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Variability of Hydrodynamic and Lithodynamic Coastal Processes in the East Part of the Gulf of Gdańsk

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Abstract

The paper presents new findings concerning motion of water and sediment in the coastal zone of the east part of the Gulf of Gdańsk, from the Vistula River mouth at Świbno (Poland) to Cape Taran (Russia, Kaliningrad Oblast). The presented study deals with spatial variability of parameters of hydrodynamic and lithodynamic processes which have been subject to theoretical modelling. For the considered coastal segment, deep-water wave conditions reconstructed for a 44-year period have been analysed and transformed to the nearshore zone. Next, velocities of wave-driven longshore currents for the mean statistical year have been calculated, along with the longshore sediment transport rates. Regarding the net longshore sand motion, its detected direction is from Cape Taran towards the Vistula Spit. Very high annual rates of longshore sediment transport have been obtained for the coastal segment at Sambian Peninsula. These rates decrease considerably along the Vistula Spit, reaching zero at a distance of about one third of the Polish part of the Spit, measured from its root. At this location, the net longshore sediment transport (resulting from net longshore wave-current impact) reverses from westward to eastward.

Key words: sediment transport, waves, currents, deep-water wave climate

1. Introduction

The coastal zone of the east part of the Gulf of Gdańsk, from the Vistula mouth at Świbno (Poland) to Cape Taran (Russia, Kaliningrad Oblast) is less developed than the west part of the Gulf, spreading westwards of the Vistula mouth to Cape Rozewie (PL). There is only one Russian harbour located close to the open coast, namely the Baltiysk harbour, while there are no Polish harbours at all. As regards inland harbours (on the shores of the Vistula Lagoon, including the internal coastline of the Vistula Spit), there is one big harbour in Kaliningrad (RU, KO) and a smaller one – and economically less important – in Elbląg (PL), as well as a few very small fishery harbours and marinas both on the Polish side (Piaski, Krynica Morska, Kąty Rybackie, Tolkmicko, Frombork) and on the Russian side of the lagoon (Krasnoflotskoye, Ushakovo, Pribrezhnyy). Aside from harbour industry, the touristic infrastructure is also less developed than in the west part of the Gulf of Gdańsk. For instance, the Hel Peninsula (a coastal form similar to the Vistula Spit) is visited by tens of time more tourists than the Polish part of the Vistula Spit. The Russian part of the Vistula Spit is almost "untouched" by tourism.

The region has huge economic and touristic potential and its role will presumably grow in the nearest future. One should expect rapid development of the coastal touristic infrastructure at a few villages and towns which are becoming ever more "fashionable", both in Poland (e.g. Jantar, Stegna, Krynica Morska) and in Russia (e.g. Yantarnyy). The number of harbour investments will also increase. Currently, these investments on the open sea side are related mainly to maintenance of the Baltiysk (former Pilawa) Strait (RU, KO), an inlet in the Vistula Lagoon. In the Vistula Lagoon, engineering activities concentrate on modernisation of small harbours and upkeep of waterways (dredging works in navigable canal and at harbour areas). In Poland, the growing popularity of yachting along with plans for the full activation of the harbour in Elbląg, as well as the other harbours and marinas, have given rise to an idea of an artificial cross-cut through the Polish part of the Vistula Spit. In this way, an alternative passage for Polish boats from the Vistula Lagoon to the Gulf of Gdańsk would be available, independent of the Russian waterway through the Baltiysk Strait. Besides, in further perspective, new small harbours and marinas can be constructed on the open sea side, both in Poland and Kaliningrad Oblast.

All the above activities, either planned or currently being carried out, have a considerable impact on the sea shore. To minimise possible drawbacks of future investments and to optimise anticipated coastal engineering ventures, more detailed knowledge on coastal hydro- and lithodynamic processes occurring in this part of the Gulf of Gdańsk is required. In particular, identification of directions and rates of the longshore sediment fluxes is crucial in the design of coastal structures and in predicting potential damage to the sea shore by these structures.

According to previous studies concerning the Vistula River mouth, the net longshore sediment transport in the south part of the Gulf of Gdańsk is directed from west to east. The sandy material is transported from the Vistula River mouth towards the Vistula Spit. There is a common opinion among scientists that the north-east edge of the Gulf of Gdańsk, namely Cape Taran (RU, KO), constituting the north-west corner of the Sambian Peninsula, represents a point at which longshore sediment fluxes diverge distinctly. This denotes mean annual resultant sediment transport along the north and west coasts of the Sambian Peninsula, directed eastwards and southwards, respectively. According to all concepts and ideas, the latter southward direction of longshore sediment motion continues until the Baltiysk Strait and farther along Vistula Spit. A question exists whether such a longshore sediment flux reaches a region nearby the Polish-Russian border and meets the eastward directed opposite flux. Opinions of various Polish and Russian coastal researchers on this issue differ considerably, but all researchers agree that somewhere between the Baltiysk Strait and the Vistula River mouth, the longshore sediment fluxes converge. The location of this convergence point (being an objective of the scientific argument) is very important for understanding of coastal morphodynamics in the region and all resulting consequences in the domain of coastal engineering.

In order to clarify the above uncertainties, the research team at the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) undertook investigations sponsored by the Ministry of Science and Higher Education within the national project N N306 280535 entitled "Variability of hydrodynamic and lithodynamic processes in the coastal zone of the east part of the Gulf of Gdańsk". Described in the present paper, a part of these investigations comprising the theoretical analysis was concentrated on mathematical modelling. The computations concerned the following coastal physical processes occurring in the Gulf of Gdańsk: waves, wave-driven currents and longshore sediment transport. The field surveys have provided bottom sediment characteristics used in modelling of the sediment motion. The input wave conditions have been taken from the IBW PAN database comprising a long-term reconstruction of the deep-water wave climate in the Baltic Sea. Nearshore waves and currents have been modelled using bathymetric data provided by the Maritime Office in Gdynia – the Inspectorate of Coastal Protection (the Polish coastal segment) and the Shirshov's Institute of Oceanology of the Russian Academy of Sciences – Atlantic Branch in Kaliningrad (the Russian coastal segment). The bottom sediment sampling has been carried out on the beach and in the nearshore zone. The samples have been subject to sieve analysis.

2. Deep-Water Wave Climate and Energy

For the needs of the present study, determination of the offshore wave climate has been based on the numerical prognostic wave model WAM4, in which the input is determined from meteorological (wind and air pressure) fields.

A few years ago, the spectral wave model WAM4 was used under the HIPOCAS project (coordinated by GKSS, Germany), in which IBW PAN participated, for reconstruction of the long-term European wave climate in the period from 1958 to 2001. The reconstruction procedure is described in detail by Weisse et al (2009). In brief, the National Centres for Environmental Prediction – National Centre for Atmospheric Research (NCEP – NCAR) global reanalysis (Kalnay et al 1996), was applied in combination with the spectral nudging technique (von Storch et al 2000), as the forcing to the REgional Climate MOdel (REMO) which is based on the numerical weather prediction model EM of the German Weather Forecast Service (DWD), (Feser et al 2001). In this way, wind parameters (velocity and direction) at a height of 10 m above the sea and pressure fields were obtained. The results of the REMO model were next used in the WAM4 model.

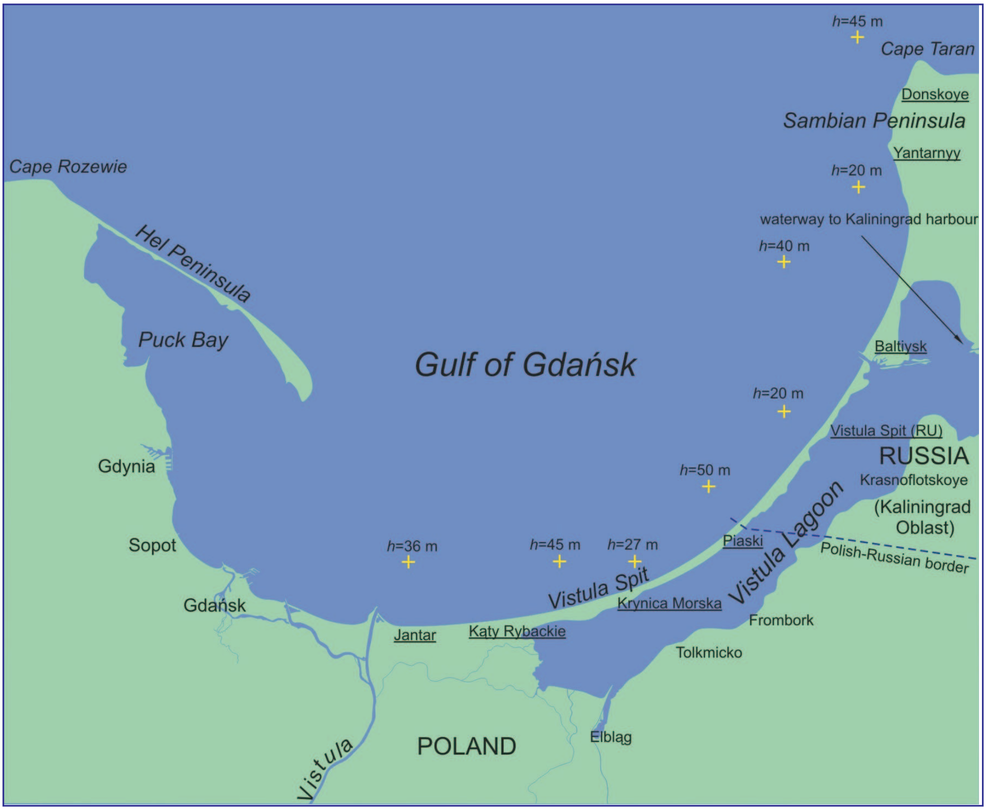

Fig. 1. Locations of deep-water wave prognostic points in the east part of the Gulf of Gdańsk

The WAM4 model is based on a so-called wave action balance equation and takes into account the energy transfer from wind to the sea, "white-capping" wave breaking, bottom friction and resonance interactions of wave components. For the Baltic waves reconstruction, the model resolution of the spatial grid was $5' \times 5'$ (about 9 km). The model time step of the input wind data amounted to 1 hour. This input was then interpolated, yielding a computational resolution of 300 s. At each grid point for each hour of the 44 year long reconstruction period, the computational results comprised the following representative wave parameters: significant wave height, wave period and wave ray direction.

Results of the wave climate reconstruction described above have been used in determination of the offshore wave parameters in the mean statistical year. The deep-water wave prognostic points have been chosen to represent wave conditions along the coastline of the east part of the Gulf of Gdańsk. In total, eight points have been selected: four located in Polish territorial waters and four others in the Russian coastal zone. The locations of these points are given in Fig. 1 while their coordinates, distances from the shoreline and corresponding water depths are given in Table 1.

Table 1. Geographical coordinates, distances from the shoreline and related water depths of deep-water points selected from long-term wave climate reconstruction data

Approximate respective coastal location	Geographical coordinates		Distance from shoreline [m]	Local depth [m]
	Latitude	Longitude		
Jantar (PL)	54°25.0′	19°08.0′	7950	36
Kąty Rybackie (PL)	54°25.0′	19°18.0′	5850	45
Krynica Morska (PL)	54°25.0′	19°26.6′	2850	27
Piaski (PL)	54°30.0′	19°35.2′	5700	50
Russian part of the Vistula Spit (RU, KO)	54°35.0′	19°43.9′	4500	20
Baltiysk (RU, KO)	54°45.0′	19°44.0′	13800	40
Yantarnyy (RU, KO)	54°49.0′	19°52.7′	5000	20
Donskoye (RU, KO)	54°59.0′	19°52.8′	8000	45

On the basis of the reconstructed long-term wave data, so-called wave scenarios have been elaborated for all deep-water points. This means that at each point the wave parameters occurring in the mean statistical year have been determined. The ranges of wave height were assumed with resolution of 0.5 m. For each range of the wave height, the wave climate at each of the chosen deep-water location has been determined, represented by the significant wave height H_s (mean of one third of the highest waves in a wave series), the wave period corresponding to the energy peak in the wave spectrum T_p (a so-called wave peak period), the direction (azimuth) of wave propagation A_z and duration of individual wave events.

These wave conditions, together with coastal bathymetric data, were a basis for numerical modelling of wave transformation, wave-driven longshore currents and sediment transport on the cross-shore profiles at eight selected coastal locations (see first column in Table 1).

Prior to this, however, the deep-water wave energy for all points was analysed. Conventionally, wave energy is calculated as $E = 0.125\rho g H^2$ (where ρ and g denote water density and acceleration due to gravity, respectively). In the present study, two indicators of wave energy have been computed, namely the indicators of wave energy in the directions perpendicular ($E_{perpendicular}$) and parallel ($E_{parallel}$) to the coastline. Within these computations, the total wave energy indicator (H_s^2) was projected on the above two directions. The applied formulas read, respectively:

$$E_{perpendicular} = \frac{1}{n} \sum_{i}^{n} H_{s_i}^2 \cdot \cos\theta_i, \quad (1)$$

$$E_{parallel} = \frac{1}{n} \sum_{i}^{n} H_{s_i}^2 \cdot \sin\theta_i, \quad (2)$$

where:

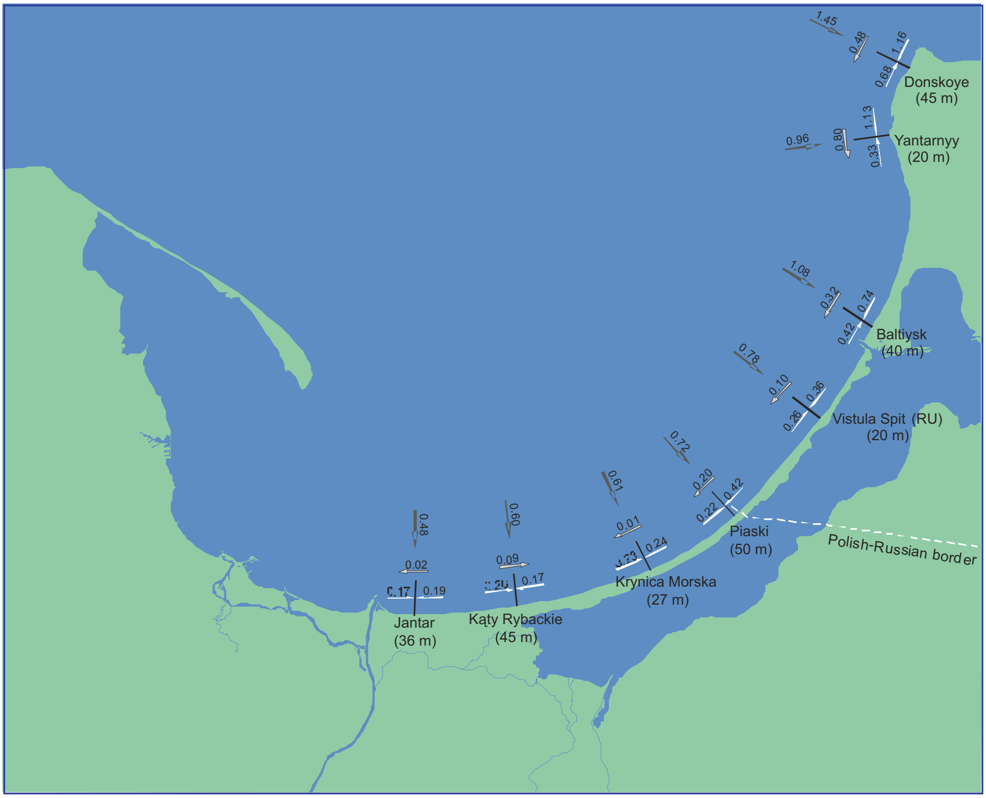

Fig. 2. Deep-water wave energy indicators in directions perpendicular and parallel to the shoreline (values in brackets denote local water depths at the wave prognostic points)

H_{s_i} – significant wave height in the one-hour period;
θ_i – angle between the wave crest and the shoreline in the wave event;
n – number of 1-hour wave events in the 44-year long period of reconstruction ($n = 24 \cdot 365 \cdot 44 = 385440$).

In the computations, the deep-water waves directed seawards from the local shore have been skipped. Thus, in the direction perpendicular to the coastline only onshore wave energy has been obtained. In the direction parallel to the coastline, two components of wave energy have been calculated, yielding a certain resultant longshore wave energy at each location on the coastline. Results of computations of the wave energy indicators are depicted in Fig. 2.

It can be concluded from Fig. 2 that the resultant (net) longshore wave energy is directed from Cape Taran to the Vistula River mouth everywhere except for Kąty Rybackie in Poland (root of the Vistula Spit). The biggest value has been obtained for Yantarnyy in Russia (0.80) and the smallest one for Krynica Morska in Poland (0.01). The cross-shore wave energy computations have yielded the maximum quantity at

Donskoye close to Cape Taran (1.48) and indicate a distinctly decreasing trend towards the Vistula River mouth, reaching a minimum at Jantar (0.48).

The above results concerning cross-shore wave energy imply that the shores of the Sambian Peninsula are subject to significantly stronger wave impact than the shores of the Vistula Spit and the Vistula River mouth region. The extreme wave load at the shore has been obtained for the north part of the western coast of the Sambian Peninsula. Indeed, this coastal segment, much exposed to winds and waves coming from a wide sector W-N, is said to be frequently eroded by heavy storms.

The computational findings concerning the wave energy component parallel to the coast suggest that the most intensive longshore impact of waves in the considered region takes place along the coast of the Sambian Peninsula, up to the Baltiysk Strait. This deep-water impact, however, cannot be directly related to longshore sediment transport since the motion of sediment in the coastal zone is driven by a complex influence of waves transformed on the cross-shore profile and nearshore wave-induced currents, including the longshore current.

3. Longshore Sediment Transport

The wave-induced longshore currents, together with the wave-generated nearbed oscillatory flows, form the driving force of the longshore sediment transport. This coastal physical process has been modelled by the UNIBEST-LT numerical program.

UNIBEST (UNIform BEach Sediment Transport) is a generic term for a software package that computes sediment transport along a uniform sandy coast and the coastal behaviour during human interference or storm. The software package UNIBEST consists of four separate modules; UNIBEST-LT, -CL, -TC, and -DE. UNIBEST-LT (Longshore Transport) can be used for the computation of net sand transport in the longshore direction and its cross-shore distribution. UNIBEST-LT supplies the boundary conditions for UNIBEST-CL (CoastLine dynamics), which can be used to assess coastline changes due to human influence (e.g. breakwaters, groins). UNIBEST-TC (Time-dependent Coastal profile model) can be used to assess coastal profile developments due to wave action. UNIBEST-DE can be used to compute dune erosion, and is quite similar to the TC module, but is especially intended to compute the effects of stormy episodes.

UNIBEST-LT is an acronym for "UNIform BEach Sediment Transport – Longshore Transport". The module has been developed to compute tide- and wave-induced longshore currents and sediment transports on a beach of arbitrary profile. The surf zone dynamics is derived from a built-in random wave propagation and decay model, which transforms offshore wave data to the coast, taking into account the principal processes of linear refraction and non-linear dissipation by wave breaking and bottom friction. The longshore sediment transports and cross-shore distribution can be evaluated on the basis of different transport formulae (e.g. Bijker 1971, van Rijn 1993 and Bailard 1981).

One characteristic cross-shore profile, representative for the entire analysed coastal zone, is assumed in UNIBEST-LT. The longshore sediment transport rate is calculated for a variety of assumed angles between the characteristic profile and wave incidence. The computations comprise a series of wave events and yield the coefficients of approximate transport formula, being a function of wave-to-coastline angle. Within UNIBEST-CL the sediment transport variability along shore is modelled by using the shoreline angles at grid points and the coastline evolution is determined in each time step by the single line model.

Major quantities and characteristics required in modelling by UNIBEST-LT are:
(a) The initial bottom profile;
(b) Time series of the offshore boundary conditions such as:
- water level,
- deep-water significant wave height,
- deep-water wave incidence angle,
- peak wave period,
- longshore tide-induced velocity.

There are a variety of theoretical models describing the motion of sediment in the longshore direction. The most important are the approaches of Bailard (1981), Bijker (1971), CERC (Shore Protection Manual 1984) and van Rijn (1993). All of them are included in the UNIBEST-LT computational package (ver. 4.0) in use at IBW PAN. The present study is not devoted to tests of the models' accuracy, applicability, limitations, drawbacks and advantages. On the basis of a long-term modelling experience, the model of van Rijn (1993) has been chosen as the most reliable tool in a class of "engineering models".

The computations have been carried out for 4 cross-shore profiles in Poland and 4 profiles in Russia (Kaliningrad Oblast). Locations and azimuths of these profiles, together with characteristic grain diameters, are shown in Table 2.

The bathymetric cross-shore transects for the Polish coastal zone are shown in Fig. 3, while the profiles showing bathymetry on the Russian coast are plotted in Fig. 4.

Figs. 3 and 4 show that there are 1–3 bars on each cross-shore transect. The mean inclination of all Polish cross-shore profiles, as well as the Russian profiles at Vistula Spit and Baltiysk, amounts to about 0.01 while the Russian profiles at Yantarnyy and Donskoye have steeper slopes, especially in the nearshore zone (500 m offshore) – with inclinations reaching 0.02 m. It should be noted that a mildly sloped coastal seabed generally occurs at accumulative shores built of fine sand while a steeper nearshore sea bottom is usually observed at erosive coasts built of coarser sediments.

For each cross-shore transect, waves resulting from individual deep-water wave climates (having parameters determined for the respective mean statistical years), have been numerically transformed to the shoreline, yielding cross-shore distributions of wave parameters. The wave transformation process has been modelled by use of the Battjes, Janssen (1978) approach, included in the UNIBEST-LT package. Within these computations, the longshore wave-induced flow velocities have also been determined.

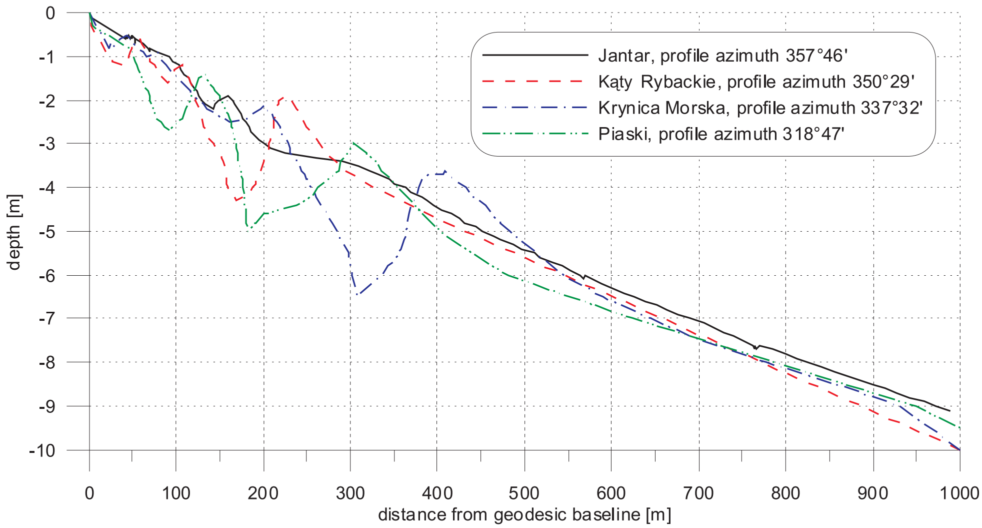

Fig. 3. Cross-shore profiles on the Polish side of the east part of the Gulf of Gdańsk

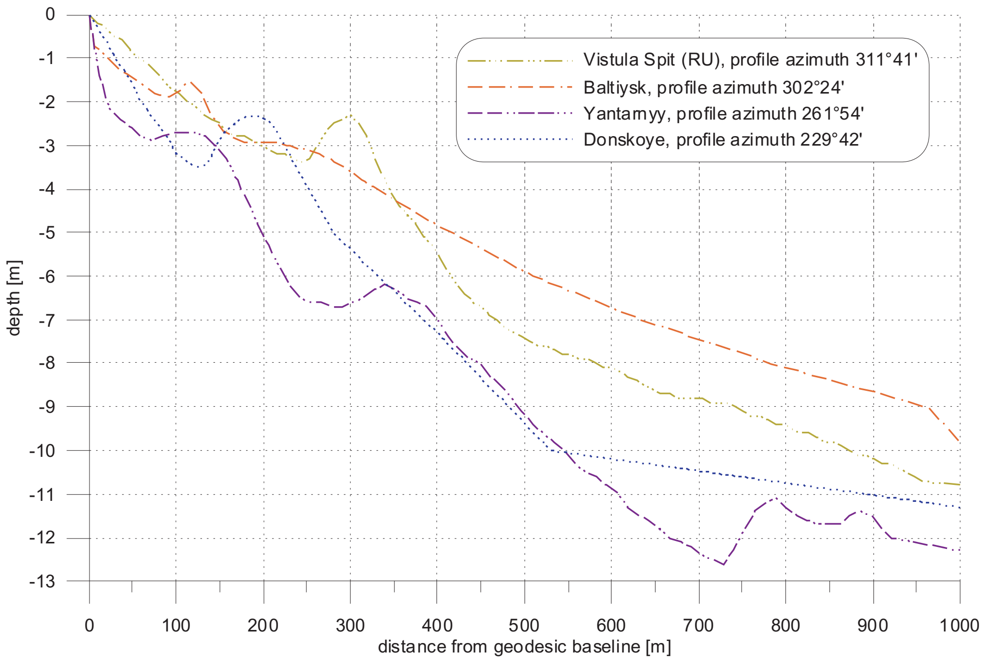

Fig. 4. Cross-shore profiles on the Russian side of the east part of the Gulf of Gdańsk

Table 2. Locations, azimuths and nearshore seabed grain size characteristics of computational cross-shore profiles in the east part of the Gulf of Gdańsk

Location	Bathymetric profile		Nearshore seabed grain diameter	
	KM*	Azimuth	d_{50} [mm]	d_{90} [mm]
Jantar (PL)	42.5	357°46′	0.20	0.31
Kąty Rybackie (PL)	27.0	350°29′	0.22	0.30
Krynica Morska (PL)	14.0	337°38′	0.19	0.27
Piaski (PL)	0.5	318°47′	0.24	0.28
Russian part of the Vistula Spit (RU, KO)	–15.0**	311°41′	0.27	0.37
Baltiysk (RU, KO)	–27.5**	302°24′	0.36	0.49
Yantarnyy (RU, KO)	–51.0**	261°54′	0.33	0.44
Donskoye (RU, KO)	–60.0**	299°42′	0.44	0.73

* location in the longshore coordinate system used by the Maritime Offices in Gdynia (KM 0.0 stands for the Polish-Russian border)

** approximate distance from the Polish-Russian border in virtually extrapolated Polish longshore coordinate system

Table 3. Durations of the longshore sediment transport directed from Cape Taran to the Vistula mouth and from the Vistula mouth to Cape Taran in the mean statistical year

Location	Duration of longshore sediment transport from the Vistula mouth to Cape Taran		Duration of longshore sediment transport from Cape Taran to the Vistula mouth		Total duration of longshore sediment transport in the mean statistical year	
	[days]	[%]	[days]	[%]	[days]	[%]
Jantar (PL)	139.4	45.56	166.6	54.44	306.0	100
Kąty Rybackie (PL)	157.8	50.67	153.6	49.33	311.4	100
Krynica Morska (PL)	146.9	47.43	162.8	52.57	309.7	100
Piaski (PL)	143.3	47.03	161.4	52.97	304.7	100
Russian part of the Vistula Spit (RU, KO)	105.6	35.13	195.0	64.87	300.6	100
Baltiysk (RU, KO)	108.4	43.24	158.3	56.76	266.7	100
Yantarnyy (RU, KO)	61.4	24.49	189.3	75.51	250.7	100
Donskoye (RU, KO)	160.8	56.18	125.4	43.82	286.2	100

Next, the longshore sediment transport rates have been computed using van Rijn's (1993) model as functions of coupled influence of nearshore waves and wave-driven longshore current. Durations of the longshore sediment transport directed from Cape Taran to the Vistula mouth (and oppositely) at the considered coastal locations in the mean statistical year are given in Table 3. It appears from Table 3 that in the mean

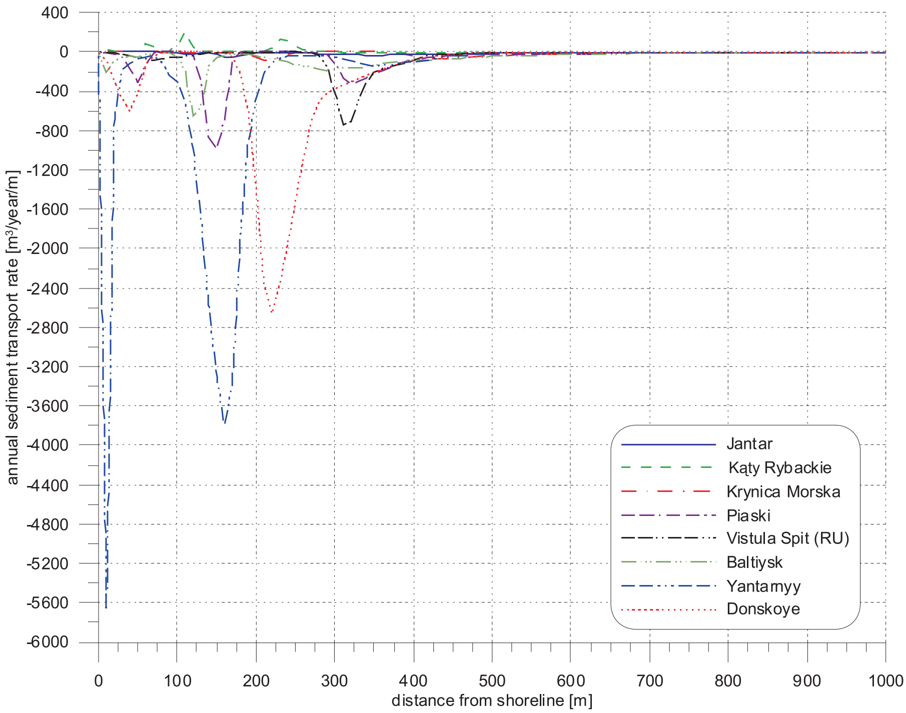

Fig. 5. Cross-shore distributions of the annual net longshore sediment transport rates in the east part of the Gulf of Gdańsk computed by use of van Rijn's (1993) model for wave conditions of the mean statistical year

statistical year the longshore sediment transport directed towards Cape Taran lasts longer than the transport towards the Vistula mouth only at Kąty Rybackie (PL) and Donskoye (RU, KO). This predominance is very slight at Kąty Rybackie (50.67%) and distinctly bigger at Donskoye (56.18%). At the other considered locations, the longshore motion of sediment is directed towards the Vistula mouth during most of the mean statistical year. The extreme predominance has been obtained for Yantarnyy (RU, KO), amounting to 75.51%.

Detected for Kąty Rybackie, the balanced durations of longshore sediment transport directed towards the Vistula mouth and Cape Taran could imply that this region may be a location where two opposite longshore sediment fluxes converge. An ultimate clarification of this issue, however, has been provided by computations of the net sediment transport rates for all analysed coastal locations in the mean statistical year.

Results of computations of the net annual rates of longshore motion of sandy sediments (with grain sizes as given in Table 2) along the coast of the east part of the Gulf of Gdańsk for wave conditions of the mean statistical year are plotted in Fig. 5.

It can be seen in Fig. 5 that the net longshore sediment transport rates at Yantarnyy and Donskoye are significantly higher than at the other locations. The intensity of

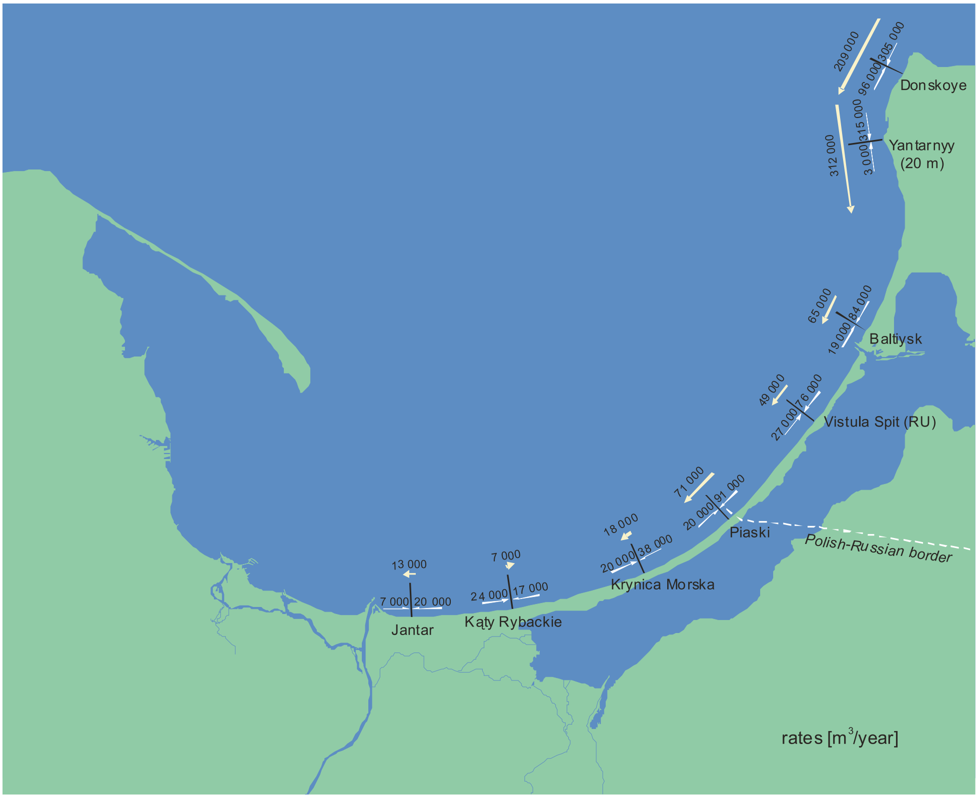

Fig. 6. Total annual longshore sediment transport rates and the resultant (net) rates in the east part of the Gulf of Gdańsk computed by use of van Rijn's (1993) model for wave conditions of the mean statistical year

longshore sediment fluxes at Jantar and Kąty Rybackie is incomparably smaller than elsewhere in the analysed east coast of the Gulf of Gdańsk.

Further, it is clearly visible that the distributions of the longshore sand transport rates on the cross-shore profile's are dependent on the profiles shape. The highest rates occur at locations where waves are subject to rapid breaking and related energy dissipation, giving rise to the appearance of intensive wave-driven currents, including the longshore current. The above processes mostly take place above crests of the underwater bars and on steeply inclined seabed in close vicinity of the shoreline (cf. Fig. 5 and Figs. 3–4). Due to huge differences between shapes of the individual transects, the respective longshore sediment transport rates display distinct differences as well. Certainly, variability of the wave climates at the considered coastal locations also plays an important role.

Final results of computations of the longshore sediment transport rates are obtained by integration of their distributions over the cross-shore profiles, yielding the total annual net longshore sediment transport rates, depicted in Fig. 6.

The picture of modelled net longshore transport of sand in the east part of the Gulf of Gdańsk implies that, in the mean statistical year, the sediment moves from Cape Taran in Russia to the vicinity of the root of the Vistula Spit in Poland. The highest rate of this motion amounts to 312 000 m^3/year (at Jantarnyy, RU, KO) and generally decreases while approaching the region of Krynica Morska in Poland. On the Polish part of the Vistula Spit, between Krynica Morska and Kąty Rybackie (most probably closer to Kąty Rybackie), the rate of this sediment flux decreases to zero. At Kąty Rybackie, the modelled longshore sediment motion is directed reversely (eastwards) and at a much lower rate (7000 m^3/year) than elsewhere. Near the Vistula mouth, at Jantar, the net longshore sediment transport is directed westwards and has the rate of 13 000 m^3/year.

4. Final Remarks and Conclusions

Described in the present paper, results of the theoretical analysis of the deep-water wave energy and the longshore sediment transport in the east part of the Gulf of Gdańsk shed more light on coastal hydro- and lithodynamics in the considered area. Aside from the fact that these investigations provide some scientific progress, they seem to be helpful in planning regional coastal and harbour engineering ventures, e.g. a new waterway in the Vistula Lagoon and the artificial cross-cut through the Vistula Spit, accompanied by moles (entrance breakwaters), as well as any other local Polish or Russian investments which can be implemented in future.

The modelling results obtained for the cross-shore and longshore wave energy directions (see Fig. 2) can be useful in rough assessment of the coastal lithodynamic response. The cross-shore wave energy computations yield the maximum quantity at Donskoye close to Cape Taran and slightly less at the coast from Yantarnyy to Baltijsk. These results imply that the shores of the Sambian Peninsula are subject to distinctly stronger wave impact than the shores of the Vistula Spit and the Vistula River mouth vicinity.

Focused as it is on longshore sediment motion, the present study ensures qualitative indicators of longshore sediment transport patterns on the basis of analysis of the deep-water wave energy component. More precise quantitative estimation of the longshore sediment transport rates is, however, achieved by the detailed theoretical solution of wave transformation on the actual cross-shore profiles, generation of the longshore wave-driven currents and motion of sand caused by the coupled wave-current action.

The abovementioned detailed mathematical modelling gives rise to determination of variability of the longshore sediment transport rates along the coast of the east part of the Gulf of Gdańsk. In particular, values of the total annual net sediment transport rates, determined for the mean statistical year, give information on potential capacity of longshore sediment transport (see Fig. 6). The highest rates of this motion amount to 209 000 m^3/year at Donskoye and 312 000 m^3/year at Jantarnyy. The sediment moves from Cape Taran in Russia to the vicinity of the root of the Vistula Spit in Poland. The annual net rate of this sediment flux decreases to zero a few kilometres eastwards of Kąty Rybackie. At Kąty Rybackie, the modelled longshore sediment motion is directed reversely (from the Vistula River mouth towards the Polish-Russian border) and its net rate is far lower (7000 m^3/year) than elsewhere. Near the Vistula River mouth, at Jantar, the resultant annual longshore sediment transport is directed westwards and has the net rate of 13 000 m^3/year. The tendency to considerable decrease of the annual net longshore sediment transport rates along the shore segment from Baltiysk to the root of Vistula Spit is in conformity with results from the lithological study of Babakov et al (2010).

The above picture agrees with the concept presented recently by Boldyrev & Bobykina (2008), according to which the shores of the Vistula Spit have been fed by sediments from the eroded west coast of the Sambian Peninsula and by way of the huge supply of sand near Yantarnyy, resulting from the multi-year operation of the amber mining factory during the 20th century. The obtained net annual longshore sediment transport rate at Baltiysk (66 000 m^3/year) is distinctly underestimated in comparison to the previously known assessment (500 000 m^3/year) given in the publication of Chechko et al (2008). The computational results achieved for the Polish shores of the Vistula Spit are rather compliant with the numerical simulations of Gajewski et al (1995). The theoretical findings of the present study roughly agree with hypotheses of Jednorał (1996) and Zawadzka-Kahlau (1999) who have claimed that the region of Krynica Morska is a place where two opposite longshore sand fluxes converge.

Acknowledgements

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References

Babakov A., Chubarenko B., Ostrowski R., Pruszak Z. (2010) Variability of characteristics of coastal sediments on the natural shore and the shore adjacent to harbour structures, *Inżynieria Morska i Geotechnika*, **31** (3), 409–416 (in Polish).

Bailard J. A. (1981) An energetics total load sediment transport model for a plane sloping beach, *Journal of Geophysical Research*, **86** (C11), 10938–10954.

Battjes J. A., Janssen J. P. F. M. (1978) Energy loss and set-up due to breaking of random waves, *Proc. 16th ICCE.*, **I**, 569–587.

Bijker E. W. (1971) Longshore Transport Computations, *Journal of Waterways, Harbour and Coastal Engineering*, **99** (WW4), 687–701.

Boldyrev V. L., Bobykina V. P. (2008) Coasts of Vistula and Curonian Spits as transboundary territories, [in:] *Trasnsboundary Waters and Basins in the South-East Baltic* (ed. by B. Chubarenko), Terra Baltica, Kaliningrad, 225–236.

Chechko V. A., Chubarenko B. V., Boldyrev V. L, Bobykina V. P., Kurchenko V. Yu., Domnin D. A. (2008) Dynamics of the Marine Coastal Zone of the Sea Near the Entrance Moles of the Kaliningrad Seaway Channel, *Water Resources*, **35** (6), 652–661.

Feser F., Weisse R., Von Storch H. (2001) Multi-decadal atmospheric modelling for Europe yields multi-purpose data, Eos Trans AGU, *Trans. Am. Geophys. Union*, **82** (28), 305.

Gajewski J., Gajewski L., Jednorał T., Lewandowski A. (1995) Simulation of marine lithodynamic processes along the Vistula Spit, *Inżynieria Morska i Geotechnika*, **16** (6), 284–291 (in Polish).

Jednorał T. (Ed.) (1996) *Dynamics of sea and coastal zone in the Gulf of Gdańsk. Influence of the planned navigable channel in the Polish part of the Vistula Spit on changes of marine hydrodynamic processes on the seaward side of the Vistula Spit*, Publishers of the Maritime Institute in Gdańsk (in Polish).

Kalnay E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K. C., Ropelewski C., Wang J., Leetmaa A., Reynolds R., Jenne R., Joseph D. (1996) The NCEP/NCAR 40-Year Reanalysis Project, *Bulletin of the American Meteorological Society*, **77** (3), 437–471.

Shore Protection Manual (1984). US Army Coastal Eng. Research Center.

UNIBEST-LT Version 4.0 (1993) *User's Manual MS-DOS PC-program*, Delft Hydraulics, the Netherlands.

Van Rijn L. C. (1993) *Principles of sediment transport in rivers, estuaries and coastal seas*, Aqua Publications, the Netherlands.

Von Storch H., Langenberg H., Feser F. (2000) A spectral nudging technique for dynamical downscaling purposes, *Mon. Weather Rev.*, 128, 3664-Ő3673.

WAMDI Group (1988) The WAM model – A Third Generation Ocean Wave Prediction Model, *J. Phys. Oceanogr.,* **18**, 1775–1810.

Weisse R., von Storch H., Callies U., Chrastansky A., Feser F., Grabemann I., Günther H., Plüss A., Stoye T., Tellkamp J., Winterfeldt J., Woth K. (2009) Regional meteorological-marine reanalyses and climate change projections, Results for Northern Europe and potential for coastal and offshore applications, *Bull. Amer. Meteor. Soc.*, **90** (6), 849–860.

Zawadzka-Kahlau E. (1999) *Developmental tendencies of the Polish south Baltic shores*, Gdańskie Towarzystwo Naukowe, Gdańsk (in Polish).