Tallinn University of Technology

ADCP measurements for the collection of data on current profiles and salinity and oxygen content in the demersal zone in the area of the wreck of the ferry *Estonia* (December 2021 – March 2022)

Report

Public procurement No. 241513

TALLINN

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ANNOTATION

The aim of the survey was to record the vertical profiles of the currents and the salinity, temperature, and oxygen concentration in the demersal zone in the area of the wreck of the ferry *Estonia* under winter conditions, when no seasonal thermocline is present in the water column. The measurements were carried out using the SeaGuard II measurement platform from Aanderaa, which was connected to an acoustic Doppler current profiler and pressure, electrical conductivity, temperature, and oxygen sensors. The platform, connected to a submersible buoy and anchored to the seafloor, was deployed from the Estonian Police and Border Guard Board's vessel *Raju* in the vicinity of the wreck of the *Estonia* on 12 December 2021 at 59° 23,0515' N, 21° 41,2294' E. The depth of the seafloor at the measurement site was 80 m. The platform was retrieved by the Tallinn University of Technology's research vessel *Salme* on 21 March 2022. The series of data collected are presented in the annex to this report. This report describes the temporal variability of currents in the water column at a depth of 34–76 m, i.e. 4 m above the seafloor within a range of 42 m. Due to high water transparency, the measurements obtained from the surface layer are unreliable (with a high signal-to-noise ratio) and will not be analysed in this report. Periods of higher current velocity in the deep layer are identified, and, based on meteorological data for the measurement period, the conditions that prevailed during strong currents are described. The temporal variability of the salinity and dissolved oxygen concentration in the demersal zone of the area of the wreck of the *Estonia* is analysed from December 2021 to March 2022 when no seasonal stratification was present. A comparative analysis of the results of two measurement periods is provided.

The work has been carried out in accordance with the public contract awarded by the Estonian Safety Investigation Bureau (public procurement reference number 241513) from 13 October 2021.

The measurements, data analysis, and preparation of the report were carried out with the involvement of experts Villu Kikas, Oliver Samlas, Kai Salm, Stella-Theresa Stoicescu, and Urmas Lips from the Department of Marine Systems of Tallinn University of Technology.

1. INTRODUCTION

During the period of 1994–2021, no long-term measurements of oceanographic parameters have been carried out at the shipwreck site of the *Estonia* in the northern Baltic Sea proper. The first longer-term measurements were carried out under this project from 10 July 2021 to 9 November 2021. These measurements were carried out during the summer period, corresponding to the stratified conditions of the water column. The measurements analysed in this report were carried out during the winter period when no seasonal stratification was present and the water column was destratified down to the halocline. Based on the data collected, a description will be given of the variability of the currents, salinity, and oxygen conditions in the demersal zone and how it relates to the prevailing meteorological conditions and/or physical processes and to compare the results with summer measurements.

In this report, measurement data are provided along with the analysis of the history and variability of currents, temperature, salinity and oxygen concentration in the area of the wreck of the ferry *Estonia* in winter conditions. The data were collected between 12 December 2021 and 21 March 2022.

The work included the recording of vertical current profiles and time series in one-hour increments for the salinity, temperature, and oxygen content in the demersal zone. The measurements were carried out using the SeaGuard II measurement platform from Aanderaa, which was connected to an acoustic Doppler current profiler and pressure, electrical conductivity, temperature, and oxygen sensors. The depth of the sea at the measurement site (59° 23,0515' N, 21° 41,2294' EE; all coordinates in the report are given in the WGS84 system) was 80 m. Among other things, maximum current velocities near the seafloor are identified and an analysis of what these events might have been related to is presented. A description of the variability of salinity and oxygen conditions near the seafloor in winter conditions is provided. All of the data collected can be used for the validation of modelling results.

The report is structured as follows. Section 2 (measurements and data) explores the instrumentation used, the design of the buoy station, the sensors, the collected data, and the analysis methods. Additionally, the meteorological data used in the analysis are identified.

Section 3 presents the results. Subsection 3.1 describes the temporal variability of currents in the water column 4–46 m above the seafloor (i.e. between a depth of 34–76 m). The dynamics of the demersal zone are explored separately. Time series for the currents and progressive vector diagrams are presented graphically, and statistical characteristics are presented for the currents, including maximum velocities, periods where the velocity exceeded a certain limit (e.g., 10 cm/s and 20 cm/s), and other parameters.

Subsection 3.2 describes the meteorological conditions during the measurement period based on ERA5 data, including wind statistics along with a wind rose, maximum speeds, and winds during periods of higher velocities near the seafloor. An analysis of what the mechanism for the generation of the high current velocities might have been, i.e. what kind of winds prevailed during high current velocities (including with regard to the direction and the speed) in the area, is presented.

Subsection 3.3 describes the variability of salinity and dissolved oxygen concentration in the demersal zone throughout the measurement period. The causes of this variability and the relationship between oxygen conditions and changes in currents and wind conditions are analysed.

In section 4, the results obtained during the second measurement period are analysed and compared with the results from the first period.

Section 5 briefly summarises the findings and conclusions from the measurement.

2. DATA AND METHODOLOGY

The work was carried out using the SeaGuard II measurement platform from Aanderaa, which was connected to an acoustic Doppler current profiler (DCPS, sn 505), a pressure sensor (4117, sn 1857), a conductivity sensor (4319, sn 1545), and an oxygen optode (4835, sn 3766). All three of the latter sensors were also equipped with a temperature sensor. Sensor specifications are given in Table 2.1.

Table 2.1. Specifications for the sensors connected to the Aanderaa SeaGuard II platform used for the work.

Sensor/parameter	Unit	Range	Resolution	Accuracy
DCPS speed	cm/s	0–500	0.1	0.3
DCPS direction /compass	degree	0–360	0.1	2
Pressure	MPa	0–60	0.0001% of scale	0.01% of scale
Electrical conductivity	S/m	0–7.5	0.0002	0.005
Oxygen	µM	0–500	1	8
Oxygen	%	0–150	0.4	5
Temperature	°C	–4 – +36	0.001	0.03

Other technical specifications for the DCPS: frequency 600 kHz, vertical measurement range up to 80 m, layer thickness (vertical resolution) 0.5–5 m, concealed distance from sensor to first measurement interval 1 m, 4 transmitters/receivers, inclinometer accuracy with respect to vertical axis 0.5 degrees.

The measurements were carried out using the following profiler configuration parameters: measurement range from a depth of 76 m (i.e. 4 m from the seafloor), a total of 40 layers, 35 of which were in the water and not substantially perturbed by the signal reflected back from the water surface. The measurement interval was 1 hour. The hourly result for the current velocity and direction was recorded as the mean value of 30 signals received over around 1.5 minutes. As the relatively thick upper sea layer was completely destratified in winter conditions and the water contained no suspended solids, the signal that was reflected back more than 40 m away from the profiler was relatively weak. Based on the quality indicators of data (signal-to-noise ratio), the upper layer data have been excluded from the analysis contained in this report, meaning data between a depth of 34 to 76 m were analysed. The results are attached to this report as original data (including the values of the parameters characterising quality).

The same system equipped with a buoy and anchor that was used during the first measurement period was used to fix the SeaGuard II platform to the seafloor (see Figure 2.1). The anchor of sufficient weight was fitted with a chain, which was connected to an acoustic trigger and which, in turn, was connected, by means of a shackle, to the SeaGuard II sensors. The length of the system from the anchor to the current profiler (DCPS) was 3 m, which, combined with the hidden measuring range of 1 m, yielded 4 m as the distance of the lower end of the first measuring range from the seafloor. The vertical position of the SeaGuard II platform in the water column was secured by means of a buoy with sufficiently high buoyancy, which was connected to the platform with a line of around 3 m.

Data on the temperature, salinity, and oxygen content in the demersal zone are presented in this report as measured at the depth of the SeaGuard II platform (77 m, i.e. 3 m from the seafloor). Temperature is given as the measured *in-situ* temperature in °C. Salinity values are calculated from measured temperature, electrical conductivity, and pressure, using TEOS-10[1] relationships, and the data are given in g/kg. Oxygen content is given as dissolved oxygen concentration in µM (or µmol/l) and saturation percentage.

The measurement system was deployed from the Estonian Police and Border Guard Board's vessel *Raju* in the sea near the wreck of the *Estonia* on 12 December 2021, at the coordinates 59° 23,0515' N, 21° 41,2294' E. The topography of the larger area together with the survey zone is shown in Figure 2.2, and a more detailed topography of the zone together with the location of the measurement system during both measurement periods and the ERA5 meteorological data point is shown in Figure 2.3. The depth of the seafloor at the measurement site was 74 m. The platform was retrieved by the Tallinn University of Technology's research vessel *Salme* on 21 March 2022. The data collected in their original form and converted into physical units are presented in the annex to this report.

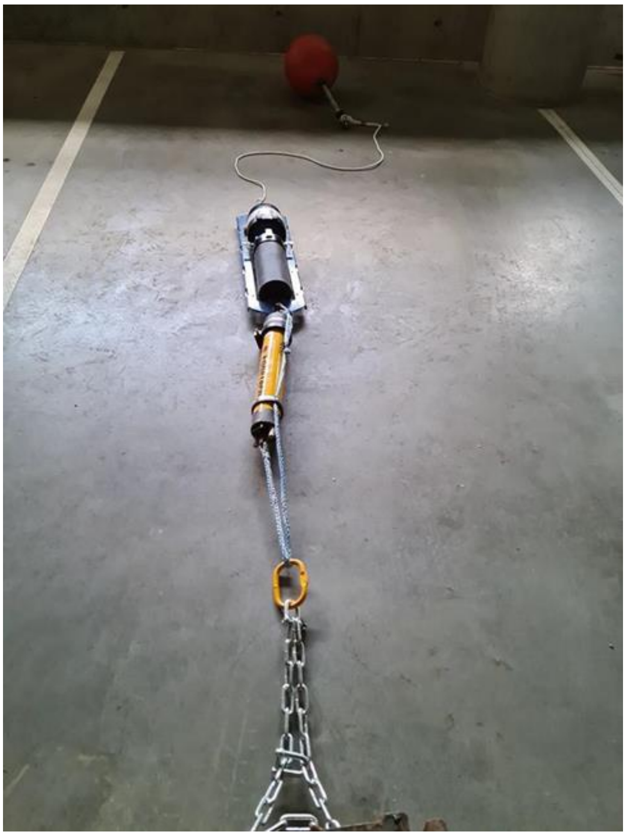

Figure 2.1. Buoy station configuration – buoy, Aanderaa SeaGuard II platform together with the

[1] IOC, SCOR, and IAPSO: The International Thermodynamic Equation of Seawater - 2010: Calculation and Use of Thermodynamic Properties, Intergovernmental Oceanographic Commission, Manuals and Guides No. 56 UNESCO, 196, 2010.

acoustic Doppler current profiler and oxygen, temperature, and conductivity sensors, and acoustic trigger attached to an anchor.

The survey site lies north-west of Hiiumaa, within the Finnish EEZ, which geographically belongs to the northern Baltic Sea proper. On a larger scale, this is an area where the depth of the sea increases from north to south (Figure 2.2). A more detailed look at the topography of the area shows that the seafloor in the immediate vicinity of the wreck of the *Estonia* (Figure 2.3) is highly variable. If in the first period the survey station was located about 2 km west of the wreck, in the second period, the platform was placed approximately 500 m northeast of the wreck. The survey station was located near the western slope of the deeper furrow running north to south in the less pronounced channel running northeast to southwest, extending to the wreck of the ferry *Estonia*.

Similarly to the first measurement period, meteorological data from the reanalysis product *ERA5 hourly data on single levels from 1979 to present* in the ERA5 database were used to describe the meteorological conditions during the measurement period. Data on the u and v components of the wind at 10 m above sea level from the period of December 2021 to March 2022 were extracted from the database. The temporal resolution of the data is one hour and the horizontal resolution is 0.25° x 0.25°. The analysis was prepared using data from the nearest ERA5 grid point (59° 22.8' N, 21° 40.8' E; see Figure 2.3).

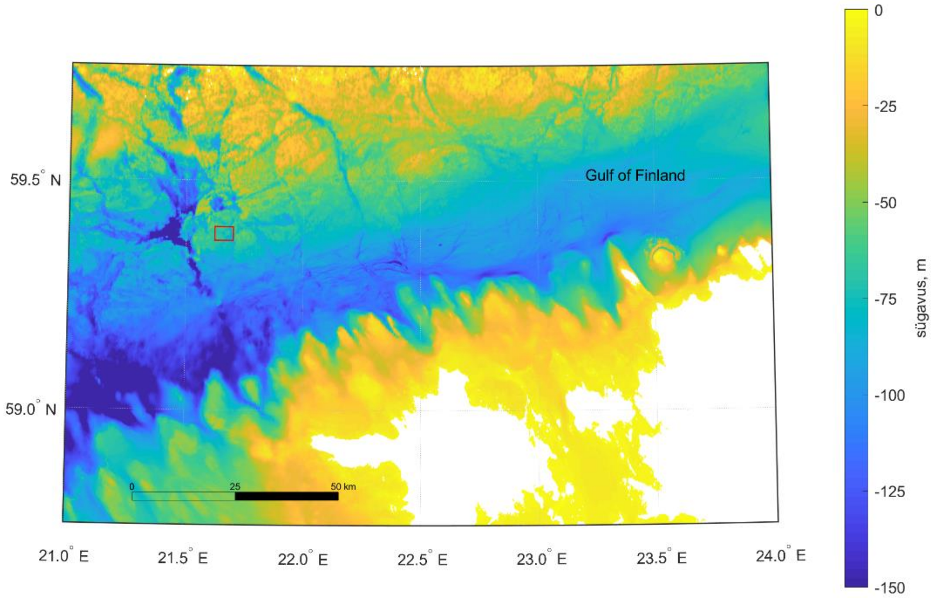

Figure 2.2. Topography of the northern Baltic Sea proper and the western section of the Gulf of Finland together with the survey location (red rectangle)

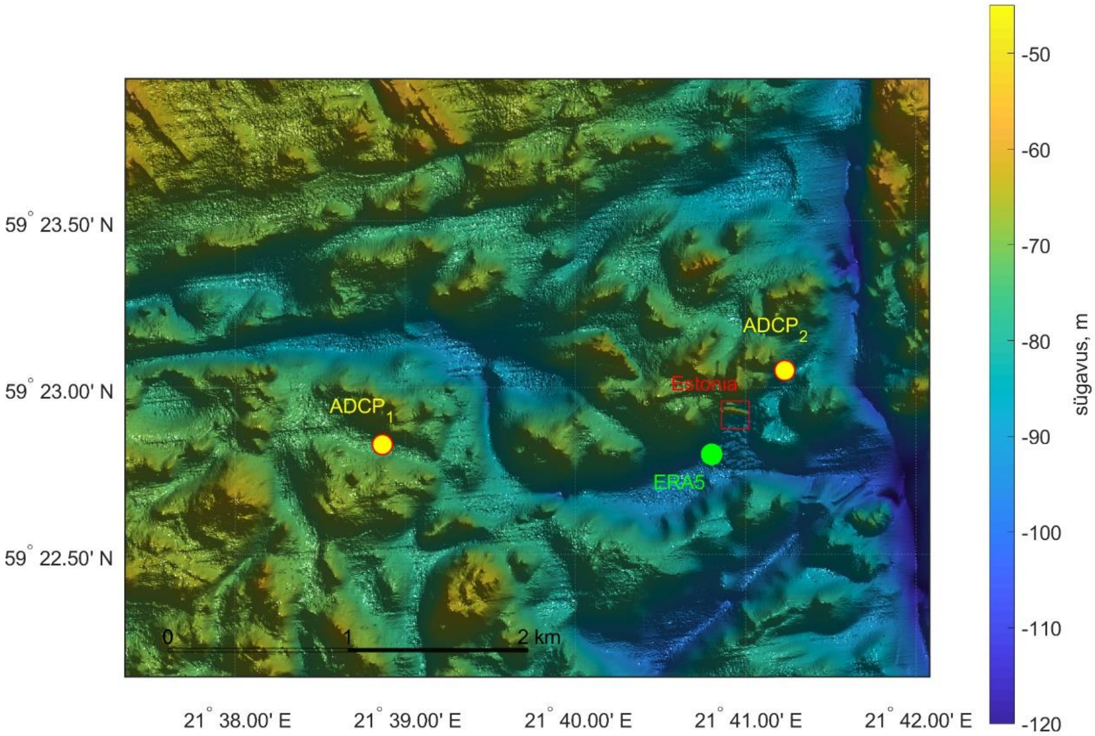

Figure 2.3. Detailed topography of the area of the wreck of the ferry *Estonia* together with the locations of the ferry (red square, *Estonia*, coordinates 59° 22.9252' N, 021° 40.8451' E), the meteorological data point (green circle, ERA5), and the locations of the survey platform during the first survey period (yellow circle, $ADCP_1$) and the second survey period (yellow circle, $ADCP_2$).

3. RESULTS

3.1. CURRENTS

The vertical distribution of the current velocity and its temporal variability during the survey period is shown in Figure 3.1. In accordance with this figure, it appears that there were only a few short periods of stronger currents during the winter survey period. In the first half of the survey (until mid-February), the variability of currents in the demersal zone (64–76 m) was different from the regime of currents recorded in higher layers. This was most likely due to the occurrence of halocline at a depth of 60–70 m. After mid-February, when the strongest currents were recorded in the entire water column at a depth of 40 m down to the seafloor, the currents changed synchronously in the entire observed layer (40–76 m). This means that pycnocline did not occur in the deep layer and the regime of currents became more balanced. In addition, in the last third of the survey, there were almost no current velocities above 10 cm/s.

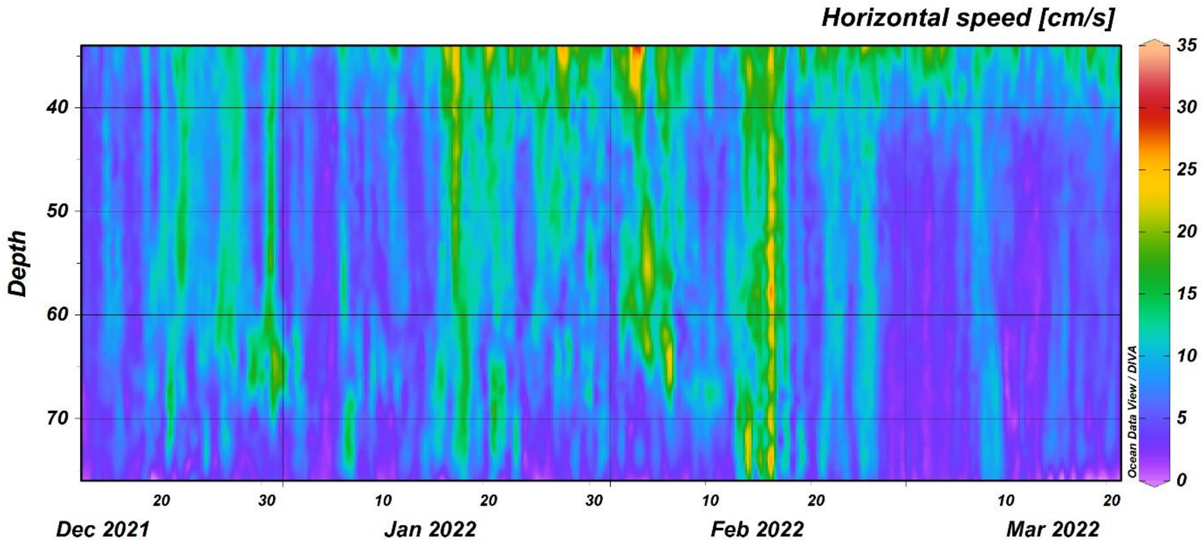

Figure 3.1. Changes over time in the vertical distribution of current velocities in the area of the wreck of the *Estonia* between a depth of 34 and 76 m over the measurement period from 10 July to 9 November 2021.

The variability of the currents in the demersal zone is described below through statistical parameters such as mean velocity and maximum velocity (Table 3.1). A layer of water up to 16 m thick was selected for analysis (4 to 20 m from the seabed). During the survey period, the mean current velocity in the observed layer was 6.6 cm/s and the median current velocity 5.3 cm/s. This means that more than half of the time the current velocity in this 16 m layer was 5.3 cm/s or less. Maximum current velocities ranged up to 32.6–36.9 cm/s. At all observed depths, these maximum velocities were related to the strong current event recorded across the entire water column on 13–16 February 2022.

Table 3.1. Statistical indicators of the recorded current velocity in the demersal zone per 2 m layer in the area of the wreck of the *Estonia* from 12 December 2021 to 21 March 2022.

Depth (m)	Arithmetic average (cm/s)	Median (cm/s)	Maximum velocity (cm/s)
74–76)	5.1)	3.8	36.9
72–74	4.7	3.6	32.6
70–72	6.3	5.1)	34.9
68–70	6.5	5.3	34.6
66–68	6.9	5.6	33.7
64–66	7.5	6.4	34.8
62–64	7.7	6.6	34.5
60–62	7.8	6.7	34.4
Averages/max	6.6	5.3	36.9

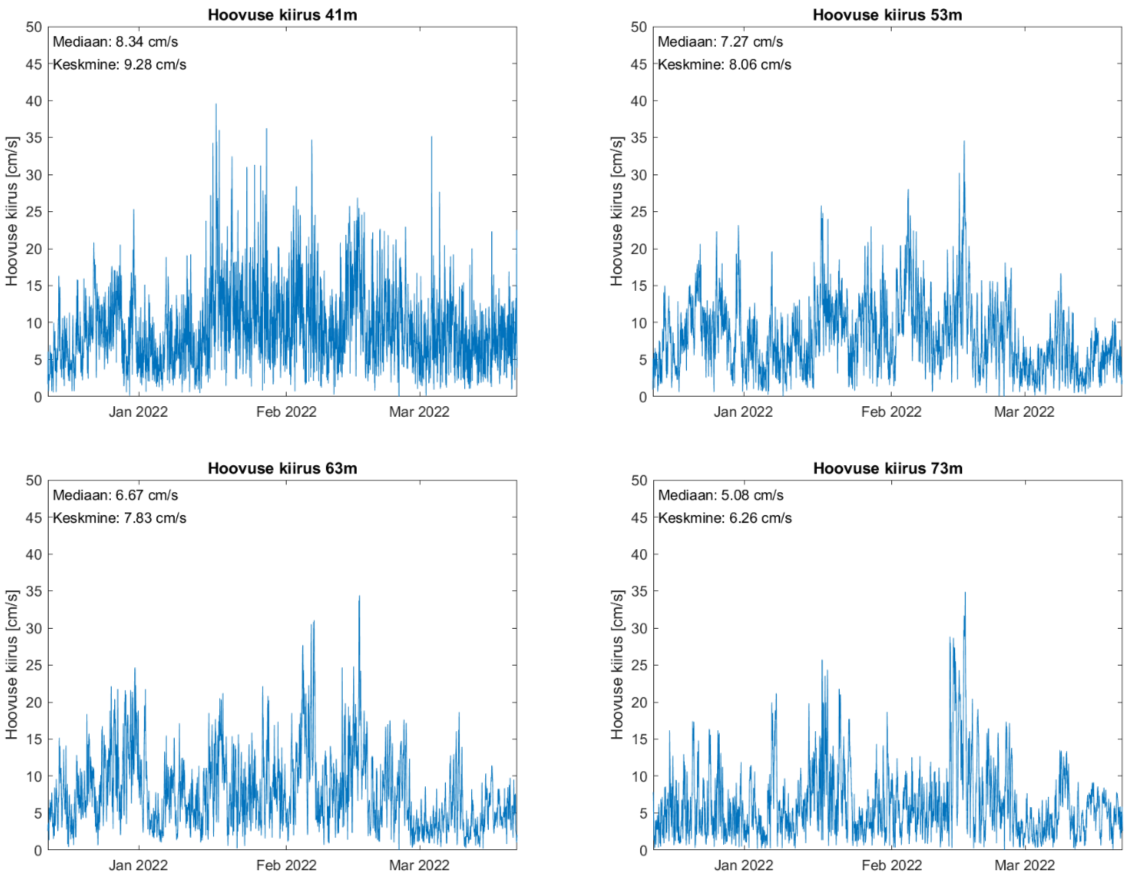

Figure 3.2. Current velocity history at depths of 40–42 m, 52–54 m, 62–64 m and 72–74 m in the area of the wreck of the *Estonia* over the measurement period from 12 December 2021 to 21 March 2022.

A comparison of current velocities between different layers (Figure 3.2) also shows that maximum velocities occurred in deeper layers during the aforementioned strong current event on 13–16 February. Above the water column, events of stronger currents also occurred in other periods. For example, at a depth of 40–42 m, maximum velocities exceeded 35 cm/s, also in January, early February, and early March 2022 (Figure 3.2).

In the demersal zone, the current velocity only periodically exceeded 20 cm/s during the period from 13 to 16 February 2022 and in isolated cases during the period from 17 to 18 January 2022 (Figure 3.3). On average, demersal currents were also the strongest during these periods, i.e. in mid- and late February, and late January.

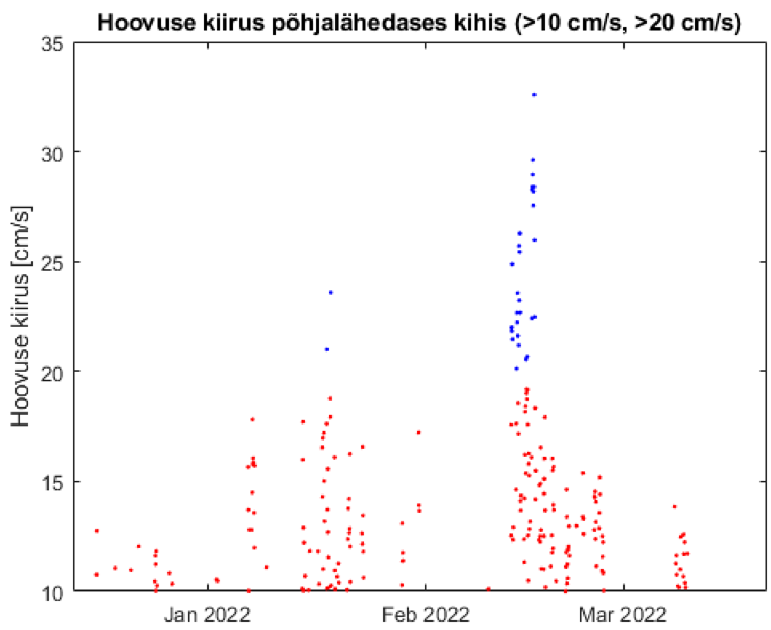

Figure 3.3. Current velocities between 10–20 cm/s (red dots) and above 20 cm/s (blue dots), measured at a depth of 72–74 m in the area of the wreck of the *Estonia* from 12 December 2021 to 21 March 2022.

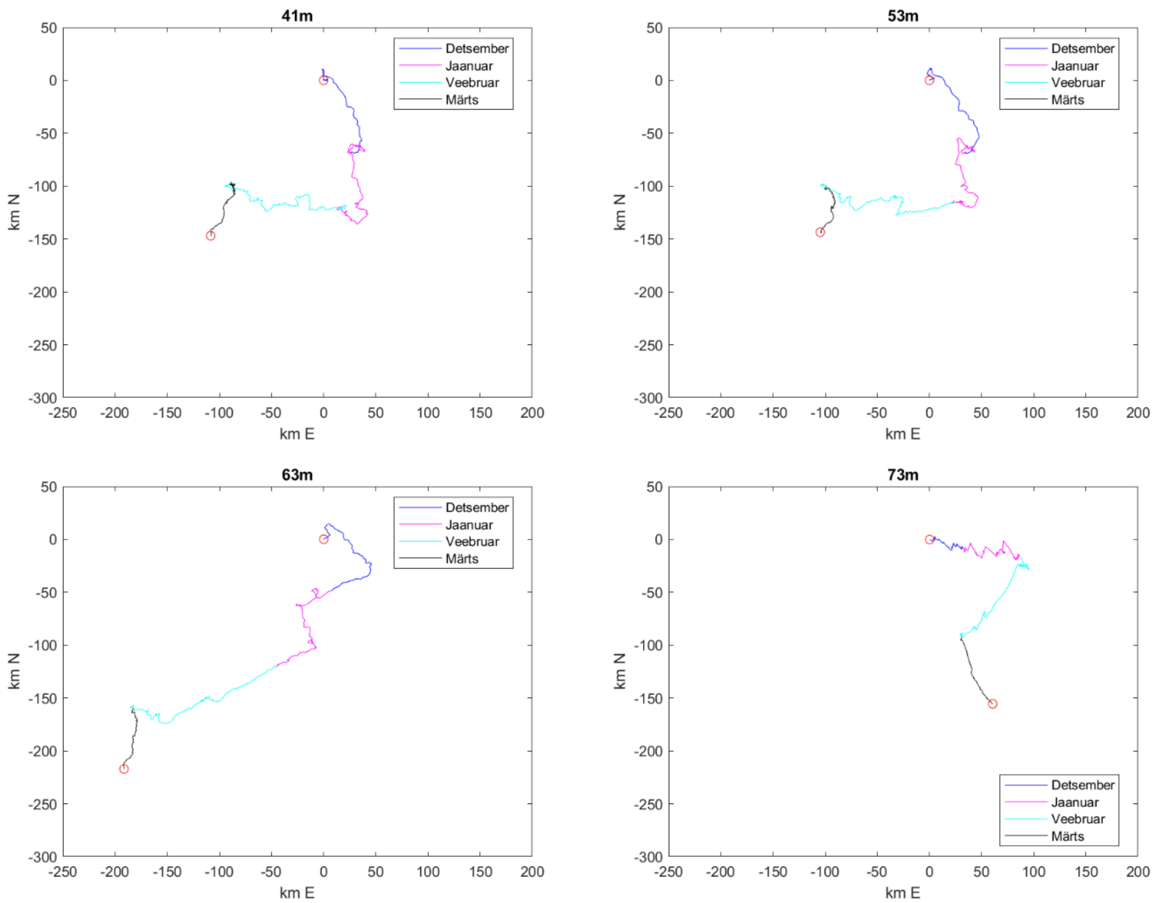

Figure 3.4. Current progressive vector diagrams at depths of 40–42 m, 52–54 m, 62–64 m and 72–74 m in the area of the wreck of the *Estonia* over the measurement period from 12 December 2021 to 21 March 2022.

The progressive vector diagrams show the prevailing direction and strength of flow over longer periods. Figure 3.4 shows that, in December and January, the flow direction in the demersal zone (73 m) was eastward, in February (when maximum current velocities also occurred), the flow was southwesterly, i.e. from the survey platform towards the wreck of the *Estonia*, and in March, the flow was predominantly southeasterly. Ten metres higher in the water column, the current was predominantly southwesterly during the entire measurement period, except in mid-December (i.e. at the start of the survey). At a depth of 53 m and 43 m, flow and its variability were relatively similar, i.e. in December and January, the prevailing flow direction was southward, in February, it was westward, and in March, similarly to bottom water layers, southward.

3.2. EFFECT OF METEOROLOGICAL CONDITIONS ON CURRENT DYNAMICS

During the survey period, southwesterly winds prevailed in the area, although relatively strong north and northwesterly winds occurred frequently as well (Figure 3.5). There were virtually no east winds during the entire survey period (i.e. those blowing from the direction between southeast and northeast), which is not typical for the winter period. Normally, east-northeasterly winds also dominate the area for given periods. In the observed period, maximum wind speeds occurred on 17 January 2022, with hourly speeds reaching up to 22 m/s. As illustrated by the graph of 24-hour smoothed wind speeds (Figure 3.6), in the longer term (within a time-slot of 24 hours), maximum wind speed occurred on 19 January. During that period (14–22 January), north and southwesterly winds alternated, with north winds having the maximum daily mean values (Figure 3.7).

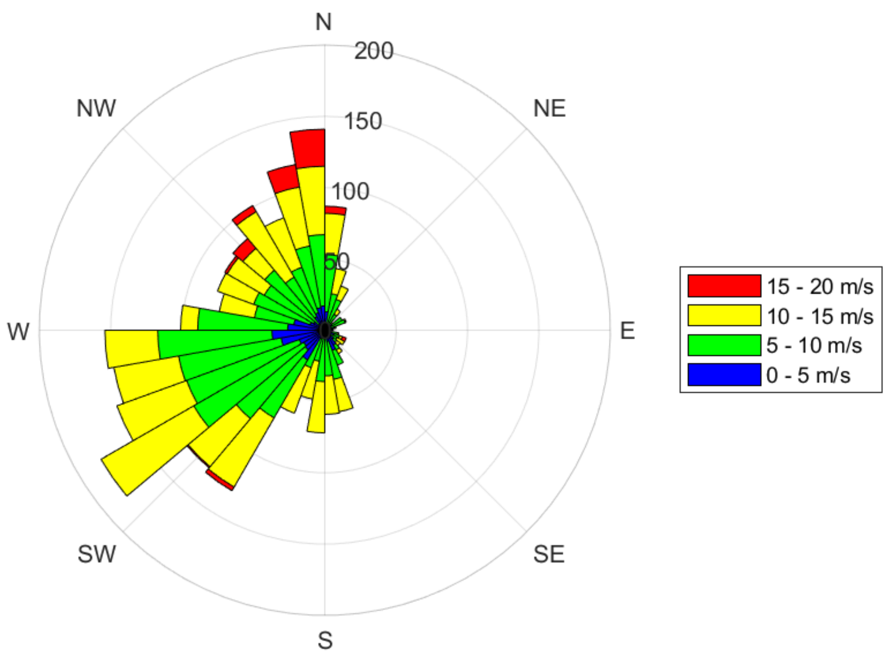

Figure 3.5. Wind rose based on modelling results obtained from the nearest ERA5 point to the survey area (wind speed at 10 m above sea level) during the survey period from 12 December 2021 to 21 March 2022.

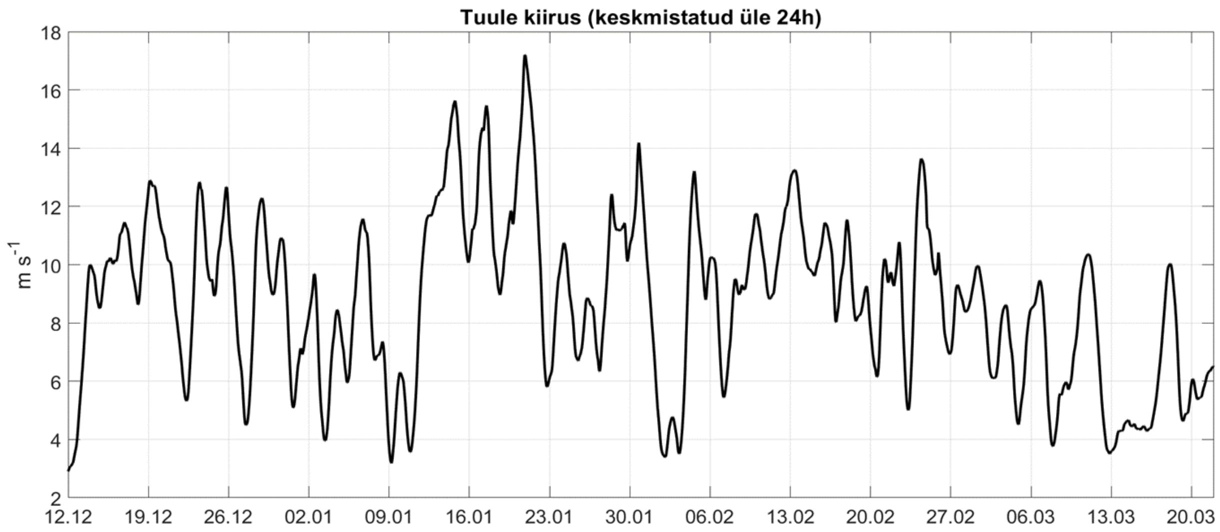

Figure 3.6. 24-hour smoothed wind speeds based on modelling results obtained from the nearest ERA5 point to the survey area during the survey period from December 2021 to March 2022.

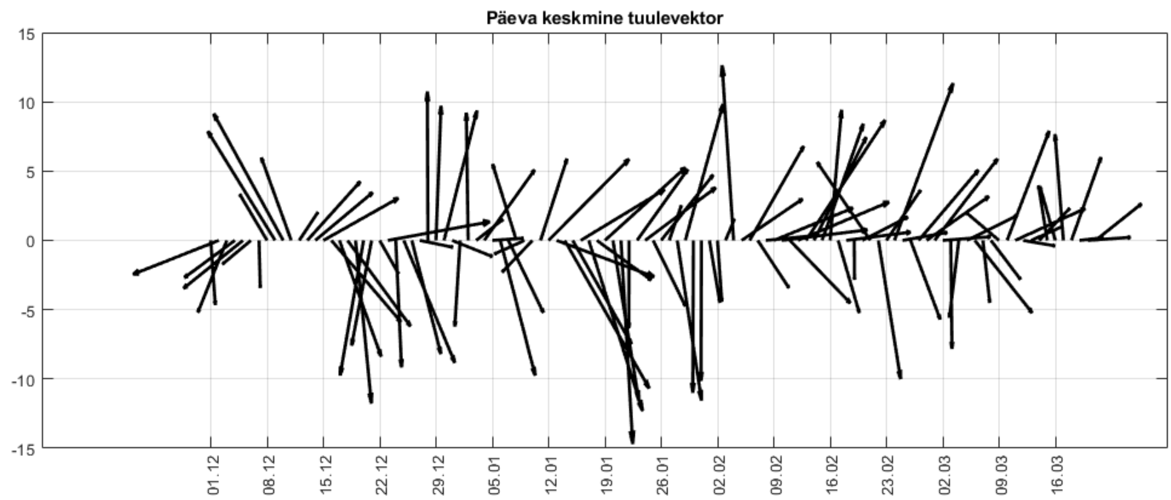

Figure 3.7. Daily average wind vectors based on modelling results obtained from the nearest ERA5 point to the survey area from December 2021 to March 2022.

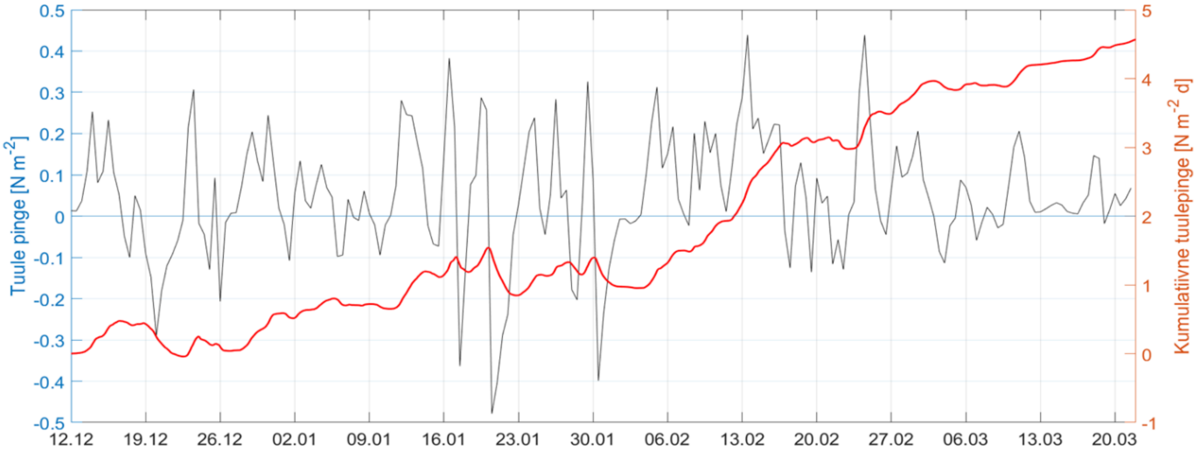

Figure 3.8. 6-hour smoothed wind stress (black line) and cumulative wind stress (red line) based on modelling results obtained from the nearest ERA5 point to the survey area during the survey period from 12 December 2021 to 21 March 2022. The shown wind stress component has a positive northeasterly direction (rotated 45 degrees clockwise from the north axis).

The wind stress time series, the positive values of which correspond to southwesterly winds, i.e., their effect on the surface layer, is shown in Figure 3.8. Positive values dominated during the entire survey period, also indicating the fact that southwesterly winds dominated at that time. However, during the abovementioned period in late January, very high wind stress from the opposite direction occurred, corresponding to the occurrence of strong north wind (Figure 3.8). Cumulatively, wind stress changed significantly and continuously in one direction during the period from 5 to 16 February 2022. During this period, southwesterly winds prevailed, causing the strongest currents and oscillation throughout the water column. i.e., in the demersal zone, at the end of this period (13–16 February).

A comparison of prevailing winds and dominant flow directions at different depths shows that the flow in the water column was influenced by prevailing winds, however, there is also a clear difference between the direction of the wind and the direction of the current in the analysed layer. In December and January, when winds were variable, with south-southwesterly and north winds alternating, the flow direction near the seabed (i.e., down to the halocline; see Figure 3.4, 73 m) was easterly. Higher up in the water column, transfer was southward. Strong southwesterly winds caused a change in the flow direction at all depths: in the deeper part of the deep layer (see Figure 4.3, depths 73 and 63 m), the flow direction was southwesterly (i.e., in the direction opposite to that of the wind), and in the intermediate layer (43 and 53 m), the flow direction was westward. During the last three weeks of the measurement period (in March 2022), when winds were relatively variable (winds from southwest, west and northwest), the flow in the observed layer was relatively weak and directed southward. It can, therefore, be argued that, similarly to the first half of the survey period, the flow in the demersal zone was predominantly opposite to the direction of the wind. This means that even in destratified conditions of the water column, the currents of the deep layer are influenced by the wind and the indirect effect is most likely caused by the occurrence of the hydraulic gradient. The result is the oscillation of currents, with the predominant flow direction (residual current) being opposite to that of the wind.

In the context of the present survey, it was important to identify the meteorological conditions that occurred during the recording of the maximum current velocities in the demersal zone. A more detailed analysis of simultaneous changes in wind conditions and currents shows that maximum current velocities near the seabed were related to the long-term winds from the west (predominantly from the southwest; Figure 3.9). The demersal current, however, was directed almost 180 degrees in the opposite direction. The current vector time series shows that the current was oscillatory in nature, i.e., high speeds alternated with lower speeds in the same direction. It may also be argued that the predominant direction near the seabed was influenced by the topography of the seabed: if in the bottom layers, the current direction was southwesterly, then 20 m above the seabed, the current direction was predominantly westward. This suggests that the ferry *Estonia*, which was located southwest of the current meter along a slightly deeper topographic channel, was also affected by the strong southwesterly currents during that period. At the same time, the current velocities that occurred under these specific conditions were not very high, moreover, the wind speeds that caused current velocities exceeding 30 cm/s did not constitute storm winds as maximum wind speeds reached up to 15 m/s.

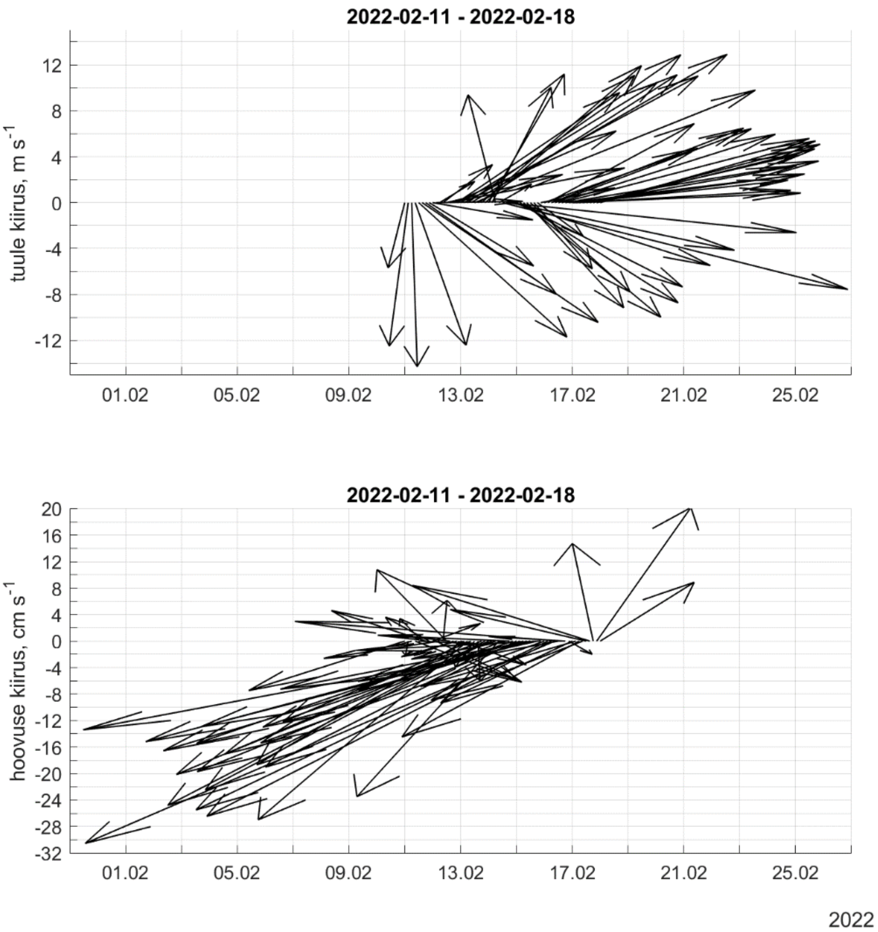

Figure 3.9. Wind (top) and demersal current (72–74 m; bottom) vectors with maximum current velocities during the period from 11 to 18 February 2022.

3.3. SALINITY, TEMPERATURE, AND OXYGEN

The variability of the salinity, temperature, and oxygen content in the demersal zone in the area of the wreck of the ferry *Estonia* is characterised by the average, minimum, and maximum values of these parameters over the measurement period, as shown in Table 3.2. The temperature varied between 3.15 and 6.49 °C, salinity between 7.63 and 10.89 g/kg, and oxygen content between 0 and 368 µM, or 0 and 88% of saturation. The average temperature in the demersal zone during the survey period was 5.39 °C and salinity 9.50 g/kg. The oxygen conditions are not so much characterised by the average concentration than the fact that the dominant anoxic conditions in the first half of the measurement period were replaced by oxygen-rich conditions in mid-February, i.e., the measurements covered two periods with completely different oxygen conditions.

Table 3.2. Recorded minimum, maximum, and average values for temperature, salinity, and oxygen content in the demersal zone in the area of the wreck of the ferry *Estonia* during the period 12

December 2021 to 21 March 2022.

Parameter	Minimum	Maximum	Average
Temperature (°C)	3.15	6.49	5.39
Salinity (g/kg)	7.63	10.89	9.50
Oxygen (µM)	0	368	99
Oxygen (%)	0	88	24

The measurement period is characterised by the long-term presence of anoxic or hypoxic conditions from the beginning of the measurements until mid-February. The anoxic and hypoxic conditions present from December 2021 until mid-February 2022 were accompanied by higher salinity values in the demersal zone (Figure 3.10): salinity varied between 9.5 to 10.9 g/kg. In early January, when the salinity was the lowest of the period, the oxygen concentration rose above 10% of the saturation value, but overall, anoxic conditions dominated in this area. During this hypoxic period, the temperature of the demersal zone varied between 5.9 and 6.5 °C (Figure 3.11).

A significant change in the area occurred in mid-February, when the hypoxic water near the seabed was replaced by a water mass with a relatively high oxygen concentration (temporarily above 80% of the saturation concentration), and salinity dropped to 7.7 g/kg and temperature to 3.2 °C. Similar changes caused by strong southwesterly winds have been recorded in the western part of the Gulf of Finland, also in the winter of 2011 and 2014 (Liblik et al., 2013[2]; Lips et al., 2017[3]). The replacement of water masses and the weakening of stratification (until the collapse of stratification) is related to the movement of the surface layer directly affected by winds in the direction of the wind and the movement of the deep layer water in the opposite direction. This suggests that the changes in water parameters are attributable to both horizontal transport (in this case, from northeast and east, i.e. from the Gulf of Finland, to the area of the wreck of the ferry *Estonia*) and vertical mixing.

From the beginning of March until the end of the survey period, both temperature and salinity increased, while the oxygen concentration decreased (Figures 3.10 and 3.11). This means that a water mass with higher salinity and lower oxygen content was slowly returning to the area. Such water movement corresponds to the restoration of estuarine circulation under the conditions of weaker winds. The key information obtained from this measurement period is that, in the area of the wreck of the ferry *Estonia*, long periods of hypoxia may occur near the seafloor that, upon the arrival of certain meteorological conditions, may be replaced by relatively long periods of high oxygen concentration. Such variation in oxygen conditions promotes the corrosion of metals in the marine environment.

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[2] Liblik, T., Laanemets, J., Raudsepp, U., Elken, J., Suhhova, I. (2013). Estuarine circulation reversals and related rapid changes in winter near-bottom oxygen conditions in the Gulf of Finland, Baltic Sea. Ocean Science, 9, 917−930. DOI: 10.5194/os-9-917-2013.

[3] Lips, U., Laanemets, J., Lips, I., Liblik, T., Suhhova, I., Suursaar, Ü. (2017). Wind-driven residual circulation and related oxygen and nutrient dynamics in the Gulf of Finland (Baltic Sea) in winter. Estuarine Coastal and Shelf Science, 195, 4−15. DOI: 10.1016/j.ecss.2016.10.006.

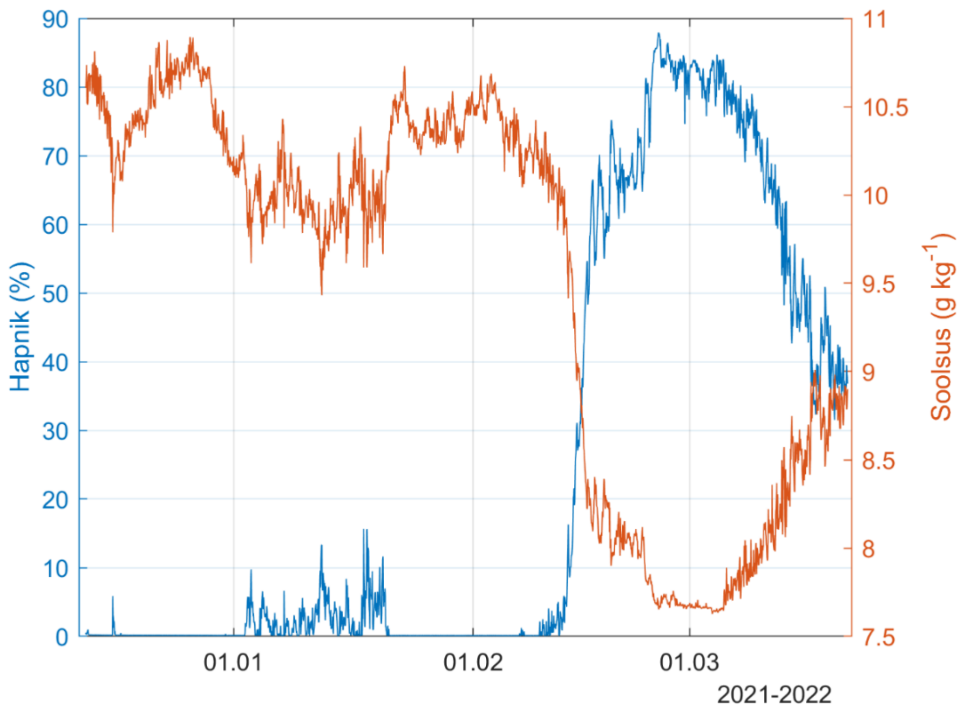

Figure 3.10. History of dissolved oxygen concentration (%; blue line) and salinity (g/kg; red line) in the demersal zone in the area of the wreck of the *Estonia* during the period 12 December 2021 to 21 March 2022.

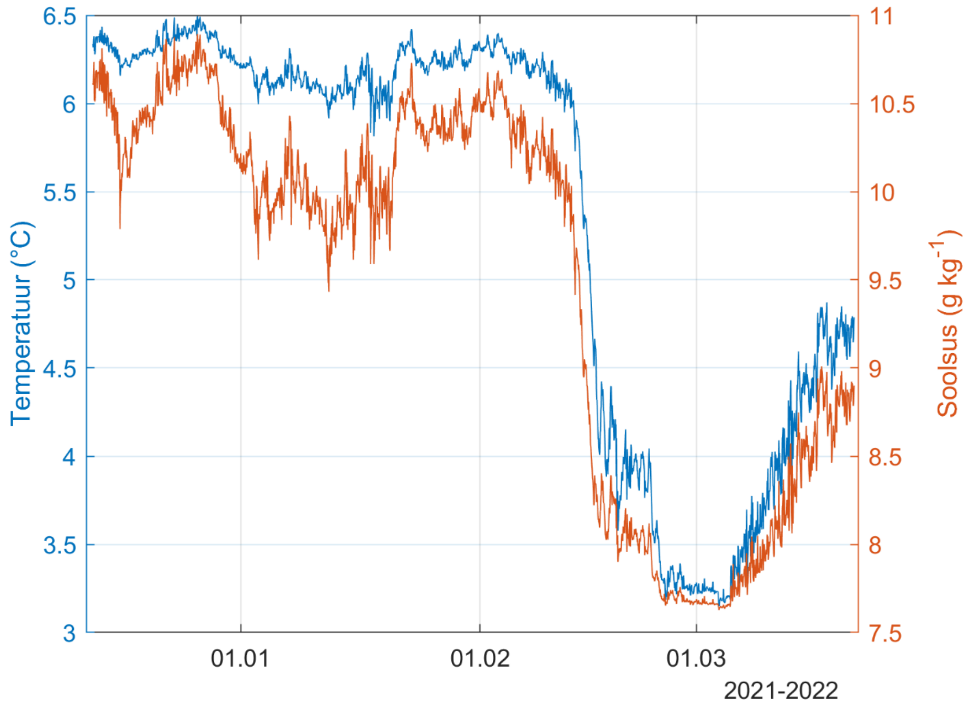

Figure 3.11. History of temperature (°C; blue line) and salinity (g/kg; red line) in the demersal zone in the area of the wreck of the *Estonia* during the period 12 December 2021 to 21 March 2022.

4. COMPARISON OF STRATIFIED AND DESTRATIFIED CONDITIONS

The objective was to record sufficiently long current time series in the demersal zone to characterise the regime of currents both under the stratified conditions of the water column and the winter conditions with weaker vertical stratification. During both periods, southeasterly winds dominated the area, the only difference being that strong north winds also occurred in the winter, with virtually no winds from the east, whereas in spring and autumn, northeasterly and southeasterly winds occurred occasionally. On average, wind speeds were higher in winter, with maximum daily average wind speeds occasionally exceeding 15 m/s during the period from 14 to 22 January 2022. During both periods, cumulative wind stress, which characterises the stress exerted by the wind on the circulation of the surface layer of the sea over a longer period of time, was similar in that the wind cumulatively caused eastward flow in the surface layer. This is in line with the normal wind regime in the Baltic Sea region. From July to November, shorter periods occurred where the strong winds forced the surface layer water to flow in the direction of west-southwest.

The statistical values of the current velocity of the demersal zone did not differ significantly between the two periods. The maximum current velocities in the 20-metre-thick layer near the seabed during both measurement periods were 35-36 cm/s. The median velocity values were slightly higher under stratified conditions, i.e. 6.0 cm/s compared with the 5.3 cm/s in winter. During both periods, there were shorter time periods when the current velocity exceeded 20 cm/s. The most notable strong current event was recorded on 13 to 16 February 2022. The analysis of the connection between strong currents and winds suggests that the occurrence of strong currents was indirectly caused by wind in all cases. The events of strong currents were preceded by strong winds blowing from the opposite direction. The effects of wind reached the demersal zone through the movement of surface layer water in the approximate direction of the wind, which changed the hydraulic gradient and resulted in opposite movement in the deep layer. At the same time, higher speeds did not correspond to the short-term stronger winds, but rather to the long-term strong winds blowing from one dominant direction (for a few days up to a week).

Polar histograms of currents occurring in layers closest to the seafloor (Figure 4.1, top panels) show that the prevailing current directions were significantly affected by local topography. From July to November 2021, the current meter was located at the edge of the deeper area stretched in the east-west direction (see Figure 2.3) and the demersal currents were predominantly occurring along that channel. From December 2021 to March 2022, the current meter was located in the channel running northeast to southwest at the edge of a larger depression running north to south, and the currents were directed roughly along this topographic feature. According to the data of both measurements, the polar histograms of currents occurring slightly higher in the water column (Figure 4.1, bottom panels) show that these currents were also influenced by local topography, however, the distribution of directions was significantly more uniform, meaning the influence of topography decreases with the observed height in the water column.

Considering the location of the wreck of the *Estonia* and the topography of the nearby area (Figure 2.3), it can be assumed that the prevailing currents in this area flow along the deeper east-west depression. However, the wreck of the *Estonia* is also exposed to northeast-southwesterly currents in the less pronounced depression, where the current meter was located during the second period. The currents from this direction are practically perpendicular to the wreck's axis, i.e. they may exert the strongest impact on the wreck. At the same time, the current velocities measured during the seven months never exceeded 36 cm/s, meaning no very strong currents were recorded.

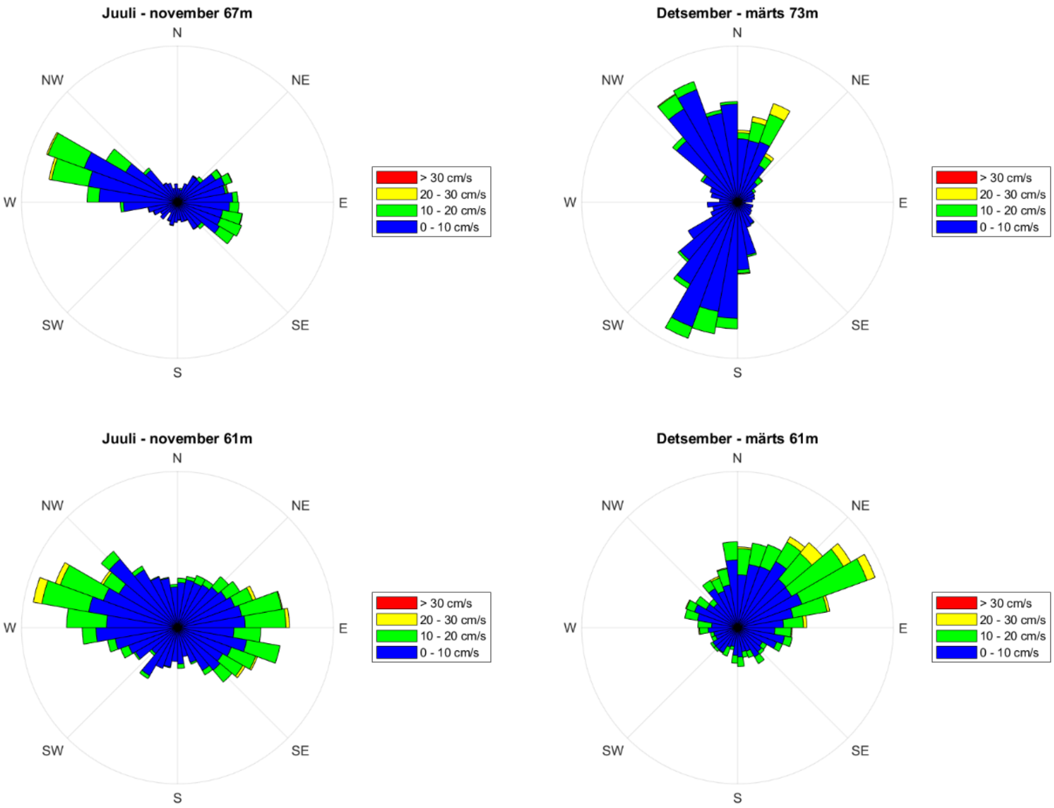

Figure 4.1. Polar histograms of currents in the demersal zone (top panels) and at a depth of 60–62 m (bottom panels) in the area of the wreck of the ferry *Estonia* during the periods from 10 July 2021 to 9 November 2021 (left panels) and from 12 December 2021 to 21 March 2022 (right panels).

The temperature, salinity and oxygen concentration measurements conducted near the seafloor over a period of seven months showed that the conditions in the area of the wreck of the ferry *Estonia* are highly variable: anoxic conditions and conditions with relatively high oxygen concentration alternated (Figure 4.2). Cumulative wind stress and oxygen concentration time series show the impact of strong southwesterly winds in October 2021 and in late February 2022. This was reflected in the flow of the demersal zone water in the direction opposite to that of the wind, resulting in the occurrence of water with lower salinity and higher oxygen content in the survey area. When the southwest-northeasterly wind stress weakened or reversed, normal circulation was restored and hypoxic water returned to the area of the wreck. The highest oxygen concentration values were measured in late February 2022, prior to which relatively strong southwesterly winds had prevailed in the area for a longer period of time. As no seasonal thermocline occurred during this period, it created a situation in which the water column was essentially destratified: the salinity of the demersal zone fell below 8 g/kg and oxygen concentration rose above 80% of saturation. Similar collapses of stratification and their impact on the environmental conditions of the demersal zone in winter have been recorded in the Gulf of Finland

(Liblik et al., 2013[4]; Lips et al., 2017[5]).

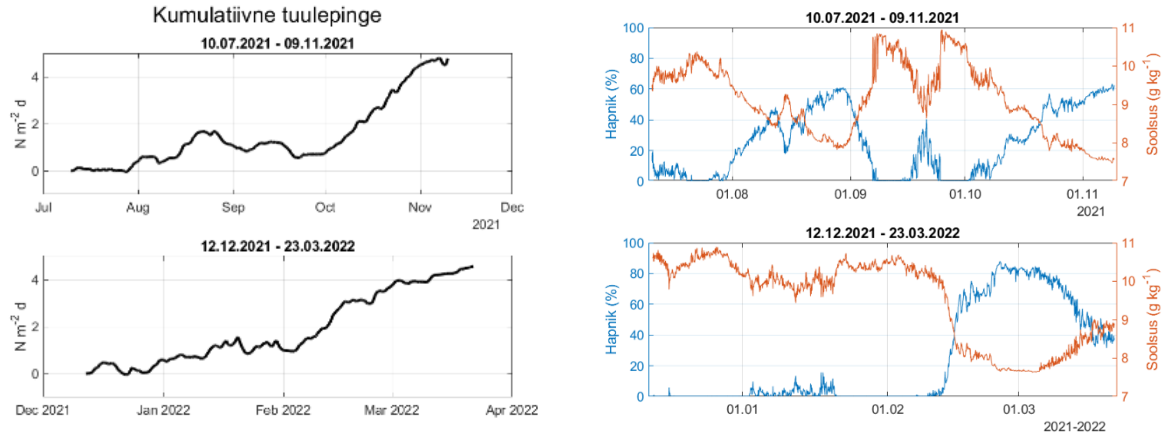

Figure 4.2. Temporal variability of cumulative wind stress (left panels) and salinity and oxygen concentration (right panels) in the demersal zone in the area of the wreck of the ferry *Estonia* during the periods from 10 July 2021 to 9 November 2021 (top panels) and from 12 December 2021 to 21 March 2022 (bottom panels).

Highly variable environmental conditions in the demersal zone in the area of the wreck of the ferry *Estonia* suggest that the wreck is subject to both oxidation in oxygen-rich seawater and microbiological corrosion[6,7]. In order to make more accurate assessments, the existing model data must be validated and a long-term analysis of the variability of environmental conditions must be conducted. For the assessment of microbiological corrosion, it would also be appropriate to collect relevant bacteria samples and analyse them (e.g. by using eDNA methods).

[4] Liblik, Taavi, Laanemets, J., Raudsepp, U., Elken, J., & Suhhova, I. (2013). Estuarine circulation reversals and related rapid changes in winter near-bottom oxygen conditions in the Gulf of Finland, Baltic Sea. Ocean Science, 9, 917–930.

[5] Lips, U., Laanemets, J., Lips, I., Liblik, T., Suhhova, I., & Suursaar, Ü. (2017). Wind-driven residual circulation and related oxygen and nutrient dynamics in the Gulf of Finland (Baltic Sea) in winter. Estuarine, Coastal and Shelf Science, 195, 4–15. https://doi.org/10.1016/J.ECSS.2016.10.006

[6] Gu, 2012. New Understandings of Biocorrosion Mechanisms and their Classifications. Microbial Biochem Technol, 4:4, DOI: 10.4172/1948-5948.1000e107.

[7] Li and NING, 2019. Latest research progress of marine microbiological corrosion and biofouling, and new approaches of marine anti-corrosion and anti-fouling. Bioactive Materials 4, 189–195.

5. SUMMARY

The aim of the survey was to record the vertical profiles of the currents and the salinity, temperature, and oxygen concentration in the demersal zone in the area of the wreck of the ferry *Estonia* over a period of at least three months in conditions where the water column is destratified. The work was carried out using the SeaGuard II measurement platform from Aanderaa, which was connected to an acoustic Doppler current profiler and pressure, electrical conductivity, oxygen, and temperature sensors. Measurements were carried out between 12 December 2021 and 21 March 2022 at the coordinates 59° 23,0515' N, 21° 41,2294' E, at a depth of 80 m.

The main results and conclusions of the initial analysis, as compared with the first measurement period, are as follows:

- The maximum current velocities in the demersal zone reached up to 37 cm/s and were thus about the same as in the first period under stratified conditions.
- The median current velocity near the seafloor was 5.1 cm/s, however, on one occasion, the current velocity exceeded 20 cm/s, and there also occurred shorter periods throughout the entire measurement period where current velocities were above 10 cm/s.
- The strongest demersal currents were caused by relatively strong southwesterly winds blowing for a long period of time in mid-February 2022.
- Similarly to the results obtained under stratified conditions (measurements taken from July to November 2021), the flow direction in the demersal zone of the survey area was opposite to that of the wind.
- From the start of the survey until mid-February 2022, anoxic (temporarily hypoxic) conditions dominated in the demersal zone of the survey area.
- As a result of long-term southwesterly winds, a water mass with a high oxygen concentration (above 80% of saturation) was carried into the demersal zone of the area in mid-February.
- During the last three weeks of measurements, the estuarine circulation was restored, the oxygen concentration decreased, and the temperature and salinity in the demersal zone increased.
- Based on the alternation of long-term anoxic periods and periods of high oxygen concentration in the area of the wreck of the ferry *Estonia*, it may be presumed that these constitute conditions that promote high levels of marine corrosion.

Measurement data have been appended to the report both in their original form and as time series of verified and calculated physical quantities.

As the next step of the study of the impact of the marine environment on the wreck of the ferry *Estonia*, it would be appropriate to validate existing numerical model data (e.g. Copernicus Marine Service) with measurement data. If the validation results indicate that the model data are sufficiently reliable (correspond to measurement data), it is possible to conduct the analysis of the long-term changes in the salinity and oxygen concentration of currents and the demersal zone (from 1994). Such an analysis could be used to assess the potential impact of the marine environment (including dynamics) on the wreck.

ANNEX 1.

Raw data from the memory card of the SeaGuard II have been appended to the report (files Data000.bin, Data001.bin, Data002.bin, Data003.bin, Data004.bin, Data005.bin) along with information about the configuration of the instrument (Config.xml) and the setup of the measurements (Layout.xml). All these files can be read using the dedicated software application DataStudio 3D (Aanderaa).

All of the raw data, in physical units, for the entire measurement period, extracted using the abovementioned software application from Aanderaa, have also been saved and transmitted as *.csv and *.xlsx files (Estonia_Dec-Mar_2021-22.csv ja Estonia_Dec-Mar_2021-22.xlsx), which can be read using word processing and spreadsheet software (e.g., Excel). These files contain both preliminary measurement data and information on the current profile measurement quality and the state of the instrumentation over the measurement period.

The measurement data have been formatted as a separate Excel file containing only quality-controlled data from sensors and calculated values of physical quantities. The table columns show the following data:

- Record Time – time of day (UTC)
- Record Number – number of the data series
- Conductivity [mS/cm] – electrical conductivity
- Temperature[Deg.C] – water temperature (measured by the conductivity sensor)
- Salinity[PSU] – calculated salinity in PSU
- Salinity[g/kg] – calculated salinity in g/kg
- Density[kg/m3] – calculated density of water
- Soundspeed[m/s] – calculated speed of propagation of sound in the water
- Pressure[kPa] – pressure
- Temperature[DegC] – temperature (measured by the pressure sensor)
- O2Concentration[uM] – dissolved oxygen concentration in the water (in µM, i.e. µmol/l)
- AirSaturation[%] – oxygen saturation percentage
- Temperature[Deg.C] – temperature (measured by the oxygen optode)

The following columns show the measured (sensor DCPS #505) and calculated parameters of currents in all layers from 76–74 m to 36–34 m, taking into account the measured current velocities and the orientation of the instrument as recorded by the compass:

- modulus of current velocity (Horizontal Speed [cm/s]),
- current direction (Direction [Deg.M]),
- northward component of current velocity (North Speed [cm/s]),
- eastward component of current velocity (East Speed [cm/s]).