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Dimension and Roughness Distribution of Bed Forms in Tidal Channels in the German Bight

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Summary

The results of investigations of the spatial and temporal variations of the dimensions of bed-form features and associated bed roughness are presented in this paper. The study was carried out in the main tidal channels of the central Dithmarschen Bight on the German North Sea coast. Measurements of the dimensions of bed forms were carried out at several locations using side scan sonar and echo sounders. Current velocities were also measured using acoustic profilers in the near-bed region. The spatial variation of the dimensions of bed-form features was found to be quite significant and highly dependent on the layer thickness of potentially mobile sediments, the characteristics of surficial seabed sediments and local flow conditions. The temporal variation of bed-form dimensions during a tidal cycle was found to be appreciable, especially with regard to length. A verification of existing empirical equations proposed for predicting bed-form dimensions showed poor agreement with observed values. Fair agreement was obtained, however, with regard to bed-form roughness values. A numerical procedure for predicting bed-form dimensions and associated bed roughness values is suggested. The identification of bed-form types and the estimation of bed-form dimensions and equivalent roughness sizes were obtained using the results of flow model simulations. Maps of bed-form dimensions and roughness in the tidal channels were derived from the latter. The importance of bed roughness is highlighted in relation to simulated current velocities and suspended sediment concentrations. The results clearly indicate the relevance of bed roughness, particularly with regard to sediment transport predictions. It was found that the accuracy of simulated sediment transport rates is highly dependent on the formulation used to predict the bed roughness. Different bed roughness sizes were found to influence both the magnitude and phase of suspended material concentrations.

Zusammenfassung

In diesem Beitrag sind die Ergebnisse räumlicher und zeitlicher Variationen der Dimensionen von Bodenformen am Seegrund und der damit in Zusammenhang stehenden Rauigkeit zusammengefasst. Die Untersuchungen erfolgten in den Hauptgezeitenströmen der Zentralen Dithmarscher Bucht an der Deutschen Nordseeküste. Die Messungen zur Dimensionierung von Bodenformen wurden an mehreren Lokalitäten unter Anwendung von Seitensicht-Sonar und Echolot durchgeführt. Auch Messungen der Strömungsgeschwindigkeiten erfolgten mit Akustik-Profilern nahe der Seegrundoberfläche. Die räumliche Variation der Dimensionen der Bodenform-Ausprägungen waren signifikant und hochgradig abhängig von der Schichtdicke potentiell mobiler Sande, den Charakteristiken oberflächennaher Sedimente und den örtlichen Strömungsbedingungen. Die zeitlichen Variationen der Bodenform Dimensionen im Verlauf eines Tidezyklus waren in Bezug auf deren Längen beträchtlich. Die Ergebnisse der Verifizierungen bestehender empirischer Gleichungen, die zur Vorhersage von Bodenform-Dimensionen und -Rauigkeiten vorgeschlagen sind, zeigten nur geringe Übereinstimmungen mit den beobachteten Werten. Eine mäßige Übereinstimmung wurde jedoch zu den Bodenform-Rauigkeiten erzielt. Es wird eine Prozedur zur Vorhersage von Bodenform-Dimensionen und damit in Zusammenhang stehenden Bodenrauigkeitswerten vorgeschlagen. Die Identifikation von Bodenform-Typen und die Abschätzung der Bodenform-Dimensionen und äquivalenten Rauigkeitsgrößen wurden aus den Ergebnissen von Strömungsmodell-Simulationen erzielt. Aus diesen wurden Karten von Bodenform-Dimensionen und -Rauigkeiten in den Gezeitenrinnen abgeleitet. Die Bedeutung *der Bodenrauigkeit wird in ihrer Beziehung zur simulierten Strömungsgeschwindigkeit und den Konzentrationen suspendierten Sediments beleuchtet. Die Ergebnisse weisen deutlich auf die Relevanz der Rauigkeit insbesondere in Bezug auf Vorhersagen des Sediment Transports hin. Die Genauigkeit der simulierten Sediment-Transportraten erwiesen sich als hochgradig abhängig von den Formulierungen, die zur Vorhersage des Bodenrauigkeit verwendet wurden. Es ergab sich ferner, dass unterschiedliche Bodenrauigkeiten sowohl Größe als auch die Phase der suspendierten Sedimentkonzentrationen beeinflussen.*

Keywords

Bed Forms, Bed Roughness, Spatial Bed-Form Distribution, Temporal Bed-Form Variation, Field Measurements, Modelling, Dithmarschen Bight, Tidal Flats, Tidal Channels, North Sea, DELFT3D, SWAN, PROMORPH

Contents

1. Introduction

The seabed exhibits a variety of morphological patterns as a result of sediment motion due to current and/or wave action. These features, known as bed forms, interact with the flow by introducing resistance. The fact that information on bed-form dimensions and roughness sizes in the field is normally not available continues to represent one of the greatest obstacles to the accurate prediction of sediment transport rates. The bed roughness, which is difficult to measure or estimate in engineering practice, is a sensitive parameter in the computation of current velocities and sediment transport rates. Investigations carried out by VAN RIJN et al. (2001) and WINTER and MAYERLE (2003) have shown that relatively small changes in the prescribed bed roughness can have a major effect on sediment transport rates. A proper understanding and estimation of the variation of bed-form dimensions and associated roughness sizes is thus essential for satisfactory predictions of flow and sediment transport rates.

The type and dimensions of bed-form features depend primarily on the magnitude and nature of the flow, wave-induced motion, geological features and sediment characteristics. In the case of movable beds consisting of non-cohesive sediments the effective bed roughness is mainly comprised of grain roughness due to skin friction and form roughness generated by pressure forces acting on the bed forms. Although various equations for estimating bed-form dimensions and roughness sizes have been proposed, most of these rely on experiments carried out in the laboratory. Due to a lack of field measurements very little information is available on the effectiveness of the equations under field conditions, particularly in tidal channels. The flow conditions in tidal channels are subject to continuous change and the behaviour of bed forms under the action of shear stress is not clearly understood.

This paper presents the results of field investigations of the spatial and temporal variation of the dimensions of bed-form features and associated bed roughness. The investigations were carried out in the main tidal channels of the central Dithmarschen Bight on the German North Sea coast. Measurements of bed-form lengths were made in the main tidal channels. Simultaneous measurements of bed-form dimensions and current velocities were also carried out at one location in each of the tidal channels in order to obtain information on the temporal variation of bed-form dimensions and associated roughness values. Equivalent roughness values were estimated from a best-fit line of measured velocity profiles in the bottom boundary layer. The characteristics of the surficial seabed sediments as well as the geological features of the channels were also taken into consideration in the analysis. The dimensions of bed forms and equivalent roughness values were used to verify existing empirical equations for predicting bed-form dimensions and form roughness, most of which are based on laboratory experiments. A numerical procedure is also outlined for predicting bed-form dimensions and roughness values in the tidal channels of the study area based on a two-dimensional depth-integrated (2DH) flow model implementing existing empirical equations. The relative effects of seabed geological features, bed-form dimensions and roughness, and varying roughness sizes on flow velocities and sediment transport are also demonstrated by way of numerical simulations.

2. Description of the Investigated Coastal Area

Investigations were carried out in a tidal flat area on the German North Sea coast. The area is located between the Eider and Elbe estuaries. The morphology of the study area is dominated by tidal flats, tidal channels and sandbanks over the outer region. This study focuses on flow and morphological conditions along the intertidal channels, i.e. the Norderpiep located in the northwest part of the domain and the Suederpiep in the southwest. These two channels converge within the study area to form the Piep tidal channel (Fig. 1). Maximum water depths in the channels are of the order of 23 m, and approximately 50 % of the study area is intertidal. The hydrodynamics and sediment dynamics of the study area are driven by the combined effects of tides, waves and wind-induced currents. Under average conditions the tidal influence is predominant. The semi-diurnal tide has a mean range of 3.2 m, varying between 2.4 m at neap tides and 4.2 m at spring tides. Westerly winds (SW-W) prevail in the study area. Wave heights in the outer region may attain 3.5 m, with wave-breaking occurring along the outer margins of the area of interest. Maximum current velocities in the tidal channels are of the order of 2 m/s. The temporal and spatial variations of the currents are strongly influenced by the complex bathymetry. Storm surges can result in water level set-ups of up to 5 m, favouring wave propagation into normally shallow regions. The surficial seabed sediment in the tidal channels and on the tidal flats consists mainly of sands with varying proportions of silt and clay. The grain sizes of material in suspension are up to 5 times smaller than those of mobile sediments on the sea bed (POERBANDONO and MAYERLE, in this volume).

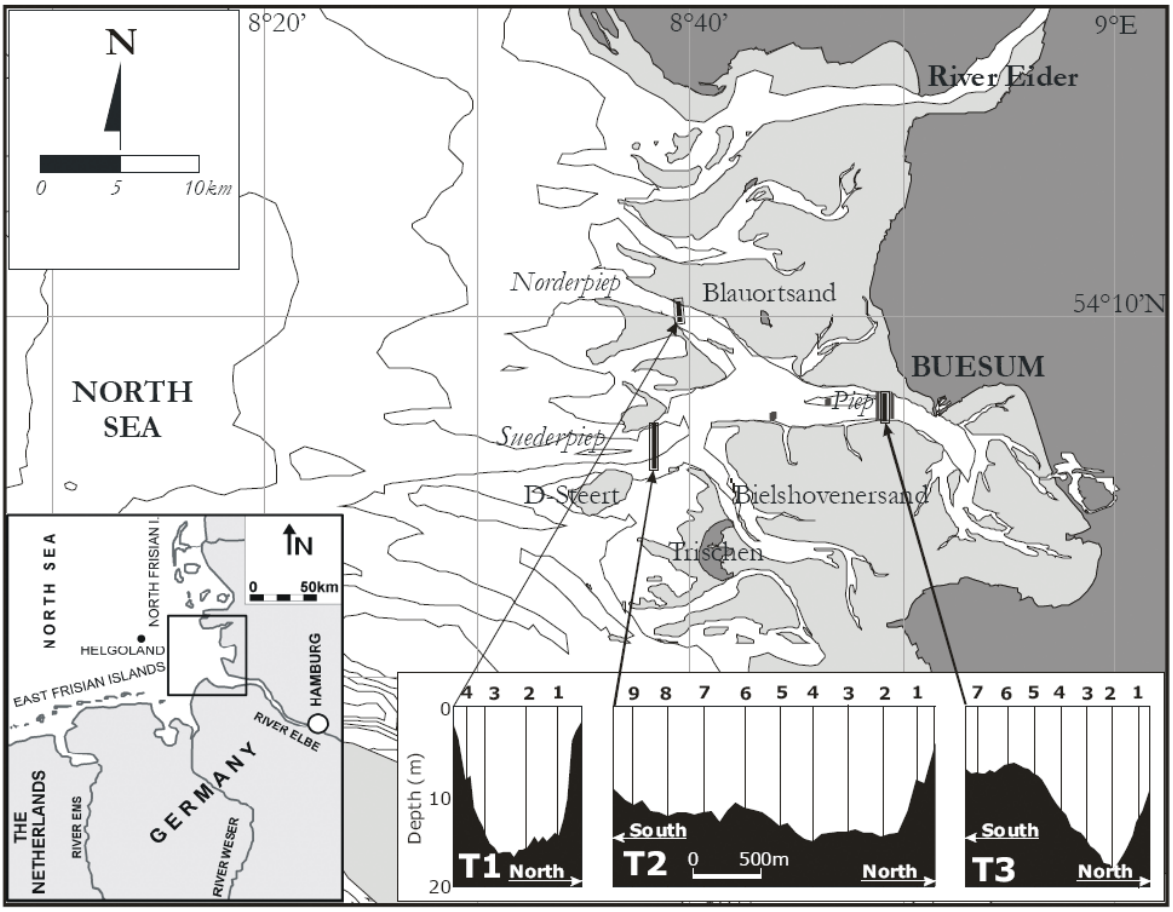

Fig. 1: Investigation area

3. Recent Sediment Deposits and Surficial Seabed Sediments

The composition of the sediment deposits in the study area largely corresponds with recent tidal flat sediments. As shown in Fig. 2, the layer thickness of the intertidal sediment deposits in the study area is about 20 m (ASP NETO et al., 2001; ASP NETO, 2004). The early Holocene layer (EHL) consists of consolidated cohesive sediments and forms a type of natural base that hinders erosion in the tidal channels. In the central parts of the channels, where shear stresses are high, entire removal of the non-cohesive deposits has resulted in exposure of the EHL. The thickness of the potentially mobile sediment layer increases towards the northern and southern banks of the main tidal channels.

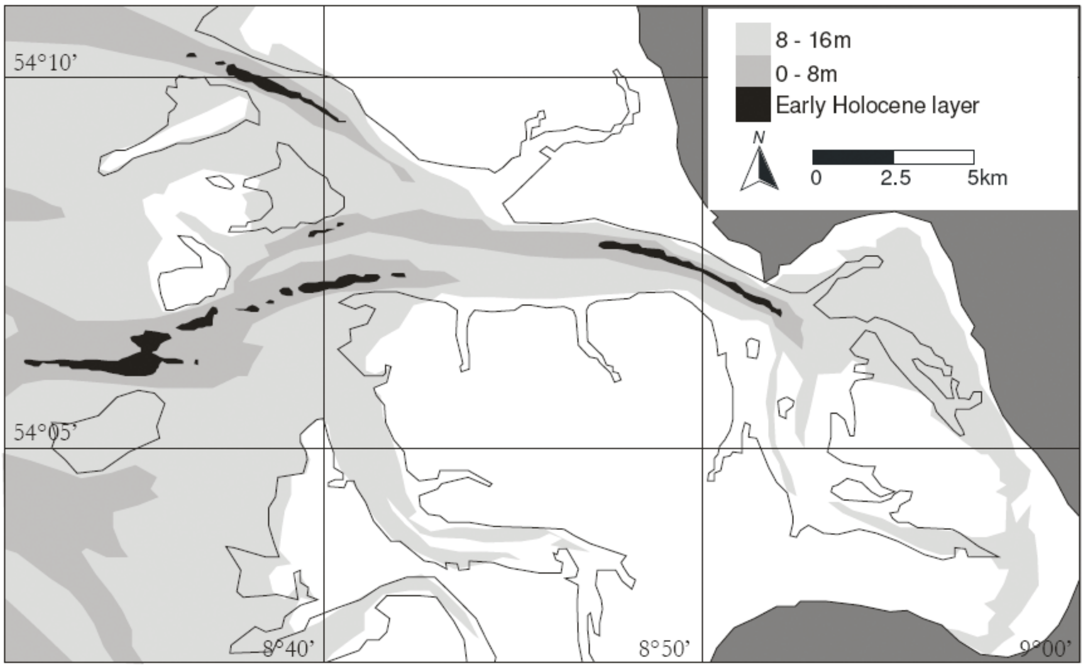

Fig. 2: Thickness of the potentially mobile sediment layer above the EHL (modified after ASP, 2004)

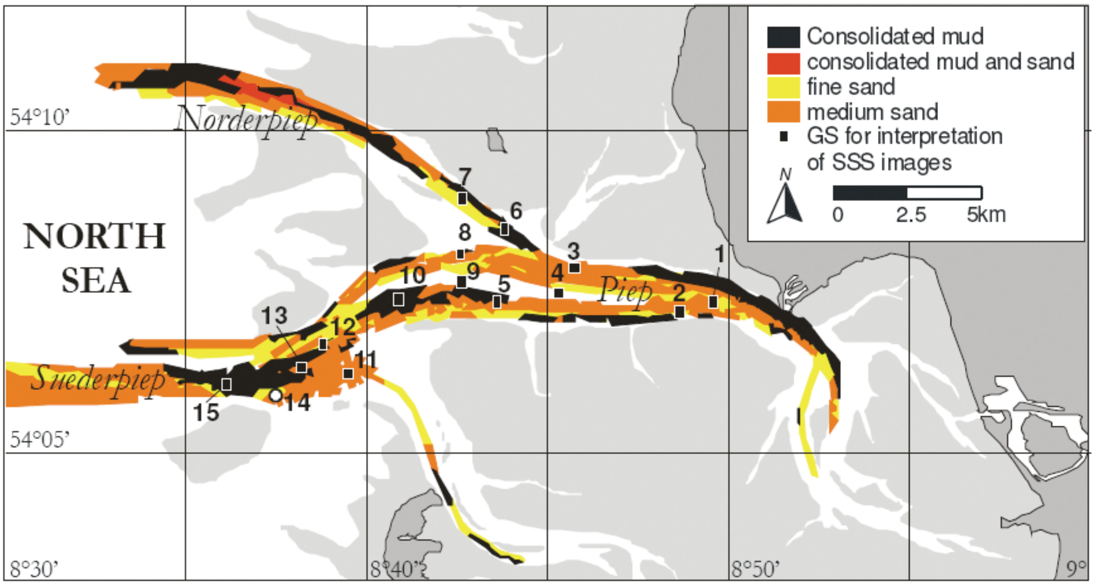

Fig. 3: Surficial seabed sediment distribution in the main tidal channels
(modified after VELA-DIEZ, 2001)

Fig. 3 shows sediment types in the tidal channels derived from side-scan sonar images (SSS) calibrated with grab samples (VELA-DIEZ, 2001). The spatial distribution of the surficial seabed sediments is quite variable. Areas were identified with essentially sandy sediments and mud, and often with consolidated deposits. The sands are mainly very fine to fine with some isolated patches of medium sands. The d_{50} of the surficial seabed sediments of the grab samples taken for interpretation of the SSS images varies between 80 µm and 230 µm, corresponding to very fine to fine sands. The majority of these sands was found to be well-sorted.

Consolidated fine sediments are found at a number of deeper locations in the tidal channels. An analysis of the mud content (% of fines) in the less-exposed tidal channels confirmed the presence of mud in all grab samples. A sediment analysis indicated that the silt and clay content of the sediment samples is generally greater than 5 %, attaining maximum values of 75 %–80 %. Moreover, values exceeding 10 % were found in about 50 % of all samples (POERBANDONO and MAYERLE, in this volume).

4. Spatial Variation of the Dimensions of Bed Forms

Spatial variations of the lengths and heights of bed forms in the tidal channels were derived from SSS images and echo soundings, respectively. Fig. 4 shows the scope of the measurements in the main tidal channels covering an area of about 30 km². Details of these measurements are given in VELA-DIEZ (2001) and POERBANDONO and MAYERLE (in this volume). Fig. 5 shows typical SSS images obtained at several locations in the tidal channels at different stages of the tidal cycle. In order to obtain adequate information on the lengths of the bed forms the SSS images were arranged rectilinearly to avoid distortions in the along-track and across-track directions.

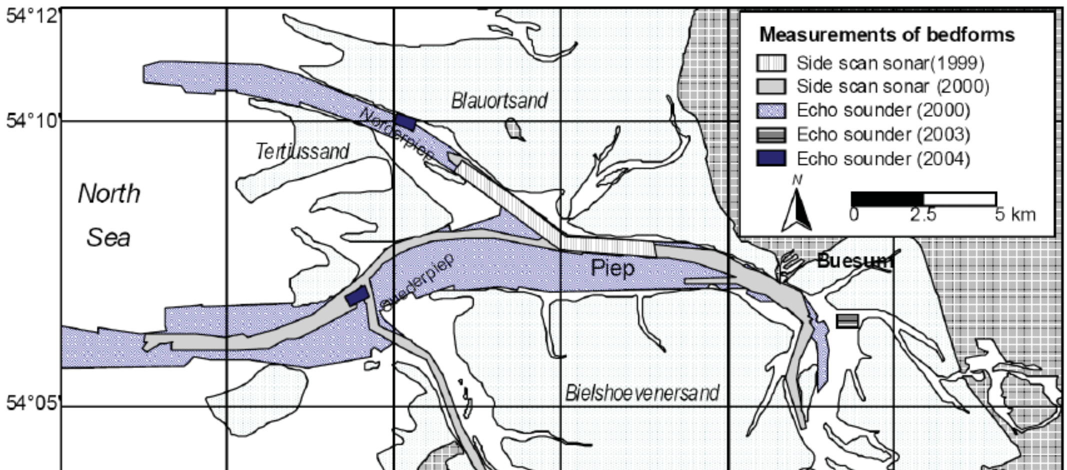

Fig. 4: Coverage of field measurements of bed forms in the tidal channels

Fig. 6 shows the bed-form types and lengths obtained from SSS surveys. It is noted that although the measurements achieved full spatial coverage, the hydroacoustic detection of bed-form features, particularly smaller ripples, was not always clear. Moreover, the fact that the measurements were carried out during different tidal cycles and phases explains the variations in the dimensions of bed-form lengths at the same locations. Mainly megaripples and dunes were detected during the surveys. These surveys revealed that bed forms develop primarily in the most exposed areas of the Suederpiep, at the intersection of the Suederpiep and the Bielshoevener Loch, and along the sides of the channels, especially in the Norderpiep and Piep. Megaripples with lengths varying from about 3 m to 22 m were mainly observed. The average bed-form lengths varied between 7 m and 10 m in the Suederpiep and Piep tidal channels and between about 3 m and 6 m along the Norderpiep channel. The largest bed forms were observed at the intersection of the Suederpiep tidal channel and the Bielshoevener Loch. Sand dunes with lengths of up to 22 m were recorded. Measurements of bed-form heights using echo sounders, which were limited to only a few locations (see Fig. 4), gave values of up to about 0.7 m. In general, the crests of sand dunes and ripples, which are not very steep, are perpendicular to the flow direction, i.e. parallel to the sonar track (Fig. 5).

Fig. 7 shows regions in the tidal channels with potentially mobile sediment deposits and locations where bed forms were observed. As may be seen in the figure, these regions overlap. The majority of the bed forms were observed at locations with mobile sediment deposits characterized by relatively low percentages of mud content. The mud content of sediments may significantly increase the critical shear stress above that required for non-cohesive sediments. Bed forms were not detected in the deeper parts of the tidal channels due to the exposed EHL.

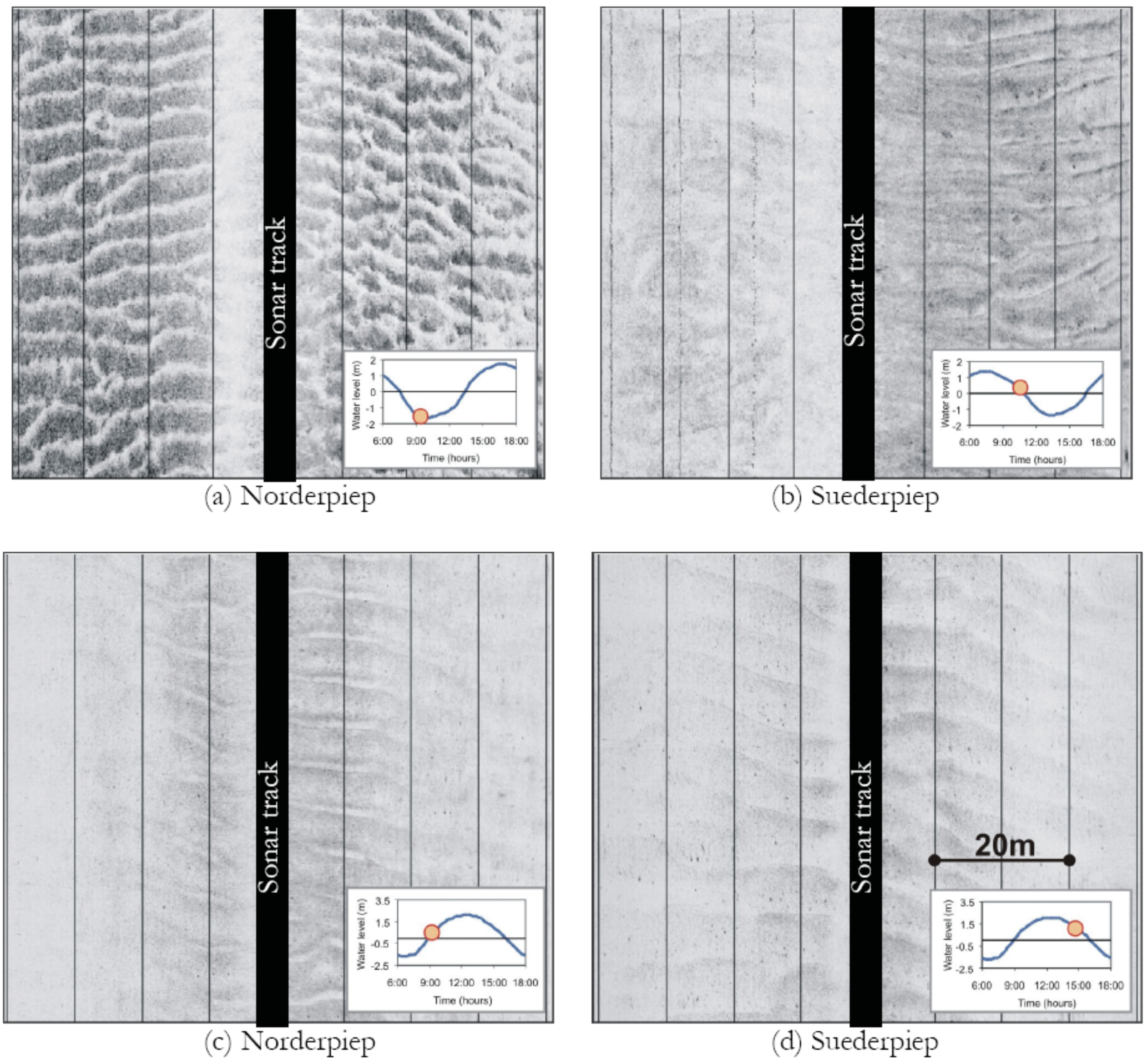

Fig. 5: Typical SSS images

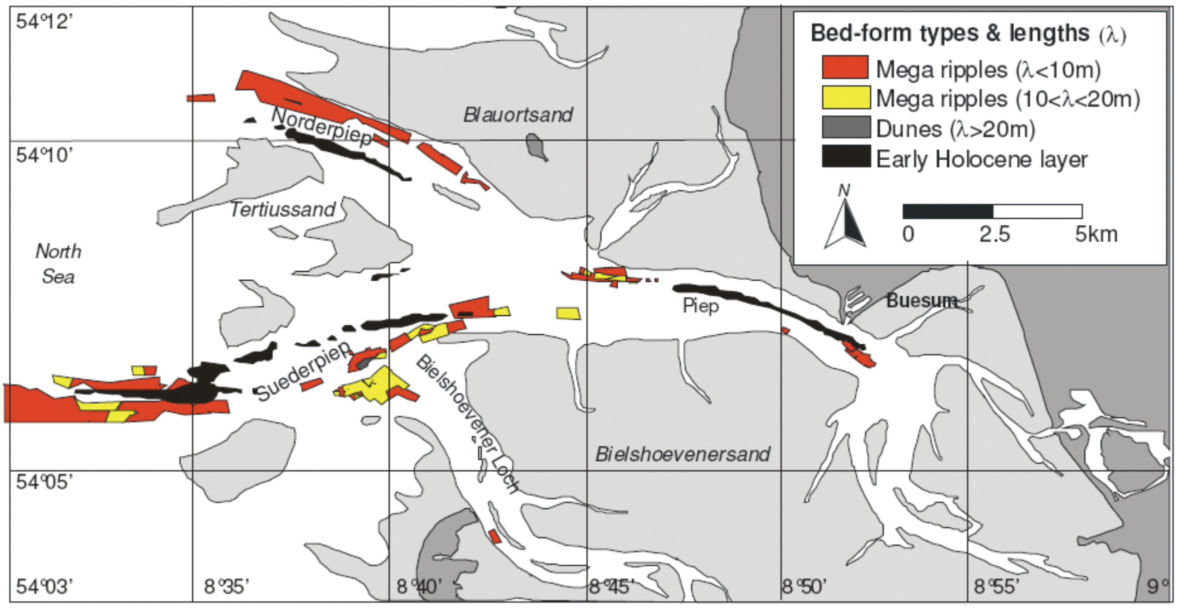

Fig. 6: Spatial variation of bed forms (MAYERLE et al., 2002)

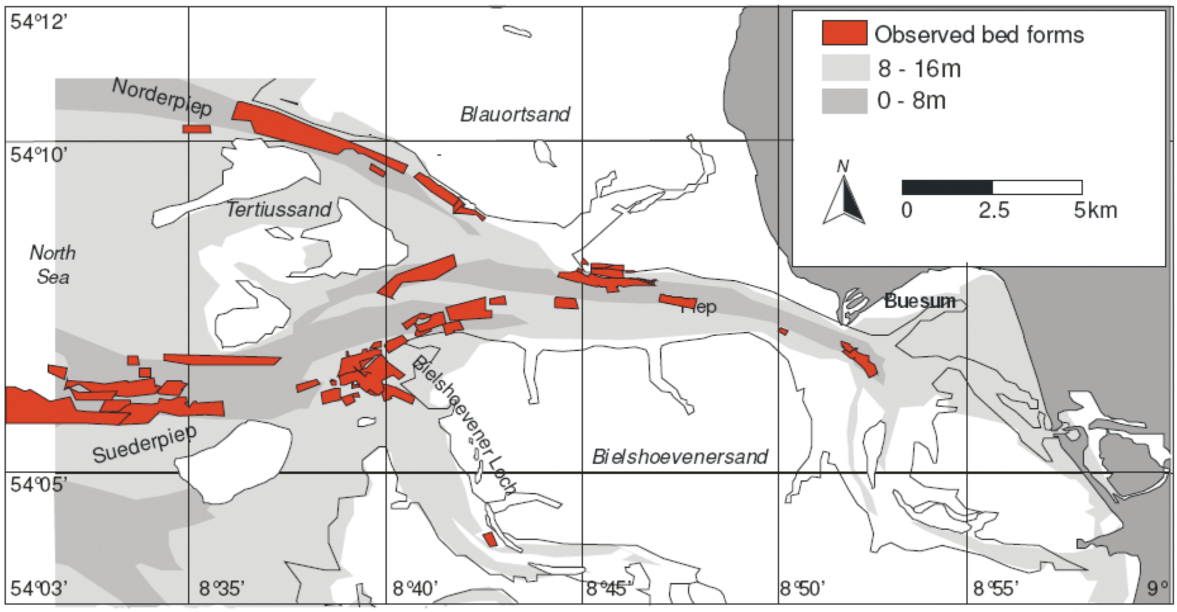

Fig. 7: Regions where bed forms were observed, also indicating the thickness of the potentially mobile sediment layer above the EHL

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5. Temporal Variation of the Dimensions of Bed Forms

In order to study the temporal variation of bed-form heights (Δ) and lengths (λ), measurements of bed-form dimensions were carried out using an echo sounder in conjunction with measurements of current velocity profiles by means of an acoustic profiler. The location of measurements in the inner Piep tidal channel is shown in Fig. 4 (see echo sounder measurements made in 2003). Altogether, 32 profiles of 200 m in length were surveyed from a moving vessel at regular time intervals on a track perpendicular to the crest of the sand dunes. The measurements were made using an echo sounder operating at a frequency of 200 kHz. The seabed at this location consists of very fine and loosely deposited sandy sediments with a mean particle size of about 100 µm. Measurements were carried out over 9 hours during the tidal period of a spring tide with a tidal range of 3.9 m. The water depths during measurements varied between 2.5 m and 6.4 m.

Calm weather conditions prevailed during the survey, which commenced at low water slack and covered the entire flood phase and part of the ebb phase. The maximum depth-integrated velocities during the flood and ebb phases were about 0.8 m/s and 0.5 m/s, respectively. Typical measured bed profiles with exaggeration of the vertical scale are shown in Fig. 8. Bed forms were detected during the entire observation period. The small steepness of the bed features and smoothness of the seabed profile are clearly evident in Fig. 9, which shows a typical bed form without scale distortion.

Fig. 10 shows the temporal variation of a bed-form height (upper figure) and length (lower figure) with varying water depth and depth-averaged current velocity. The mean values of the heights and lengths of bed forms were determined by averaging the measured values along each 200 m transect. The differences in bed-form dimensions observed during the same back-and-forth survey are due to the different paths followed by the survey vessel. The mean bed-form heights ranged between 0.22 m and 0.36 m, with standard deviations ranging between 0.05 m and 0.11 m. Despite the difficulty of following the same path in the back and forth directions, no significant temporal variation of the mean bed-form heights was detected during the observation period. VAN RIJN (1993) reported an increase in the bed-form heights with increasing bed shear stresses for unidirectional flow conditions in rivers and flumes. Although a similar behaviour was not observed in the present study, care should be taken in the interpretation of the results, bearing in mind the relatively small heights of the observed bed-form features and the averaging procedure adopted for estimating their dimensions.

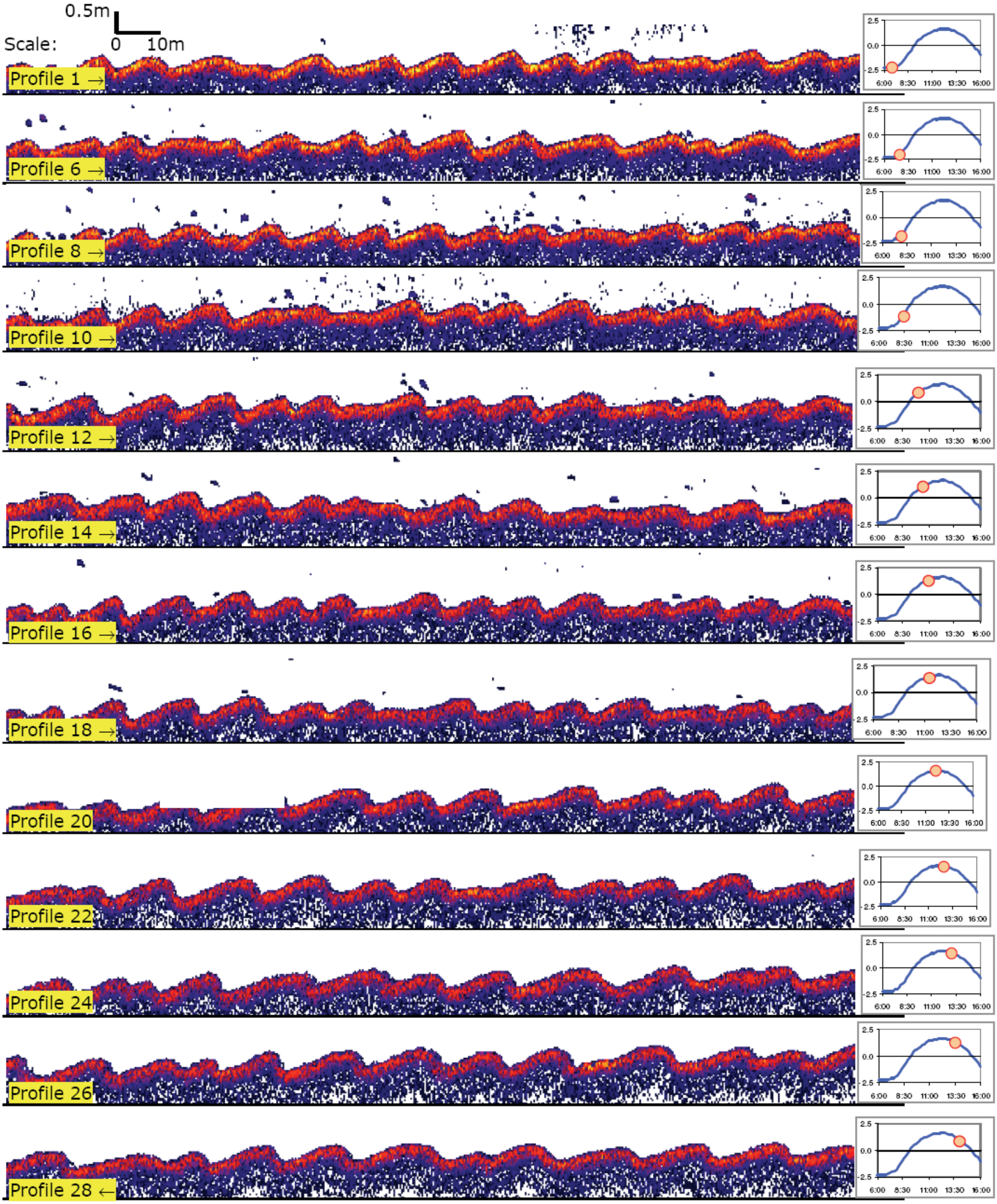


Fig. 8: Measured bed profiles with exaggeration of the vertical scale in the inner Piep tidal channel

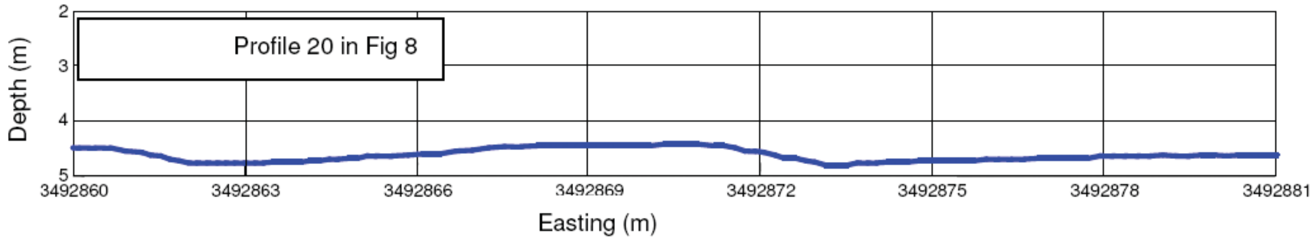


Fig. 9: Typical bed-form feature without scale distortion in the inner Piep tidal channel

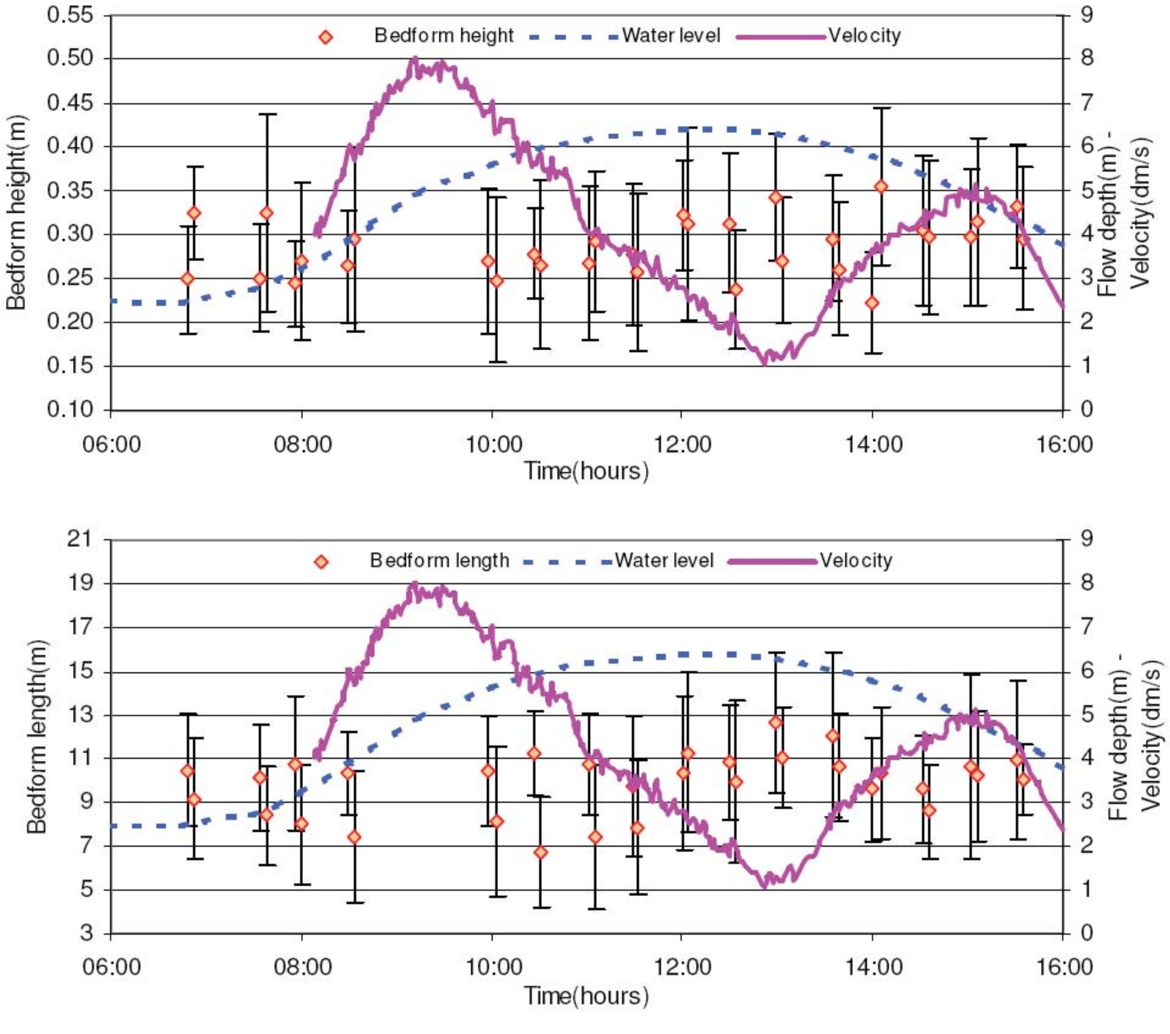


Fig. 10: Temporal variation of bed-form dimensions in the inner Piep tidal channel; upper: bed-form heights; lower: bed-form lengths

The mean lengths of the observed bed forms ranged from about 6.7 m to 12.7 m during the flood phase and just after high water, respectively. An increase in bed-form length was observed with increasing flow depth (h = German reference datum ± water level). Larger lengths were observed during the phase of smaller flow velocities around high water. The observed bed-form lengths at the measuring location in the inner Piep tidal channel (Fig. 4) were of the order of four times and two times the measured flow depth ($\lambda = 4$ h and $\lambda = 2$ h) at low and high water, respectively. The standard deviations of the bed-form lengths in each profile varied between 1.6 m and 4.2 m.

Migration of the bed forms during the measurement period was subsequently analysed. Echo soundings of the bed profiles measured along approximately the same vessel path from about mean water level during the flood phase to mean water level during the ebb phase are plotted in Fig. 11. The times at which the bed profiles were recorded are also indicated in Fig. 8. The bed forms were found to migrate in the shoreward direction (strongest currents) at a rate about 1 m/h.

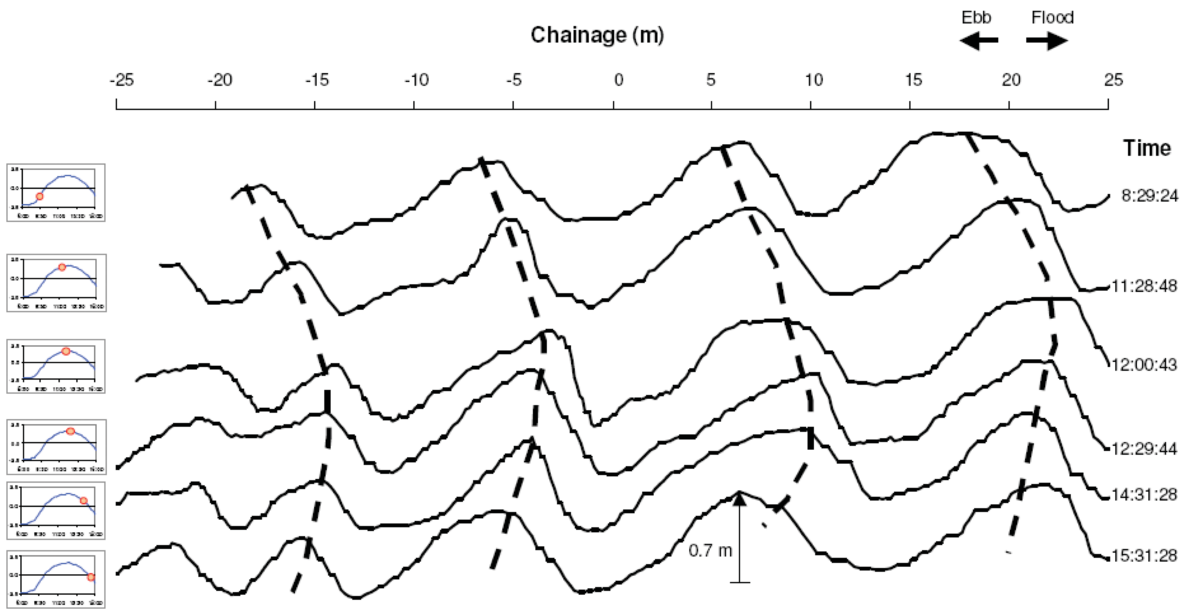


Fig. 11: Migration of bed forms during a tidal period

6. Roughness Values Associated with Different Bed Forms

The bed roughness values associated with the various bed forms observed in the field were analysed. Roughness values (*ks*) were estimated from continuous velocity profiles obtained using a 1200 MHz Acoustic Doppler Current Profiler (ADCP) manufactured by RD Instruments. The ADCP, which was set to record a 0.15 m bin size at a time interval per sub-ping of 0.04 s, was deployed pointing downwards from a stationary rubber dinghy for the continuous measurement of current velocity profiles (Fig. 12). Estimates of the bed shear stress and effective roughness were derived from the measured profiles averaged over a period of 300 s.

Only mean velocity profiles with depth-integrated velocities exceeding 0.3 m/s and small standard deviations of the velocity directions were considered. This procedure guarantees a logarithmic distribution over the vertical. Shear stresses and roughness values were obtained by fitting a logarithmic profile to the velocity data in the lower 20 % of the flow depth from the bed. About five point measurements were obtained in the wall region. Only

Fig. 12: Deployment of the acoustic profiler

those profiles with log-law fit correlation coefficients exceeding 0.90 were included in the analysis. Bearing in mind the limited number of point measurements in the wall region, the selected bin size, which does not reflect point measurements, and uncertainties in defining the reference datum of the measured velocity profiles, the interpretation of the results showed be treated with caution. The resulting roughness values were found to range between 0.03 m and 0.17 m with an average equivalent roughness of 0.1 m. Due to the limited number of velocity profiles selected for determining the roughness sizes, it was not possible to investigate the variation of bed-form roughness during the tidal period.

7. Empirical Equations for Predicting the Dimensions and Roughness of Bed Forms

Several methods for identifying bed-form types, including equations for determining bed-form dimensions and associated bed roughness coefficients, have been proposed (YALIN, 1972; RAUDKIVI, 1988; SOULSBY, 1997; VAN RIJN, 1993). The underlying experiments cover a wide range of flow conditions and sediment characteristics. The large majority of these empirical formulae, however, are based on the results of laboratory experiments with well-controlled, unidirectional steady flows mainly under equilibrium conditions, and with loosely packed non-cohesive sediments.

For such conditions the analysis is usually carried out in three stages. Firstly, the type of bed form is defined. Secondly, the bed-form dimensions are estimated for the given conditions and sediment characteristics. Finally, the associated roughness values are determined on the basis of the bed-form dimensions and flow conditions. The roughness values are usually determined by combining grain and form roughness. Grain roughness (*ks'*) is related to the largest particles of the uppermost seabed sediment layer, whereas form roughness (*ks"*) depends on the height (Δ), length (λ) and steepness (Δ/λ) of the bed form. Under tidal conditions, in which current velocities are subject to continuous change, bed forms are unable to fully adapt to varying flow conditions. For this reason the validity of the equations may be questionable.

VAN RIJN (1993) proposed a classification diagram for identifying bed-form types based on the particle-size parameter (D_*) as follows:

$$D_* = d_{50} \left[(\rho_s/\rho - 1)g/\nu^2\right]^{1/3} \tag{1}$$

with d_{50} = medium particle diameter of bed material in m
ρ_s = sediment density in kg/m^3
ρ = fluid density in kg/m^3
ν = kinematic viscosity coefficient in m^2/s
g = gravitational acceleration in m/s^2.

and the bed shear stress parameter (T):

$$T = (\tau'_b - \tau_{b,er})/\tau_{b,er} \tag{2}$$

with τ'_b = grain-related bed shear stress in N/m^2
$\tau_{b,er}$ = critical shear stress after Shields in N/m^2.

Table 1 summarizes the proposed equations for predicting bed-form dimensions and associated roughness values based on flume and river measurements. The bed-form heights are determined on the basis of the transport stage parameter (T), the water depth (h) and the particle size. In the case of non-cohesive sediments the lengths of bed forms are usually related to the water depth only. The variation of form roughness, on the other hand, depends on the steepness and shape factor (γ) of the bed form.

Comparisons between the results given by the equations of VAN RIJN (1993) and the corresponding relative bed-form heights and associated bed roughness values determined in the present study are shown in Figs. 13 and 14, respectively. According to the morphological bed-form classification of VAN RIJN (1993), megaripples are expected to develop at the measurement location. Reasonable agreement exists between the results given by the proposed equations and the results obtained in the present study, despite the fact that the empirical equations were derived from experiments under unidirectional flow conditions. The scatter of the experimental results is comparable to the scatter observed in other measurements carried out in the laboratory and in rivers. The relative bed-form heights were found to be as much as 8 times greater than the values predicted by the empirical equations (Fig. 13).

More significant discrepancies were identified in the length of the bed forms. The observed lengths (λ = 2 h to 4 h) were found to lie between the values predicted by the empirical equations for megaripples (λ = h/2) and dunes (λ = 7.3 h). The fact that the flow conditions during a tidal period are subject to continuous change may explain why the bed-form features are unable to fully develop. As illustrated by Fig. 14, on the other hand, the estimated bed-form roughness values are in reasonable agreement with those predicted by VAN RIJN'S equations (Table 1). As already pointed out, form roughness is highly dependent on the dimensions and steepness of bed forms. The fact that the larger heights of the bed forms at the measurement location are counterbalanced by longer lengths explains why the effective roughness values based on measurements are comparable to those predicted.

Table 1: Equations proposed by VAN RIJN (1993)

	Bed-form type	Equations	
Bed-form dimensions	Megaripples	$\frac{\Delta_r}{h} = 0.02\,(1 - e^{-0.1T})\,(10 - T)$	(3.a)
		$\lambda_{mr} = 0.5\,h$	(3.b)
	Dunes	$\frac{\Delta_r}{h} = 0.11 \left(\frac{d_{50}}{h}\right)^{0.3} (1 - e^{-0.5T})\,(25 - T)$	(4.a)
		$\lambda_d = 7.3\,h$	(4.b)
Form roughness	Megaripples	$k''_{s,r} = 20\,\gamma \Delta_r \frac{\Delta_r}{\gamma_r}$	(5)
	Dunes	$k''_{s,r} = 1.1\,\gamma \Delta_d\,(1 - e^{-25\Delta_d/\lambda_d})$	(6)

Note: Subscripts r and d denote megaripples and dunes, respectively

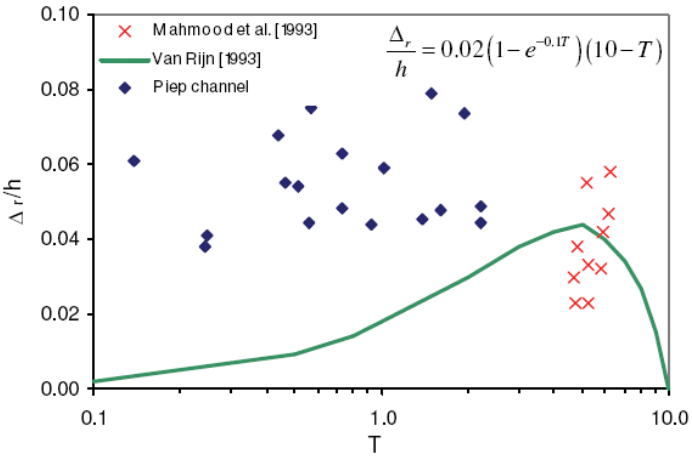


Fig. 13: Relative bed-form heights of megaripples after VAN RIJN (1993)

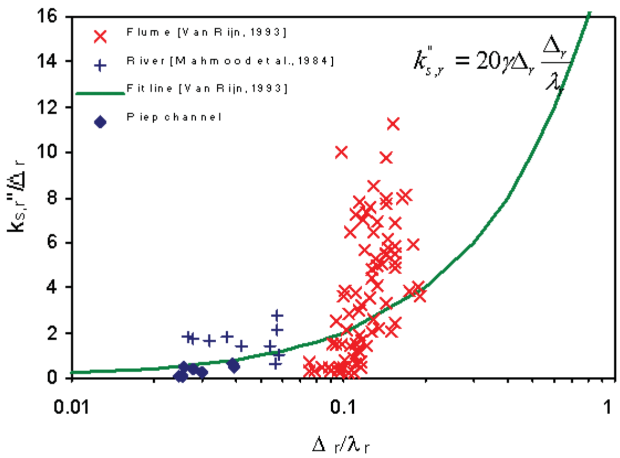


Fig. 14: Relative form roughness of megaripples after VAN RIJN (1993)

8. Numerical Procedure for Predicting the Dimensions and Roughness of Bed Forms

After analysing the spatial and temporal variations of bed-form features in the tidal channels, a numerical procedure was developed for predicting the dimensions of bed forms and hence the associated bed roughness. The identification of bed-form types and the estimation of bed-form dimensions and equivalent roughness sizes were derived from the results of flow model computations.

The methods proposed by VAN RIJN (1993) for identifying bed-form types and formulating bed-form dimensions and equivalent roughness sizes were implemented in a numerical model. The roughness values (k_s) were determined for given sediment characteristics and flow conditions as follows. Firstly, the type of bed form is identified. Secondly, the bed-form dimensions are estimated for the corresponding shear stress values. Shear stress values at maximum current velocities were considered in the present study, i.e. the temporal variations of bed-form dimensions were disregarded. Finally, the characteristics of the surficial seabed sediment and the dimensions of the bed forms were used to estimate the grain roughness (k_s') and form roughness (k_s"), respectively, hence yielding the effective bed roughness value. The k_s values were obtained by iteration. Constant Chezy coefficients were assumed throughout the domain initially. Updates were then determined iteratively until the computed *ks* values approximately matched the assumed values.

This procedure was applied to the tidal channels of the Dithmarschen Bight using a two-dimensional depth-integrated flow model covering the entire Dithmarschen Bight area. A curvilinear grid with a grid spacing ranging from 60 m to 180 m was employed. Details of the flow model are presented in PALACIO et al. (in this volume).

The layer thickness of the potentially mobile sediment deposits and the sediment characteristics in the tidal channels shown in Figs. 2 and 3 were taken into consideration in the simulations. The simulations were carried out for a spring tide with a tidal range of about 4 m.

Maps of the predicted heights and lengths of bed forms in the tidal channels are shown in Figs. 15 and 16, respectively. Regions with mud content and EHL sediment deposits are indicated. A considerable variation in the size of the predicted bed forms is evident, with bed-form heights attaining as much as 1 m. Larger heights are predicted in the central parts of the main tidal channels and in the most exposed areas of the Suederpiep tidal channel at locations where the shear stresses are larger. The predicted bed-form lengths are as much as about 40 m.

Fig. 17 shows the predicted roughness values in the tidal channels using the procedure outlined above. Higher values were obtained in the central parts of the main tidal channels (Suederpiep and Piep) and in the most exposed areas of the Suederpiep tidal channel. In regions with non-cohesive tidal deposits the predicted roughness values were as much as about 1 m. At locations where the EHL has already been reached the roughness sizes were set to 0.06 m (SOULSBY, 1997).

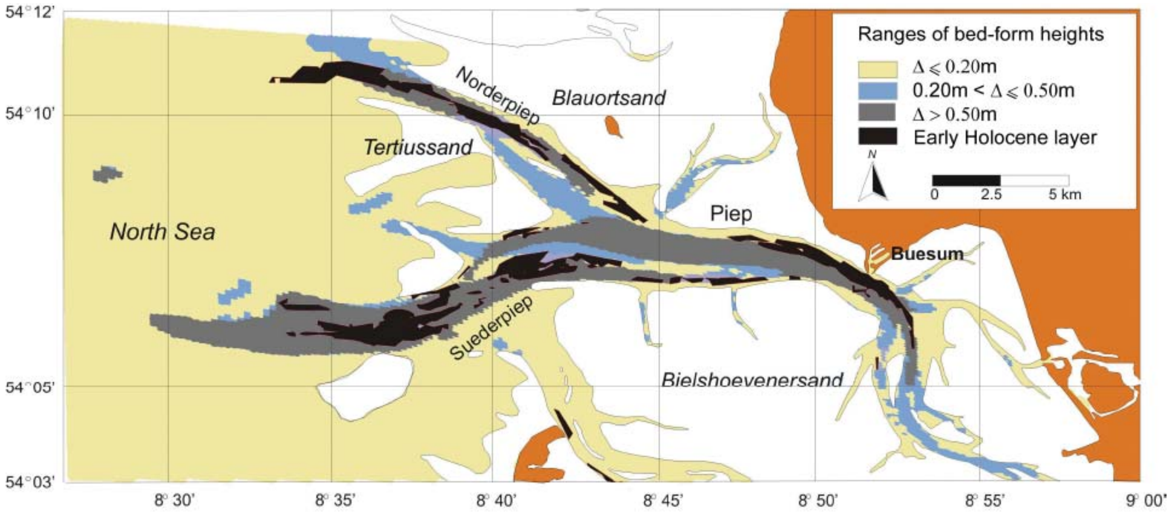


Fig. 15: Predicted heights of bed forms in the tidal channels for a spring tide

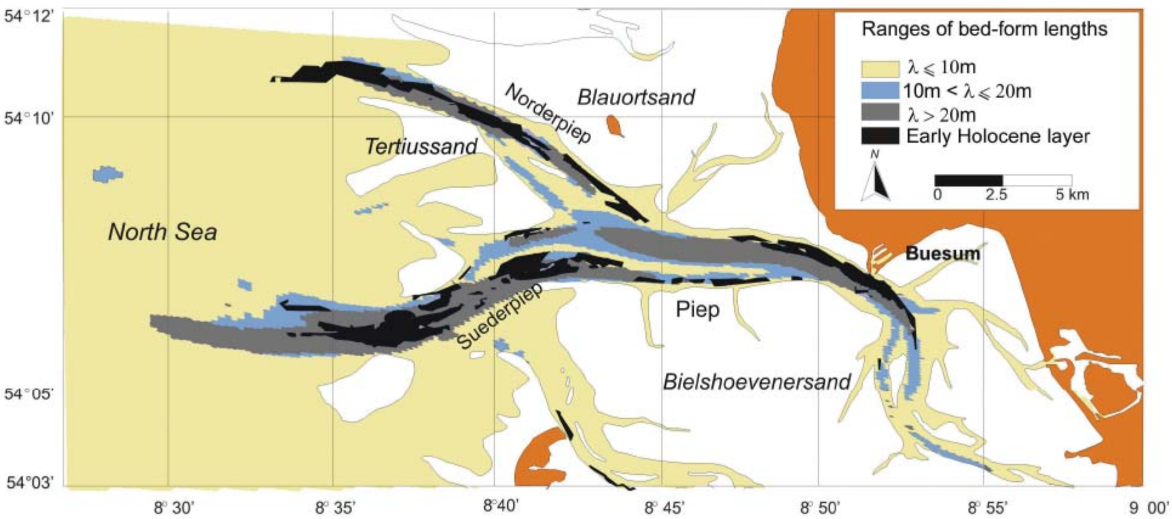


Fig. 16: Predicted lengths of bed-form features in the tidal channels for a spring tide

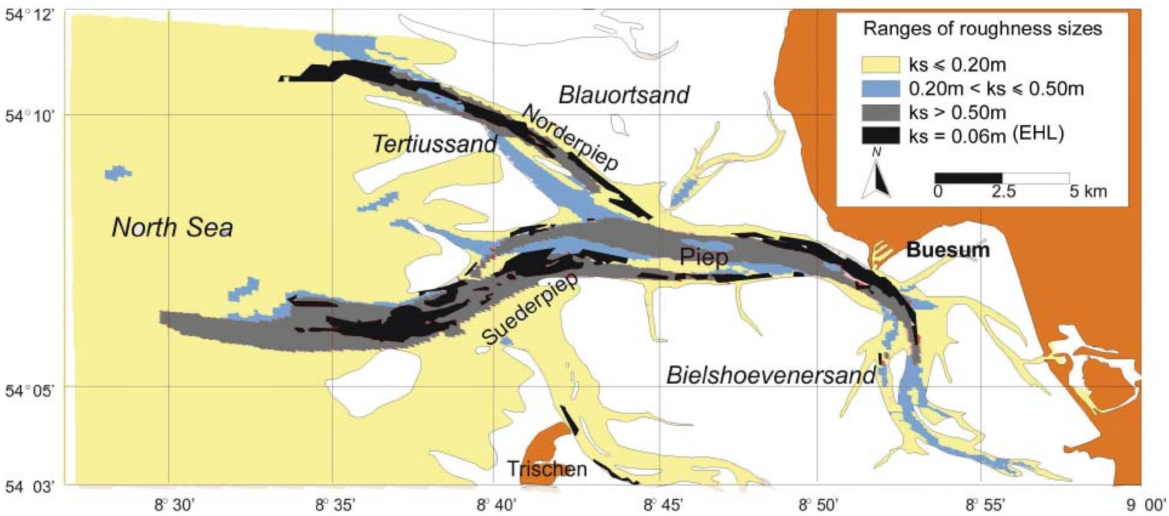


Fig. 17: Roughness values computed using empirical equations

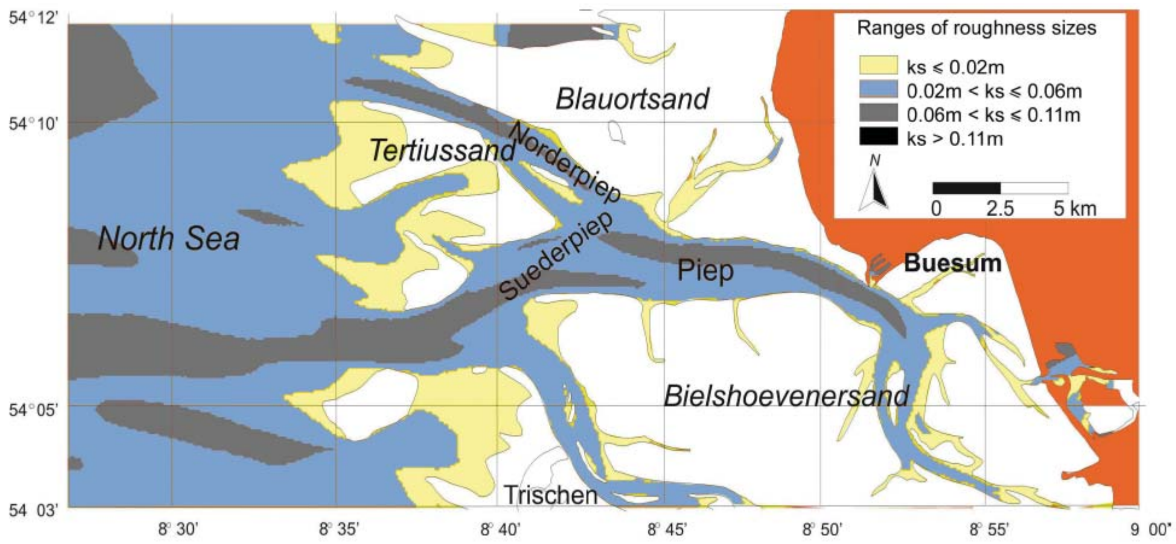


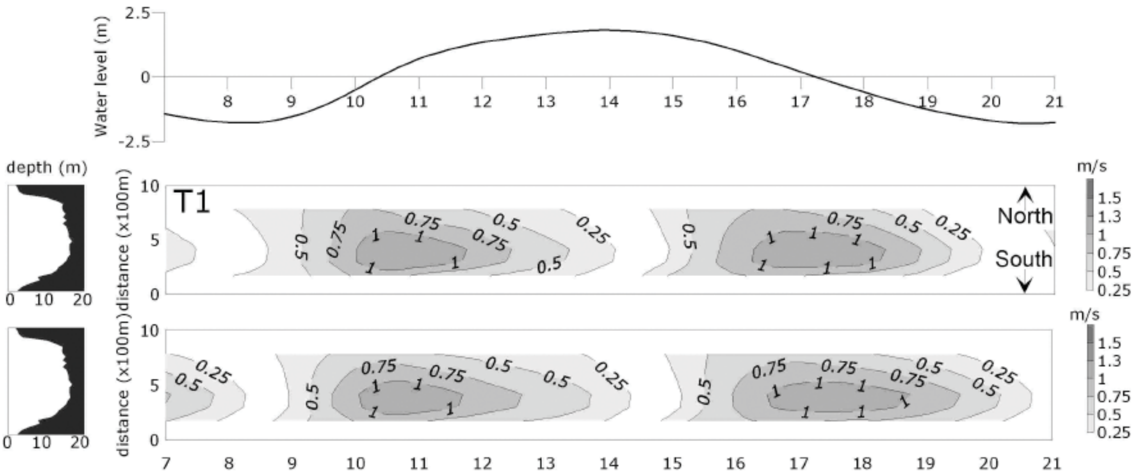
Fig. 18: Roughness values based upon a constant Chezy coefficient of 60 $m^{½}/s$

9. Effect of Bed Roughness on Current Velocity and Sediment Concentration

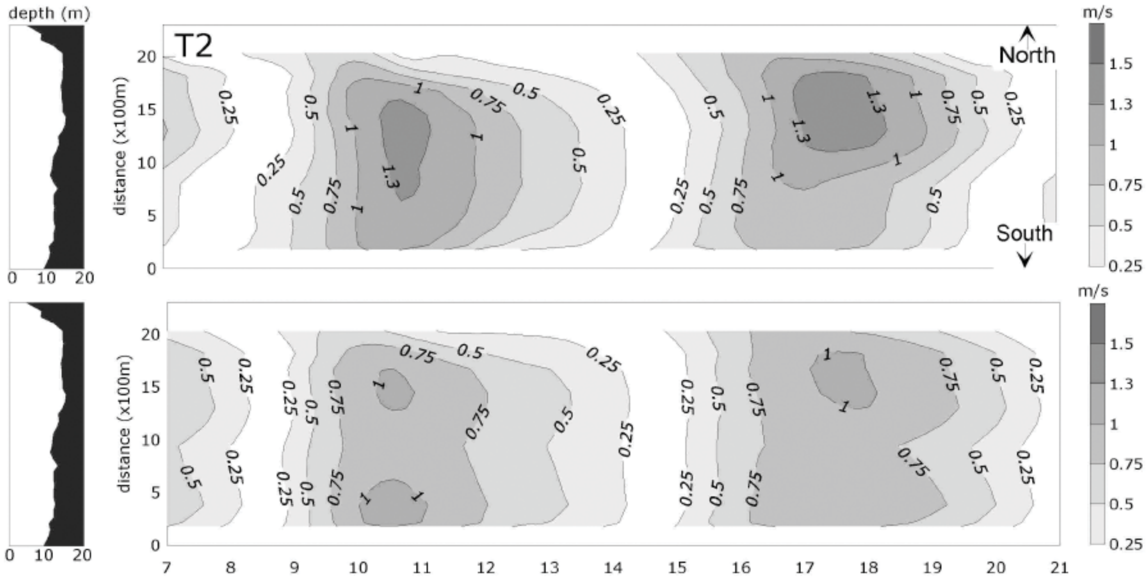
In order to illustrate the sensitivity of current velocity and suspended sediment concentration to the choice of bed roughness (k_s), simulations were carried out using a two-dimensional depth-integrated process-based flow and sediment transport model (PALACIO et al., in this volume; WINTER et al., in this volume). Bed load and suspended load were treated separately in the sediment transport model. Whereas bed-load transport was calculated using algebraic formulations, suspended material concentration and transport were computed by solving the advection-diffusion equation with appropriate bed boundary conditions. The pick-up function proposed by VAN RIJN (1984) was implemented with the same model settings as those adopted in the calibration and validation of the sediment transport model (WINTER et al., in this volume).

In order to demonstrate the effect of different bed roughness values on simulated current velocities and suspended sediment concentrations two prescribed bed roughness conditions were considered in the tidal channels of the Dithmarschen Bight: a) bed roughness obtained by applying the procedure outlined above (see Fig. 17) and b) bed roughness based on a constant Chezy coefficient of 60 $m^{1/2}/s$ (see Fig. 18). A uniform grain size of 100 m was assumed in the simulations, which were carried out for a spring tide with a tidal range of about 3.7 m.

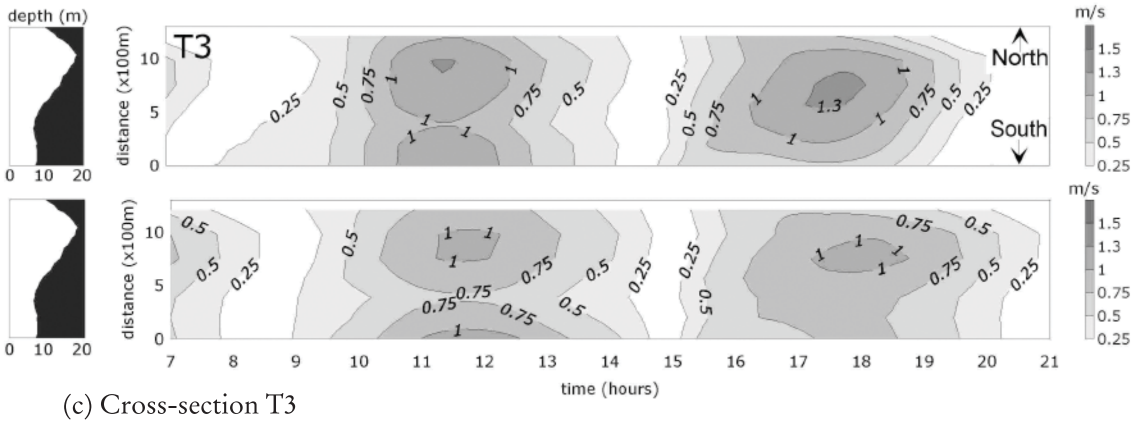
Comparisons of the simulated depth-averaged current velocities and suspended sediment concentrations obtained using the two maps of bed roughness (Figs. 17 and 18) are shown in Figs. 19 and 20, respectively. The resulting variation of current velocities and suspended sediment concentrations over a tidal period are shown at three cross-sections of the main tidal channels, i.e. T1 and T2, representing Norderpiep and Suederpiep at the entrance to the tidal area, respectively, and T3 across the Piep tidal channel in the inner part of the study area (Fig. 1). T1, located in the Norderpiep tidal channel in the northeast part of the study area, is about 775 m wide with water depths varying from 2.8 m to 16.1 m. T2, located in the Suederpiep tidal channel in the southeast part of the study area, is about 2040 m wide with water depths varying from 7.3 m to 15.6 m, and T3, located in the Piep tidal channel near the coast, is about 1200 m wide with water depths varying from 6.2 m to 17.9 m.



(a) Cross-section T1

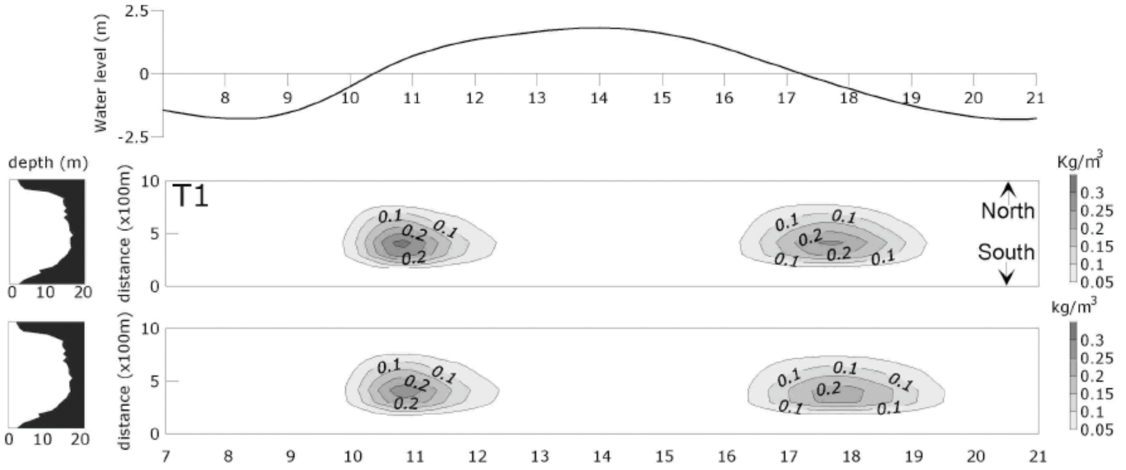


(b) Cross-section T2

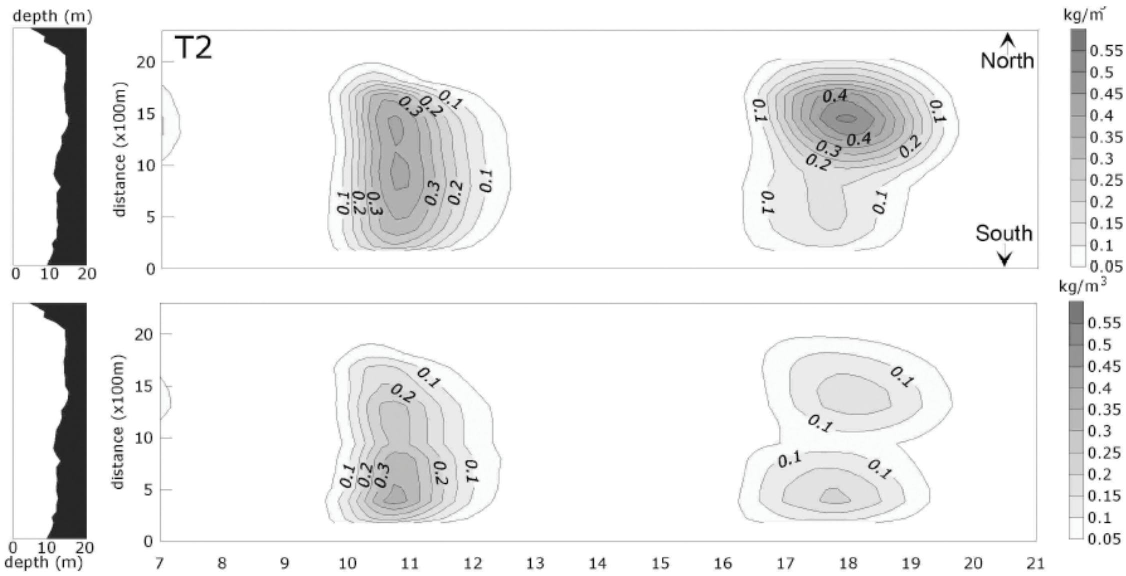


(c) Cross-section T3

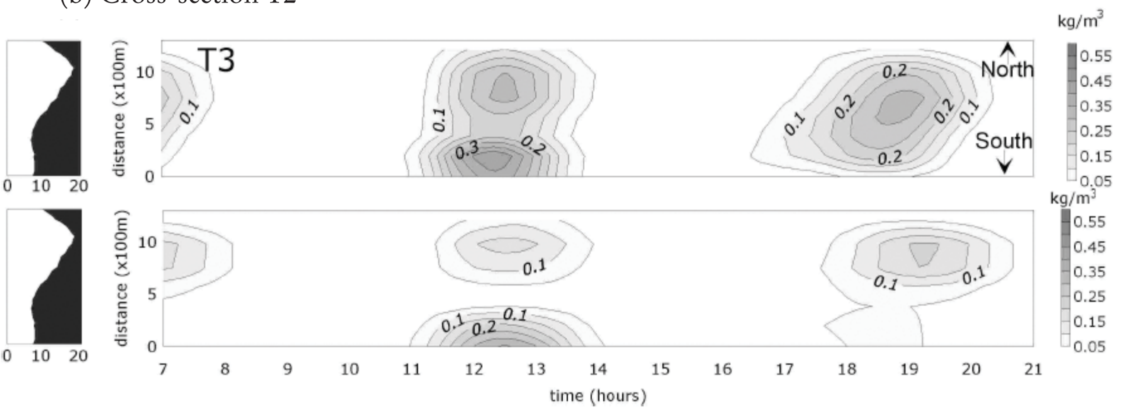
Fig. 19: Influence of bed roughness on the computed variation of depth-averaged velocity for a spring tide at cross-sections T1, T2 and T3. Upper plot: constant Chezy coefficient; lower plot: predicted bed roughness



(a) Cross-section T1



(b) Cross-section T2



(c) Cross-section T3

Fig. 20: Influence of bed roughness on the computed variation of depth-averaged suspended sediment concentration for a spring tide at cross-sections T1, T2 and T3. Upper plot: constant Chezy coefficient; lower plot: predicted bed roughness

The effect of bed roughness on flow velocities and suspended sediment concentrations is clearly evident. A slight reduction in the magnitudes and changes in the patterns of depth-averaged current velocities due to a higher bed roughness are observed particularly at cross-sections T2 and T3. At cross-section T1 in the northwest part of the study area the differences are only marginal. A similar behaviour is observed regarding the effect of bed roughness on the simulated depth-averaged suspended sediment concentrations. More significant differences were observed at cross-sections T2 and T3. Besides a change in the patterns of concentration distribution over the cross-sections, an approximately twofold reduction in the magnitude of depth-integrated concentrations resulted at cross-section T2 due to the larger bed roughness values at this location. These findings are in accordance with the results of previous studies by VAN RIJN et al. (2001) and WINTER and MAYERLE (2003). It is interesting to note that higher roughness values tend to delay the times of occurrence of peak velocities.

10. Conclusions

A realistic characterization of surficial seabed sediments and geological features based on field measurements has proved to be of major importance for correctly describing flow and sediment transport conditions in the study area. The spatial variation of the dimensions of bed-form features in the tidal channels of the Dithmarschen Bight was found to be highly dependent on the thickness of the potentially mobile sediment layer as well as the characteristics of surficial seabed sediments and flow conditions. An analysis of field measurements has shown that bed-form features develop primarily in the most exposed areas of the Suederpiep, at the intersection of this tidal channel with the Bielshoevener Loch and along the channels banks, especially in the Norderpiep and Piep. In regions with mobile sediment deposits, megaripples and dunes with lengths of up to 20 m were mainly observed. The maximum height of bed forms measured at only a few locations was found to be of the order of 0.7 m. Bed forms were not found in regions of the tidal channels where the surficial seabed sediments are mainly comprised of mud or at locations with consolidated deposits. At locations where the EHL is exposed, consolidated sediment bed forms cannot develop.

Investigations of the temporal variation of the dimension of bed forms at a single location showed that the heights of observed bed forms remain approximately unchanged during a tidal period, whereas their lengths may double in size. The small steepness of the observed bed forms gives the impression of a fairly smooth seabed. The largest values of measured roughness sizes correspond to about half of the observed bed-form heights. This is in accordance with the initial estimate of form roughness suggested by VAN RIJN (1993).

The effectiveness of empirical equations for predicting the dimensions and roughness of bed-form features was tested on the basis of observations in the tidal channels. A comparison between predicted and observed bed-form dimensions showed significant differences, with observed relative bed-form heights of up to 8 times higher and observed lengths of about 4 to 8 times longer than those predicted by the empirical equations. Fairly good agreement was obtained, however, between the bed-form roughness values estimated from measurements and those predicted by the empirical equations.

The numerical procedure outlined for predicting the dimensions of bed forms, and hence bed roughness, in the tidal channels proved to be quite effective. Bed-form dimensions and equivalent roughness values were estimated from the results of two-dimensional depth-integrated flow model computations, taking into account sediment characteristics and the thickness of the potentially mobile sediment layer. The sensitivity of flow and suspended sediment concentration to the choice of bed roughness was demonstrated. Numerical model simulations using a 2DH flow and sediment transport model were also carried out. These simulations indicated that bed roughness has a significant effect on sediment concentrations. Increased bed roughness was found to result in an approximately twofold reduction in the maximum depth-averaged suspended sediment concentration. This underlines the importance of accurately estimating the dimensions of bed forms and associated roughness values. The results of the simulations also showed that an increase in roughness values additionally leads to changes in the patterns of distribution of depth-averaged suspended sediment concentration over a tidal period. This effect is more pronounced in the main tidal channels, i.e. in the Suederpiep and Piep, at cross-sections T2 and T3, respectively.

Field measurements of bed-form dimensions and associated roughness values proved to be extremely valuable for adjusting the empirical equations so as to obtain a better representation of conditions in the tidal channels and hence improve the predictive capability of numerical models. Additional measurements at different locations and for a wider range of surficial seabed sediment characteristics and flow conditions are recommended to improve our understanding of the spatial and temporal variation of the dimensions of bed forms and associated roughness values. Simultaneous measurements of current profiles and suspended sediment concentrations in the near-wall region with higher vertical resolution are also recommended to permit a more precise determination of equivalent roughness values, which is an essential prerequisite for future investigations of the effects of roughness on sediment concentration and transport.

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