| Journal of Coastal Research | SI 56 | pg - pg | ICS2009 (Proceedings) | Portugal | ISSN |
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# On the modeling of bio-physical influences on seasonal variation in sandwave dynamics

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## ABSTRACT

BORSJE, B.W., BUIJSMAN, M.C., BESIO, G., DE VRIES, M.B., HULSCHER, S.J.M.H., HERMAN, P.M.J. and RIDDERINKHOF, H., 2009. On the modeling of bio-physical influences on seasonal variation in sandwave dynamics. Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), pg – pg. Lisbon, Portugal, ISBN

Seasonal variation is observed in sandwave migration and sandwave length for a tidal inlet between the North Sea and the Dutch Wadden Sea (Marsdiep tidal inlet). Modeling experiments demonstrate that this seasonal variation is induced both by physical and biological processes. By including seasonal variations in (1) tides, (2) fall velocity of sediment and (3) a reduction of the near bottom flow by tube building worms, in an idealized sandwave model, we find a quantitatively agreement between the model outcomes and field measurements.

**ADDITIONAL INDEX WORDS:** *biogeomorphology, morphodynamic modeling, stability analysis, parameterization, benthos, field measurements*

## INTRODUCTION

The bottom of the North Sea shows a wide variety of bedforms, among which sandwaves are the most mobile. These sandwaves originate from the interaction between tidal flow and the sandy seabed. Residual vertical circulation cells transport sediment at the bed towards the crests (Hulscher, 1996). Sandwaves have wavelengths between 100-1000 m, heights of several meters and the orientation of the crests is almost perpendicular to the direction of the main current. Field observations give an estimate of the migration of sandwaves in the Dutch part of the continental shelf of 0 m year$^{-1}$ for offshore sites up to 20 m year$^{-1}$ for coastal sites (Van Dijk and Kleinhans, 2005).

Understanding the dynamic character of the seabed is of high economic value, for example for selecting suitable locations for sandpits and windfarms (Roos and Hulscher, 2003), as well as to determine a safe burrowing depth for pipelines and telecommunication cables (Morelissen et al., 2003), and a safe navigation depth for vessels (Németh et al., 2003).

Studying the dynamics of the bottom of the seabed is not only of interest from an engineering point of view, but also from an ecological perspective. Given the high biodiversity in the subtidal area (e.g. Heip et al., 1992), insight is needed in the relation between geomorphodynamic processes and biota for the conservation and management of the biodiversity in the coastal zone. Moreover, these benthic organisms are known to influence their habitat, resulting in bio-geomorphological interactions. Recently, Borsje et al. (2008a) showed that biota is able to influence the length of sandwaves significantly on the Belgian Continental Shelf. They showed that predicted sandwave lengths were closer to observations by including biological activity in an idealized model (Besio et al., 2006).

Recent studies already showed that the migration of sandwaves is caused by a tidally induced residual flow (Németh et al., 2007) and higher tidal constituents (Besio et al., 2004). At the site studied in this paper, the Marsdiep inlet in the Netherlands, the migration rate of the sandwaves is up to 90 m year$^{-1}$ (Buijsman and Ridderinkhof, 2008a). This high migration rate is caused by the relatively high flow velocities in the tidal inlet, compared to the more moderate flow velocities in the offshore area.

The migration rate and wavelength of sandwaves in the Marsdiep tidal inlet show a seasonal variation, with the highest migration rate and wavelength in winter and early spring. These relatively slowly varying seasonal variations could not be explained by the abrupt occurrence of storms or estuarine circulation (BUIJSMAN and RIDDERINKHOF, 2008b).

Physical processes responsible for the seasonal variation in sandwave length and sandwave migration rate could be the variation in tides or fall velocity of sediment particles (BUIJSMAN and RIDDERINKHOF, 2008b). Tidal currents are stronger in winter than in summer. Moreover, water temperature shows a minimum in winter. While the kinematic viscosity is related to water temperature, the lowest settling velocities and corresponding highest suspended sediment concentrations are expected to occur in winter. Given the strong tidal currents and high suspended sediment concentrations in winter, highest migration rates are expected in this period of the year (BUIJSMAN and RIDDERINKHOF, 2008b).

The aim of this paper is (1) to model the sandwave length and migration rate in the Marsdiep inlet and (2) to explore to what extent the seasonal variability in sandwave length and migration rate can be caused by biological and physical processes, by varying the input parameters of an idealized sandwave model.

The structure of this paper is as follows. Section 2 introduces the study area. The data obtained from an ADCP that is mounted under a ferry, which navigates between the south and north border of the study area and the model set-up is discussed in Section 3. Section 4 discusses the results of the model, also a discussion about the main findings of the paper is presented in Section 4. We end by drawing some conclusions in Section 5.

## STUDY AREA

The study area encompasses the inlet of the Marsdiep tidal basin (52.985° N and 4.785° W), located in the western Dutch Wadden Sea (Figure 1). The tidal basin consists of deep tidal channels flanked by shallow sand and mud flats. The inlet is bordered by the island of Texel to the north and the town of Den Helder to the south and is about 4 km wide and maximally 27 m deep at the location where the ferry crosses. The seafloor in the inlet is covered with sand with grain sizes of 0.3-0.6 mm (BUIJSMAN and RIDDERINKHOF, 2008b). The inlet is considered well-mixed and tides constitute up to 81% of the total variance of the water levels and 98% of the currents (BUIJSMAN and RIDDERINKHOF, 2007). The semidiurnal tidal constituent $M_2$ is the most dominant in the vertical and horizontal tides. The amplitude of water level variation is between 1 and 2 m. Near-surface streamwise current amplitude is between 1 and 2 m $s^{-1}$ for neap and spring tides, respectively. Currents are flood dominated in the southern half and ebb dominated in the northern half of the inlet. The bottom of the Marsdiep is inhabited by the tube building worm *Lanice conchilega* (HOLTMANN et al., 1996). *Lanice conchilega* protrudes several centimeters from the sediment in the water column (max. 15 cm), and thereby influences the near-bottom flow. For dense tube assemblages the near-bottom flow reduces (FRIEDRICHS et al., 2000), and consequently lower ripples are present on top of the sandwaves (FEATHERSTONE and RISK, 1977). The ripples are the main origin of bottom roughness (SOULSBY, 1983). The abundance of *Lanice conchilega* in the Marsdiep is locally extremely large (over 3,000 ind. $m^{-2}$).

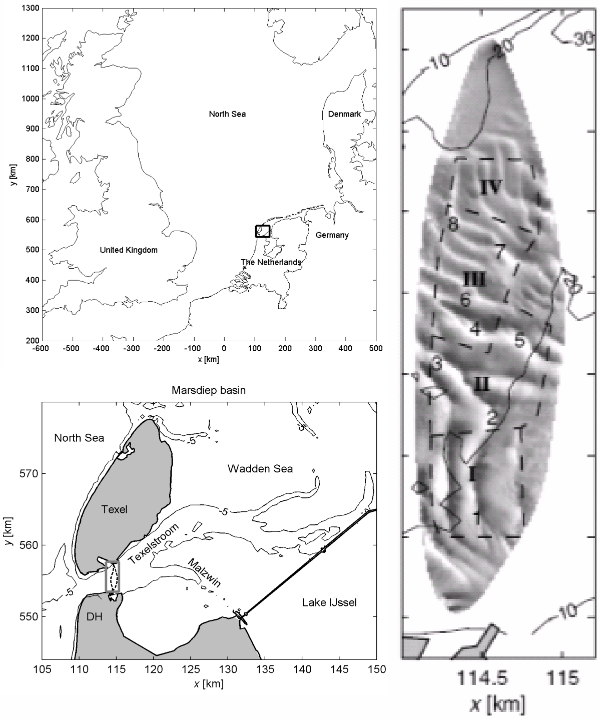

Figure 1. Overview of the study area. Sand-wave field (right), marked by the grey-lined box in the Marsdiep tidal basin (under), located in The Netherlands (top). The town of Den Helder is abbreviated with DH and the envelope of ferry crossings is indicated by the dashed line in the left plot. The NIOZ jetty and the location of the velocity data are marked by the grey circle and the triangle in the right plot respectively. Dark (light) shades of grey indicate troughs (crests).

## DATA AND MODEL SET-UP

For the investigation of the seasonal variation in sandwave length and migration rate, we use ADCP velocity data from 1999 to the end of 2002. The methodology to analyse the current data is presented in BUIJSMAN and RIDDERINKHOF (2007). The ADCP was mounted under the ferry Schulpengat at 4.3 m below the water surface and recorded eastward velocities u, northward velocities v, and upward velocities w in bins of 0.5 m. The ferry crosses the inlet every half hour up to 32 times per day. Similar to BUIJSMAN and RIDDERINKHOF (2008b), time gaps in the time series were filled with harmonic fits.

In addition to velocities, the ADCP also measured water depth. As is extensively discussed in BUIJSMAN and RIDDERINKHOF (2008a), for the period 1998-2005 water depths collected during 30-d periods were corrected for offsets and assembled in bathymetric maps (digital elevation models; DEMs) with a grid size of 15x15 $m^2$. An example of a DEM is presented in Figure 1. From these DEMs sand-wave height H and wavelength L were extracted. Moreover, the sand-wave migration rate $(U_w,V_w)$ was obtained by spatially correlating patterns on DEMs that were about three months apart. In this paper we use $U_{ws}$, which is the migration rate along the main axes of $(U_w,V_w)$. A striking result is the seasonal variability in $U_{ws}$, H and L. We computed the mean seasonal variability for $U_{ws}$, H and L around the annual mean (i.e. $\{U_{ws}\}'$, $\{H\}'$ and $\{L\}'$, where {} indicates area averaging). The results are presented in Figure 2. It shows that the sandwaves migrate fastest (slowest) in winter (summer), have the largest (smallest) wave heights in spring (fall), and have the largest (smallest) wave lengths in spring (fall).

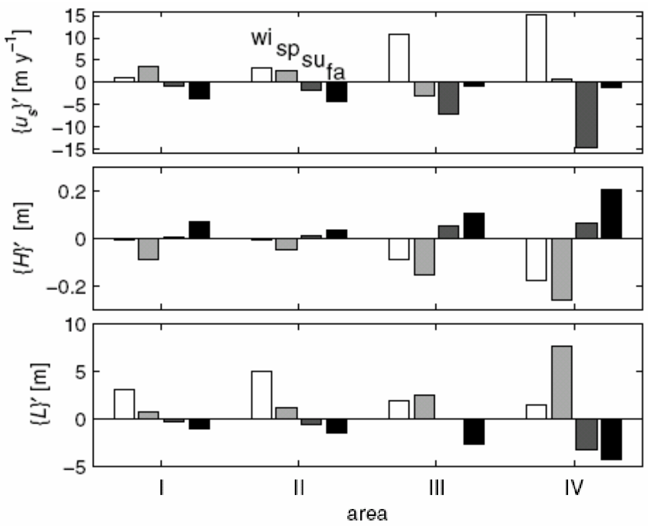

Figure 2. Seasonal variability around the annual mean of $U_{ws}$, H and L in the four areas (Figure 1: right). Winter, spring, summer, fall are indicated with wi, sp, su, fa (BUIJSMAN and RIDDERINKHOF, 2008a).

To model the bio-physical influences on sandwave migration rate and sandwave length, an idealized model is adopted, which is based on a stability analysis and extensively discussed in BORSJE et al. (2008a). A parameterization is added to the model to include the influence of *Lanice conchilega* on the deceleration of the near bed flow. For a detailed description of the parameterization of *Lanice conchilega*, see BORSJE et al. (2008b).

In order to show the physical and biological contribution to the seasonal variation in migration rate and length of the sandwaves, five cases will are considered. The first case is the default case, in which the processes parameters are kept constant throughout the year and only different combinations of the tidal forcing are investigated. Based on the best combination of tidal components (the default case), Case 2 adds seasonal variation in water temperature. Case 3 adds seasonal variation in tides tot the default case. Case 4 adds seasonal variation in biological activity to the default case. Case 5 combines all seasonal variations in cases 2-4. Evaluation of the model results is based on the seasonally averaged sandwave length and migration rate in the Marsdiep inlet (Figure 2).

The water temperature shows a seasonal variation, as shown in Figure 3. The fall velocity of the sediment is influenced by a change in water temperature, showing relative high fall velocities for warm water (0.05 m s$^{-1}$) and relative low fall velocities for cold water (0.04 m s$^{-1}$).

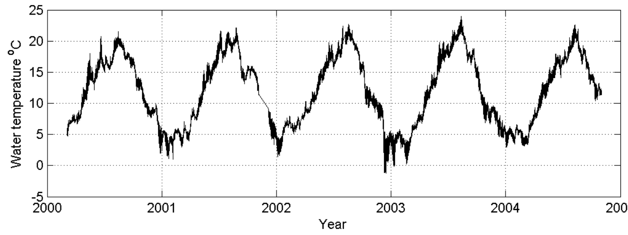

Figure 3. Variation in water temperature measured in the Marsdiep tidal inlet.

Moreover, the Reynolds particle number is related to the kinematic viscosity, which in turn is related to water temperature. The lower kinematic viscosity of the water in summer will induce lower bed load transport rates for equal bed shear stresses, compared to the winter period. The seasonal variation in input parameters is expressed relative to the yearly mean value (Figure 4a).

Seasonal variation in the tide is based on the measured tidal velocities (BUIJSMAN and RIDDERINKHOF, 2008a). For the Marsdiep inlet, the tidal velocities are highest in winter and spring and lowest in summer and fall (Figure 4b).

Data on temporal variation of *Lanice conchilega* are not available for the Marsdiep tidal inlet. However, *Lanice conchilega* is sensitive to low temperatures and therefore shows low densities in the area of the Wadden Sea after cold winters (BEUKEMA, 1979). In this study, we adopt the temporal variation in biomass *Lanice conchilega* from a modeling study on two different bio-engineering species in the Western Wadden Sea (BORSJE et al., 2008c). These two species (*Macoma balthica* and *Hydrobia ulvae*) have their smallest biomass in late winter and spring, and their largest biomass in fall (Figure 4c).

The default model settings are shown in Table 1. The default model settings represent a typical Marsdiep location (area II).

## RESULTS AND DISCUSSION

For Case 1, the modeled wavelength is around 250 m (Figure 5a). This value is comparable to the measured wavelength of around 200 m in the Marsdiep inlet. The wavelength of the sandwaves is hardly dependent on the combination of tidal constituents, showing that the $M_2$ tidal component has the largest contribution to the wavelength of the sandwaves (Table 1). However, the migration rate of the sandwaves is greatly dependent on the different combinations of the tidal forcing. For the given settings of the tidal forcing, the $Z_0$ component has a positive impact on the migration rate and the $M_4$ component has a negative impact on the migration rate.

Given a measured migration rate of around 60 m year$^{-1}$ we can conclude the model is able to represent both the wavelength and migration rate of the sandwaves in the Marsdiep inlet.

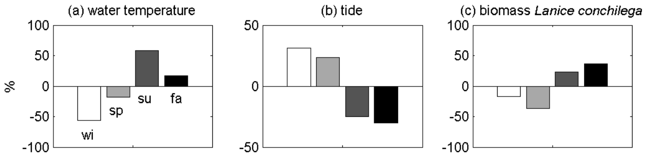

Figure 4. Seasonal variability around the annual mean of water temperature (a), tidal velocity (b) and biomass *Lanice conchilega* (c).

Table 1: Process parameters; comparable to area II.

| Parameter | Value |
|---|---|
| grain size | 0.4 mm |
| water depth | 24 m |
| flow velocity ($M_2$) | 1.1 m s$^{-1}$ |
| flow velocity ($M_4$) | 0.11 m s-$^{1}$ |
| residual flow ($Z_0$) | -0.09 m s$^{-1}$ |
| relative phase difference between $M_2$ and $M_4$ | 84$^{\circ}$ |

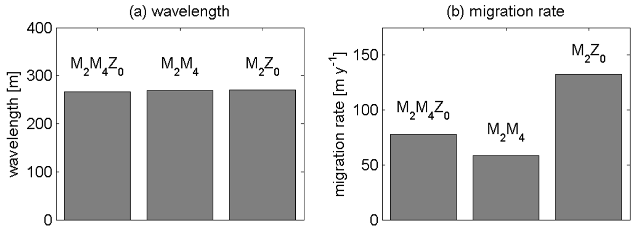

Figure 5. Modeled wavelength (a) and migration rate (b). For different combinations of the tidal forcing (Case 1).

Concerning the seasonal variability in the wavelength and the migration rate of the sandwaves, there is a striking difference (Figure 6). The variation in water temperature and biomass of *Lanice conchilega* are the main potential contributions to the seasonal variability in wavelength, while the seasonal variation in tidal velocity is mainly causing the seasonal variability in migration rate. Moreover, physical and biological processes show a non-linear interaction, when both processes are combined in Case 5.

The seasonal variability in sandwave migration rate is related to the variation in tidal velocity (Figure 4b), in such a way that higher tidal velocities cause a higher migration rate for sandwaves. However, the relation between causal factors and variability in the wavelength of sandwaves is much more complicated. In the winter period, a relative low biomass of *Lanice conchilega* causes higher suspended sediment concentrations compared to the default case (BORSJE et al., 2008b). Furthermore, the low water temperature induces a relatively low fall velocity, resulting in sediment which is carried longer in suspension compared to the default case. Suspended sediment has a stabilizing effect on the wavelength of sandwaves (BORSJE et al., 2008a), therefore the sandwave length in winter is much higher, compared to the default case. In spring, the biomass of *Lanice conchilega* is even lower. However, the water temperature is higher compared to the winter period. Therefore, the amount of sediment in suspension is comparable for both periods and consequently also the wavelength of the sandwaves is comparable in both periods of the year. In summer, the biomass of *Lanice conchilega* is relatively high, resulting in relatively low suspended sediment concentrations. Combined with a high water temperature and corresponding high fall velocity, the sandwave length is much smaller, compared to the default case. Finally, in fall, both the water temperature and the biomass of *Lanice conchilega* are relatively high, resulting in smaller wavelength of the sandwaves. In general, the physical and biological processes show a dynamic interaction concerning the wavelength of the sandwaves (BORSJE et al., 2008d). Biological processes determine the amount of bed load and suspended sediment transport. Water temperature determines how long the sediment is carried in suspension. Therefore whether the wavelength of the sandwaves is either larger or smaller compared to the default case is determined by the biological processes. However, the exact change in wavelength is determined both by the biological and physical processes. Concerning the migration rate of the sandwaves, the physical process (tidal velocity) is dominant compared to the biological process and as a result no dynamic interaction is found.

Seasonal variability in sandwave lengths is as much as 15% of the annual mean sandwave length, while variability in migration rates are about 60% of the annual mean migration rate, as measured in the field by BUIJSMAN and RIDDERINKHOF (2008a). Based on a comparison between the modeling results and the field measurements (Figure 6), we can conclude that both physical and biological processes are capable of determining the seasonal variability in wavelength and migration rate of sandwaves in the Marsdiep inlet. The modeled variation is comparable in magnitude to the measured variation in the field.

This paper explores the causes for seasonal variation in sandwave length and migration rate. In this study, we took a representative case, for which the parameter setting is comparable to the Marsdiep inlet (area II). However, without knowing the exact seasonal and spatial variation in biomass of *Lanice conchilega* in the study area, we are not able to model the site specific variation in sandwave length and migration rate. Moreover, the grain size used in this study is uniform, while in the field a sorting process is observed with almost twice as large medium grain sizes in the crests of the sandwaves compared to the troughs at some locations (BUIJSMAN and RIDDERINKHOF, 2008a). Finally, there is a relatively strong spatial variation of both driving parameters and of the resulting sandwave parameters, which will be addressed in a follow-up study.

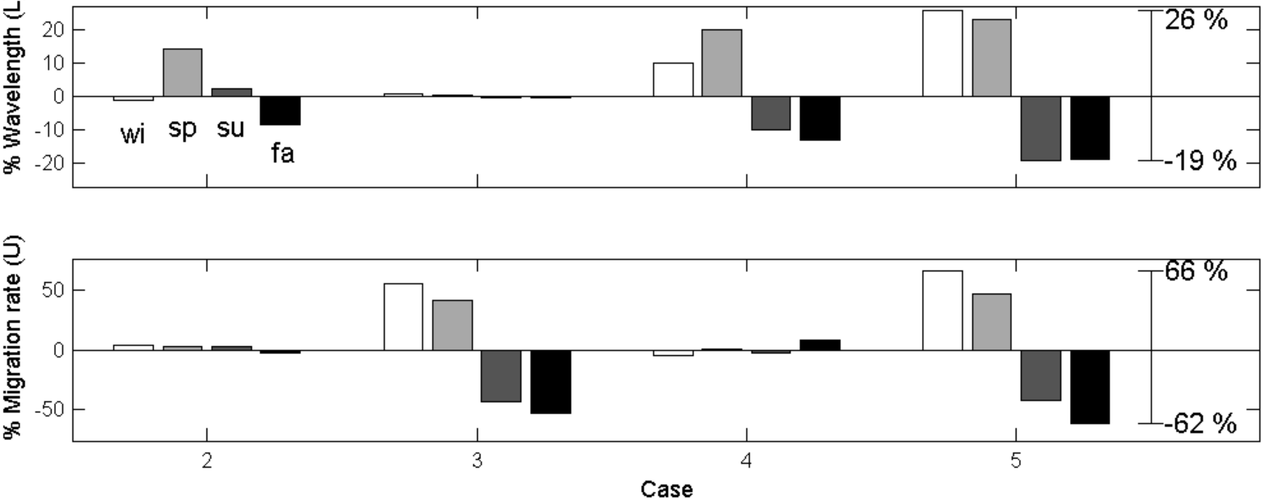

Figure 6. Seasonal variability expressed in percentage of the mean wavelength and migration rate (Case 1) caused by a seasonal variation in Water temperature (Case 2), Tidal velocity (Case 3), Biomass *Lanice conchilega* (Case 4) and a combination of these bio-physical processes (Case 5).

As observed by BUIJSMAN and RIDDERINKHOF (2008b), also the height of the sandwaves shows a seasonal variation (Figure 2). The code used in this study, is based on a linear stability analysis, and therefore not able to give a prediction for the sandwave height. By including the physical and biological processes in a non-linear code (e.g. NÉMETH et al., 2007), we are able to model the seasonal variation in sandwave height as well. Moreover, a non-linear code will give us the possibility to include sorting effects and the corresponding implications for seasonal variation in sandwave length and migration rate.

Despite the shortcomings mentioned above, the present study demonstrates that an idealized model may be an useful way of assessing the impact of biological and physical processes on seasonal variation in sandwave dynamics.

## CONCLUSIONS

This paper demonstrates that biological and physical processes are capable of causing the seasonal variation in migration rate and wavelength of sandwaves in the Marsdiep inlet (The Netherlands).

As model input the measured variation in (i) flow velocity and (ii) water temperature is used and moreover, an assumption on (iii) the biomass variation of the tube building worm *Lanice conchilega* is included in the bio-geomorphological model (BORSJE et al., 2008a).

Model results reveal that the three processes contribute differently to the seasonal variation in sandwave characteristics. Firstly, both the variation in water temperature and the biological processes may cause the variation in wavelength of the sandwaves. Variation in tidal velocity is the main determinant for the variation in migration rate of the sandwaves in the Marsdiep inlet. Finally, biological processes and physical processes show a non-linear interaction, meaning that the outcome of the interaction is not simply the sum of the two different components. As a result, the biological process dominates the seasonal variation in sandwave length while the variation in tidal velocity dominates the seasonal variation in sandwave migration.

## LITERATURE CITED

BESIO, G., BLONDEAUX, P. BROCCHINI, M., VITTORI, G., 2004. On the modeling of sandwave migration. Journal of Geophysical Research 109. doi 10.1029/2002JC001622.

BESIO, G., BLONDEAUX, P., VITTORI, G., 2006. On the formation of sandwaves and sand banks. Journal of Fluid Mechanics 557, 1-27.

BEUKEMA, J.J. 1979. Biomass and species richness of the macrobenthic animals living on a tidal flat area in the Dutch Wadden Sea: effects of a severe winter. Netherlands Journal of Sea Research 13, 203-223.

BORSJE, B.W., BESIO, G., BLONDEAUX, P., HULSCHER, S.J.M.H., VITTORI, G., 2008a. Exploring biological influence on offshore sandwave length. Marine and River Dune Dynamic III, International Workshop, April 1-3 2008, Leeds. Parsons D.R., Garlan T., Best J.L. (Eds), pp 31-38.

BORSJE, B.W., HULSCHER, S.J.M.H., HERMAN, P.M.J., DE VRIES, M.B., 2008b. On the parameterization of biological influences on offshore sandwave dynamics. Proceedings PECS 2008, Liverpool.

BORSJE, B. W., DE VRIES, M. B., HULSCHER, S. M. J. H. and DE BOER, G. J. 2008c. Modelling large scale cohesive sediment transport by including small scale biological influences. Estuarine, Coastal and Shelf Science 78, 468-480.

BORSJE, B.W., BOUMA, T.J., DE VRIES, M.B., HULSCHER, S.J.M.H., HERMAN, P.J., BESIO, G., 2008d. Bio-geomorphological interactions in offshore seabed patterns. 31st International Conference on Coastal Engineering (ICCE), Hamburg.

BUIJSMAN, M.C., RIDDERINKHOF, H., 2007. Long-term ferry-ADCP observations of tidal currents in the Marsdiep inlet. Journal of Sea Research 57, 237–256.

BUIJSMAN, M.C., RIDDERINKHOF, H., 2008a. Long-term evolution of sandwaves in the Marsdiep inlet. I: high-resolution observations. Continental Shelf Research 28, 1190-1201.

BUIJSMAN, M.C., RIDDERINKHOF, H., 2008b. Long-term evolution of sandwaves in the Marsdiep inlet. II: Relation to hydrodynamics. Continental Shelf Research 28, 1202– 1215.

FEATHERSTONE, R.P., RISK, M.J., 1977. Effect of tube-building polychaetes on intertidal sediments of the Minas Basin, Bay of Fundy. Journal of Sedimentary Petrology 47, 446– 450.

FRIEDRICHS, M., GRAF, G., SPRING, B., 2000. Skimming flow induced over a simulated polychaete tube lawn at low population densities. Marine Ecology Progress Series 192, 219-228.

HEIP, C., BASFORD, D., CRAEYMEERSCH, J.A., DEWARUMEZ, J.-M., DÖRJES, J., DE WILDE, P., DUINEVELD, G., ELEFTHERIOU, A., HERMAN, P.M.J., NIERMANN, U., KINGSTON, P., KÜNITZER, A., RACHOR, E., RUMOHR, H., SOETAERT, K., SOLTWEDEL, T., 1992. Trends in biomass, density and diversity of North Sea macrofauna. Journal of Marine Science 49, 13-22.

HOLTMANN, S.E., et al., 1996. Atlas of the zoobenthos of the Dutch Continental Shelf. Ministry of Transport, Public Works and Water Management, North Sea Directorate, Rijswijk, 1-244 pp.

HULSCHER, S.J.M.H. 1996. Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model. Journal of Geophysical Research C9, 101, 20727-20744.

MORELISSEN, T., HULSCHER, S.J.M.H., KNAAPEN, M.A.F., NÉMETH, A.A., BIJKER, R., 2003. Mathematical modelling of sandwave migration and the interaction with pipelines. Coastal Engineering 48, 197-209.

NÉMETH, A.A., HULSCHER, S.J.M.H., DE VRIEND, H.J., 2003. Offshore sandwave dynamics, engineering problems and future solutions. Pipeline and Gas Journal 230, 67-69.

NÉMETH, A.A., HULSCHER, S.J.M.H., VAN DAMME, R.M.J., 2007. Modelling offshore sandwave evolution. Continental Shelf Research 27, 713-728.

ROOS, P.C. and HULSCHER, S.J.M.H., 2003, Large-scale seabed dynamics in offshore morphology: Modeling human intervention, Rev. Geophys., 41(2), 1010.

SOULSBY, R. L., 1983. The bottom boundary layer of shelf seas, in Physical Oceanography of Coastal and Shelf Seas, edited by B. Johns, pp. 189–266, Elsevier Sci., New York.

VAN DIJK, T.A.G.P., KLEINHANS, M.G., 2005. Processes controlling the dynamics of compound sandwaves in the North Sea, Netherlands. Journal of Geophysical Research 110. doi 10.1029/2004JF000173.

## ACKNOWLEDGEMENTS

The presented research is part of the PhD research of the first author, which is supported by the Dutch Technology Foundation STW, applied science division of NWO and the Technology Program of the Dutch Ministry of Economic Affairs. We acknowledge Hendrik Aken of NIOZ for providing the data for the Marsdiep inlet used in this study. Finally we acknowledge one anonymous reviewer for the suggestions which improved the readability of the paper enormously. This is NIOO publication number 4504.