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Composition and Dynamics of Sediments in Tidal Channels of the German North Sea Coast

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Summary

This paper presents the results of the analysis of field measurements used for identifying the basic patterns of sediment composition and sediment dynamics in the main tidal channels of the central Dithmarschen Bight on the German North Sea coast. The study was carried out within the framework of the research project "Predictions of Medium Scale Morphodynamics – PROMORPH" funded by the German Ministry of Education and Research. The spatial distribution of the characteristics of the upper layer of seabed sediments and the composition of the material transported in suspension were determined on the basis of measurements using side-scan sonar imagery, grab and water samples. It was found that the seabed in the tidal channels is essentially comprised of sandy sediments and mud as well as consolidated deposits. Contrary to the tidal flats, no clear trends could be identified regarding spatial distribution. The material transported in suspension is much finer than that on the bottom and consists of very fine to medium-grain silt. The spatial and temporal distributions of suspended material concentration and transport were investigated. Current velocities and suspended material concentrations were measured simultaneously from moving vessels at several cross-sections by means of Acoustic Doppler Current Profilers and optical beam transmissometers, respectively. The measurements were performed for tidal ranges of 2.3 m to 4.2 m under essentially calm weather conditions. Due to the small grain sizes of material transported in suspension its vertical distribution was found to be fairly uniform with maximum depth-averaged values of 0.55kg/m^3. It is estimated that approximately 35,000 and 105,000 metric tons of suspended material are transported through the two main tidal channels during neap and spring tidal cycles, respectively. The adopted measuring strategy proved to be quite satisfactory for the purpose of the present investigation, and the results were found to be very helpful for clarifying various strategic aspects of numerically modelling these processes.

Zusammenfassung

Dieser Beitrag stellt Ergebnisse der Analyse von Feldmessungen vor, die zur Identifikation von grundlegenden Mustern der Sedimentzusammensetzung und -dynamik in den Haupttiderinnen der zentralen Dithmarscher Bucht an der deutschen Nordseeküste führen. Die Studie wurde im Rahmen des Forschungsprojekts „Prognose mittelfristiger Küstenmorphologieänderungen – PROMORPH" vom deutschen Bundesministerium für Bildung und Forschung gefördert. Die räumliche Verteilung der Merkmale der Oberflächensedimente des Meeresbodens wird mit Hilfe von Side-Scan Sonar-Messungen, Greifer- und Wasserproben ermittelt. Es wurde herausgefunden, dass sich die oberste Schicht des Meeresbodens in den Tiderinnen im Wesentlichen aus sandigen Sedimenten, Schlamm und konsolidierten Ablagerungen zusammensetzt. Im Gegensatz zu den Sandbänken konnte kein klarer Trend hinsichtlich der räumlichen Verteilung gefunden werden. Das in Suspension transportierte Material, das feinem bis mittlerem Schluff entspricht, ist viel feiner als das oberflächliche Meeresbodensediment. Die räumliche und zeitliche Verteilung der Konzentration und des Transports des suspendierten Materials wurde untersucht. Strömungsgeschwindigkeiten mittels ADCP und Konzentrationen des suspendierten Materials mittels optical beam transmissometer wurden gleichzeitig von fahrenden Schiffen an verschiedenen Querschnitten gemessen. Die Messungen wurden bei einem Tidehub von 2,3 bis 4,2 m während ruhiger Wetterbedingungen durchgeführt. Aufgrund der geringen Korngröße des in Suspension transportierten Materials ergaben sich ziemlich gleichförmige vertikale Verteilungen der Konzentration. Mit maximalen tiefengemittelten Werten von 0,55 kg/m^3. Es wird geschätzt, dass etwa 35.000 bzw. 105.000 t suspendierten Materials durch die beiden Haupttiderinnen während eines

Nipp- bzw. Springtidezyklus befördert werden. Die benutzte Messstrategie stellte sich als sehr geeignet heraus, und die Ergebnisse halfen, verschiedene Aspekte bezüglich der Strategie bei der numerischen Modellierung der Vorgänge zu klären.

Keywords

Seabed Sediment, Suspended Material Concentration, Sediment Transport, Field Measurements, Tidal Channel, Numerical Modelling, Dithmarschen Bight, North Sea.

Contents

1. Introduction

An understanding of the hydrodynamics, sediment dynamics and morphodynamics in coastal regions requires detailed knowledge of the various processes involved. Field measurements are of vital importance for improving this knowledge in view of the relatively poor understanding of the physical system and hence the corresponding uncertainties associated with mathematical models. Within the framework of the research project "Predictions of Medium-Scale Coastal Morphodynamics – PROMORPH" funded by the German Ministry of Education and Research, process-based numerical models for simulating flow, waves and sediment transport have been developed and evaluated for simulating morphological changes over time scales of several years in a tidally-dominated area of the German Wadden Sea (Overview in MAYERLE et al., 2005; WILKENS et al., 2005; WINTER et al., 2005; WILKENS and MAYERLE, 2005). The investigation area is a tidally-dominated region of the central Dithmarschen Bight between the Elbe and Eider estuaries. For the purpose of model development, continuous monitoring of wind speed, water levels and bathymetry by the relevant authorities were supplemented by specially-designed field surveys for high-resolution measurements of the spatial and temporal variations of waves, current velocities and suspended material concentrations. The purpose of collecting field data was to identify the dominant acting physical processes, thereby assisting in the definition of the modeling strategy as well as providing data for developing and evaluating the models. Considering the fact that sediment motion is very difficult to estimate using state-of-the-art numerical and analytical techniques, the present research project marks a first step towards a better understanding of sediment transport processes in the study area.

In this paper particular attention is given to the analysis of field measurements in order to provide a better understanding of sediment composition and sediment dynamics in the investigation area. The investigation focuses on the main tidal channels of the central Dithmarschen Bight. The results of an analysis of seabed sediment characteristics and material transported in suspension as well as suspended material concentration and transport along the main tidal channels are presented. The characteristics of seabed sediments were obtained by means of side-scan sonar surveys validated with seabed sediment samples. A large number of water samples were also collected at various locations in the tidal channels to provide information on the characteristics of material transported in suspension. Current velocity and suspended material concentration were measured simultaneously from moving vessels along several tracks at different tidal cycles by means of Acoustic Doppler Current Profilers and optical beam transmissometers, respectively. The ranges of suspended material concentration and transport variations were identified and the main patterns of sediment dynamics responsible for spatial and temporal variations were investigated. The suspended load transport through the main tidal channels over the ebb and flood period was also estimated in order to assess the morphological evolution in the study area. From the multitude of field measurements only typical results could be included in this paper.

2. Description of the Study Area

The investigation focuses on the main tidal channels of the central Dithmarschen Bight on the German North Sea coast (Fig. 1). The study area is located about 100 km north of Hamburg between the Eider and Elbe estuaries.

The morphology of the study area is dominated by tidal flats and a tidal channel system comprised of three channels: Norderpiep in the northwest, Suederpiep in the southwest, and the Piep tidal channel, which originates at the junction of the Norderpiep and Suederpiep. For average conditions the maximum water depth in the tidal channels is 18 m. The tidal flats and sandbanks are exposed at low water. The area is characterized by a meso-tide regime with a mean tidal range of 3.2 m and neap and spring tidal ranges of about 2.8 m and 3.5 m, respectively. According to the classification by EHLERS (1988) this leads to an open tidal flat without barrier island. Westerly winds (SW-W) prevail and the area is classified as a storm wave environment. Wave heights in the outer region can reach 3 to 4 m but break along the edge of the tidal flats on intertidal and supratidal sandbanks. Locally generated waves of up to 0.5 m in height are observed in the study area. The influence of local waves on currents is moderate on the tidal flats and negligible in the tidal channels. Storm surges can result in water level setups of up to 5 m, favoring the propagation of waves into shallow regions. Even under such conditions, however, wave effects are mostly confined to the outer sandbanks. The seabed sediments in the tidal channels and flats consist mainly of sands with varying proportions of silt and clay. The grain sizes of sediment transported in suspension are much finer.

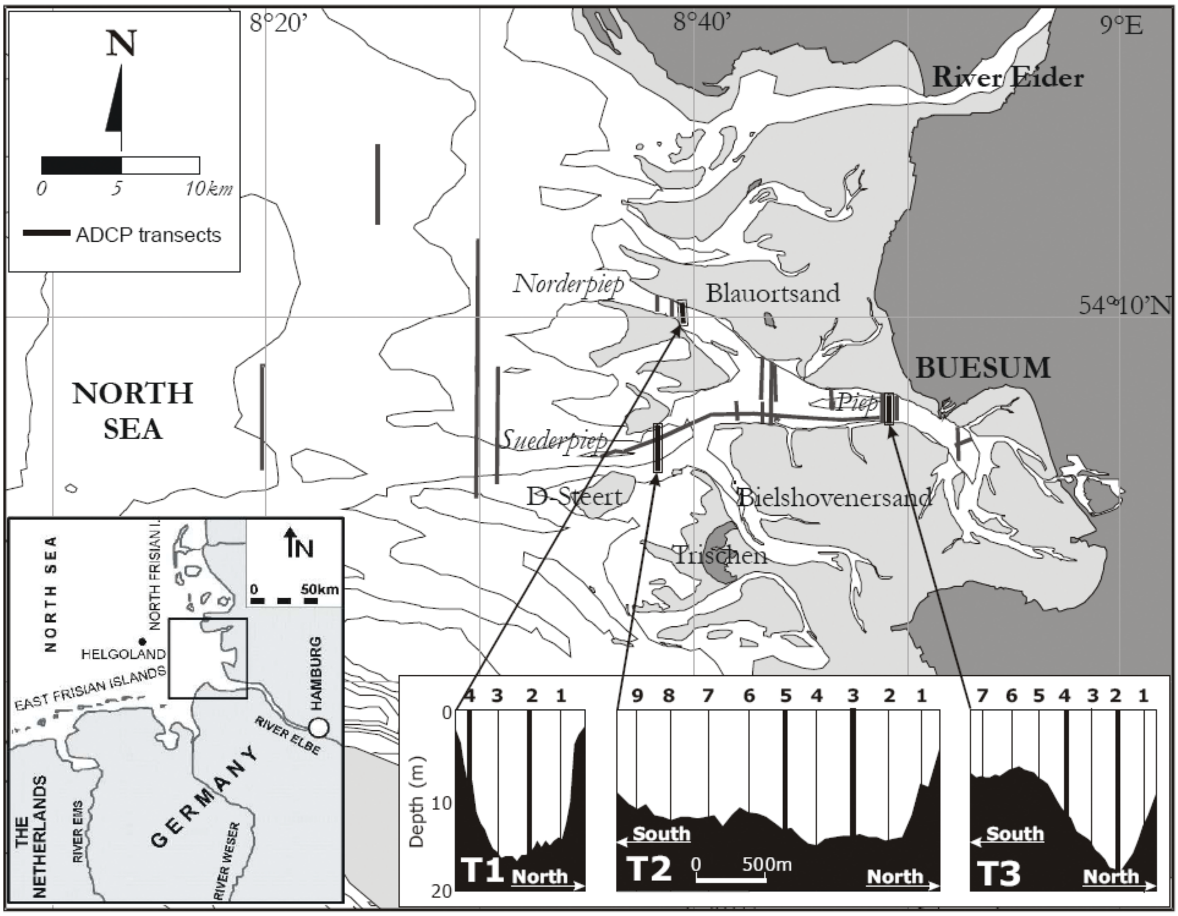


Fig. 1: Investigation area and selected cross-sections

3. Sediment Deposits and Characteristics

An investigation of recent sediment deposits, their layer thickness and the characteristics of mobile sediments was carried out by Asp Neto (2004) and Ricklefs and Asp Neto (in this volume), while seabed sediments in the tidal channels were mapped by Vela-Diez (2001). The characteristics of the seabed sediments and material transported in suspension were studied by Poerbandono (2003).

3.1 Recent Sediment Deposits

Fig. 2 shows the distribution of the layer thickness of sediment deposits in the study area. The composition of the sediment deposits corresponds extensively with recent tidal flat sediments. The layer thickness of the intertidal deposits is up to about 20 m on the tidal flats. The layer thickness of potentially mobile sediments increases towards the northern and the southern banks of the main tidal channels. The results of field observations have shown that the thickness of sediment deposits above the Early Holocene layer (EHL) may be as much as 16m along the channel banks, reducing to zero towards the deeper parts of the channels.

The early Holocene consolidated cohesive sediments form a natural base that delays or even prevents erosion in the tidal channels, thereby restricting morphological changes to lateral displacements. In the central and deeper parts of the tidal channels where shear stresses are generally larger sediment deposits have been entirely eroded and the EHL shows (Asp, 2004).

Fig. 3 shows the evolution of three cross-sections in the main tidal channels over the past two decades, indicating layer thickness of mobile sediments. In the deeper parts of the cross-sections the EHL, resulting in a lateral displacement of the bed profiles towards the North.

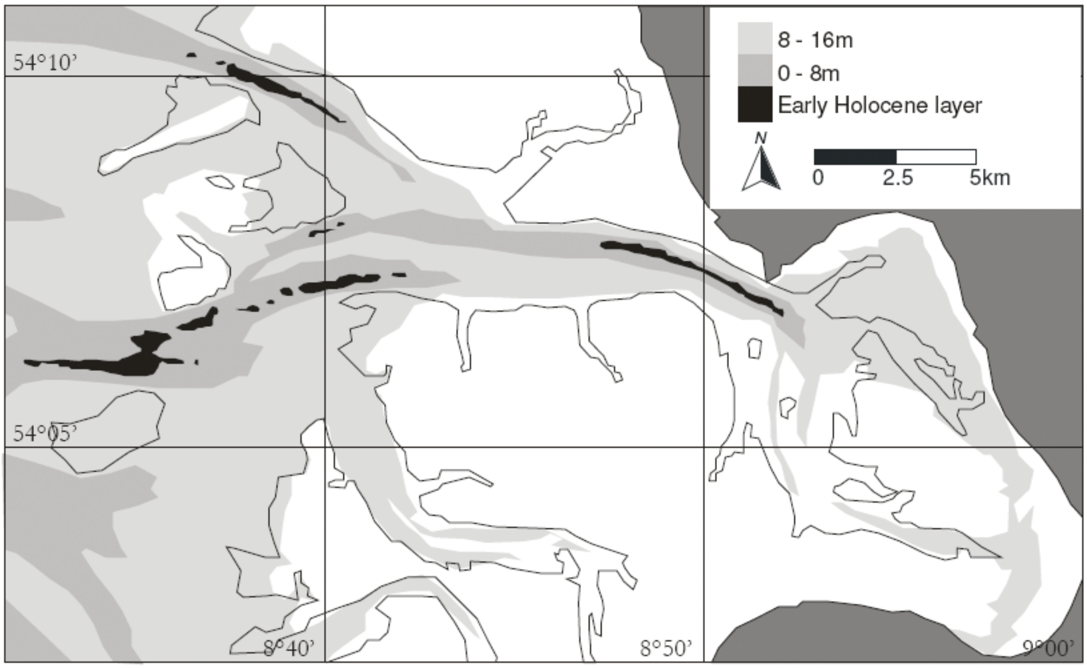


Fig. 2: Thickness of the potentially mobile sediment layer above the EHL (modified after Asp, 2004)

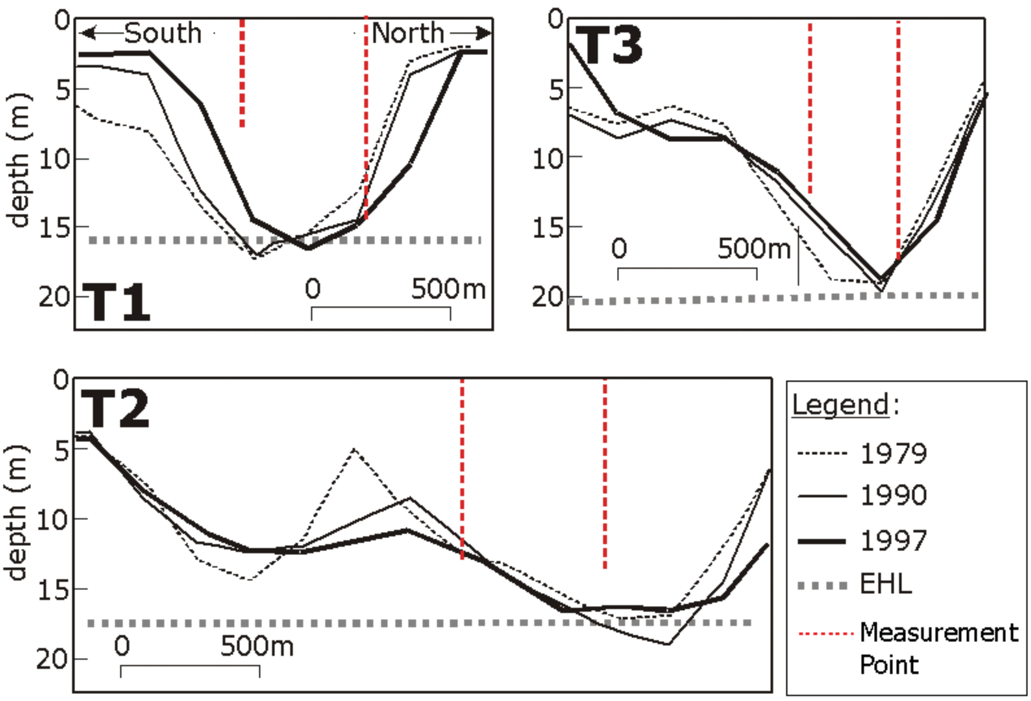


Fig. 3: Thickness of the potentially mobile sediment layer at selected cross-sections (modified after Asp, 2004)

3.2 Seabed Surface Sediments

On the basis of side-scan sonar (SSS) images and grab samples (GS) VELA-DIEZ (2001) mapped the distribution of seabed surface sediments in the tidal channels. The SSS surveys were carried out using a *Klein* system operating at a frequency of 500 kHz. The horizontal distribution of sediment patterns on the seabed was determined by towing the measuring device alongside a survey vessel. The SSS surveys over an area of approximately 30 km^2 were carried out in May and June, 1999 and September and November, 2000. Fig. 4 shows the area covered and the locations where samples were taken.

The SSS images were interpreted through correlation of their texture with characteristic grain-size parameters obtained from 15 GS, which were collected from the survey vessel using a van Veen sampler. Sampling is restricted to some parts of the domain. GS were taken mainly along the regions of transition between fine and medium sands to distinguish them on the grey scale of SSS images. Fig. 5 shows the distribution of seabed sediments in the tidal channels. The distribution appears variable. Areas with sandy sediments and mud as well as zones of consolidated deposits were identified. Consolidated fine-grained sediments were found to show at a number of deeper locations in the channels. The sands are mainly very fine to fine with isolated patches of medium sands. Although the measurements achieved full spatial coverage, the hydroacoustic detection was not sufficiently clear to distinguish between very fine and fine sands.

Sediment size analyses were carried out by dry sieving. The resulting sieve curves are shown in Fig. 6. Table 1 summarizes the results. The d_{50} varied between 80 µm and 230 µm, corresponding to very fine (63 µm < d_{50} < 125 µm) to fine (125 µm < d_{50} < 250 µm) sand,

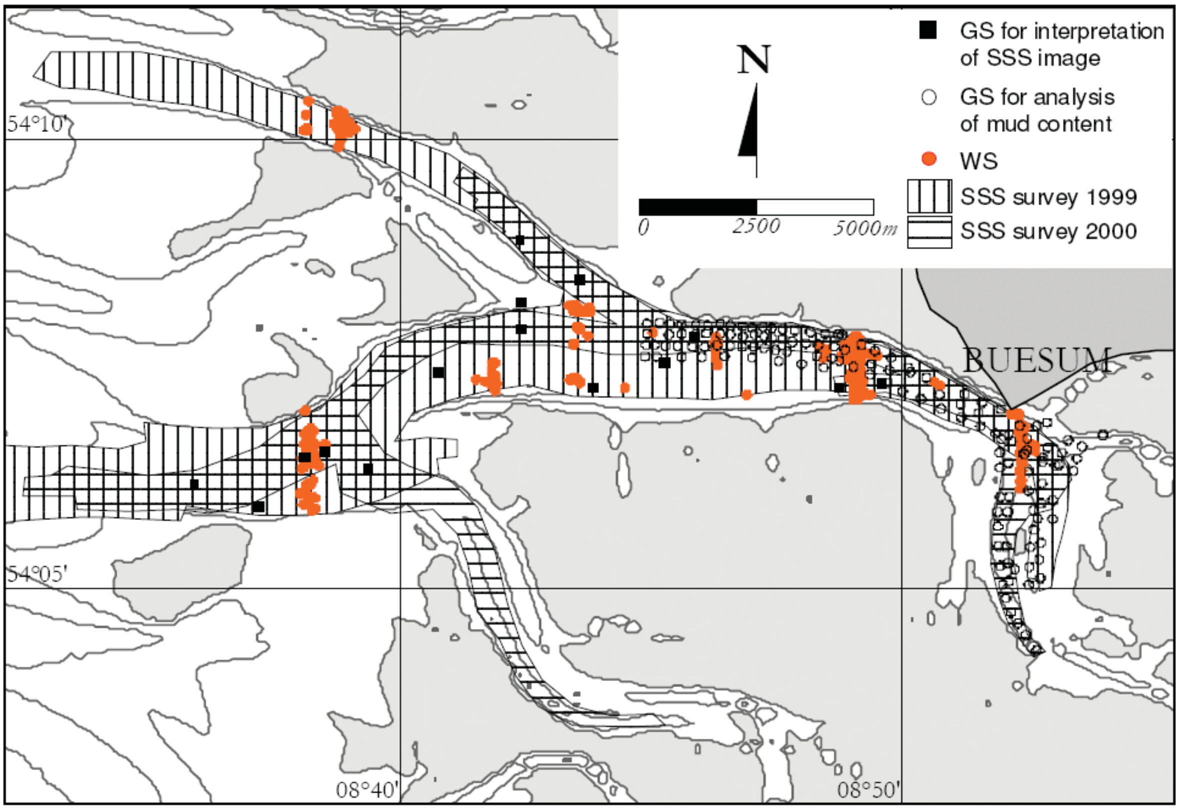


Fig. 4: Locations of side-scan sonar (SSS) surveys, grab samples (GS) and water samples (WS)

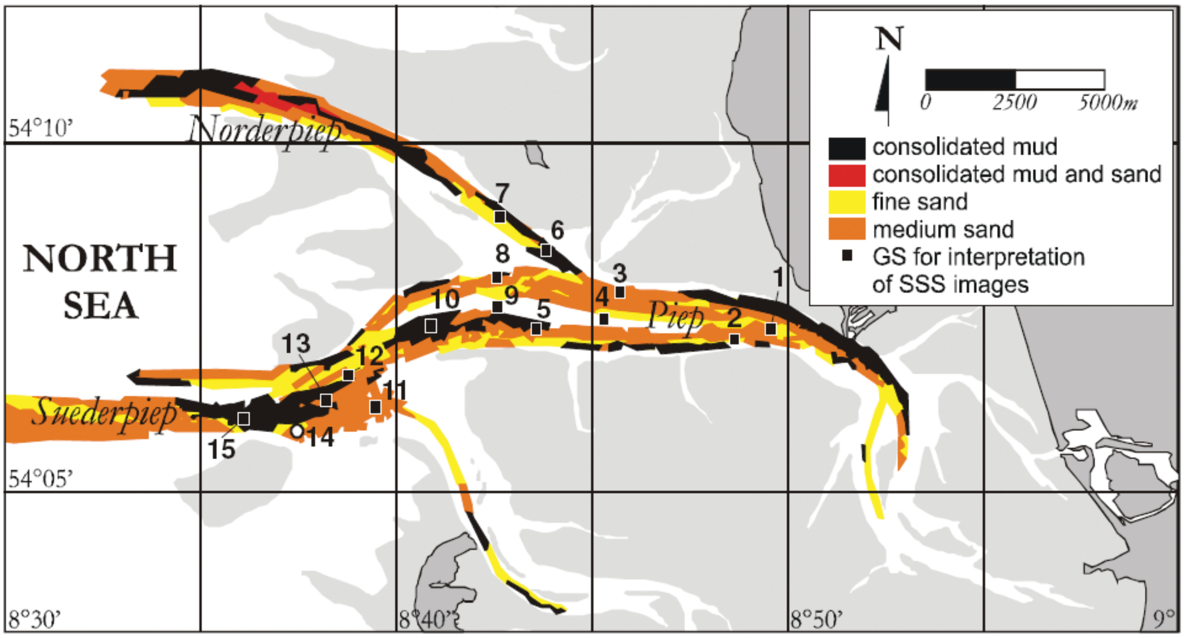


Fig. 5: Seabed surface sediment distribution in the main tidal channels (modified after VELA-DIEZ, 2001)

respectively. Moreover, the median sediment sizes of most of the samples were found to be equal to or less than 100 µm. The majority of the samples were well-sorted, as also confirmed by the small values of the geometric standard deviation (σ_g) and the d_{90} to d_{50} ratio.

An analysis of the mud content (% of fines; $d < 63$ µm) of 145 seabed sediment samples collected with a van Veen sampler in the less exposed tidal channels at the locations shown in Fig. 4 was also carried out. The mud content was determined by separating the fines from the samples with water using a 63 µm sieve. Mud was found in all samples. The measurements indicate that the percentage of fines in the sediments of the sampling area is generally greater than 5 %, attaining maximum values of 75 %–80 %. Moreover, the percentage of fines was found to exceed 10 % in about 50 % of the samples. Although no clear trend could be identified regarding the spatial distribution of mud content, a tendency of increasing values with increasing depth was observed at the sampling locations. This is illustrated in Fig. 7, which shows the variation of mud content with water depth for all sediment samples collected in the study area. It can be seen that sediments with higher silt and clay fractions are found in the deeper areas of the main channels.

The characteristics of seabed surface sediments in the intertidal areas have been studied by REIMERS (2003). He found that the characteristic median sediment size ranges from fine sand ($d_{50} \approx 230$ µm) to coarse silt ($d_{50} \approx 70$ µm). Fine sands are found mainly at the supratidal sites and on the exposed sandbanks of Blauort, Bielshovenersand and Blauortsand (Fig. 1). RICKLEFS and ASP NETO (in this volume) identified a clear gradual decrease in the grain size of the seabed sediments from the outer regions to the inner tidal flat region, changing from coarse sand (grain size of about 355 µm) to coarse silt (grain size of about 38 µm). In the more exposed outer regions in the proximity of the main tidal channels the content of fines ($d < 63$ µm) is generally less than 5 %. Towards the inner parts of the study area the content of fines increases to between 50 % and 100 %.

Table 1: Characteristics of seabed sediments

Station	Position N	Position E	Depth (m)	d_{50} (µm)	d_{90} (µm)	d_{90}/d_{50}	σ_g	Sorting
1	54° 7‘ 15.6“	8° 49‘ 36.6“	10.0	103	124	1.2	1.3	Well-sorted
2	54° 7‘ 13.8“	8° 48‘ 46.2“	6.3	104	130	1.3	1.0	Well-sorted
3	54° 7‘ 48.6“	8° 45‘ 56.4“	14.4	137	203	1.5	1.5	Intermediate
4	54° 7‘ 29.4“	8° 45‘ 20.4“	1.0	86	115	1.3	1.2	Well-sorted
5	54° 7‘ 12.6“	8° 43‘ 56.4“	5.0	124	189	1.5	1.4	Well-sorted
6	54° 8‘ 26.9“	8° 43‘ 40.2“	7.0	107	222	2.1	1.7	Intermediate
7	54° 8‘ 54.8“	8° 42‘ 29.4“	12.4	103	132	1.3	1.3	Well-sorted
8	54° 8‘ 11.4“	8° 42‘ 31.6“	10.0	109	134	1.2	1.3	Well-sorted
9	54° 7‘ 52.8“	8° 42‘ 30.6“	12.5	100	131	1.3	1.3	Well-sorted
10	54° 7‘ 22.8“	8° 40‘ 54.4“	3.0	125	207	1.7	1.5	Intermediate
11	54° 6‘ 15.7“	8° 39‘ 32.3“	7.5	230	295	1.3	1.6	Intermediate
12	54° 6‘ 28.0“	8° 38‘ 40.8“	11.0	84	117	1.4	1.3	Well-sorted
13	54° 6‘ 24.0“	8° 38‘ 17.5“	10.5	90	136	1.5	1.4	Well-sorted
14	54° 5‘ 49.8“	8° 37‘ 23.4“	5.0	159	210	1.3	1.4	Well-sorted
15	54° 6‘ 5.4“	8° 36‘ 8.0“	15.4	80	123	1.5	1.3	Well-sorted
		Minimum	1.0	80	120	1.2	1.0	
		Maximum	15.4	230	300	2.1	1.7	

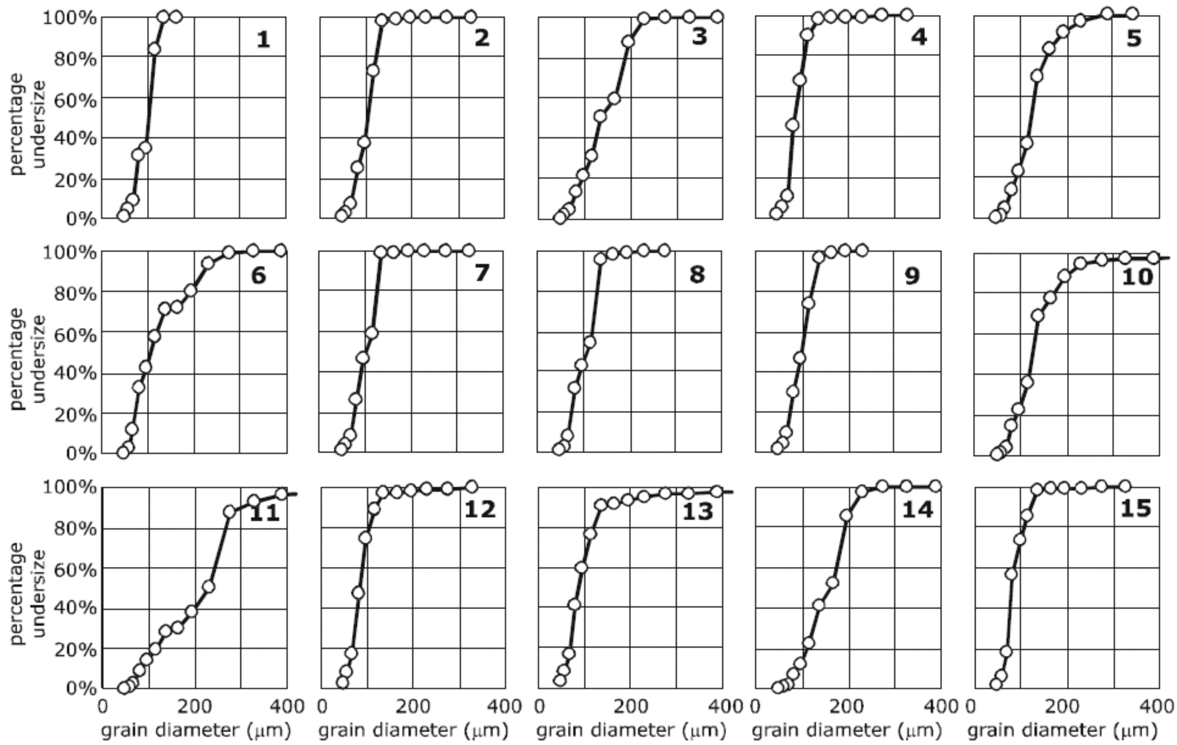


Fig. 6: Sieve curves of seabed sediment samples used for interpreting SSS images

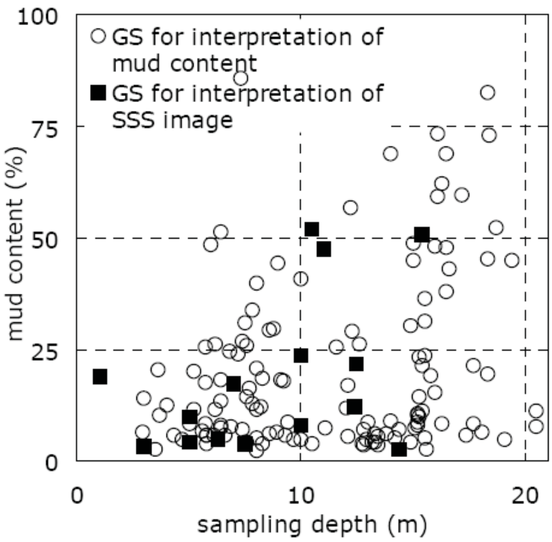
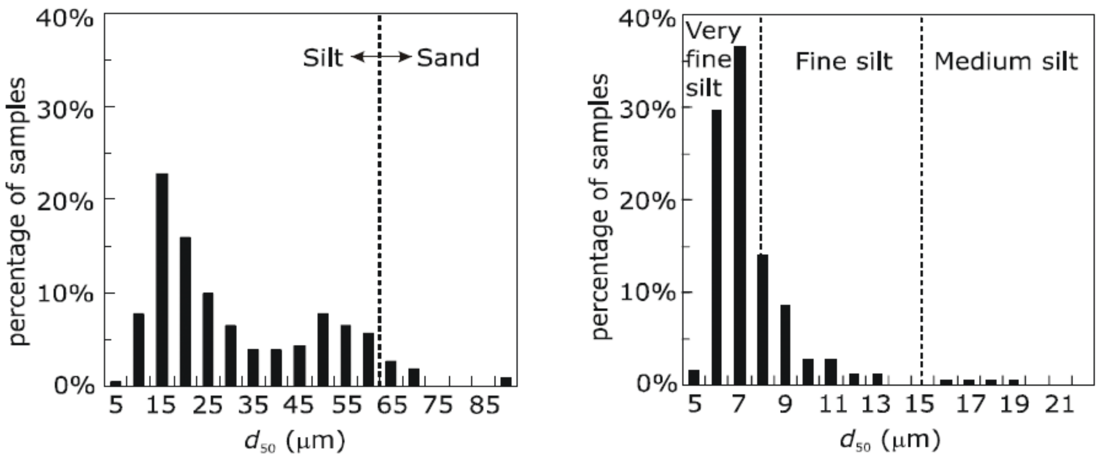


Fig. 7: Variation of mud content with water depth

3.3 Material Transported in Suspension

The characteristics of the material transported in suspension were investigated by POERBANDONO (2003). 233 water samples (WS) were collected at three cross-sections in the main tidal channels as shown in Fig. 4. The WS were taken at 1 m above the seabed using a Niskin bottle sampler in water depths ranging from 5 m to 26 m. Depth-averaged current velocities of up to 1.6 m/s and point sediment concentrations ranging from 0.04 kg/m^3 to 1.1 kg/m^3 were measured at the sampling stations. The sample grain sizes were determined using a Galai CIS-1 laser granulometer. Since the fine particle fraction of the samples tends to flocculate soon after collection, a pre-analysis treatment was undertaken. This involved exposing the water samples to ultrasonic waves for a period of about 10 minutes before carrying out the grain-size analysis.

It was found that the material transported in suspension is much finer than the seabed sediments in the tidal channels and on the tidal flats. Besides, the sandy material on the seabed is seldom found in suspension. In general, the mean grain-sizes of suspended material are about 1 to 5 times smaller than those of seabed sediment. Fig. 8 shows histograms of median sediment sizes for the samples with pre-treatment (186 samples out of 233) and without pre-treatment (233 samples). Although the samples without pre-treatment exhibit a wide band of median sediment sizes ranging from about 5 µm to 90 µm, the median grain size of about 60 % of the samples was found to be between 10 µm and 25 µm, corresponding to very fine to medium silt. The median sediment sizes of samples with pre-treatment were found to be between 4 µm and 19 µm. No clear pattern could be identified regarding the spatial and temporal variation of the sizes of suspended material.



(a) Without pre-treatment (233 samples) (b) With pre-treatment (186 samples)

Fig. 8: Frequency histogram of the median sizes of suspended material

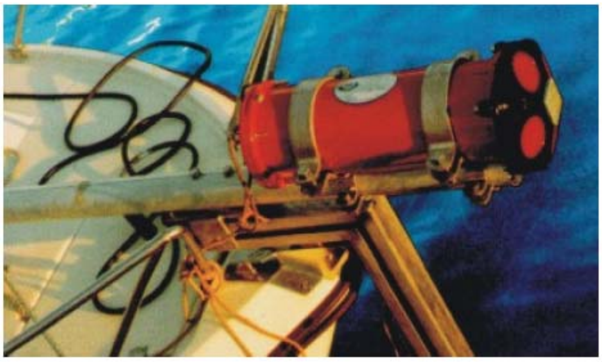
4. Suspended Material Concentration and Transport

The aim of the present investigation is to identify patterns of sediment dynamics in the tidal channels of the central Dithmarschen Bight based on the spatial and temporal variations of suspended material concentration and transport derived from field measurements. The results of investigations of near-bed sediment transport in the same tidal channels are summarized in SCHROTTKE and ABEGG (2005).

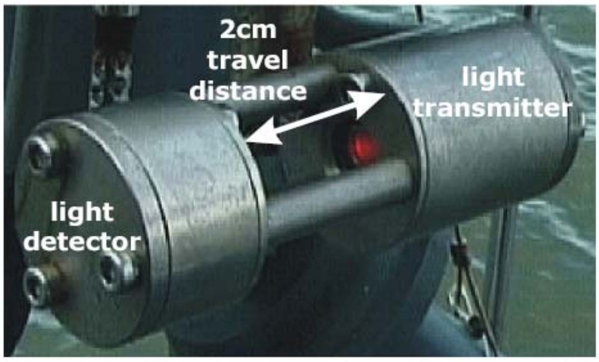
4.1 Measuring Devices and Experimental Set-up

The data that required for investigating the patterns of suspended material concentration and transport were derived from simultaneous measurements of current velocity and suspended material concentration at several cross-sections in the main tidal channels. These measurements were mainly made from moving vessels provided by the University of Kiel.

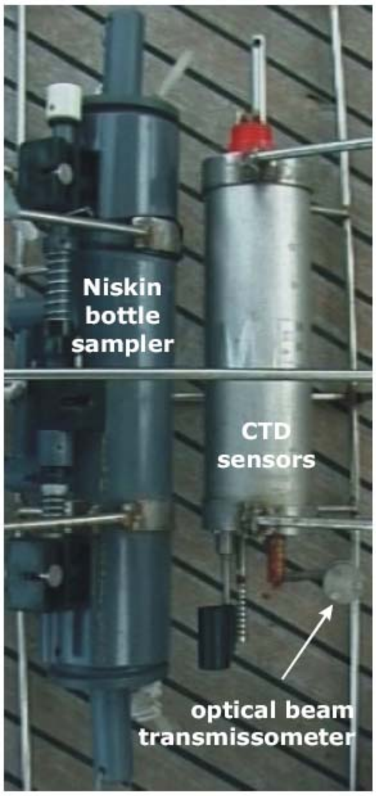
Current velocity data was obtained using 1200 kHz Acoustic Doppler Current Profilers (ADCPs), as shown in Fig. 9a. The instrument was set to record a 0.5 m bin size over a 12 seconds averaging ensemble. Details of the device and its accuracy for point measurements under laboratory conditions and for cross-sectional measurements of current velocities in the investigated tidal channels are summarized in JIMÉNEZ-GONZÁLEZ et al. (in this volume). The accuracy of ADCPs for point measurements in the field is found to be fairly constant, with standard deviations of 0.14 m/s and 0.06 m/s for vertical distances below and above 1m from the seabed, respectively. The ADCP was directed downward from the bow of the vessel and deployed for the continuous measurement of current velocity profiles. Measurements over the water column were made from 1.6 m below the free surface (due to the effects of transducer draught and blanking distance) down to 6 % of the depth above the seabed (due to side lobe effects). Since the measurements of current velocity did not cover the entire water column, extrapolations were carried out in order to provide an adequate description of the velocity distribution over the full depth. For this purpose a constant velocity was assumed between the uppermost point measurement to the free surface and a linear variation from the lowest measured value to zero at the seabed.



(a) Acoustic Doppler Current Profiler



(b) Optical beam transmissometer



(c) Niskin bottle and CTD

Fig. 9: Measuring devices used in the study

Suspended material concentrations were measured by means of optical beam transmissometers mounted in CTD sensors and equipped with a Niskin bottle sampler (Fig. 9c). The device, which employs visible light with a wavelength of 660 ± 12 nm and a 2 cm travel distance, provides a relative measure of suspended material concentration in terms of the percentage of optical transmission. In order to convert the optical transmission data into suspended material concentrations the device was calibrated against the concentrations determined from direct samples. The accuracy of the optical measurements and details of the device and calibration procedure are summarized in POERBANDONO and MAYERLE (2005). It was found that the representative relative agreement between optical and direct sampling measurements is about 30 %. The devices were lowered midships at the vessels starboard side, and optical measurements in the water column were performed from close to the free surface to approximately 0.25 m above the seabed. This restriction is due to the separation distance between the optical transmissometer and the protective frame mounted below the device (Fig. 9b). In order to describe the suspended sediment concentration over the entire water column an extrapolation based on the last three lowest point measurements was undertaken.

In order to investigate the variation of suspended sediment concentration and transport during a tidal period measurements of current velocity and optical transmission profiles from moving vessels were carried out in various cross-sections, as illustrated in Fig. 10. The vessel moves back and forth in a cross-section during the entire measuring period. The number of measurement verticals and the separation distance between them depend on shape and dimensions of the cross-section. The vertical resolution of the optical beam transmissometer was set to 0.2 m. The number of runs during a tidal cycle depends primarily on the width of the cross-section and measuring conditions. In order to obtain simultaneous measurements at different cross-sections, which is ideal for the calibration and validation of numerical models, two vessels equipped with similar devices were deployed during several of the measurement campaigns.

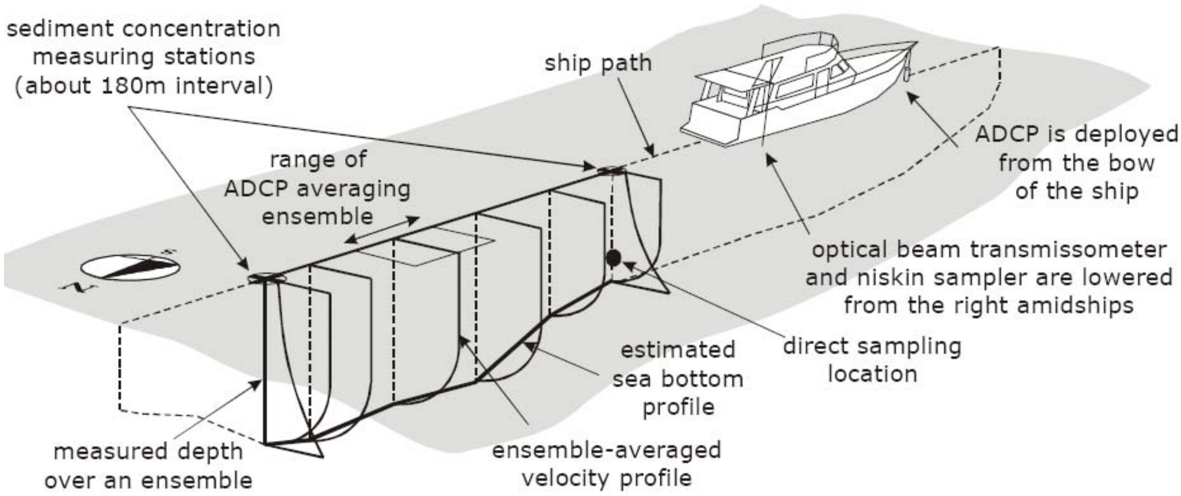


Fig. 10: Measuring technique along a transect

In order to study the variation of suspended material concentration and transport during a lunar cycle measurements were performed for a variety of tidal conditions. Measurement campaigns were undertaken at three months intervals in order to account for seasonal variations, with repetitions at approximately seven day intervals to account for neap and spring tide variations. A wide range of tidal conditions was also covered in order to investigate spatial (vertical and horizontal) and temporal (tidal and lunar cycles) variations. Details of the vessels operated by the Research and Technology Centre Westcoast simultaneously are given in TORO et al. (in this volume).

4.2 Field Measurements

Within the framework of the research project PROMORPH field measurements were performed in the tidal channels of the central Dithmarschen Bight. These measurements were made during the period May 1999 to June 2002 and covered a wide range of tidal conditions. Most of the field data used in this study were collected from moving vessels under calm weather conditions over the investigated cross-sections in different tidal channels. Although extensive measurements were undertaken over a wide area, only typical results are considered in this paper. The analysis is focused on conditions in the cross-sections of the main tidal channels, i.e. T1 and T2 at the entrance to the tidal area, representing the channels Norderpiep to the northeast and Suederpiep to the southeast, respectively, and T3 in the Piep tidal channel located in the coastal region of the study area. The locations and bed profiles of these three cross-sections are shown in Fig. 1. T1 is about 775 m wide with water depths varying from 2.8 m to 16.1 m, T2 is about 2040 m wide with water depths varying from 7.3 m to 15.6 m, and T3 is about 1200 m wide with water depths varying from 6.2 m to 17.9 m. In order to obtain good coverage over one tide 20 to 75 transects were surveyed during each measurement campaign. The measuring technique adopted has already been described in Section 4.1 (Fig. 10).

The measuring stations were positioned at approximately 180 m intervals along each transect. Simultaneous measurements of current velocity and suspended material concentration were made at each measuring station. The number of measuring stations in cross-sections T1, T2 and T3 were 4, 9 to 12, and 6 to 7, respectively.

Table 2 summarizes the results of the measurement campaigns undertaken between March 2000 and September 2001. The measurements covered entire tidal cycles under relatively calm wind conditions. The tidal range during the survey period varied from 2.3 m at neap tides to 4.2 m at spring tides. The maximum point values, depth-averaged values and cross-sectional average values of suspended material concentration and transport are given in the table. Negative values refer to offshore conditions. Intermediate values of suspended material concentration in each cross-section were obtained by linearly interpolating values between the measuring stations. The ranges of variation of these quantities during slack water are also entered in Table 2 to provide an indication of background values. The maximum rates of suspended material transport in each cross-section as well as the values integrated over a tidal phase (ebb and flood) are also shown. Depth-averaged values were obtained by integration from the reference level up to the free surface and subsequent division by the corresponding vertical distance.

Cross-sectional average values were obtained by integration over the entire cross-section and subsequent division by the corresponding cross-sectional area. The cross-sectional distribution of suspended material concentration was obtained by linear integration between the measuring stations. The material transported through each cross-section during a tidal phase (ebb or flood) was calculated by linear integration of the cross-sectional averages over the duration of measurements for each phase.

4.3 Ranges of Measured Values

The variation of the distribution of suspended material concentration and transport was investigated by comparing the measured values of suspended material concentration and transport in cross-sections T1, T2 and T3, as summarized in Table 2. The maximum depth-averaged sediment concentrations at cross-sections T1, T2 and T3 were computed to be 0.27 kg/m^3, 0.55 kg/m^3 and 0.40 kg/m^3, respectively. The maximum computed value is at cross-section T2 in the main tidal channel whereas the maximum value at cross-section T1 is generally much smaller than the values computed at the other two cross-sections.

The differences in magnitude are more significant at higher tidal ranges. During neap tidal cycles there is a definite tendency towards convergence of the observed values at the three cross-sections. Minimum values were measured during slack water (= 60–90 min) at high and low tidal ranges. Depth-averaged suspended material concentrations at cross-sections T1, T2 and T3 varied from 0.04 to 0.10, 0.06 to 0.14 and 0.06 to 0.14 kg/m^3, respectively.

The range of approximate ebb to flood ratios of tidally-integrated transport at cross- sections T1, T2 and T2 were found to be 0.61 to 0.95, 0.82 to 1.09 and 0.79 to 1.30, respectively. A tendency towards flood domination was observed at cross-section T1. Bearing in mind the inaccuracies of measurements and interpolations in space and time, it was not possible to identify any clear pattern of ebb or flood domination at cross-sections T2 and T3. It is estimated that approximately 35,000 and 105,000 metric tons of suspended material are transported through the two main tidal channels (T2 and T3) during one tide in a neap and spring cycle, respectively. Based on these figures, for the two main channels (T1 and T2) one can assume that more than 80 % is conveyed through cross-section T2 located in the southwest.

Table 2: Resume of current and sediment dynamics measurements

Cross section [width]	Date	Tidal range (m)	Number of transects – Measuring duration (h)	Maximum current velocity (m/s)				Maximum suspended matter concentration (kg/m^3)				Maximum sediment transport rate (kg/m^2s)				Slack water concentration (kg/m^3)		Slack water transport (kg/m^2s)		Tide-intgrd. sediment transport in cross-section (10^3tons)	
				Depth-avg.		Cross-sect.- avg.		Depth-avg.		Cross-sect.- avg.		Depth-avg.		Cross-sect.- avg.		Depth-avg.	Cross-sect.-avg.	Depth-avg.	Cross-sect.-avg.		
				F	E	F	E	F	E	F	E	F	E	F	E					F	E
	Mar. 16, 2000	3.2	31 – 11.7	1.3	-1.2	1.0	-1.0	0.27	0.23	0.19	0.18	0.23	-0.24	0.19	-0.17	0.10	0.10	0.10	0.03	20.2	-18.7
	Mar. 22, 2000	4.0	31 – 11.6	1.5	-1.4	1.1	-1.2	0.14	0.20	0.13	0.14	0.20	-0.17	0.14	-0.15	0.09	0.09	0.09	0.01	18.4	-17.5
T1	Jun. 5, 2000	3.7	10 – 6.1	1.7	-1.4	1.5	-1.2	0.19	0.15	0.15	0.10	0.25	-0.18	0.20	-0.11	0.05	0.06	0.06	0.02	19.0[u]	- 4.7[u]
[775m]	Sep. 5, 2000	3.0	26 – 10.4	1.2	-1.3	1.0	-1.0	0.10	0.08	0.07	0.07	0.09	-0.08	0.06	-0.06	0.04	0.04	0.04	0.01	7.8	- 4.8
	Sep. 12, 2000	3.4	33 – 11.6	1.3	-1.2	1.1	-1.0	0.13	0.19	0.09	0.09	0.13	-0.13	0.09	-0.08	0.05	0.06	0.06	0.01	10.1	- 9.0
	Dec. 5, 2000	2.3	11 – 5.5	0.6	-0.9	0.5	-0.7	0.12	0.11	0.09	0.09	0.06	-0.07	0.05	-0.06	0.07	0.07	0.07	0.01	1.7[u]	- 4.7[u]
	Mar. 21, 2000	4.1	15 – 11.9	1.6	-1.4	1.2	-1.0	0.55	0.53	0.29	0.33	0.64	-0.54	0.29	-0.33	0.11	0.14	0.14	0.03	84.2	-89.5
T2	Jun. 5, 2000	3.7	10 – 8.4	n/a	-1.5	n/a	-1.1	n/a	0.26	n/a	0.16	n/a	-0.24	n/a	-0.17	0.06	0.07	0.07	0.02	n/a	-40.6
[2040m]	Sep. 5, 2000	3.1	8 – 9.8	1.3	-1.1	1.0	-0.9	0.40	0.29	0.18	0.17	0.39	-0.22	0.19	-0.14	0.06	0.07	0.07	0.01	32.2	-32.1
	Sep. 12, 2000	3.3	10 – 10.8	1.6	-1.2	1.1	-0.9	0.42	0.33	0.18	0.20	0.41	-0.32	0.20	-0.17	0.06	0.07	0.07	0.02	40.6	-33.3
	Dec. 5, 2000	2.3	9 – 10.8	0.8	-1.1	0.7	-0.7	0.23	0.28	0.16	0.17	0.13	-0.24	0.10	-0.12	0.06	0.09	0.09	0.02	29.3	-32.0
	Mar. 14, 2000	3.6	14 – 8.8	1.2	-1.3	1.0	-1.0	0.39	0.39	0.29	0.29	0.46	-0.39	0.28	-0.25	0.12	0.14	0.14	0.03	30.5[u]	-32.1[u]
	Mar. 23, 2000	4.2	24 – 13.0	1.2	-1.4	1.1	-1.0	0.40	0.35	0.22	0.22	0.44	-0.39	0.22	-0.20	0.10	0.11	0.11	0.01	31.4	-31.0
	Jun. 6, 2000	3.9	15 – 8.2	1.4	n/a	1.1	n/a	0.34	n/a	0.19	n/a	0.26	n/a	0.19	n/a	0.06	0.07	0.07	0.01	27.1	n/a
	Jun. 14, 2000	3.6	19 – 11.8	1.3	-1.4	0.9	-1.1	0.31	0.32	0.14	0.21	0.31	-0.24	0.13	-0.14	0.06	0.08	0.08	0.01	19.5	-21.8
T3	Sep. 6, 2000	2.9	14 – 10.7	0.9	-1.1	0.8	-0.8	0.26	0.33	0.15	0.17	0.19	-0.24	0.13	-0.13	0.07	0.08	0.08	0.01	16.0[u]	-19.2
[1200m]	Sep. 13, 2000	3.5	8 – 4.6	1.3	n/a	1.1	n/a	0.30	n/a	0.13	n/a	0.38	n/a	0.14	n/a	0.07	0.09	0.09	0.01	17.8	n/a
	Dec. 6, 2000	2.5	22 – 12.0	0.9	-0.9	0.7	-0.8	0.20	0.20	0.11	0.12	0.12	-0.13	0.08	-0.08	0.07	0.09	0.09	0.01	14.2	-15.6
	Jun. 22, 2001	3.9	9 – 5.9	1.4	n/a	1.1	n/a	0.24	n/a	0.17	n/a	0.28	n/a	0.17	n/a	0.08	0.10	0.10	0.02	24.5	n/a
	Jun. 28, 2001	3.6	13 – 11.4	1.2	-1.1	1.0	-0.8	0.22	0.28	0.15	0.13	0.23	-0.23	0.15	-0.11	0.07	0.08	0.08	0.01	18.5	-14.6
	Sep. 11, 2001	3.1	14 – 11.1	1.1	-1.3	0.9	-0.9	0.27	0.35	0.18	0.20	0.20	-0.32	0.13	-0.18	0.07	0.10	0.10	0.02	21.7	-28.2

Notes:

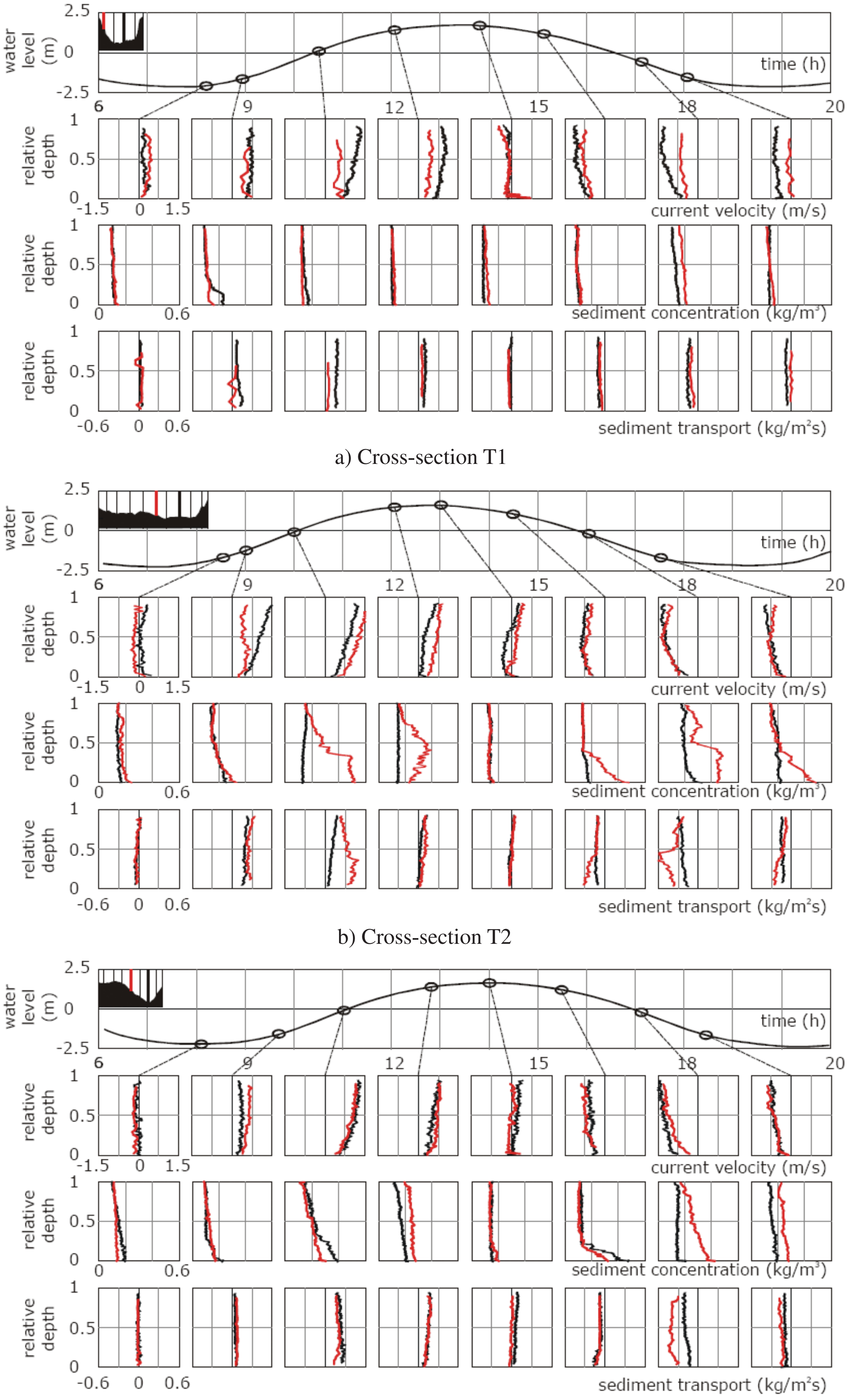
- \- negative current velocities and sediment transport rates refer to offshore directions
- n/a not available
- F Flood phase
- E Ebb phase
- [u] underestimation due to incomplete tidal cycle coverage

4.4 Vertical Variations

The variation of suspended material concentration and transport over the water column was studied by analyzing the measured profiles. Typical profiles of measured current velocity and suspended material concentration and transport at two measuring stations in cross-sections T1, T2 and T3 are shown in Fig. 11. The results presented here are based on a data set obtained on March 21, 22 and 23, 2000, during a sequence of spring tides with an average tidal range of approximately 4m. Due to the small grain sizes of sediment material transported in suspension and the strong levels of turbulence maintained by the tidal currents the vertical distributions of suspended material concentration and transport were generally found to be fairly uniform.

In cross-section T1 the variation in the magnitude of suspended material concentration remains approximately constant throughout the entire tidal cycle. In cross-sections T2 and T3 increases in the suspended material concentration of less than one order of magnitude are observed in the lower layers of parts of the cross-sections during periods of high current velocities. The outcropping EHL in the deeper parts of the tidal channels is responsible for it (see also Fig. 3). As there is no loose sediment to be entrained the sediment concentration remains approximately uniform over the depth and unchanged throughout the entire tide. This can be noticed at both measuring stations in cross-section T1 (see Figs. 11a and 12b), and even more clearly in cross-section T2 in which one of the measuring stations is located on top of EHL and the other in places with potentially mobile sediment layer. Figs. 11b and 13b show that sediment is entrained from the bed during highest current velocities only in places in which loose material is available.

At low current velocities below the threshold of motion background concentration values raging between 0.04 to 0.14 kg/m^3 are observed. The high levels of turbulence sustained by the tidal currents in combination with small falling velocities of the material transported in suspension prevent the material from settling.



a) Cross-section T1

b) Cross-section T2

c) Cross-section T3

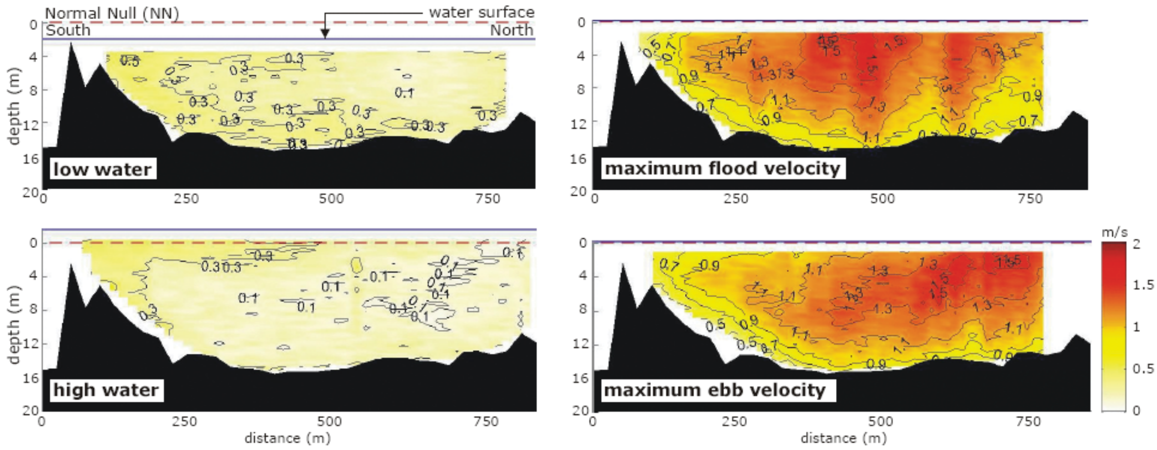
Fig. 11: Profiles of current velocity and suspended material concentration and transport at measuring stations in cross-sections T1, T2 and T3 on March 21 to 23, 2000

4.5 Cross-Sectional Variations

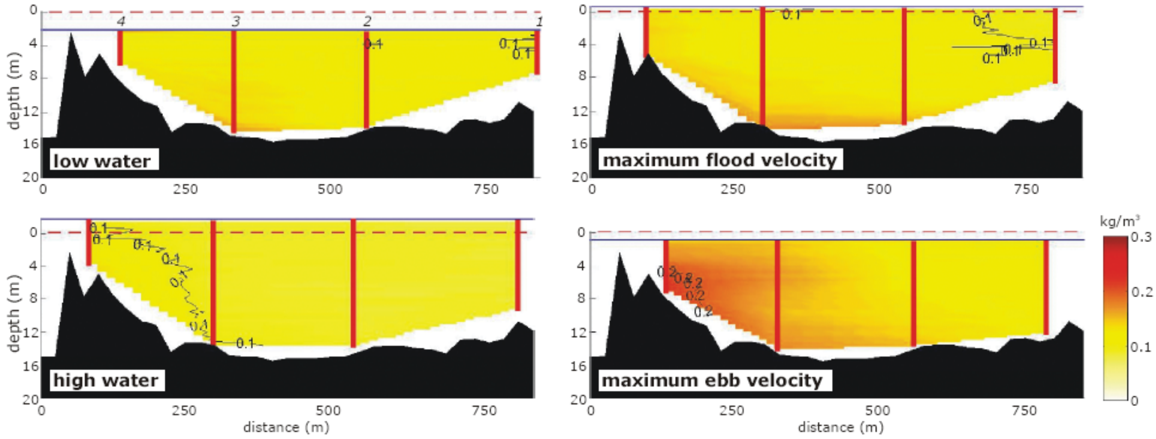
Cross-sectional variations of suspended material concentration and transport were studied by analyzing the distributions of these quantities over the investigated cross-sections. Figs. 12 to 14 show typical examples of the cross-sectional distributions of current velocity and suspended material concentration and transport. Values are shown for cross-sections T1, T2 and T3 surveyed on March 21 to 23, 2000 during a succession of spring tides with an average tidal range of about 4m. Intermediate values of suspended material concentration were determined by interpolating between the observed values at the measuring stations indicated in the figures.

The results reveal that the distributions of suspended material concentration and transport are in general fairly uniform, particularly over cross-section T1. Minimum current velocities as well as suspended material concentrations and transport values are also found to be fairly uniform over the cross-section at slack water. Resuspension of the seabed material is clearly evident during maximum flood and ebb currents, leading to non-uniform variations of these quantities over some parts of cross-sections T2 and T3. Isolated zones of higher suspended material concentrations and transport can be clearly seen in the close proximity of the seabed at maximum current velocities. These increases are more pronounced at cross-section T2 and to some extent also at cross-section T3. Intensive morphological activity is observed in parts of the cross-sections where resuspension takes place (see RICKLEFS and ASP NETO, in this volume). On the other hand, no increase in near-bed sediment concentration is observed where the EHL shows due to the lack of sediment available for entrainment at these locations (see Figs. 2 and 3).

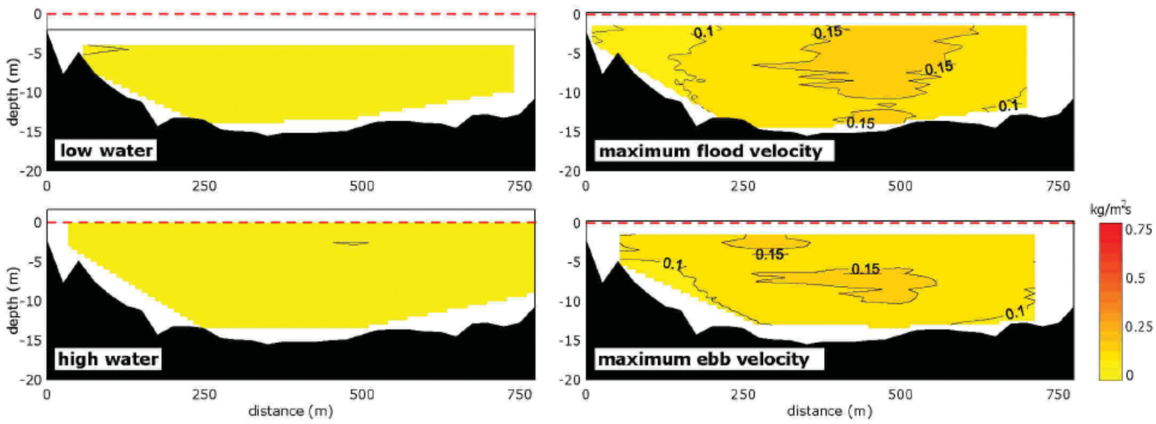
Fig. 15 shows the variation of the estimated distributions of tidally-integrated transport over the width of the cross-sections T1, T2 and T3 (flood and ebb phases). The results were obtained by integrating the cross-sectional suspended material concentrations over time during the flood (onshore) and ebb (offshore) phases of the tide. These computations were based on the data collected during 31, 15 and 24 transects at cross-sections T1, T2 and T3, respectively. Although the distribution at cross-section T1 remains fairly uniform over the entire tidal cycle, regions of higher transport rates can be identified in the other two cross-sections. Under the investigated spring tide conditions the total amount of tidally-integrated suspended material transported during the flood and ebb phases was computed to be about 18,400 and 17,500 metric tons, 84,200 and 89,500 metric tons, and 31,400 and 31,000 metric tons through cross-sections T1, T2 and T3, respectively. Bearing in mind the inaccuracies of measurements as well as interpolation and integration errors, it would appear that the total amount of suspended material transported onshore and offshore during flood and ebb phases, respectively, is fairly well balanced at each of the investigated cross-sections.



a) Current velocity

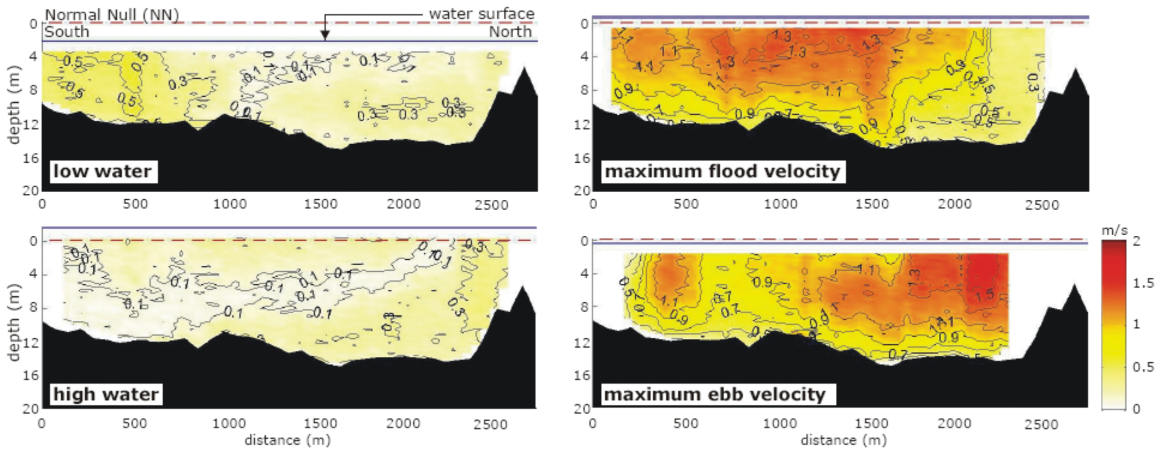


b) Suspended material concentration

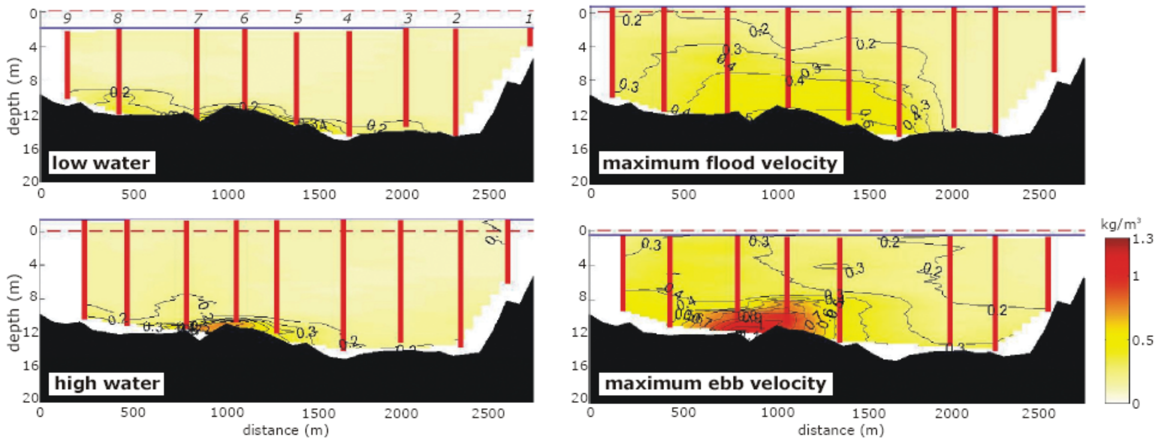


c) Transport of suspended material concentration

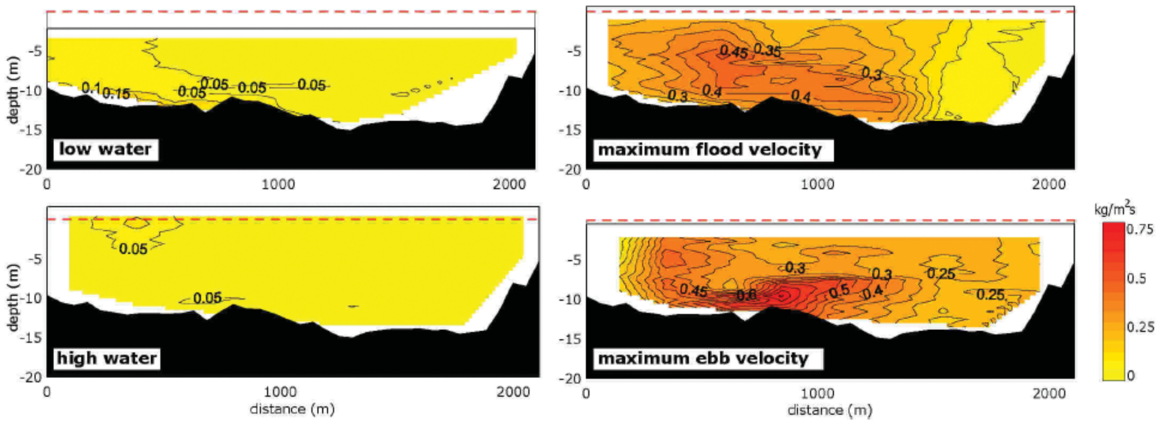
Fig. 12: Variations of current velocity, suspended material concentration and transport in cross-section T1 during a spring tide on March 22, 2000



a) Current velocity

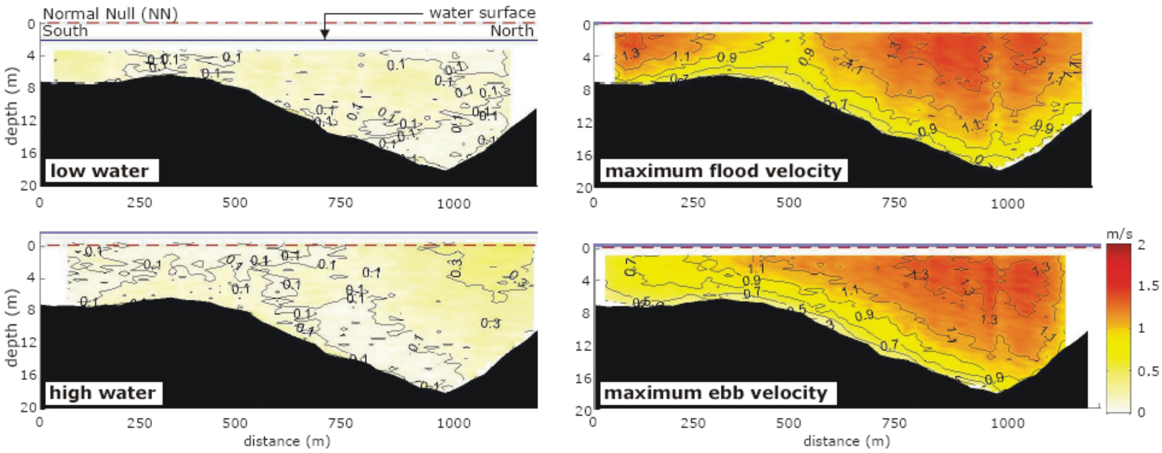


b) Suspended material concentration

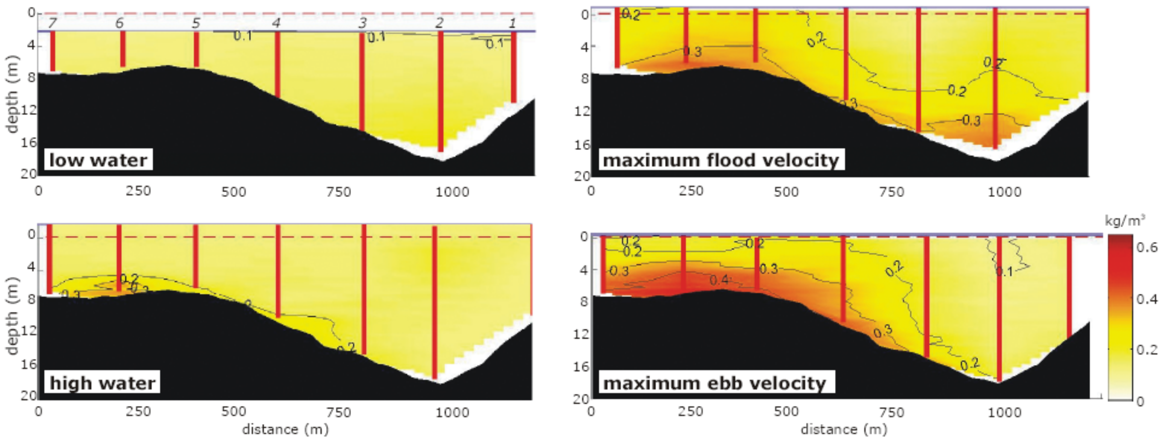


c) Transport of suspended material concentration

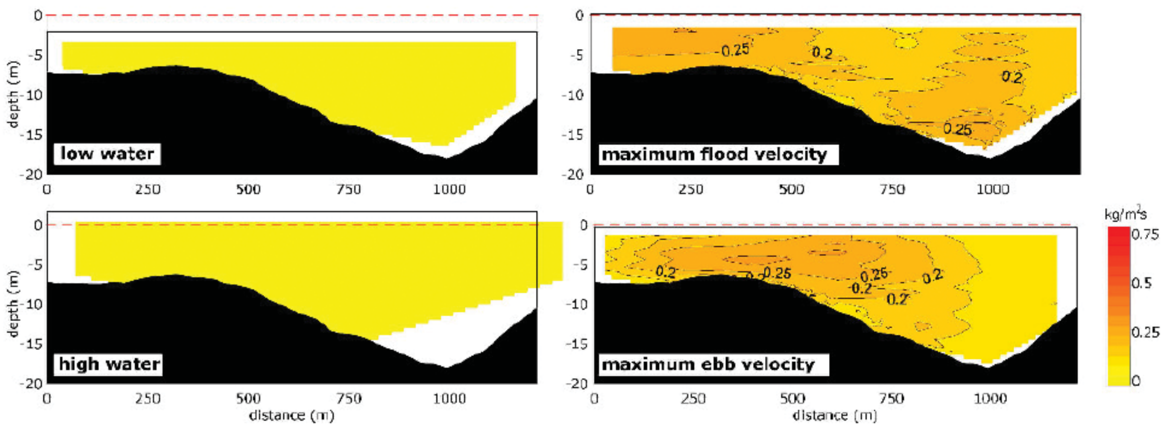
Fig. 13: Cross-sectional variations of current velocity, suspended material concentration and transport in cross-section T2 during a spring tide on March 21, 2000



a) Current velocity



b) Suspended material concentration



c) Transport of suspended material concentration

Fig. 14: Cross-sectional variations of current velocity, suspended material concentration and transport in cross-section T3 during a spring tide on March 23, 2000

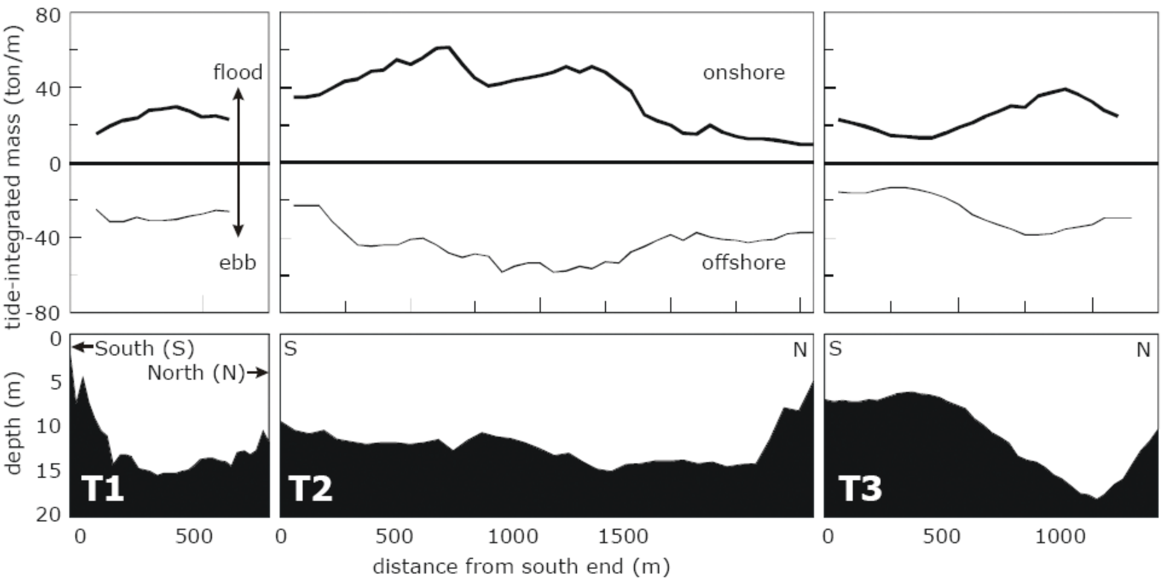
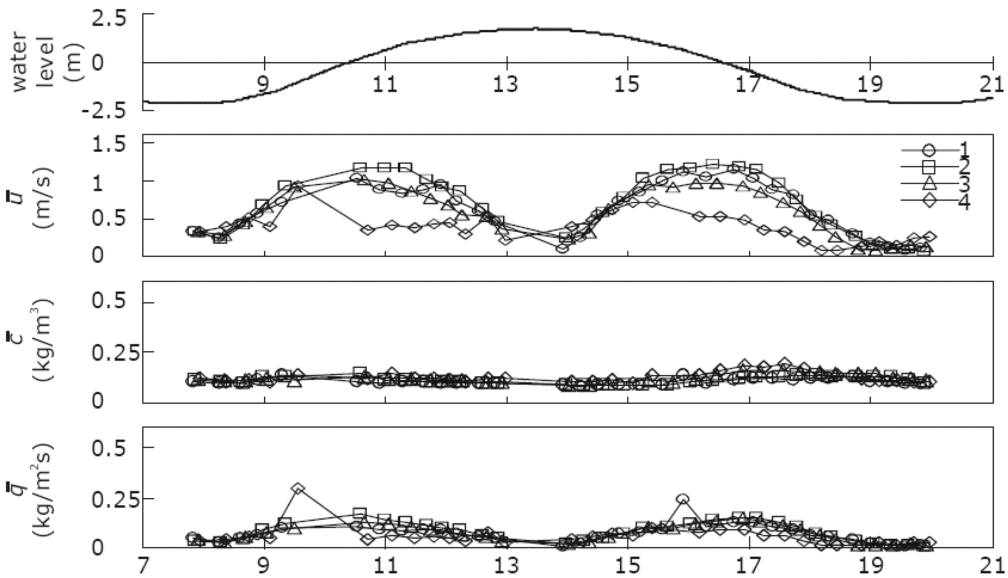


Fig. 15: Accumulation of suspended material transported during one tide based on data collected during a spring tide sequence from March 21 to March 23, 2000

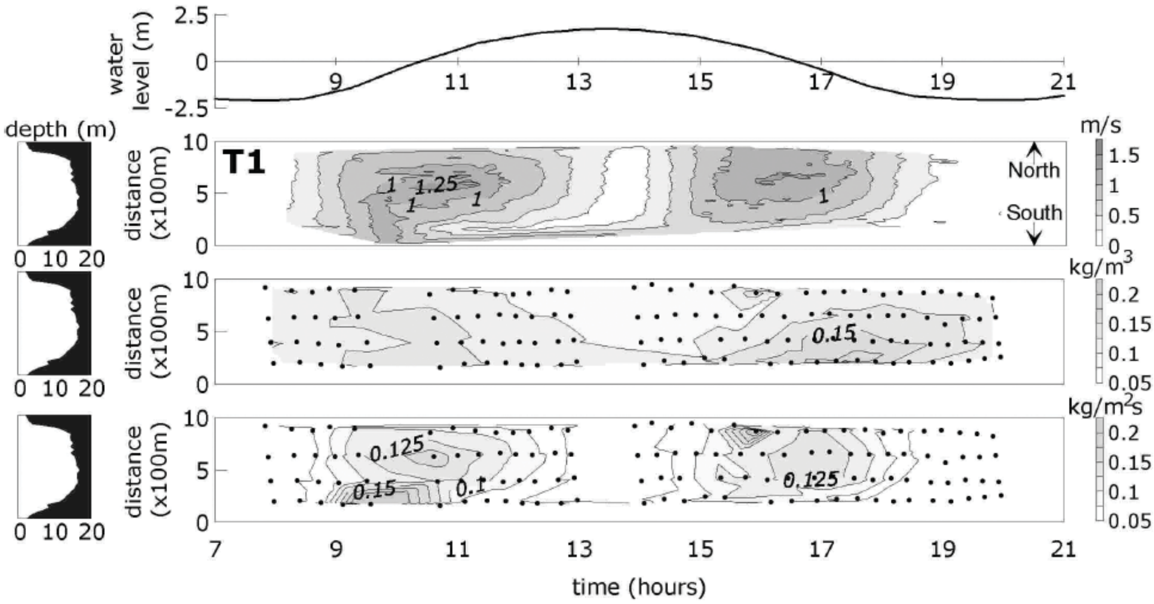
4.6 Variations During a Tide

Figs. 16, 17 and 18 show the variations of depth-averaged current velocity and suspended sediment concentration and transport during a tide at cross-sections T1, T2 and T3, respectively. The values observed at the measuring stations as well as the values determined from interpolations in space and time are shown in the figures. The dots in the figures indicate the positions of the measuring stations between which the interpolations were carried out. Values are shown for a succession of spring tides (tidal range of about 4m) from March 21 to 23, 2000. The results show that for the period in question the suspended material concentrations and transport values increase from a minimum during slack water (at both high and low water) to a maximum during phases of maximum current velocities. A more detailed analysis of local variations at the three cross-sections reveals that suspended material concentrations are generally out of phase with tidal velocities, with maxima occurring towards the end of the flood phase. This fact would indicate that the observed variations are generally governed by advective transport rather than current-induced local resuspension. As already pointed out, resuspension is restricted to just a few locations over short periods in cross-sections T2 and T3.

The variations of flow discharge and suspended material transport through cross-sections T1, T2 and T3 are shown over the entire period from March 21 to 23, 2000, in Fig. 19. It may be seen that the flow discharges and sediment transport rates at cross-section T2 are much higher than at the other two cross-sections (T1 and T3). Compared to the values determined for cross-section T1, the maximum sediment transport through cross-sections T3 and T2 may be as much as 2 and 5 times greater, respectively. Bearing in mind the inaccuracies of the measurements and the errors associated with spatial and temporal interpolations, the flow discharges and suspended material transport values during the ebb and flood phases were found to be fairly similar at each cross-section.

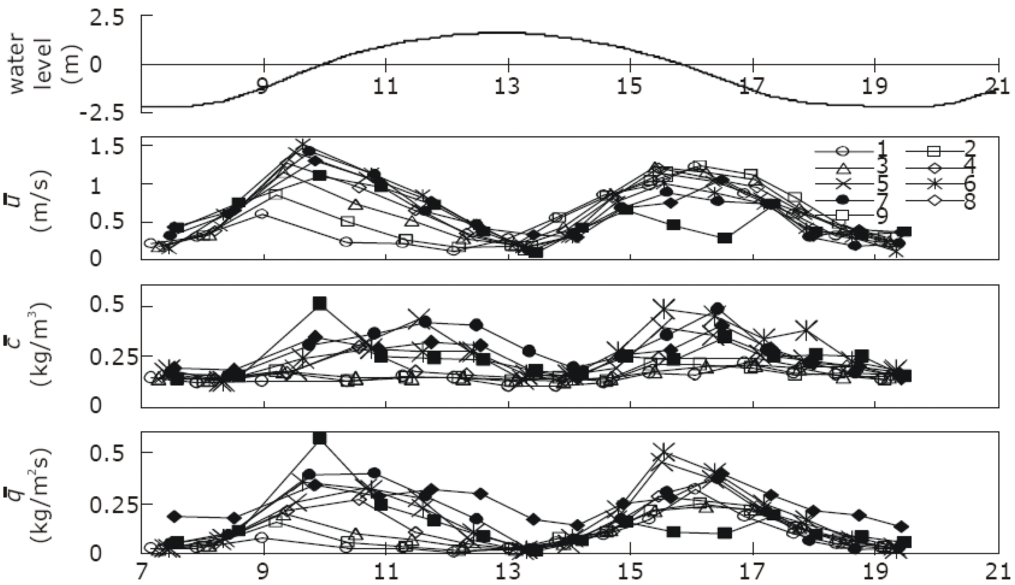


a) Observed values at the measuring stations

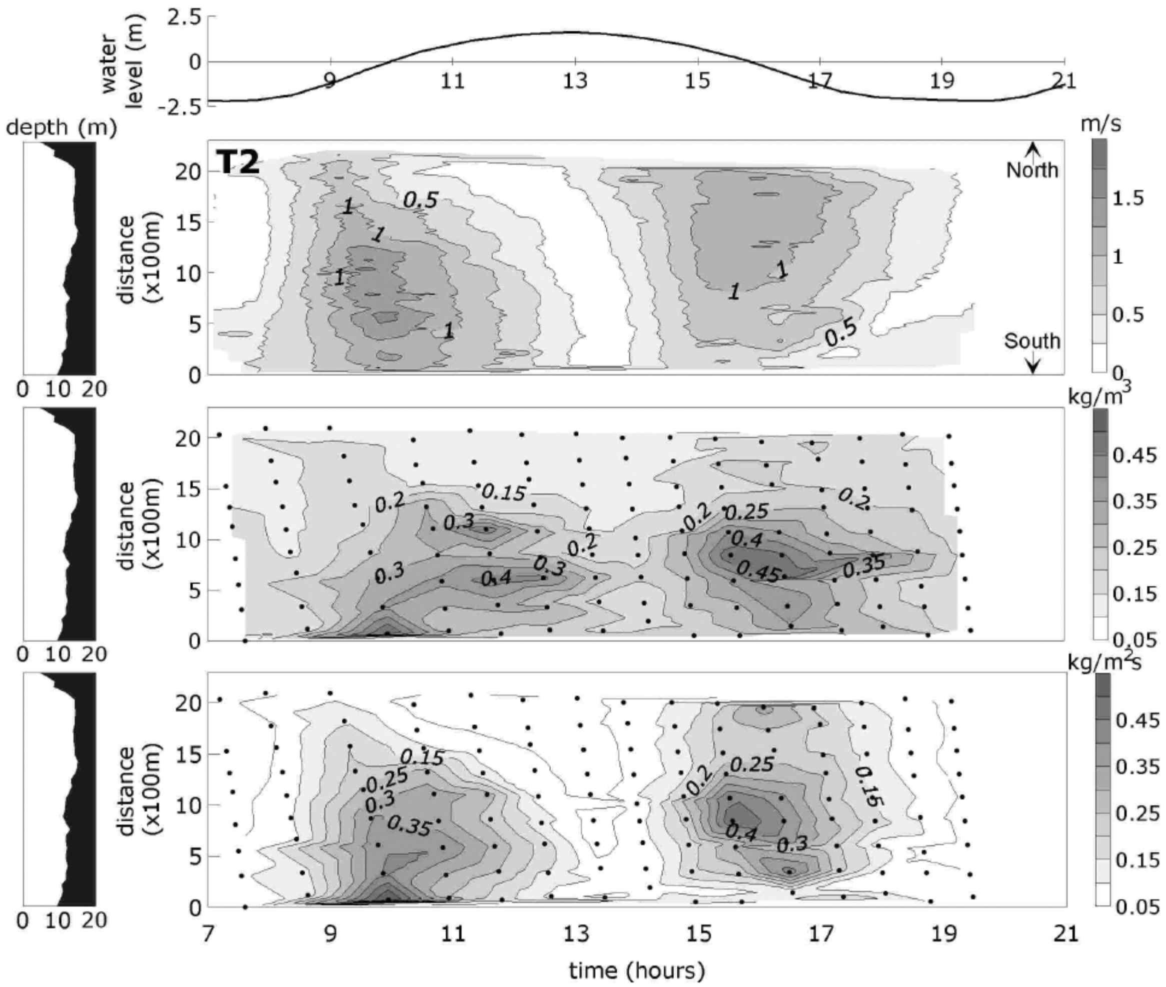


b) Spatial and temporal interpolation

Fig. 16: Variation of depth-averaged current velocity (top), suspended sediment concentration (middle) and transport (bottom) at cross-section T1 during a spring tide on March 22, 2000

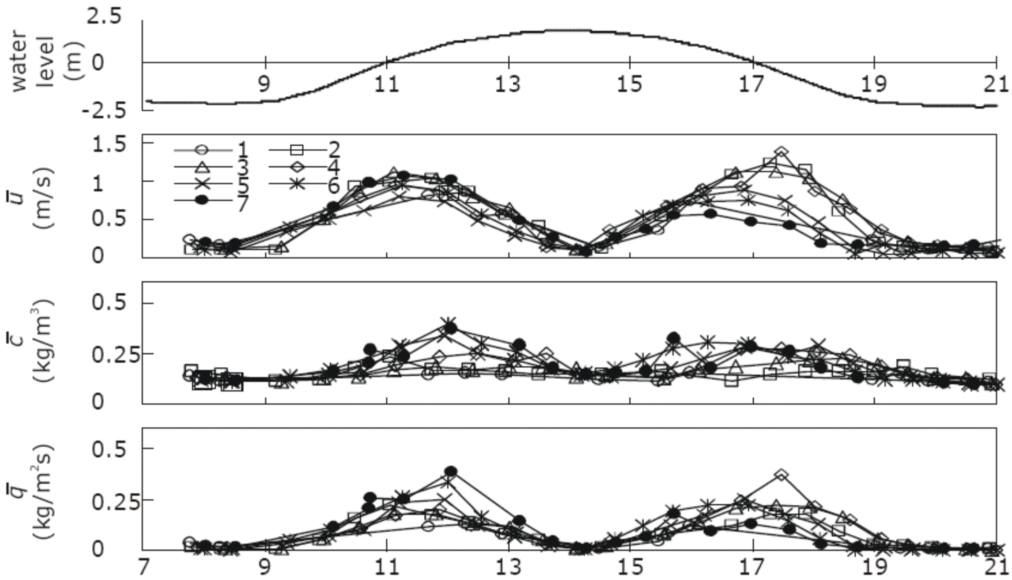


a) Observed values at the measuring stations

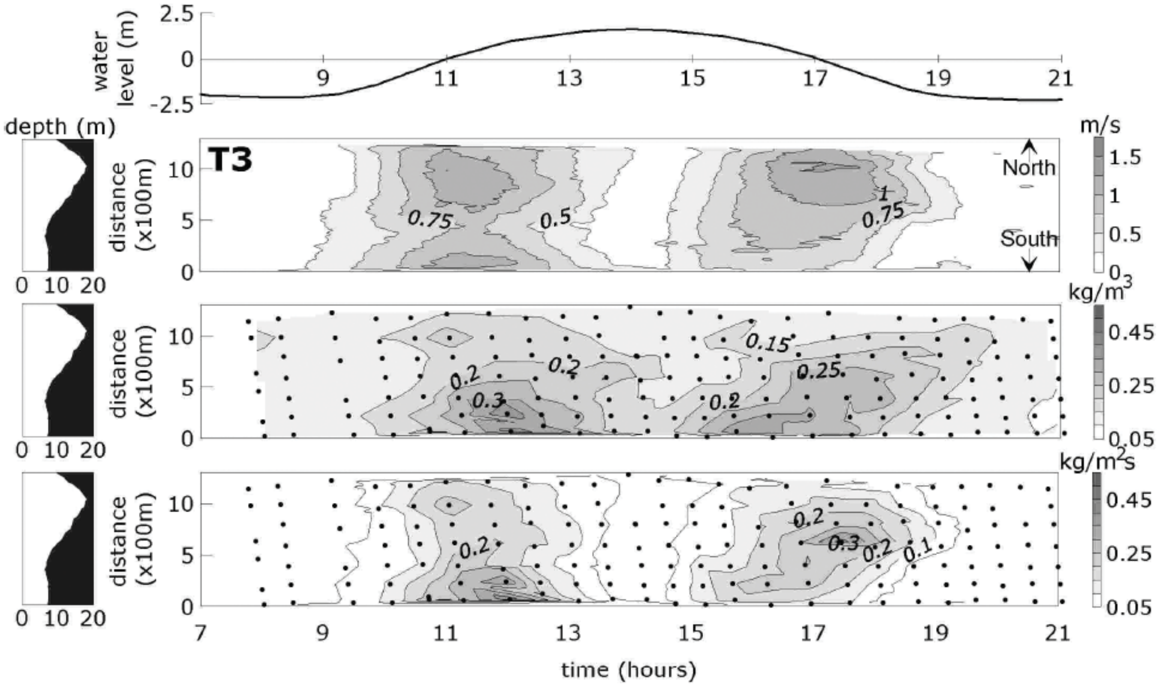


b) Spatial and temporal interpolation

Fig. 17: Variation of depth-averaged current velocity (top), suspended sediment concentration (middle) and transport (bottom) at cross-section T2 over a spring tide on March 21, 2000

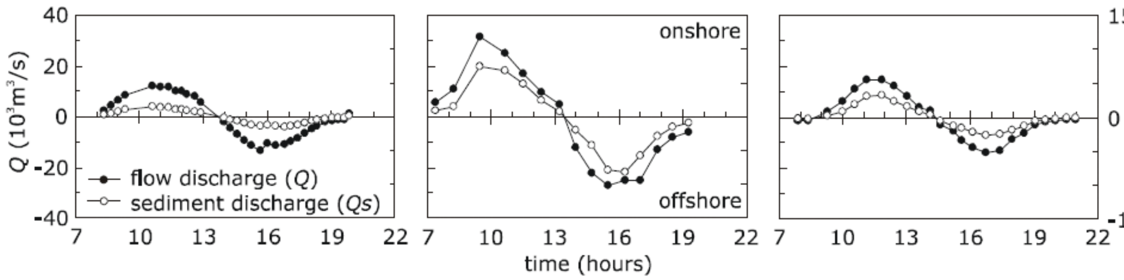


a) Observed values at the measuring stations



b) Spatial and temporal interpolation

Fig. 18: Variation of depth-averaged current velocity (top), suspended sediment concentration (middle) and transport (bottom) at cross-section T3 over a spring tide on March 23, 2000



a) Cross-section T1 b) Cross-section T2 c) Cross-section T3

Fig. 19: Total flow discharges and transport during spring tide from March 21 to 23, 2000

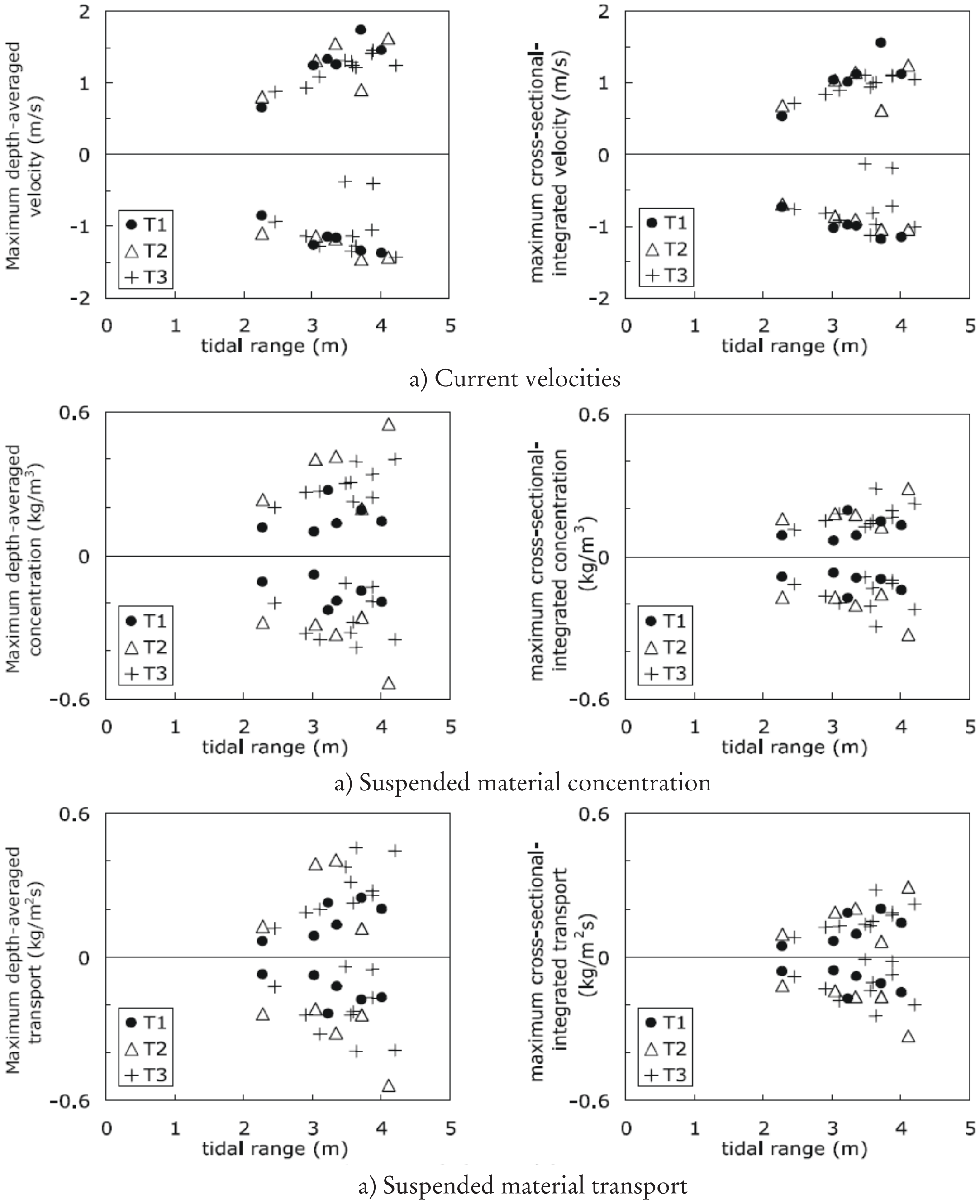


Fig. 20: Dependency of current velocity (top), suspended material concentration (middle) and transport (bottom) on tidal range at cross-sections T1, T2 and T3

4.7 Variations over a Lunar Cycle

An investigation of the variation of suspended material concentration and transport over the lunar cycle was undertaken by comparing the measured values obtained for different tidal ranges. The measurements covered the full range of tidal conditions typical of the study area (Table 2). Fig. 20 shows the dependency of maximum depth and cross-sectionally averaged current velocities, suspended material concentrations and transport on tidal range. The results indicate that the measured current velocities and quantities of transported sediment increase with tidal range. Maximum depth-averaged and cross-sectionally averaged current velocities were found to be similar at each cross-section for a given tidal range. With regard to suspended sediment concentration and transport, an increase with increasing tidal range was more far more pronounced at cross-sections T2 and T3 than at cross-section T1. In contrast to cross-sections T2 and T3, the maximum values of suspended material concentration at cross-section T1 were found to remain approximately constant over the full range of tidal conditions.

4.8 Bed Load versus Suspended Load

The magnitude of the bed load relative to the suspended load was investigated with the aid of numerical model simulations. Details of the sediment transport model are given in WINTER et al. (in this volume). Based on the model results, it is found that the contribution of the bed load to the total amount of transported material is far less significant. This confirms the importance of suspended sediment concentration as the primary mode of material transport in the investigation area. The average contribution of bed load transport to the total load transport amounts to only about 2 %. In the main tidal channels it is found that the suspended load transport contribution is equal to or greater than 99 %, compared to about 96 to 98 % on the tidal flats (POERBANDONO, 2003).

5. Conclusions

The results of extensive field measurements at several cross-sections of a tidally dominated coastal area have provided a valuable insight into the patterns of sediment composition and sediment dynamics. The measuring strategy, involving a combination of side scan sonar, grab sampling, Acoustic Doppler Current Profilers and optical transmissometers deployed from moving vessels, proved to be highly satisfactory for gathering information on the distribution of seabed surface sediments and the spatial and temporal variation of suspended material concentration and transport over a wide area. The investigations focused on the main tidal channels of the central Dithmarschen Bight on the German North Sea coast.

The results show that the spatial distribution of seabed sediments in the tidal channels is quite variable. Areas with essentially sandy sediments and mud as well as areas with consolidated deposits were identified. The sands are mainly very fine to fine with the occasional occurrence of medium sands. Consolidated fine-grained sediments are found at a number of deeper locations in the channels. Most of bed sediment samples were found to be well-sorted. The percentage of fines in the seabed sediment samples is generally higher than 5 %. It was also found that the material transported in suspension is essentially silt. The grain sizes of material in suspension are up to 5 times smaller than those of mobile sediments on the bottom. The transport of sandy material is thus restricted to the near-bed layers.

The distribution of sediment concentration and transport was found to be fairly uniform over the depth as well as over the investigated cross-sections. As a result, most of the sediment is transported in suspension. On the basis of numerical model simulations it was found that the average percentage contribution of bed load transport to the total transport is only about 2 %. Results of the analysis of field measurements showed that a background concentration of suspended material ranging from 0.04 to 0.14 kg/m^3 persist even during slack water. Deposition is prevented by the high levels of turbulence sustained by tidal currents in combination with the small settling velocities of the fine material transported in suspension. As a result, large amounts of fine material are always in motion, thus restricting the entrainment of seabed sediments to short periods of high current velocities during the ebb and flood phases. The characteristics of seabed sediments in the main channels also seem to play a significant role in governing entrainment activity and thus morphological changes. At locations where the EHL is not covered there is no sediment available for entrainment. Moreover, the high percentage of mud found in the seabed sediment delays or prevents the transport of seabed material. An increase in the suspended material concentration in the lower flow layers as a result of resuspension during maximum ebb and flood currents was identified in the southern part of cross-sections T3 and T2 where potentially mobile sediment is present. Intensive morphological activity is observed at such locations.

The maximum depth-averaged suspended material concentration along the main tidal channels was found to be about 0.55 kg/m^3. It was also found that about 80 % of all material entering and leaving the system are via the main tidal channel located in the southwest. Bearing in mind the inaccuracies in the measurements, it was not possible to identify any clear patterns regarding ebb or flood domination in the channels. At each of the investigated cross-sections a balance could be identified between the total amount of suspended material transported onshore and offshore during the flood and ebb phases, respectively. With regard to the magnitude of sediment concentrations and transport, a clear dependency on the tidal range was evident; sediment concentrations and transport were found to increase with increasing tidal range. It is estimated that approximately 35,000 and 105,000 metric tons of suspended material are transported through the two main tidal channels at the entrance to the study area during neap and spring tide, respectively.

The extensive field measurements provide an ideal data set for clarifying various aspects of the modelling strategy as well as for testing the performance of the numerical model. The measurements also provide reliable input data regarding particle sizes and sorting of the material transported near the bed and in suspension. Moreover, the composition of the seabed can have a significant effect on the dimensions of bed forms and hence bed-form roughness. Differences in the grain sizes of material transported in suspension and near the seabed should also be taken into consideration. The fairly uniform sediment concentration profile observed during most of the tidal period favours the use of two-dimensional depth-averaged formulations. The existence of the EHL has consequences for the modeling of medium-scale morphodynamics since it constrains morphological developments to lateral displacements. To provide adequate descriptions of the suspended sediment concentration the boundary condition near the seabed required for solving the convection-diffusion equation should account for the rigid and loose characteristics of the seabed. Similarly the EHL should also be accounted for in the solution of the depth-integrated mass-balance equation for the bed level changes constraining the morphological development to lateral displacements. Moreover, the spatial and temporal variations derived from the measurements serve as valuable criteria for testing the performance of the numerical model. The measurements along the two main inlets are particularly helpful for testing and improving the treatment of the open-sea boundary conditions in transport simulations. An advantage offered by the large amount of collected information is the ability to split the data into separate sets for the purpose of model calibration and validation. The cross-sectional measurements performed in deeper water (see Fig. 1) also provide valuable supplementary information regarding conditions along the open sea boundaries.

6. Acknowledgements

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