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Modelling of shoreface nourishment in the Lithuanian nearshore of the Baltic Sea

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Various measures have been used to protect coastal areas controlling beach erosion. During the last decades, all over the world there has been a gradual change from engineering to soft coastal defense techniques, among which artificial beach nourishment is particularly popular. This study evaluates the suitability of the shoreface nourishment, when borrow materials are placed to form a nearshore berm, for the Lithuanian coast of the Baltic Sea. The analysis is based on the results of the MIKE 21 modeling system for sediment transport, bottom erosion and dynamic equilibrium processes under varying climatic conditions, first of all in stormy weather that has the major impact on hydrodynamic and sediment processes. The current study aims to demonstrate the importance of the nourishment project assessment prior to its actual implementation and to provide an example of methodology for such an assessment which demonstrates the importance of climatic data and possibilities of modelling.

Key words: sediment transport, shoreface nourishment, MIKE 21 model, Baltic Sea

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1. INTRODUCTION

Extreme storms have caused the changes of hydrodynamic and sediment processes in the Baltic Sea. These investigations are described by many researchers (Bobertz, 2005; Harff, 2001; Harff, 2005; Kaczmarek, 2005; Pruszak, 2004; Szmytkiewicz, 2000). Lithuanian nearshore is a part of the Baltic Sea and has a short sandy coastline of approximately 94 km (Gudelis, 1998). The main harbor of the country, Klaipėda State Seaport, is located in the Klaipėda Strait on the eastern coast of the sea, which connects it with the Curonian Lagoon. During the recent decade the port has been rapidly developing and thus required several major reconstruction projects, including construction of new quays and fairway dredging. These works have significantly altered sediment transport processes in the Klaipėda Strait and nearshore (Pustelnikovas, 2002; Gailiušis, 2000; Kriaučiūnienė, 2000; Trimonis, 2000, Trimonis, 2005). The consequential activation of coastal processes is also presumed to be associated with the global climate change and a significant increase of stormy days observed in Lithuania for the last 20–30 years. The state of the beach has particularly worsened in the recent years.

There are various possible measures to control beach erosion. During the last decades, all over the world there has been a gradual change from engineering to so-called soft coastal defense techniques (Hanson et al., 2002). Hamm et al. (2002) highlight the vast variety of historical development patterns and current experiences existing in Europe in technological, legal and various other aspects. Polish scientists have implemented numerous interesting coastal researches (Kaczmarek et al., 2005; Pruszak, 2004; Szmytkiewicz et al., 2000). Their experience is useful in solving the problems of Lithuanian coastal protection.

At present, due to its environmental acceptability, beach nourishment is one of those most frequently applied soft measures. This is especially true for the USA, which has become the world's leading country in terms of experience, number of projects, and nourishment volumes, although summarized information is "fragmented and incomplete" (Valverde et al., 1999). Two major types of artificial beach nourishment can be distinguished: a) beach replenishment, when borrow materials are placed directly on the beach to increase its width, and b) shoreface fill, when materials are placed underwater on the shoreface to form nearshore berm (Johnson et al., 2001; Pruszak, 2004). The nearshore berm protects the coast by reducing wave impact on the protected coast (Mangor, 2001). In some cases, it can operate as a feeder berm supplying sediments to the coast, as demonstrated, *e.g.*, by Charlier and De Meyer (2000).

Shoreface nourishment is usually cheaper than conventional beach nourishment. There has therefore been an increased interest in projects concentrating on this type of construction as well as the combined approach, i.e. applying beach replenishment together with shoreface nourishment. The general success of the case studies under EU NOURTEC (Nourtec…, 1997), Eurosion and SAFE programs demonstrates the attractiveness of the shoreface nourishment as a viable alternative to simply filling the beach.

Big quantities of borrow material, however, are needed for shoreface nourishment. For protecting the segment of the Lithuanian coast that is close to the harbor, one of possible sand sources is the fairway of the Klaipėda Seaport. At present, dredged material from the Klaipėda Strait is dumped into the Baltic Sea, but clean sand which is extracted could be used for beach nourishment. It would also be an economically sound solution, because the sand for nourishment would not have to be transported far from the place of extraction, which is the current practice since the dumping sites are located far offshore because of the safety requirements.

The overall aim of this study is to determine the best sites for shoreface nourishment in the Lithuanian nearshore of the Baltic Sea by analyzing sediment transport, bottom erosion and dynamic equilibrium processes under varying climatic conditions, especially in stormy weather which has the major impact on hydrodynamic and sediment processes. There are very few on-site measurements made for the currents in the nearshore zone in stormy conditions. Therefore wind- and wave-generated currents were modelled using wind velocities and directions corresponding to high energy events as input data. A more detailed study of one of the proposed sites intends to demonstrate the importance of close examination of hydrodynamic and sediment transport processes prior to implementation of a nourishment project and to propose an inceptive methodology for such an assessment.

2. METHODOLOGY

Course of the study

Evaluation of the Lithuanian nearshore for the shoreface nourishment conditions was done in the following order:

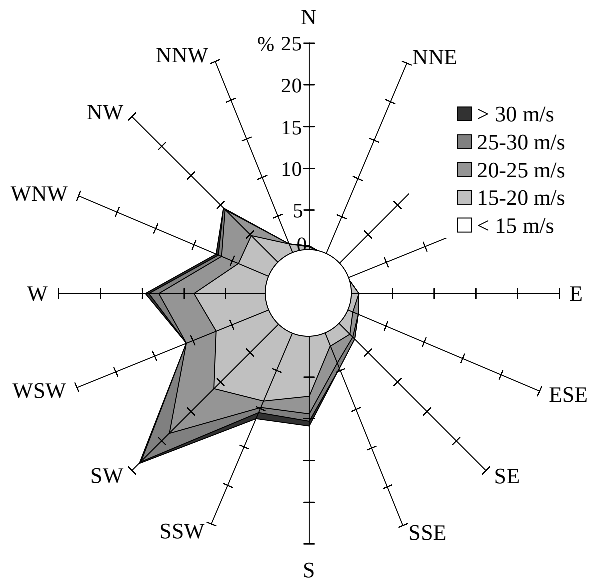

Fig. 1. Wind rose of strong winds according to observations of 1995–2000 (data from Lithuanian Hydrometeorological Service under the Ministry of Environment)

1 pav. Stiprių vėjų rožė 1995–2000 m. (pagal Lietuvos hidrometeorologinės tarnybos duomenis)

- characteristics of wind at the Klaipėda seashore were investigated, with particular attention to strong (for definition refer to section "Characteristics of wind and wave regime at Klaipėda seashore") and durable winds (Fig. 1);
- wave and hydrodynamic regimes in the nearshore zone were modelled under different directions of wind (hydrodynamic model was calibrated using measuremet data);
- sediment transport was modelled for selected directions of wind with 20 m/s velocity for the greater part of the Lithuanian coast of the Baltic Sea, and on a more detailed scale for the case study area;
- processes of sediment transport, accumulation and bottom erosion were analyzed under 20 m/s wind of different directions evaluating wave conditions;
- analysis of the specific site for shoreface nourishment (case study) and investigation of sediment transport processes during an actual year.

Description of the modelling

The wave, hydrodynamic and sand transport processes were modelled using the two-dimensional MIKE 21modelling system, more specifically the Near-Shore Spectral Wind-Wave (NSW), Hydrodynamic (HD) and Sand Transport (ST) modules. The biggest influence on lithodynamic processes of the Southeast Baltic has directions, periods and heights of waves in the surf zone.

The NSW model (Danish…, 2002) defines the dispersion of wind-generated surface waves in the nearshore zone. For this model, the following initial data are necessary: depths of coastal water (bathymetry), wind velocity and direction, limiting conditions in the deepest water depth (average wave height and period, average direction of wave dispersion, biggest declination from the wave direction, direction of distribution of wave energy). The results of applying the NSW model are the following in each grid cell of the modeling area: period and height of wave, direction of wave dispersion and its standard deviation. The modelled wave parameters are used for modelling hydrodynamic and sand transport processes as the initial data in HD and ST models.

Hydrodynamic modelling was carried out for simulating wind- and wave-generated currents on the shoreface for different wind conditions. The unevently changing flows of the two-dimensional HD model (Danish…, 2001) is the solution of a non-linear equation system. The changes of flow and water level in the directions of *x* and *y* are described according to vertical integrated equations of continuity and conservation of momentum. The initial data necessary for the HD model are the following: the orientation of water territory, geographical latitude and bathymetry, wave parameters (modeled by NSW), time step and duration of modelling, wind velocity and direction, boundary conditions (the water level or discharge is to be indicated for each open boundary of the model) and the coefficients of the bottom roughness and turbulence. The water level variations and flows in the directions of the *x* and *y* axes in each modelled grid cell are the result of the HD model.

To evaluate the sediment transport in the nearshore of the Baltic Sea, we used the ST model (Danish…, 2002a). It enables the calculation of sediment transport rates and possible bottom changes (erosion and accumulation areas) caused by flows and waves. The bottom changes of the nearshore caused by sediment transport are calculated solving the equation of the conservation of sediment mass per modelling period. Initial data of the ST modelare: nearshore bathymetry, structure of flow velocities (modelled by the HD model) and wave parameters (modelled by the NSW model); the coefficient of bottom roughness, relative density of sediments, porosity of bottom materials, median grain size of sediments and their geometric standard deviation. Results of the ST model are: unit discharge of sand transport (m^3/year/m) at any time and in any grid cell of a modelled area; average unit discharge of sand transport (m^3/year/m) per investigated period in any grid cell of a modelled area; discharge of sediments (m^3/year) in any section of the modelled area and at any time; the bottom changes of the modelled area (erosion and accumulation) per investigated period (m/day).

For modelling sediment transport (ST), it is necessary to define the average grain diameter in a sediment load and the grain distribution. According to Galkus (1997), the average diameter of sediment grains in the Lithuanian nearshore is $d_{50\%}$ = 0.2 mm. The characteristic of the grain distribution used in MIKE 21 is σ_g, calculated from the curve of sediment distribution as the ratio:

$$\sigma_g = \sqrt{\frac{d_{84\%}}{d_{16\%}}}\ .$$

For our study, we used σ_g = 1.30 based on the sediment distribution curve and the above formula.

Calibration of the hydrodynamic model

Flow velocities were modelled by the hydrodynamic model HD. The Baltic near-shore area 74 km in length was chosen (Fig. 2a). The model was calibrated using data of flow measurements in the Baltic Sea and data from the meteorological station near Klaipėda (Gailiu-

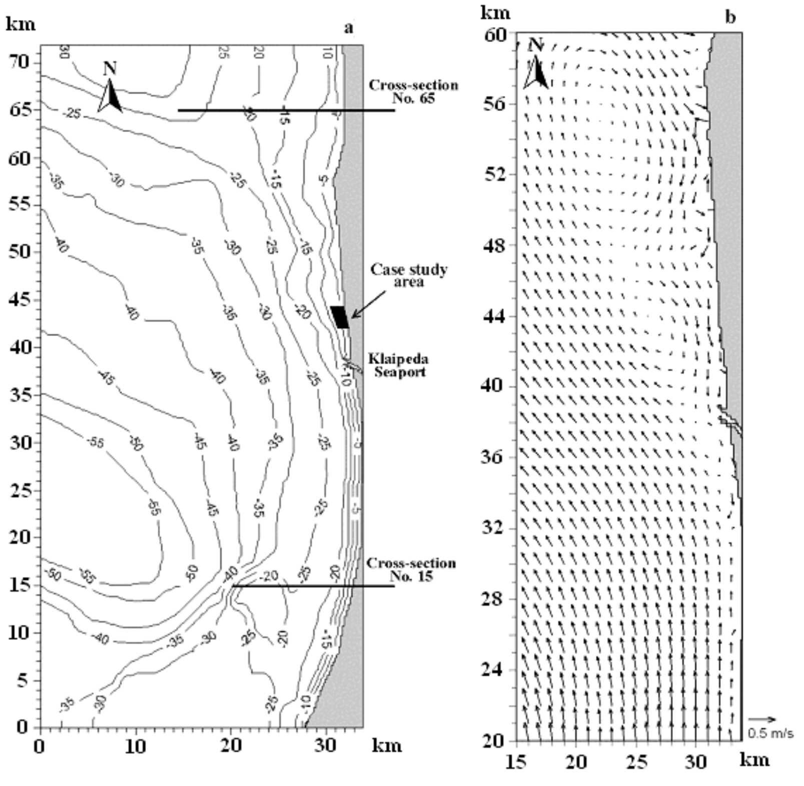

Fig. 2. Bathymetry of the modeling area (case study area – Melnrage II) (*a*) and simulated flow structure under the west wind of 20 m/s (*b*) (bathymetry prepared according to the map (*Baltic Sea. Middle part. Lithuanian Coast and EEZ.* 1:200000. Klaipėda, 2005))

2 pav. Modeliuojamos srities batimetrija (*a*) (pažymėta sritis – Melnragė II) ir tėkmių struktūra pučiant vakarų krypties 20 m/s vėjui (*b*) (batimetrija parengta pagal jūrlapį (*Baltijos jūra. Vidurinė dalis. Lietuvos priekrantė ir išskirtinė ekonomikos zona*. 1:200000, Klaipėda, 2005))

Table 1. **Timing and conditions of model calibration**
1 lentelė. **Modelio kalibravimo laikotarpiai**

No. of measurement	Date	Time period	Wind velocity (m/s)	Wind direction (degrees)
1	17 06 2000	12:00 – 18:00	10–11	350–360
2	11 01 2001	14:00 – 22:00	16–18	300–350
3	12 02 2001	03:00 – 10:00	12–13	230–240

Table 2. **Characteristics of stormy winds in Klaipeda according to data of 1995–2000 (data from Lithuanian Hydrometeorological Service under the Ministry of Environment)**
2 lentelė. **Štorminio vėjo charakteristikos Klaipėdoje 1995–2000 m. (parengta pagal Lietuvos hidrometeorologijos tarnybos duomenis)**

Year	Number of storms	Duration (hours)		Velocity (m/s)		Maximum velocity (m/s)
		average	maximum	average	margin of change	
1995	39	20	63	9.5	(8–12)	22
1996	29	20	64	8.8	(7–10)	21
1997	33	24	51	9.1	(8–11)	22
1998	37	21	75	9.1	(8–11)	25
1999	38	33	106	9.9	(8–14)	38
2000	32	30	91	9.5	(8–13)	28
Average	35	25	–	9.3	(8–12)	–

šis et al., 2002). The location of measurements is shown in Fig. 4a, timing and conditions of calibration are provided in Table 1. Comparing the measured and calculated values of flow velocities and directions, it was determined that in all cases the difference of flow directions was not bigger than 20°, and the biggest difference of flows was 35%. Rather good calibration results allow modelling the structure of flows under different hydro-meteorological conditions. During calibration it was determined that the most suitable Manning number was 0.033, and the coefficient of eddy viscosity was calculated according to the formula of Smagorinski (Danish…, 2001).

3. CHARACTERISTICS OF WIND AND WAVE REGIME AT KLAIPĖDA SEASHORE

The wind regime before 1995 in the Lithuanian nearshore at Klaipėda has been summarized in several written sources (Bukantis, 1994; Klimato…, 1996). According to the long-term observations, the average monthly wind speed ranges from 4 m/s in June to 6 m/s in November. For average daily winds, the prevailing directions are southeast (SE) in autumn and winter, west (W) in summer and northwest (NW) in spring.

The strong winds of rather long duration and permanent direction have the greatest influence on the processes of current and wave formation in the nearshore zone. In this article, we follow the classification used in (Klimato…, 1996) that identifies winds with velocity above 15 m/s and below 20 m/s as intense winds, between 20 m/s and 25 m/s as stormy winds, and those above 30 m/s as hurricanes. All these winds jointly are referred to as "strong winds". For Lithuanian conditions, during storms wind velocity in gusts can reach well above their intense or even stormy states, while winds with high velocities (10–14 m/s) are characteristic of prolonged periods.

Table 3. **Average periods and heights of waves in deep water when the velocity of wind blowing from different directions is 20 m/s (prepared according to the report "Математическое моделирование волнового режима на подходном канале и акватории порта". Акционерное общество „Волна", Сочи, 1998)**
3 lentelė. **Bangų aukščiai ir periodai giliame vandenyje pučiant įvairių krypčių 20 m/s vėjui (parengta pagal ataskaitą (*Математическое моделирование волнового режима на подходном канале и акватории порта*, Акционерное общество „Волна", Сочи, 1998))**

	NW	W	SW	S
Average height of waves, m	3.70	4.00	3.80	3.00
Average period of waves, s	6.20	6.50	6.30	6.00

There are 73 days per year in Klaipėda on average when wind velocity of any single measurement exceeds 15 m/s. Strong winds are observed in all the months but have the greatest probability to occur from October to January. The prevailing strong winds are of south (S), southwest (SW), west (W) and northwest (NW) directions. The average number of storms per year constitutes approximately 29. Comparing the prevailing wind directions, strong winds clearly differ from average winds. This difference is predetermined by weak and average winds which are observed in Klaipėda 290 days per year on average.

The period 1995–2000 was analyzed summarizing daily wind observation data for 16 wind directions from the Klaipėda coastal meteorological station. The total number of storms during this period reached 208, their more detailed characteristics are provided in Table 2 Southwest winds clearly dominate among strong winds: SW winds constitute 23.8%, W – 14.6%, SSW – 11.3%, S and WSW – 10.9% (Fig. 1). NW (9.5%) and WNW (7.1%) do contribute as well, while the rest of the winds all together compose merely 12% of the total among which winds of NNE, NE and ENE equal zero.

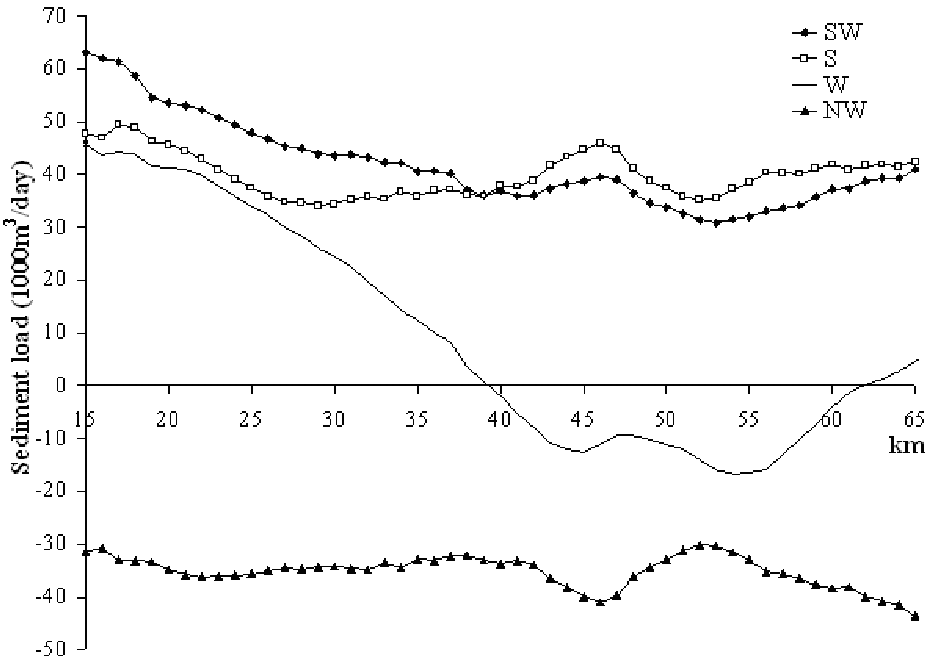

Fig. 3. Estimated sediment load (average sediment discharge in sections 15–65) for sections 15–65 for 20 m/s S, SW, W and NW winds

3 pav. Nešmenų debito pasiskirstymas 15–65 skerspjūviuose pučiant P, PV, V ir ŠV krypčių 20 m/s vėjui

It was determined that winds of S, SW, W and NW directions raise the biggest waves in the nearshore of the Lithuanian coast of the Baltic Sea. Therefore, the nearshore waves were modeled using the latter wind directions and the wind velocity of 20 m/s (Table 3). Wave parameters necessary for determining the limiting conditions of a model in the deepest section of modeled area were defined according to the previous investigations of wave regime in Klaipėda Seaport development projects (Frederic et al., 2000).

4. RESULTS

Currents in the Lithuanian Nearshore of the Baltic Sea

The actual modeling of waves, hydrodynamic processes and sediment transport was performed for the Baltic Sea nearshore area 74 km in length and 33 km in width (Fig. 2a). The modeling area was a rectangular grid composed of 100 × 100 m square cells. The initial data for the ST model were the wave parameters from the NSW model and the flow structures from the HD model that had been simulated for the winds of south (S), southwest (SW), west (W), and northwest (NW) directions. As mentioned earlier, these winds are dominant among strong winds and therefore have the biggest potential for causing sediment transport.

According to the modelling results, with wind blowing from the northwest, currents propagate from the north towards the south with velocities ranging between 0.2 and 0.5 m/s. The western winds generate circulations with currents of different directions intersecting close to the Klaipėda Strait (Fig. 2b). Under such conditions, flow velocities range from 0.05 to 0.35 m/s. The southwest and south winds cause the currents flow at a speed between 0.2 and 0.6 m/s directing them northwards. Consequently, the highest velocities in the Lithuanian Baltic nearshore are observed for the southwest and south winds, thus making them most significant for sediment transport.

Sediment regime

The modelling of sediment transport allows us to examine the direction and magnitude of such processes as well as define the areas of sediment erosion and accumulation. In order to identify such areas, the Lithuanian nearshore was divided into 65 cross-sections located 1 km from each other and perpendicular to the shoreline (Fig. 2a). The gate of the Klaipeda Seaport is located at the cross-section No. 39. Each cross-section extends from the shoreline to the depth of 30 m, beyond which the impact of wave processes on the seabottom is generally considered minimal so that even during stormy conditions sediment transport does not occur. Sediment transport rate (m^3/day) was calculated for each section. The period of one day was chosen, because the average duration of a storm in the Lithuanian nearshore is approximately 25 hours.

Figure 3 shows the areas of bottom erosion and sediment accumulation under strong winds of different directions, most important for sediment transport. The rising segments of the curves indicate bottom erosion in the appropriate cross-sections, and the falling parts imply the opposite process of sediment accumulation. The peaks (representing both local maximums and minimums) of the curves identify changes from the accumulation areas to erosion zones or vice versa. For instance, with the wind blowing from the southwest, sediment accumulation occurs between cross-sections No. 15 and No. 39 as well as throughout cross-sections No. 46–53 (sediment transport decreases), while erosion is observed between cross-sections No. 39 and No. 46 as well as beyond the cross-section No. 53 (sediment transport increases). These peaks are considered to be the best sites for shoreface nourishment (Mangor, 2001).

Figure 3 also illustrates that positive transport (sediments being carried to the North) is observed for the S and SW winds, while negative transport (sediments being carried to the South) occurs with the winds of NW direction. The sediment transport of the opposite directions occurring at the same time forms with the wind blowing from the west. The biggest quantities of sediment are carried with the winds of SW and S directions and the lowest ones with W winds.

Case study

Based on the modeling results and taking into account the recreational value of the beach, the necessity for restoration as well as considering the economic feasibility of the projects the following nearshore beach nourishment sites should be considered: Melnragė II, Plytinė – Birutės kalnas, Smiltynė I, Juodkrantė. These sites are located 3 km and 15 km to the north, 1 km and 22 km to the south from the Klaipėda Seaport gate, respectively. Further, sediment transport processes in one of these sites, Melnragė II, will be analyzed in more detail.

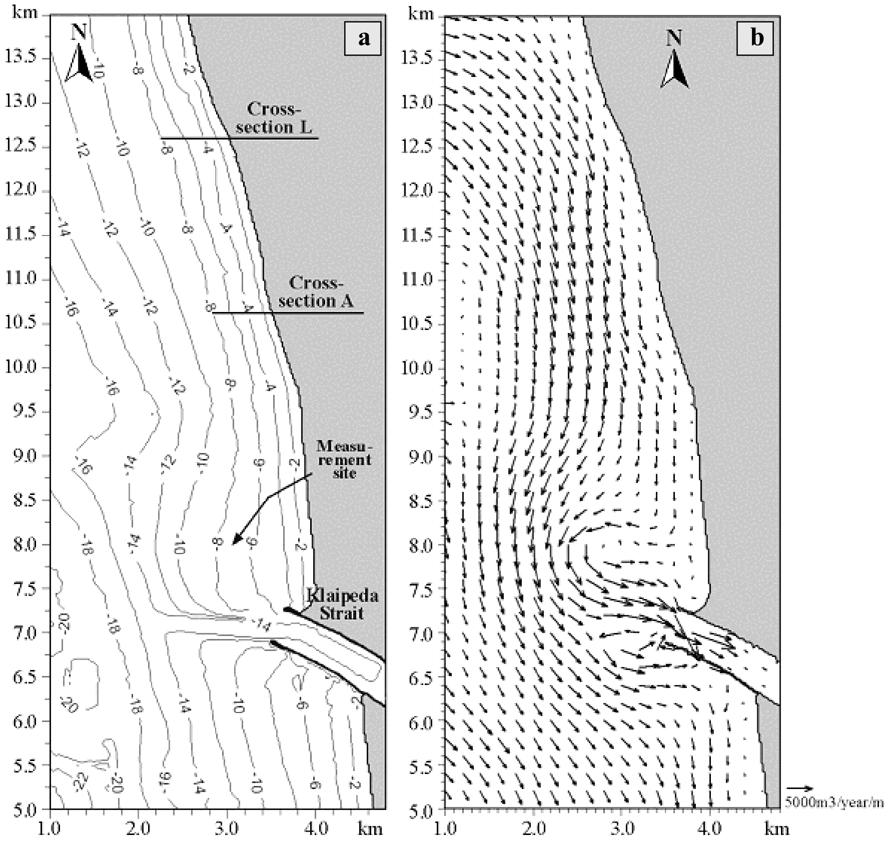

Fig. 4. Bathymetry (territory between cross-sections A and L – Melnrage II) (*a*) and unit discharge of sediment transport (m^3/year/m) with W wind 20 m/s (*b*)

4 pav. Batimetrija (*a*) (teritorija tarp A ir L skerspjūvių – Melnragė II) ir nešmenų vienetinio debito (m^3/metai/m) pasiskirstymas pučiant vakarų krypties 20 m/s vėjui (*b*)

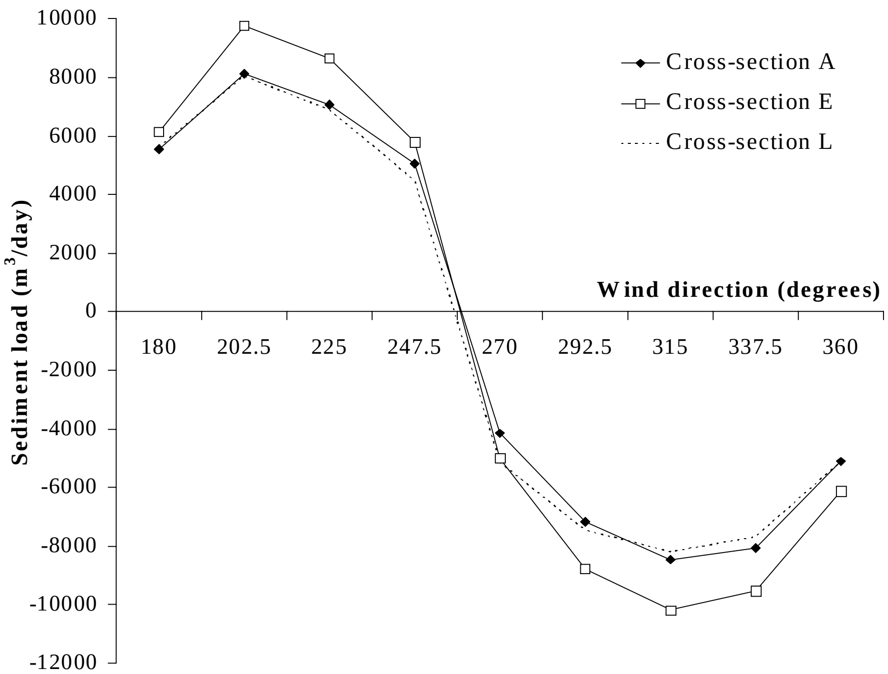

Fig. 5. Estimated sediment discharge for sections A, E and L under the winds of S, SSW, SW, WSW, W, WNW, NW, NNW and N directions and 20 m/s velocity

5 pav. Nešmenų debito pasiskirstymas A, E ir L skerspjūviuose pučiant P, PPV, PV, VPV, V, VŠV, ŠV, ŠŠV ir Š krypčių 20 m/s vėjui

Simulation for the Melnragė II site was performed on a more refined scale, with a case study area (Fig. 2a) covered by a rectangular grid extending 14 km in the south-north direction and 5 km in the east-west direction, with 20 × 20 m square cells for modelling purposes. Also, the number of wind directions studied increased from 4 to 9. Boundary conditions were obtained from the simulation results described in the previous section. Further, the study area was divided into twelve sections (Fig. 4) by total 12 cross-sections (from A to L). Each cross-section starts at the shoreline and extends for approximately 700 m seaward until reaching the depth of 8 m. For all sections the sediment load (m^3/day) in the beach nourishment area was calculated based on the unit discharge characteristics obtained during modelling. Sediment loads under strong winds of various directions for nearshore sections A, E and L are shown in Fig. 5. Wind directions here are expressed in degrees, so that the range from 180˚ to 360˚ (every 22.5˚) corresponds to the winds from the South to the West and to the North.

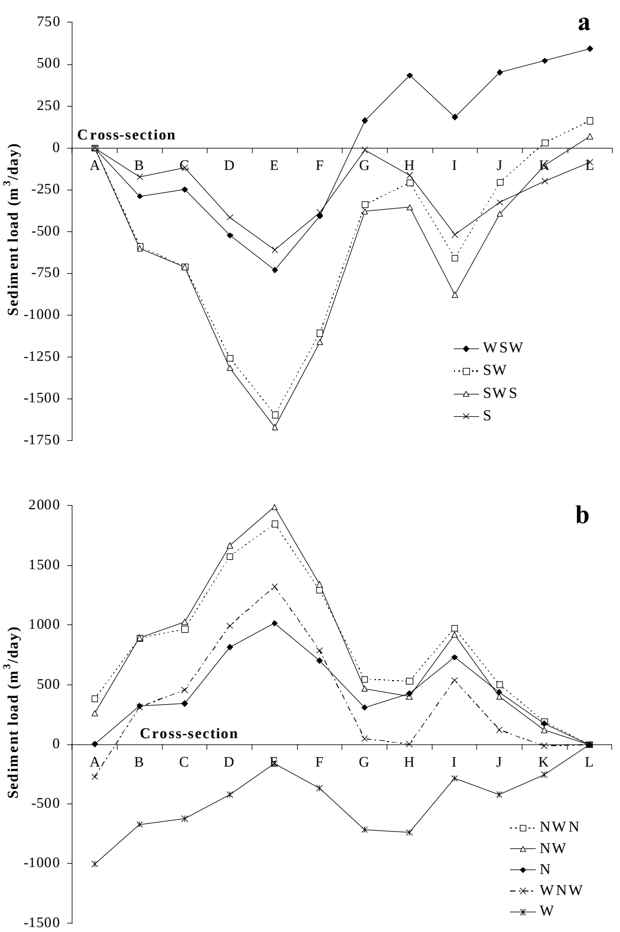

Fig. 6. Cumulative curves of sediment discharge starting at section A with WSW, SW, SWS, S winds (*a*) and section L with NWN, NW, N, WNW, W winds (*b*) of 20 m/s

6 pav. Nešmenų debito suminės kreivės nuo skerspjūvio A iki skerspjūvio L pučiant VPV, PV, PPV bei P krypčių vėjui (*a*) ir nuo skerspjūvio L iki skerspjūvio A pučiant ŠŠV, ŠV, Š, VŠV bei V krypčių 20 m/s vėjui (*b*)

The most intensive sediment transport is observed with the winds blowing from the SSW and NW, i.e. 9786 and 10186 m^3/day in section E in absolute values, while the average for this section is 7778 m^3/day. Figure 5 also demonstrates that in the first section (A) and the last section (L) of the study area sediment discharges are similar under the various winds analyzed. It means that most of the time the sediments will not be transported from this potential beach nourishment area and will be instead redistributed among different sections in this site. Sediment accumulation, limited though, occurs only with the winds of W and WSW directions. Therefore, this site can be efficiently used as a nearshore beach nourishment area, because once filled with sediments it will effectively reduce the propagation of waves thus reducing their impact on the beach.

For a more in-depth analysis of the area, areas of erosion and accumulation were determined for winds of different directions. In order to identify these areas, cumulative curves of sediment transport were made. They show the amount of sediments that will be deposited or taken away in the region between the first section and the section under investigation. Figure 6a shows the cumulative curves for the winds of S, SSW, SW and WSW directions with a 20 m/s velocity. The seabed erosion can be observed between cross-sections A and E as well as H and I. Sediment accumulation occurs between cross-sections E and G as well as I and L. The most intensive transport can be noticed for the winds of SW and SWS directions – approximately 1600 m^3 of sediments per day will be eroded between cross-sections A and E, while accumulation will reach 1000 m^3 of sediments per day between cross-sections E and G.

Figure 6b shows the cumulative curves for the NWN, NW, N, WNW, W winds of 20 m/s velocity. The sediments here are transported in the opposite direction (from the north to the south), therefore cross-section L becomes the first cross-section of the case study site. Seabed erosion is observed between cross-sections L and I as well as G and E, while accumulation occurs between cross-section I and H as well as E and A. The highest discharges in the whole study area are achieved with winds of NW and NWN directions and the lowest ones with the W winds. The latter winds generate the most intensive accumulation processes, while all other winds cause redistribution of sediments within a potential nourishment area.

Analysis of the actual year

In order to estimate the actual bottom deformations during one year, strong wind statistics was analyzed for the year 1998, which can be characterized as an average year according to the distribution statistics. The frequency of winds of various directions is provided in Table 4. The most recurrent were W and SW winds with the velocity of 20 m/s, and WSW, NW and W

Table 4. **Strong wind statistics for 1998 (data from Lithuanian Hydrometeorological Service under the Ministry of Environment)**
4 lentelė. **Duomenys apie stiprų vėją 1998 m. (parengta pagal Lietuvos hidrometeorologijos tarnybos duomenis)**

Wind direction	W	WSW	SW	NW	W	NW	S	W	NNW	WNW	N	SSW
Wind velocity (m/s)	20	15	20	15	15	20	20	20	20	20	20	20
Frequency (%)	23.7	20.9	14.8	9.5	8.9	7.8	5.6	3.3	2.8	1.1	1.0	0.6

winds with the velocity of 15 m/s. Among them, W and WSW were most common, constituting together 44.6% of strong winds in 1998.

These statistics were used to estimate sediment transport during an average year. The calculations showed that the cumulative effect of varying winds resulted in an overall sediment flow directed towards the North. During the average year, 110,000 m^3 of sediments in the beach nourishment area will be accumulated with the bottom level fluctuations of ±0.01 m/day. According to the cumulative curve derived from data of sediment transport through various cross-sections for the case study area in 1998, seabed erosion is observed between cross-sections A and E, and H and I, while accumulation occurs between cross-sections E and H as well as I and L.

Within a year, the number of days with strong wind can range from 30 to 50, therefore changes in the seabed in some areas can reach ±0.5 m/year. During extreme years when severe storms hit the Lithuanian nearshore, even more intensive sediment transport and consequently bigger bottom changes will be observed. For instance, on 4 December 1999, during the hurricane "Anatol" when the average wind velocity was 17–25 m/s during 17 hours, reaching 38 m/s in gusts, serious bottom changes occurred and many beaches were completely washed away.

5. DISCUSSION

Assessment of sediment transport processes in Melnragė II, after performing a more in-depth simulation, proves that this site can be efficiently used as a shoreface nourishment area, because once filled with nourishment materials (sand) from the Klaipėda Strait as the borrow site it will effectively reduce wave propagation thus reducing their impact on the beach. These modelling results are confirmed by the outcome of the nearshore nourishment project implemented in Melnragė II in 2001, the first and only such project in Lithuania so far. Based on the measurement results, Žilinskas et al. (2003) concluded that during seven months after the start of nearshore fill, approximately 61% of dumped sand moved towards the shore, while the remaining 38% were retained in the dumping site. The perpendicular (south–north) transport was only significant in the upper part of the nearshore where it extended for a few hundred meters in both directions. Around 67% of the dumped sand remained within the nourishment area at least during one year after implementing the project. The study period was marked by several major storms, some of similar coastal erosion potential to that of the remarkable hurricane "Anatoly" in 1999. These storms, although severely damaging many other Lithuanian coastal areas, inflicted almost no harm on Melnragė II, which was nevertheless strongly damaged by "Anatoly", confirming once more the importance of properly designed nourishment programs for coastal protection.

Concluding, we would like to indicate once more that the current study aims to demonstrate the importance of the nourishment project assessment prior to its actual implementation and to provide an example of methodology for such an assessment, which demonstrates the importance of climatic data and possibilities of modelling. At the same time, we acknowledge that the nourishments projects are only part of the long-term strategical tasks for preservation of Lithuanian beaches (Grigelis, Gelumbauskaitė, 2004).

6. CONCLUSIONS

Analysis of long-term meteorological observations at Klaipėda showed the prevailing wind directions and velocities, which determine conditions of beach and nearshore formation, namely strong winds blowing from the south, southwest, west and northwest. This conclusion proves to be particularly important when contrasted with the average wind distribution statistics, which show only an 8% difference between the least and the most prevailing winds with those of southeast and west slightly dominating. These results formed the basis for modelling the sediment transport in the Lithuanian nearshore of the Baltic Sea, allowing to reduce the number of simulation runs as well as to focus on the winds that are important for local shoreface nourishment projects, which can be made more efficient if tailored taking into account the region of specific wind patterns.

Examination of the modelling results enabled us to identify the best nearshore sites for releasing the nourishment materials in order to successfully protect, restore or improve Lithuanian beaches. The sites where sediment discharge reaches its local extreme values are regarded as such areas, *i.e.* after reaching the minimum level the discharge starts increasing (entry into the erosion area) or after reaching the maximum begins declining (entry into the accumulation area). However, under different winds, the locations of potential nourishment sites do not necessarily coincide. Out of total 7 sites with the highest congruence rate, after estimating the recreational value of the beach, the necessity for its restoration and considering the economic feasibility of a potential project, the following final four shoreface nourishment sites were deemed to have priority: Melnragė II, Plytinė – Birutės kalnas, Smiltynė I, Juodkrantė.

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SMĖLIO IŠPYLIMO VIETŲ POVANDENINIAME JŪROS ŠLAITE MODELIAVIMAS BALTIJOS JŪROS LIETUVOS PRIEKRANTĖJE

Santrauka

Baltijos jūros paplūdimių būklės pagerinimas tampa aktualia problema. Vienas jos sprendimo būdų yra priekrantės nešmenų srauto papildymas išpilant smėlį povandeniniame jūros šlai-

te. Siekiant nustatyti smėlio išpylimo vietą, buvo išanalizuota nešmenų pernaša esant įvairioms hidrometeorologinėms sąlygoms. Pagrindiniai tyrimų aspektai yra šie: 1) ištirtos Klaipėdos pajūrio daugiametės meteorologinės sąlygos, nusakančios štormų trukmę ir vėjo greitį, jo pasikartojimo dažnį, 2) sumodeliuoti bangavimo ir hidrodinaminiai režimai bei smėlio pernašos procesai Baltijos priekrantėje pučiant įvairios krypties ir stiprumo vėjui, 3) tinkamiausių smėlio išpylimo vietų povandeniniame jūros šlaite nustatymo metodika, įvertinant akumuliacijos ir erozijos procesus Baltijos priekrantėje. Litodinaminių procesų modeliavimui buvo panaudota Danijos hidraulikos instituto dviejų dimensijų skaitmeninių modelių sistema MIKE 21: hidrodinaminis modelis, bangų modelis ir smėlio pernašos modelis. Modeliuojant nustatyta tėkmės kryptys ir greitis, nešmenų debitai, dugno erozijos židiniai bei smėlio akumuliacijos vietos. Įvertinus jūros paplūdimių smėlio papildymo būtinumą bei modeliavimo rezultatus, pasiūlytos konkrečios smėlio išpylimo vietos.

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Р е з ю м е

В последние годы ухудшилось состояние пляжей побережья Балтийского моря на территории Литвы. Восстановление пляжей стало актуальной проблемой, одним из способов решения которой является дополнительная искусственная подпитка пляжей песком с помощью его отсыпки в зоне подводного склона берега моря.

Для определения наиболее подходящих мест отсыпки песка анализируются процессы переноса наносов при различных метеорологических условиях. Исследование проводилось в следующем порядке:

1. Проведен анализ метеорологических условий за многолетний период, по которым установлены характеристики повторяемости и продолжительности штормов, скоростей и направлений ветра (по данным Клайпедской метеорологической станции).

2. Смоделированы процессы волнения и гидродинамический режим, а также процессы переноса песка в прибрежной зоне Литвы при различных скоростях и направлениях ветра.

3. Установлены наиболее подходящие места высыпки песка с учетом процессов переноса наносов прибрежной зоны Балтийского моря.

Для моделирования литодинамических процессов была применена система двумерных численных моделей MIKE-21 (Датский гидравлический институт): гидродинамическая модель, модель волнения и модель переноса песка. В процессе моделирования переноса наносов определяются направление течения и расходы наносов, а также области донного размыва и аккумуляция песка при ветрах различных румбов. На основе результатов моделирования процесса перемещения наносов вдоль Балтийского побережья Литвы и затем оценки необходимости рекультиваций пляжей предложены конкретные места для высыпки песка вблизи Клайпеды (Мелнраге).