Deltares

Memo

Date
20 December 2023

Number of pages
1 of 85

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Subject
Data Analysis Holwerd-Ferwerd periode juli 2023 - juni 2023

Samenvatting

In de geulen bij Holwerd en Ferwerd zijn in juli 2022 twee meetframes geplaatst om de troebelheid gedurende een periode van meerdere jaren te meten. Dit is gedaan om de invloed van diverse factoren op de troebelheid beter in kaart te brengen, zoals getijstroming, wind, golven en zoetwaterafvoer, maar mogelijk ook menselijke factoren zoals de veerboot en baggeronderhoud in de vaargeul naar Holwerd.

Dit verslag beschrijft de analyse van deze meetgegevens en bestaan uit verschillende onderdelen. De eerste stap is een beoordeling van de kwaliteit en bruikbaarheid van de data. De volgende stap is het verwerken van de data en het vaststellen in welke mate de troebelheid afhangt van de genoemde factoren. Hierbij wordt een onderscheid gemaakt tussen natuurlijke en menselijke factoren. Overeenkomsten en verschillen tussen Holwerd en Ferwerd en met eerdere metingen elders zijn vastgesteld. Ook is een eerste vergelijking gemaakt tussen de gemeten data en met het huidige KRW-slibmodel berekende slibconcentraties.

Uit deze analyse wordt onder meer het volgende geconcludeerd:

- Wat betreft de bruikbaarheid van de data geldt dat de meetreeks van Holwerd completer is dan die van Ferwerd. Dit heeft o.a. te maken met aangroei, instrumentinstellingen en bemonstering voor kalibratie. In het komende jaar wordt het onderhoud aangepast zodat de meetreeks naar verwachting completer wordt. Ondanks enkele gaten in de data is de meetreeks van afgelopen jaar goed bruikbaar voor de beoogde analyse.
- Natuurlijk gedrag: op beide locaties is sprake van een hoge slibconcentratie die op korte termijn sterk wordt gestuurd door de lokale stroomsnelheid. Op langere termijn spelen ook andere aspecten een rol zoals het aanbod (o.a. door golven) en de eigenschappen van slib. Deze ondervinden een seizoensdynamiek, waardoor op langere termijn de slibconcentratie sterk kan variëren bij gelijke stroomsnelheid.
- Verschil Holwerd-Ferwerd: In tegenstelling tot de verwachting is de slibconcentratie bij Ferwerd hoger dan die bij Holwerd. Bij Ferwerd is de geul dieper en is er geen sprake van lokale verstoring door scheepvaart of baggeronderhoud. De gemiddelde stroomsnelheid is er groter. Ook is bij Ferwerd de seizoensdynamiek in de slibconcentratie groter dan bij Holwerd, waarschijnlijk wordt dit o.a. veroorzaakt door een grotere variatie in het aanbod en de eigenschappen van slib en een grotere invloed van organisch materiaal.
- Invloed van de veerboot en baggeren bij Holwerd. Deze invloed is op korte tijdschaal niet met zekerheid vast te stellen uit de data. De gemeten slibconcentratie is periodes met en zonder verstoring ongeveer gelijk. Mogelijk speelt deze invloed wel om een

langere tijdschaal, door een algehele verhoging van de achtergrondconcentratie. Dit vraagt om nader onderzoek.
- Vergelijking met eerdere data: bij Holwerd zijn geen inconsistenties geconstateerd met eerdere metingen. Bij Ferwerd is er nog geen vergelijkingsmateriaal. Wel is de slibconcentratie hier veel hoger dan bij het MWTL-meetpunt Dantziggat, maar dit te ver weg zeewaarts van de huidige meetlocatie om hieraan conclusies te verbinden.
- Vergelijking met slibconcentraties bij Holwerd en Ferwerd volgens het KRW-slibmodel: Een directe vergelijking was nog niet mogelijk omdat het model nog niet is gedraaid voor de periode waarin de huidige metingen zijn uitgevoerd, maar op basis van een eerste vergelijking lijkt de relatie tussen slibconcentratie en hydrodynamische omstandigheden volgens het model af te wijken van die volgens de metingen. Een mogelijke oorzaak hiervoor is een onderschatting van de intensiteit van de water-bodemuitwisseling. De meetreeks is bruikbaar om het modelgedrag verder te verbeteren.
- Aanbevelingen voor verdere analyse en aanvullende monitoring: Het wordt aanbevolen om de metingen het komende jaar door te zetten op beide huidige locaties. Daarna kan herplaatsing worden overwogen, b.v. in het kader van een pilot voor alternatieve verspreidingsstrategieën van baggerspecie. De waarde van de monitoring neemt verder toe als naast slibconcentratie ook slibeigenschappen worden bepaald zoals vlokgrootte, valsnelheid, organisch gehalte etc. Om een beter onderscheid te kunnen maken tussen horizontale en verticale transportprocessen is een tweede meetframe op de nabijgelegen platen nuttig, of flankerende scheepsmetingen rondom de meetframes. Dit geldt ook voor de monitoring van variaties in slibgehalte of sliblaagdikte in of op de bodem rondom de meetframes onder invloed van hydrodynamische omstandigheden.

1 Introduction

Within the SITO project ‘WVH 07 2023 - Kennis voor Beheer en Onderhoud Waddenzee (BenO Waddenzee)’, a sub-project on data analysis Holwerd-Ferwerd has been defined. At both locations, frames have been placed to measure turbidity and related parameters for a long period (up to 3 years) and at a high frequency (every 10 minutes).
The rationale for these measurements is to better understand the fine sediment dynamics at these locations and to possibly identify human impacts on turbidity, such as by dredging and ferry crossings. These impacts may be significant near Holwerd, whereas the Dantziggat (located near Ferwerd) has been chosen as a reference location without nearby dredging or ferry activities. Also, Ferwerd is a potential new location for the ferry crossing to Ameland. These measurements also support further validation of the existing 3D model on fine sediment dynamics in the Wadden Sea. An in-depth discussion on the rationale for these measurements is given by Vroom et al. (2020a).

2 Objectives

After about one year of observations, data are inspected and analysed for the first time within the framework of this study. The present first analysis aims at:
- Assessment of the data quality and usability. As calibration and quality control of the data has not yet been performed by RWS-CIV, this is part of the present project. Especially biofouling is a potential important issue, as the sensor wipers did not yet function properly in the first year.
- Analysis of the turbidity variations and their possible causes, such as tidal forcing, wind and waves, set-up, ferry traffic and dredging activities.
- Analysis of differences in turbidity between Holwerd and Ferwerd

- Analysis of possible human impacts on turbidity by ferry traffic and dredging near Holwerd.
- Comparison with previous data from other sources.
- Recommendations on further data analysis, application and additional measurements contributing to the objectives of the long-term monitoring programme.

3 Approach

The approach to this study is as follows. First an overview of the data is given including information of frame positions, sensor types and vertical positions (Section 4). Second, data checking, quality control and filtering is discussed (Section 5). Subsequently, the data is analysed to identify the dominant forcing factors for turbidity variations at multiple timescales (Section 6). By discerning time windows with and without shipping or dredging activities, the effect hereof on turbidity levels is quantified. Also, a first comparison with results from the numerical model for fine sediment dynamics is made. Results are discussed in the context of previous turbidity measurements in Section 7. Finally, conclusions are given (Section 8) and recommendations are made on additional data analysis, application and on the usefulness of additional monitoring (Section 9).

4 Data overview

The long-term observations at Holwerd and Dantziggat (Figure 4-1.) contain measurements related to various water and sediment related parameters, captured at high frequency (15-minute averages) from July 2022 to June 2023. The information about the monitoring stations and the period of data is in Table 1.

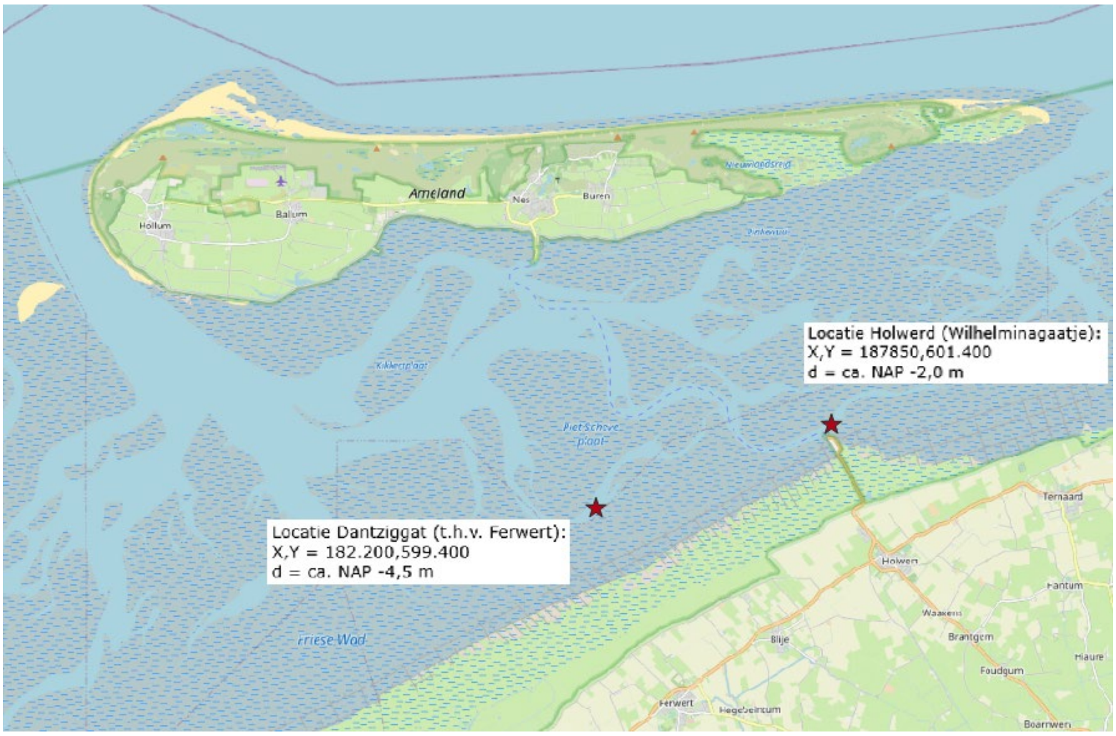


Figure 4-1. The monitoring stations Holwerd and Dantziggat (data from *Posthuma, 2021)*

Table 1. Information about the monitoring stations and period of data

Station	Coordinates	MPP sensor level	Bed level	Data period
Holwerd	(53.3983, 5.8824)	50 cm below LAT	-2.0 m+NAP	2022/07/21 - 2023/06/20
Dantziggat	(53.3797, 5.7949)	50 cm below LAT, 1 m above bed	-4.5 m+NAP	2022/07/21 - 2023/06/20

Table 2. Overview of the main indicators in the measured data at both stations.

Dataset	Variable	Unit	Remark
ADCP	flow direction	degree	direction with respect to north
	velocity north	m/s	velocity in the north direction (averaged over vertical layers)
	velocity east	m/s	velocity in the east direction (averaged over vertical layers)
	velocity up	m/s	velocity in the upward direction (averaged over vertical layers)
MPP	conductivity	mS/cm	conductivity of the water, can be influenced by various factors, including temperature, salinity, and the presence of dissolved substances in the water.
	concentration chlorophyll-a	μg/L	concentration of chlorophyll-a in the water, which indicates the presence of phytoplankton. Peaks might correspond to algal blooms or increased phytoplankton activity.
	turbidity	NTU	high turbidity values can be due to increased suspended particles in the water, possibly from runoff, resuspension of sediments, or algal blooms.
	water temperature	°C	
	concentration oxygen	mg/L	concentration of dissolved oxygen in the water, crucial for aquatic life and can be influenced by factors like temperature, salinity, and biological activity.
	saturation level oxygen	%	oxygen saturation level in the water, which indicates how saturated the water is with oxygen.
STB (tailored)	average water level	m+NAP	Mean water level on time interval of 15 min
	significant wave height	m	represents the average height of the highest one-third of waves, peaks might correspond to storm events or strong wind conditions that lead to larger waves.
	peak period	s	represents the time interval between successive waves with the highest energy. Fluctuations in the peak period might indicate changes in weather conditions, wind patterns, or distant storm events.

The following instruments were used in monitoring (Posthuma, 2021):

- turbidity, temperature, conductivity, Chl-a, and oxygen with YSI MPP
- flow rate using ADCP (mounted below water, upward-looking)
- wave height with step marker (STB)

There are three datasets available at both Holwerd and Dantziggat, namely the ADCP dataset, MPP dataset and STB dataset. The measured variables are given in detail in Table 2. It is worth mentioning that the STB dataset contains both the ‘original’ high frequency water level signals

(4 Hz), and the ‘tailored’ products as indicated in Table 2. For convenience, the STB (tailored) is used instead of the original high frequency water level signals. In total there are 13 variables selected in the data analysis in this study. Table 2 gives a brief overview of the measurements collected at both stations. The raw data can be found in the Appendix.

In the monitoring period, maintenance of the sensors was carried out according to the following schedule (Table 3). During the maintenance, the status of the device was checked, and sensors were cleaned if they were affected by the biofouling. It is worth mentioning that the wipers installed on the instrument at Dantziggat, at both depths, did not work until June 13, 2023. After that, they functioned well.

Table 3. List of dates of the maintenance scheduled during the monitoring period.

date	date	date	date	date	date	date
19-07-22	05-09-22	14-12-22	25-04-23	25-05-23	10-07-23	28-08-23
10-08-22	15-09-22	15-02-23	11-05-23	13-06-23	25-07-23	11-09-23
25-08-22	17-10-22	15-03-23	24-05-23	15-06-23	14-08-23	10-10-23

5 Data quality control

The initial check of the monitoring data at Holwerd-Dantziggat shows that some variables may have potential outliers in the original measurements (see 10A.1 and 10A.2). They can arise due to various reasons, including measurement errors, data entry errors, or genuine extreme observations. Addressing outliers is crucial because they can distort statistical analyses and violate the assumptions of many statistical procedures. Outliers, especially non-physical ones, suggest the need for data verification, sensor calibration checks, or additional data cleaning.

One popular method to identify and potentially remove outliers is the Interquartile Range (IQR) method that is suitable for non-normal distributed data (Tukey, 1977). The IQR, defined as the difference between the 75th percentile (Q3) and the 25th percentile (Q1), provides a measure of statistical dispersion or spread of the data. Typically, outliers are considered as data points that fall below $Q1 - n \times IQR$ or above $Q3 + n \times IQR$. However, the multiplier n (commonly set to 1.5) can be adjusted based on the specific needs of the analysis. A larger multiplier may be more lenient and retain more data points, while a smaller one may be stricter. The IQR method works effectively because it is based on the spread of the central 50% of the data, making it less sensitive to extreme values compared to methods that rely on means and standard deviations. By focusing on the middle 50% of data and offering the flexibility of an adjustable multiplier, the IQR provides a robust and adaptable measure to identify outliers, especially in datasets with skewed distributions or heavy tails. In this study, the IQR method is adopted for removing outliers in the measurements when it is needed. For both Holwerd and Dantziggat, various of n values were tested, and in the end $n = 3$ is used for effectively removing outliers and meantime preserving certain rare events in the original signals.

In addition to automated outlier removal, some additional data points are considered as suspicious if:

- Absolute values were physically impossible or outside the sensor range.
- Differences between the upper and lower sensor at Dantziggat or between Dantziggat and Holwerd were suddenly very large without any plausible physical explanation.
- During servicing fouling was observed and a step in the baseline value was observed after sensor cleaning.

In Chapter 6, the suspicious data points falling in the above category are carefully examined and considered when interpreting the results, making sure they will not impact the main conclusions in the analysis.

5.1 Holwerd

Overall, the monitoring data from Holwerd is of good quality, exhibiting fewer data gaps during the observation period, with most measurements falling within a reasonable range. It's evident that near the end of the period, specifically around 15th May 2023 (refer to section 10A.1.1), the three velocity components deviate from previous months, indicating unrealistic negative velocities in the timeseries. As a result, the data analysis only includes information from 21st July 2022 to 15th May 2023. Additionally, the conductivity measurements exhibit abrupt fluctuations over relatively brief intervals, with readings frequently plummeting to nearly zero. Consequently, values below 16 mS/cm are deemed outliers and have been excluded. Lastly, to ensure accuracy in data analysis, zero values in all the variables have been removed. The final processed data used in analysis is shown Figure 5-1. – Figure 5-4.

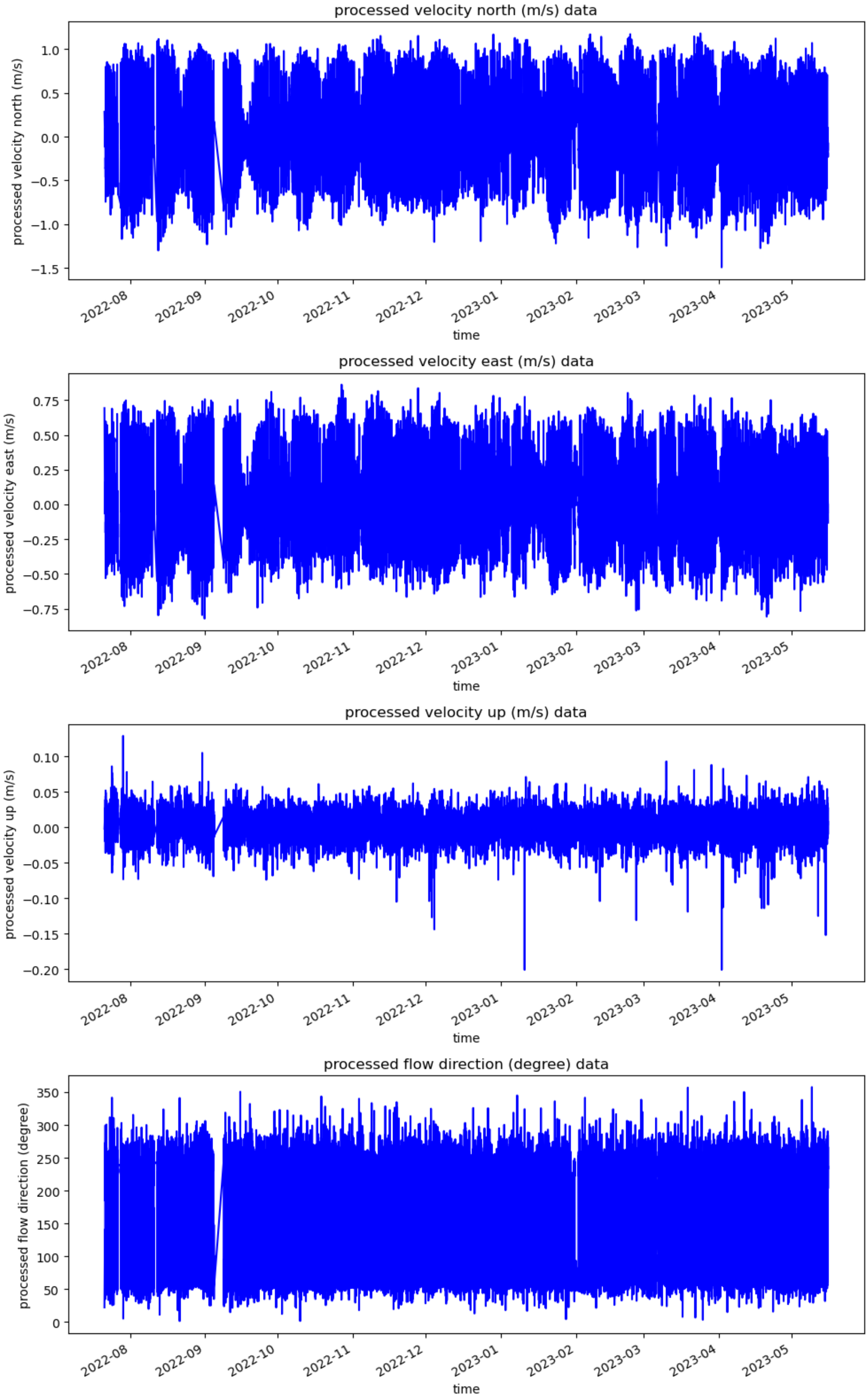


Figure 5-1. Processed flow velocities and directions at Holwerd.

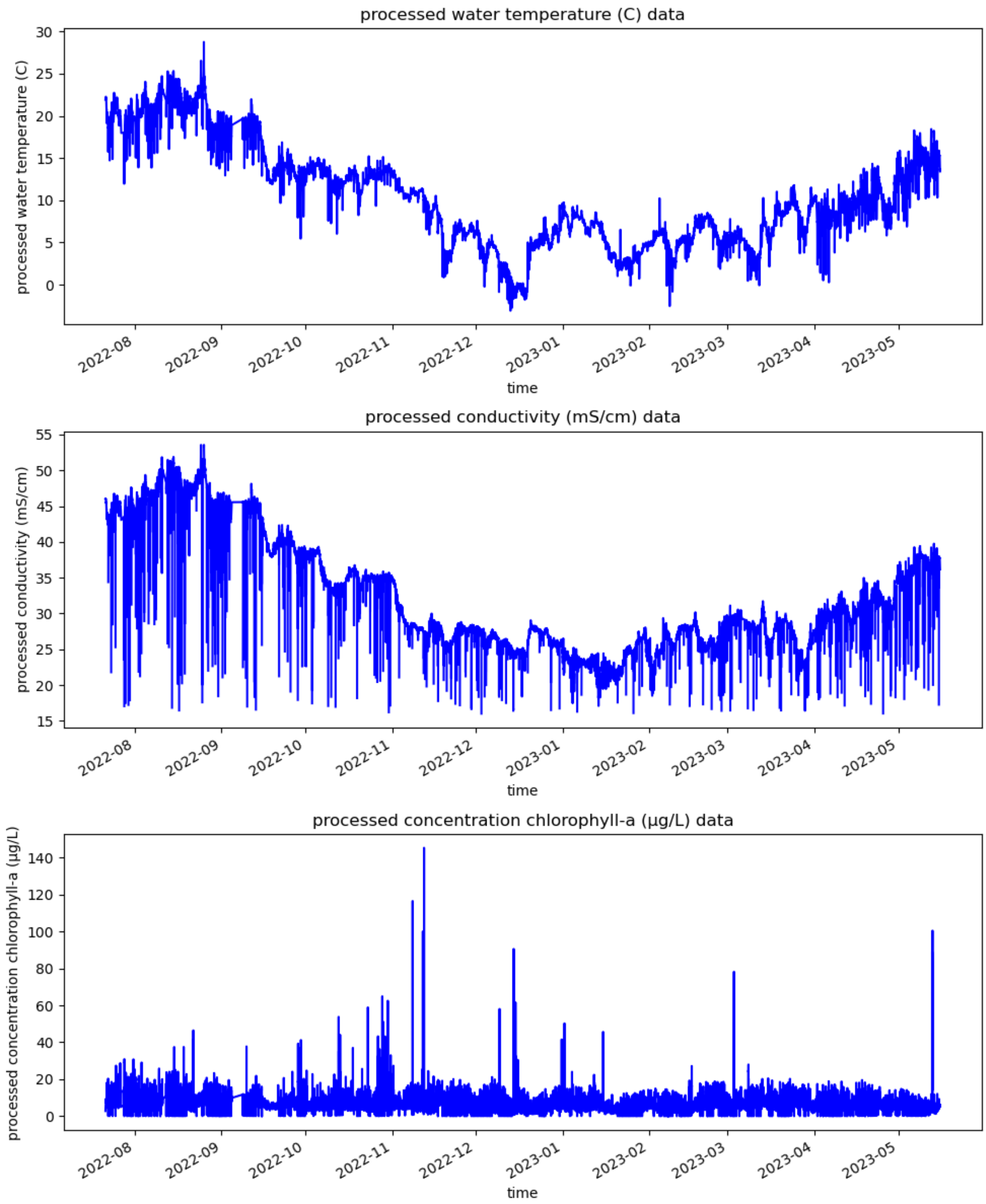


Figure 5-2. Processed water temperature, conductivity and chlorophyll-a concentration at Holwerd.

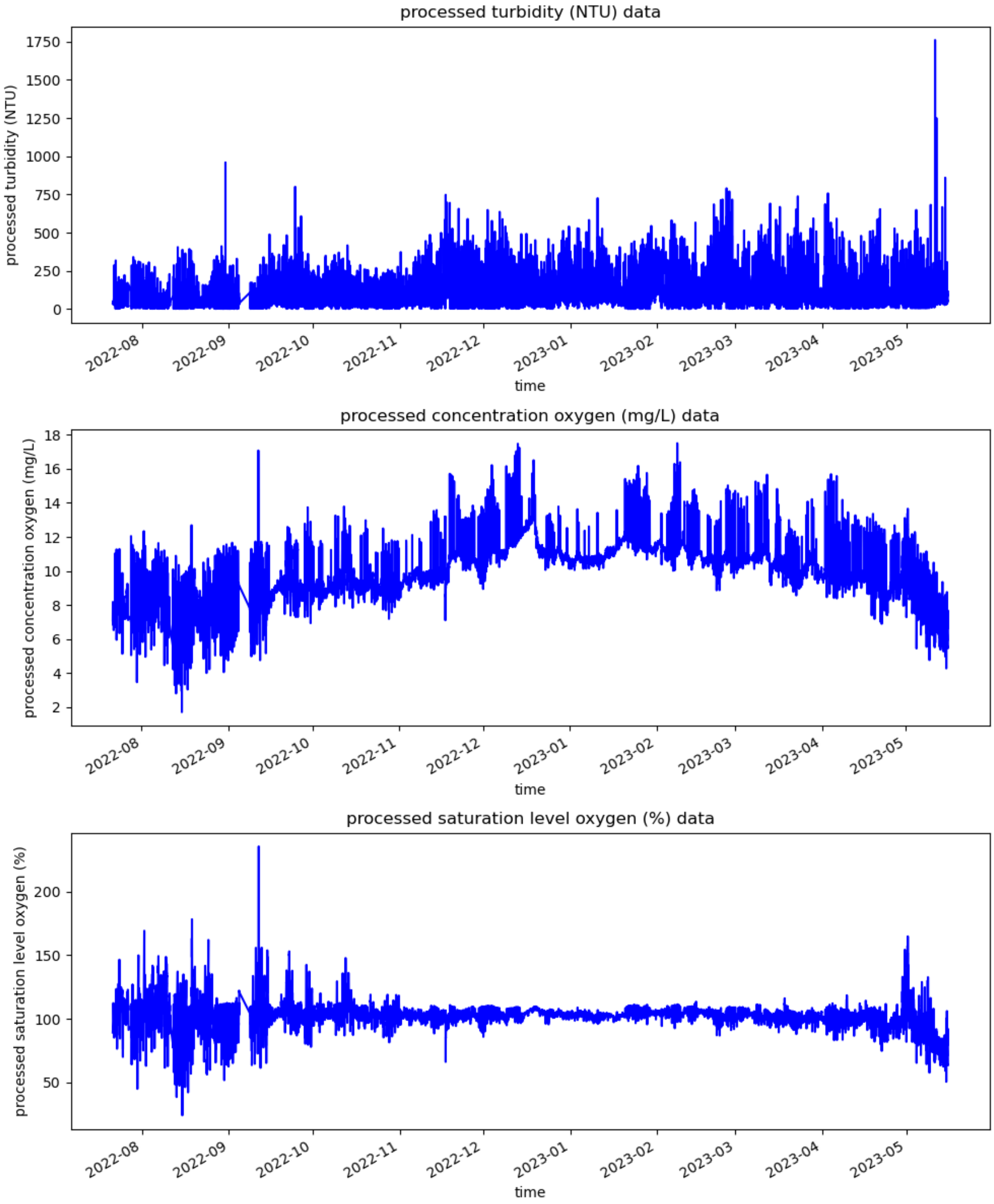


Figure 5-3. Processed turbidity, oxygen concentration and oxygen saturation level at Holwerd.

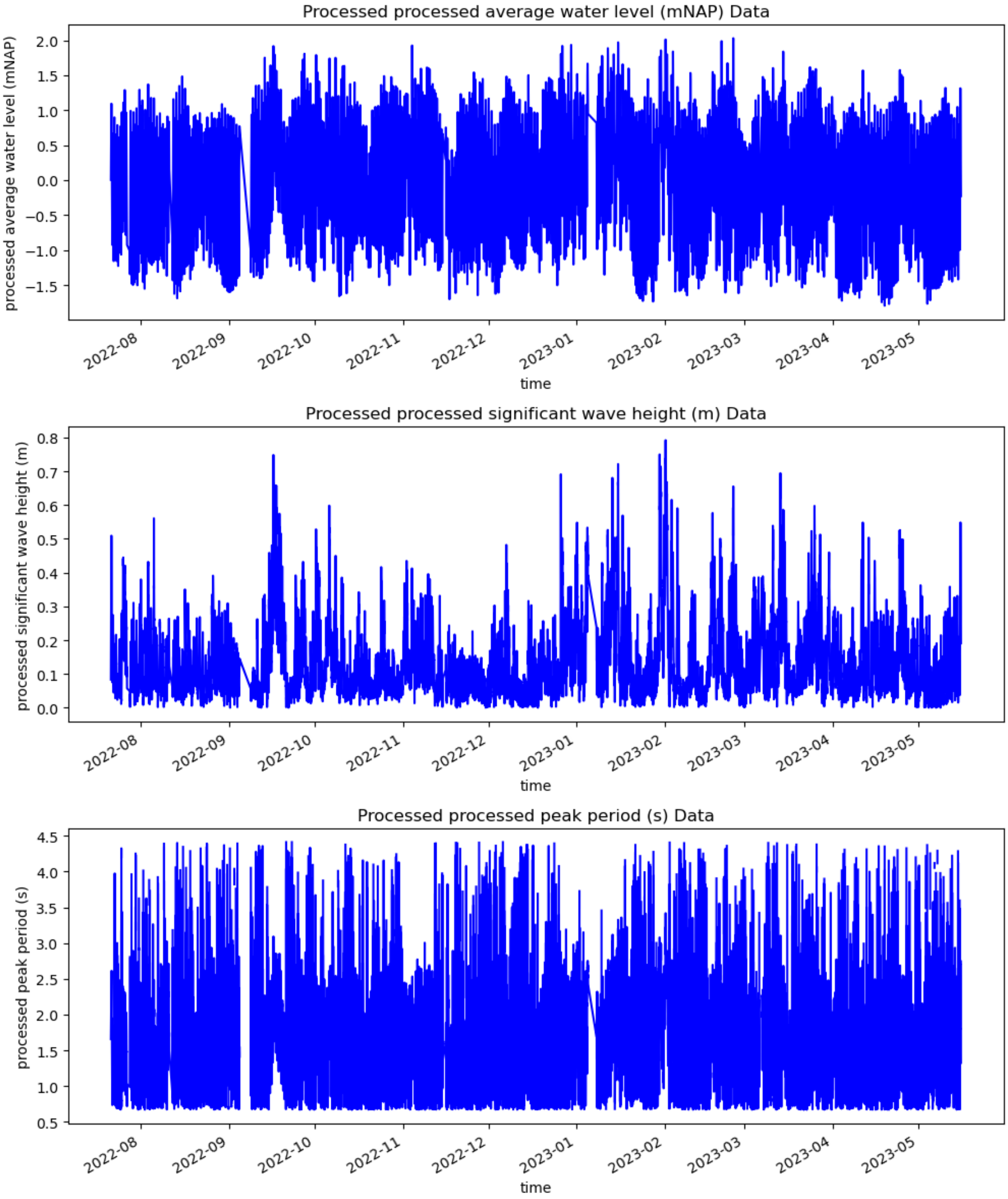


Figure 5-4. Processed water level, significant wave height and wave peak period at Holwerd.

5.2 Dantziggat

The monitoring data at Dantziggat has revealed further gaps. Specifically, in the ADCP dataset, sensor malfunctions led to an absence of velocity measurements from November 2022 until approximately mid-January 2023. The other noticeable gaps are found in the STB dataset, which are about 15~20 days in November 2022 and January 2023, respectively.

Besides, more outliers can be observed in the velocity measurements, variables in the MPP and STB datasets. Hence, the IQR method has been applied to further clean the data. The final processed data (after removing outliers and zeros) is shown in Figure 5-5., Figure 5-6., Figure 5-7. and Figure 5-8.

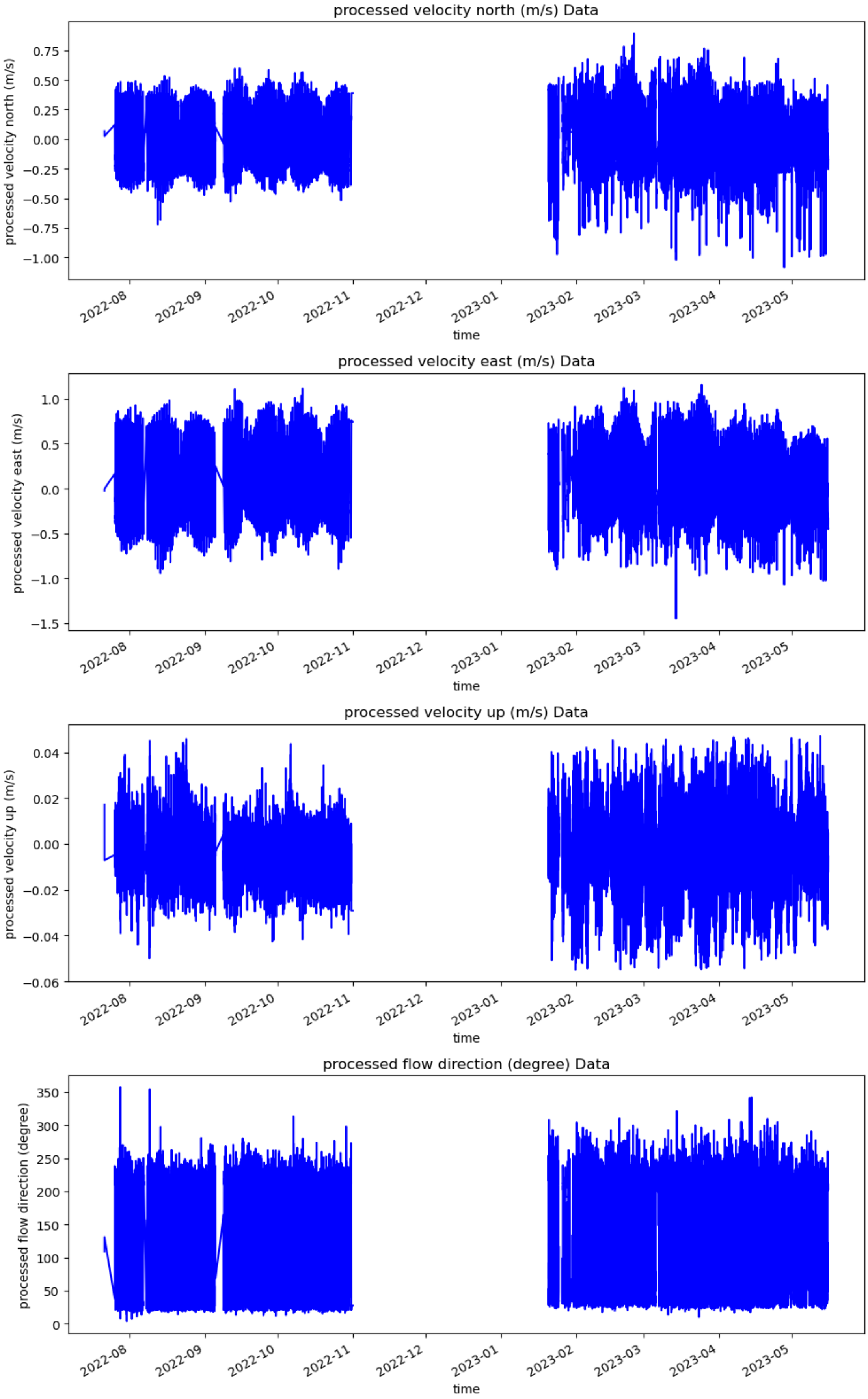


Figure 5-5. Processed velocities and flow directions at Dantziggat.

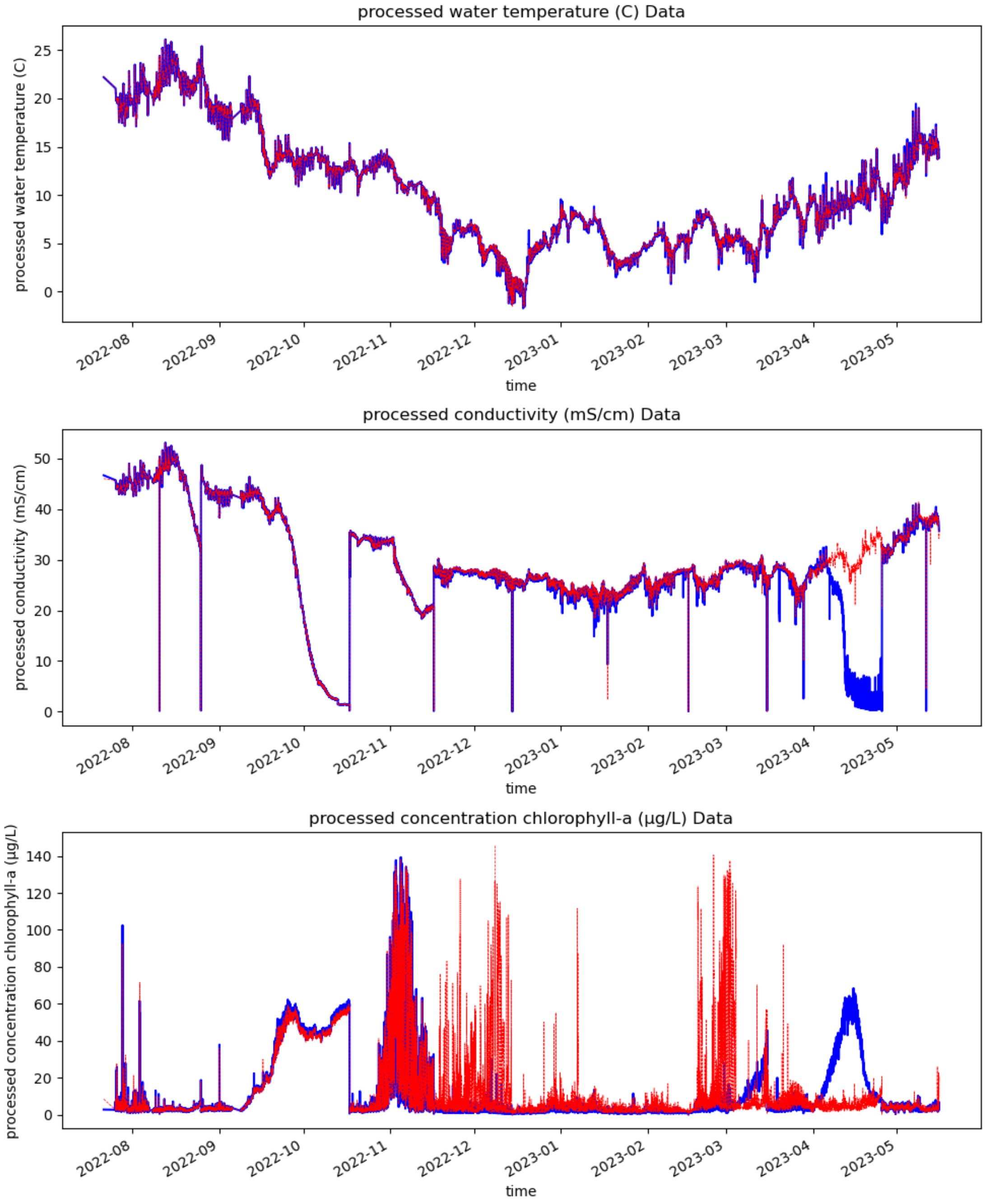
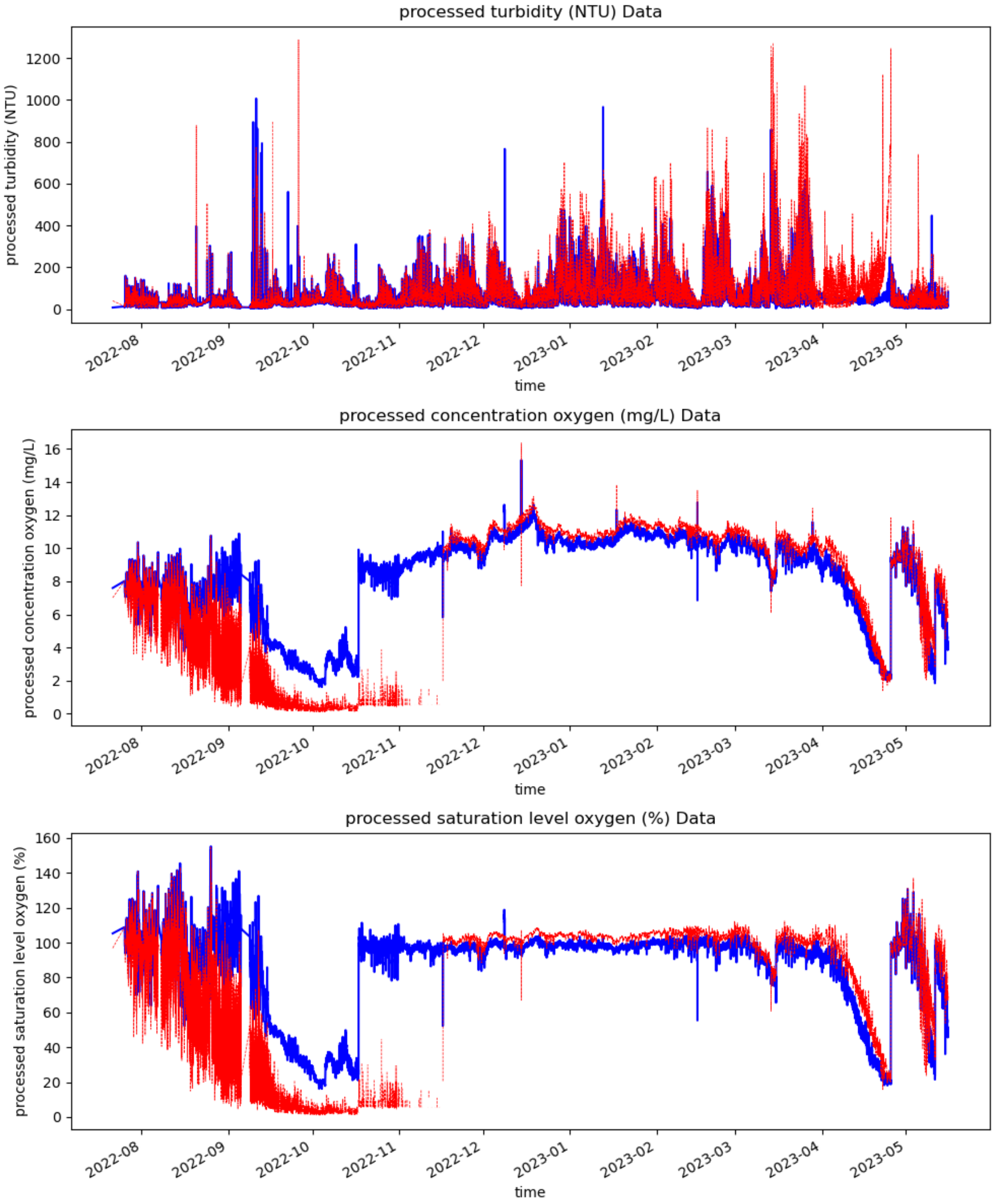


Figure 5-6. Processed water temperature, conductivity and chlorophyll-a concentration at Dantziggat (blue: 0.5m below LAT, red: 1m above bed).



processed turbidity (NTU) Data

processed concentration oxygen (mg/L) Data

processed saturation level oxygen (%) Data

Figure 5-7. Processed turbidity, oxygen concentration and oxygen saturation level at Dantziggat (blue: 0.5m below LAT, red: 1m above bed).

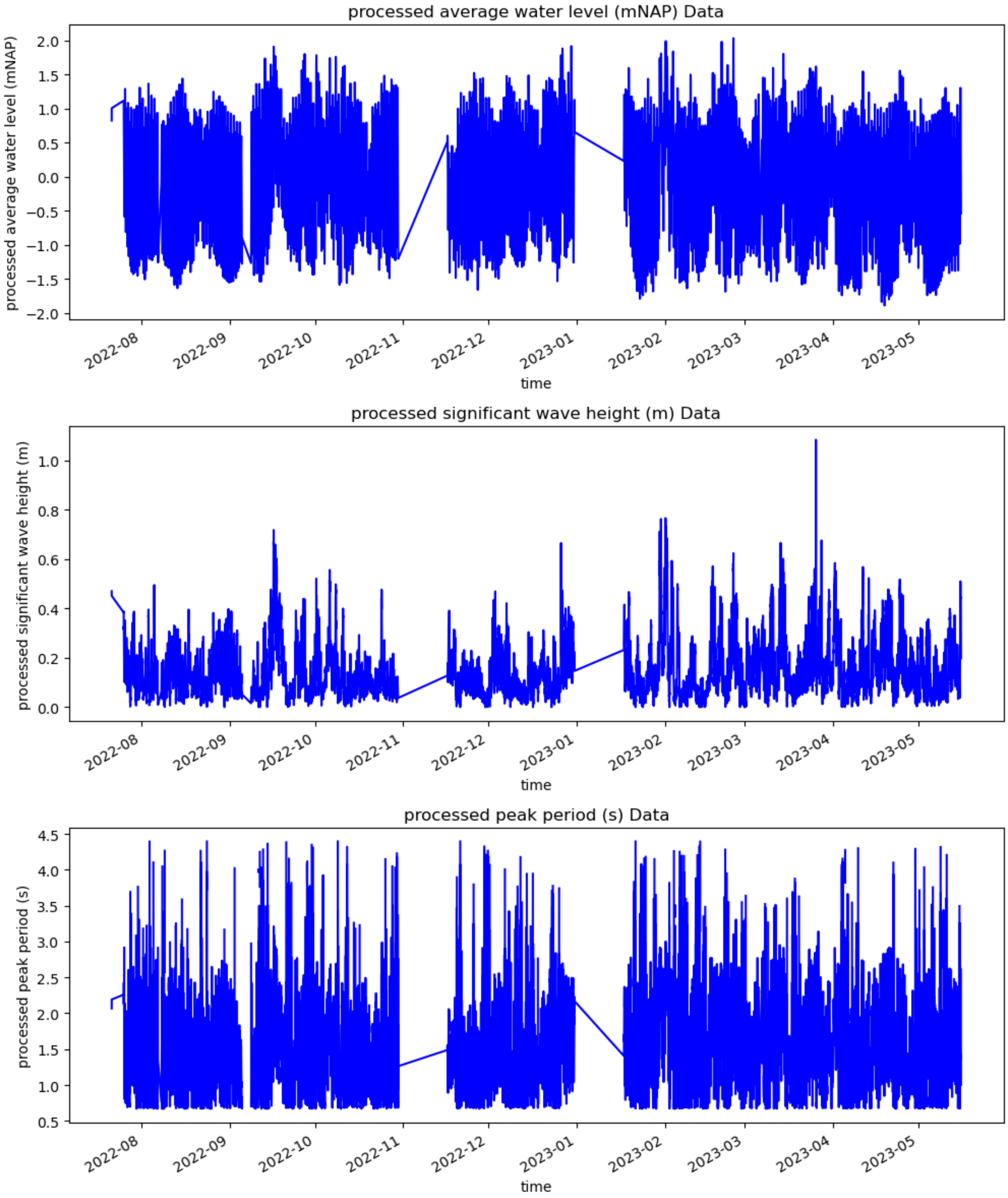


Figure 5-8. Processed water level, significant wave height and wave peak period at Dantziggat.

5.3 Synthesis

At Holwerd, monitoring data is generally of good quality, with few gaps and most measurements within a reasonable range, whereas at Dantziggat, data availability revealed gaps due to sensor malfunctions, particularly in velocity measurements from November 2022 to mid-January 2023, and additional gaps in the STB dataset. Also signs of biofouling have been observed in the measurements at Dantziggat, this can lead to difficulties in the data analysis, but it can also provide additional information of the environment and reveal the different characteristics of two locations.

The main statistics of the processed data (after removing outliers) can be found in Table 4 and Table 5. It is remarked that if stricter criteria on data quality would be applied, this may change these statistics, notably for Dantziggat. However, this is unlikely to change the overall conclusions from the following data analysis.

Table 4. The statistics of the processed data at Holwerd.

parameter	Mean	Std.	Min.	25th pctl.	50th pctl.	75th pctl.	Max.
velocity magnitude (m/s)	0.353	0.292	0.001	0.116	0.256	0.533	1.647
flow direction (degree)	155.249	82.112	1.500	68.970	155.686	238.800	357.700
water temperature (C)	10.454	6.018	-3.080	5.650	9.350	13.950	28.760
conductivity (mS/cm)	32.234	8.040	16.012	26.160	29.133	37.925	53.563
concentration chlorophyll-a (µg/L)	6.408	4.607	0.000	3.798	5.682	8.210	145.207
SPM concentration (mg/L)	154.275	151.422	2.387	51.763	103.728	207.390	3042.494
concentration oxygen (mg/L)	9.870	1.694	1.700	8.880	9.950	10.960	17.510
saturation level oxygen (%)	102.754	9.717	24.070	99.740	102.830	105.670	235.580
average water level (mNAP)	0.118	0.736	-1.796	-0.464	0.159	0.699	2.030
significant wave height (m)	0.140	0.111	0.000	0.060	0.105	0.188	0.792
peak period (s)	1.644	0.653	0.669	1.174	1.568	1.966	4.411

Table 5. The statistics of the processed data at Dantziggat

parameter	Mean	Std.	Min.	25th pctl.	50th pctl.	75th pctl.	Max.
velocity magnitude (m/s)	0.457	0.262	0.002	0.215	0.475	0.681	1.346
flow direction (degree)	131.840	77.675	4.000	51.345	132.443	212.522	357.600
water temperature (C)	10.622	5.960	-1.750	5.720	9.500	14.030	26.130
conductivity (mS/cm)	28.662	11.397	0.016	24.347	27.554	35.724	53.141
concentration chlorophyll-a (µg/L)	12.127	18.600	0.039	2.227	3.413	10.589	139.328
SPM concentration (mg/L)	210.393	223.757	7.754	86.271	148.098	242.154	3948.072
concentration oxygen (mg/L)	8.361	2.579	1.630	7.290	9.240	10.310	15.330
saturation level oxygen (%)	87.012	24.724	16.170	87.110	97.080	99.720	155.220
water temperature 2 (C)	10.667	5.916	-1.630	5.820	9.570	14.020	26.140
conductivity 2 (mS/cm)	30.263	9.677	0.024	25.509	28.176	35.898	53.142
concentration chlorophyll-a 2 (µg/L)	12.042	18.377	0.000	2.840	4.403	9.088	145.472
SPM concentration 2 (mg/L)	283.102	366.365	8.095	93.056	165.520	331.170	5048.445
concentration oxygen 2 (mg/L)	7.177	4.253	0.100	2.730	9.150	10.860	16.360
saturation level oxygen 2 (%)	73.543	40.492	0.950	34.210	99.250	104.070	155.150
average water level (mNAP)	0.071	0.744	-1.893	-0.476	0.174	0.621	2.032
significant wave height (m)	0.148	0.109	0.000	0.067	0.119	0.200	1.084
peak period (s)	1.567	0.585	0.669	1.144	1.455	1.949	4.394

* Parameters water temperature, conductivity, concentration chlorophyll-a, SPM concentration, concentration oxygen, saturation level oxygen were collected by the sensor at 0.5m below LAT, while water temperature 2, conductivity 2, concentration chlorophyll-a 2, SPM concentration 2, concentration oxygen 2, saturation level oxygen 2 were at 1m above the bed.

6 Data Analysis

The Wadden Sea presents a dynamic environment where hydrodynamics, sediment transport, and ecological activities interplay in complex ways. These result in various spatial patterns (e.g., temporal variations in flow conditions, sediment concentration, biological activity indices, etc.) and temporal variations of turbidity, depending on forcing factors such as tide, wind, waves, freshwater discharge. These variations often occur at differing time scales, ranging from short-term fluctuations to long-term changes. To effectively comprehend the temporal trends in the measurements taken within this ecosystem, and to discern the intricate relationships between the monitored indicators, we employ several data analysis methods. Each of these methods is tailored to provide specific insights, ensuring a thorough understanding of the multifaceted interactions and trends of turbidity in the Wadden Sea.

6.1 Seasonality analysis

When analysing time series data, it's common to see patterns that repeat over time, indicating seasonality. The seasonality analysis provides a mechanism to deconstruct a time series into its basic components (Cleveland and Cleveland, 1990):

- Seasonal: The underlying trend in the data showing the seasonal variations, which can be increasing, decreasing, or stable over time. Due to the limited data (less than one year), it cannot show the long-term trend.
- Spring-neap: Patterns that repeat at regular intervals of 14.76 days. This component captures the variations during typical spring-neap cycles in the data.
- Residual: The remainder after the trend and seasonal components have been subtracted from the original time series. It's the "noise" or unexplained variation in the data.

The period, often referred to as frequency, in the seasonality analysis represents the number of data points at a regular time interval within a single seasonal cycle of the time series. In simpler terms, it denotes the number of observations for each season. For this study, the period is set to 14.76 days (a spring-neap cycle), and we resampled the time series data to a consistent 10-minute interval prior to analysis. This allows us to have uniformity in the number of data points across each cycle. The results of the seasonality analysis can be found in Figure 6-1. - Figure 6-5.

Water level (Figure 6-1.):

- Seasonal: Both Holwerd and Dantziggat exhibit a parallel long-term seasonal trend when it comes to water levels. This similarity suggests that broader regional factors likely influence both stations in a consistent manner. This is logical as both stations are nearby and strong water level differences are not expected. Despite the overall consistency, there are noticeable deviations in the months of November 2022 and January 2023 at the Dantziggat station. This discrepancy can be attributed to data gaps during these months. A notable seasonal variation is evident, where water levels tend to peak during the winter months and dip during the summer. The range of this seasonal fluctuation is approximately 0.6 meters.

- Spring-neap: The spring-neap variations in water levels, which are inherently tied to the spring-neap cycle, appear consistent between Holwerd and Dantziggat. Both stations show a roughly 0.5-meter variation throughout this cycle, indicating a shared response to lunar influences on tides.

- Residual: The residual variations, or the short-term fluctuations after accounting for the seasonal and spring-neap components, are consistent between the two stations. These residual variations over the tidal cycle are more pronounced than both the seasonal and long-term trend variations.

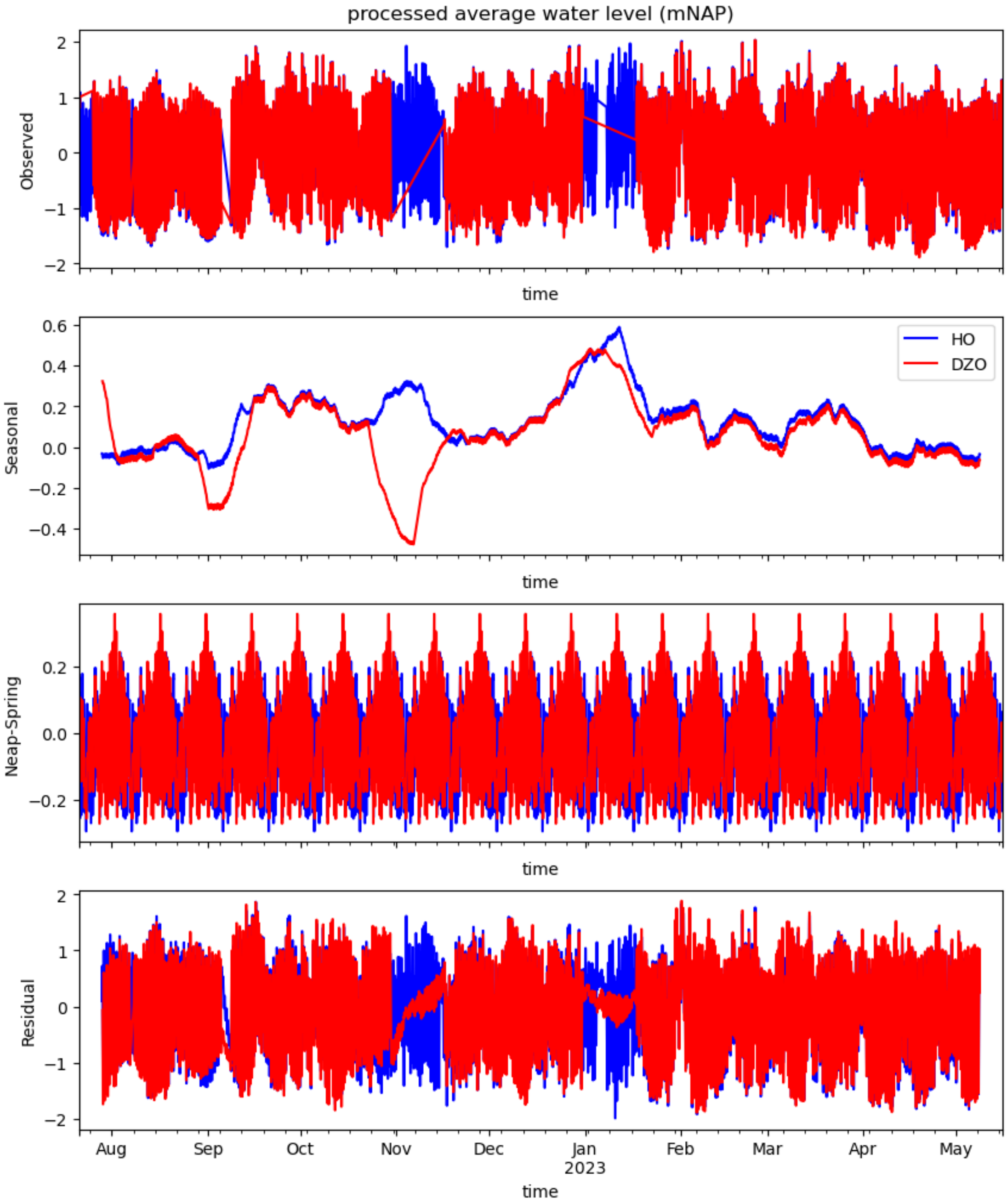


Figure 6-1. Seasonality analysis with the processed average water level.

Significant wave height (Figure 6-2**):**

The significant wave height is the average height of the highest third of waves, serving as a key metric in oceanography and coastal engineering. It provides a good representation of the wave conditions and the potential for wave-induced erosion or resuspension.

- Seasonal: Both Holwerd and Dantziggat exhibit comparable seasonal trends in significant wave height, ranging from 5 cm to 25 cm, with slightly higher waves were sometimes observed at Dantziggat in certain short period in September 2022 and April – May 2023. This consistency may suggest the broader meteorological and oceanographic factors that shape wave patterns in the region. Although the data incompleteness at Dantziggat skewed its overall trend, we still can see the average significant wave height is larger in autumn-winter due to hasher weather conditions and smaller in spring-summer. Setting aside the periods with data gaps, Holwerd seems to exhibit a slightly reduced seasonal trend compared to Dantziggat. This reduction at Holwerd might stem from its shallower depth, which facilitates greater wave damping or reduction in wave energy.

- Spring-Neap: The spring-neap tidal cycles show similarly in the significant wave height at both locations. The variations are usually between -6 cm and 7.5 cm. However, these tidal-induced variations are relatively subtle when compared against the original signal. This indicates that the influence of tidal currents on the significant wave height is minimal.

- Residual: Residual patterns, which capture deviations from the average or trend, are in general similar at both Holwerd and Dantziggat. This overall resemblance suggests that the mechanisms governing wave propagation remain consistent across both locations, whereas the differences arise due to unique local conditions, including factors like seabed topography, nearby landforms, or human-made structures, all of which can modulate wave propagation, growth and breaking.

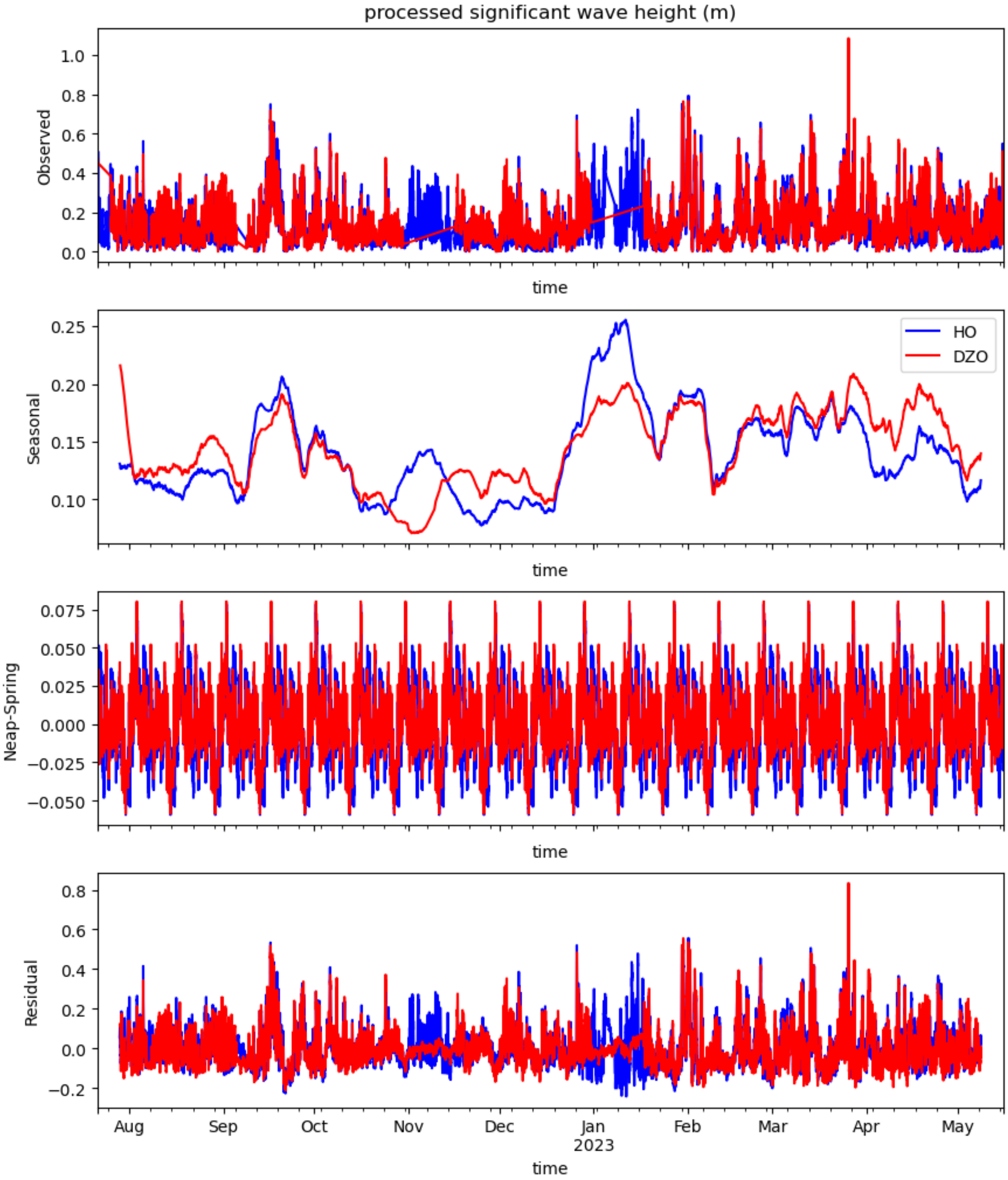


Figure 6-2. Seasonality analysis with the processed significant wave height.

Water temperature (Figure 6-3**):**

The water temperature readings at both the Holwerd and Dantziggat stations have exhibited strong similarities, suggesting a consistent thermal response to the surrounding environmental factors (Figure 6-3).

- Seasonal: The water temperature displays a clear seasonal pattern. During the summer months, temperatures increase up to around 22 °C. In the winter months, the water becomes colder, with readings dropping to about 2 °C in December to January.

- Spring-Neap: The water temperature experiences approximately 1.5 °C variations throughout a spring-neap cycle. Note that the variations in a spring-neap cycle is small but consistent. Hence it can likely be attributed to the changing water depths during this cycle, which can affect the volume of the water body, resulting in temperature variations as well.

- Residual: Beyond the seasonal and spring-neap variations, the water temperature also undergoes daily fluctuations, transitioning between day and night. The amplitude of these daily variations is particularly pronounced during the summer months, where temperature differences can span up to 10 °C within a 24-hour period. In contrast, the winter months witness more subdued daily variations, ranging between 3 to 5 °C. These daily fluctuations can be influenced by factors such as solar radiation, cloud cover, and atmospheric temperature.

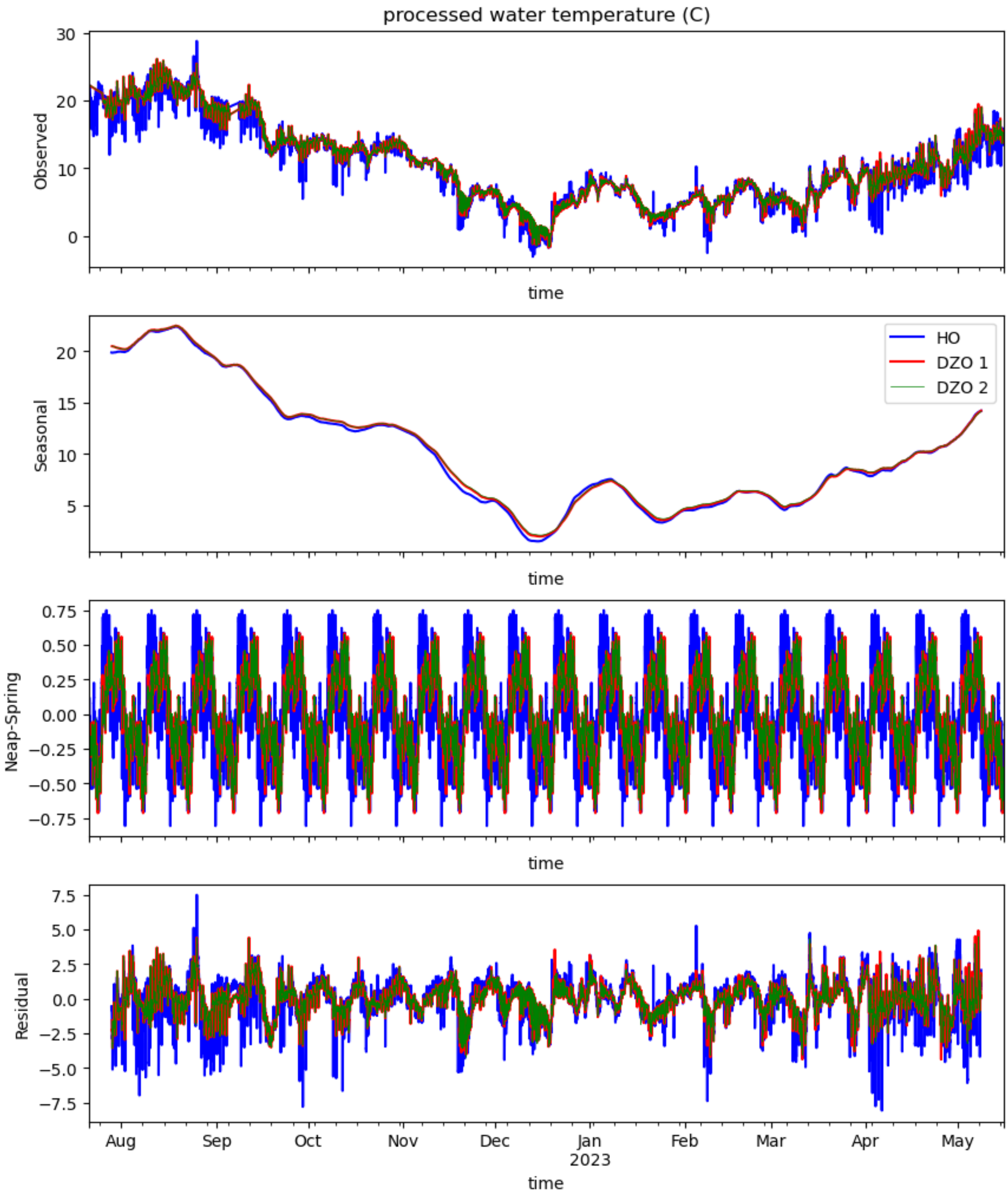


Figure 6-3. Seasonality analysis with the processed water temperature.

Salinity (derived from conductivity) (Figure 6-4**):**
Water conductivity in coastal areas is primarily influenced by salinity, with higher salt concentrations leading to increased conductivity. Tidal movements can cause fluctuations, with incoming tides increasing and outgoing tides decreasing conductivity. Freshwater influx, from sources like rivers or rainfall, dilutes salt concentration, reducing conductivity. Other factors include temperature, since warmer water has higher conductivity, and local sediment resuspension which can introduce minerals into the water. Additionally, organic matter decomposition can also influence conductivity.

Since conductivity is mainly influenced by salinity, in the analysis, it is converted to salinity using the formula Practical Salinity Scale of 1978 (PSS-78) (UNESCO, 1981). When comparing the salinity measurements from the two stations (Figure 6-4), patterns observed at Dantziggat indicate signs of biofouling, evident from the gradual increases followed by sudden drops in the timeseries data (also confirmed in the observed oxygen level and chlorophyll-a amd SPM concentrations). This aligns with the understanding that Dantziggat, being less affected by human activities, likely exhibits stronger biological activity when conditions are more favourable, hence more chances to be influenced by that. In contrast, Holwerd faces greater human influences, such as the passage of ferries, which can disrupt the local environment and might result in higher sediment concentrations and potentially limiting the level of biological activity.

- Seasonal: While the overarching trends in salinity are comparable between the two stations, Dantziggat showcases deviations that hint at the influence of biofouling. This presence of biofouling leads to a more pronounced divergence from the trend observed at Holwerd. Both stations demonstrate a pattern where water conductivity peaks during summer and decreases in winter. This phenomenon can likely be attributed to the higher freshwater discharge during the winter months, diluting the salt concentration in the coastal waters and subsequently reducing the salinity level.

- Spring-Neap: The fluctuations in salinity within the spring-neap cycles are more subtle when compared with the pronounced seasonal shifts between summer and winter. Holwerd, in general, exhibits smaller variations in salinity across these cycles compared to Dantziggat. This difference might stem from the unique environmental and biological factors at play in each location.

- Residual: On average, the short-term, residual fluctuations in salinity are comparable between the two stations. However, the more considerable short-term variations at Holwerd suggest the possibility of human-induced disturbances. It is worth pointing out that the IQR method is not able to remove all the data outliers automatically, hence in the residual signals we still could see some larger unphysical variations. This can be improved in future study.

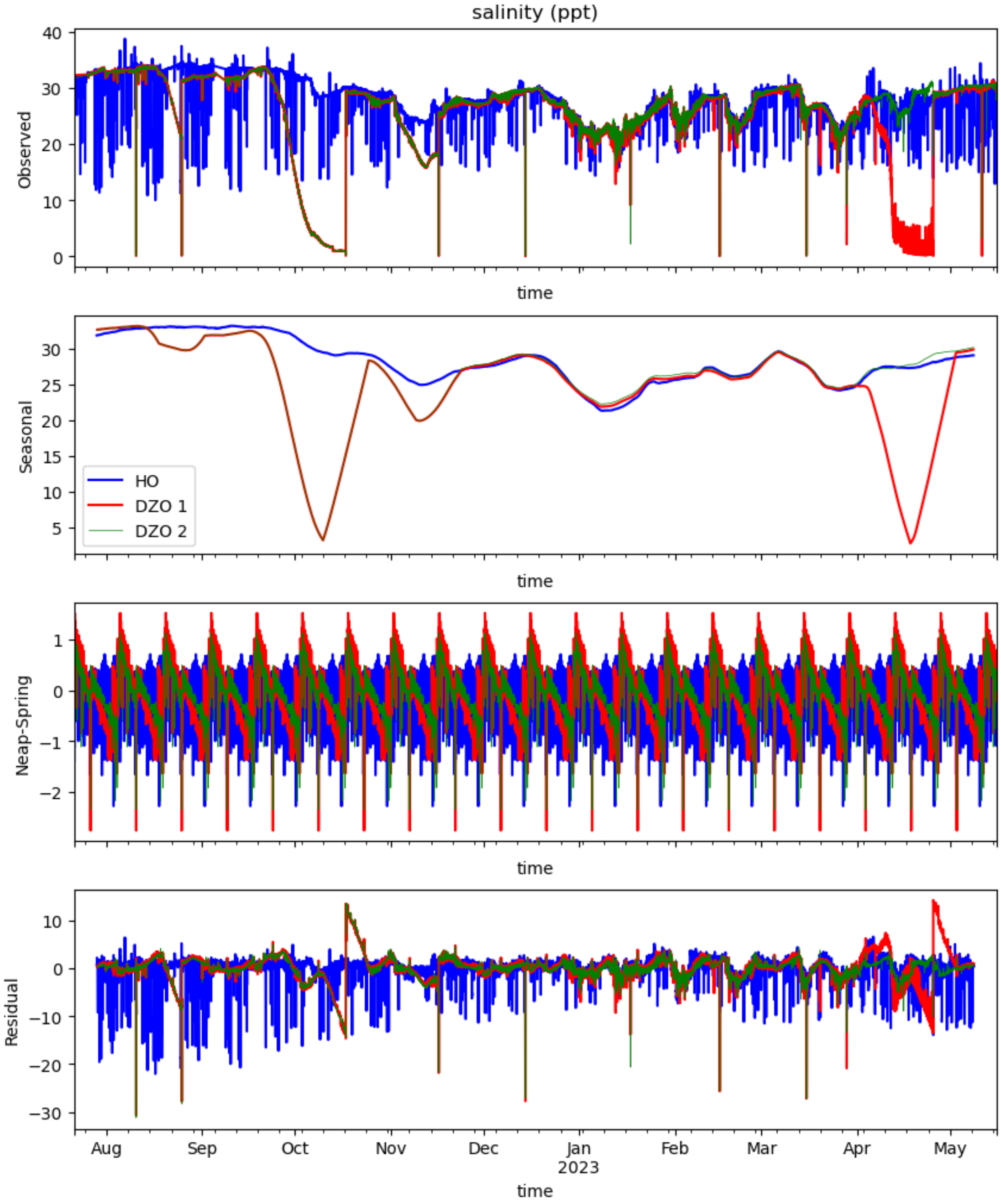


Figure 6-4. Seasonality analysis with the processed salinity.

Chlorophyll-a concentration: (Figure 6-5**):**

Chlorophyll-a concentration in coastal areas indicates primary production levels, with higher concentrations pointing to an abundance of photosynthetic organisms like phytoplankton. Sudden spikes can signal harmful algal blooms, which may produce toxins. Elevated levels often suggest nutrient enrichment, hinting at potential eutrophication from sources like agricultural runoff. Moreover, fluctuations in Chlorophyll-a can reveal environmental stressors, e.g., as a result of human impacts.

When analysing the chlorophyll-a concentrations at the Holwerd and Dantziggat stations, distinct temporal patterns, both long-term and short-term, become evident (Figure 6-5).

- Seasonal: Throughout the year, Holwerd exhibits a relatively consistent chlorophyll-a concentration. While there's a slight increase during the summer months, the fluctuations remain minimal, showcasing the station's stable biological activity/inactivity level. In contrast, Dantziggat displays more pronounced variations, with differences further emphasized by sensors placed at varying elevations. Notably, from mid-September to around the 20th of October, from the beginning to the middle of March, and from the middle to the end of May, signs of biofouling become noticeable (also indicated by the sudden changes observed in conductivity and oxygen level). This can be confirmed in the maintenance records in Table 3. Additionally, both sensors at Dantziggat detected strong increases in chlorophyll-a levels in November 2022 and April 2023, indicating a potential algae bloom. Post mid-November, intermittent high concentrations from December through March were recorded, albeit inconsistently, by only one of the two sensors. This inconsistency hints at localized processes or phenomena influencing chlorophyll-a concentrations. It's important to highlight that Holwerd has shallower waters, potentially allowing for less dilution hence could account for the marginally elevated long-term seasonal trend observed at Holwerd. On the other hand, Dantziggat, with its deeper waters and reduced disturbances, might serve as a nutrient reservoir. Such conditions at Dantziggat could promote more biological activities, especially when upwelling or mixing events occur in conjunction with other favourable conditions.

- Spring-neap: Dantziggat exhibits larger chlorophyll-a fluctuations during the spring-neap tidal cycles compared to Holwerd, suggesting larger variations in the level of biological activity as well. A contributing factor could be Dantziggat's greater depth relative to Holwerd, and less disturbance by human, which allows for a more diverse range of aquatic interactions.

- Residual: Dantziggat continues to show greater residual variations in chlorophyll-a concentrations. The significant surge in November 2022 and Aril 2023 raises the possibility of an algal bloom, potentially triggered by a substantial influx of nutrients. Taking into account the warmer water temperatures during this period, coupled with an observed increase in significant wave height, there's a likelihood that deeper, nutrient-rich waters got mixed with the surface. Such mixing events can serve as catalysts, providing the necessary ingredients for rapid algal growth and subsequent blooms.

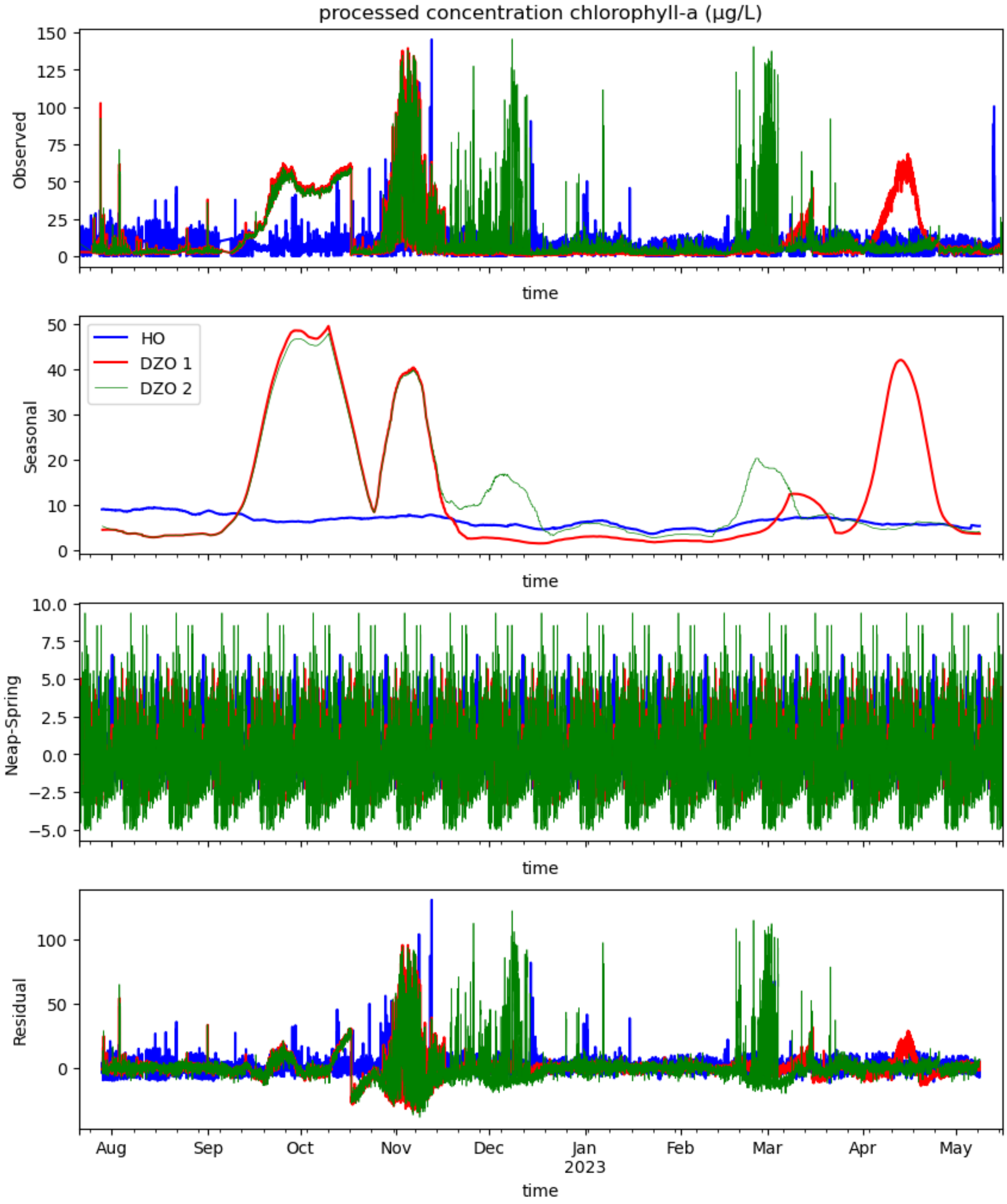


Figure 6-5. Seasonality analysis with the processed chlorophyll-a concentration.

SPM concentration (derived from turbidity) (Figure 6-7)**:**

Turbidity measures the concentration of suspended particles (both mineral and organic matters) in water column. **It**It is assessed using a nephelometer and is presented in Nephelometric Turbidity Units (NTU). Based on the analysis on the water samples at the measured locations (Figure 6-6), the turbidity has been converted to the concentration of suspended particulate matter (SPM) according to the calibration lines for total SPM concentration.

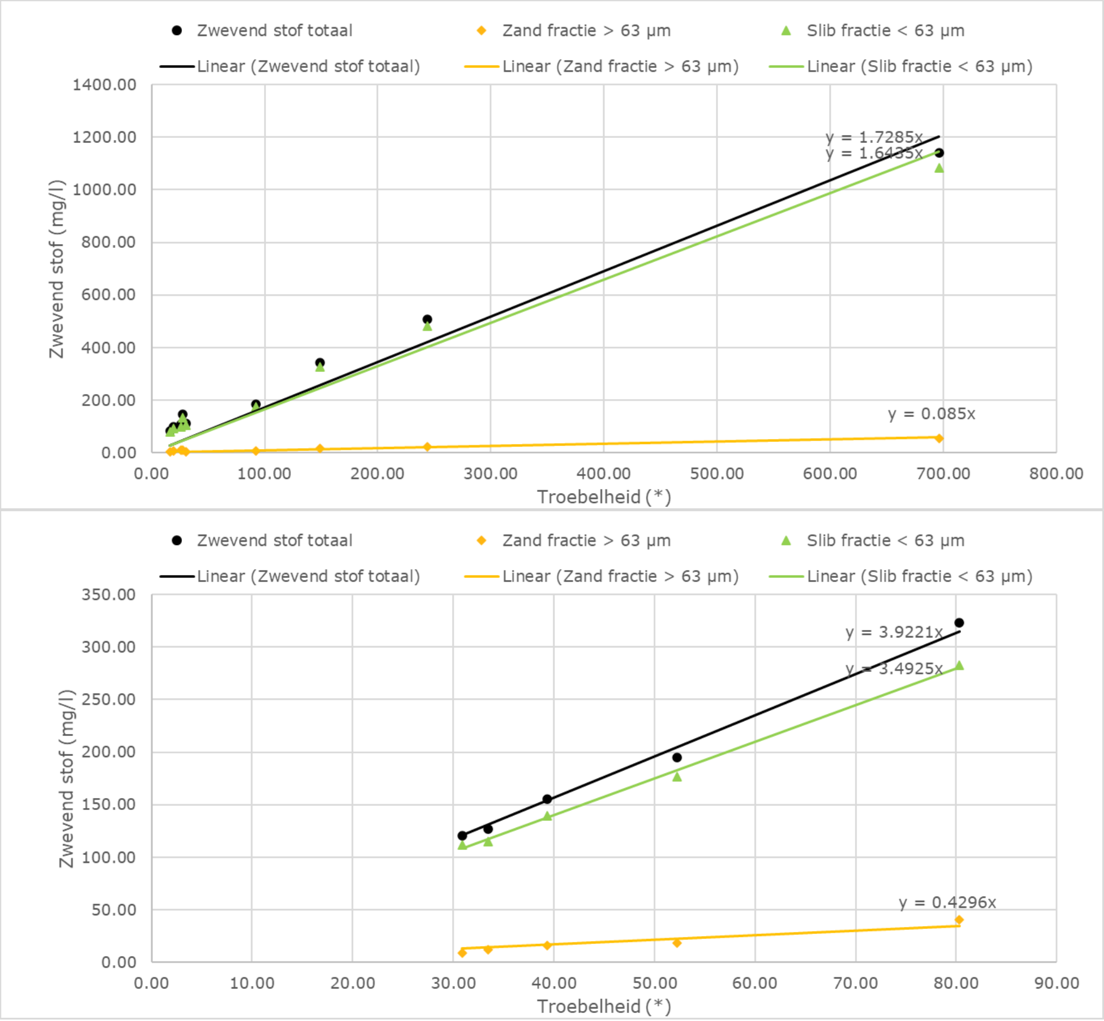


Figure 6-6. The derived relationships between measured turbidity and SPM concentration based on the water samples collected at Holwerd (top) and Dantziggat (bottom).

It is worth noting that, for converting turbidity data at Holwerd, the water samples for deriving the calibration lines were collected on 25th May 2023 and 14th August 2023, covering the range of turbidity from 15 to 700 NTU, meaning that the data points above this range are extrapolated; At Dantziggat, the water samples were collected on 14th August 2023, only covering the turbidity range from 30 to 80 NTU, which means a large portion of the data points are extrapolated and this could result in more uncertainties in the converted SPM concentration. This could be improved in the future monitoring, to collect more water samples that can cover wider range of the SPM concentration.

High SPM concentrations can be resulted from resuspension of solids, erosion, runoff, algal blooms, and certain disturbances like storms. Elevated SPM concentration levels can signal reduced water quality, affecting aquatic ecosystems by decreasing light penetration and primary production.

The SPM concentrations at Holwerd and Dantziggat reveal a blend of differences and similarities in their temporal patterns (Figure 6-6). These shared long-term trends suggest common underlying processes at play in both locations. However, the differences also indicate the influence of each site's unique local environment on SPM concentration levels.

- Seasonal: Holwerd exhibits less variations in the long-term seasonal SPM concentration levels, whereas Dantziggat shows lower concentration in summer and higher in winter. This suggests potentially larger impact of biological activities at Dantziggat, which may change the sediment properties, hence its settling behaviours. There's an intriguing deviation in the measurements from the two sensors at Dantziggat, particularly evident from mid-November onwards. It seems that some short-term fluctuations picked up only by one sensor and caused large deviations in the seasonal component. Despite these differences, both locations display similar overarching trends. SPM concentration peaks in the winter and decreases in the summer. This seasonal fluctuation hints at changes in particle characteristics throughout the year, such as variations in size, settling speeds, or shifts in their mineral and organic compositions. Another important observation is that the SPM concentration patterns at both locations correlate with trends in significant wave height especially in winter season, periods of heightened wave activity align with intervals of increased SPM concentration.

- Spring-neap: The changes in SPM concentration, especially during the spring-neap tidal cycles, are larger at Dantziggat than at Holwerd. This may indicate different particle properties, resulting in larger variations in SPM concentration during the cycles, or the differences in hydrodynamic and/or wave conditions.

- Residual: Residual SPM concentration signals are notably prominent at both stations. They are in general exceed the seasonal components, suggesting the stronger influence of short-term processes on SPM concentration. Factors such as erosion and deposition, driven by tidal currents, wind, and wave activity, also play an important role in determining SPM concentration levels.

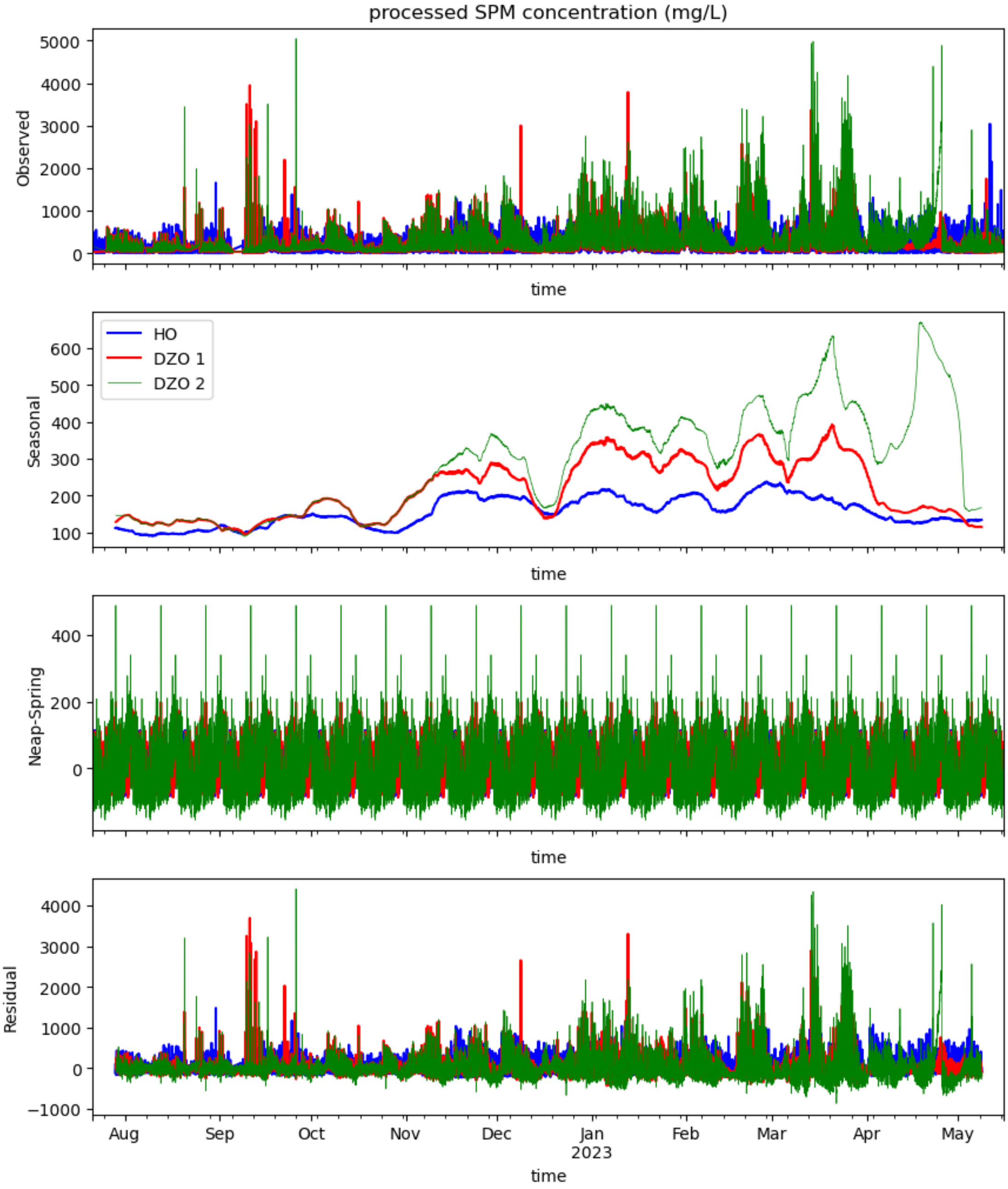


Figure 6-7. Seasonality analysis with the processed SPM concentrations.

6.2 Multivariate analysis

6.2.1 Correlation analysis

Correlation analysis is a statistical method used to evaluate the strength and direction of the linear relationship between two quantitative variables (Draper and Smith, 1998). Positive correlation usually indicates that as one variable increases, the other also increases, and vice-versa, whereas negative correlation indicates that as one variable increases, the other decreases. In this study, the non-parametric Spearman's method is applied, which has advantages when dealing with the data that has non-normal distributions. There are also limitations in this type of analysis, such as it doesn't imply causation, and only measures linear relationships. In addition to the parameters used in the previous seasonality analysis, velocity magnitude is also considered here. The velocity magnitude is derived by projecting both north and east velocity components along a direction of 70 degrees relative to the north, where positive values signify flood conditions and negative values indicate ebb. The correlation matrix derived from the analysis is shown in Table 6 and Table 7.

Based on the correlation matrices, the following observations can be made:

- Water depth has a notable correlation with significant wave height and velocity magnitude. The former implies that waves are attenuated more in shallow water and vice versa. The latter simply states that velocities are in general smaller during high water in this tidal environment.
- Velocity magnitude influences SPM concentration and has a relationship with chlorophyll-a concentration, suggesting both are subjected to flow-induced local erosion/resuspension processes Especially at Holwerd, this seems to be the dominant factor, whereas at Dantziggat temperature also has important influence.
- SPM concentration has a multifaceted relationship, being influenced by both velocity and chlorophyll-a concentration (which is also partially measured by SPM concentration). It also has weak negative correlation with temperature, indicating long-term seasonal variations. It is surprising to see low correlation with significant wave height. Further examination shows that, this is likely due to the orientation of the channel at Holwerd and Dantziggat, waves propagate towards shore and pass the two stations before peak ebb or peak flood flows (Figure 6-8). There might be minor changes in winter due to strong local wind, but in general it suggests wave actions alone cannot cause strong resuspension; it can only lead to high SPM concentration when they are aligned with high flow velocities.
- Although the values in the correlation matrix at Holwerd and at Dantziggat cannot be directly compared, it still shows the different characteristics at the two locations: SPM concentration is mainly driven by flow velocities at Holwerd, whereas it is more influenced by seasonal-changing processes at Dantziggat, such as salinity andbiological activity (chlorophyll-a concentration).

Table 6. Correlation analysis with the data at Holwerd

	water depth (m)	**velocity magnitude (m/s)**	**flow direction (degree)**	**water temperature (C)**	**salinity (ppt)**	**concentration chlorophyll-a (µg/L)**	**SPM concentration (mg/L)**	**significant wave height (m)**
water depth (m)	1.000	-0.543	-0.335	-0.008	0.035	0.024	-0.202	0.600
velocity magnitude (m/s)	-0.543	1.000	-0.125	-0.034	-0.099	0.285	0.527	-0.217
flow direction (degree)	-0.335	-0.125	1.000	0.022	0.045	-0.191	-0.152	-0.220
water temperature (C)	-0.008	-0.034	0.022	1.000	0.542	0.216	-0.197	-0.025
salinity (ppt)	0.035	-0.099	0.045	0.542	1.000	0.144	-0.152	-0.132
concentration chlorophyll-a (µg/L)	0.024	0.285	-0.191	0.216	0.144	1.000	0.479	0.050
SPM concentration (mg/L)	-0.202	0.527	-0.152	-0.197	-0.152	0.479	1.000	0.038
significant wave height (m)	0.600	-0.217	-0.220	-0.025	-0.132	0.050	0.038	1.000

Table 7. Correlation analysis with the data at Dantziggat

	water depth (m)	**velocity magnitude (m/s)**	**flow direction (degree)**	**water temperature (C)**	**salinity (ppt)**	**concentration chlorophyll-a (µg/L)**	**SPM concentration (mg/L)**	**significant wave height (m)**
water depth (m)	1.000	-0.224	-0.047	-0.044	-0.026	-0.062	-0.168	0.517
velocity magnitude (m/s)	-0.224	1.000	-0.366	0.133	-0.080	0.180	0.300	-0.126
flow direction (degree)	-0.047	-0.366	1.000	0.007	-0.002	-0.101	-0.100	0.063
water temperature (C)	-0.044	0.133	0.007	1.000	0.109	0.156	-0.230	-0.039
salinity (ppt)	-0.026	-0.080	-0.002	0.109	1.000	-0.533	-0.069	-0.057
concentration chlorophyll-a (µg/L)	-0.062	0.180	-0.101	0.156	-0.533	1.000	-0.030	-0.047
SPM concentration (mg/L)	-0.168	0.300	-0.100	-0.230	-0.069	-0.030	1.000	0.073
significant wave height (m)	0.517	-0.126	0.063	-0.039	-0.057	-0.047	0.073	1.000

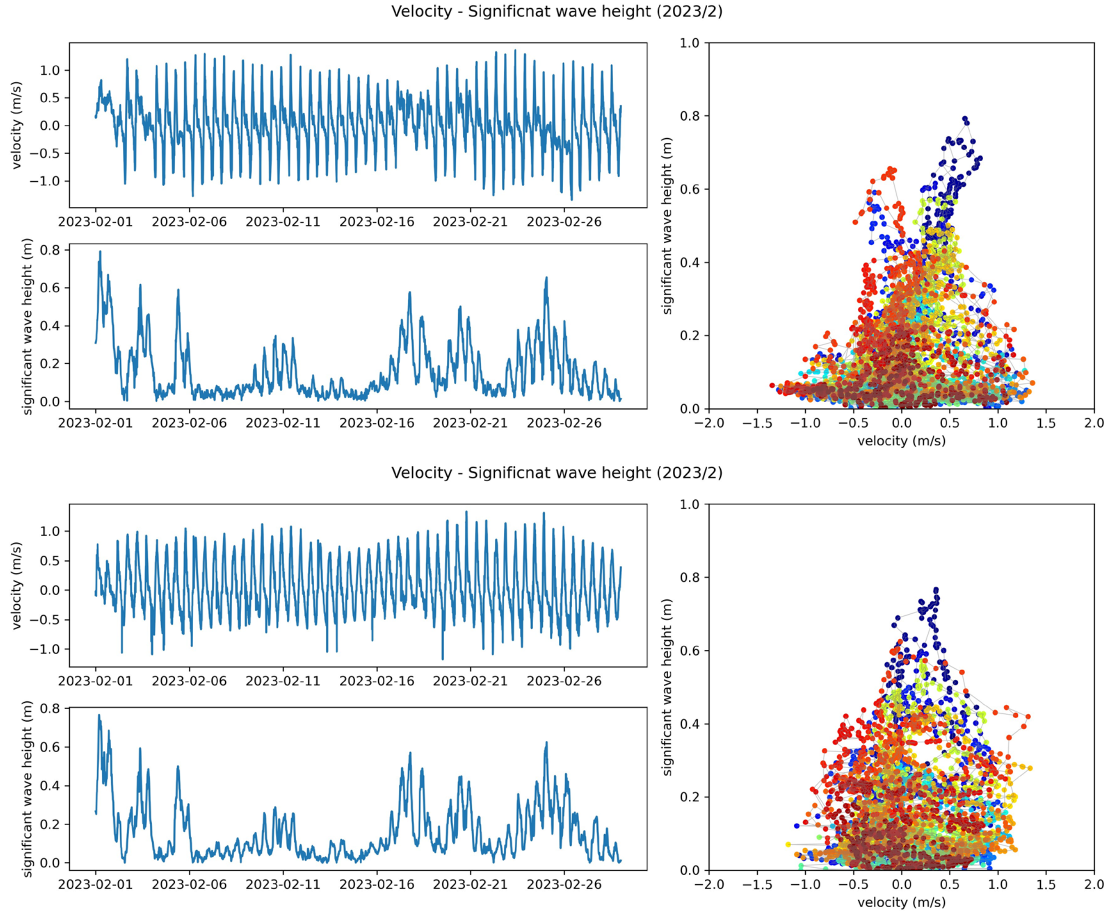


Figure 6-8. Measured velocity – significant wave height at Holwerd (top) and Dantziggat (bottom) in February 2023.

Both correlation matrices depict relationships among the same parameters. However, given the more extensive data gaps at Dantziggat and the potential impact of biofouling on certain measurements, the intensity of these correlations might differ. This variation is evident in relationships like that between water temperature and salinity, between SPM concentration and chlorophyll-a concentration, and between velocity and SPM concentration.

Yet, these matrices also offer intriguing comparative insights. For instance, the correlation between water depth and significant wave height is marginally weaker at Dantziggat than at Holwerd. This difference possibly stems from the varying water depths at the two locations. The stronger influence of temperature at Dantziggat may suggest that the biological effects are more pronounced compared to those at Holwerd.

6.2.2 Principal Component Analysis and clustering

The primary goal of Principal Component Analysis (PCA) is to transform the original variables into a new set of variables, the principal components, which are orthogonal (uncorrelated), and which reflect the maximum variance in the data (Everitt, et al, 2011). The first principal component reflects the most variance, the second principal component (which is orthogonal to the first) reflects the second most, and so on. Once all the principal components are obtained, it's possible to reduce the number of dimensions by selecting the top *k* principal components, where *k* is less than the original number of variables. This reduced set can capture a significant proportion of the total variance of the original data. This dimensionality reduction is useful in visualization, identifying patterns in the data. Before applying PCA, it's typically essential to standardize the data (mean of 0 and variance of 1 for each feature). This ensures that the principal components aren't influenced by the natural scales of the features. The results from PCA are shown in Table 8 and Table 9.

It is worth noting that the normalization of the data is done for each location separately. Because the derived principal components and the loadings of parameters are different, they cannot be compared directly. But the relative importance among the parameters at each location are still comparable.

Table 8. PCA results with data at Holwerd (variables and their loadings on the principal components)

	PC1	**PC2**	**PC3**
velocity magnitude (m/s)	0.534	-0.336	-0.041
flow direction (degree)	-0.273	-0.540	0.093
water temperature (°C)	-0.035	0.090	0.882
concentration chlorophyll-a (µg/L)	0.517	0.144	0.387
SPM concentration (mg/L)	0.610	-0.057	-0.201
significant wave height (m)	-0.006	0.751	-0.147

At Holwerd, based on the PCA results (Table 8), the following observations can be made:

- PC1: main parameters with higher loading are SPM concentration, velocity, and chlorophyll-a concentration. This could represent close relationships between velocity and the SPM and chlorophyll-a concentrations. It might capture the variability due to local erosion and resuspension.

- PC2: main parameters are significant wave height, and flow direction. PC2 could be capturing variability related to wave action and flow direction. Higher values are associated with higher wave heights and lower flow directions (flood phase) and velocities. It might represent certain stage during tidal wave propagation with wave height being a dominant factor.

- PC3: main parameter is water temperature. PC3 seems to capture temperature variability primarily. Higher PC3 values are associated with higher water temperatures and chlorophyll-a concentrations, and lower SPM concentrations and wave heights. It could be related to seasonal changes, where temperature and biological activity (indicated by chlorophyll-a concentration) vary.

Based on the derived principal components, the original data can be remapped in the PCA space and further investigated (Figure 6-9 and Figure 6-10) in clustering analysis.

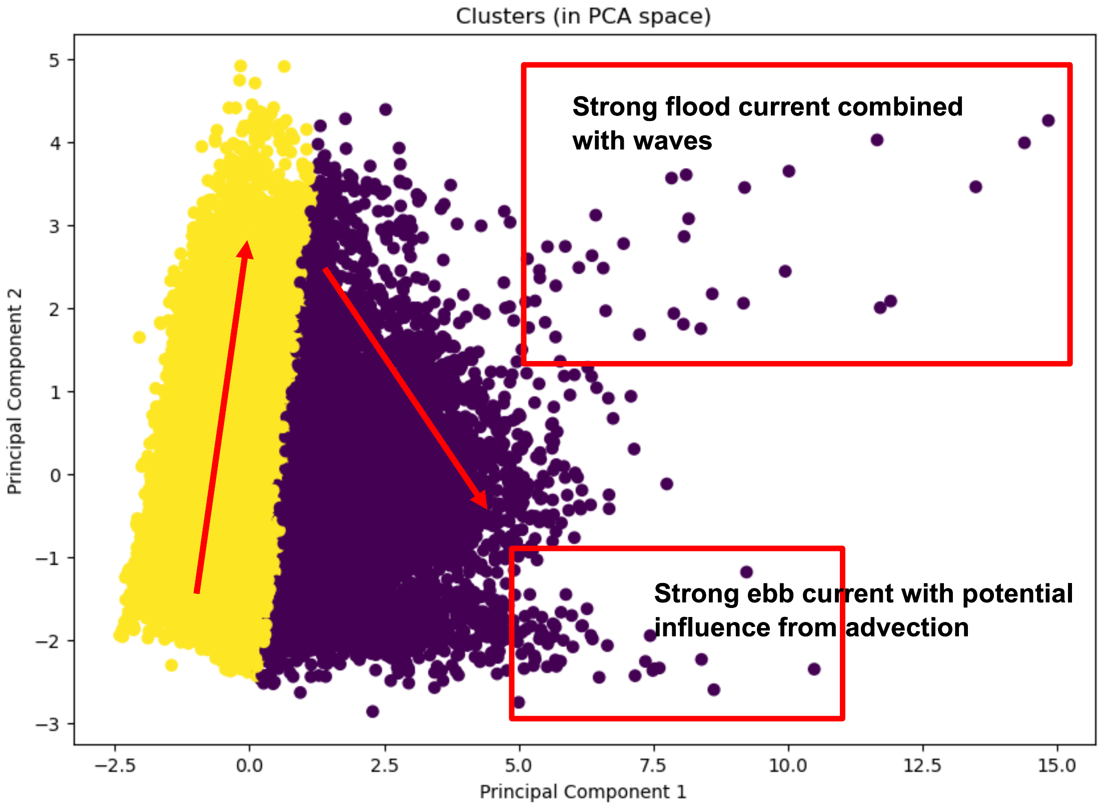


Figure 6-9. Remapped data at Holwerd in PCA space (PC2 against PC1).

In Figure 6-9, several patterns can be recognized from clustered results. For example:

- The yellow cluster mainly represents the conditions with relatively low velocities and low SPM and chlorophyll-a concentrations, basically the lower bounds of these parameters. The upper section corresponds to the flow during flood phase with strong wave actions, while the lower section the ebb flow with weak wave actions. The negative correlation between waves and flow directions indicates that strong waves are more likely to happen during flood than during ebb. It is interesting to notice that even when the PC2 values are higher at some moments, it doesn't trigger higher SPM and chlorophyll-a concentrations when velocities are low. This means waves have to be combined with high velocity to strongly impact SPM concentration. Another thing that can be observed is the asymmetry, the lower bounds of velocities and concentrations increase from ebb to flood.

- The purple cluster could belong to the conditions with strong velocities, and high SPM and chlorophyll-a concentrations. The upper right section corresponds to the strong flood current combined with strong waves, the result is high SPM and chlorophyll-a concentrations. The lower right section mainly represents the strong ebb currents and high concentrations, with small waves. If ignoring the scattered points at the upper right corner, one can notice the higher velocities and concentrations increase during the transition from flood to ebb, which shows the overall asymmetry (slightly ebb dominant) in the data, this may indicate that the possible influence from nearby tidal flats during ebb flow.

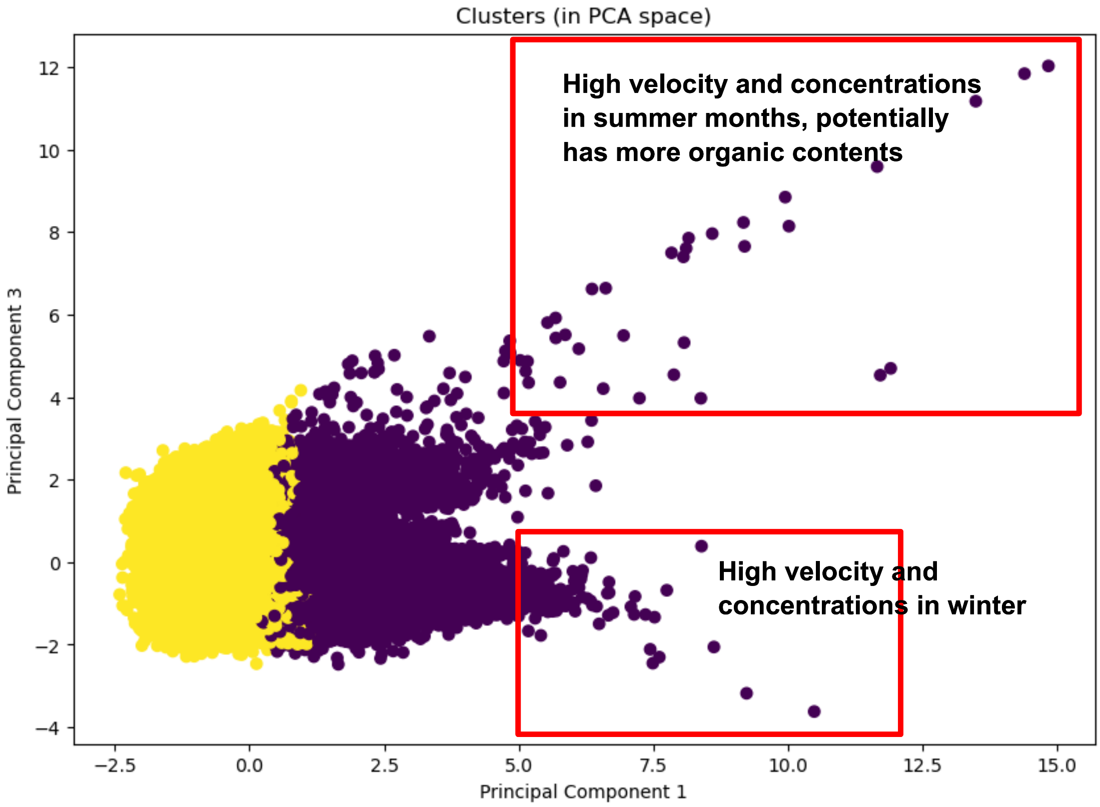


Figure 6-10. Remapped data at Holwerd in PCA space (PC3 against PC1)

In Figure 6-10, different patterns and events can be revealed from different aspects:

- The yellow cluster represent the lower bounds of flow velocities, SPM and chlorophyll-a concentrations. In this group, the influence of temperature (PC3) is not strong.

- The purple cluster shows that in summer months (higher values on PC3), high velocity could lead to high concentrations with potentially more organic contents due to the association of temperature with chlorophyll-a concentration; in winter months, high velocity again could result in high concentrations, but the organic content may be low (higher inorganic content). In general, this shows the seasonal variations in flow conditions and SPM and chlorophyll-a concentrations.

At Dantziggat, based on the derived principal components and parameters loadings (Table 9) one can conclude as follows:

Table 9. Results from PCA with data at Dantziggat (variables and their loadings on the principal components)

	PC1	**PC2**	**PC3**
velocity magnitude (m/s)	0.665	0.016	0.029
flow direction (degree)	-0.539	-0.044	0.066
water temperature (C)	0.105	-0.650	0.257
concentration chlorophyll-a (µg/L)	0.317	-0.391	0.352
SPM concentration (mg/L)	0.347	0.596	0.127
significant wave height (m)	-0.188	0.260	0.888

PC1: Positively correlated with "velocity" (0.665), "concentration chlorophyll-a" (0.317), and "SPM concentration" (0.347). Negatively correlated with "flow direction" (-0.539) and slightly with "significant wave height" (-0.188). Higher values of PC1 are associated with higher velocities and concentrations of chlorophyll-a and SPM, while being associated with a flood flow direction and small waves. This might capture the variability in concentrations due to flow velocity especialy during flood.

PC2: Positively correlated with "SPM concentration" (0.596) and "significant wave height" (0.260). Strongly negatively correlated with "water temperature" (-0.650) and also with "concentration chlorophyll-a" (-0.391). PC2 appears to represent a contrast between hydrodynamic and biological conditions. Higher values of PC2 are associated with higher SPM concentrations and wave heights, but lower water temperatures and chlorophyll-a concentrations. This might indicate a scenario where SPM concentration is higher in winter months due to wave actions when biological activity are more superessed.

PC3: Strongly positively correlated with "significant wave height" (0.888). Also positively correlated with "concentration chlorophyll-a" (0.352) and "water temperature" (0.257). PC3 seems to be predominantly influenced by wave conditions. Higher values of PC3 are associated with higher wave heights. The positive correlation with chlorophyll-a and water temperature might indicate that higher waves are associated with increased biological activity or mixing events and warmer water temperatures, which could be seasonal or related to specific events like storms.

As seen in §6.2.1, the dominant processes that affect SPM concentration are different at Dantziggat. Hence, the loadings of different parameters on the principle components also become different. Based on the derived principal components, the original data can be projected in the PCA space as shown in Figure 6-11 and Figure 6-12, and the prjected data points can be divided into two groups.

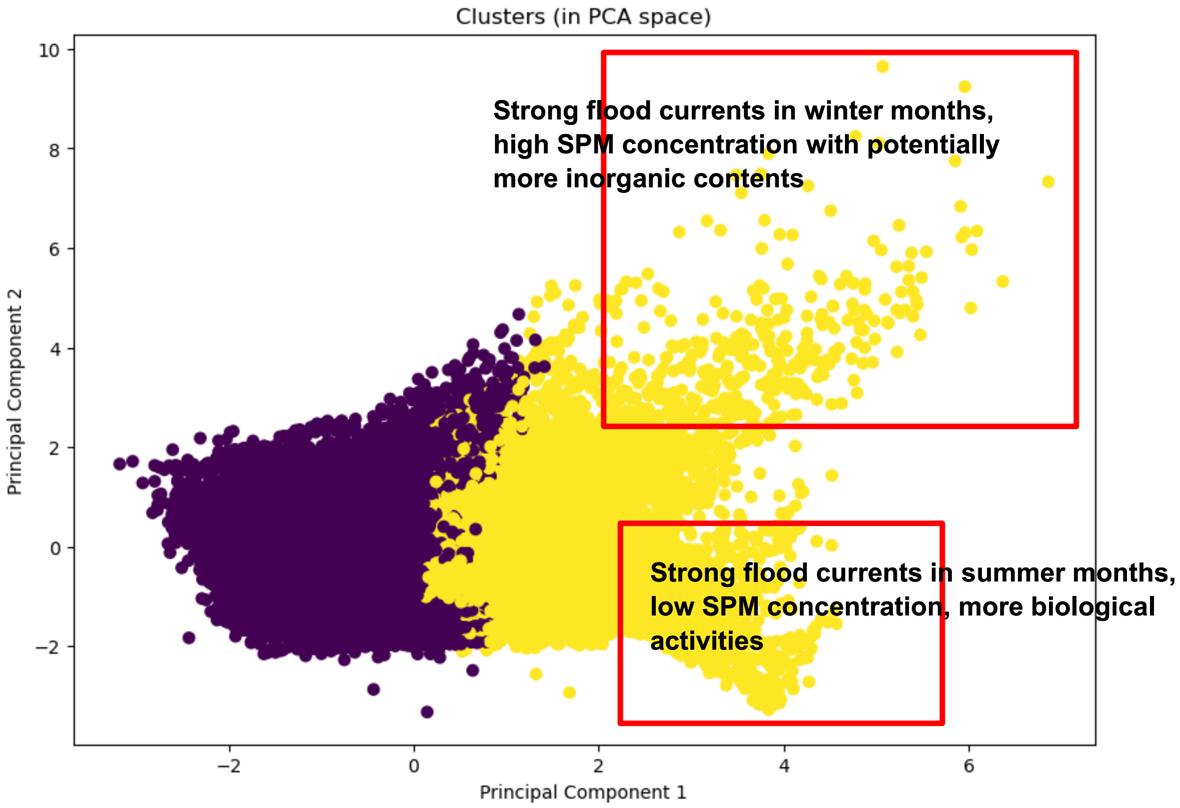


Figure 6-11. Remapped data at Dantziggat in PCA space (PC2 against PC1).

According to Figure 6-11, one can observe that the purple cluster represents conditions characterized by relatively low velocity, typically observed during the ebb phase, coupled with reduced SPM concentrations. The yellow cluster represents conditions with high flow velocities, especially during flood phase. If combining the two clusters, it is obvious that high SPM concentrations with more inorganic contents (low chlorophyll-a concentrations) more likely appear during strong flood flow in winter season; whereas low SPM concentration with high high organic contents can be found in summer months marked by elevated water temperatures and relatively high concentrations of chlorophyll-a.

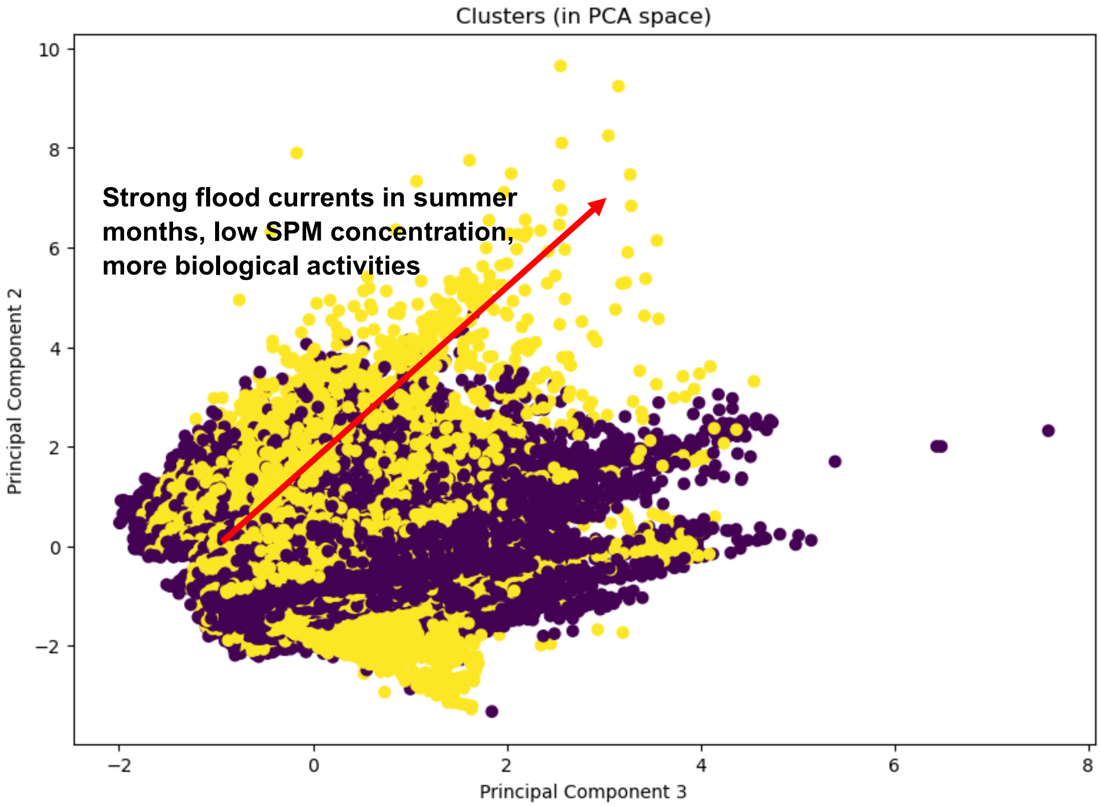


Figure 6-12. Remapped data at Dantziggat in PCA space (PC2 against PC3).

Figure 6-12 shows that, from summer to winter SPM concentration increases as significant wave height becomes larger. But the highest SPM concentration doesn't corespond to the largest wave height. Instead, the wave actions only show large impact on the SPM concentrations when they are aligned with flood currents. Another observation is that the increase of significant wave heigh is also accosiated with the increase of chlorophyll-a concentration. When water temperature increases, it seems to result in higher chlorophyll-a concentration due to potential mixing events from wave actions, and based on the previously clustering results, those data points (purple) are linked to the ebb flow, indicating potential impact from nearby intertial areas.

6.2.3 Regression analysis

Multivariate regression analysis predicts a dependent variable using two or more independent variables. It extends simple linear regression to incorporate multiple predictors. The key components include the dependent variable (outcome) and independent variables (predictors). The relationship is expressed through an equation where each independent variable has an associated coefficient indicating its influence on the dependent variable, while keeping other variables constant (Neter et al. 1996). The analysis has certain assumptions like linearity and independence of errors. Potential challenges include multicollinearity, where predictors are highly correlated. This could result in problems such as unstable coefficients, reduce model accuracy, and overfitting. To reduce multicollinearity when predicting SPM concentration, some known highly correlated variables are excluded, e.g., concentration chlorophyll-a, and conductivity (correlated with water temperature). Each data has been standardized before performing the regression analysis, therefore, it allows for direct comparison of the strength of relationships between different predictors and the dependent variable at the same location. The fitted coefficients are shown in Table 10. The comparisons between the predictions and measurements are shown in Figure 6-13 and Figure 6-14.

Table 10. features and their coefficients in the fitted linear regression model (Holwerd)

Feature	Coefficient (Holwerd)	Coefficient (Dantziggat)
velocity magnitude (m/s)	0.546088	0.305728
significant wave height (m)	0.170375	0.275476
water depth (m)	-0.022464	-0.267194
water temperature (C)	-0.182535	-0.276782

The fitted coefficients show that:

- Velocity has a positive effect on SPM concentration at both locations, but the effect is stronger at Holwerd.
- Significant Wave Height positively influences SPM concentration at both sites, with a slightly more substantial impact at Dantziggat.
- Water Depth has a negative relationship with SPM concentration at both sites, but the association is more pronounced at Dantziggat.
- Water Temperature negatively impacts SPM concentration at both locations, with a more substantial effect at Dantziggat.

In the regression analysis, again, it shows that there is no strong influence of significant wave height on SPM concentration, as explained in section 6.2.1, the wave actions should be combined with high velocity to have big impact on SPM. This is consistent with previous findings.

It's also noteworthy that during winter at Holwerd, the SPM concentration measurements exhibit high-frequency oscillations that the regression model fails to predict. In contrast, at Dantziggat, such oscillations are more suppressed. It is also worth noting that the performance of the regression model at both locations is far from satisfying in some months. The full results can be found in Appendix A.4.

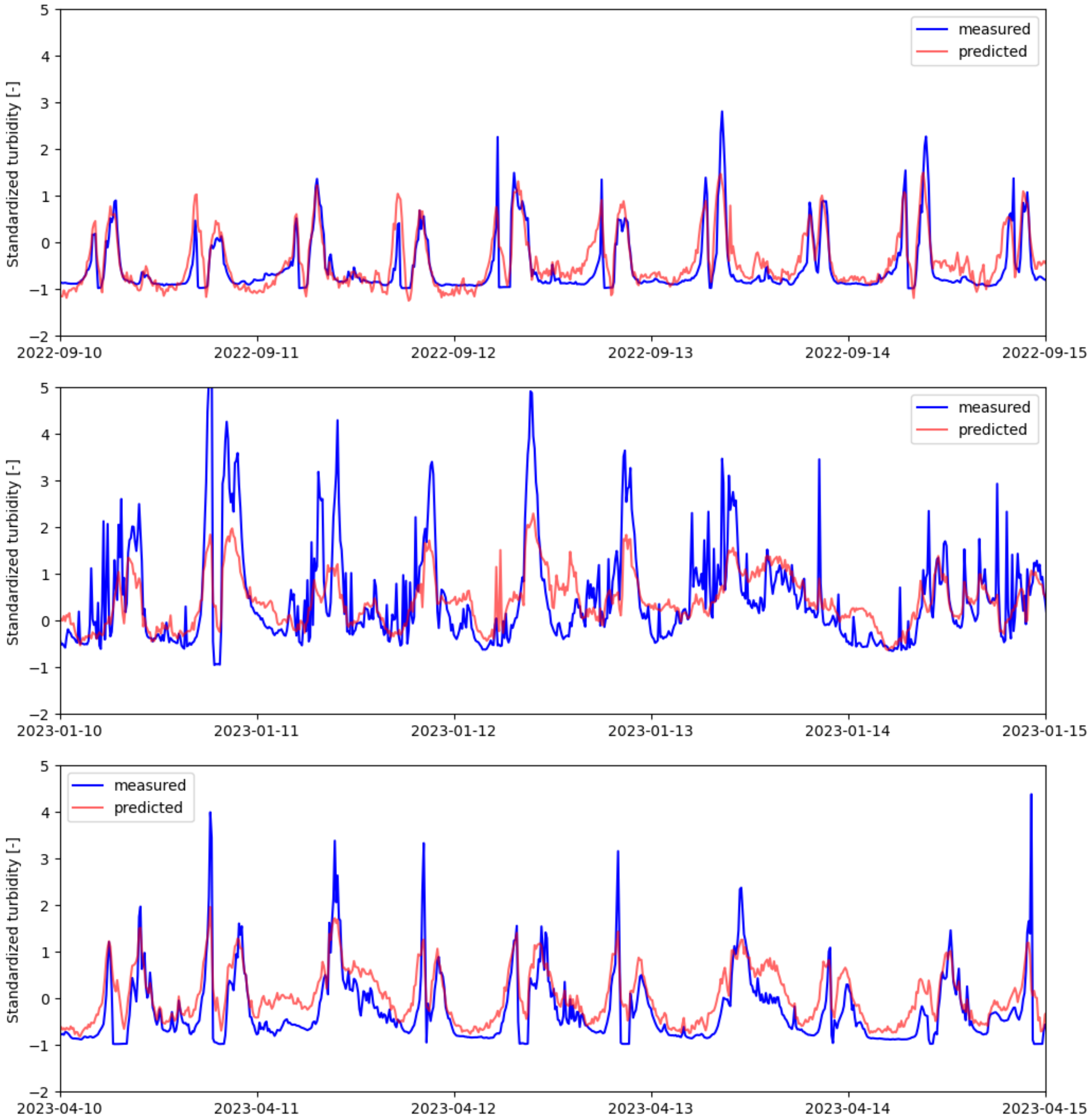


Figure 6-13. Fitted regression model and measurements in selected periods at Holwerd.

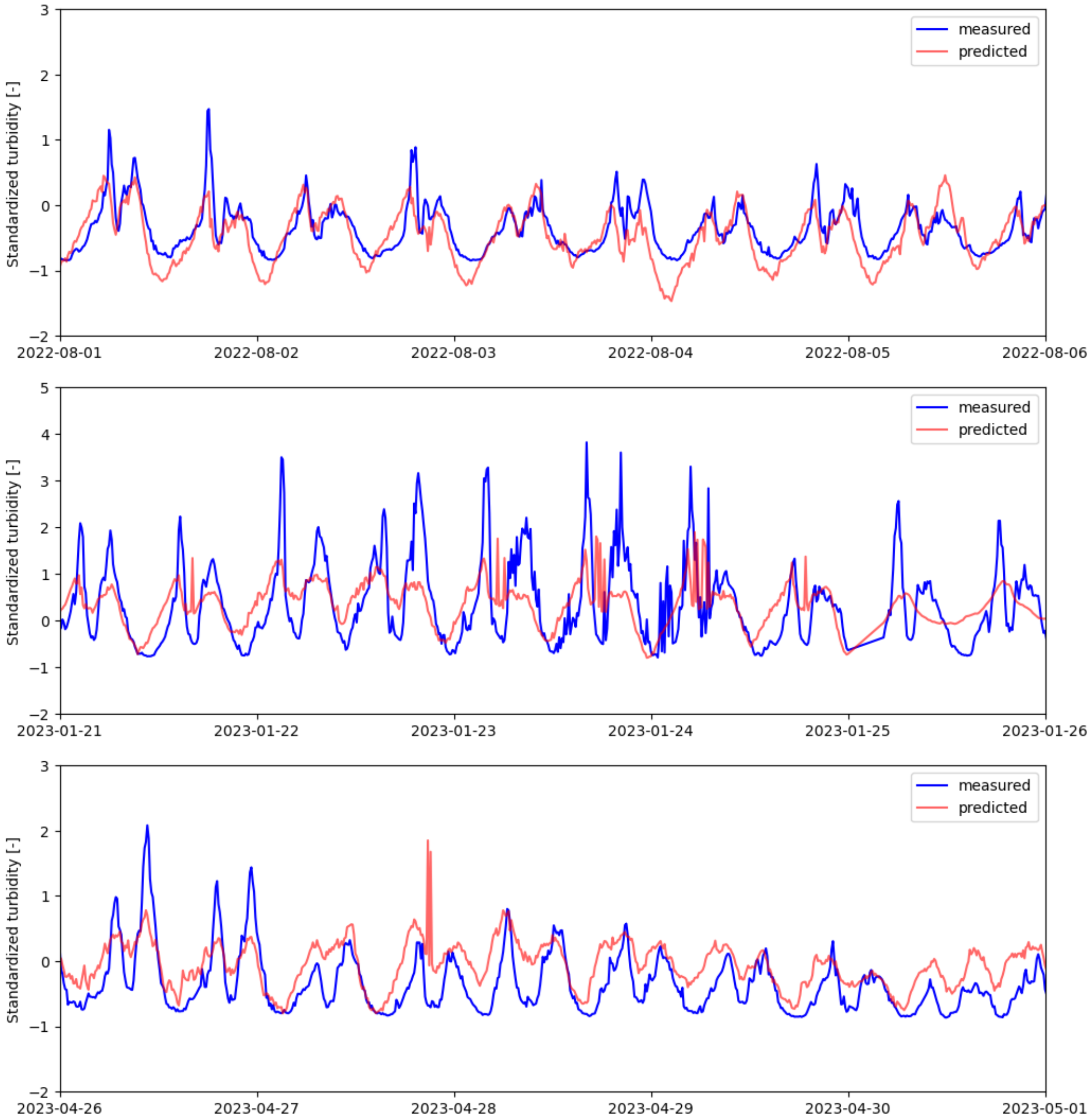


Figure 6-14. Fitted regression model and measurements in selected periods at Dantziggat.

6.2.4 Influencing factors on SPM concentration

To gain a more profound understanding of the connection between flow conditions and SPM concentration at Holwerd and Dantziggat, we've generated plots showing SPM concentration as a function of flow velocity (horizontal tide) and SPM concentration as a function of water depth (vertical tide), aiming to reveal more patterns. Velocities are projected in a direction of 70 degrees relative to the north, where positive values signify flood conditions and negative values indicate ebb. The selected results are shown in Figure 6-15 - Figure 6-17.. The full set of plots can be found in 10A.5 and 10A.6.

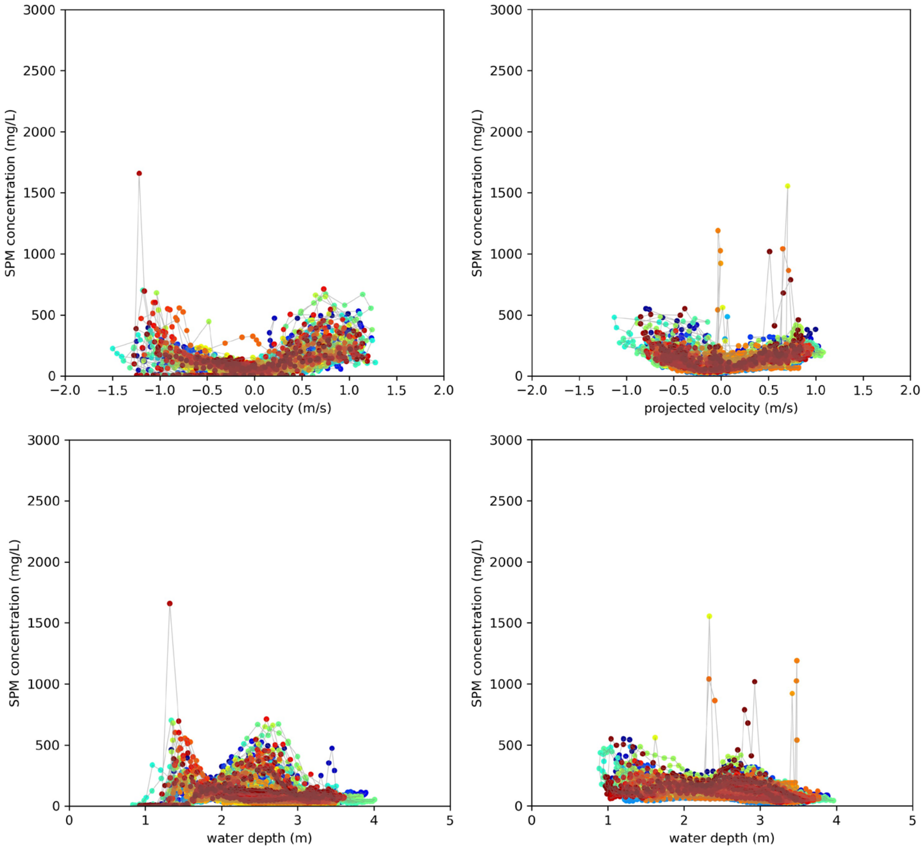


Figure 6-15. SPM concentration against velocity and water depth at Holwerd (left column) and at Dantziggat (right column) in August 2022

In the month of August, a positive correlation occurs between SPM concentration and flow velocity at the Holwerd station. Peaks in SPM concentration coincide with peaks in velocity magnitudes, with a slightly higher SPM concentration level during the flood phase. A similar trend is identified at the Dantziggat station, albeit with a reduced SPM concentration magnitude. This could be due to stronger biological activities in summer that changes the particle properties and/or bed erodibility, hence the SPM concentration level, especially at Dantziggat, shows a minor elevation during the ebb flow.

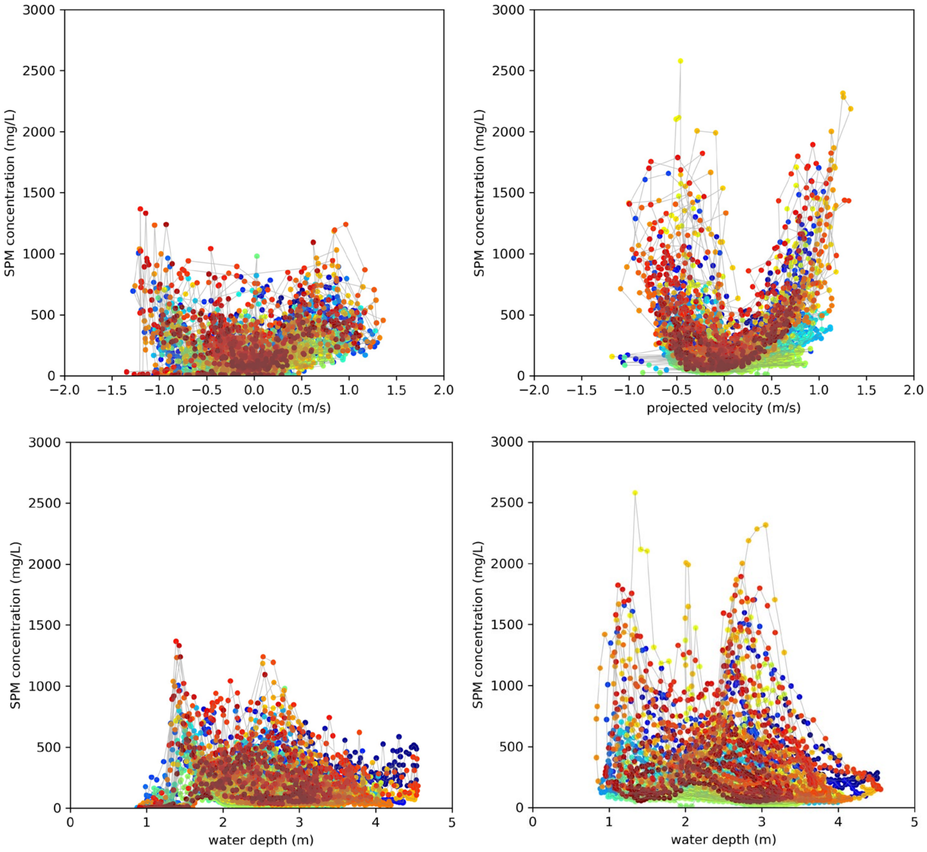


Figure 6-16. SPM concentration against velocity and water depth at Holwerd (left column) and at Dantziggat (right column) in February 2023

Transitioning to February, the differences between the two locations becomes more pronounced. At Holwerd, high SPM concentration is not exclusively related to the high velocities. Intervals of slack tides also show relatively large SPM concentration values. This phenomenon could be attributed to Holwerd's shallower depth, where the wind, especially during the winter months, may play a more influential role in stirring up sediments, thereby augmenting SPM concentration.

At Dantziggat, the SPM concentration level is increased considerably in winter compared to the summer, indicating larger seasonal variations, possibly due to the changes in suspended particle properties and biological activity levels. Unlike Holwerd, Dantziggat is deeper and there aren't any noticeable peaks in SPM concentration during slack water. Overall, SPM concentration at Dantziggat during flood is slightly higher than during ebb.

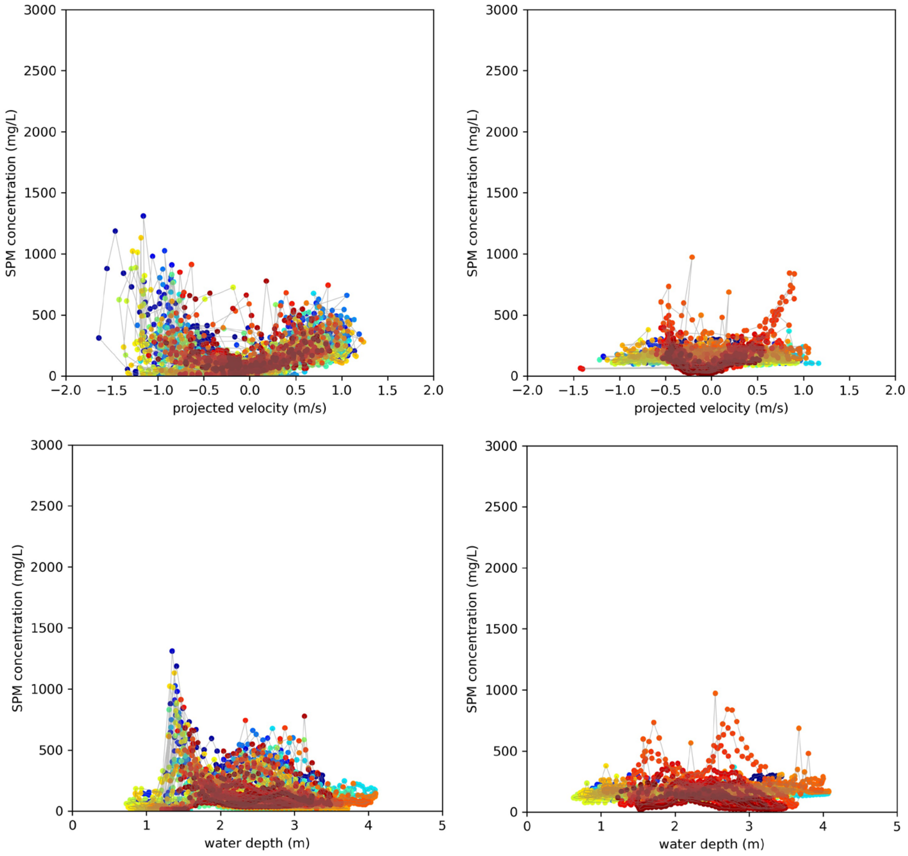


Figure 6-17. SPM concentration against velocity and water depth at Holwerd (left column) and at Dantziggat (right column) in April 2023

In April, SPM concentration levels at Dantziggat are lower, also in comparison to SPM levels at Holwerd. Nevertheless, a modest increase in SPM concentration during the flood phase persists. At Holwerd, the previously observed SPM concentration peak during slack tide disappears. Instead, there emerges a clear correlation between SPM concentration peaks and large flow velocities. What is particularly intriguing is Holwerd's ebb dominance, characterized by larger velocities during the ebb flow phase. Consequently, SPM concentration levels also exhibit a higher level during this ebb phase.

6.3 Impact of human activities

Holwerd and Dantziggat, while geographically proximate, are quite different in terms of human interference. Holwerd is largely influenced by human activities, such as ferry movements and dredging/disposal operations for maintaining the navigation channels nearby. These activities may introduce various influences on the ecosystem dynamics. On the contrary, Dantziggat remains largely unaffected by human activities, hence, by comparing the data between both stations, it will help to gain better understanding of the consequence of human interventions to the system.

6.3.1 Influence of ferries

Holwerd is located close to a pier frequently used by ferries. One of the assumptions is that the movement (departure and arrival) and idling of these ferries might stir up the bottom sediments, leading to increased SPM concentration level. To investigate this, ferry tracking data (known as AIS) has been analysed together with SPM concentration at Holwerd (Figure 6-18. and Figure 6-19.).

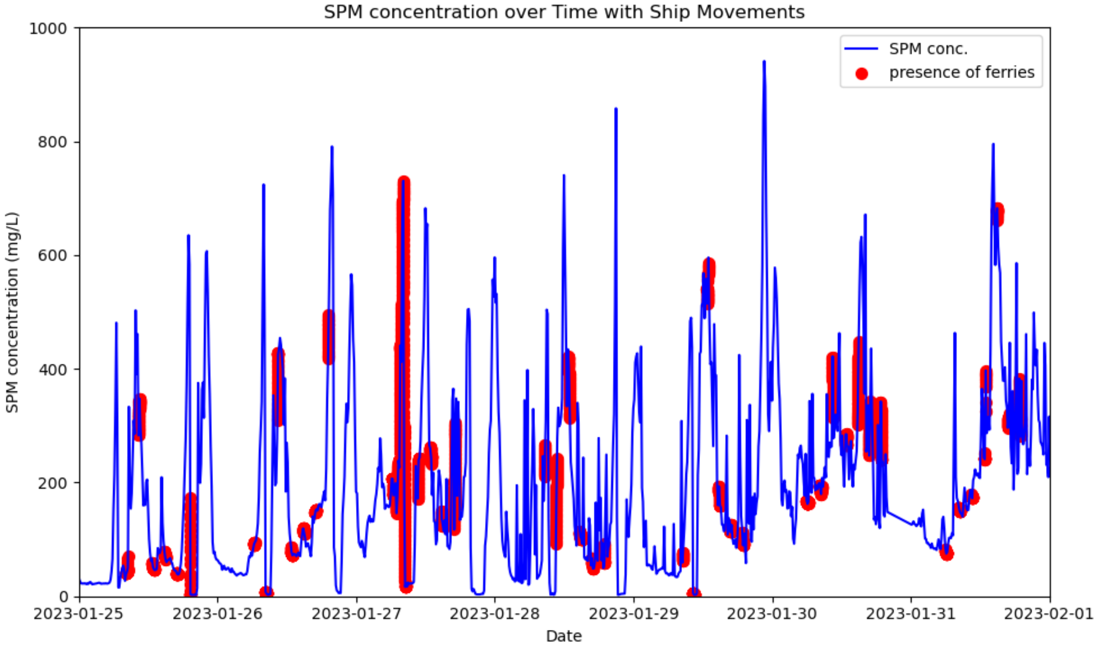


Figure 6-18. The zoom-in comparison between measured SPM concentration at Holwerd and the moments of ferry presence.

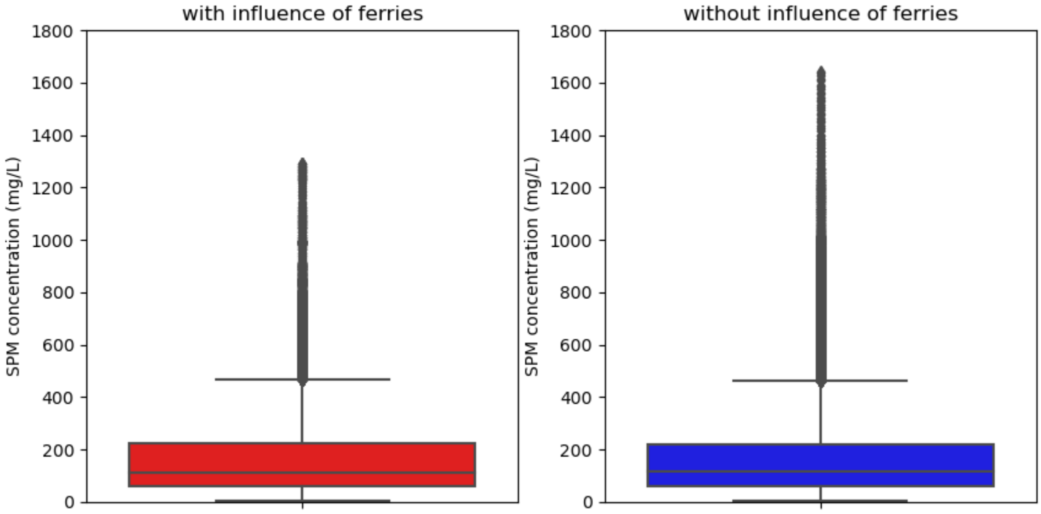


Figure 6-19. Derived statistics from the SPM concentration data at Holwerd with and without potential influence of ferries.

Above analysis shows that there are instances when SPM concentration peaks temporally coincide with recorded ferry movements at the pier, implying a possible causal relationship. But there are also other moments without any coincidence of SPM concentration peaks and presence of ferries.

Therefore, a statistical analysis is performed to get more insights. A boxplot, comparing SPM concentration metrics during periods of ferry presence (left) and absence (right), reveals an unexpected trend. Contrary to assumptions, high SPM concentration values more frequently coincide with periods without ferry activities.

Several hypotheses might explain this phenomenon. It could be that the ferry-induced disturbances are highly localized, or the influence of the disturbances might be so persistent that they become a 'background' SPM concentration level, i.e., the time scale of the impact is larger than the interval of the disturbances. But currently there is no evidence to support the latter hypothesis.

6.3.2 Influence of dredging and disposal

Dredging and disposal activities in the Wadden Sea, including near Ameland, have been topics of environmental concern and research. These activities can have various environmental impacts, such as:

- Disturbance to the seabed: Dredging can disturb the seabed, impacting benthic organisms and habitats.
- Sediment plumes: The resuspension of sediments during dredging can lead to the formation of sediment plumes, which can smother marine habitats and reduce light penetration, affecting photosynthetic organisms.
- Release of contaminants: If the dredged sediments contain pollutants or contaminants, these can be released into the water column.
- Physical alteration of habitats: The disposal of dredged material can lead to the physical alteration of marine habitats, potentially impacting the species that rely on them.

However, it's worth noting that dredging and disposal activities can be managed to reduce their environmental impacts. There are guidelines and best practices that can be followed to ensure that these activities are conducted in an environmentally responsible manner. Hence, monitoring and research are also crucial to understanding the potential impacts and ensuring that they are minimized.

In this study, the data regarding the dredging and disposal activities has been collected and analysed. For comparison, monitored SPM concentration data at Holwerd, the results from a calibrated point model (6.4.1) and the SPM concentration during the dredging/disposal activities in the ‘ferry dam Holwerd’ are plotted together. A few examples can be seen in Figure 6-20. and Figure 6-21.. Observed turbidity is plotted in blue for time intervals without dredging or disposal activities and in red for time intervals with dredging or disposal activities.

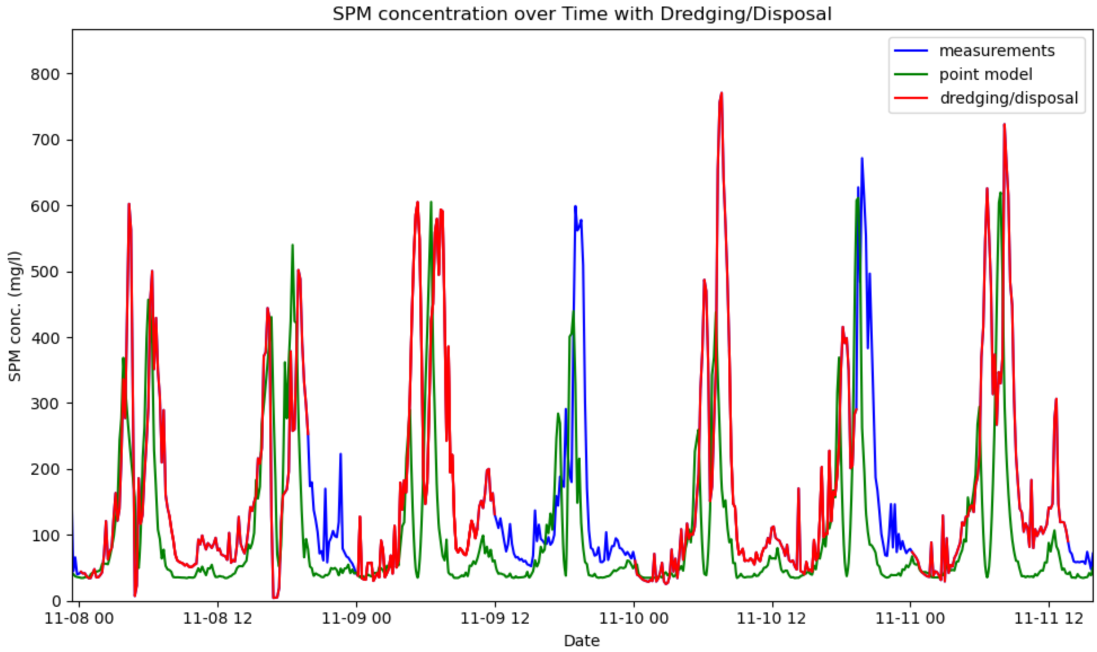


Figure 6-20. Comparison between monitored SPM concentration and point model results at Holwerd, with indication of the moments of dredging/disposal activities (8th – 12th Nov. 2022)

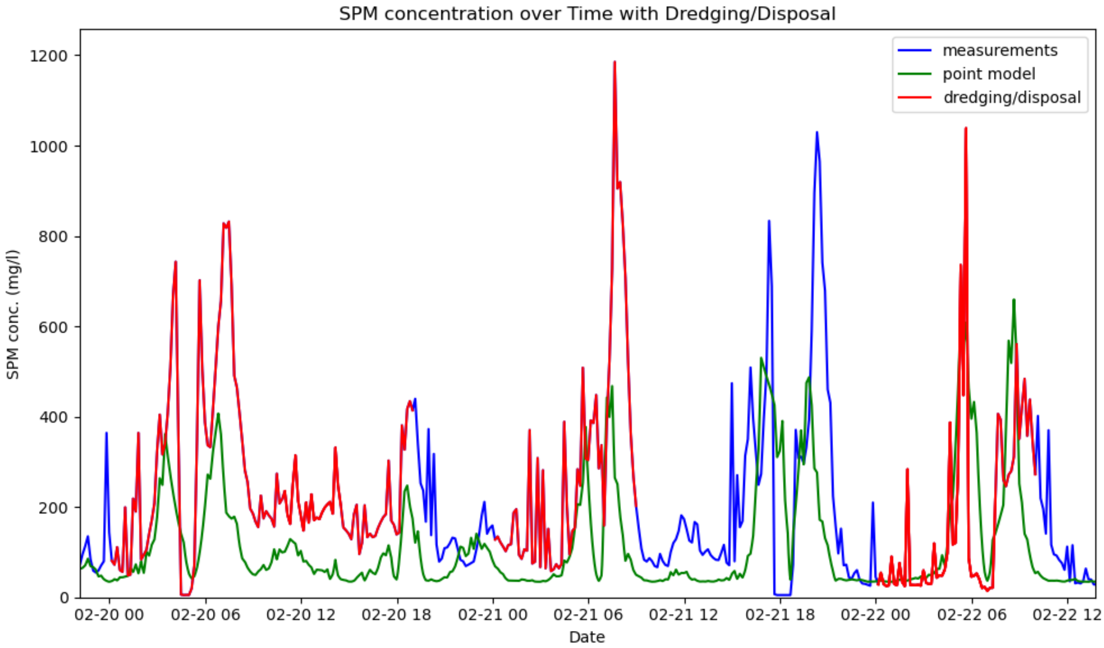


Figure 6-21. Comparison between monitored SPM concentration and point model results at Holwerd, with indication of the moments of dredging/disposal activities (19th – 22nd Feb. 2023)

As described in 3.4.1, the point model only consists of erosion and deposition processes that are linked to the water depth and velocity magnitude. The computed SPM concentration signals thus don’t account for the potential influence of the dredging and disposal activities. In Figure 6-20. and Figure 6-21., we can observe overall higher SPM concentration during the dredging and disposal activities compared to the modelled results. In the monitored data, the SPM concentration peaks decrease slower that the predictions from the model (e.g., 8th – 11th Nov. 2022), and some high frequency oscillations that cannot be captured by the point model could be potentially caused by the disturbance from dredging and disposal (e.g., 20th – 21st Feb. 2023).

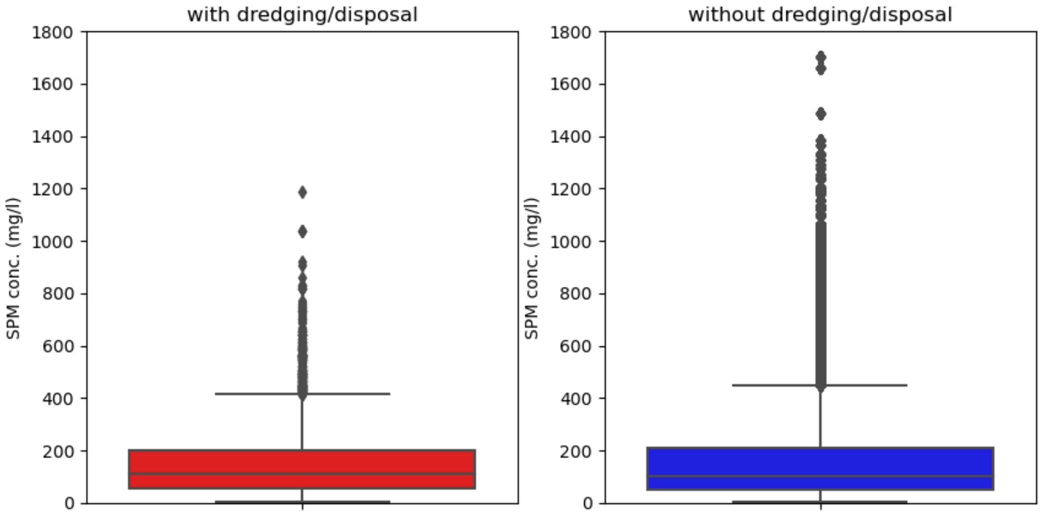


Figure 6-22. Derived statistics from the SPM concentration data at Holwerd with and without potential influence of dredging/disposal activities.

However, if focusing on the statistics computed from the SPM concentration measurements, one can find that statistically it is not obvious to see the influence of dredging and disposal activities, suggesting that the impact is often short-term, and it doesn't drastically increase the SPM concentration level at Holwerd. However, it is not clear if the sediment plume will spread into other areas due to dredging and disposal activities. Moreover, even short but high SPM can impact ecology significantly. This may require more investigations in future studies.

6.4 Comparison with numerical models

Data analysis can give insights about the system and the interplay between different parameters. But sometimes due to the quality of the data, and the noises in the measurements, some phenomena observed in the data cannot be easily understood. Therefore, a comparison with numerical models, which are often based on formulations of physical processes, may help to explain some of the patterns in the data. In this study, two types of numerical models are used, a point model with simplified erosion/deposition processes, and a more sophisticated Delft3D KRW model including hydrodynamics, wave actions and sediment transport.

6.4.1 Point model with erosion/deposition

The point mode is based on simplified erosion and deposition processes, assuming the changes in SPM concentration are the result of the balance between erosion and deposition fluxes. Here is a brief description about the model:

- Bed shear stress τ_{bed} is computed from the depth-averaged velocity, depth and the friction coefficient computed from the dynamic friction law (Bi and Toorman, 2015) without considering wave effects.
- Erosion flux $E = M * (\tau_{bed}/\tau_{crit,E})$ is based on Krone-Partheniades erosion law.
- Deposition flux $D = w_s * C * P(\tau_{bed}, \tau_{crit,D})$ is computed with a critical shear stress for deposition $\tau_{crit,D}$ derived from the suspension capacity theory (Toorman, 2012), and treated implicitly.
- The SPM concentration is given by $C = (E * dt + C_0) / (1 + w_s * P * dt)$, in which C_0 is the background concentration, *dt* is the time step, w_s is the settling velocity, *P* is the deposition probability. This ensures the positivity of the concentration *C*.

An optimization algorithm is used to find optimal settling velocity w_s, critical shear stress for erosion $\tau_{crit,E}$ and erosion rate *M*. The full results can be found in 10A.7, the results in selected periods are shown in Figure 6-23. and Figure 6-24.

At Holwerd, the point model can capture the main trend in September 2022, and April 2023, but in January during winter season, it cannot capture the high frequency oscillations (happening multiple times within a typical tidal cycle) in the measured SPM concentrations. This means these high frequency oscillations are unlikely due to the velocity induced local erosion/resuspension caused by tidal forcing. Instead, since Holwerd is shallow area, it could be influenced by strong wind in winter months, and/or easily be disturbed by human activities. Previous analysis (6.3.2) suggests, some of these high frequency oscillations could be due to dredging/disposal operations carried out near Holwerd. It is also interesting to notice that these oscillations often happen during the ebb phase (e.g., around 01-22 00 and 01-23 00), this could imply that they may be originated in the disturbance happening in the nearby shallow areas during ebb flow. In contrast, the similar high frequency oscillations are not often present at Dantziggat in the winter months, which indicates some difference in the processes between the two locations.

In general, the point model can capture the main trend in the measurements, but it apparently underestimates the concentrations in winter. This implies that the erosion/deposition by velocity along cannot reproduce the strong seasonal variations from summer to winter. In this case, previous analysis indicates the biological activities and wave actions may have impacts on SPM concentration, and they are not considered in the point model.

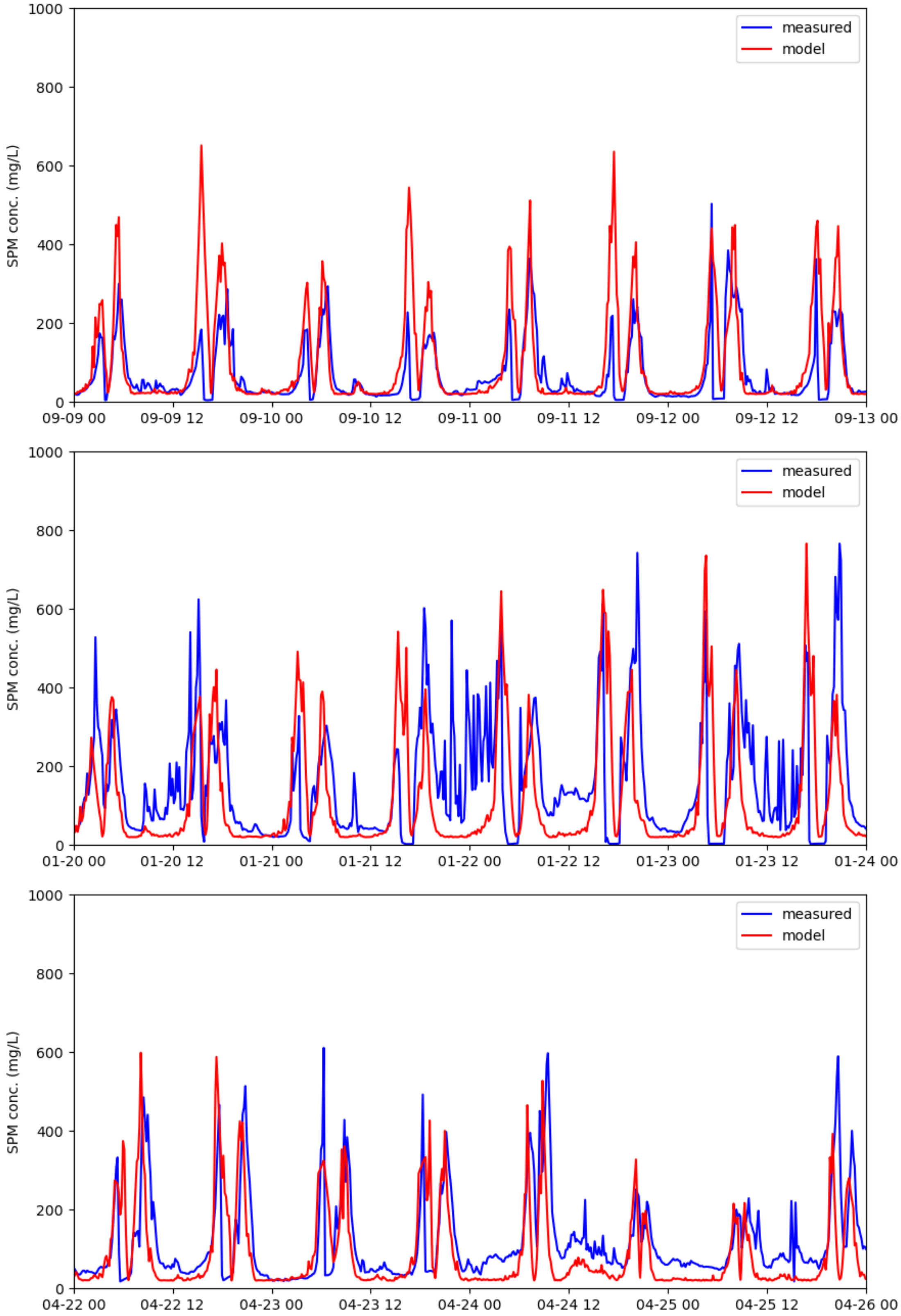


Figure 6-23. Results of SPM concentrations at Holwerd from the point model in September 2022, January, and April 2023. The optimized parameters are: w_s = 1.0 10^{-4} m/s (lower bound), tau_crit,E = 0.42 Pa, M = 6.598 10^{-4}.

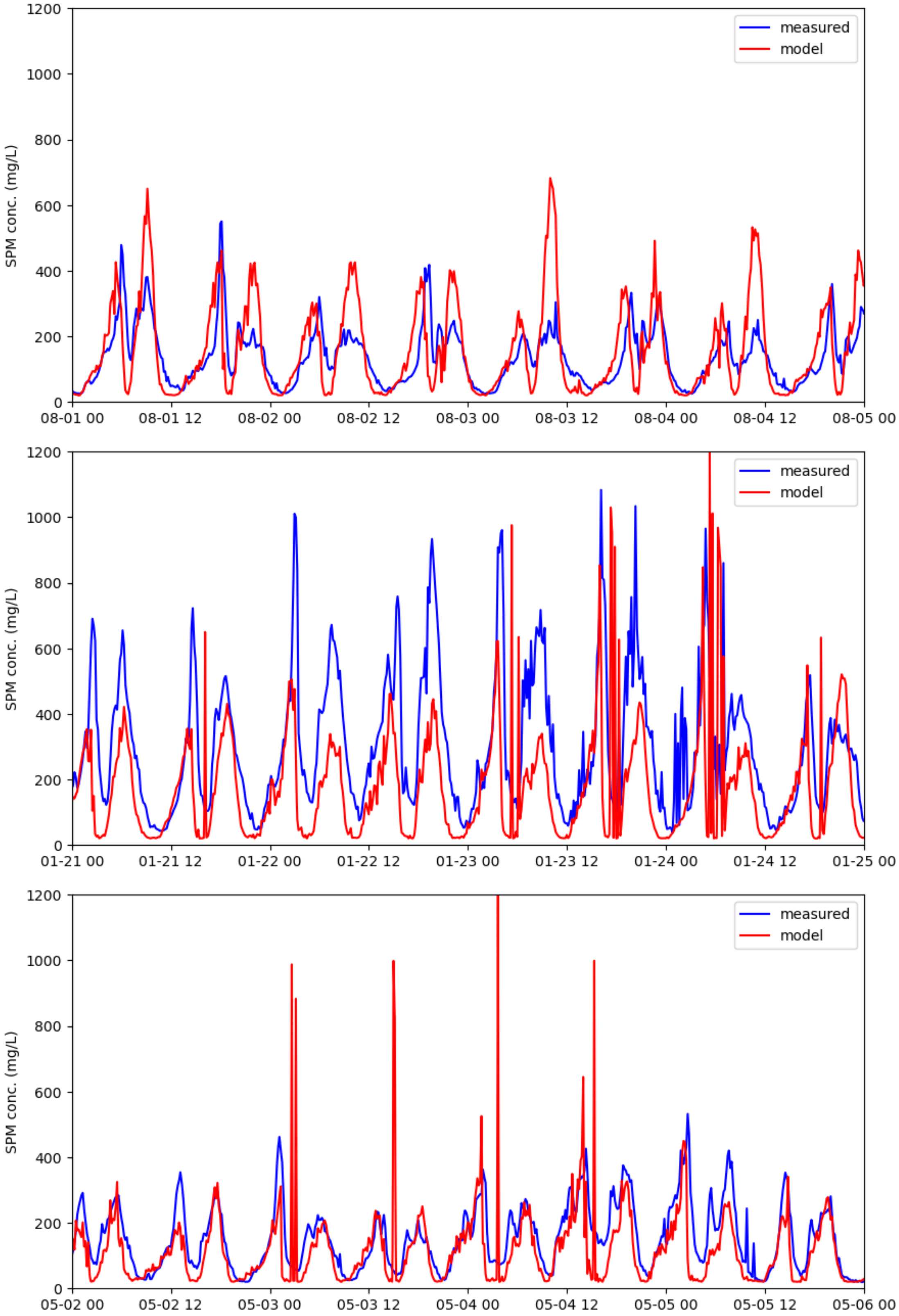


Figure 6-24. Results of SPM concentrations at Dantziggat from the point model in August 2022, January, and May 2023. The optimized parameters are: $w_s = 1.0\ 10^{-4}$ m/s (lower bound), tau_crit,E = 0.83 Pa, $M = 5.462\ 10^{-4}$.

6.4.2 KRW model (Delft3D-FM)

Another numerical model that is used for understanding the data is the KRW model. The details about this model can be found in Vroom et al. (2020).

Although the modelled period (2017) is different from the measured data, consistency can still be found. Applying the same seasonality analysis to the KRW model results, in the derived long-term trend, higher suspension concentration can be seen in winter and lower in summer, which could be explained by the influence of waves. The similar seasonal variations can be found in the long-term trend computed from the significant wave height.

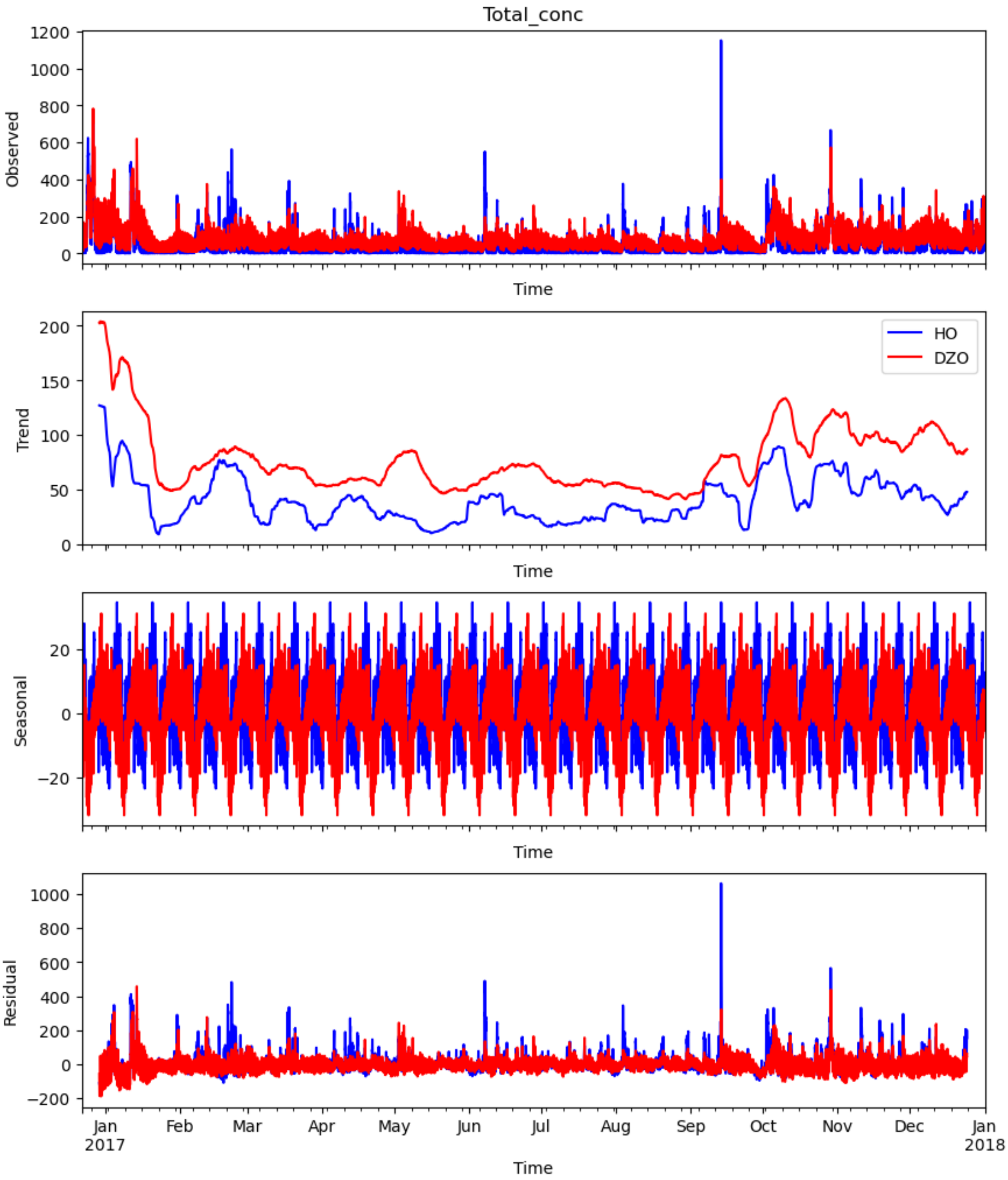


Figure 6-25. Seasonality analysis with the modelled total SPM concentration (mg/L) in 2017.

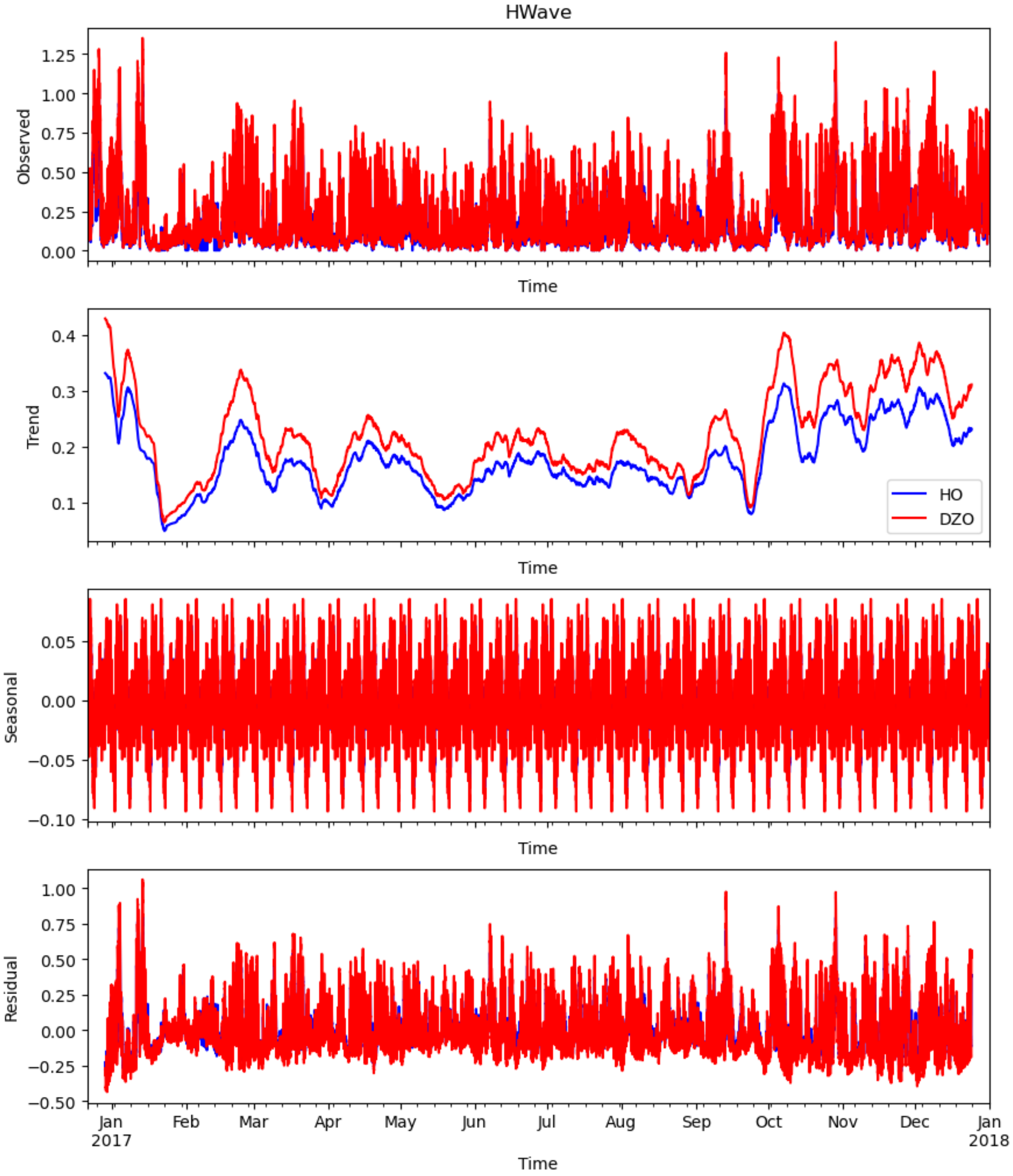


Figure 6-26. Seasonality analysis with the modelled significant wave height (m) in 2017.

It partially agrees with the measurements that the concentration is higher at Dantziggat and lower at Holwerd. The main difference is that it is only true in winter season. In summer, the concentrations at two stations are at similar level. This means the KRW model cannot reproduce the seasonal variations due to the lack of additional processes especially with regards to biological effect.

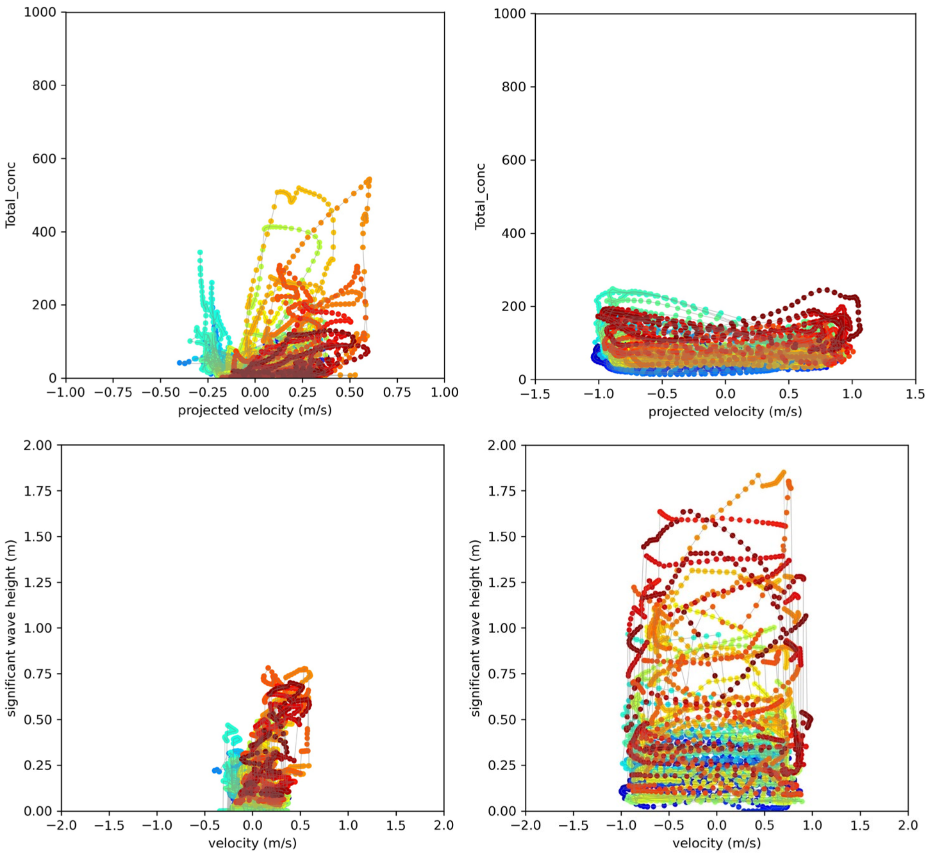


Figure 6-27. Modelled velocity-SPM concentration (mg/L) (top row) and velocity-significant wave height (bottom row) relationships at Holwerd (left column) and Dantziggat (right column) in February 2017.

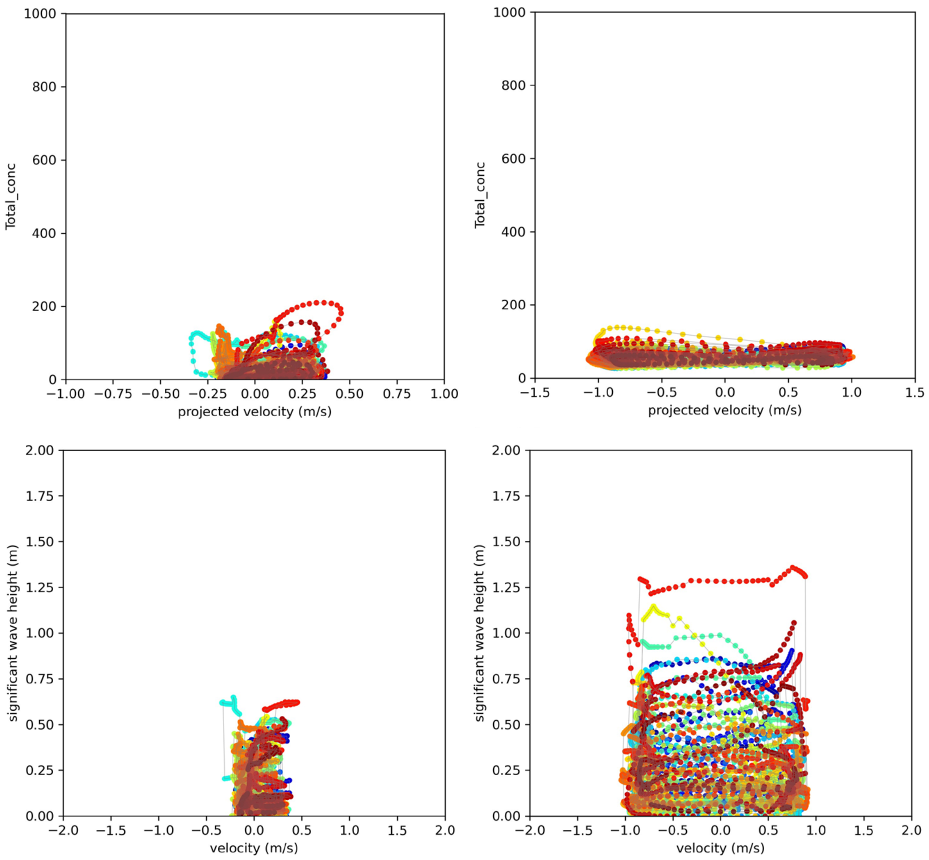


Figure 6-28. Modelled velocity-SPM concentration (mg/L) (top row) and velocity-significant wave height (bottom row) relationships at Holwerd (left column) and Dantziggat (right column) in July 2017.

In order to further evaluate the physical processes reproduced by the model, the relationships between velocity and SPM concentration, velocity and significant wave height are plotted in Figure 6-27. and Figure 6-28..

- At Holwerd, the velocity is underestimated, ranging from about -0.5 to 0.5 m/s compared to -1.0 to 1.2 m/s in the measurements, whereas the velocity at Dantziggat is similar to the measurements.

- At both locations, although the velocity-SPM concentration patterns are different from what we observed in the measurements, they still show higher concentrations during peak ebb and peak flood velocities. This is consistent with the data.

- At both locations, the velocity-significant wave height patterns are different from the ones found in the measured data, e.g., in Figure 6-8.

- At Dantziggat, the seasonal variations in SPM concentrations are not as strong as in the monitoring data, suggesting missing processes in the model.

7 Comparison with other data

7.1 MWTL Dantziggat

MWTL data at Dantziggat from 2022 is not yet publicly available. Therefore, a comparison is made with observation averaged over the period 1989 – 2017. Within this period the average suspended sediment concentration is 97.7 mg/l at Dantziggat. Within this period, there are strong yearly variations, but no significant long-term trend in the concentration (Deltares, 2023). This concentration is much lower than according to the present observations, which are in the range of a few 100 to few 1000 mg/l, also for the top sensor. The explanation for this large difference is the difference in location. The Dantziggat frame is located more towards the end of the channel (see Figure 4-1.), whereas the MWTL position is halfway the channel with stronger influence of (less turbid) North Sea water. Like other MWTL stations, MWTL station Dantziggat shows distinct seasonality. Such seasonality is also observed for the present frame measurements, see §6.1.

7.2 Previous measurements at Holwerd

At Holwerd, previous short-term ship measurements are reported by Van Kessel (2016), whereas short-term frame measurements are reported by Perk et al. (2019) and Boechat et al. (2023). No direct comparison is possible, as hydro-meteo conditions are different. However, SSC levels are within the same range, typically a few 100 mg/l in the upper part of the water column. Near the bed SSC levels > 1000 mg/l frequently occur. These can’t be compared with the present long-term frame measurements, as at Holwerd a single turbidity sensor has been mounted at 0.5 m below LAT.

Near the bed flood-dominant transport is observed, whereas higher up in the water column transport is ebb-dominant. This may be caused by a combination of a higher current velocity in the main channel at flood and a higher mud supply from the intertidal flats at ebb.

8 Conclusions

The monitoring data analysis at Holwerd and Dantziggat offers valuable insights into various hydrodynamic-SPM related parameters captured within the timeframe of July 2022 to June 2023. The detailed observations, with a temporal resolution of 15 minutes, contribute to a comprehensive understanding of the suspended sediment dynamics in the region. The dataset has some gaps with missing or unreliable data due to sensor fouling, power issues etc., notably at Dantziggat in summer. These have been identified and have resulted in changes in the instrument set-up and service protocols, to reduce the occurrence of data gaps in future.

Using various analytical methods, including seasonality analysis, multivariate analyses, this study aimed to understand the correlations between different parameters, especially the interplay between various parameters and SPM concentration at both monitored locations with their specific characteristics. Such analyses are crucial for understanding sediment transport, ecological implications, human impact, and other water-related phenomena in the region.

Seasonality analysis decomposes time series data into seasonal, spring-neap and residual components. Holwerd and Dantziggat show similar hydrodynamic conditions from the analysis, the similarities in the seasonal and spring-neap components can be observed in water level, temperature, significant wave height, etc. But the analysis also reveals distinct patterns in Chlorophyll-a and SPM concentrations between the two locations, indicating the different dominant physical processes are behind the observed changes. At Holwerd, the hydrodynamic conditions are the main influencing factors on the SPM concentration, whereas at Dantziggat the influence of seasonal variations are more pronounced, that may be caused by variations of freshwater runoff and biological activity.

The multivariate analysis, including the use of techniques such as correlation analysis, PCA and clustering, regression, etc., revealed the multifaceted relationships between SPM concentration, and flow velocity, wave conditions, temperature, salinity, and even biological activity. The analysis again shows different driving factors behind the SPM concentration, and the comparison between two monitored locations also reveals their specific bio-geo-hydro conditions.

In addition, efforts were also made to understand the potential human impacts on the environment at Holwerd, since it is located near the ferry passages hence easier subjected to ferry movements as well as dredging activities. However, no statistically significant impacts from human activities were found in the analysis, in which a distinction was made between time windows with ferry or dredging activity and time windows without. No clear difference in SPM levels between both periods was identified. This suggests that the effect of human activities on SPM levels is small compared to the (large) natural SPM variation at short time scale. But it may still be that these effects are important at long time scale and may result in an overall increase of the background concentration. This should be further investigated in future.

In conclusion, this report underscores the importance of continuous monitoring and data-driven analysis for understanding and managing the system. The insights derived from this study can serve as a foundation for future research, policy-making, and environmental management in the Holwerd and Dantziggat regions.

9 Recommendations on data application and extension of the observations

The first year of frame observations at Holwerd and Dantziggat may be considered as a start-up year with still some issues on sensor fouling and instrument calibration. For the coming year regular servicing, sensor cleaning and water sampling for instrument calibration is recommended.

Although from the existing data set of one year, already many conclusions can be drawn on the dominant forcing factors for turbidity. This period is too short to draw conclusions on the persistence of the observed seasonal variations, and on interannual variations. It is therefore recommended to extend the observations for at least another year at the present location before considering placement elsewhere.

ADCP data may be further analysed on suspended sediment concentrations and fluxes, including vertical gradients herein. This acoustic technique would support and enhance optical turbidity observations. However, with the present ADCP settings this is not yet possible, so changes in the instrument setup would be required.

The richness of the dataset could be further enhanced along three main tracks:

1. Measurement on sediment properties (floc size, organic content, settling velocity).
2. Measurement of the bed (sedimentation-erosion, bed composition (sand and mud fractions), bed properties such as strength and bulk density).
3. Measurement at the adjacent mud flat with additional (possibly smaller) frame.

The rationale for this is that from the data so far, we have seen that identical forcing does not result in identical turbidity variations, i.e. also variations in properties such as floc size, settling velocity and erodibility play a role, and the availability of mud in the seabed in the vicinity of the frames. Also, concentration peaks at ebb appear to be not locally resuspended, but advected from adjacent mud flats. These measurements also help to make a distinction between physical and biological controls for the turbidity variations.

This extension could be realised by mounting additional sensors on the frames (e.g. LISST, floc camera, bed level sensor), measuring vertical turbidity gradients in more detail (e.g. by mounting a second turbidity sensor near the bed at Holwerd), performing extra analyses on water samples (e.g. PSD, organic content, settling velocity) and by taking also bed samples during servicing of the frames, which can be analysed in the lab on bulk density, strength, sand and mud content.

To make a better distinction between local resuspension and advection, more spatial data is required than at just 1 or 2 fixed locations. For this ship-based surveys are recommended, as remote sensing is challenging in these shallow and tidal conditions and won’t deliver near-bed concentrations. If cost is an issue, combination with project monitoring may be considered, e.g in the framework of a possible dredging relocation pilot.

For the next data analysis, it is recommended to run the existing KRW mud model for the same period (i.e. hydro-meteo forcing) as the observations to make a direct comparison possible. This will help to both more easily identify ‘suspect’ data due to sensor fouling and identify model limitations for SPM dynamics. As also other water quality parameters as temperature, oxygen and Chl-a are available, data-model comparison could also include water quality models of the Wadden Sea. The preliminary comparison made within this study (based on different forcing periods for data and model) suggest that changes in model settling (and possibly also model formulations) are required on the relative importance of local resuspension-deposition from and to the bed, mixing-settling in the water column and advective transport from sea during flood and from mudflats during ebb.

The results so far also suggest that observations for a dredging relocation pilot should be sufficiently long-term, as a direct link (i.e. local and on the short term) between dredging and turbidity levels at Holwerd is not obvious from the present data, but this link may be still be there on the long term through enhanced background concentration levels.

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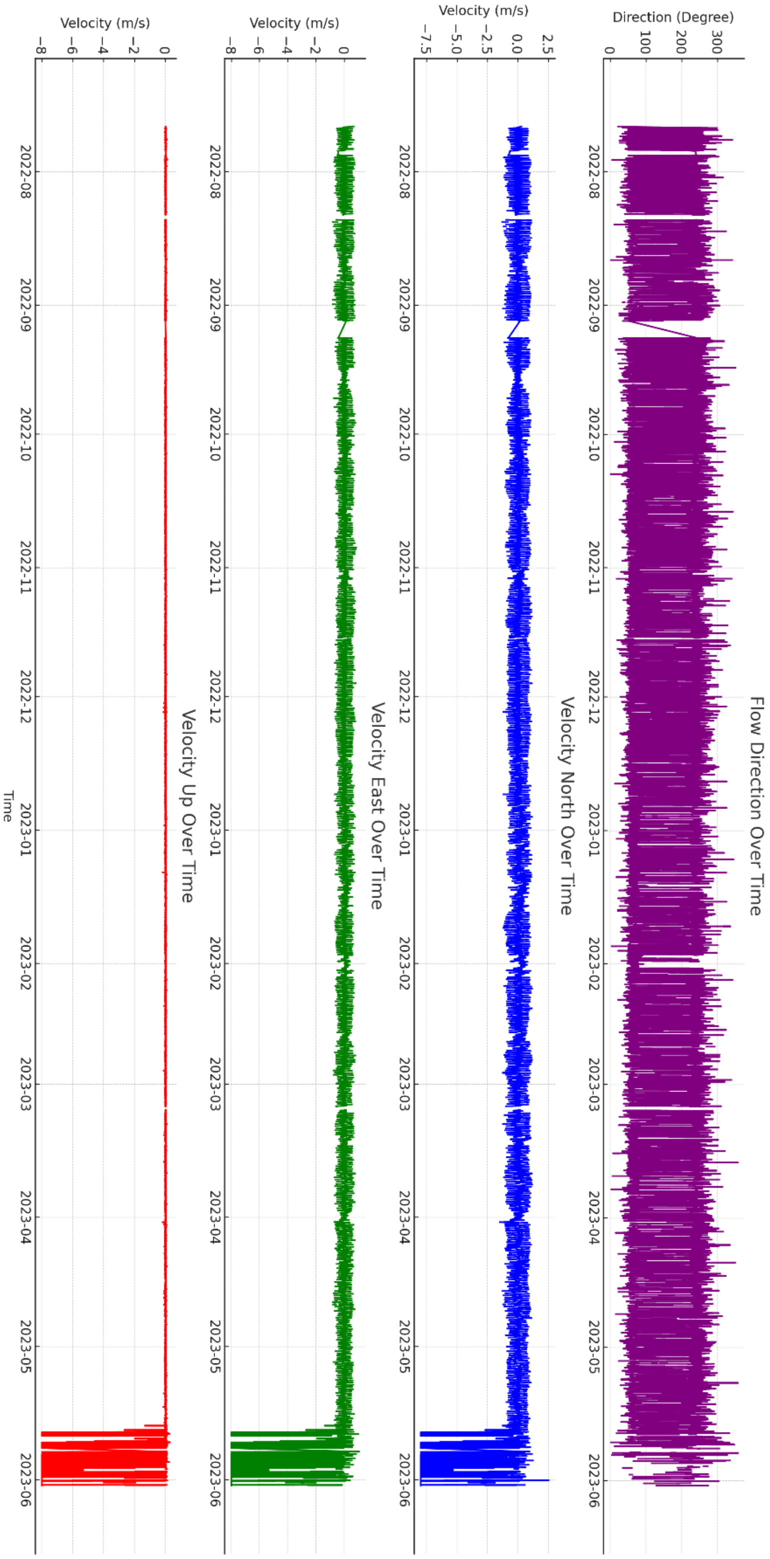
Vroom, J., van Weerdenburg, R., Smits, B. & Herman, P. (2020b). Modellering slibdynamiek voor de Waddenzee. Kalibratie voor KRW slib. Deltares rapport 11205229-001-ZKS-0001

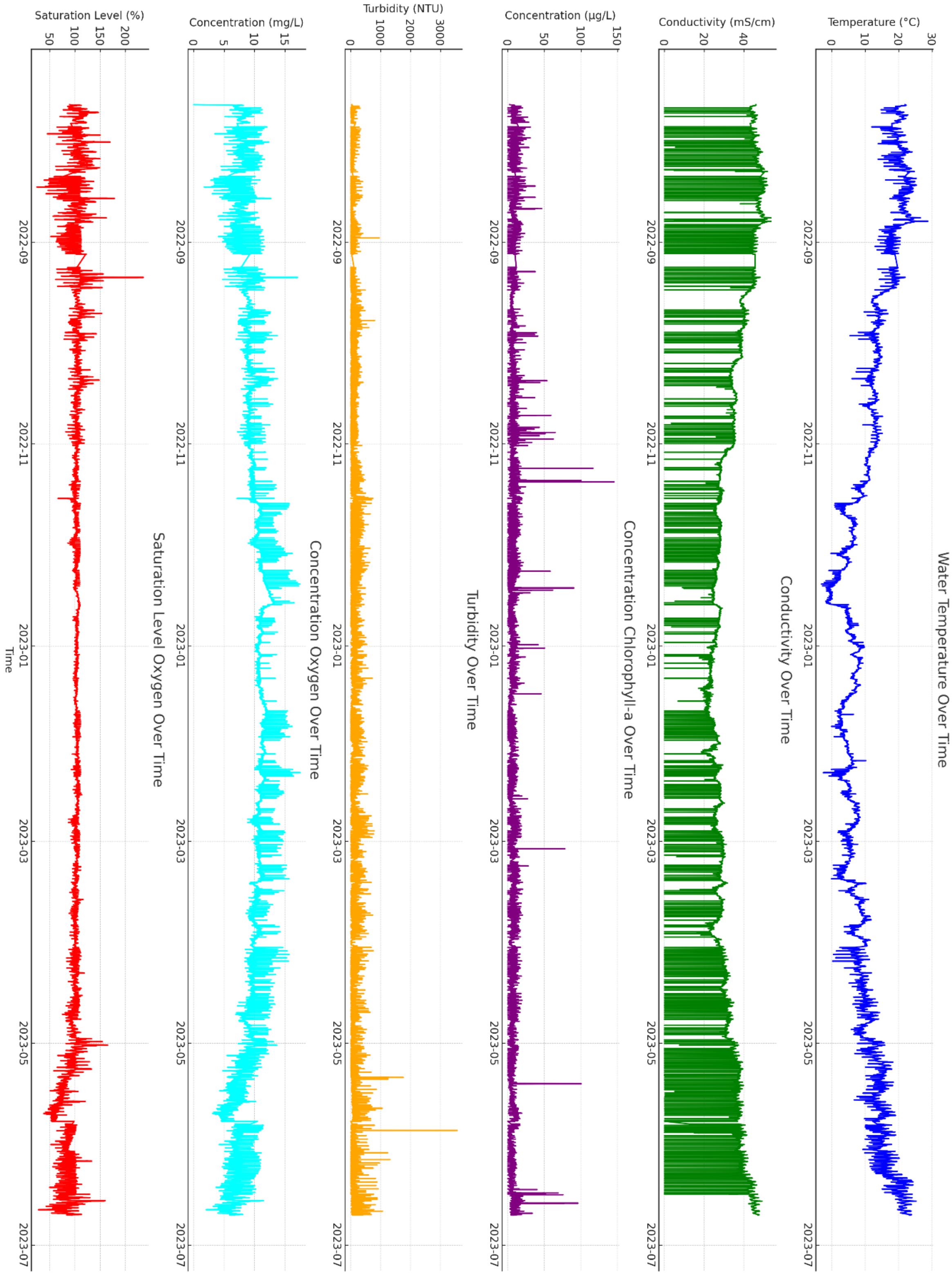
A Appendix

A.1 Monitoring data at Holwerd

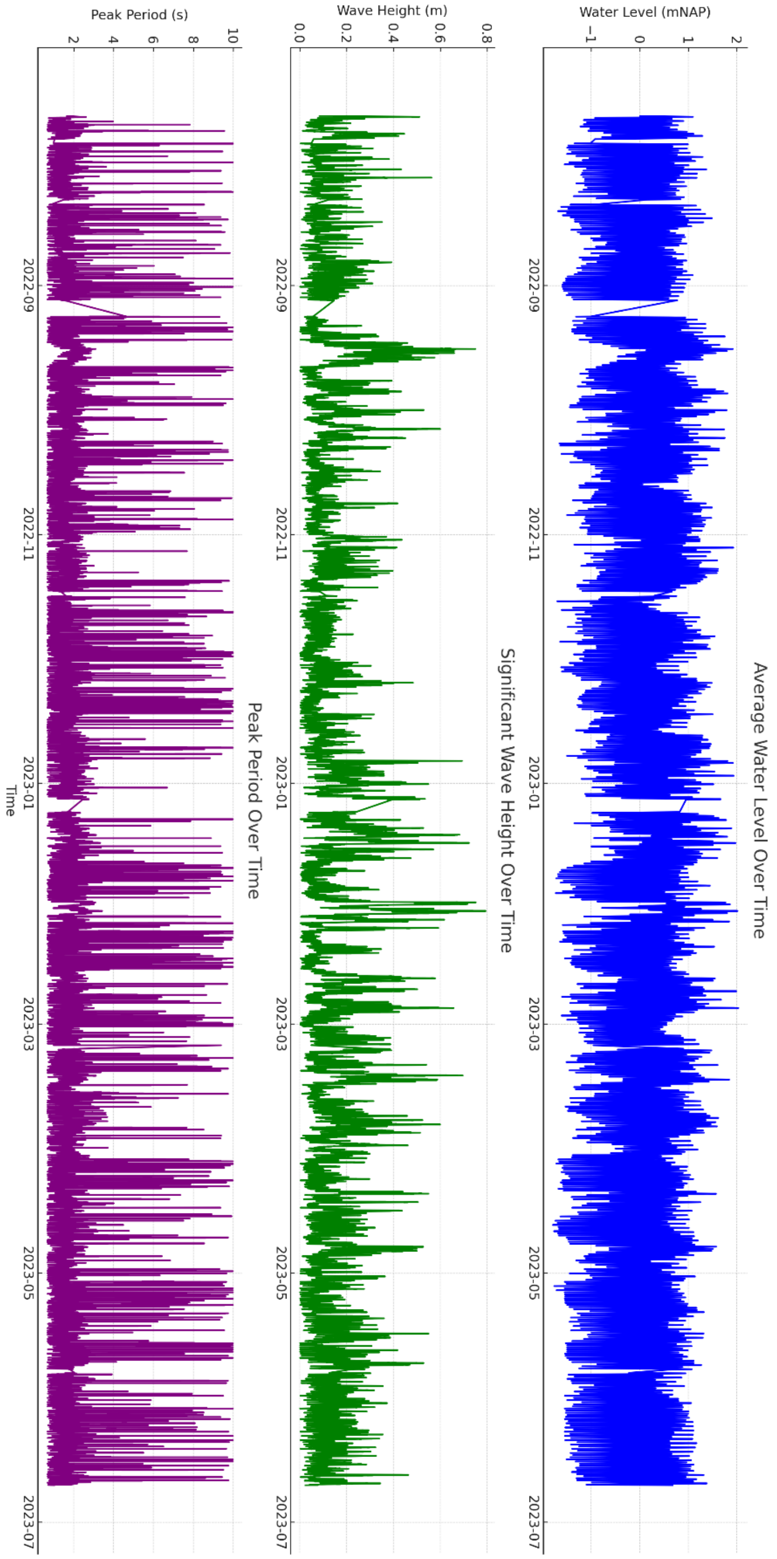
A.1.1 ADCP data



A.1.2 MPP data

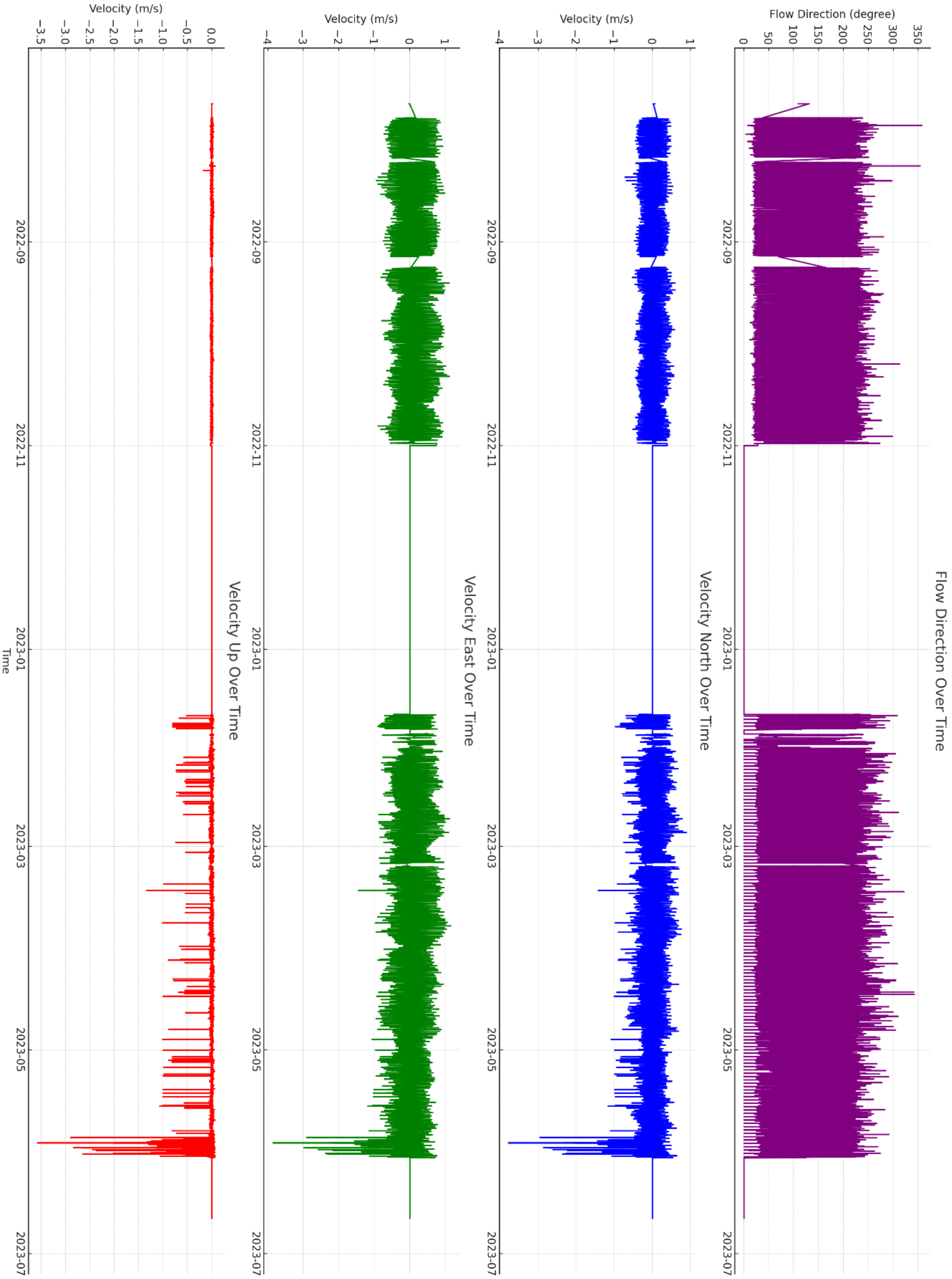

Water Temperature Over Time
Temperature (°C)
0
10
20
30
Conductivity Over Time
Conductivity (mS/cm)
0
20
40
Concentration Chlorophyll-a Over Time
Concentration (µg/L)
0
50
100
150
Turbidity Over Time
Turbidity (NTU)
0
1000
2000
3000
Concentration Oxygen Over Time
Concentration (mg/L)
0
5
10
15
Saturation Level Oxygen Over Time
Saturation Level (%)
50
100
150
200
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07
Time

A.1.3 STB data

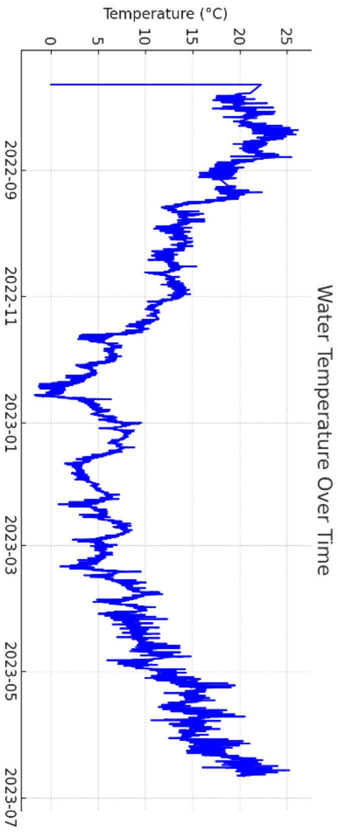

Average Water Level Over Time
Water Level (mNAP)
−1
0
1
2
Significant Wave Height Over Time
Wave Height (m)
0.0
0.2
0.4
0.6
0.8
Peak Period Over Time
Peak Period (s)
2
4
6
8
10
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07
Time

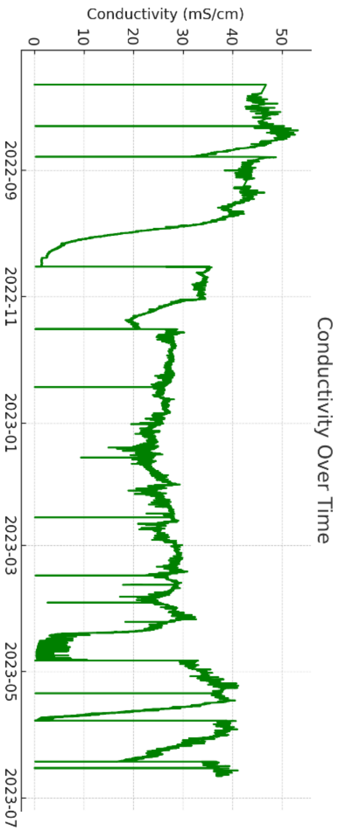
A.2 Monitoring data at Dantziggat

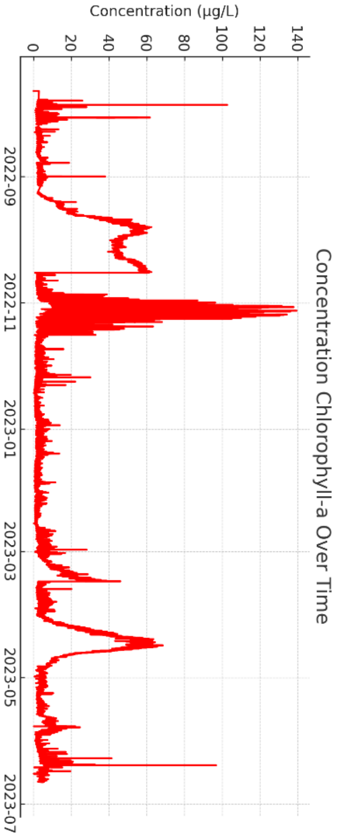
A.2.1 ADCP data

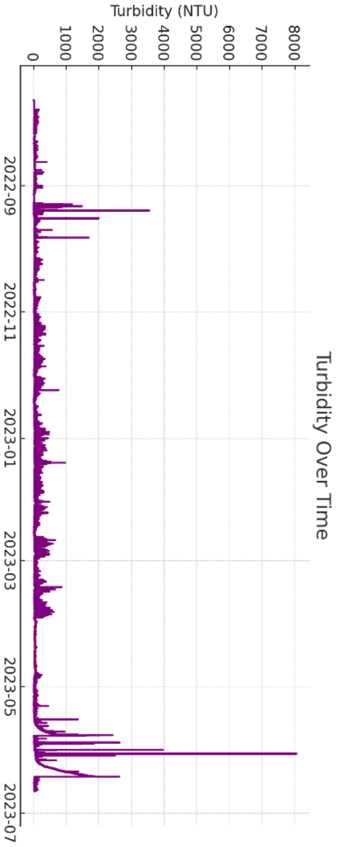


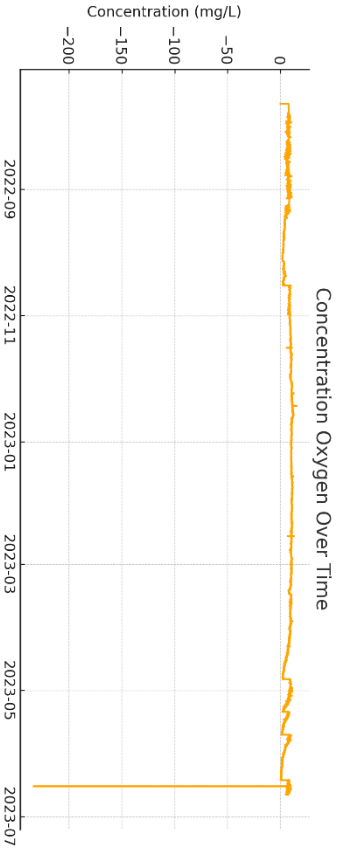
A.2.2 MPP data

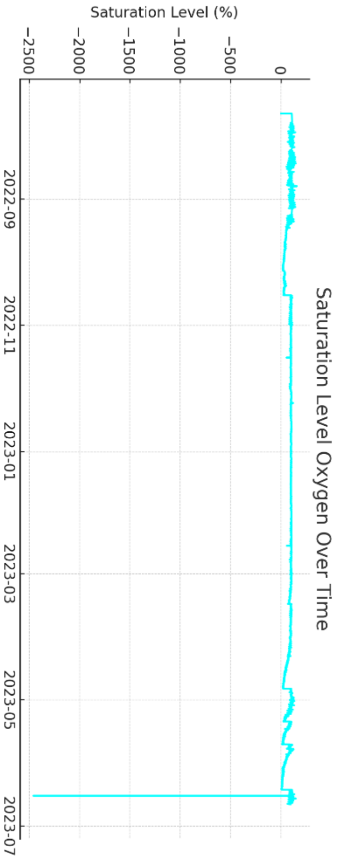

Water Temperature Over Time
Temperature (°C)
0
5
10
15
20
25
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07


Conductivity Over Time
Conductivity (mS/cm)
0
10
20
30
40
50
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07

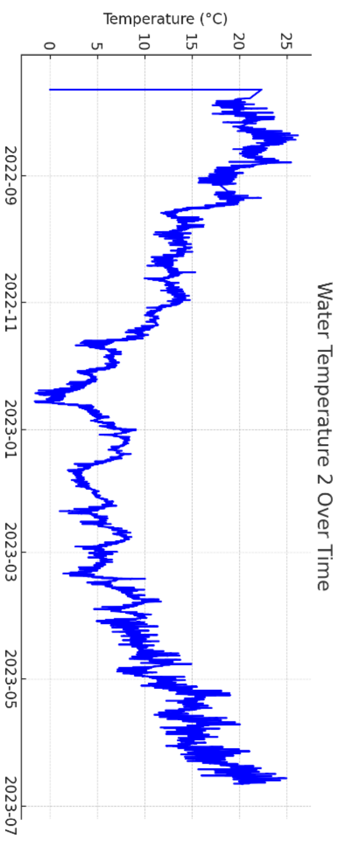

Concentration Chlorophyll-a Over Time
Concentration (µg/L)
0
20
40
60
80
100
120
140
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07

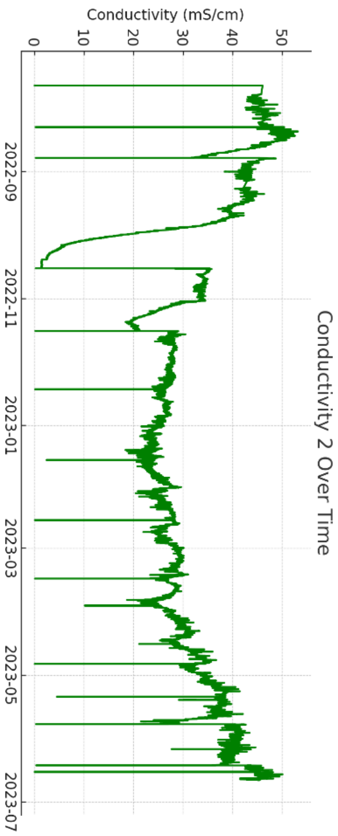

Turbidity Over Time
Turbidity (NTU)
0
1000
2000
3000
4000
5000
6000
7000
8000
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07

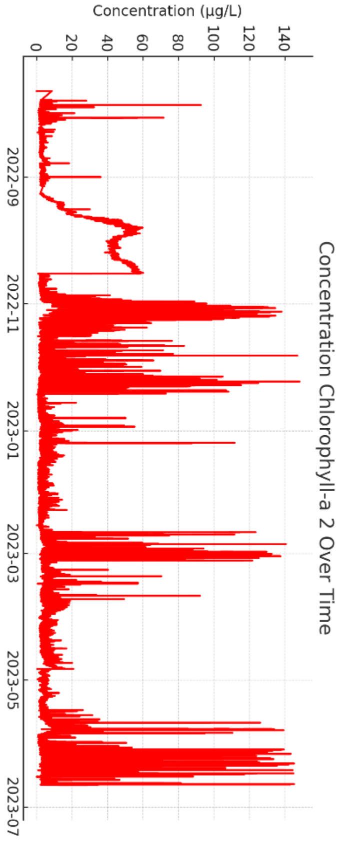

Concentration Oxygen Over Time
Concentration (mg/L)
−200
−150
−100
−50
0
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07

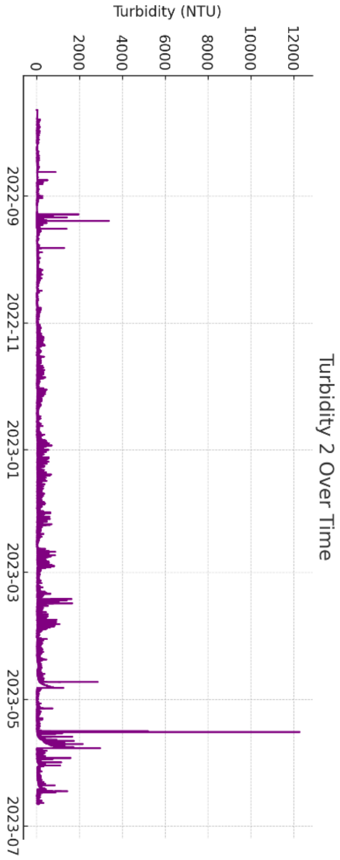

Saturation Level Oxygen Over Time
Saturation Level (%)
−2500
−2000
−1500
−1000
−500
0
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07

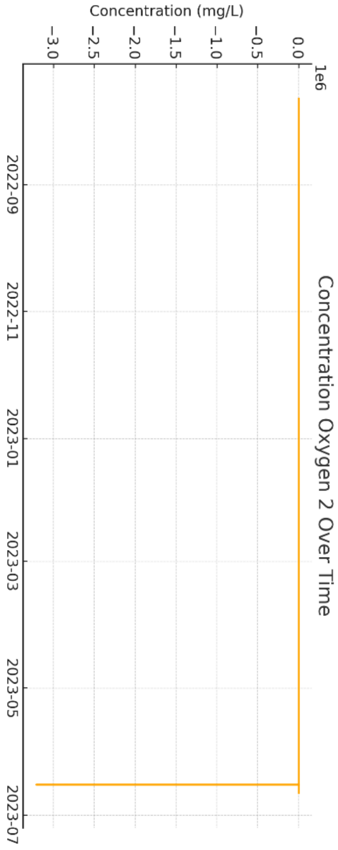
A.2.3 MPP2 data

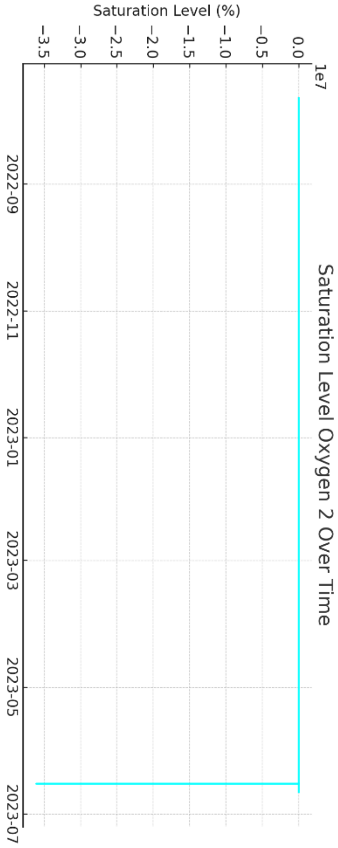




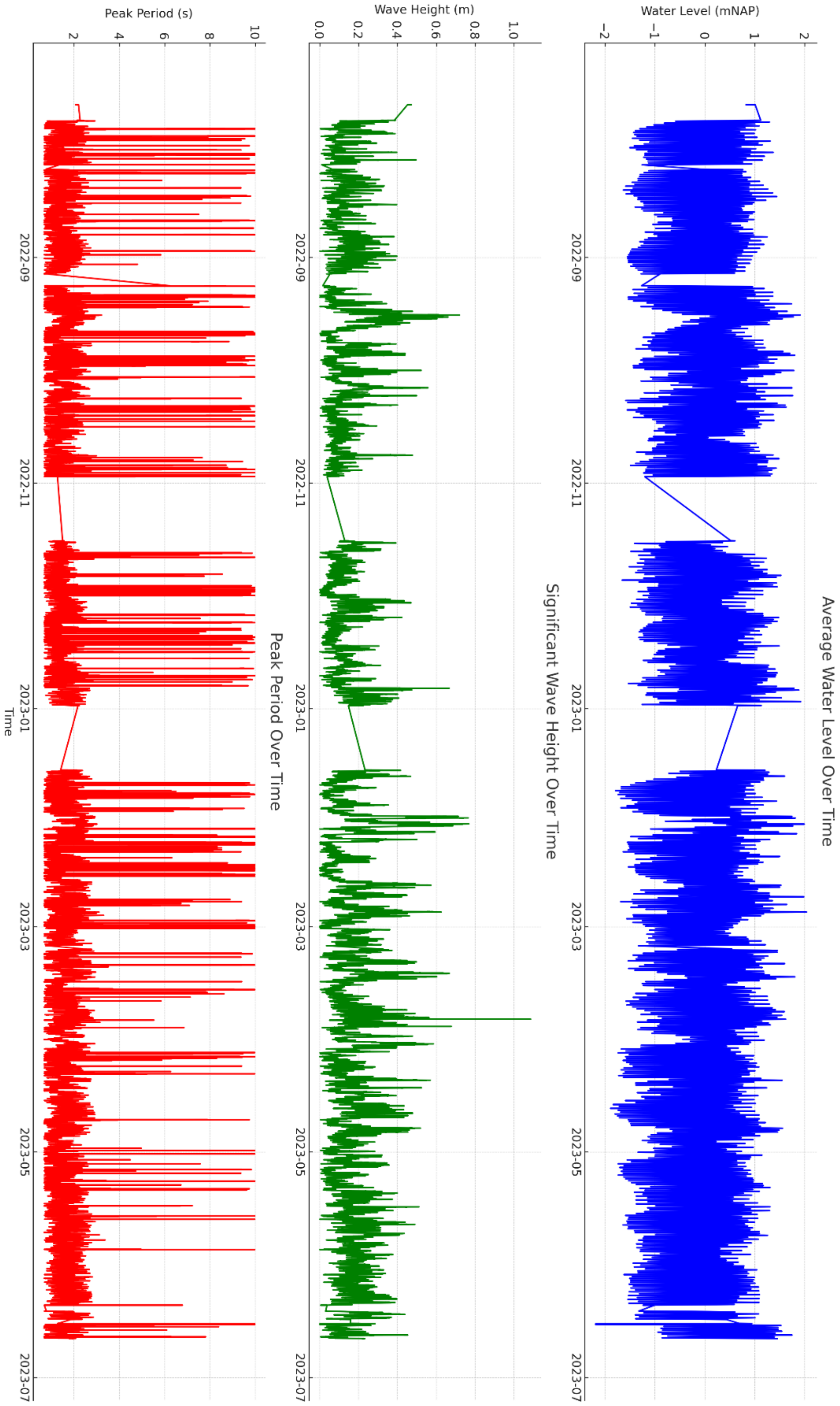




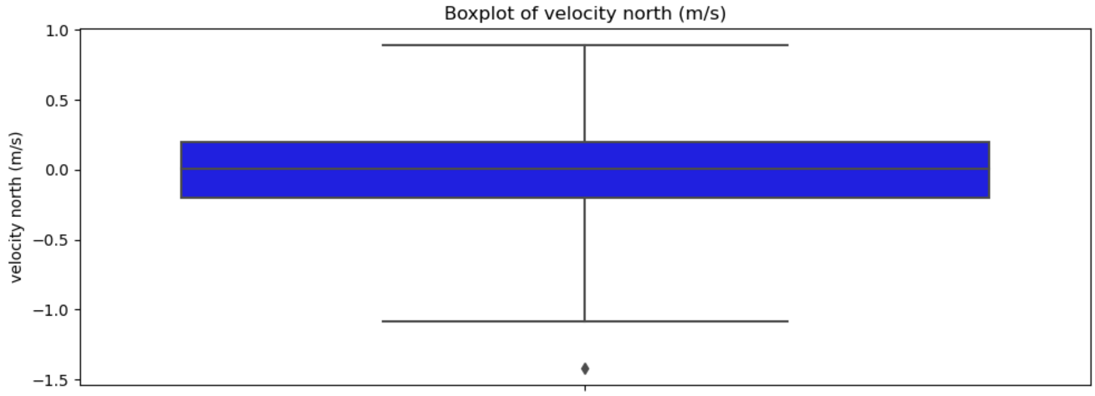


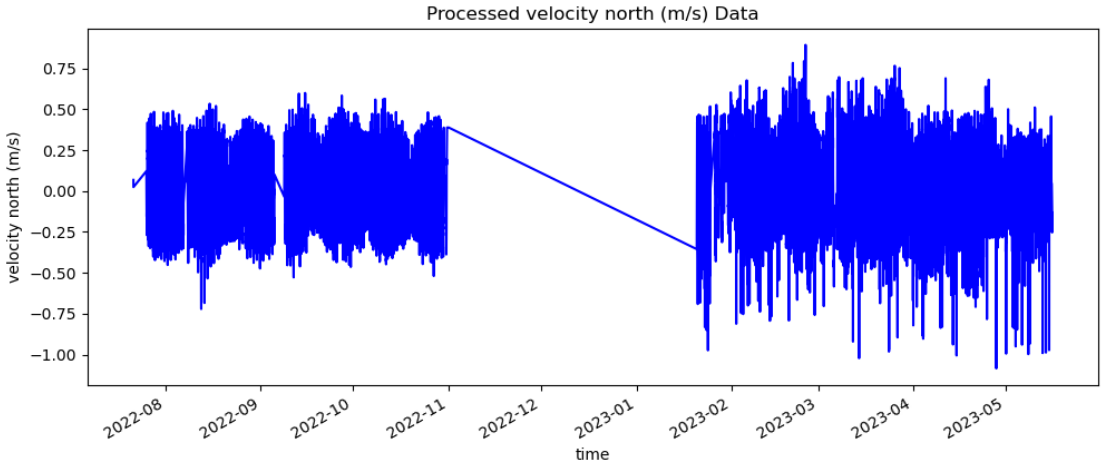


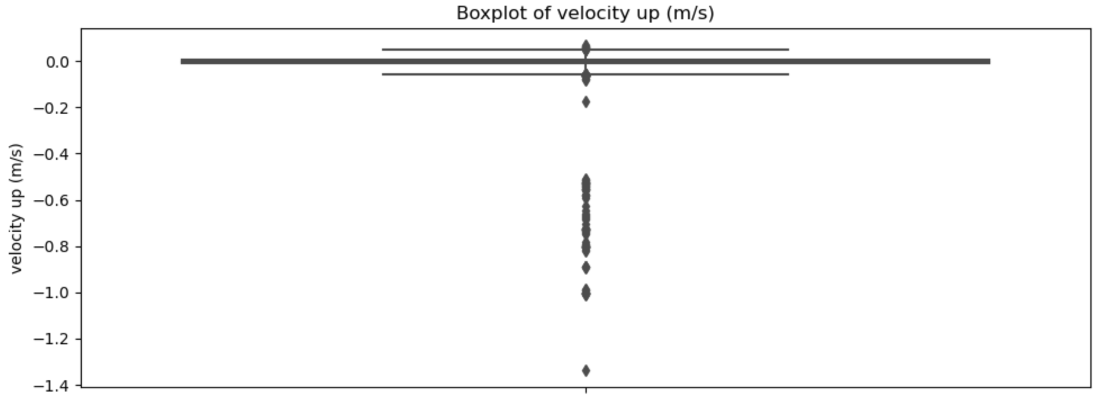
A.2.4 STB data

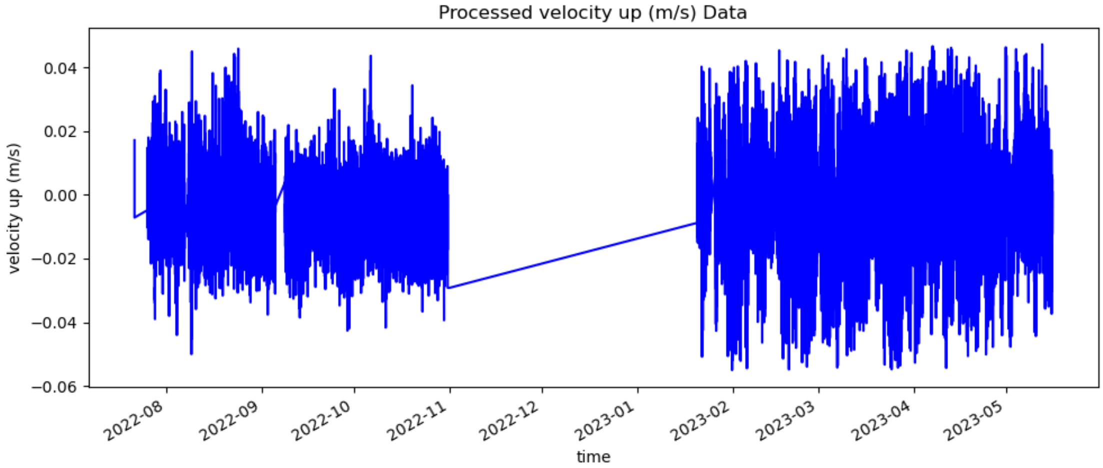

Average Water Level Over Time
Water Level (mNAP)
−2
−1
0
1
2
Significant Wave Height Over Time
Wave Height (m)
0.0
0.2
0.4
0.6
0.8
1.0
Peak Period Over Time
Peak Period (s)
2
4
6
8
10
2022-09
2022-11
2023-01
2023-03
2023-05
2023-07
Time

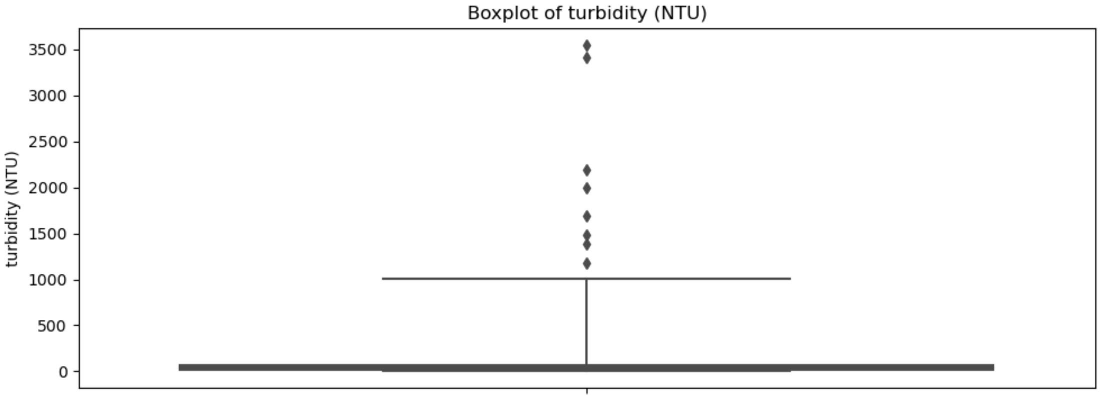
A.3 Removal of outliers in data at Dantziggat

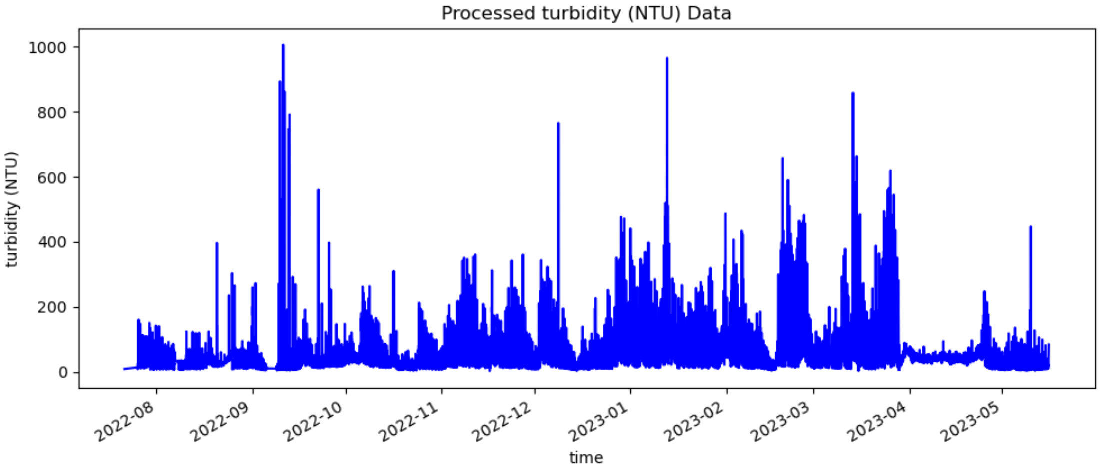


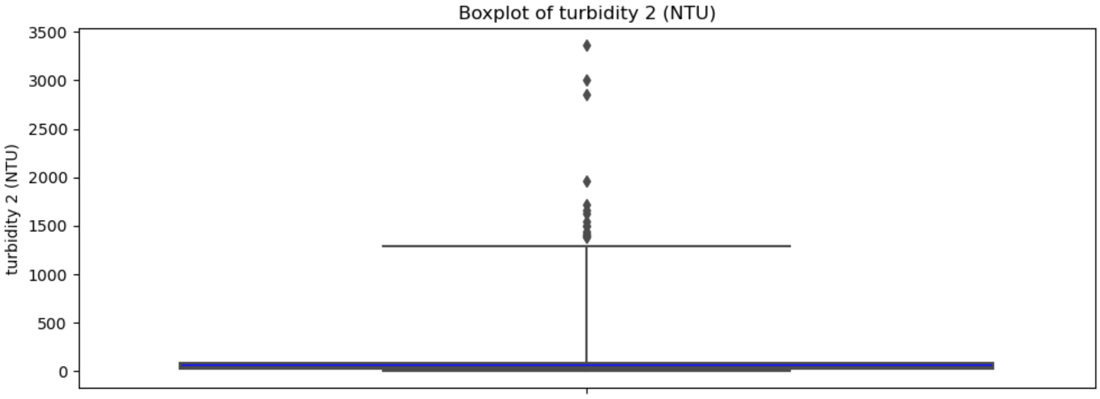


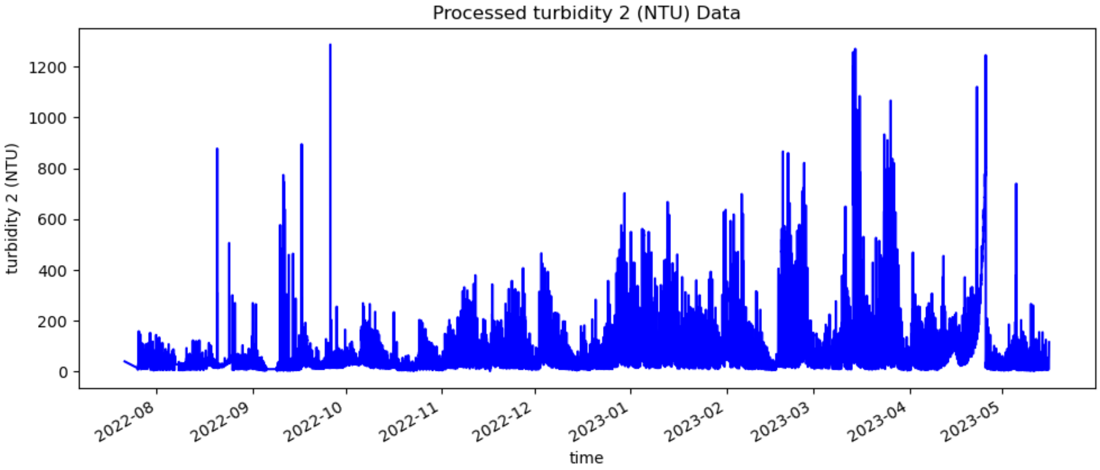





Boxplot of turbidity (NTU)

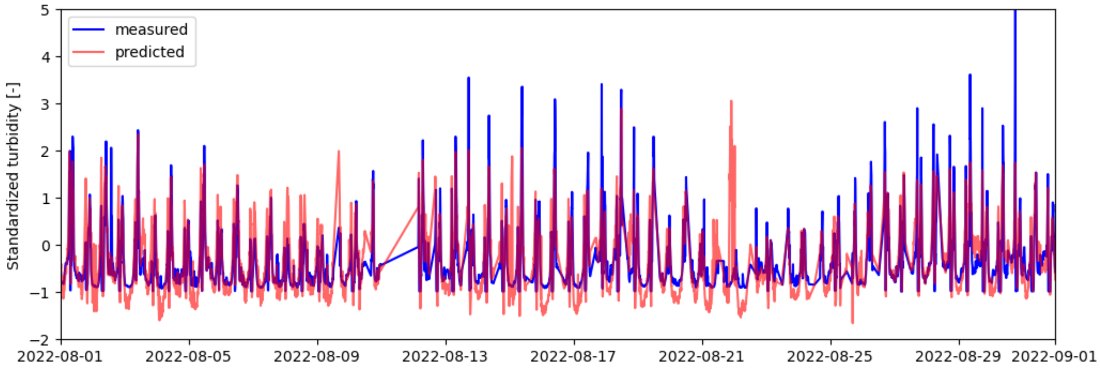

Processed turbidity (NTU) Data

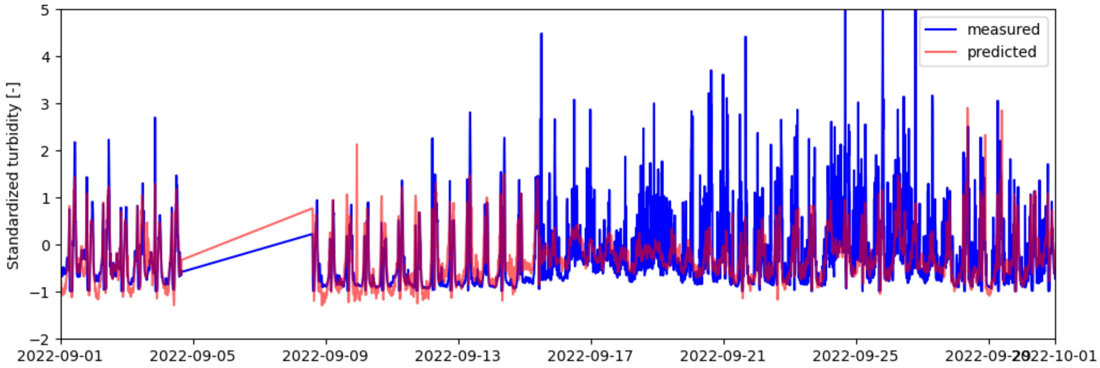

Boxplot of turbidity 2 (NTU)

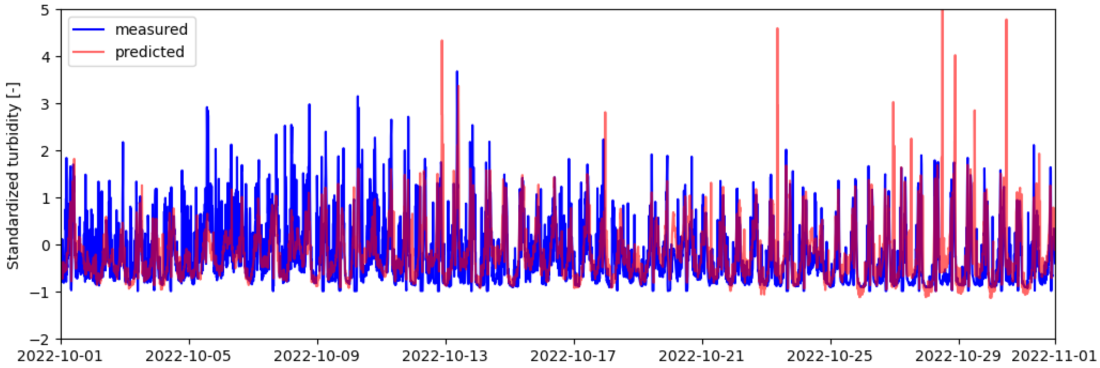

Processed turbidity 2 (NTU) Data

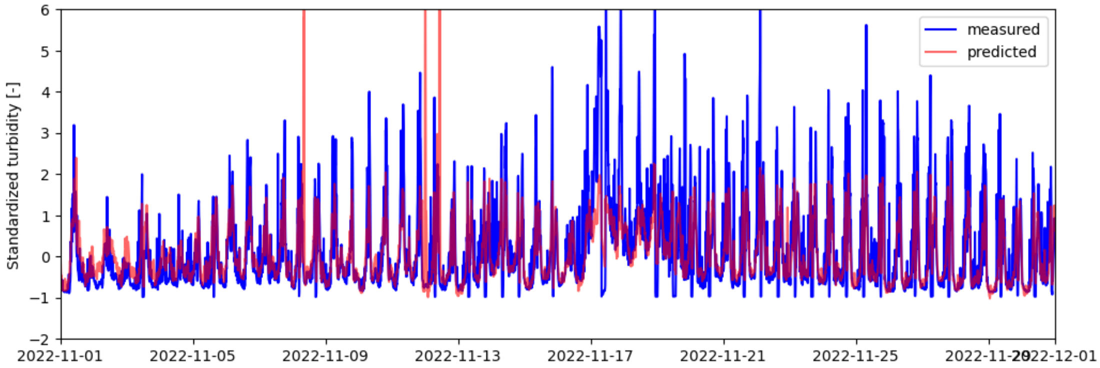
A.4 Results from regression model

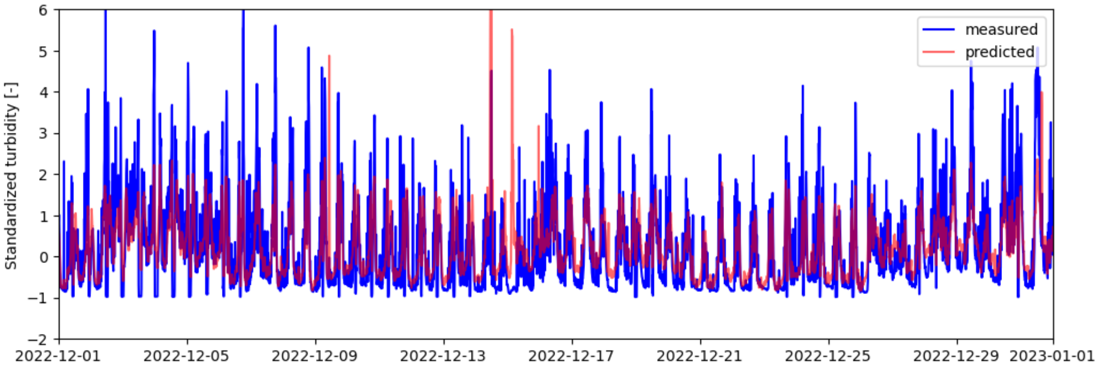
A.4.1 Holwerd

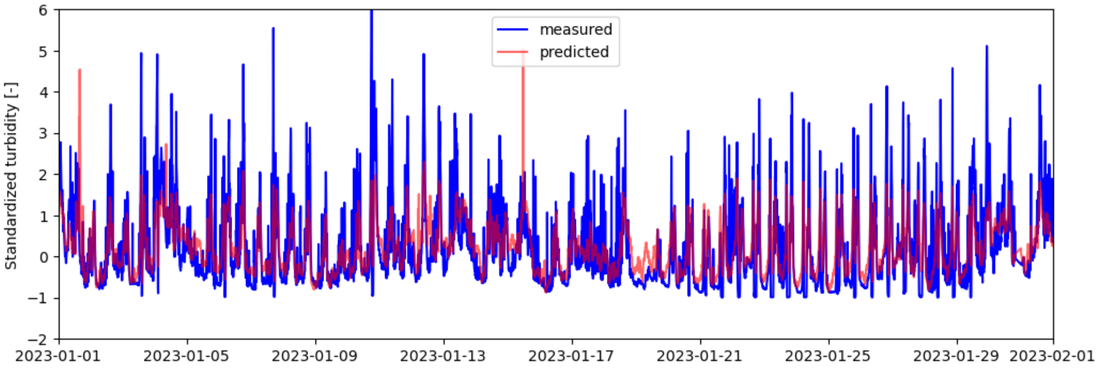


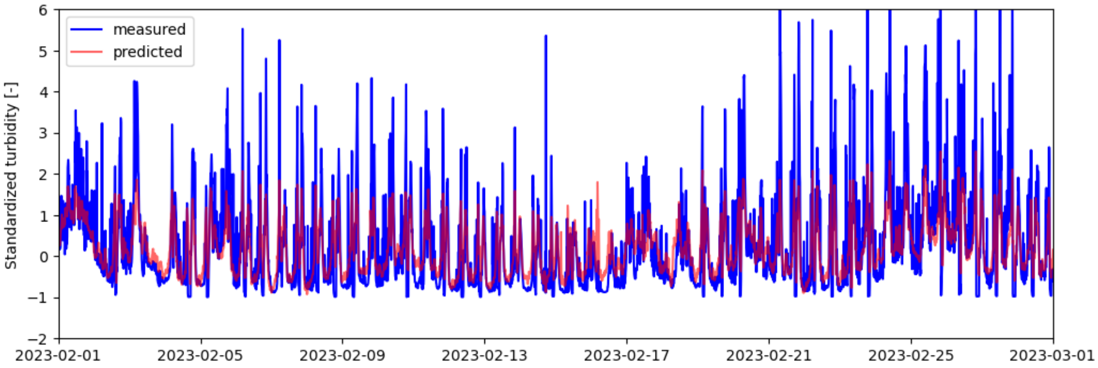


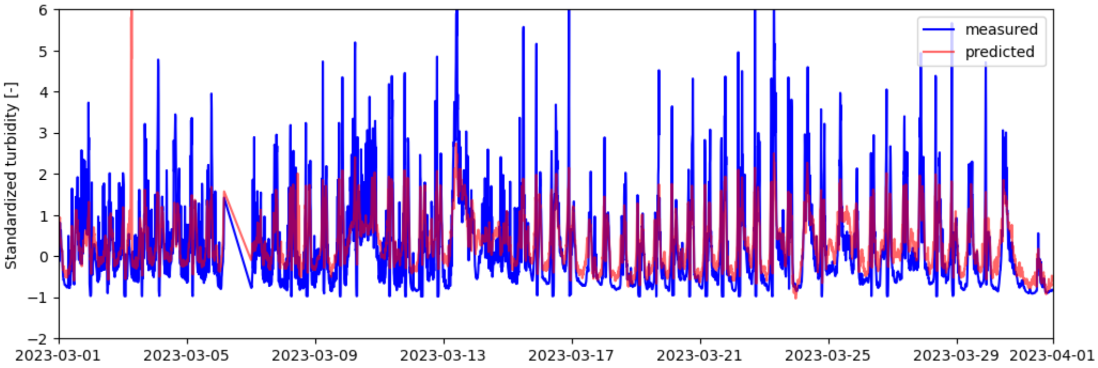


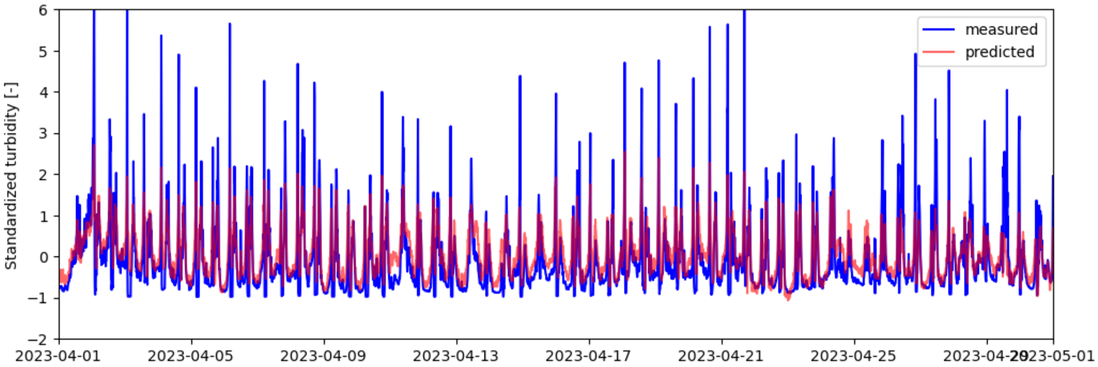



Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2022-12-01
2022-12-05
2022-12-09
2022-12-13
2022-12-17
2022-12-21
2022-12-25
2022-12-29
2023-01-01
measured
predicted

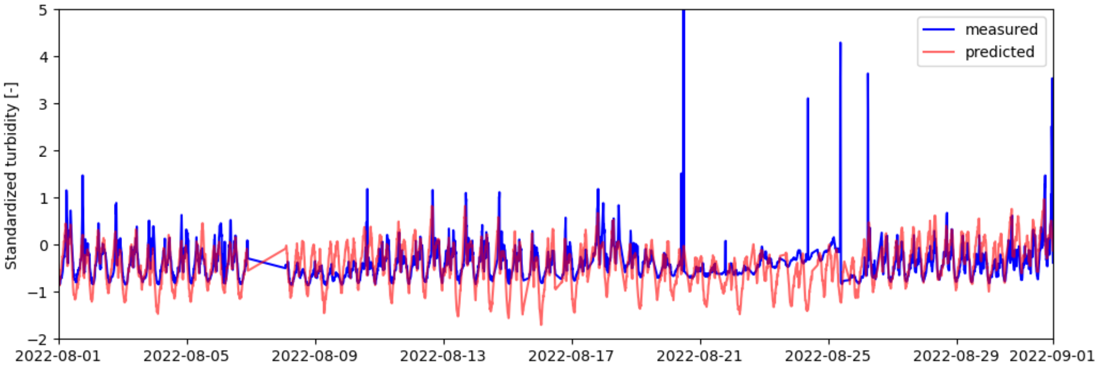

Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2023-01-01
2023-01-05
2023-01-09
2023-01-13
2023-01-17
2023-01-21
2023-01-25
2023-01-29
2023-02-01
measured
predicted

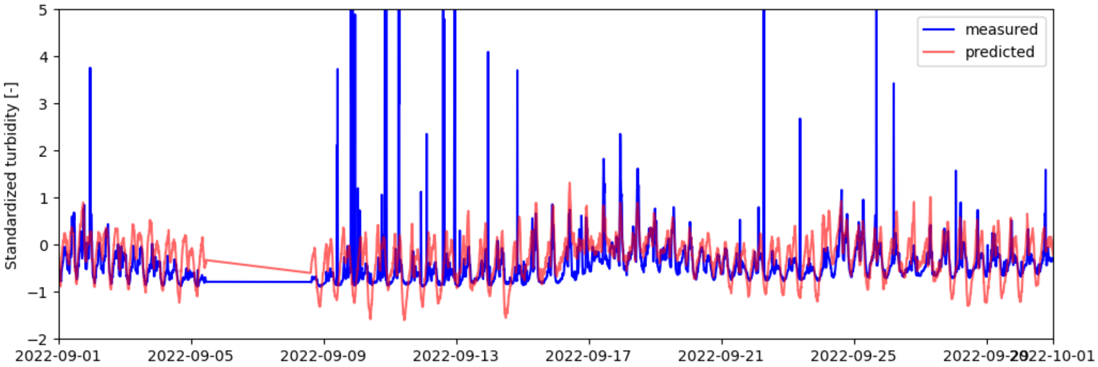

Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2023-02-01
2023-02-05
2023-02-09
2023-02-13
2023-02-17
2023-02-21
2023-02-25
2023-03-01
measured
predicted

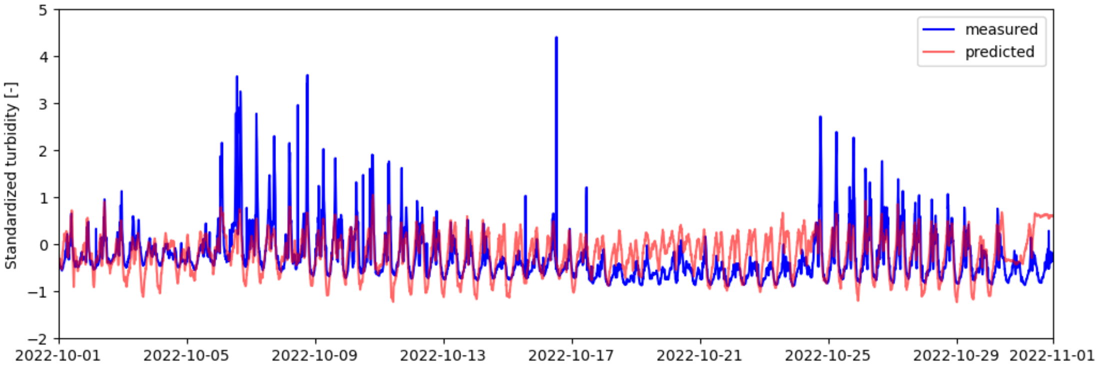

Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2023-03-01
2023-03-05
2023-03-09
2023-03-13
2023-03-17
2023-03-21
2023-03-25
2023-03-29
2023-04-01
measured
predicted

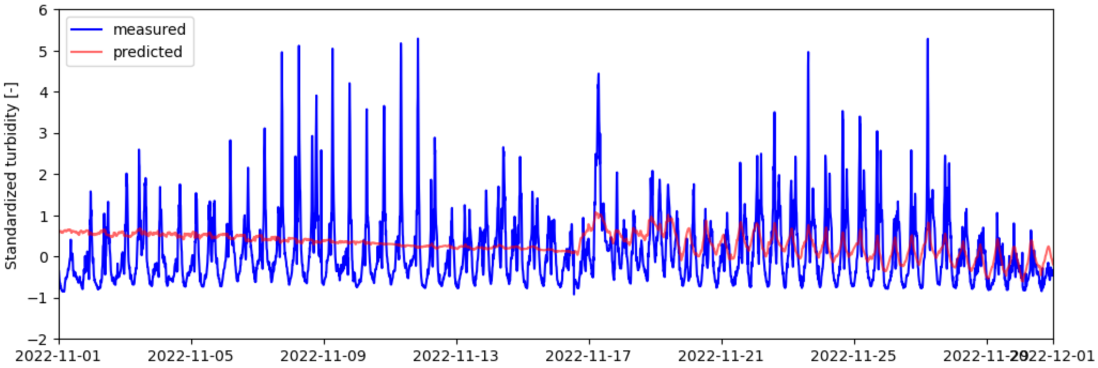


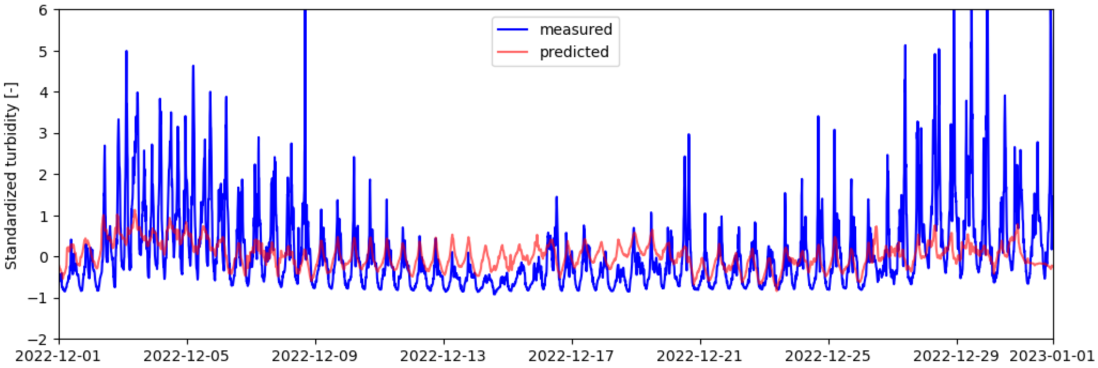
A.4.2 Dantziggat

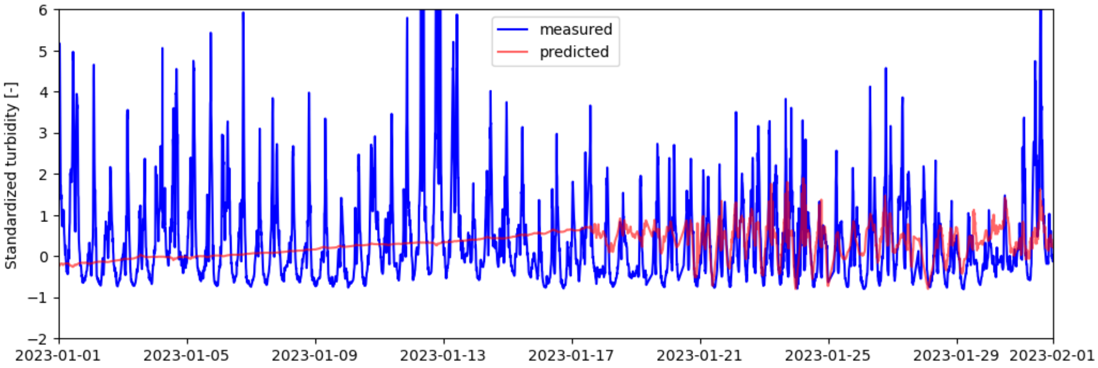


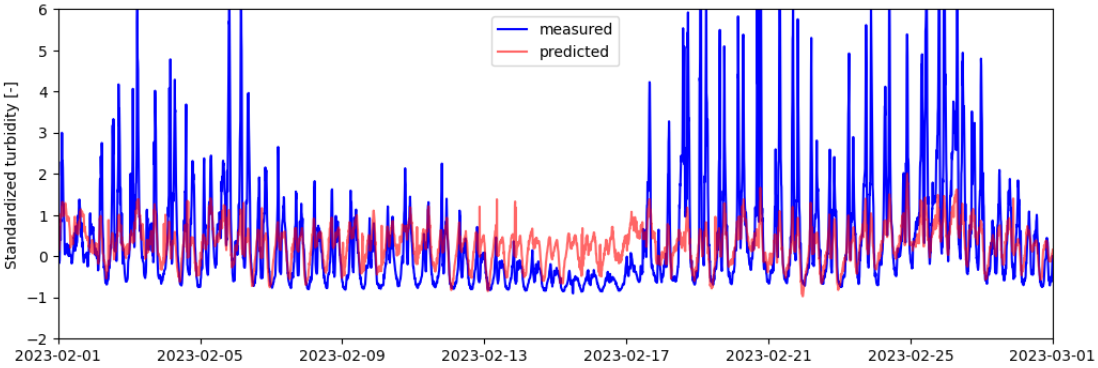


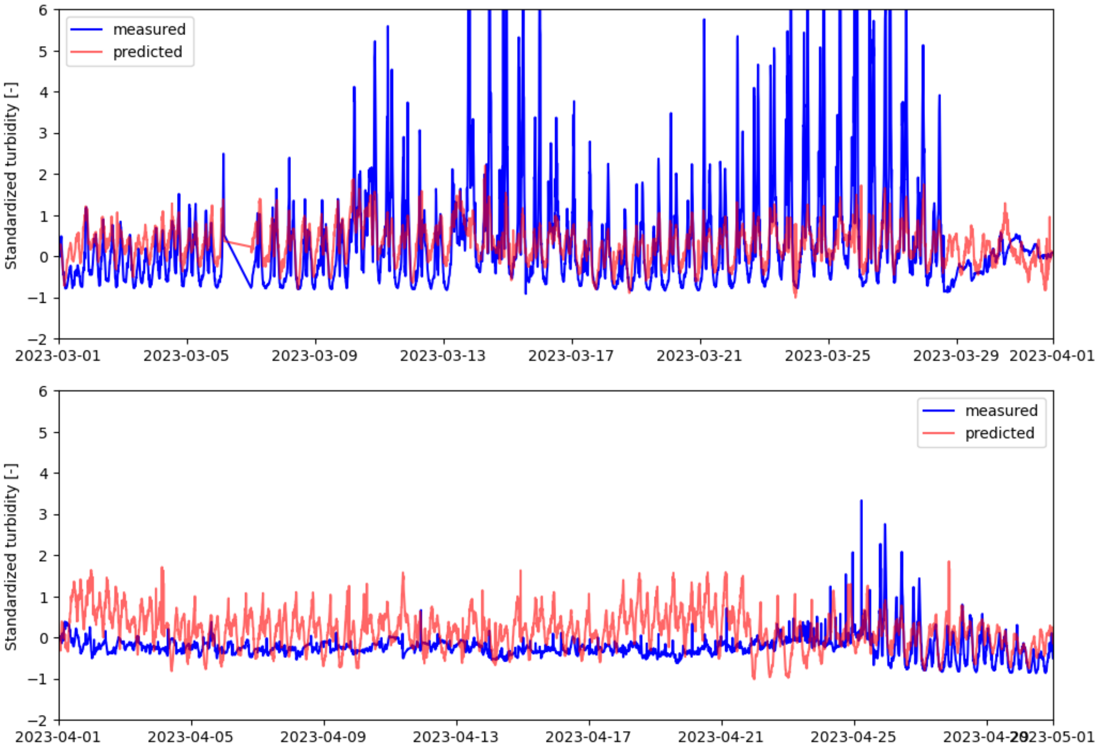



measured
predicted
Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2022-11-01
2022-11-05
2022-11-09
2022-11-13
2022-11-17
2022-11-21
2022-11-25
2022-11-29
2022-12-01


measured
predicted
Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2022-12-01
2022-12-05
2022-12-09
2022-12-13
2022-12-17
2022-12-21
2022-12-25
2022-12-29
2023-01-01

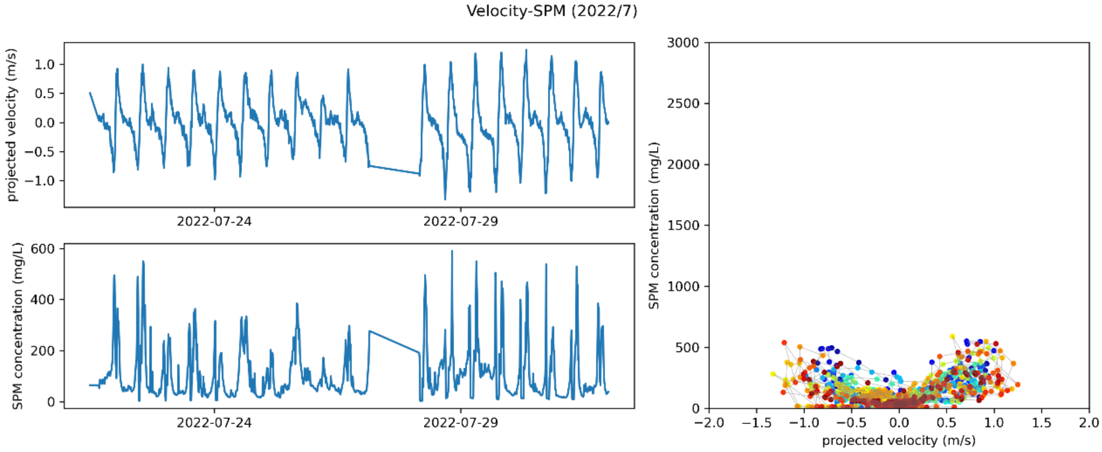

measured
predicted
Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2023-01-01
2023-01-05
2023-01-09
2023-01-13
2023-01-17
2023-01-21
2023-01-25
2023-01-29
2023-02-01

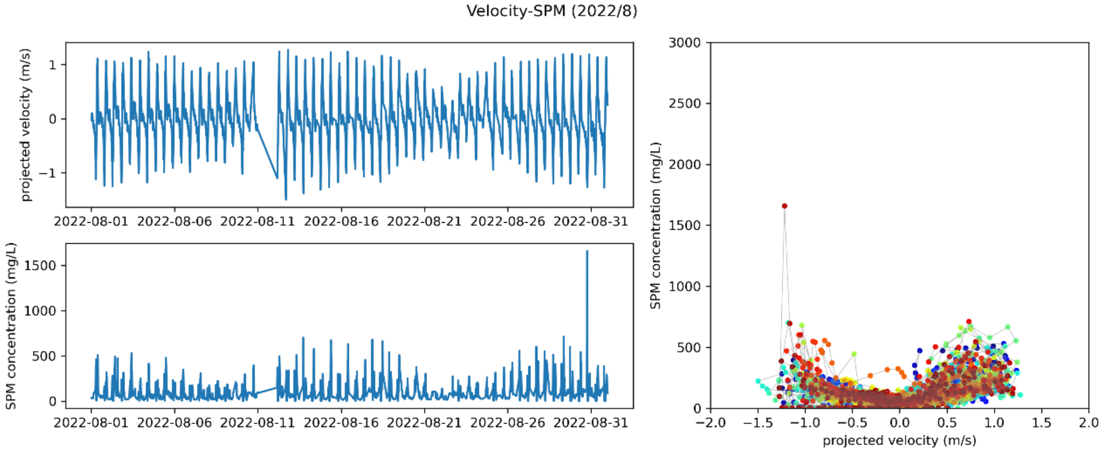

measured
predicted
Standardized turbidity [-]
6
5
4
3
2
1
0
−1
−2
2023-02-01
2023-02-05
2023-02-09
2023-02-13
2023-02-17
2023-02-21
2023-02-25
2023-03-01

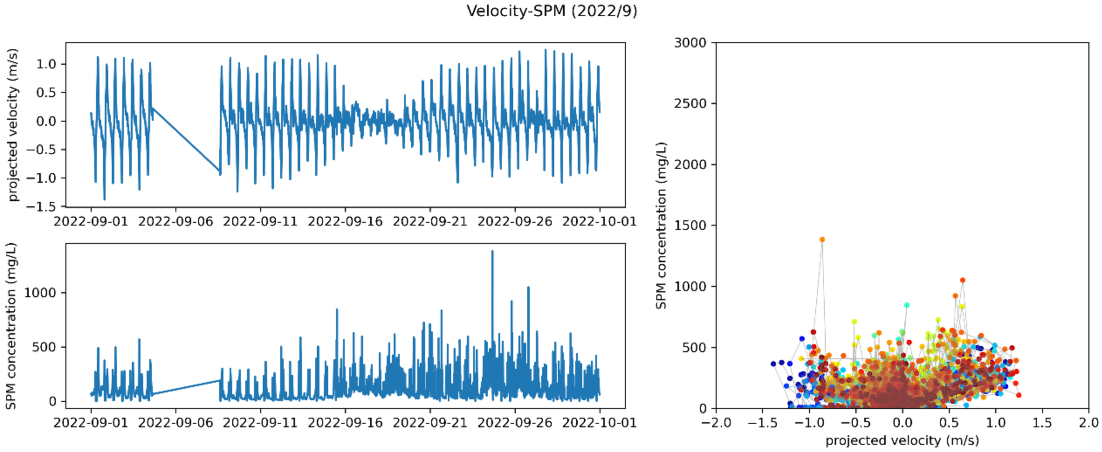


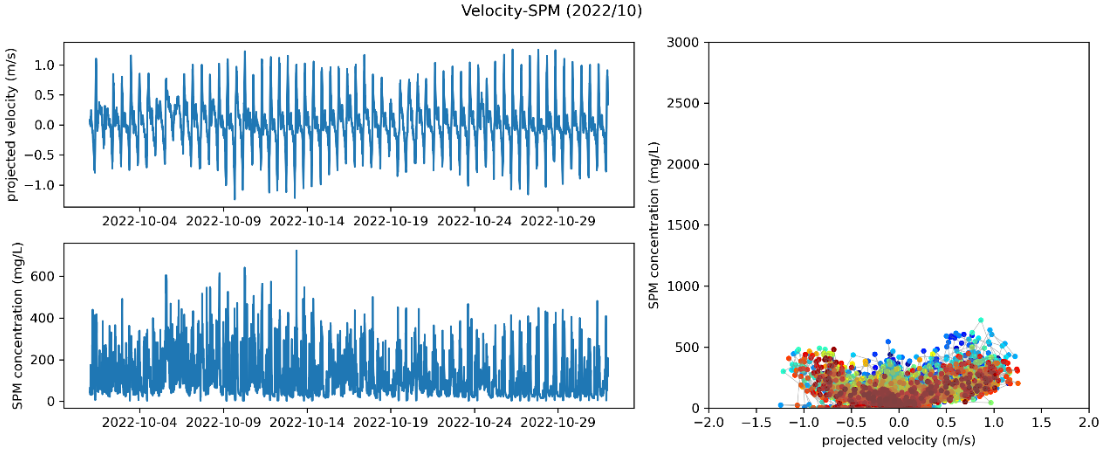
A.5 Velocity – SPM concentration plots

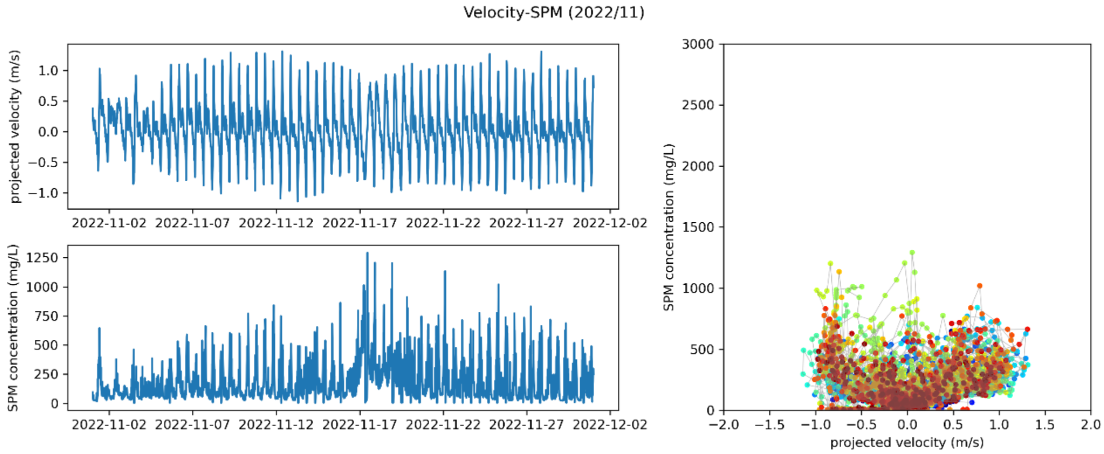
A.5.1 Holwerd

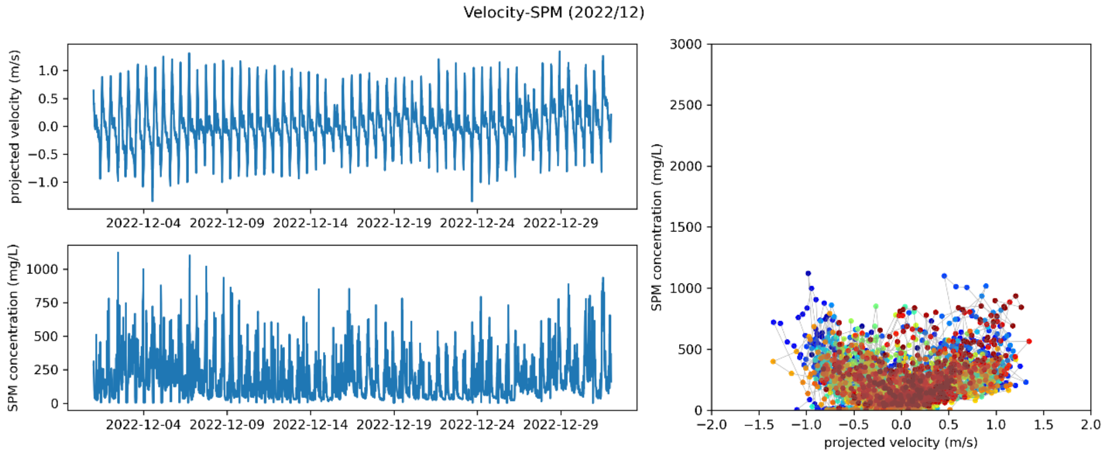

Velocity-SPM (2022/7)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2022-07-24
2022-07-29
SPM concentration (mg/L)
600
400
200
0
2022-07-24
2022-07-29
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

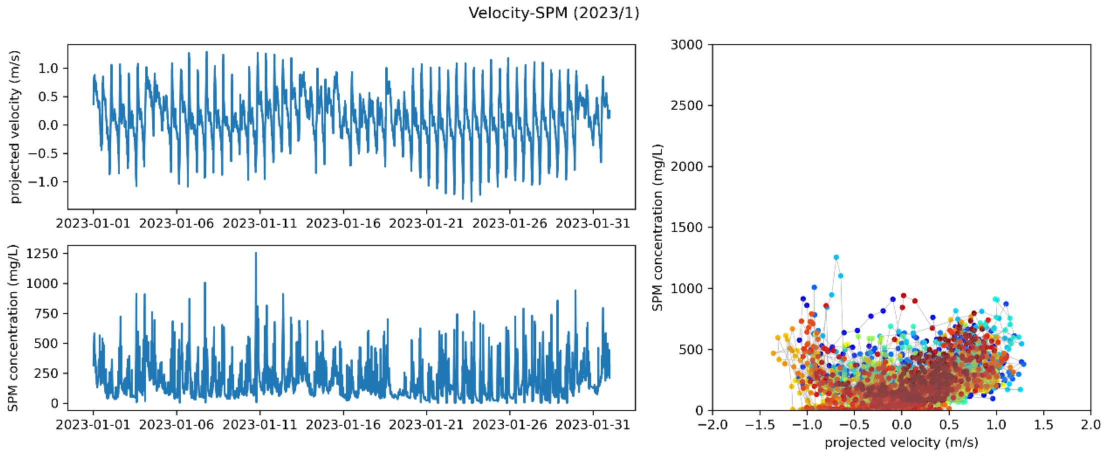

Velocity-SPM (2022/8)
projected velocity (m/s)
1
0
−1
2022-08-01
2022-08-06
2022-08-11
2022-08-16
2022-08-21
2022-08-26
2022-08-31
SPM concentration (mg/L)
1500
1000
500
0
2022-08-01
2022-08-06
2022-08-11
2022-08-16
2022-08-21
2022-08-26
2022-08-31
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

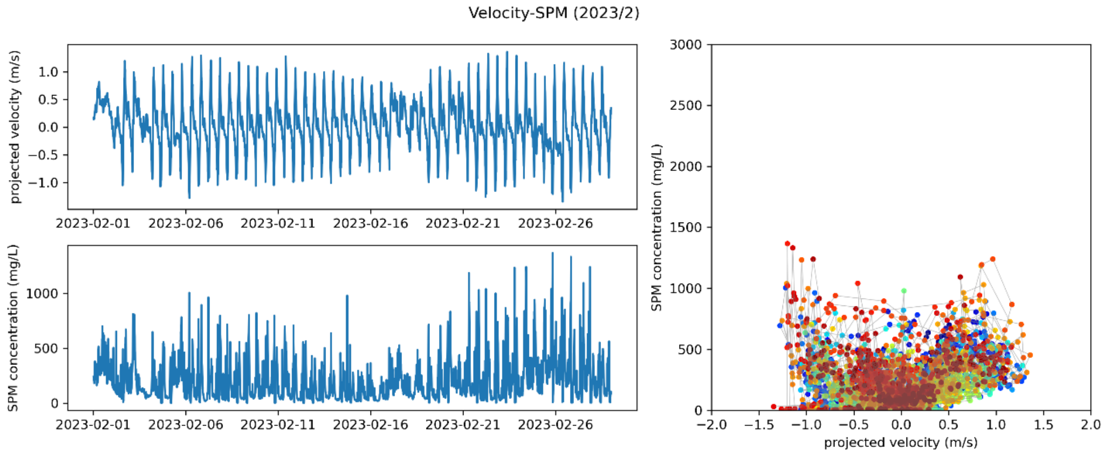

Velocity-SPM (2022/9)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
2022-09-01
2022-09-06
2022-09-11
2022-09-16
2022-09-21
2022-09-26
2022-10-01
SPM concentration (mg/L)
1000
500
0
2022-09-01
2022-09-06
2022-09-11
2022-09-16
2022-09-21
2022-09-26
2022-10-01
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

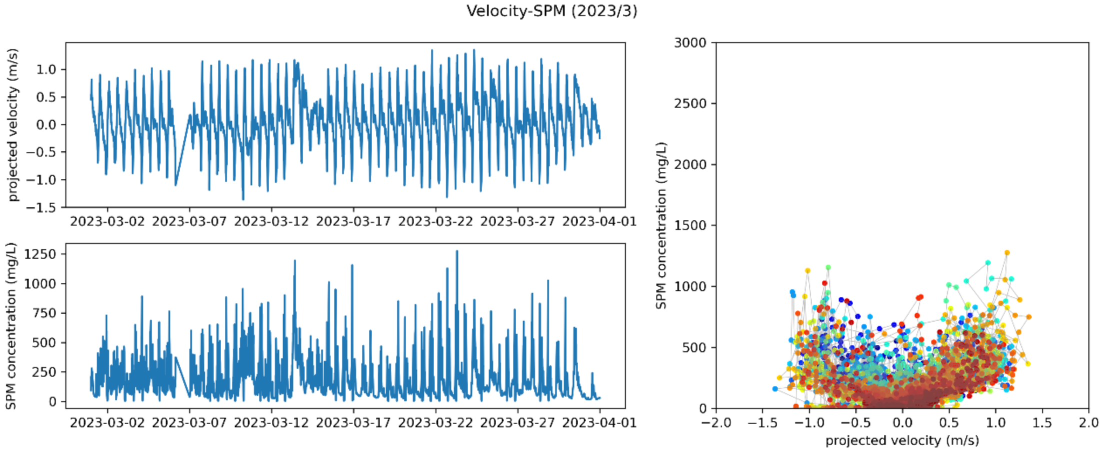

Velocity-SPM (2022/10)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2022-10-04
2022-10-09
2022-10-14
2022-10-19
2022-10-24
2022-10-29
SPM concentration (mg/L)
600
400
200
0
2022-10-04
2022-10-09
2022-10-14
2022-10-19
2022-10-24
2022-10-29
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

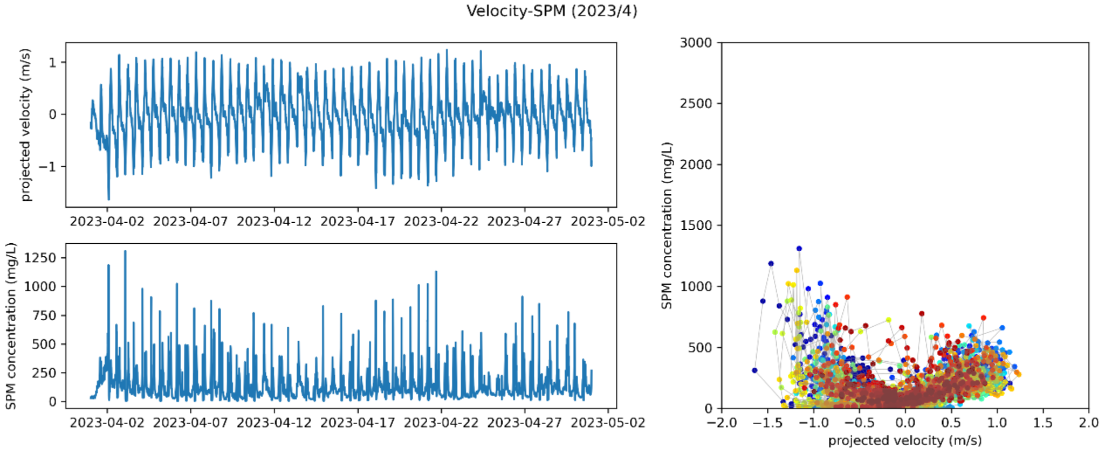

Velocity-SPM (2022/11)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2022-11-02
2022-11-07
2022-11-12
2022-11-17
2022-11-22
2022-11-27
2022-12-02
SPM concentration (mg/L)
1250
1000
750
500
250
0
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

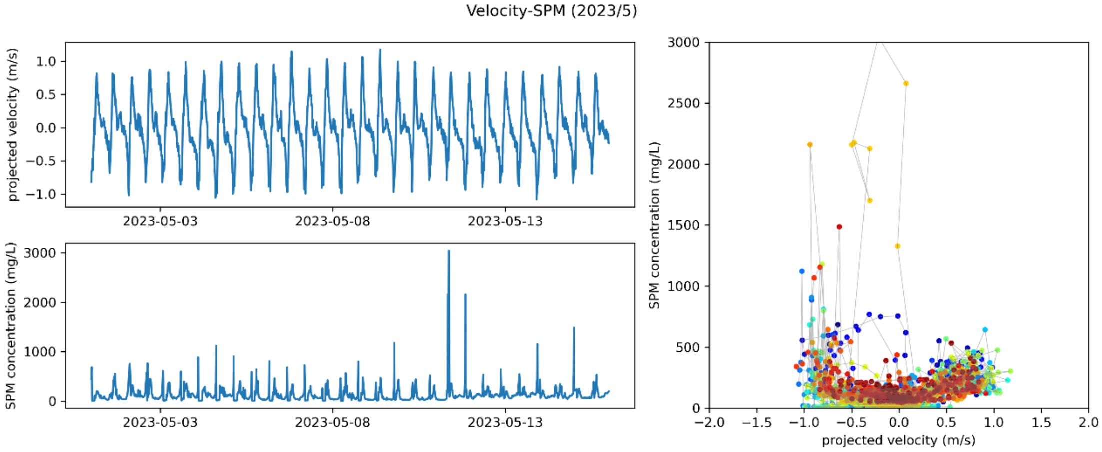

Velocity-SPM (2022/12)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2022-12-04
2022-12-09
2022-12-14
2022-12-19
2022-12-24
2022-12-29
SPM concentration (mg/L)
1000
750
500
250
0
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)


Velocity-SPM (2023/1)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2023-01-01
2023-01-06
2023-01-11
2023-01-16
2023-01-21
2023-01-26
2023-01-31
SPM concentration (mg/L)
1250
1000
750
500
250
0
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

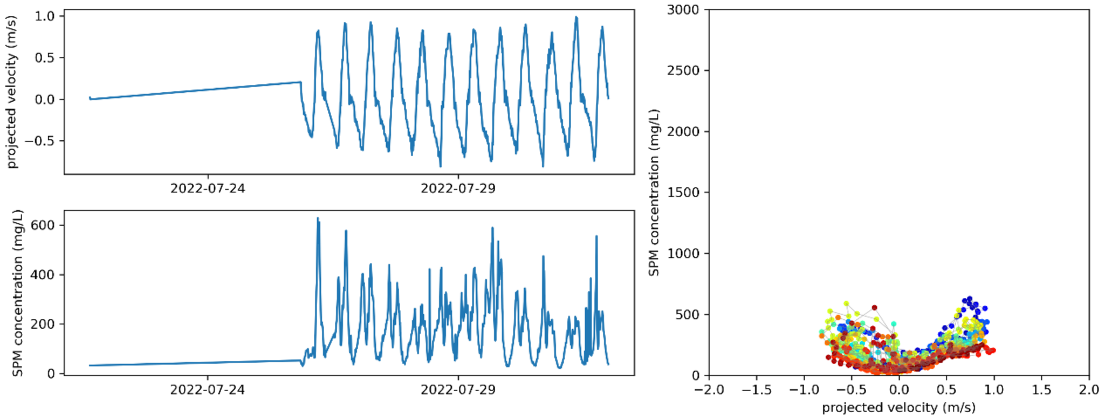

Velocity-SPM (2023/2)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2023-02-01
2023-02-06
2023-02-11
2023-02-16
2023-02-21
2023-02-26
SPM concentration (mg/L)
1000
500
0
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)


Velocity-SPM (2023/3)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
2023-03-02
2023-03-07
2023-03-12
2023-03-17
2023-03-22
2023-03-27
2023-04-01
SPM concentration (mg/L)
1250
1000
750
500
250
0
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

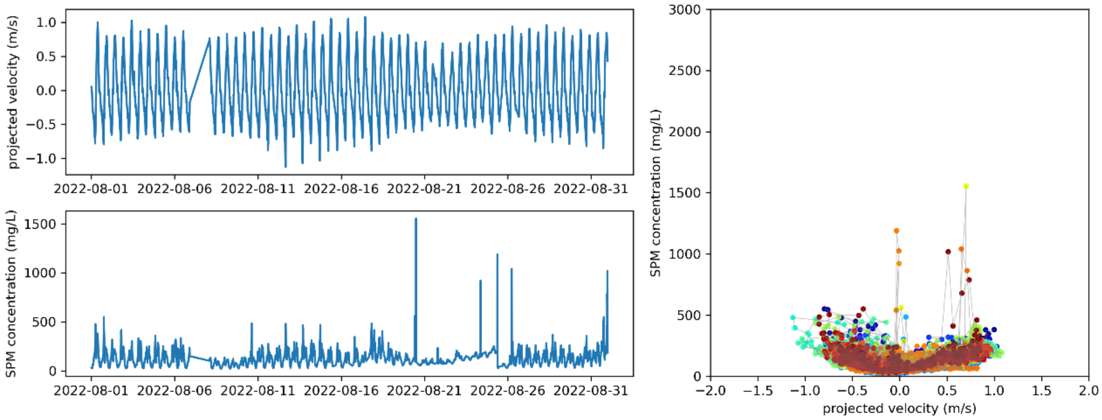

Velocity-SPM (2023/4)
projected velocity (m/s)
1
0
−1
2023-04-02
2023-04-07
2023-04-12
2023-04-17
2023-04-22
2023-04-27
2023-05-02
SPM concentration (mg/L)
1250
1000
750
500
250
0
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)


Velocity-SPM (2023/5)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2023-05-03
2023-05-08
2023-05-13
SPM concentration (mg/L)
3000
2000
1000
0
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

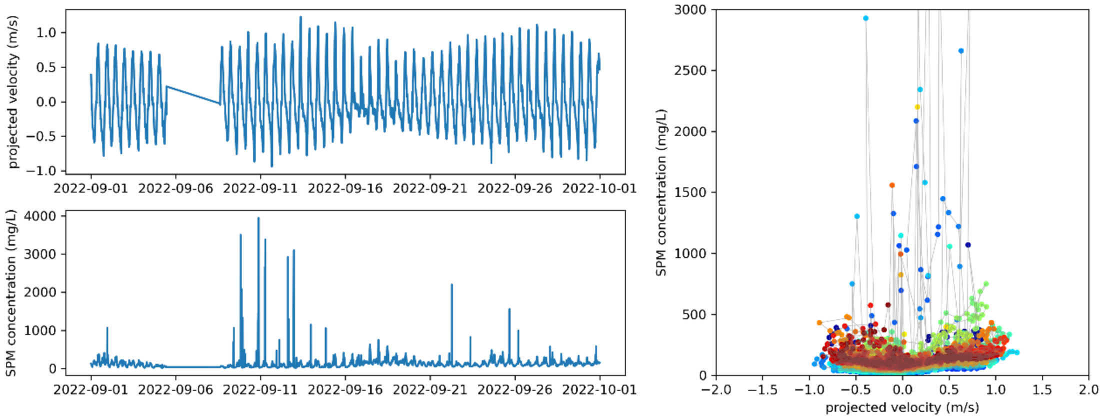
A.5.2 Dantziggat



Velocity-SPM (2022/7)

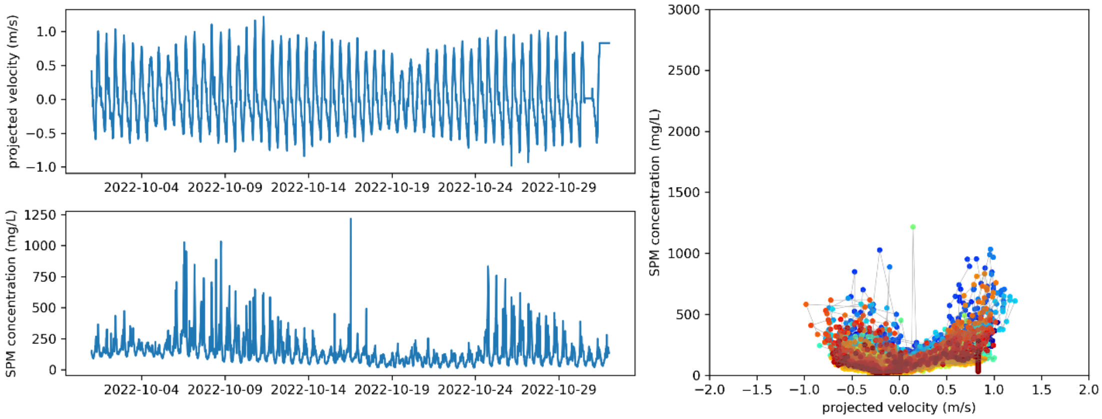


Velocity-SPM (2022/8)

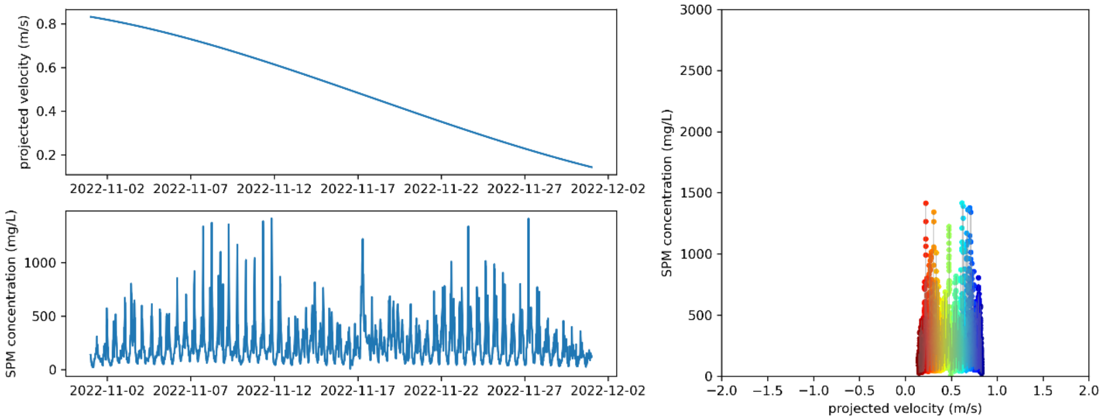


Velocity-SPM (2022/9)

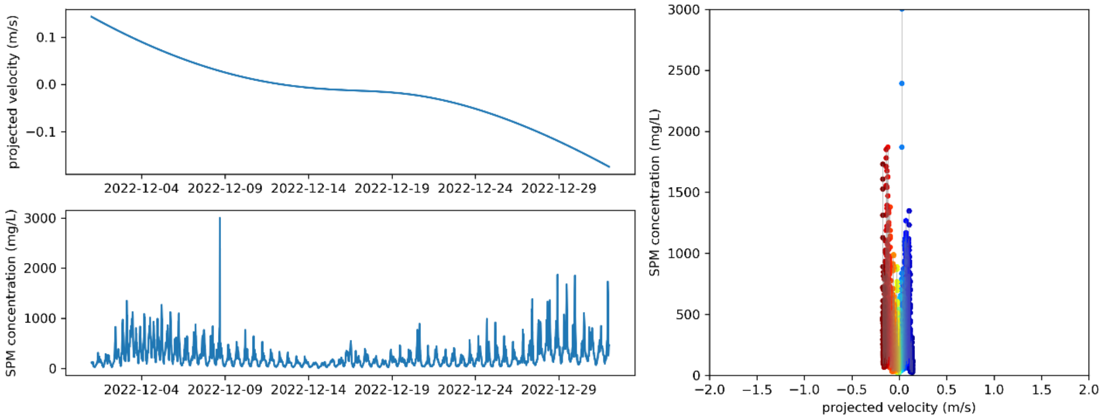
Velocity-SPM (2022/10)



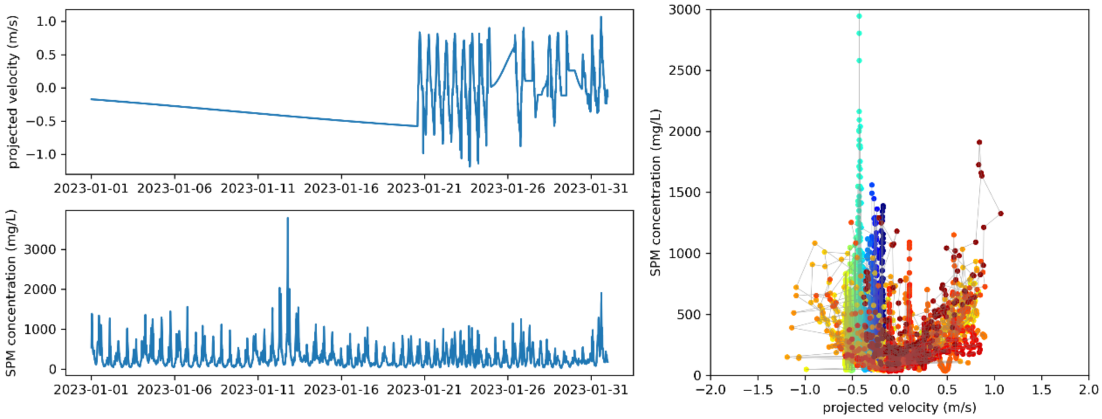
Velocity-SPM (2022/11)

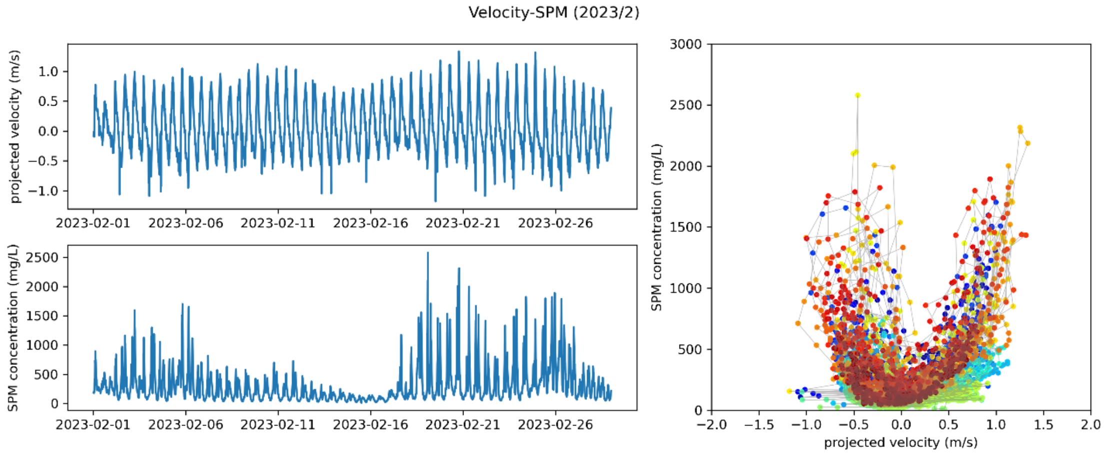


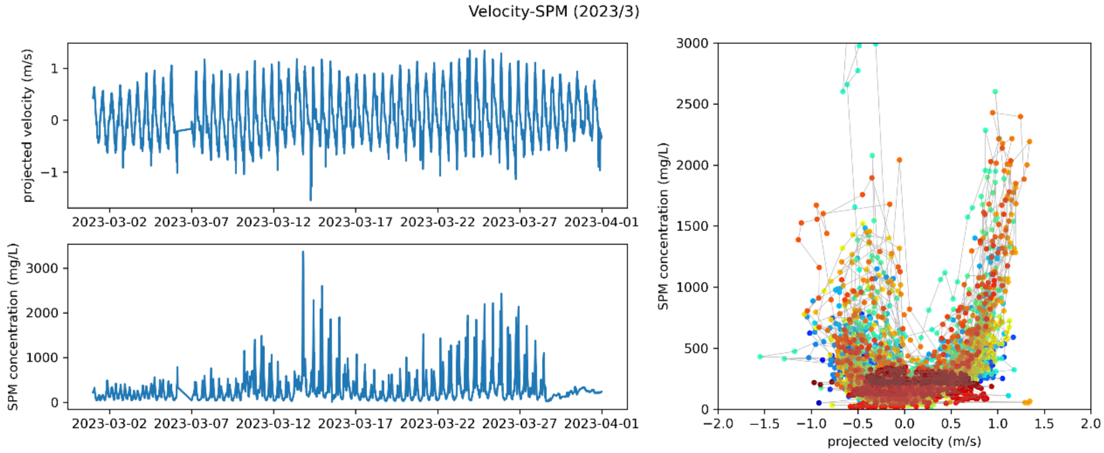
Velocity-SPM (2022/12)

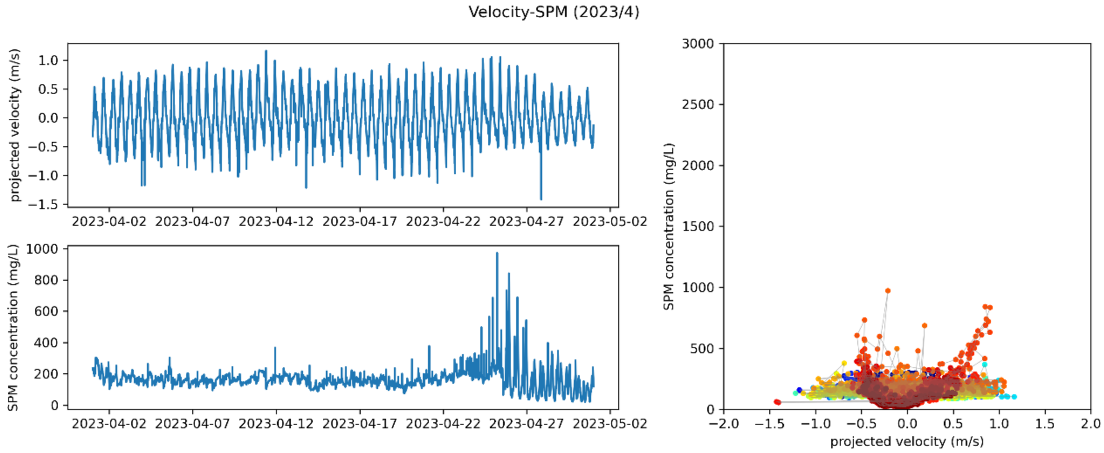


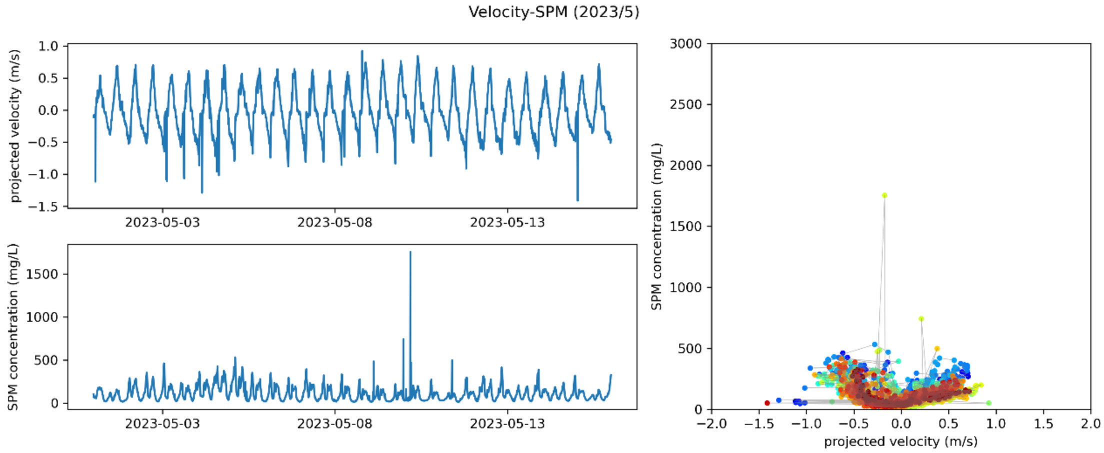
Velocity-SPM (2023/1)




Velocity-SPM (2023/2)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
2023-02-01
2023-02-06
2023-02-11
2023-02-16
2023-02-21
2023-02-26
SPM concentration (mg/L)
2500
2000
1500
1000
500
0
3000
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

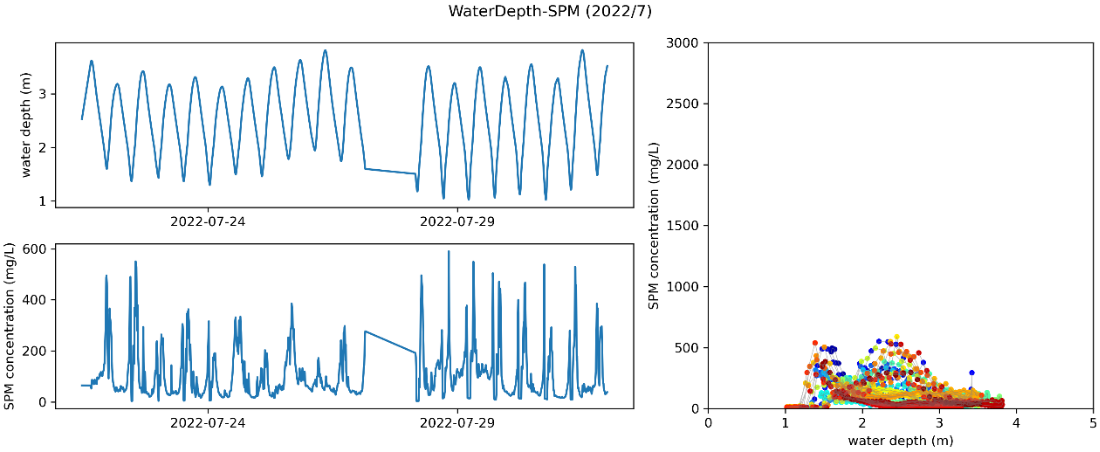

Velocity-SPM (2023/3)
projected velocity (m/s)
1
0
−1
2023-03-02
2023-03-07
2023-03-12
2023-03-17
2023-03-22
2023-03-27
2023-04-01
SPM concentration (mg/L)
3000
2500
2000
1500
1000
500
0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

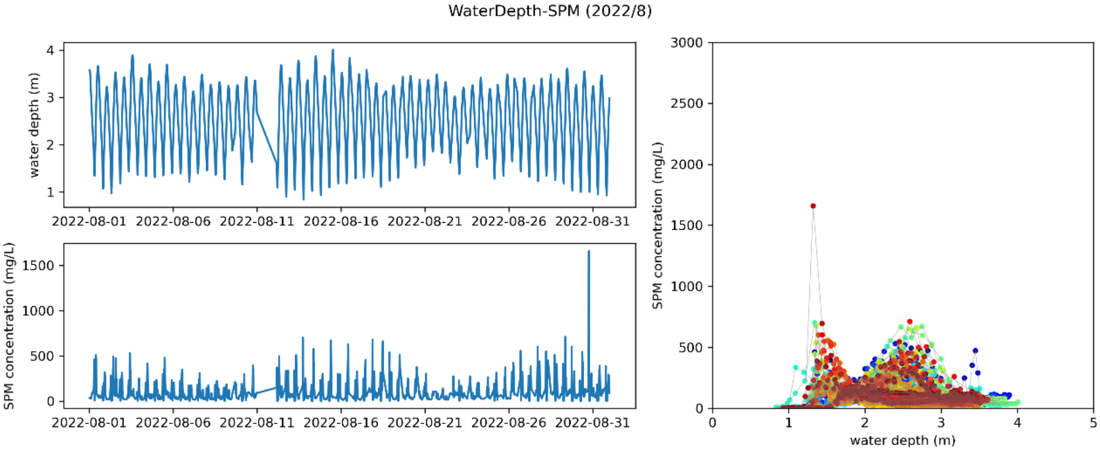

Velocity-SPM (2023/4)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
2023-04-02
2023-04-07
2023-04-12
2023-04-17
2023-04-22
2023-04-27
2023-05-02
SPM concentration (mg/L)
1000
800
600
400
200
0
3000
2500
2000
1500
500
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

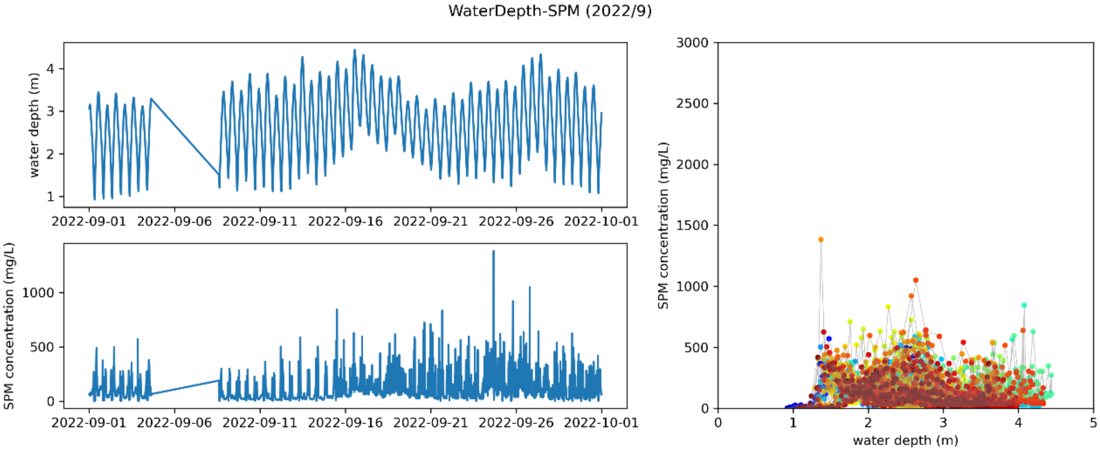

Velocity-SPM (2023/5)
projected velocity (m/s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
2023-05-03
2023-05-08
2023-05-13
SPM concentration (mg/L)
1500
1000
500
0
3000
2500
2000
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
projected velocity (m/s)

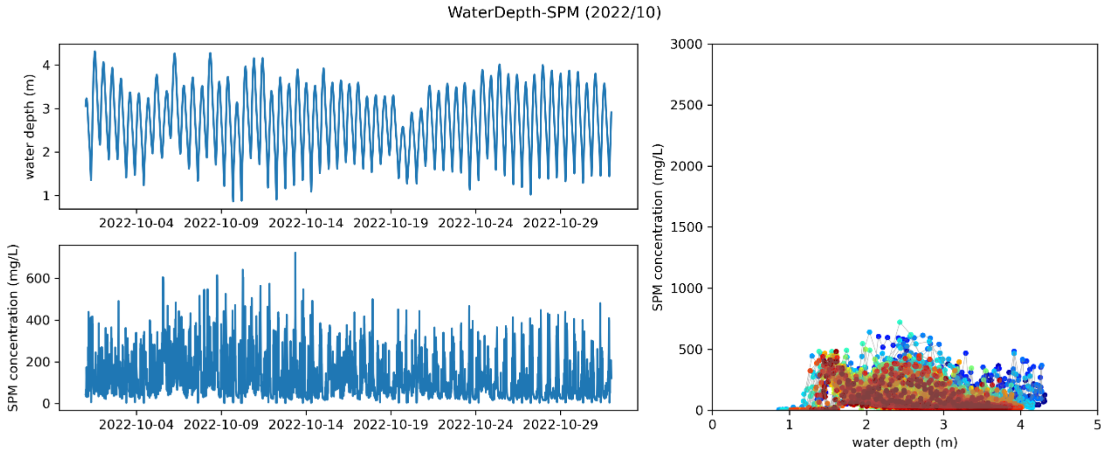
A.6 Water depth - SPM concentration plots

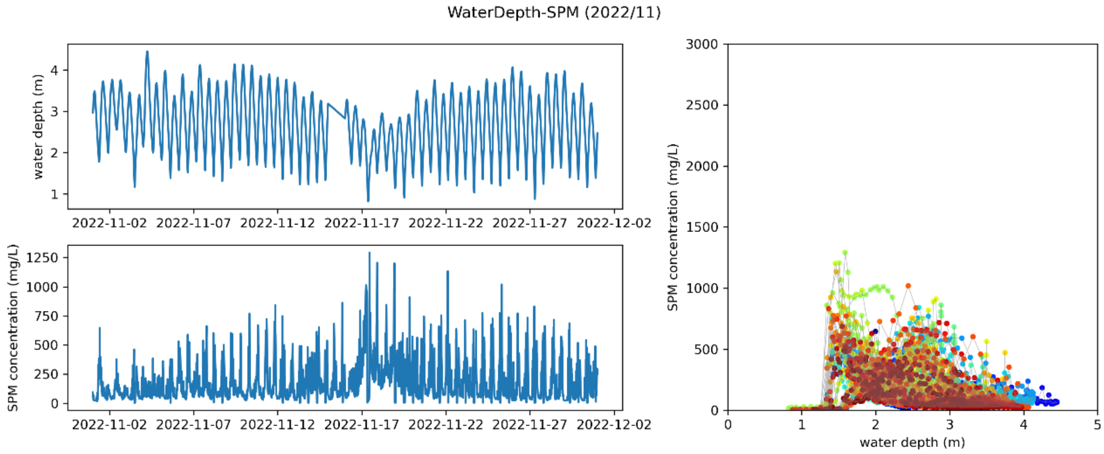
A.6.1 Holwerd

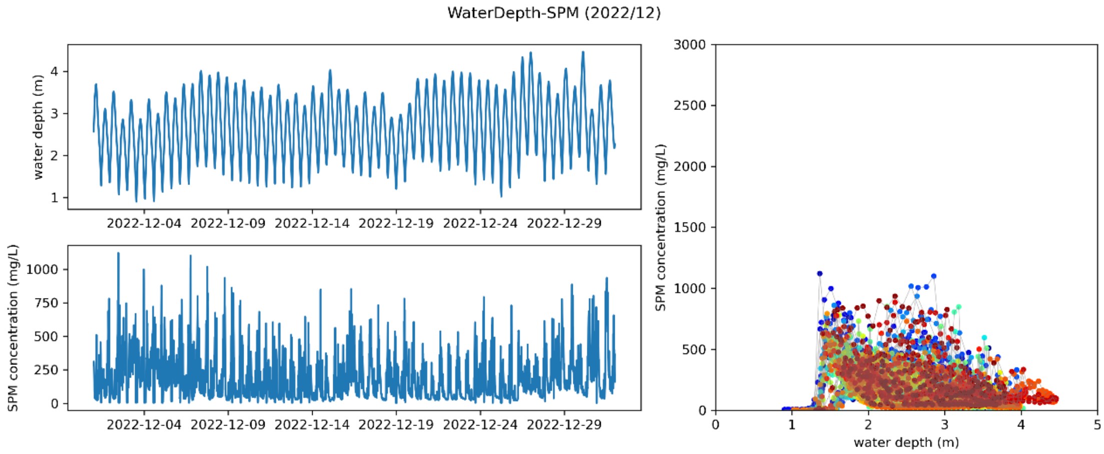


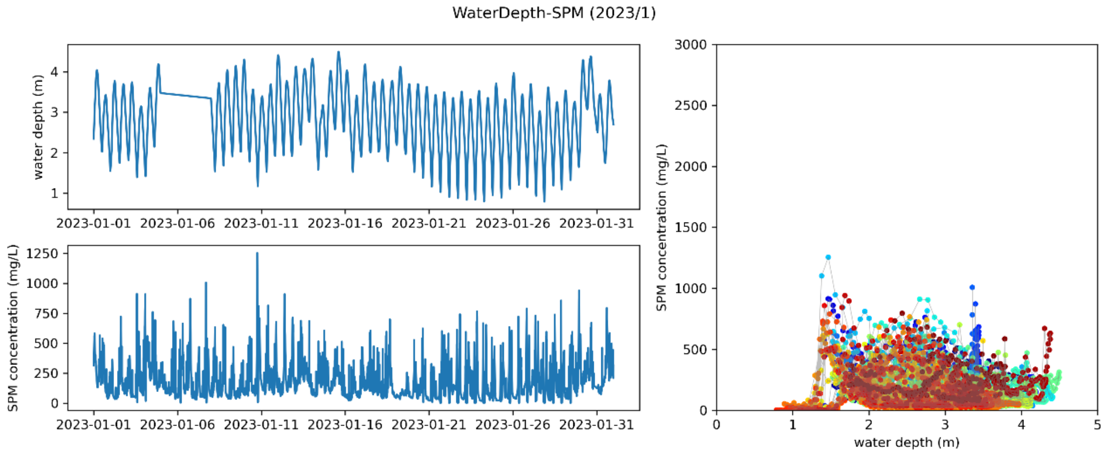


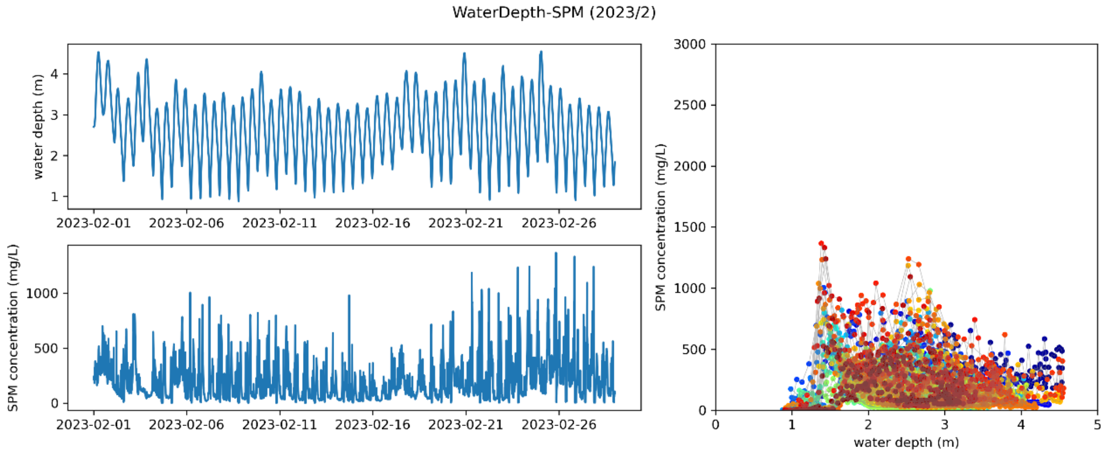


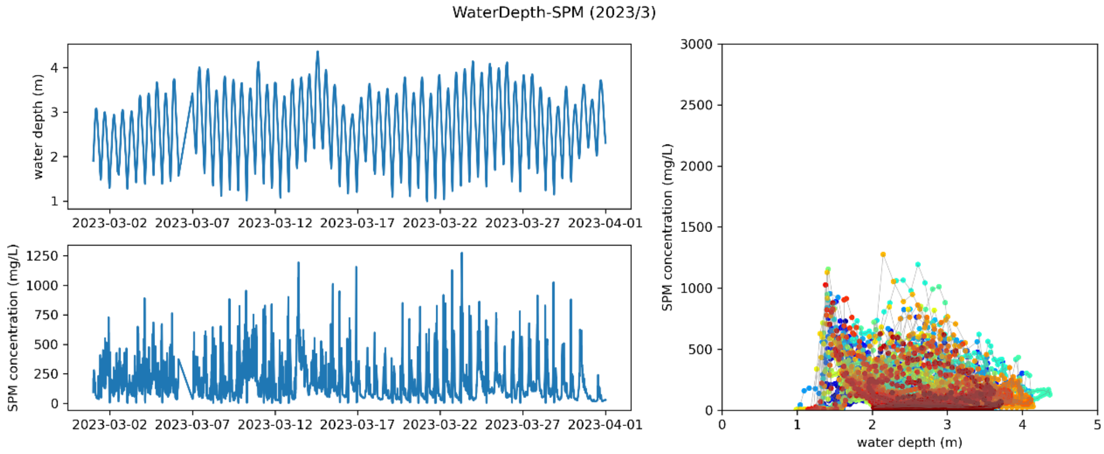

WaterDepth-SPM (2022/10)
water depth (m)
1
2
3
4
2022-10-04
2022-10-09
2022-10-14
2022-10-19
2022-10-24
2022-10-29
SPM concentration (mg/L)
0
200
400
600
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5

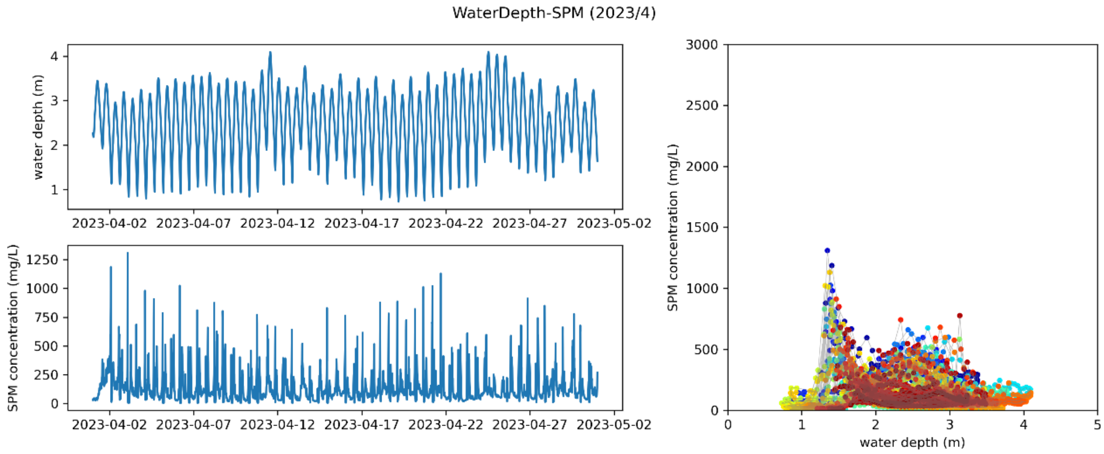

WaterDepth-SPM (2022/11)
water depth (m)
1
2
3
4
2022-11-02
2022-11-07
2022-11-12
2022-11-17
2022-11-22
2022-11-27
2022-12-02
SPM concentration (mg/L)
0
250
500
750
1000
1250
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5

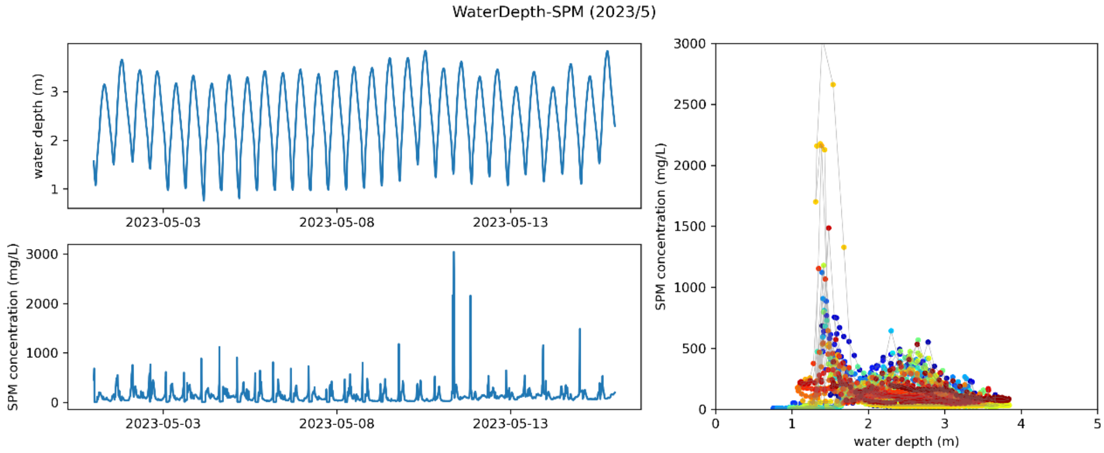

WaterDepth-SPM (2022/12)
water depth (m)
1
2
3
4
2022-12-04
2022-12-09
2022-12-14
2022-12-19
2022-12-24
2022-12-29
SPM concentration (mg/L)
0
250
500
750
1000
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5


WaterDepth-SPM (2023/1)
water depth (m)
1
2
3
4
2023-01-01
2023-01-06
2023-01-11
2023-01-16
2023-01-21
2023-01-26
2023-01-31
SPM concentration (mg/L)
0
250
500
750
1000
1250
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5

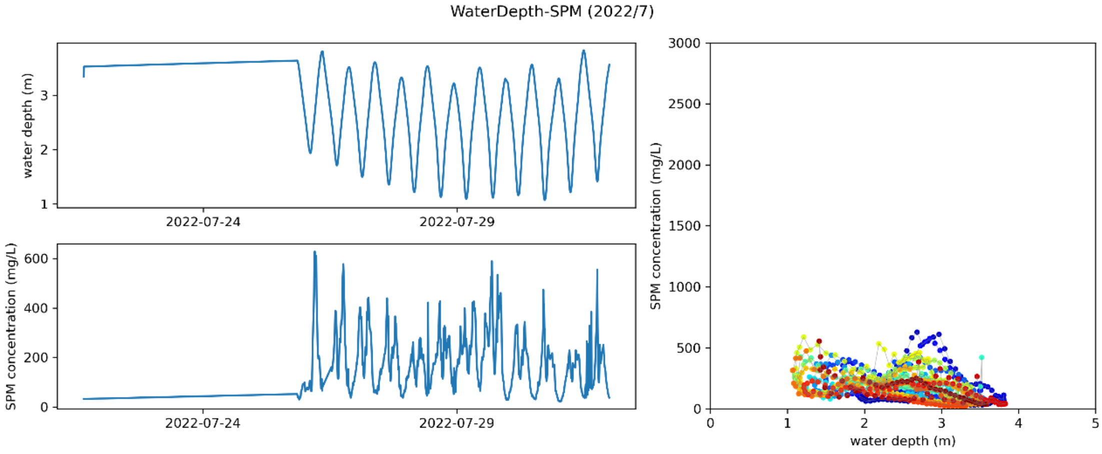

WaterDepth-SPM (2023/2)
water depth (m)
1
2
3
4
2023-02-01
2023-02-06
2023-02-11
2023-02-16
2023-02-21
2023-02-26
SPM concentration (mg/L)
0
500
1000
2023-02-01
2023-02-06
2023-02-11
2023-02-16
2023-02-21
2023-02-26
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
0
1
2
3
4
5
water depth (m)

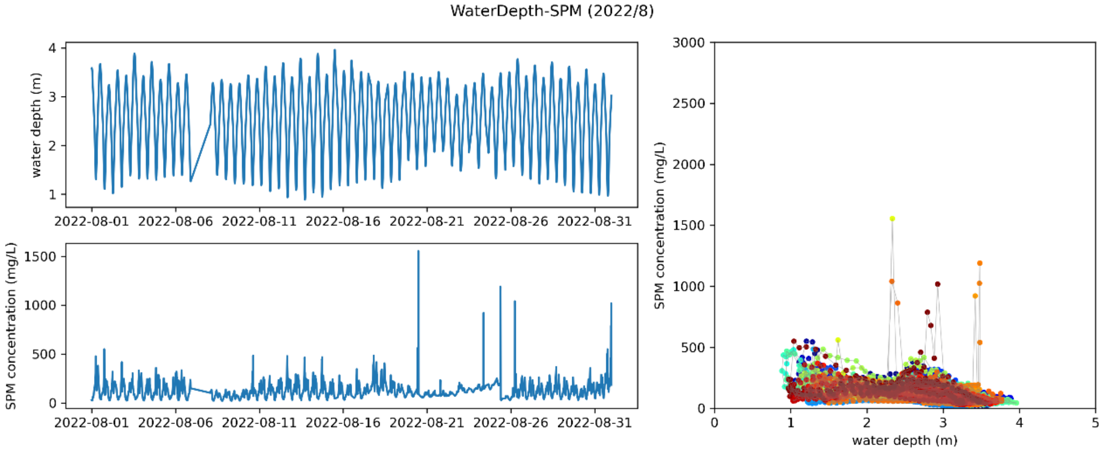

WaterDepth-SPM (2023/3)
water depth (m)
1
2
3
4
2023-03-02
2023-03-07
2023-03-12
2023-03-17
2023-03-22
2023-03-27
2023-04-01
SPM concentration (mg/L)
0
250
500
750
1000
1250
2023-03-02
2023-03-07
2023-03-12
2023-03-17
2023-03-22
2023-03-27
2023-04-01
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
0
1
2
3
4
5
water depth (m)

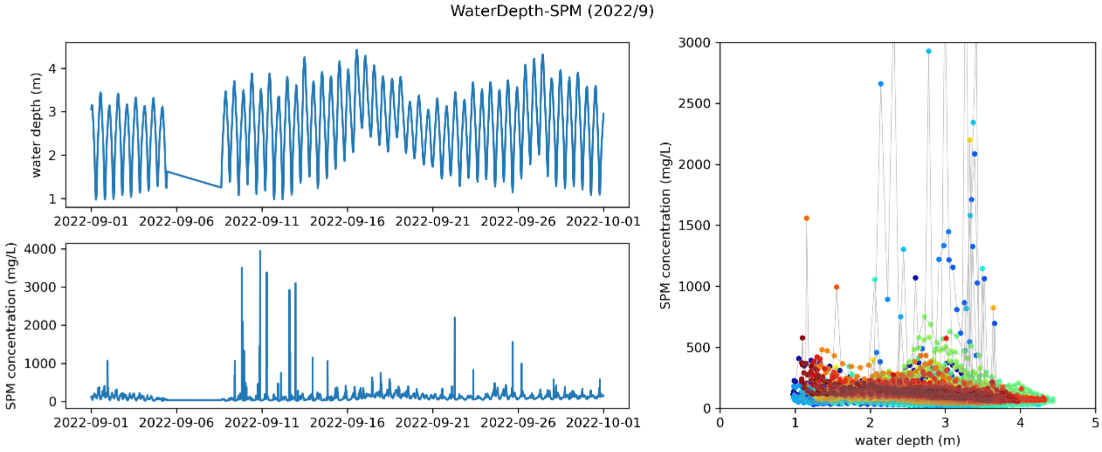

WaterDepth-SPM (2023/4)
water depth (m)
1
2
3
4
2023-04-02
2023-04-07
2023-04-12
2023-04-17
2023-04-22
2023-04-27
2023-05-02
SPM concentration (mg/L)
0
250
500
750
1000
1250
2023-04-02
2023-04-07
2023-04-12
2023-04-17
2023-04-22
2023-04-27
2023-05-02
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
0
1
2
3
4
5
water depth (m)

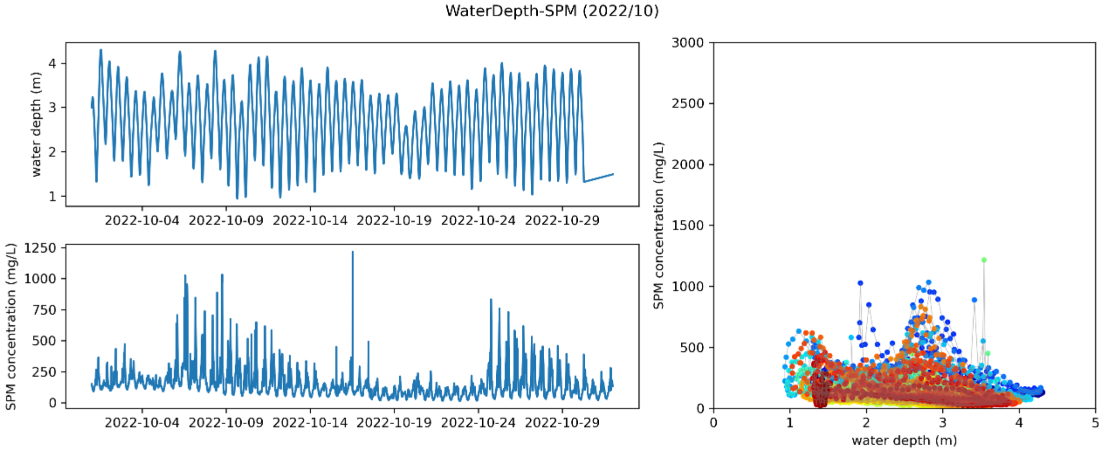

WaterDepth-SPM (2023/5)
water depth (m)
1
2
3
2023-05-03
2023-05-08
2023-05-13
SPM concentration (mg/L)
0
1000
2000
3000
2023-05-03
2023-05-08
2023-05-13
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
0
1
2
3
4
5
water depth (m)

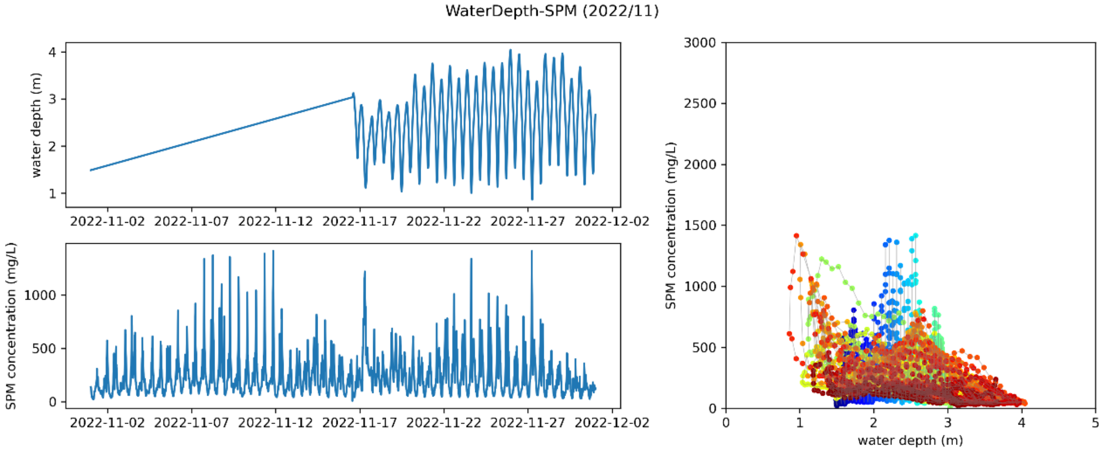
A.6.2 Dantziggat

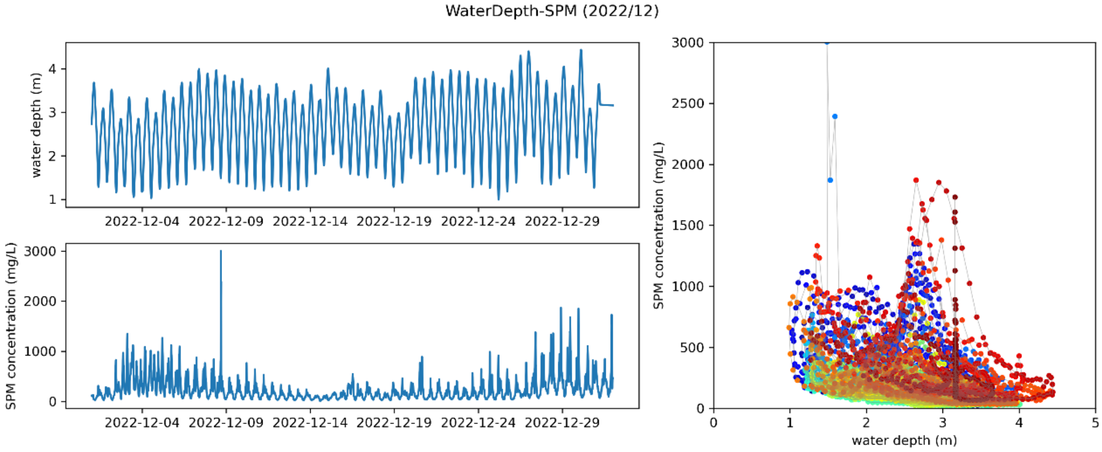


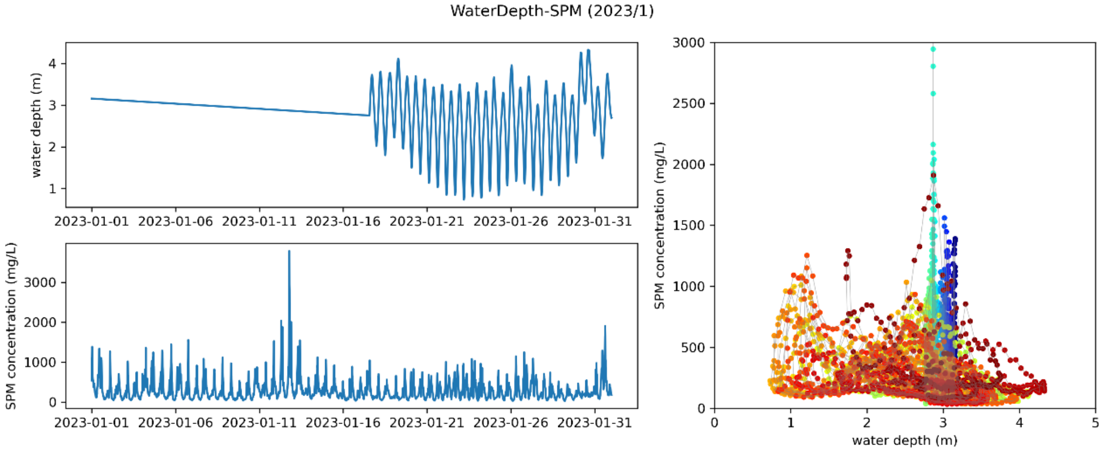


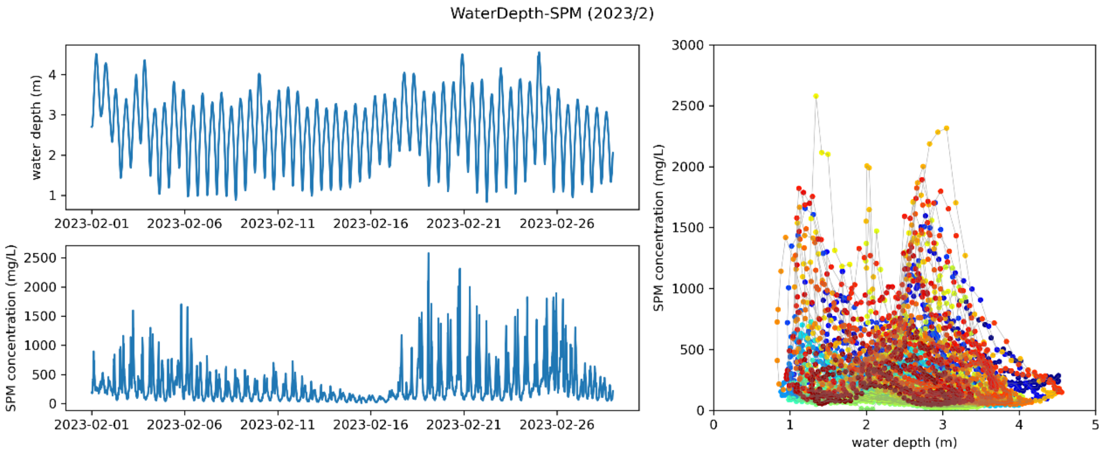


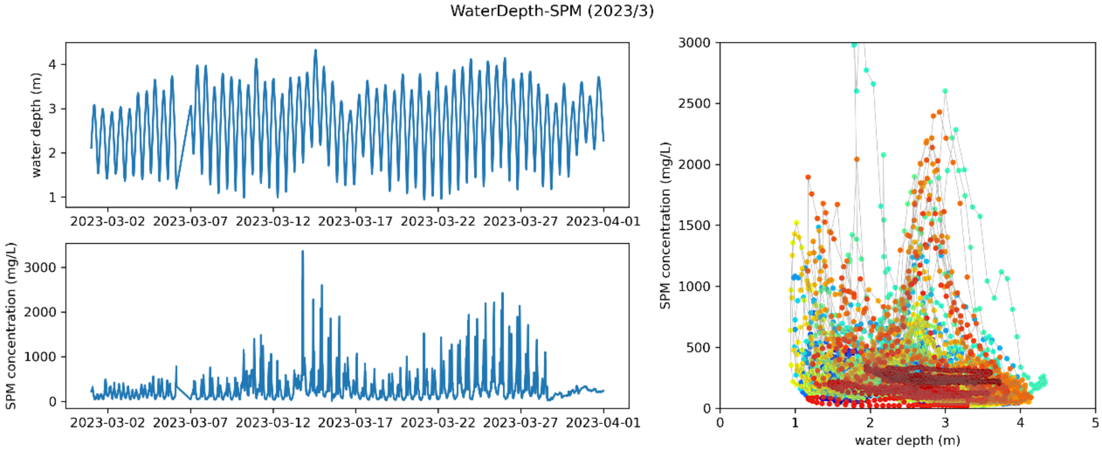

WaterDepth-SPM (2022/10)
water depth (m)
1
2
3
4
2022-10-04
2022-10-09
2022-10-14
2022-10-19
2022-10-24
2022-10-29
SPM concentration (mg/L)
0
250
500
750
1000
1250
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5

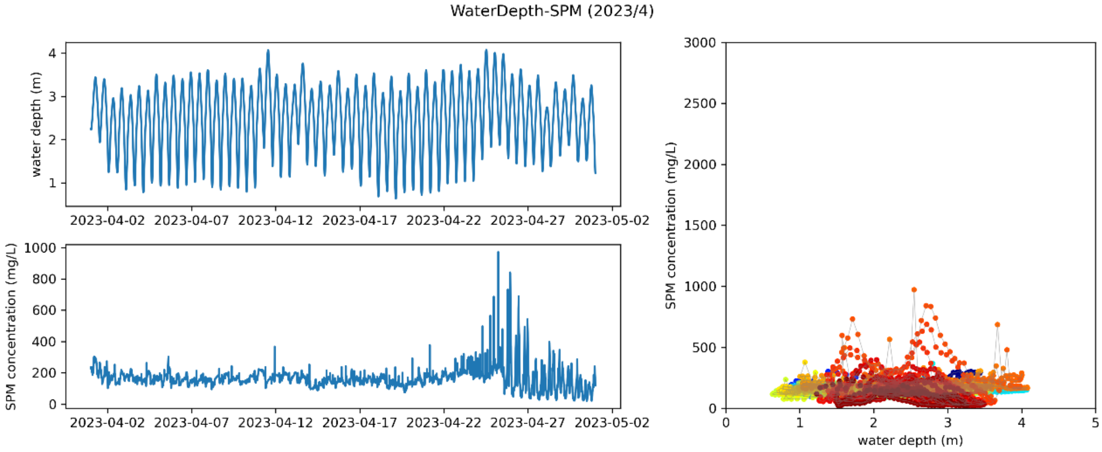

WaterDepth-SPM (2022/11)
water depth (m)
1
2
3
4
2022-11-02
2022-11-07
2022-11-12
2022-11-17
2022-11-22
2022-11-27
2022-12-02
SPM concentration (mg/L)
0
500
1000
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5

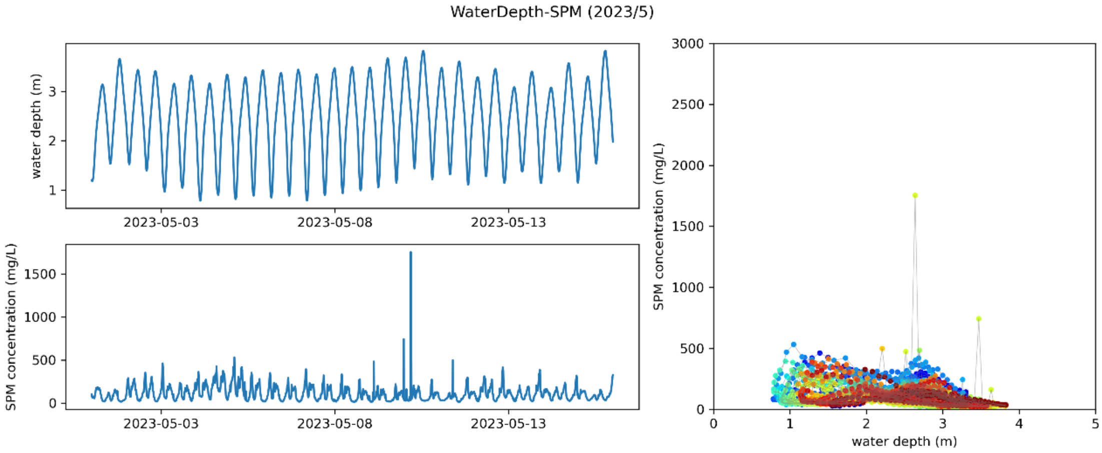

WaterDepth-SPM (2022/12)
water depth (m)
1
2
3
4
2022-12-04
2022-12-09
2022-12-14
2022-12-19
2022-12-24
2022-12-29
SPM concentration (mg/L)
0
1000
2000
3000
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5


WaterDepth-SPM (2023/1)
water depth (m)
1
2
3
4
2023-01-01
2023-01-06
2023-01-11
2023-01-16
2023-01-21
2023-01-26
2023-01-31
SPM concentration (mg/L)
0
1000
2000
3000
SPM concentration (mg/L)
0
500
1000
1500
2000
2500
3000
water depth (m)
0
1
2
3
4
5


WaterDepth-SPM (2023/2)

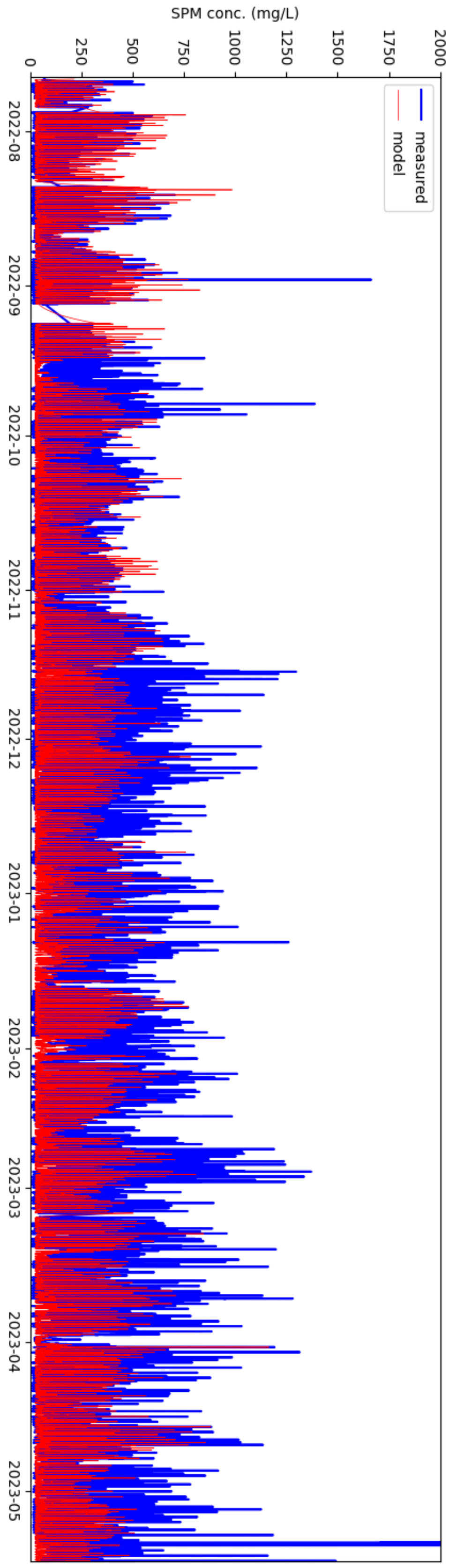

WaterDepth-SPM (2023/3)


WaterDepth-SPM (2023/4)


WaterDepth-SPM (2023/5)

A.7 Results from calibrated point model

A.7.1 Holwerd



A.7.2 Dantziggat