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Predicting the occurrence of sandy seabed macroforms in areas dominated by tidal processes

Prognozowanie występowania makroform piaszczystego dna morskiego na obszarach z dominacją procesów pływowych

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Abstract: The main aim of the article is to review the impact of semidiurnal tides on sedimentary structures of the seabed surface . The presented results of numerical modeling created on the basis of previous studies are focused on changes in marine bedforms caused by strong bottom currents and their correlation with previous research in Europe – the southern part of the North Sea and in the USA at the Long Island coast. Particular attention was given to the velocity and frequency of rhythmic tidal events. Described hydrodynamic models also include the values of depth, sediment grain size, as well as stresses between marine water and the sandy bottom. Results confirmed the effectiveness of the method used in the study regarding changes in the bedforms' height and length and the need to consider other factors to obtain more accurate results. What is also important from the point of view of research of seabed macroforms and processes causing their formation is also the fact that intense transport of sandy material may condition human activity, primarily the interference in the shape of surface sedimentary structures, e.g., during location of foundations of hydrotechnical constructions, cables and pipelines, offshore wind farms or construction of port infrastructure. Therefore, it is necessary to investigate what factors affect the areas of modern shelves and determine sediment transport.

Keywords: seabed morphology, hydrodynamics, tides, numerical modeling

Streszczenie: Głównym celem artykułu jest przegląd badań naukowych dotyczących oddziaływania pływów półdobowych na powierzchniowe struktury sedymentacyjne dna morskiego. Przedstawione wyniki uzyskane przy użyciu modeli numerycznych stworzonych na podstawie prowadzonych wcześniej badań koncentrują się na zmianach wysokości i rozstępu piaszczystych form morfologicznych w środowiskach zdominowanych przez występowanie silnych prądów przydennych przy jednoczesnej korelacji z uzyskanymi rezultatami analiz przeprowadzonych w Europie (południowa część Morza Północnego) oraz USA (wybrzeża Long Island, NY). Szczególną uwagę poświęcono prędkościom prądów pływowych i ich częstotliwości. Zastosowane modele hydrodynamiczne uwzględniają również zmiany głębokości, średnicy ziaren osadu oraz naprężenia występujące pomiędzy wodą morską a powierzchnią dna. Uzyskane rezultaty potwierdzają efektywność zastosowanej metody badań w prognozowaniu zmian rozstępu i wysokości form akumulacyjnych dna, ale także potrzebę uwzględniania większej ilości parametrów hydrodynamicznych w celu uzyskania bardziej dokładnych wyników. Istotny punktu widzenia opisywanych badań makroform oraz procesów kierujących ich powstawaniem wydaje się być fakt, iż intensywny transport materiału skalnego może warunkować działalność człowieka, przede wszystkim jego ingerencję w zmiany powierzchni dna morskiego między innymi podczas posadawiania budowli hydrotechnicznych, kabli i rurociągów, farm wiatrowych czy budowy infrastruktury portowej.

Słowa kluczowe: morfologia dna morskiego, hydrodynamika, pływy, modelowanie numeryczne

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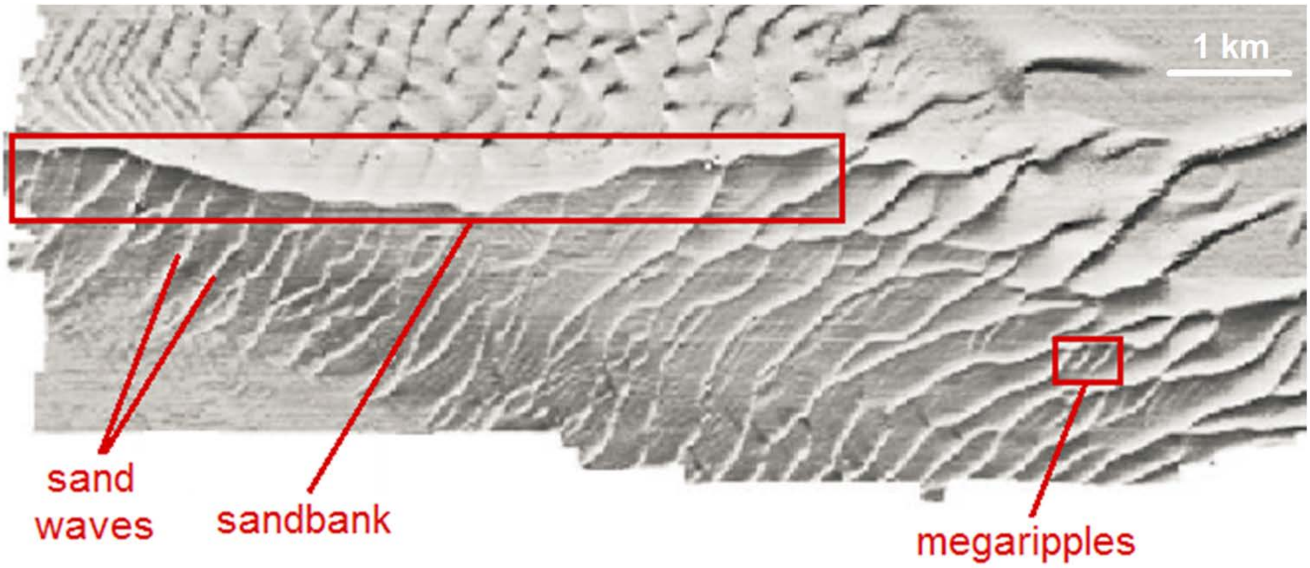

Fig. 1. Described types of the sandy bedforms (based on: Mackie et al., 2007).

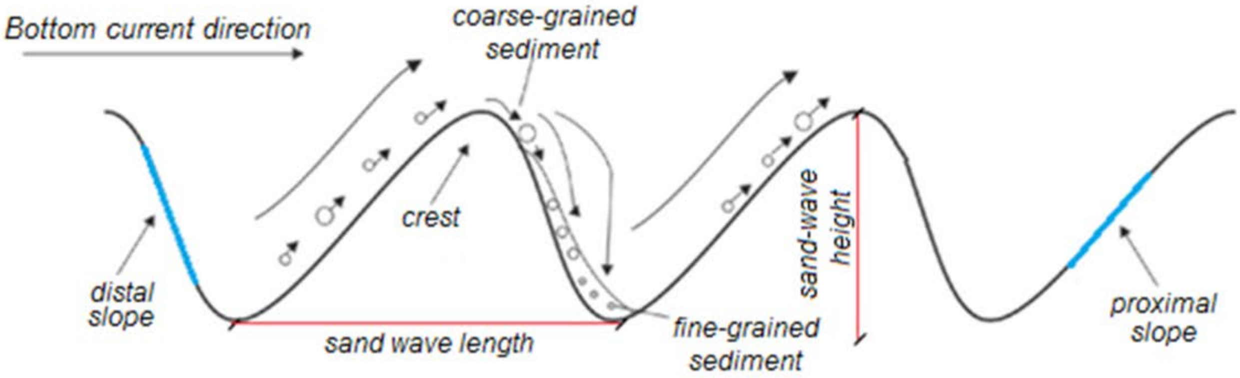

Fig. 2. Sediment transport on the surface of bedforms (based on: Waage, 2012).

INTRODUCTION

The marine shelf habitat is a specific environment with occurrence of numerous, complex processes responsible of the sediment transport. Different types of accumulative bedforms are created under significant supplies of sediment and relatively large velocities of bottom currents causing movement of debris (Passchier, 2005).

The lowermost sedimentary structures of regular surface are ripple marks, the lengths and heights of which (crest-to-crest distances) do not exceed 1 m. The largest, analogical two-sloped bedforms, called sand waves, can reach the length of several hundreds meters and a height of more than 20 m (Fig. 1.).

Larger accumulative forms such as sandbanks will are often observed with a sediment deposition rate stronger than during the formation of sand waves (Belderson et al., 1982). Erosional bedforms such as gravel waves and furrows can also appear in the case of extremely intensive bottom currents (Ashley, 1990; Waage, 2012).

Sediment grains with a diameter in the range of 0.063-2 mm move due to bottom currents reaching 0.5-1 m·s^{-1} (Waage, 2012).

After crossing the crest of such nearly sinusoidal structures, the speed of suspension decreases and causes accumulation in the lower part of the steep distal upward slope (Fig. 2.).

Precise determination of hydrodynamic parameters, referring to movement of fluids, defined as seawater and its suspensions containing sediment material is the key factor in prediction of sandy bottom changes (Tonnon et al., 2007). In regions where tides are the main marine sediment transport factor, determination of their velocity and frequency is performed (Németh et al., 2002). They allow for consideration of the laminar water flow.

However, to take into account the turbulent flow taking place

Fig. 3. Research area in the first and second part of the described numerical model (source: ESRI, 2018).

between sand wave crests, we should describe other properties of marine water, such as its dynamic viscosity, defined as the ratio of shear stress (tangent to the seabed surface) to shear rate, which determines the propensity of the difference in velocity between water layers. The value of kinematic viscosity, which is the ratio of dynamic viscosity to fluid density, is also frequently used (Dorst, 2008; Dorst et al., 2013). The parameters of transported sediment material, mainly the average grain diameter, are also significant (Besio et al., 2008).

It is also worth mentioning that hydrodynamic changes in tide-dominated environments are described in the literature most often, mainly due to the rhythmic nature of sediment transport. There are much fewer attempts to describe such processes dependent on other factors, such as wind waves, sea currents or gravitational flows (Campmans et al., 2017; Campmans et al., 2018).

Large marine surface sedimentary structures, having the ability to migrate at several hundred m per year, often constitute an obstacle from the perspective of ships' navigation. They also limit the possibilities of setting up hydrotechnical constructions, wind farms, cables or pipelines in shelf areas. For this reason, their detailed specification seems to be necessary (Hulscher, 1996; Blondeaux, & Vittori, 2016).

The aim of this article is to describe the creation of various seabed sedimentary structures and indicate the basic processes that are crucial during their formation, with particular regard to semidiurnal tidal cycles. The focus was primarily on numerical modeling of sediment transport in regions with the most frequent occurrence of large accumulative bedforms. It is also important to prove the usefulness of presented equations, which were previously described by authors of other publications referring to the tidal environment.

MATERIALS AND METHODS

Three presented numerical models predicting the occurrence of sand waves and other accumulative forms on the shelf seabed take into account the speed and frequency of bottom currents as well as the diameter of sediment grains. The focus was on the study of processes in the tidal environment due to the rhythmical nature of observed changes.

The first model was created to determine the mechanisms of sandy sediment transport in the southern section of the North Sea between 52 and 55°N, with particular emphasis on the Eurogeul channel area, whose central point (52.936°N, 3.933°E) is situated on the approach fairway to the port of Rotterdam (Fig. 3.).

These studies were particularly important from the point of view of maritime navigation. They allowed to estimate the extent to which the height and length of bedforms will change and whether the processes taking place in the study area will have any negative impact on the movement of ships near the port.

The morphological model created by the author is based on

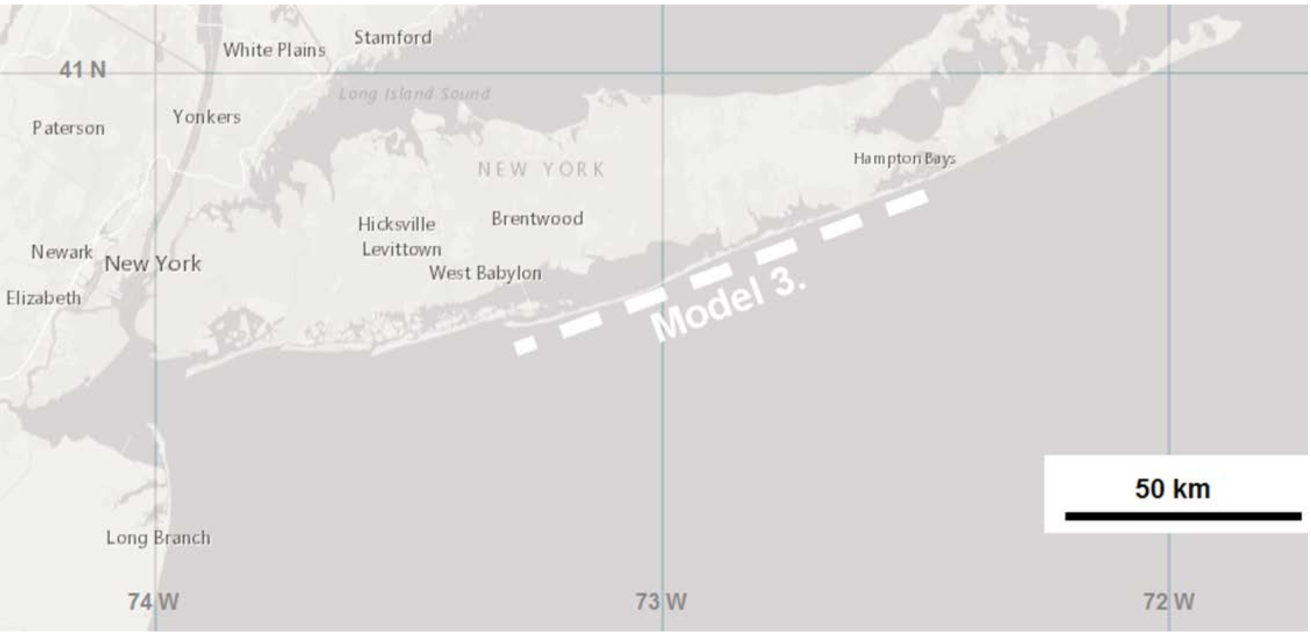

Fig. 4. Research area (white dotted line) in the third part of the described numerical model (source: ESRI, 2018).

Tab. I. Basic parameters describing the conditions in the investigated location (after: Németh et al., 2002).

PARAMETER	DEFAULT VALUES
Tidal current frequency	4,47427·10-5 s^{-1} (semidiurnal tides)
Water temperature	2–17 °C
Angle of sand repose	27°
Kinematic viscosity of water	1.06–1.64·10^{-6} m2·s^{-1}
Depth	0–120 m
Diameter of sand grains	0.5–2 ·10^{-3} m
Velocity of tidal currents	0–1.5 m·s^{-1}
Kármán constant	0.41

Tab. II. Parameters describing the conditions on the south of Long Island coast (after: Whitmeyer & Fitzgerald, 2008).

PARAMETER	DEFAULT VALUES
Water depth	0–20 m
Average sand grains diameter	0,0625–2·10^{-3} m
Ratio between real and critical shear stress	0–28

earlier analytical hydrodynamic research provided by Hulscher (1996), Gerkema (2000), Hulscher and Dohmen-Janssen (2005), and Németh et al. (2002). It assumes that the behavior of these accumulative forms can be described by only a few equations allowing to describe sediment motion processes in a two-dimensional system. Values of parameters included in this model are presented in table I.

The model for sediment transport and changes in seabed morphology aimed to determine the lengths (λ) and heights (η) of sand waves which should be expected in the analyzed region. Therefore, the following empirical equations were used: (1), (2) where ε is the kinematic viscosity of water, σ – frequency of tides and θ – the angle of natural sand repose in the marine environment.

The next part of the numerical model, referring to the forecasting of seabed morphology types, is designed to describe the formation of accumulative bedforms observed in the North Sea between the coasts of France, Netherlands, Belgium, and the United Kingdom (Fig. 3.).

In order to determine the types of investigated bedforms that can be found in this region, the model takes into account the relationship between two parameters: Stokes number Stk and the resistance parameter S, which are described by equations: (3), (4) where: (5), (6), (7) where H is the water depth, d50 – mean diameter of sediment grains, ε – kinematic viscosity of water · 10^{-6} at temperatures 0-25°C, κ – Kármán constant (dimensionless parameter used in describing turbulent motion), σ – tidal frequency in Hz, u – the velocity of tidal currents.

The third model was created in connection with the need to estimate the size of accumulative bedforms near Moriches Bay located south of Long Island in NY, United States (Fig. 4.).

This hydrodynamic transport model was mainly aimed at determining changes in the height and length of surface sedimentary structures in the southern shores of Long Island. This relation is described by equations (Whitmeyer& Fitzgerald, 2008; Soulsby, 1997; Hoan et al., 2011): (8), (9) where λ is the length of a sand wave in m, H – depth in m, η – sand wave height in m, d50 – mean sediment grains diameter in m and Ts – ratio of critical shear stress to shear stress in the observed area.

Local environmental conditions typical for the observed area were taken into account (Tab. II.).

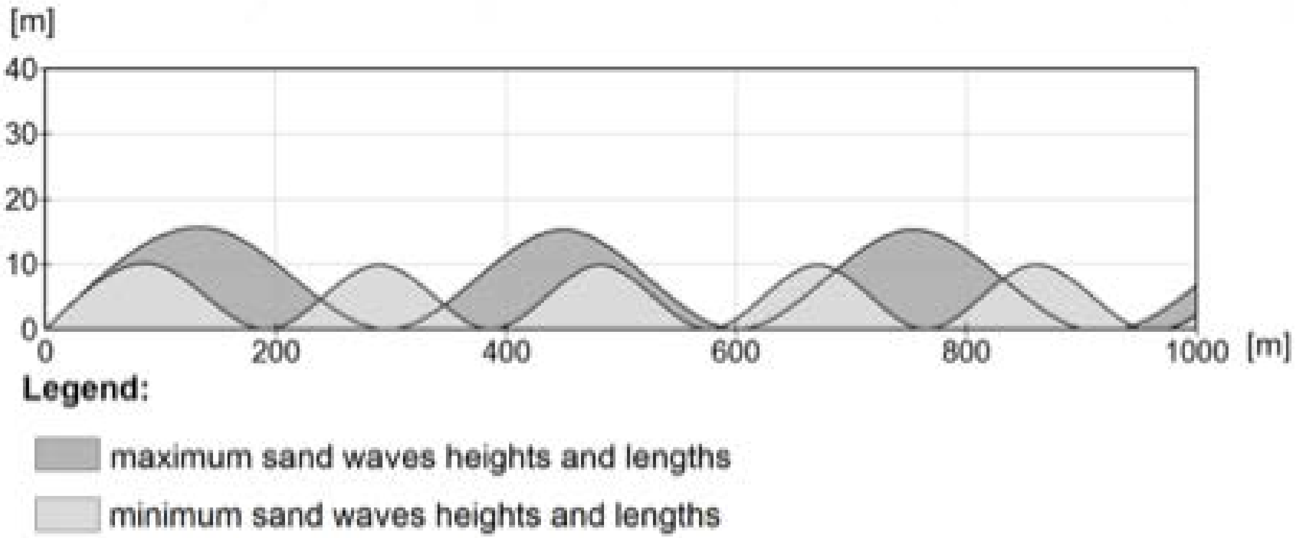

Fig. 5. Predicted maximum and minimum bedform heights and lengths in the research area (Eq. 1-2).

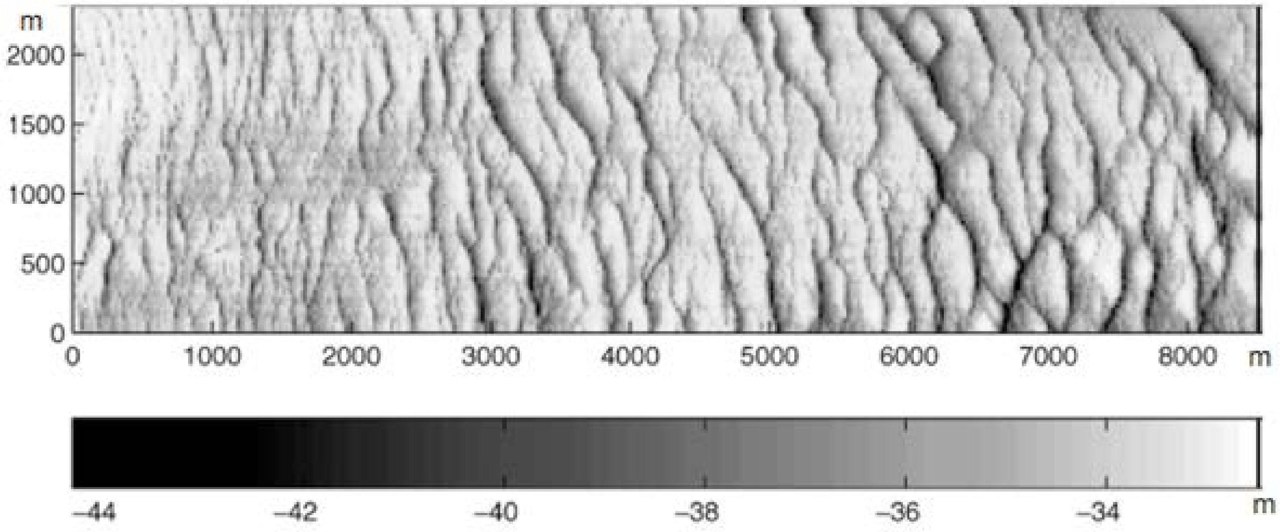

Fig. 6. The actual imaging of the Eurogeul channel seabed (Németh et al., 2002).

Therefore, the Moriches Bay research was focused on the relatively shallow, near-shore zone.

RESULTS

Based on the results of mathematical modeling using the MATLAB computing environment, it was determined that in the first studied area (Eurogeul Channel) sand waves should reach an average length above 300 m, but during domination of higher temperatures they will be approximately 100–110 m lower (Eq.1.). The expected minimum height of bedforms is almost 10 m with the water temperature reaching 17°C and slightly above 15 m (Eq. 2.) at 2°C (Fig. 5.).

The height of sand waves in this region is in fact consistent with the predicted values. However, the model does not predict accurately the maximum lengths, which can reach even 600 m (Knaapen and Hulscher, 2002). Based on the picture below showing bathymetric measurements, it can be concluded that their length is about 150-300 m (Fig. 6.).

The second part of the numerical model, relating to the larger southern part of North Sea, considers a division into three representative depth intervals: 0–20 m, 20–70 m and 70–120 m with different values of Stokes number Stk and resistance parameter S (Fig. 7.).

At depths below 20 m, where higher values of both the Stokes number and the resistance parameter begin to be visible, it can be assumed that the dominance of sand waves and sandbanks will be clearly marked.

The dependency between Stokes number and the resistance

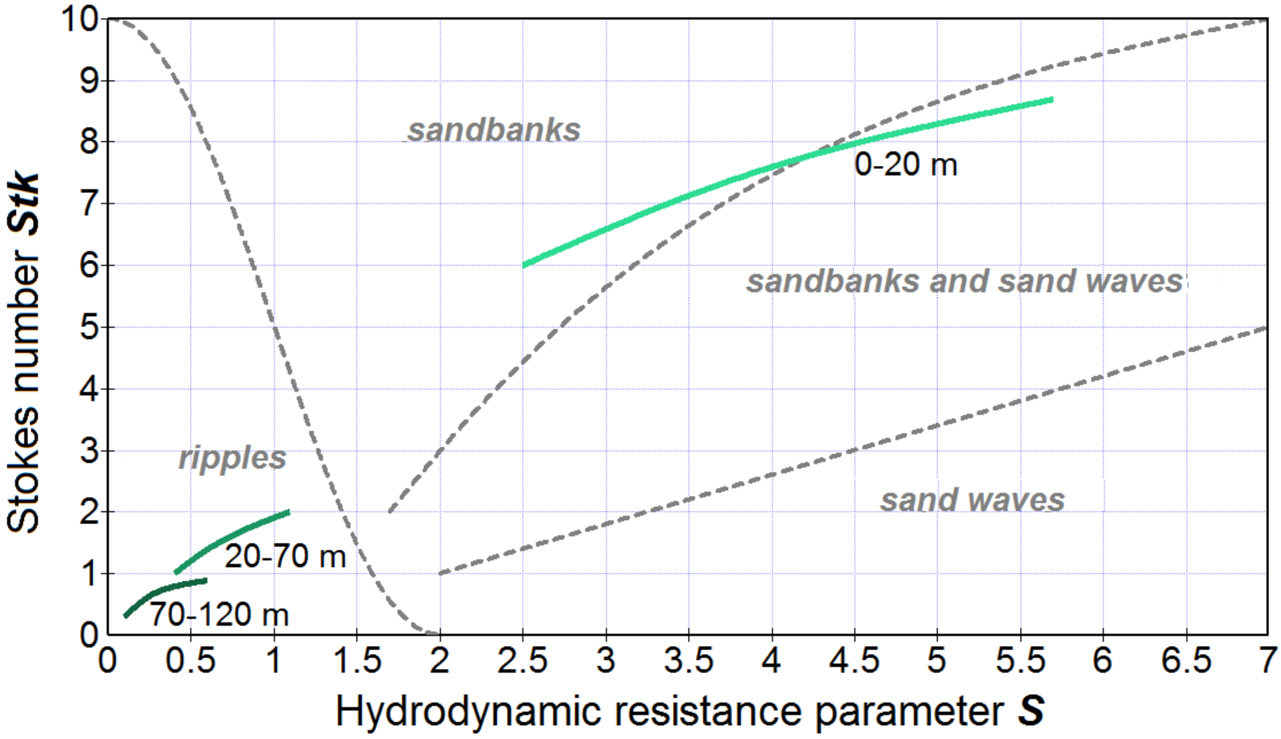

Fig. 7. Dependency between Stokes number and resistance parameter due to depth (Eq. 3-7; van der Veen et al., 2006).

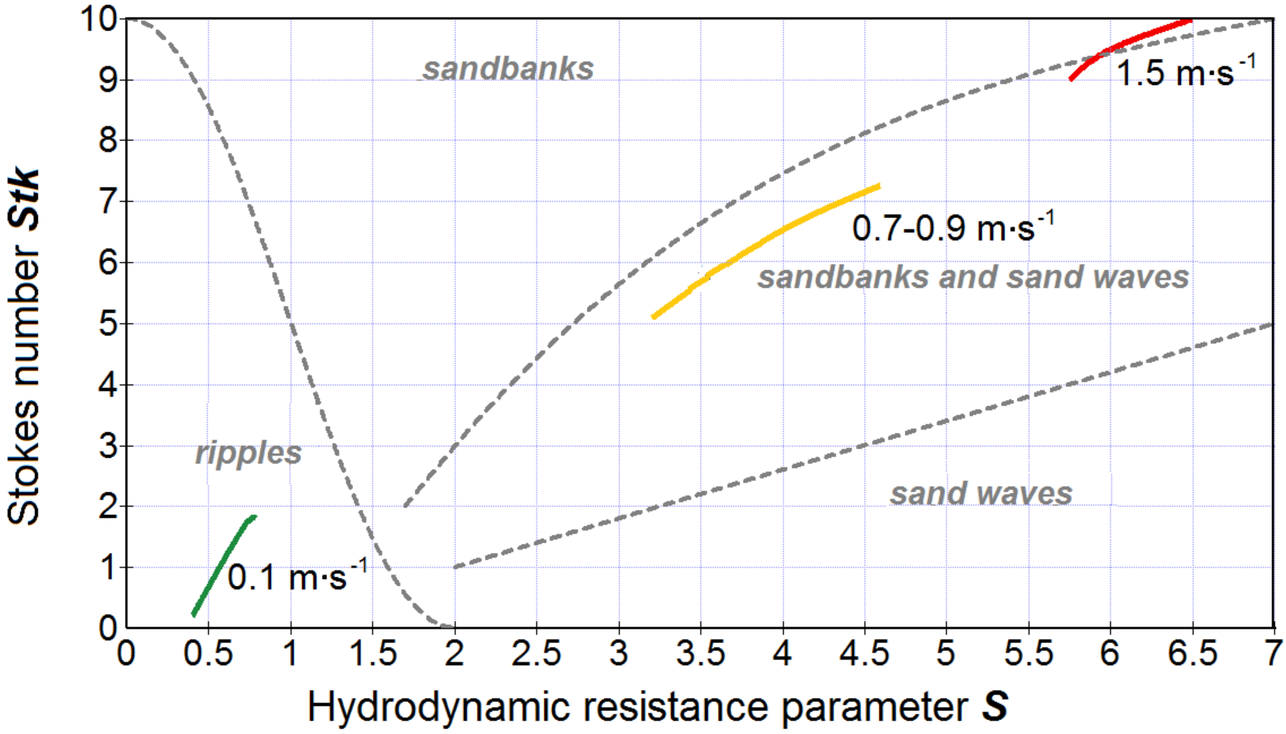

Fig. 8. Relation between Stokes number and the resistance parameter due to current velocities (Eq. 3-7; van der Veen et al., 2006).

parameter confirms the assumption that the highest probability of macroform occurrence in the North Sea bottom is also connected with the highest values of the velocity of water masses movement in the research area (Fig. 8.). The lowest values ($0.1\ m\cdot s^{-1}$) are connected with predicting the occurrence of only ripple marks, and the highest ($1.5\ m\cdot s^{-1}$) suggest the appearance of sand waves and sand banks.

The results obtained by the model described above are therefore a confirmation of the simultaneous existence of two

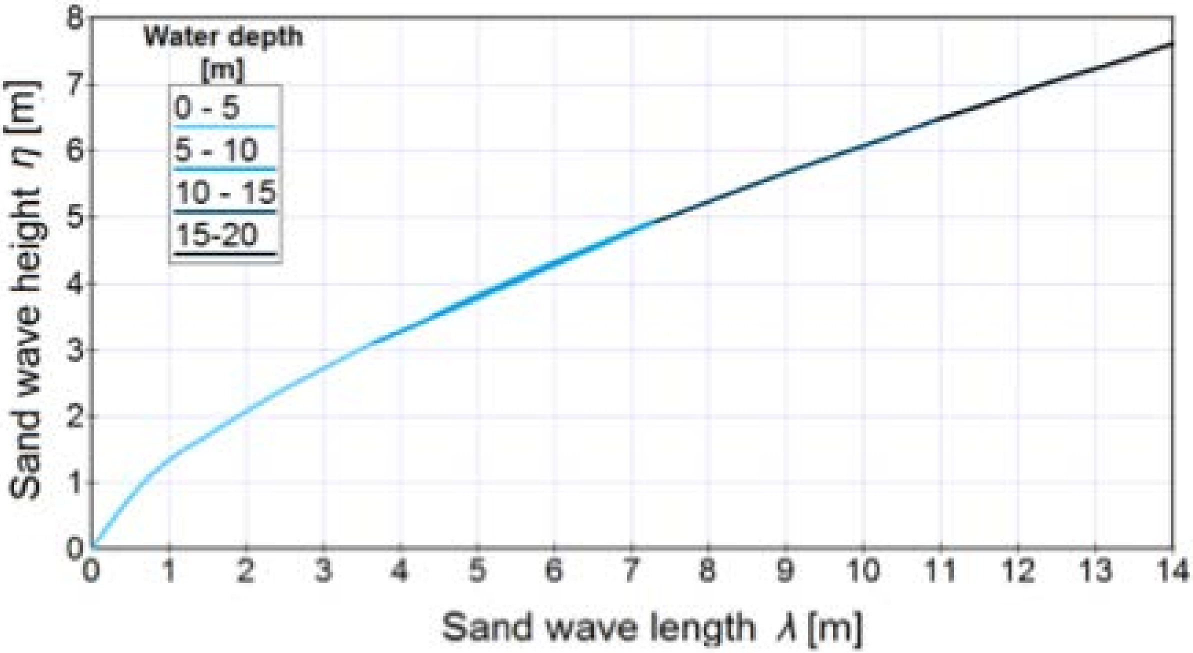

Fig. 9. Relation between bedforms height and length due to water depth (Eq. 8-9).

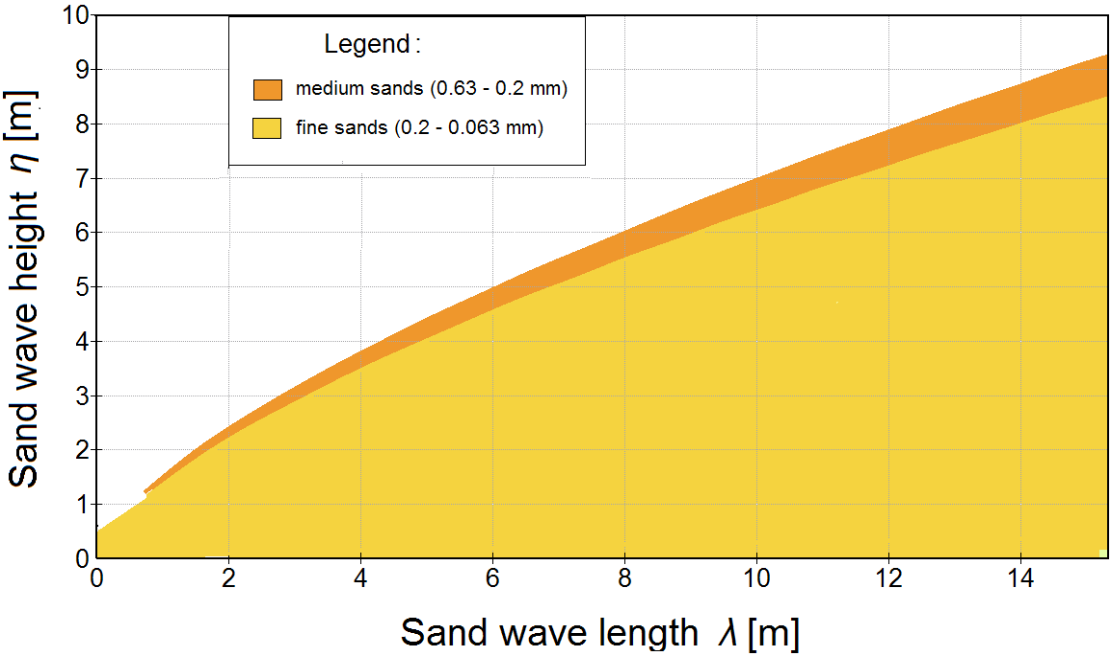

Fig. 10. Dependency of bedform height and length due to sediment grains diameter (Eq. 8-9).

regularities: a greater probability of sand waves occurrence in shallower environments and a significant influence of tidal currents on formation of these structures.

The results of the third numerical model (Eq. 8-9) correctly refer to macroforms with a length of above 12 m (Fig. 9.), which should dominate in the research area at the depth of more than 15 m, according to previous observations (Whitmeyer and Fitzgerald, 2008; Hoan et al., 2011). However, the predicted values outside this range are not correlated properly with the real sand wave heights, which usually do not exceed 3 m in this area (Whitmeyer and Fitzgerald, 2008).

A similar overstatement of results obtained by the model in relation to the real bottom morphology is also noticeable when describing the relationship between the height and range of forms taking into account the variability of sediment granulometric composition (Fig. 10.).

The average grain diameter lies in the range of 0.2–0.63 mm

(Hoan et al., 2011), which would suggest the occurrence of sand waves with average heights above 6 m. It means that the model overstates the value of bedform heights by 30–50%.

DISCUSSION

All equations based on the literature sources and used in the described hydrodynamic models take into consideration only tidal processes. The first part, relating to the Eurogeul channel area near Rotterdam, allowed for a relatively accurate prediction of average sand waves height and length. However, failure to take into account other reasons of extreme events caused lack of information regarding the possibility of formation of larger sedimentary structures. Similar remark was emphasized in previous publications of Hulscher (1996), Dorst et al. (2008, 2013), as well as Naqshband (2014). Only the latest research in this region has attempted to take into account wind waves and storm surges (Campmans et al., 2017; Campmans et al., 2018).

The second part of the described hydrodynamic model allowed for accurate prediction of sedimentary structure types both depending on depth and tidal current velocities. Analogous dependencies in the North Sea area were described, e.g., by Gerkema (2000), Hulscher & Van der Brink (2001), and van der Veen et al. (2006).

The third part, which referred to the area of Moriches Bay south of Long Island, comprised predicted sedimentary structure heights and lengths qualified as variables independent of each other. This is the probable cause of modeling non-compliance with real values. Previous research conducted by Whitmeyer and Fitzgerald (2008), as well as Hoan et al. (2011) proves the similarity of predicted and observed length of accumulative bedforms, but also the significant overestimation of their height.

All presented hydrodynamic models seem to be useful due to domination of tidal processes in the observed areas. However, deficiencies in precision of obtained results are also gently denoted. They suggest the fact, that describing other processes such as storm surges, wind waves or gravitational movements can prove to be as important as describing tides, which were included in the calculations.

SUMMARY AND CONCLUSIONS

The presented results regarding modeling of sediment transport processes obtained by the author confirm the thesis that large accumulative forms on shallow tide-dominated shelf areas are mainly formed as a result of rhythmic disturbances caused by tidal currents. These case studies covering the coasts of North Sea and Moriches Bay also made it possible to compare field data with previously published observations and morphological models. The calculations allowed for verification of previous research results obtained in these areas.

Such a method is often used particularly in predicting formation of large bedforms in tide-dominated shelves, where changes occur very often and rhythmically – usually in semidiurnal cycles.

These results enabled forecasting of average lengths and heights of surface marine sedimentary structures with relatively high precision due to the fact that several factors have been taken into account – mainly bathymetry, mean sediment grains diameter, as well as velocity and frequency of tidal currents. However, the maximum size of accumulative bedforms in the southern part of the North Sea area has not been predicted accurately with the expected high precision.

Although it can be concluded that the used method allows for a relatively large (though never 100%) accuracy to estimate the scale of evolution of large sedimentary structures. Unfortunately, a significant number of factors simultaneously affecting the processes of their formation causes difficulties in predicting changes in their size. Their forecasting in highly dynamic environments is, however, particularly important, especially in the context of human activity. For this reason, mathematical modeling of marine bottom changes is being used more often, taking into account such parameters as the mean diameter of sediment grains, size of bottom shear stress or dynamic and kinematic water viscosity.

From a scientific point of view, large marine bedforms are specific structures, where the influence of hydrodynamic processes brings significant, clearly visible changes in the environment. Such investigation in the described locations also has an invaluable practical application. Numerical modeling is a relatively effective, low-cost method of seabed monitoring, very important in areas of intense ship traffic, reconstruction of port infrastructure, foundations for cables, pipelines, wind farms and drilling platforms. Intensive anthropogenic activity is the main factor limiting seabed research and determination of their necessity.

In conclusion, the presented research methods prove to be very important in both scientific and utilitarian terms. However, hydrodynamic modeling of changes taking place in the described locations should also take into account processes other than only tidal currents and this has been increasingly noticeable in the recent years.

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