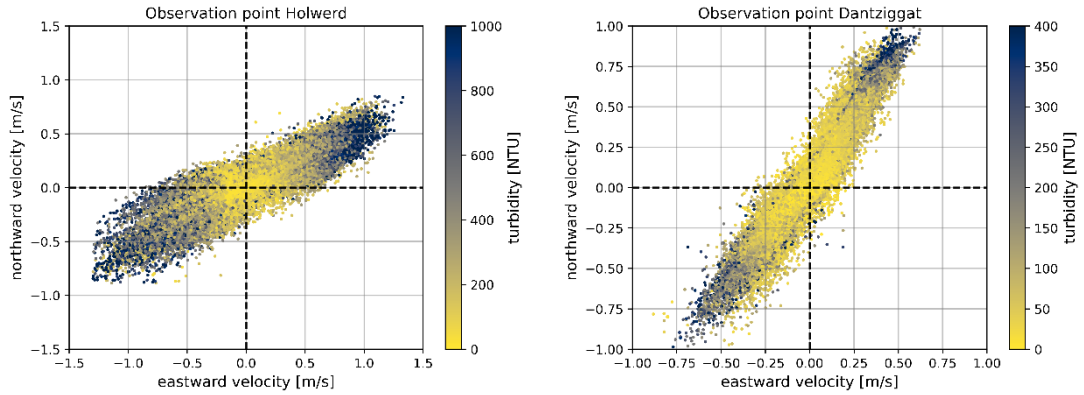

Figure 3.1: Scatterplot of the turbidity at measurement stations Holwerd (left window) and Dantziggat (right window; upper turbidity sensor) relative to the magnitude and orientation of the measured velocities.

Next to the tidal variations in turbidity, wave driven resuspension may increase the turbidity. At the observation points in the channels, however, we don't see a strong correlation between the measured (significant) wave height and the turbidity, such that variations in the wave

height in itself do not cause a variation in the observed turbidity. The largest waves are measured during high water, when not only the local water depth is large, but also the fetch is large due to the flooding of intertidal areas. This is illustrated for the measurements at Dantziggat in Figure 3.2. The relation between the water level and the wave height typically prevents the large wave heights to occur at the same time as the (tidal) velocity peaks. This is illustrated in Figure 3.3: The largest waves are observed during mild currents in flood direction, conditions during which the turbidity is relatively low. The variation in turbidity with the current velocities is much stronger than with the observed wave height.

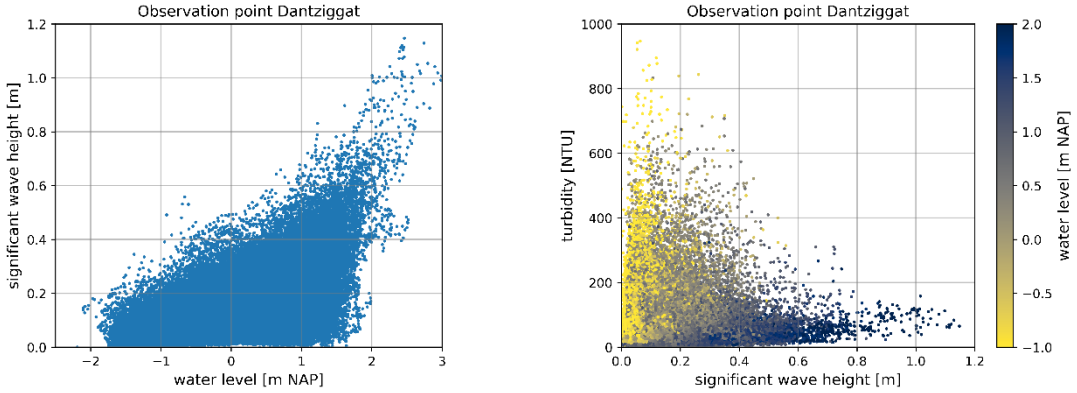

Figure 3.2: Scatterplots of the correlation between the water level and the significant wave height (left panel) and of the correlation between the significant wave height and the turbidity (right panel; upper turbidity sensor) at measurement station Dantziggat for the full measurement period.

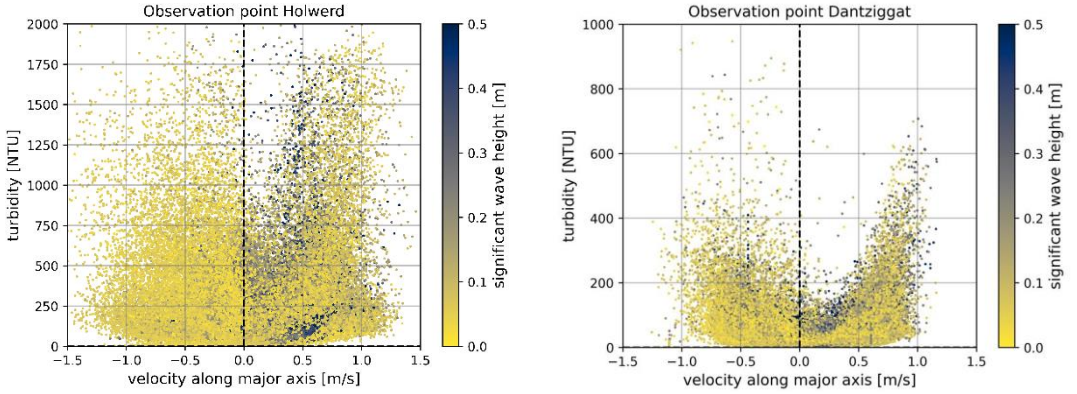

Figure 3.3: Scatterplot of the measured velocity along the channel direction (positive in flood direction; negative in ebb direction), the turbidity and the significant wave height at measurement stations Holwerd (left window) and Dantziggat (right window; upper turbidity sensor).

Figure 3.3 also shows that the turbidity during flood correlates better with the flow velocity in the channel than the turbidity during ebb. The variation in turbidity during ebb is expected to be due to the amount of sediment resuspension at the shallow (intertidal) areas during high water. The sediment resuspension is more relevant at the shallow areas than in the deep channels, as the surface waves will only generate a significant shear stress at the bottom in case the waves are relatively large compared to the local water depth. The turbidity at both Holwerd and Dantziggat is therefore shown relative to the wind conditions in Figure 3.4. The turbidity peaks during strong winds that are aligned with the orientation of the flood (from SW) and of the ebb (from NE) currents. With winds from the S-SE (i.e., coming from the intertidal areas and salt marshes along the mainland coast), the turbidity is already relatively high for low wind speeds.

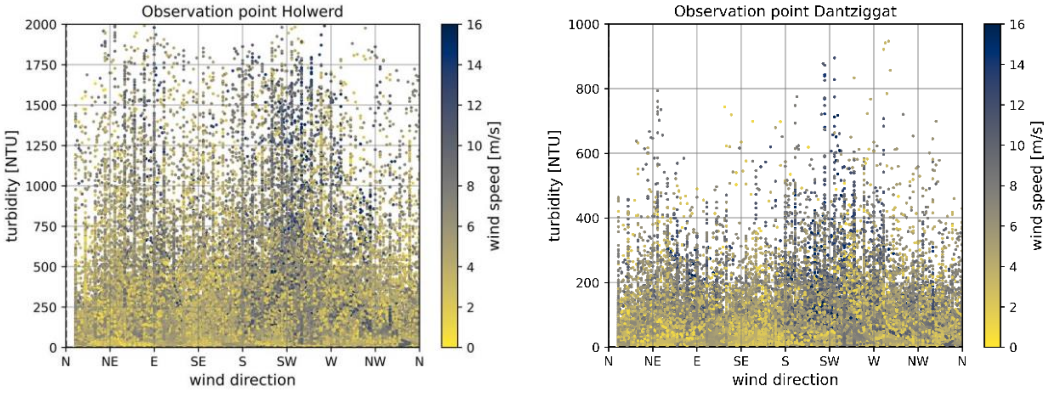

Figure 3.4: Scatterplot of the measured turbidity at measurement stations Holwerd (left window) and Dantziggat (right window; upper turbidity sensor) for the full measurement period relative to the measured wind conditions at Hoorn, Terschelling.

3.2 Transport rates

Using the measured flow velocities and turbidity, and together with the calibration from turbidity to suspended sediment concentrations (see Section 2.1), the sediment transport rates are computed as fluxes at the height of the turbidity sensor. This is illustrated for the measurements at Holwerd and Dantziggat in Figure 3.5. Note that the results for Holwerdare affected by the fact that the velocity measurements at Holwerd include gaps during low water, when the currents and the suspended sediment transport are typically directed towards the west-southwest. Figure 3.5 illustrates the occurrence of large transport rates when the turbidity is large during peak velocities in both ebb and flood direction, as was already suggested in Figure 3.1 and Figure 3.3. The peak transport rates at Holwerd are several times higher than the peak transport rates at Dantziggat.

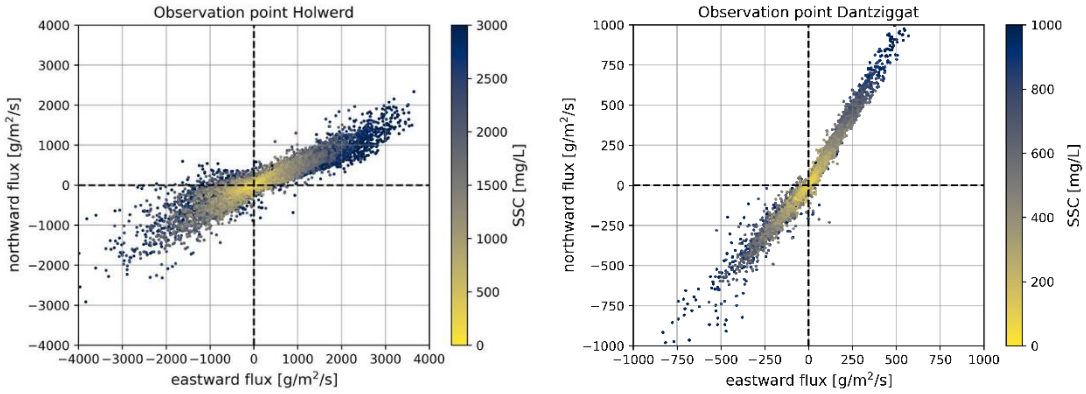

Figure 3.5: Scatterplot of the suspended sediment transport rate at measurement stations Holwerd (left window) and Dantziggat (right window; upper turbidity sensor) for the full measurement period.

The mean transport rates over the tidal periods indicate the residual suspended sediment transport direction. For this, tidal periods are defined as the period of the semidiurnal M2 constituent (i.e., T = 12 hours and 25 minutes), starting at high water at Holwerd. The measured residual transport at Holwerd is directed in flood direction, although this is affected by the gaps in the velocity measurements during low water. The measured residual transport at Dantziggat is also directed in flood direction. Figure 3.6 illustrates the variation in the mean transport rate with the wind conditions. The largest mean transport rates in flood direction are measured during relatively strong (w_{sp} > +/- 10 m/s) winds from the west-southwest. During some exceptional wind events, the mean transport rates are 1 to 2 orders of magnitude higher than during usual conditions. The large residual transport rates in ebb direction are measured

during strong winds from the east-northeast, i.e., when the wind is directed from the tidal divide of Ameland towards Holwerd. The variation in the residual transport rates with the wind conditions is stronger at Holwerd than at Dantziggat, where large residual transports in ebb direction also occur during winds from the west-southwest. Interestingly, it follows form Figure 3.6 that some high residual transport rates in flood direction at Holwerd are measured during mild winds from the southeast. The turbidity is relatively high during these periods, which may be due to the (residual) transport of mud from the shoals (and marshes) along the mainland coast towards the channels, or because the turbidity remains relatively high after more energetic conditions in the preceding days.

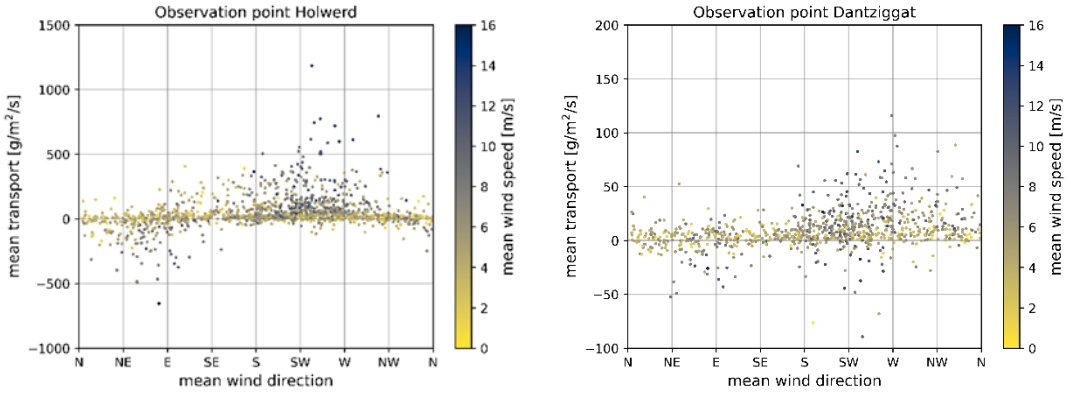

Figure 3.6: Scatterplot of the variation in the mean suspended sediment transport rate per tidal period at measurement stations Holwerd (left window) and Dantziggat (right window; upper turbidity sensor) with the wind conditions. Positive values are directed in the flood direction; negative values are directed in the ebb direction.

3.3 Variations in SPM over time

The turbidity measurements since July 2022 show variations in SPM between spring-neap periods, seasons and years. The variation over spring-neap periods is illustrated for measurement in Figure 3.7: the SPM concentrations typically peak during spring tide, and are much lower during neap tide.

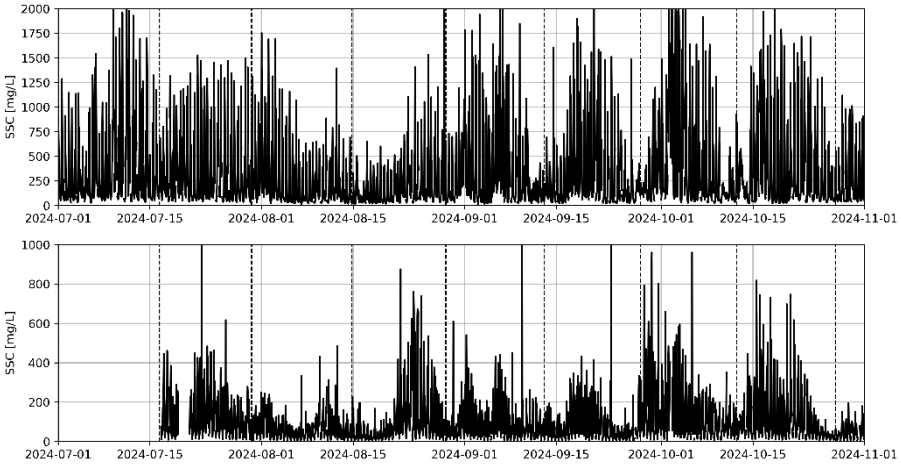

Figure 3.7: Timeseries of the SSC measurements at Holwerd (top window) and Dantziggat (bottom window; upper turbidity sensor) from July until October 2024. The vertical dashed lines indicate neap tides (occurring 5 days before full moon and new moon).

The variation between spring-neap periods at Holwerd and Dantziggat is illustrated in Figure 3.8 and Figure 3.9, respectively. Note that the SSC measurements at Holwerd before and after June 23rd, 2023 are inconsistent because of lowering the turbidity (MPP) sensor. These figures show that the SSC in autumn 2023 and winter 2023-24 has been larger than in autumn 2022 and winter 2022-23. In general, the SSC was low in the second half of 2022, which is in agreement with the relatively low SSC in MWTL measurements at DANTZGT in 2022 (discussed in Section 2.2). Also, the SIBES data suggests that the amount of mud in the seabed was relatively low in 2022, until at least the sediment sampling in June and July 2023. Although the SSC at Holwerd from October 2023 until May 2024 cannot be quantitatively compared to the year before, the high SSC levels during this period are clear from Figure 3.8.

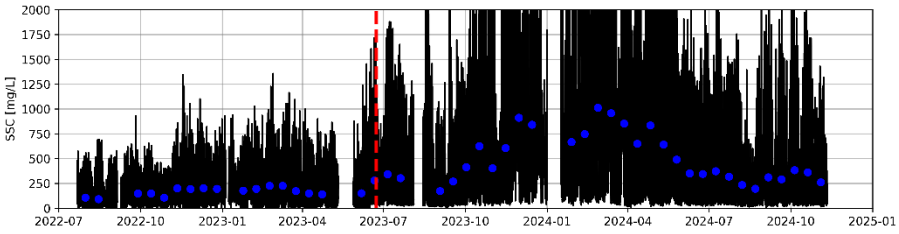

Figure 3.8: Timeseries of the SSC measurements at Holwerd for the full measurement period. Blue dots indicate the mean SSC over spring-neap periods. The red dashed line at June 23rd, 2023 indicates the moment at which the turbidity sensor at Holwerd was lowered from –2.19 to –2.56 m NAP.

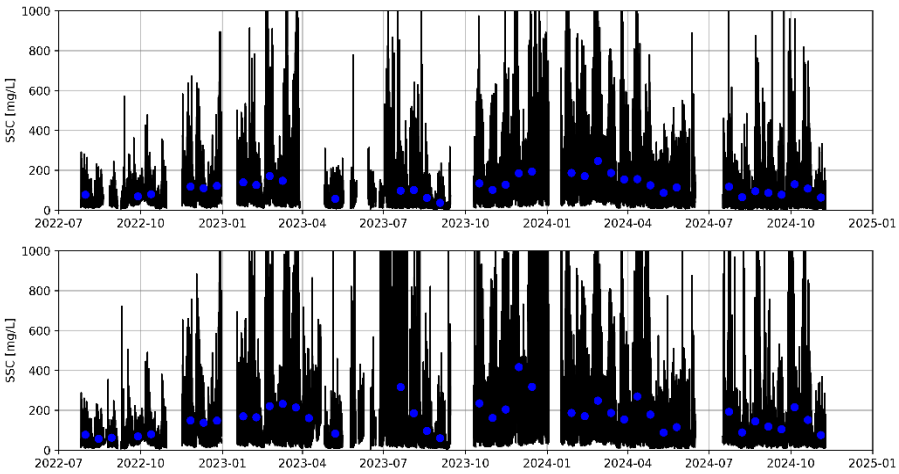

Figure 3.9: Timeseries of SSC measurements at Dantziggat at -0.5 m LAT (top) and at 1.0 m above the bed (bottom) for the full measurement period. Blue dots indicate mean SSC over spring-neap periods.

The high SSC in winter 2023-24 is likely caused by the amount of resuspension during energetic conditions. However, the measured wave conditions at Holwerd and Dantziggat (Figure 3.10) do not necessarily indicate that the amount of wave energy in this winter period was much higher than in other periods. Part of the variations over time can be explained by the relation between the wind conditions and the residual transport rates, which was discussed in the previous section. The increase in turbidity in October 2023 coincides with a period of persistent winds from the east, including the passing of a storm on October 20th and 21st. The observed wind speeds during this storm were not exceptionally high, but the storm was exceptional because of its direction. The event is represented in the wind roses in Figure 2.5 as the only moment during the measurement period in which winds from the east larger than 15 m/s were measured. The large residual sediment transport towards the west during this period may have increased the turbidity at Holwerd for a longer period, as sediment was kept in suspension during the winter conditions in the subsequent months. The turbidity only reduces when wind conditions became milder in May 2024.

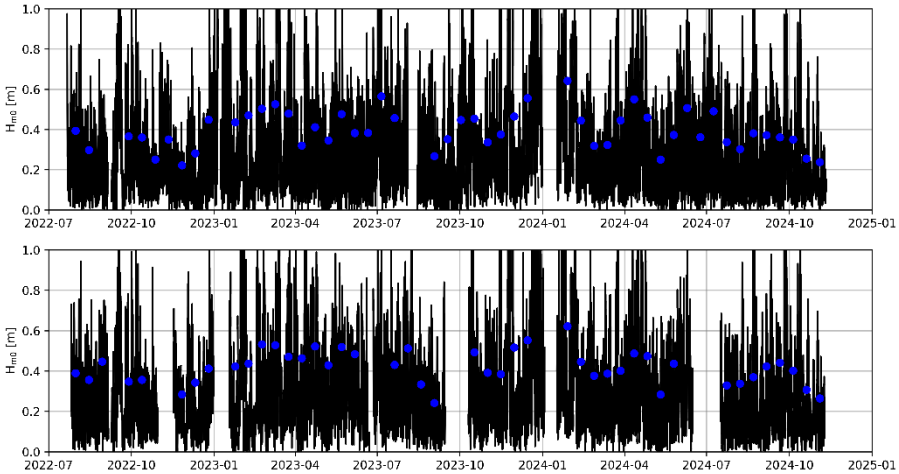

Figure 3.10: Timeseries of the significant wave height (H_{m0}) at Holwerd (top) and Dantziggat (bottom) for the full measurement period. Blue dots indicate the 80th percentile values of H_{m0} over spring-neap periods.

The conductivity measurements at the measurement stations at Holwerd and Dantziggat do not indicate important salinity differences between winter 22-23 and winter 23-24, which may be due to different amounts of freshwater being discharged into the Wadden Sea, affecting the (residual) sediment transport in the Wadden Sea.

3.4 On anthropogenic influence: maintenance dredging and navigation

Holwerd serves as an important ferry terminal, connecting the mainland to the island of Ameland. The regular movement of ferries, along with the necessary maintenance dredging to keep the navigation channels open, may influences local turbidity. These activities can resuspend sediment and introduce additional sediment into the water, complicating efforts to distinguish between natural turbidity and an increase by human actions. If the frequency of these human activities is relatively low, it may be possible to observe differences between periods of activity and inactivity, providing clearer insights into their impact. However, if the frequency is high, the continuous disturbances make it difficult to separate the human-induced changes from the baseline turbidity, obscuring the true extent of their influence on sediment concentrations. To help with the understanding, selecting another monitoring site at Dantziggat, which remains largely undisturbed by human activities, is meaningful. This site can serve as a control, providing a baseline for comparison against the impacted site at Holwerd. This comparative approach will help to isolate and quantify the specific effects of human activities on the ecosystem, leading to more accurate and reliable findings.

3.4.1 Influence of dredging and disposal

To understand the influence of dredging and disposal operations near the Holwerd (HO) pier, the monitoring data has been regrouped with the following steps:

- Focus on specific dredging areas: Identify and focus on dredging/disposal operations at specific locations, namely 'Westkant' (Baggervak: 1.7.3.1.4.3), 'Rijkssteiger' (Baggervak: 1.7.3.1.4.2), 'Veerdienst deel' (Baggervak: 1.7.3.1.4.1) and 'Holwerd - VA33 (KP) ' (Baggervak: 1.7.3.1.1).
- In the dredging/disposal dataset, select the data entries that their “Baggervak” column contain one of the focused areas. Each selected data entry represents a dredging/disposal cycle, in which the dredging operation always happened near the

Holwerd pier, whereas the disposal may be carried out in the same location or in other designated areas, such as Scheepsgat or Zuiderspruit.

- Obtain the time window of dredging/disposal cycles: For each selected cycle, record the start and end time. To account for the potential prolonged influence on SPM concentration, an extra period of 3 hours that was determined from sensitivity analysis has been added to the ‘end time’. During each cycle, both dredging and disposal activities were carried out, so within the derived time window, the potential influences from both types of operations could be present.
- Select data points within dredging/disposal time windows: Choose data points (from ADV, MPP and STB datasets) within these specific time windows and label them as ‘presence of dredging/disposal’ or ‘disturbed’. These data points correspond to periods when dredging/disposal operations were actively occurring. Compute the ranges of velocity, water depth and significant wave heigh in the selected data.
- Select data outside of the dredging/disposal time windows: For comparison, select data points that are within the same ranges of velocity, water depth, and significant wave height, but are outside the dredging/disposal periods. Label these data points as ‘no dredging/disposal’ or ‘undisturbed’.
- Process Dantziggat data: Apply the same time windows to the monitoring data at Dantziggat (DZO), and use it as the control for the comparative analysis.

At HO, from August 1, 2023, to July 31, 2024, the number of data points in the 'disturbed' group is 19,387, while the 'undisturbed' group has 26,948 data points. At DZO in the same period, the 'disturbed' group has 16,098 data points, and the 'undisturbed' group has 21,161 data points. Thus, both groups have a sufficient number of data points to be used in the analysis. An example of the processed SPM concentration can be seen in Figure 3.11.

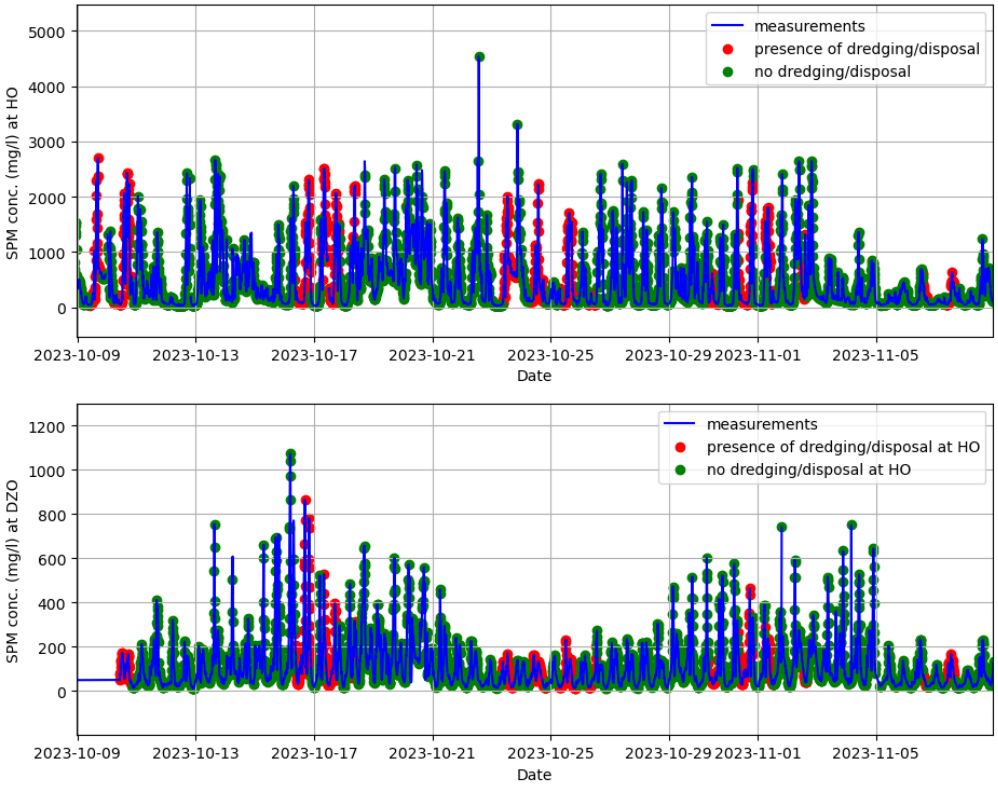

Figure 3.11. An example of processed SPM concentrations at HO (top) and DZO (bottom).

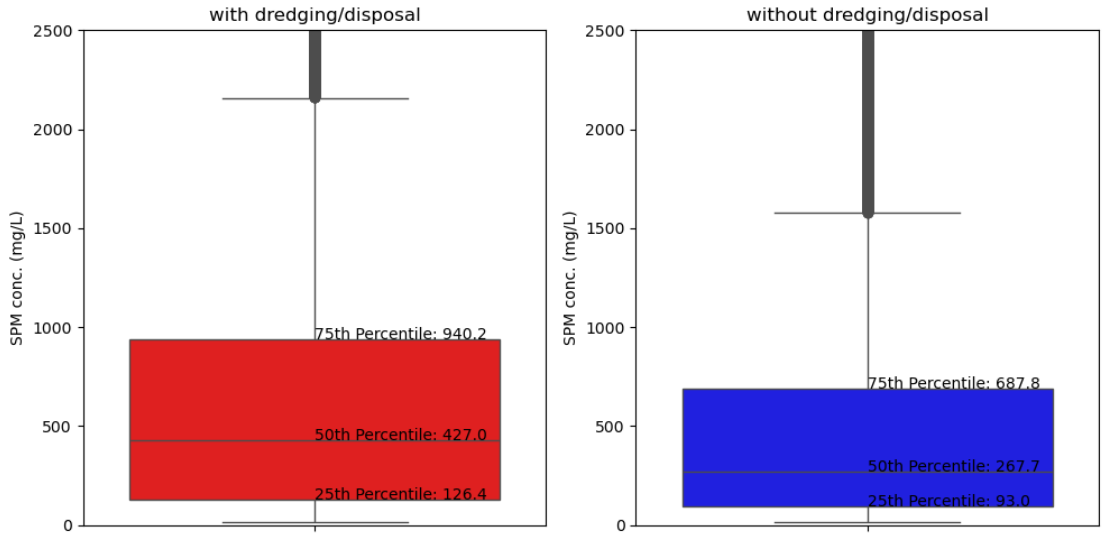

Figure 3.12. The box plot of SPM concentration at HO. The top and bottom edges are the third quartile (Q3) and the first quartile (Q1), respectively. The horizontal line within the box is the median or the 50th percentile of the data.

After separating the data into two groups, the influence of dredging and disposal can be identified from the statistical analysis performed on the whole dataset of one year (from 2023-08-01 to 2024-07-31). At Holwerd, the overall concentration is higher when dredging and disposal activities were carried out. In Figure 3.12, the majority of SPM concentrations measured during the presence of dredging/disposal are within the range of 126 – 940 mg/L with a median value of 427 mg/L, which is higher compared to the range of 93 – 688 mg/L and a median value of 268 mg/L without dredging/disposal. In contrast, at Dantziggat, the same analysis does not show such noticeable differences between the two groups of data (Figure 3.13). In the same period when dredging/disposal happened at Holwerd, the SPM concentration measured by the lower sensor at Dantziggat ranges between 55 – 224 mg/L with a median value of 108 mg/L, which is similar to the range of 55 – 222 mg/L and a median values of 112 mg/L without dredging/disposal.

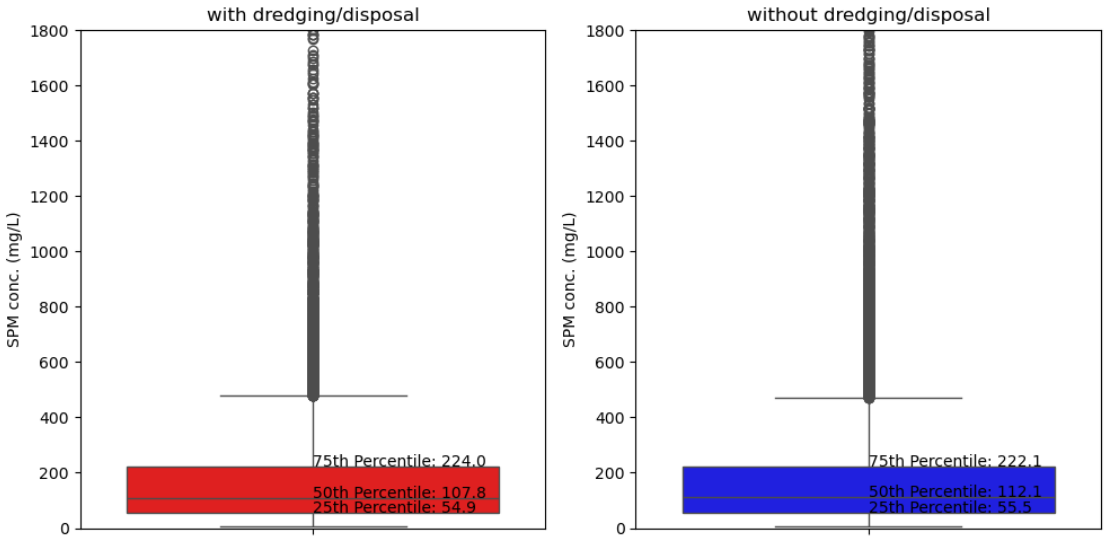

Figure 3.13. The box plot of SPM concentrations measured by the lower sensor at DZO.

In addition to the SPM concentration, the dissolved oxygen and chlorophyll-a concentrations are also considered in the comparative analysis (Figure 3.14 and Figure 3.15, Table 1 and Table 2). It can be seen that at HO, when dredging/disposal were taking place, the median values of SPM and Chlorophyll-a concentrations increased by 59.5% and 33.5%, respectively, whereas the dissolved oxygen slightly decreased by −3.8%. The correlation between SPM and Chlorophyll-a concentrations may indicate that the increase in both indexes could be originated from remobilization of bed sediments. At Dantziggat, within the same period, the changes in the mean SPM, dissolved oxygen and chlorophyll-a concentrations (measured by both sensors) were rather limited (within 4%) and even towards the opposite direction.

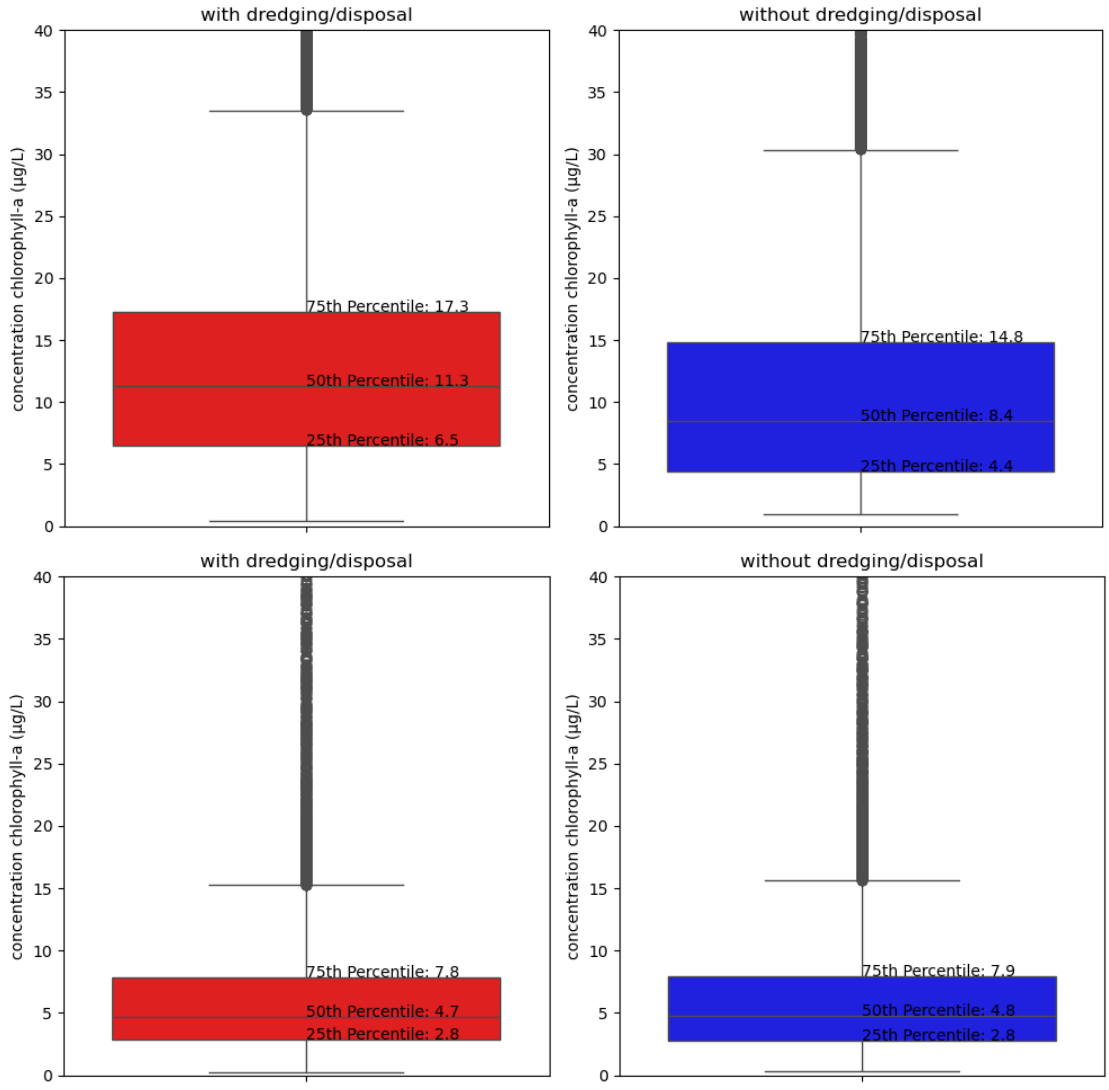

Figure 3.14. Comparison of chlorophyll-a concentration at HO (top) and DZO (bottom).

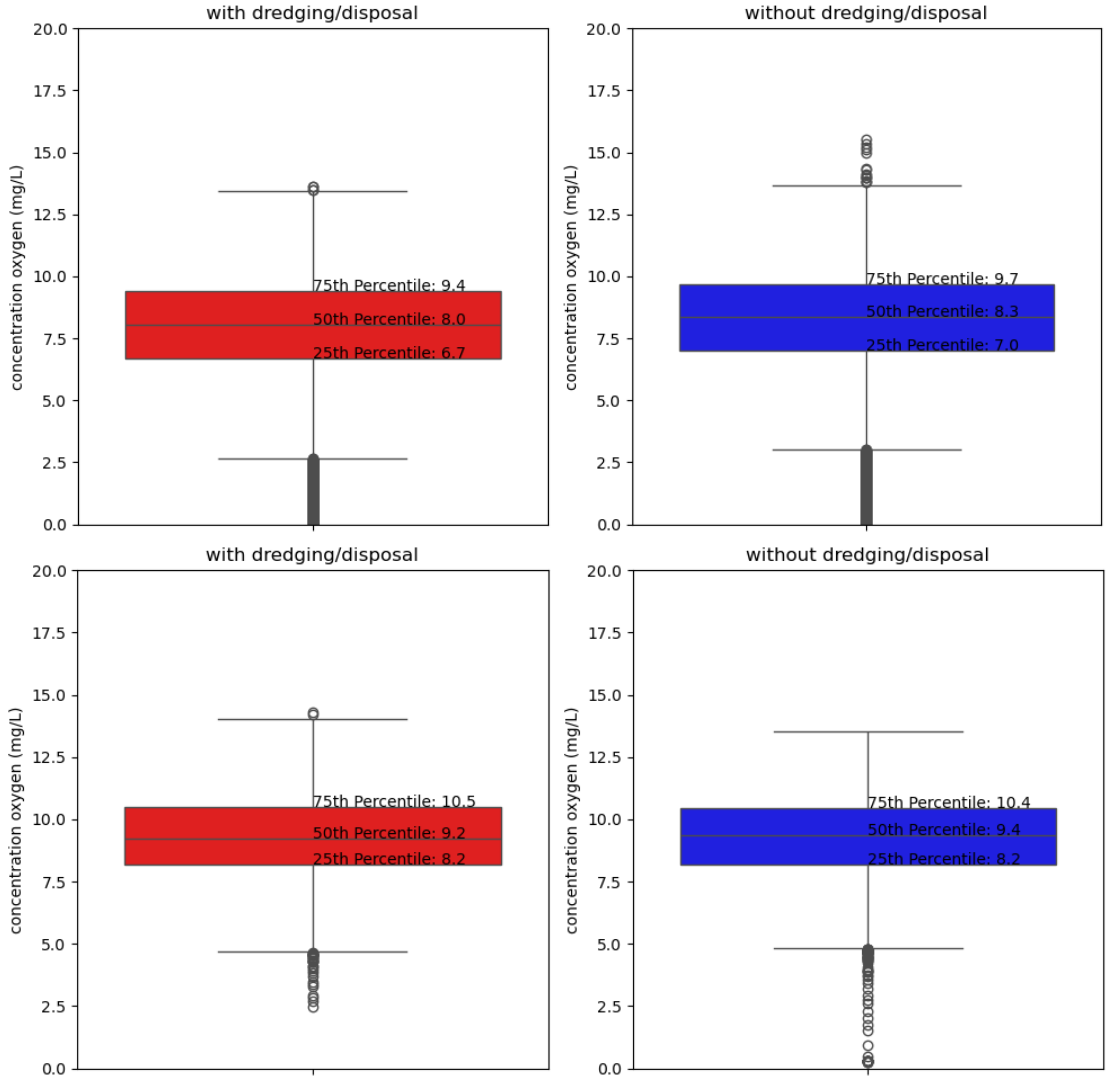

Figure 3.15. Comparison of dissolved oxygen concentration at HO (top) and DZO (bottom).

Table 1. Comparison of median values of water quality indexes at HO.

	HO (with dredging)	HO (without dredging)	Relative change
SPM concentration (mg/L)	427	268	59.5%
Chlorophyll-a (µg/L)	11.26	8.43	33.5%
Dissolved oxygen (mg/L)	8.03	8.35	-3.8%

Table 2. Comparison of median values of water quality indexes measured by the lower sensor at DZO.

	DZO (with dredging)	DZO (without dredging)	Relative change
SPM concentration (mg/L)	108	112	-3.8%
Chlorophyll-a (µg/L)	4.70	4.80	-2.1%
Dissolved oxygen (mg/L)	9.25	9.37	-1.3%

From the above comparative analysis, one can already see clearly the impact of dredging and disposal on the SPM, chlorophyll-a concentrations and possibly dissolved oxygen at Holwerd. One of the reasons could be that the frequency of these activities is relatively lower than the frequency of natural variations, hence, the system can still move from the disturbed state towards the nature state in between. This could also explain why the SPM concentration at

HO is generally higher than at DZO, potentially indicating an influenced background SPM concentration due to disturbance.

Further examination reveals that the level of impact from dredging and disposal at HO may vary between winter and summer months. Part of the reason is that the baseline of SPM concentration is higher in winter and lower in summer. This could be due to two factors: changes in resuspension and mixing caused by stronger currents, waves, and wind during winter; and changes in sediment and bed properties such as particle size, settling speed and compaction time. The disturbance from dredging and disposal activities may cause an increase in turbidity and a reduction in oxygen levels (Figure 3.16). This inversely relationship is often observed in ecosystems. Rising water turbidity limits light penetration through water, limiting aquatic photosynthetic potential and reducing oxygen content. It also means that gross primary production decreases with increasing turbidity. At HO, it is found out from the data that, when the SPM concentration is above 2000 mg/L, the high turbidity level could potentially lead to a sharp decrease in the dissolved oxygen concentration. In summer months, because the background SPM concentration is lower, the impact of dredging and disposal also becomes smaller (Figure 3.17). It still tends to increase the SPM and chlorophyll-a concentrations, but periods with low oxygen levels do occur much less frequent than in winter.

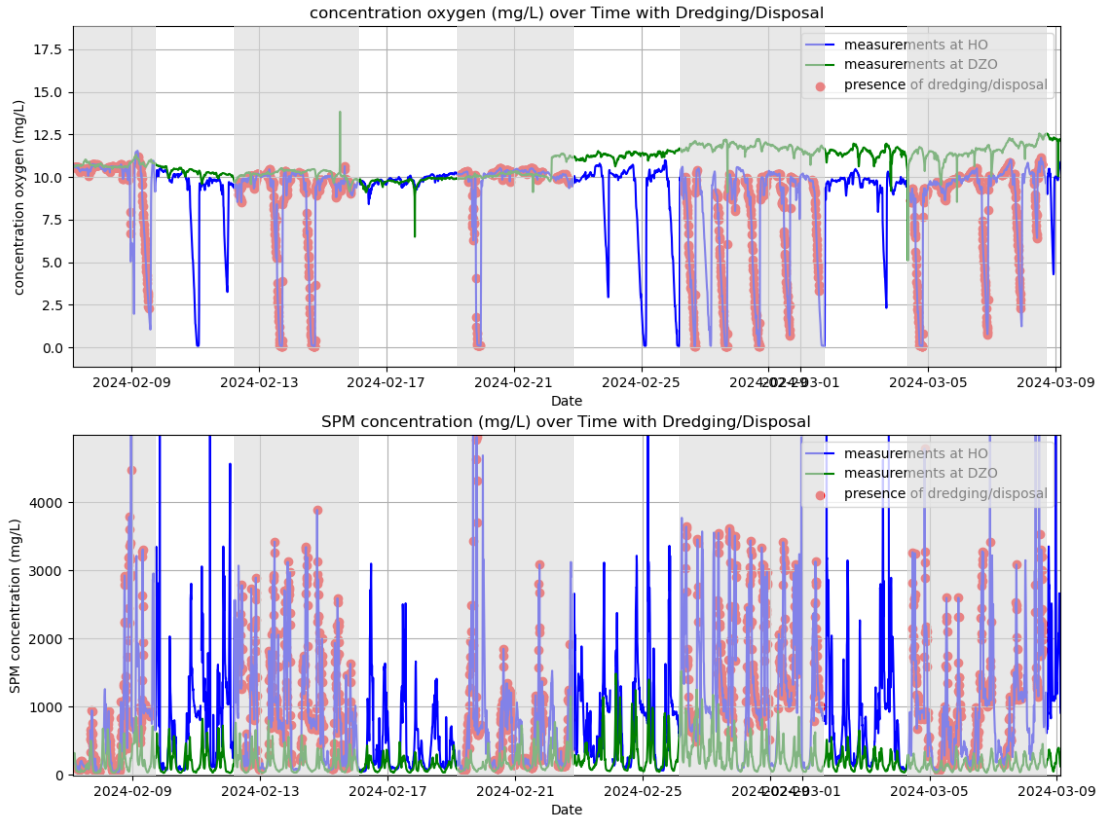

Figure 3.16. The comparison of dissolved oxygen and SPM concentrations in winter months. Light grey indicates the periods with influence of dredging/disposal.

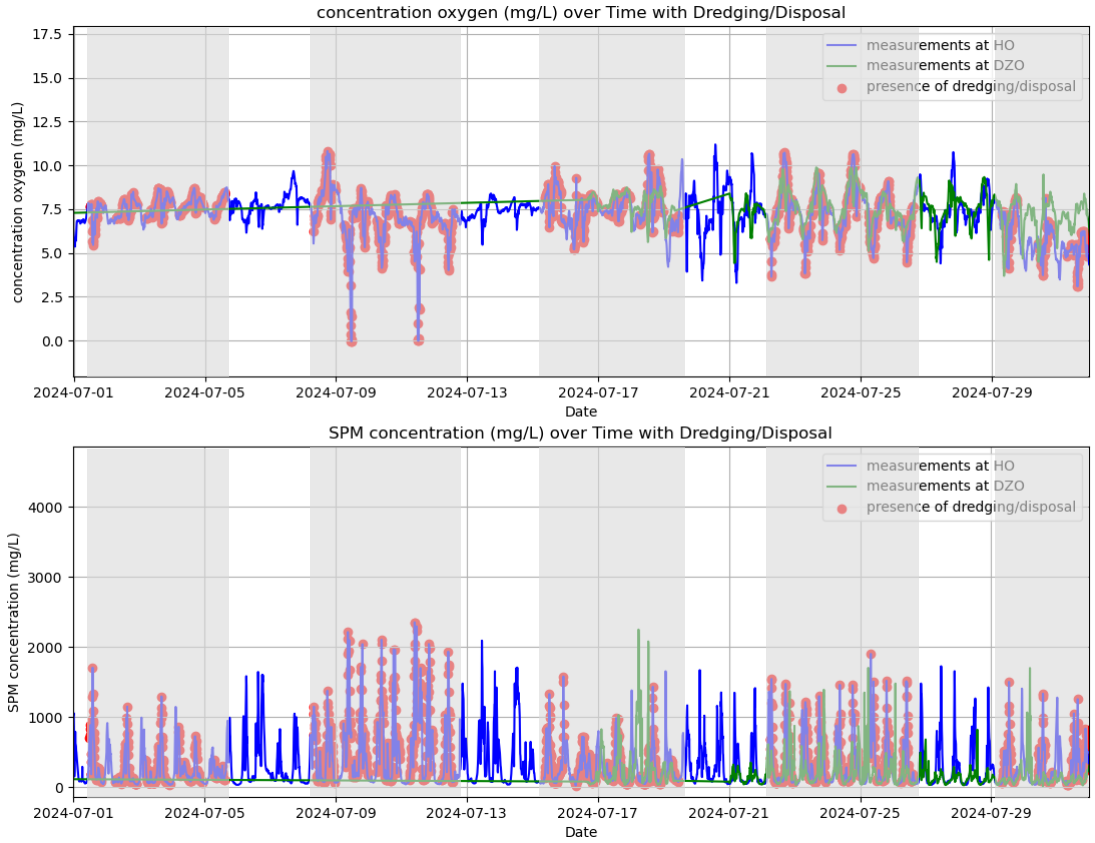

Figure 3.17. The comparison of dissolved oxygen and SPM concentrations in summer months. Light grey indicates the periods with influence of dredging/disposal.

To confirm the above findings, the same statistical analysis has been performed on the quarterly data within the period of one year (2023-08-01 to 2024-07-31) in order to show the potential changes over the seasons (Figure 3.18). It can be seen that the mean SPM concentrations during disturbed periods are always higher at HO, and the differences become larger when moving towards winter. In contrast, the same trend is not observed at DZO, where the differences between the disturbed and undisturbed periods are much smaller and sometimes the undisturbed value is even larger than the disturbed value.

In addition, to minimize the potential bias in the analysis and to reveal more information, relative changes of 25th, 50th and 75th percentiles are also computed and compared (Figure 3.19). In general, the change in percentiles indicates shifts in the distribution of the data. It can be seen at HO, when dredging/disposal was carried out, the overall SPM concentration distribution was shifting upward especially in winter, indicating general higher values during the disturbed periods. The relative change in the 75th percentile is greatest in winter and gradually decreases toward summer, indicating that dredging/disposal operations tend to cause larger and more frequent peak concentrations during winter, while in summer, the impact is more pronounced on the lower and mid-range values. This may also reflect the changes in the sediment properties over the seasons.

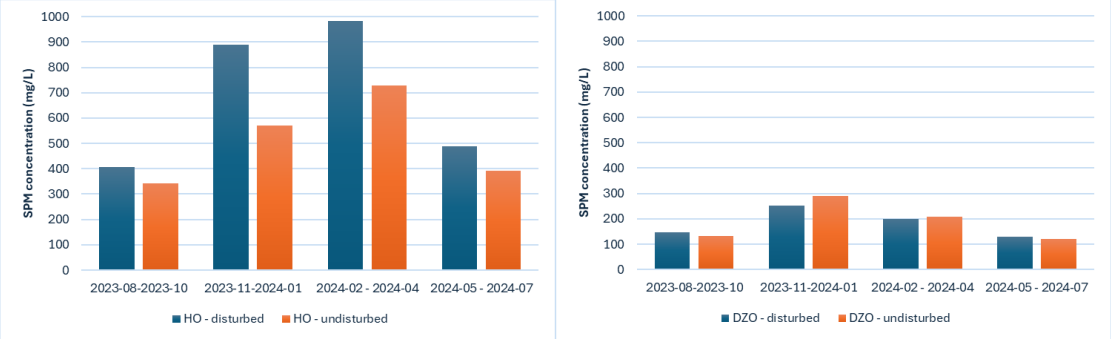

Figure 3.18. The comparison of mean SPM concentrations within and outside of dredging/disposal time windows at HO (left) and at DZO (right).

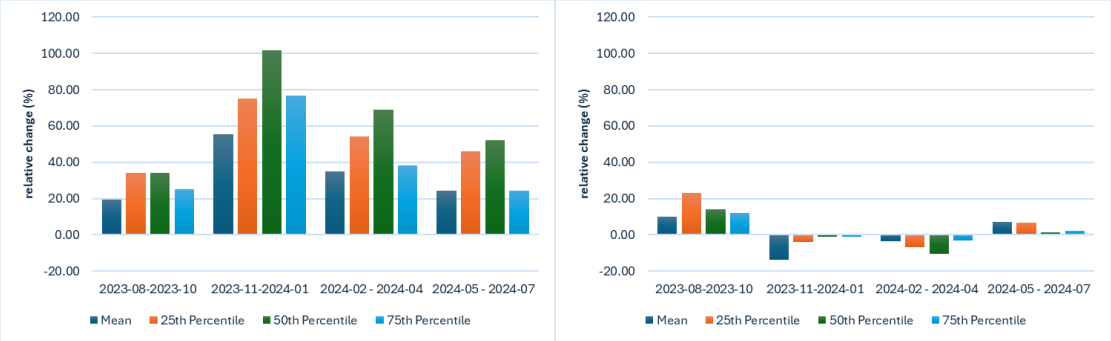

Figure 3.19. The relative changes in mean, 25th, 50th and 75th percentile SPM concentrations between disturbed and undisturbed periods at HO (left) and DZO (right).

3.4.2 Influence of ferry operations

Comparing to maintenance dredging, ferry operations may result in more frequent disturbance in water column. The movement of ferries generates waves and wakes that can enhance sediment resuspension and lead to an increase of turbidity. In some cases, waves induced by large ships may cause additional erosion of shorelines and intertidal zones.

The AIS data shows that there are mainly two types of ships operating between Holwerd and Ameland (Figure 3.20). The first type has a length of 21.5 meters, a width of 7.2 meters, and a draught of 1.2 meters. The second type is larger, with a length of 75.0 meters, a width of 15.0 meters, and a draught of 1.4 meters.

To quantify the influence of ship movements, the AIS data has been filtered with the following criteria:

- The location of the ship is within 400 m radius from the monitoring station (see Figure 3.21);
- The speed over ground is above 0 m/s.

This is to ensure that the ship is close enough to the monitoring station and still moving through water surface.

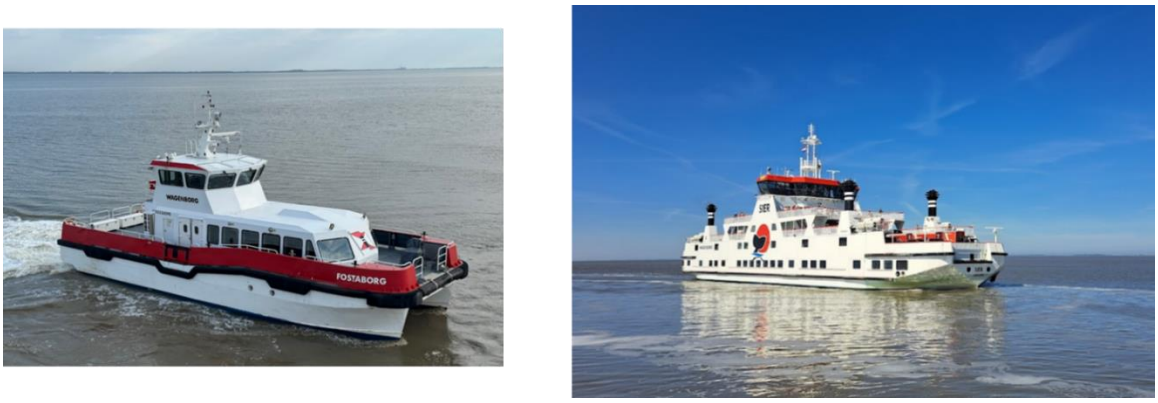

Figure 3.20. The ferry ships operating between Holwerd and Ameland (source from Google maps).

Figure 3.21. Location of the monitoring station and the ferry mooring.

After separating the data into two groups, with the presence of ships and without the presence of ships (Figure 3.22), statistical analysis is performed with each set of data. The impact on the SPM concentration is not noticeable in Figure 3.23. In fact, the SPM concentration range in the period without ship movements is higher, which might be due to the fact that the moments of the ship presence overlap more frequent with relatively low SPM concentrations (during slack tides). The lack of noticeable impact from ferry movements could be attributed to the following reasons:

- The ship movements mainly disturb the upper water column, hence the impact is limited.
- The frequency of the disturbance is high, the system does not have time to recover from the impacts so it cannot be easily separated from the background signals.
- The dredging and disposal may overshadow the influence of ferry operations.

The difficulties in revealing the impact of ferry movements may also suggest that the current method is not sufficient to deal with such short-time scale disturbances. This can be further improved in future studies, for example by taking into account the phase of the tide.

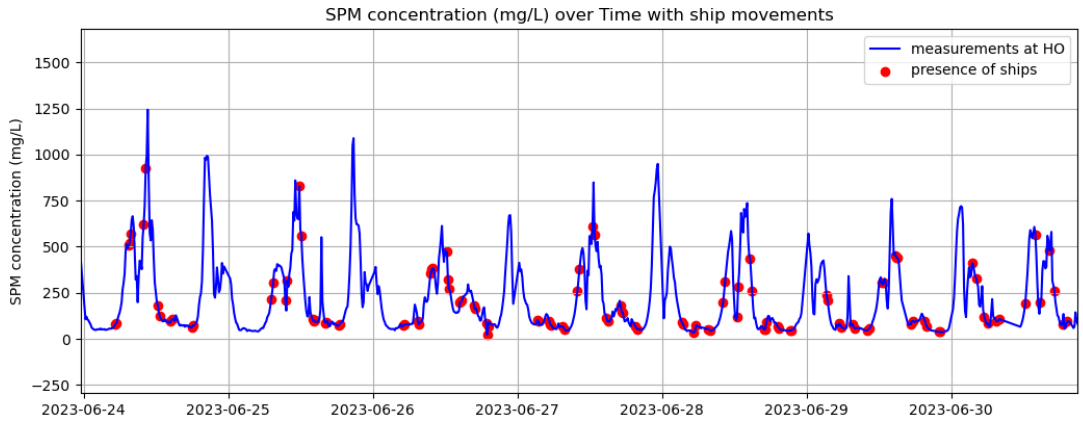

Figure 3.22. An example of SPM concentration and the moments when ship were close by.

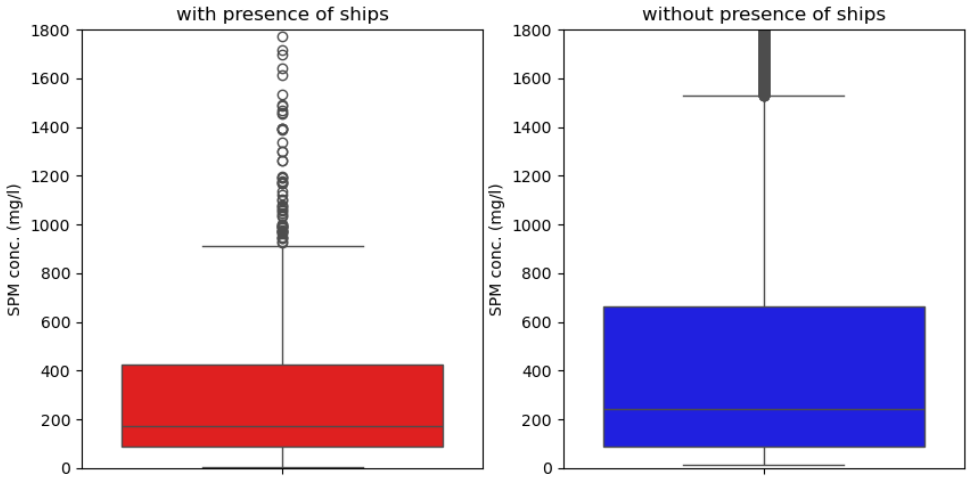

Figure 3.23. The box plot of SPM concentration at HO for investigating the influence of ship movements.

4 Conclusions

Compared to the 2023 analysis, conclusions are revised on two major points:

1. Based on the new OBS calibration curve, SSC levels at Holwerd now exceed those at Dantziggat. At Holwerd, the median SSC is 319 mg/l; at Dantziggat it is 112 mg/l.
2. By extending the period of disturbance to 3 hours after dredging operations, and by only including dredging operations close to Holwerd, it appears that average SSC during and shortly after dredging activities is about 60% higher than during undisturbed periods. This value is for all dredging time windows combined and may be even higher by including only dredging operation during flood phase (recommended for further investigation). At Dantziggat no significant SSC difference between both periods is observed. The effect of dredging on SSC is more pronounced in winter than in summer, both in absolute and in relative concentrations. This may be explained by the higher background turbidity and lower Chlorofyll-a levels in winter, suggesting more and slower settling mud.

On the understanding of local mud dynamics, the dominant role of tidal currents on short-term SSC variations as identified in the 2023 analysis was confirmed in the present analysis. On top of the tidal signal, the effects of wind (speed and direction) and waves contribute to long-term SSC variations, by remobilising and advecting mud to and from the monitoring area. This

causes pronounced changes over time in the relationship between tidal currents and SSC level in the channels. Forcing ‘events’ induced by strong and persistent winds from specific directions may trigger such changes. An example hereof is the storm passed during October 20/21, 2023 with strong easterly winds, that resulted in elevated SSC levels in the following months.

This behaviour is consistent with the conceptual framework for mud dynamics in the Wadden Sea (Herman et al., 2018; 2020), in which SSC variations at short timescale are explained predominantly by actual hydrodynamic forcing. However, to explain SSC variations at long timescale also variations in mud supply and mud properties come into play (which are more or less constant at short timescale). The data set from Holwerd and Ferwerd is essential for quantification of the main driving processes and for numerical model validation.

5 Recommendations for follow up monitoring

It is recommended to continue monitoring at the present locations for at least one more year. There are two main arguments for that:

1. A system-based argument: because of the seasonal and event-driven turbidity variations, a period of 3 years reveals more of such variations than 2 years.
2. An operational argument: as instrument settings have changed over time, this interferes with the identification of long-term variations and hence makes an extension of the (homogeneous) data set recommendable.

For residual sediment flux estimates, data gaps during a part of each tidal period should be avoided. These gaps have occurred at Holwerd, because of changes in the ADCP settings over time. Already during this project, the ADCP settings have been changed such that the ADCP at Holwerd is measuring flow velocities during a longer part of the tidal period. Gaps in the timeseries still occur when the water level decreases below -1.13 m NAP.

It is also recommended to extend the frame observations with observations on mud properties (such as settling velocity, erodibility, floc size and composition) to gain more insight into the causes for seasonal SSC dynamics, which may include variations in mud properties and supply. This has also practical importance, as the present data analysis shows that the effect of dredging activities on SSC levels are different in summer and winter.

The analysis of the effect of dredging on turbidity would benefit from a prolonged period without dredging (e.g. 1 – 3 months), for example in the form of a dredging pilot. In this way the long-term impact of dredging on background turbidity can be better assessed. Such pilot may also include a (temporary) relocation of the release area for dredged mud. It would provide valuable data on the time scale and spatial scale of the impact of maintenance dredging on SSC. However, it is challenging to combine this recommendation with the requirement to maintain ferry operations.

Present and new monitoring data are important to validate the existing KRW Wadden model on the prediction of maintenance dredging impacts on SSC, and improve the model calibration if required.

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