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ORIGINAL RESEARCH ARTICLE

Bedload transport in the Vistula River mouth derived from dune migration rates, southern Baltic Sea

Aliaksandr Lisimenka [a,b,*], **Adam Kubicki** [c]

[a] *Maritime Institute in Gdańsk, Gdańsk, Poland*
[b] *Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland*
[c] *GEO Ingenieurservice Nord-West, Wilhelmshaven, Germany*

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Summary In this paper, bedload sediment transport to the Baltic Sea in the main Vistula River mouth (Przekop Wisły) is estimated. For the first time in this area, investigations were performed based on the non-invasive measurement techniques with the using of hydroacoustic tools. Repeated bathymetric surveys were carried out using a multibeam echosounder for the period with hydrological conditions close to that of the long-term mean annual water discharge. Quantification of the bedload transport, as a main factor for the subaqueous Vistula delta development, involved applying the bedform tracking technique, and estimating the dune celerity by analysing the cross-correlation functions of bed elevation profiles (BEPs). The BEPs were obtained along two transects of 500 m in length situated in two different morphological parts of the river mouth — in the “shallow” and in the “deep” sites located upstream and downstream of the submerged sandbar, respectively. Contrarily to previous observations, the bedload transport was found to take place constantly. Moreover, a significant difference in a character of dune migration between the two sites of the investigated area was determined. The “shallow” dunes migrate 7 times faster (0.022 m/h) than the “deep” ones (0.003 m/h). Estimation of the daily bedload transport towards the Baltic Sea revealed values about 40.9 t/day and 8.4 t/day for “shallow” and “deep” sites, respectively. This result can probably indicate that a significant portion of sediments (ca. 80%) transported by the river during average hydrological conditions is deposited temporarily on the submerged sandbar, causing its growth.

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* Corresponding author at: Maritime Institute in Gdańsk, Dlugi Targ 41/42, 80-830, Gdańsk, Poland. Tel.: (+48 58) 301-16-41; fax: (+48 58) 301-35-13.

E-mail address: sasha@im.gda.pl (A. Lisimenka).

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1. Introduction

The phenomenon of sediment transport is one of the key processes taking place in marine and fluvial environments. Knowledge and understanding of sediment transport processes are particularly needed for water resource management to ensure the safety of navigation, to support hydrotechnical planning, and to minimise the risk of flooding.

In general, the total sediment load is divided into three components — bedload, suspended load and dissolved load (Bravard and Petit, 2009). The phenomenon of bedload transport is defined as the movement of sediment particles caused by their rolling, sliding and saltation along the bed in almost continuous contact with it, and is dominated by flow-induced drag forces, and by gravity forces acting on the particles (Van Rijn, 1993). It provides the major process linkage between the hydraulic and material conditions that govern river-channel morphology (Gomez, 2006). Although it is widely considered that bedload transport constitutes a relatively small percentage of the overall sediment transport budget — about 5% to 20% (Knighton, 1998), it forces the appearance and migration of bedforms on the bottom surface, and it plays a major role in controlling the bed morphology as well as the water body geometry as a whole. Similarly, Babiński (2005) pointed out that the suspended load is several times greater than the bedload transport with values commonly falling within the bounds 85—99% for suspended load, and 1—15% for bedload. He summarised that the proportion between suspended load and bedload depends on various factors such as the transport power of the river, the hydrological regime, the geological structure of the river basin, and human activity such as agriculture, industry, building construction, and river regulation.

Due to the diversity of the bedload transport mechanisms, there is no perfect method for quantification of fluvial bedload. The most commonly used are the bedload samplers, these, however, tend to interfere hydraulically with the neighbourhood of the sampling station, thus affecting the sampling results (Childers, 1999). Non-invasive methods, on the other hand, are based on bathymetry data-sets obtained by using hydroacoustic or optical methods. Having charted large river sections, a comparison of subsequent bathymetric surveys can be made. Through cut-fill volumetric calculations, one can assess the net export from the investigated sections, which is considered equal to the bedload transport (Hickin, 1995). Whenever bedforms are present on the seabed, and the identification of individual bedforms is possible in repetitive bathymetric data, one can also trace migration rates of subaqueous dunes (e.g. Kostaschuk et al., 1989).

First published data on bedload contribution into the total sediment transport at the Middle and the Lower Vistula were obtained with bedload samplers (Brański and Skibiński, 1968). Based on the author's estimation, in the case of hydrological conditions close to the mean annual water discharge ($Q_{Tczew} \approx 1000\ \mathrm{m^3/s}$), bedload transport constitutes up to about 30% of the total sediment transport (at the Tczew cross-section profile, see Fig. 1 for location). Later, based on measurements of sediment granulometry performed downstream of Tczew, and with calculations using different empirical equations, Manthey and Gilewski (1980) found that the annual bedload transport to the Baltic Sea amounted to 523,000 $\mathrm{m^3}$ on average (during the 1965 hydrological year, with the mean annual water discharge $Q_{Tczew} = 1055\ \mathrm{m^3/s}$). Moreover, the author's assessment of bedload contribution into the total sediment transport

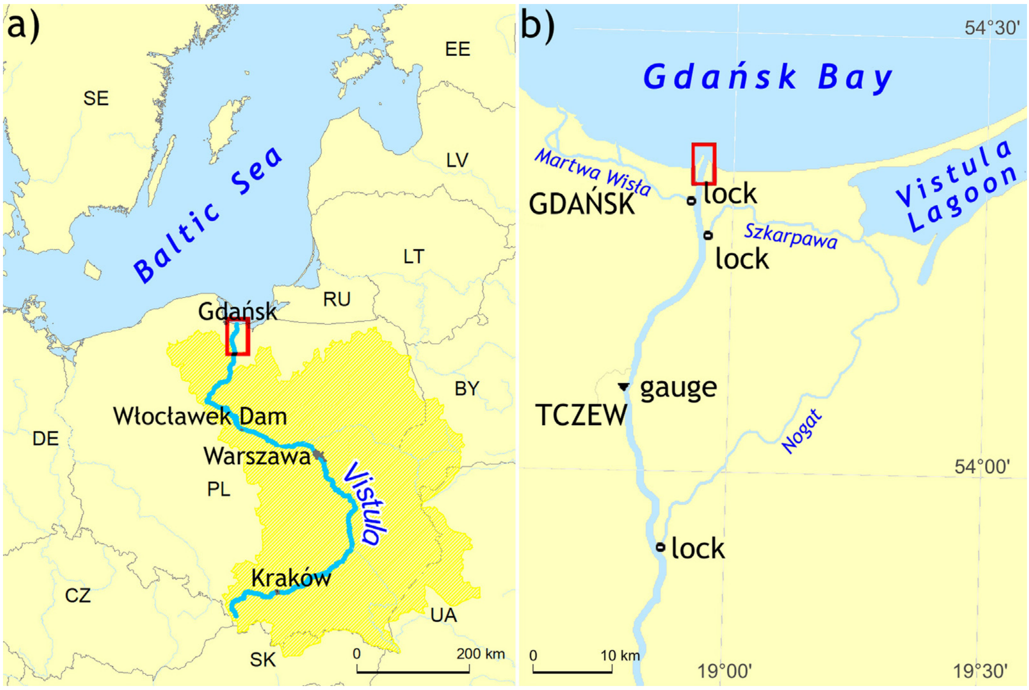

Figure 1 Location of the area of interest "Przekop Wisły" including (a) the Vistula River basin (in dark yellow), and (b) other Vistula arms closed by locks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

revealed values ranging from 35.8% up to 49.2% (41% on average), with a clear trend of decrease downstream of the river. Recent studies were focused on better estimates of suspended sediment transport, finding evidently more important suspension transport share, which accounted for forming the Vistula prodelta (Damrat et al., 2013; Szymczak and Galińska, 2013; Zajączkowski et al., 2010).

This paper presents the results of investigations aimed at estimating the bedload transport in the main Vistula River mouth (Przekop Wisły). Based on data-sets obtained by repeated bathymetric surveys, the quantification of the bedload was performed by applying the bedform tracking technique and the estimation of the dune migration rate based on the data-set obtained by repeated bathymetric surveys. Unlike previous studies, in which bedload transport was not traceable on the river sections located several kilometres upstream of the investigated area, it was found that dunes migrate constantly all the way towards the river mouth even at low hydrological conditions. Moreover, the distinct character of sand dune migration at two different morphological parts of the Vistula outlet stretch was revealed.

2. Material and methods

2.1. Geographical setting

A bathymetric survey was performed in the main mouth of the Vistula River "Przekop Wisły" located in Polish coastal waters (Fig. 1). The Vistula (Wisła) is the largest river of the southern Baltic Sea and the most important source of sediments in the area. The total length of the river is 1047 km and its basin measures 194,000 km^2 (Fig. 1a, in dark yellow). The Vistula plays a dominant role with regards to the quantity of discharged fresh water flowing into the Gulf of Gdańsk. According to Majewski (2013), the average multiyear water outflow amounts to 33.3 km^3, supplying about 7% of fresh water to the Baltic Sea.

Due to the existence of locks controlling the water levels in the old channels of the Vistula (Nogat, Szkarpawa and Martwa Wisła, Fig. 1b), about 95% of the total Vistula water outflows into the Baltic Sea through this channel. The closest gauging station is located in Tczew 31.2 km upstream of the Vistula channel mouth (Fig. 1b). This gauge represents 99.92% of the Vistula catchment area (Augustowski, 1982). Based on operational data obtained from this gauging section (IMGW-PIB, 2017), the long-term (1921—2016) mean annual water discharge reaches 1026 m^3/s. The average daily water discharge, however, varies from 238 m^3/s in dry seasons up to the 9530 m^3/s during the flood in 1924.

The main river mouth "Przekop Wisły" is a cross-cut artificial channel with a total length of about 7 km, 400 m width, and temporarily up to 10 m water depth. Since the opening of the channel in 1895 (Makowski, 1995; Szymański, 1897a,b), the Vistula waters has brought hundreds of millions of tonnes of sediments into the Gulf of Gdańsk, creating a new river-mouth alluvial fan (Graniczny et al., 2004). Based on the morphodynamic model resulting from the bathymetric plans of the contemporary Vistula mouth area over the period of 1894—2000, Franz et al. (2005) and later Koszka-Maroń (2016) estimated that the volume of the sediment accumulated in the fan was more than about 133 million m^3. According to Pruszak et al. (2005), the Vistula carries 0.6—1.5 million m^3 of sediments annually, of which about 0.5 million m^3 deposits in the subaqueous delta, thus expanding the delta front. This was confirmed by investigations performed recently by Wróblewski et al. (2015). As reported by Pruszak and Szmytkiewicz (2015), river sediment accumulation was subjected mostly to significant reduction over the years. However, the river sediment accumulation had been reducing since the early years following the channel opening, from 2.4 mln m^3/year during the first twenty-five years to ca 0.2 mln m^3/year in recent years.

It should be noted that the character of the hydrology, and consequently the sediment transport in the Lower Vistula was significantly changed in October 1970, when the Włocławek Dam was completed (264 km upstream of the investigated area, Fig. 1a). From the hydrological point of view, the reservoir minimally reduced the volume of high water in the Vistula below the dam, but reduced very low water levels as well (Babiński and Habel, 2013). The authors estimated that the Włocławek Dam trapped the entire bedload carried from the upper river, and caught 42% of the suspended load, but also caused permanent erosion of the bed below the dam.

The most recent outcomes of granulometric analysis of grab samples collected in the area of interest revealed that the sediment particles were relatively even-sized, with coarse and/or medium-grained sands, quite well-sorted, with moderately negative skewness and a leptokurtic distribution (Rudowski et al., 2017). The authors could also establish that deposition of sediments was progressing, especially in its estuarial section, which impacted significantly on the river channel patency.

The most distinctive morphological feature of the "Przekop Wisły" bottom relief is a submerged sandbar which is situated along the western bank and elongated towards the middle of the river valley. It forms the last sediment deposit before the sediment sinks in the Vistula prodelta. Both the upstream and downstream neighbourhood of the sandbar are covered by complex patterns of subaqueous dunes that were investigated recently by Lisimenka and Kubicki (2017).

2.2. Hydrological regime of lower Vistula

The time-series of the Vistula River discharge values (Fig. 2) collected at the Tczew gauge in the period of the experiment from March and April 2015 revealed that, in general, the observed discharge values were relatively close to the long-term mean annual water outflow with some short-term events characterised by increased flow between 1100 and 1400 m^3/s and connected mainly with spring snowmelt and atmospheric precipitations.

In addition, an analysis of the meteorological conditions during the measurement campaign was performed. Based on the wind speed and wind direction data obtained from the numerical weather forecast model "High Resolution Limited Area Model" (HIRLAM; Cats and Wolters, 1996) for the point located in the Gulf of Gdańsk 2 km away to NE from the Vistula mouth, no storm surges and thus no backwaters phenomena were observed during the period of the survey (Fig. 3). During the surges caused by northerly winds, marine waters can penetrate the Vistula River valley along several kilometres (Pruszak and Szmytkiewicz, 2015).

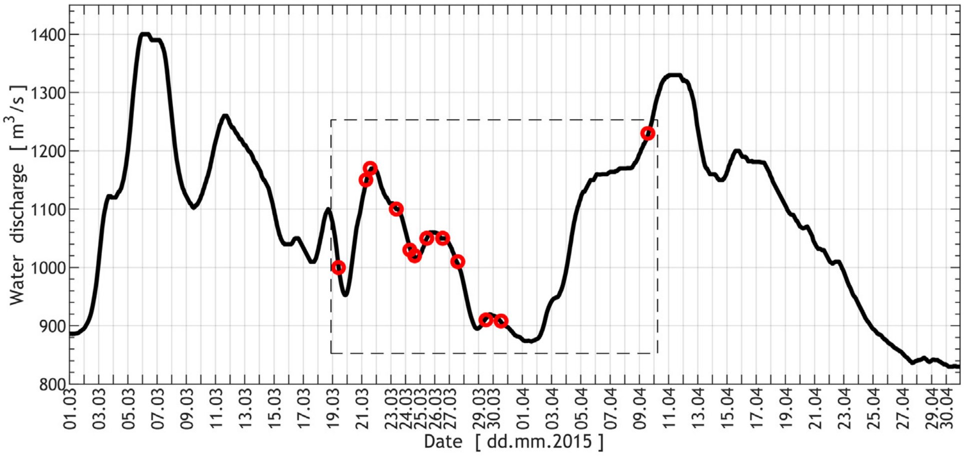

Figure 2 Hourly water discharges Q [m^3/s] (black curve) of the Vistula River at the Tczew gauge in the period between 01.03.2015 and 30.04.2015 (data source: operational data of the IMGW-PIB). Particular moments of time in a period between 19.03.2015 and 09.04.2015 when the repeated bathymetry measurements were performed are marked with red circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

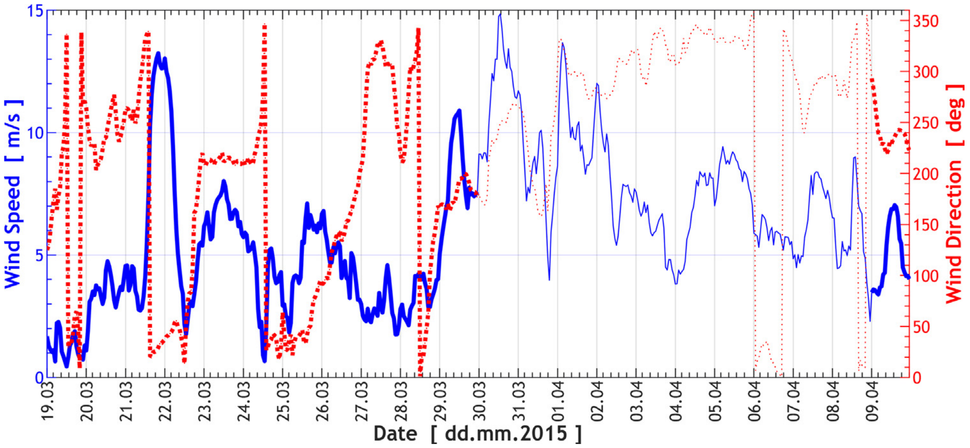

Figure 3 Time series of the wind speed (blue solid curve) and the wind direction (red dotted curve) obtained from the HIRLAM model in the period between 19.03.2015 and 09.04.2015. Period of time with a break in the measurements caused by unfavourable wind conditions in the area are marked by thin curves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. *In-situ* measurements

The measurement campaign in the Vistula River mouth area was carried out in the period between 19th of March and 9th of April 2015. The bathymetry was mapped using the Reson SeaBat 7125 multibeam echosounder (MBES) operating at 400 kHz. The MBES provides 512 discrete sounding beams across the wide 128° swath with 1° along-track transmit beam width, and 0.5° across-track receive beam width. The sound velocity probe Reson SVP-70 was fixed to the MBES head, and the portable sound velocity profiler Reson SVP-15 was used to obtain the sound speed at the depth of the MBES draft, and through the water column, respectively. The positioning system DGPS RTK Trimble BX 982 together with the Ixsea Hydrins inertial navigation system were integrated with the MBES and SVPs using the QINSy data acquisition software package. The post-processing of the MBES raw data were performed in the QINSy Processing Manager according to the standard hydrographic procedures.

A series of bathymetric measurements were made along the central axis of the investigated river channel. Two profiles, the shallower upstream and the deeper downstream of the central sandbar, 500 m long each were chosen for the analysis (Fig. 4) to avoid a complicated flow pattern at the sandbar. Between the 19th of March and the 30th of March, the measurements were, in general, conducted one per day. The last measurement on 9th of April, however, was performed after ten days of the break caused by unfavourable wind conditions in the area. Thus, the database consisting of 12-bed elevation profiles at each of the sections was collected.

2.4. Calculation of dune migration rates

In the first step, one-dimensional bedform elevation profiles were analysed using the approach of Van der Mark and Blom (2007), who were able to perform bedform tracking by determination of crest and trough positions of individual

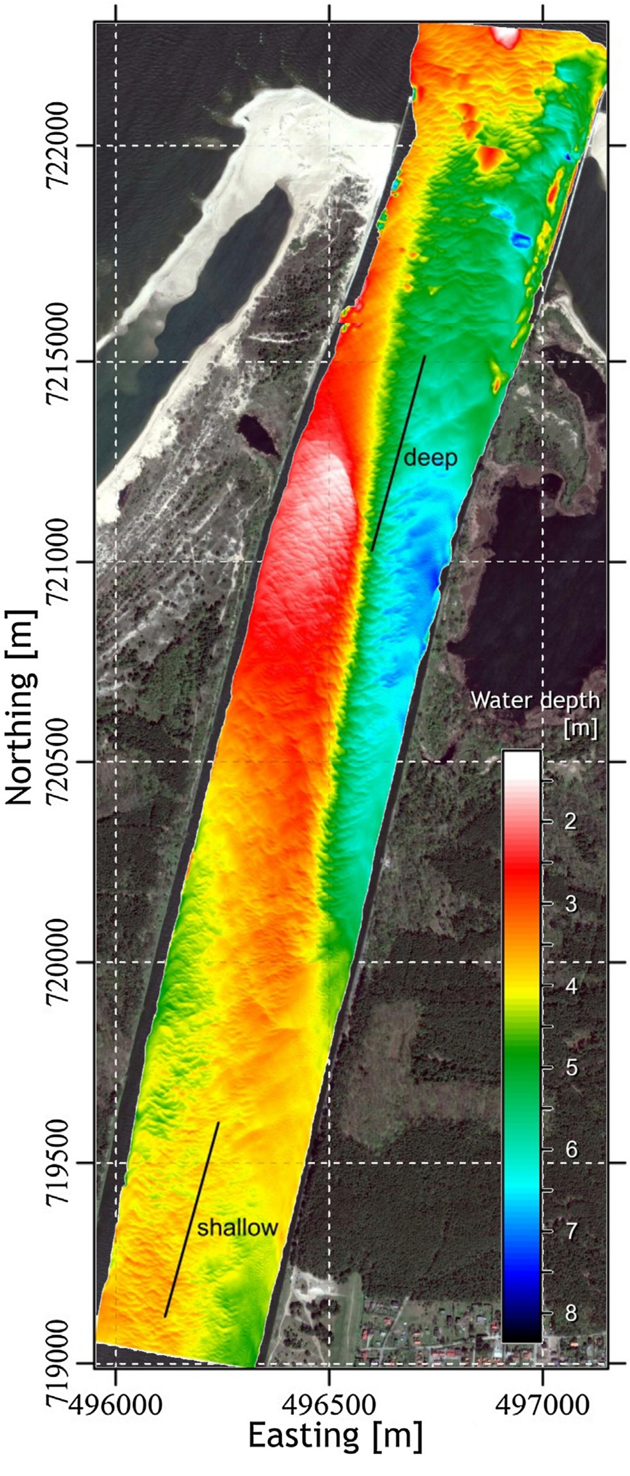

Figure 4 Bathymetry map of the Vistula River mouth (state in April 2015) with two segments of 500 m length ("shallow" and "deep") located close to the channel axis, along which the experiment was accomplished. The background consists on an aerial photo of the area from May 2017. Coordinates in Polish national geodetic coordinate system PUWG1992.

bedforms based on the zero-crossing technique (Figs. 5 and 6). Subsequently, histograms of bedform height (defined as the vertical distance between a crest and its downstream trough) and bedform length (defined as the horizontal distance between two subsequent crests) were obtained (Figs. 7 and 8). In addition, mean and median values of the appropriate dunes geometrical dimensions were derived from the statistics.

In the next step, the cross-covariance functions (using the Matlab® *xcov* function) between the initial depth data function and the subsequent ones were calculated. By definition, cross-covariance measures the similarity between two discrete-time sequences — the first one and shifted (lagged) copies of the second one as a function of the lag m. In the general case, the cross-covariance sequence c_{xy} of two jointly stationary random processes of length N, is the cross-correlation of mean-removed sequences (e.g. Orfanidis, 2007; Stoica and Moses, 2005):

$$c_{xy}(m) = E\{(x_{n+m} - \mu_x)(x_n - \mu_y)^*\}, \tag{1}$$

where μ_x and μ_y are the mean values of the two stationary random processes, the asterisk (*) denotes complex conjugation, and E is the expectation operator. In the case of real data series, Eq. (1) can also be represented in the more detailed form (Eq. (2)):

$$c_{xy}(m) = \sum_{n=0}^{N-m-1}\left(x_{n+m} - \frac{1}{N}\sum_{i=0}^{N-1} x_i\right)\left(y_n - \frac{1}{N}\sum_{i=0}^{N-1} y_i\right). \tag{2}$$

Taking into account the moments of time in which depth data were collected, the mean velocity (celerity) of dunes migration can be estimated by determining the space lag of the cross-covariance function maximum (the maximum correlation corresponds to the approximate distance the bedforms have translated).

Finally, assuming suitability of the approximation of the bedload transport for ripples and dunes formulated and proposed by Simons et al. (1965), the volume rate of bedload for idealised triangular bedforms was calculated based on Eq. (3):

$$q_b = (1-p)V_s\frac{\eta}{2}, \tag{3}$$

where q_b is the volumetric bedload transport rate per unit width [$m^2/s = (m^3/s)/m$], p the porosity of the sand bed (typically ranges from 0.26 to 0.43 in the case of coarse sand — Geotechdata.info, 2013), V_s is the mean velocity (celerity) of dunes in the direction of the flow, and η the mean dune height. Eq. (3) is widely used in literature (e.g., Aberle et al., 2012; Dinehart, 2002; Holmes, 2010; Van den Berg, 1987; Venditti et al., 2016; Villard and Church, 2003). As Simons et al. (1965) mentioned, the equation is more suited for a dune-bed configuration than for ripples and gives more reliable results for coarse bed material due to the fact that the dunes of coarse sand are more frequently near-triangular in shape than are the dunes comprised of fine material. Values of bedload q_b were subsequently converted from volume to weight by multiplying Eq. (3) by the sediment mineral density $\rho = 2650$ kg/m^3.

3. Results

The analysis of bed elevation profiles revealed the presence of small to large sand dunes (as in Ashley, 1990) with geometrical dimensions ranges up to $\eta = 0.71$ m in height and up to $\lambda = 35.4$ m in length. Comparison of bed elevation profiles

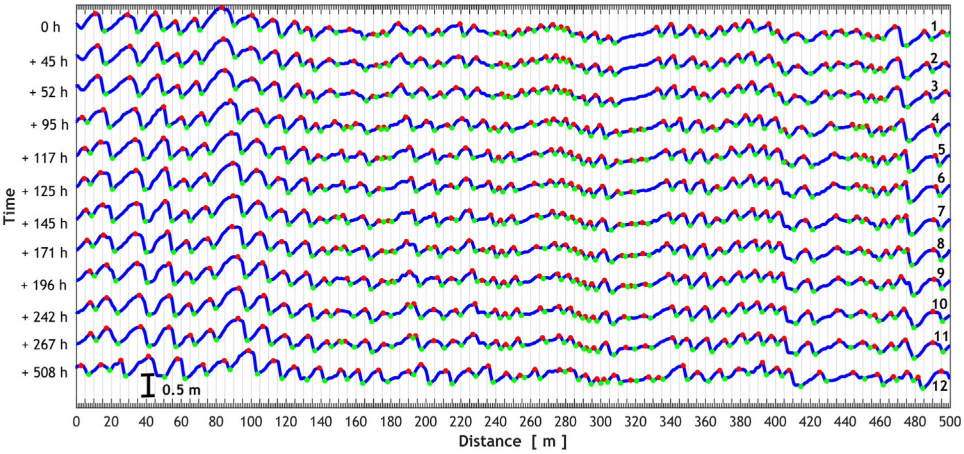

Figure 5 Depth elevation profiles along the "shallow" segment of 500 m length for all successive days of echosounding. The respective time steps are in hours relative to the initial survey. Location of crests and troughs are depicted with red and green points, respectively. The height of the black vertical scale is 0.5 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

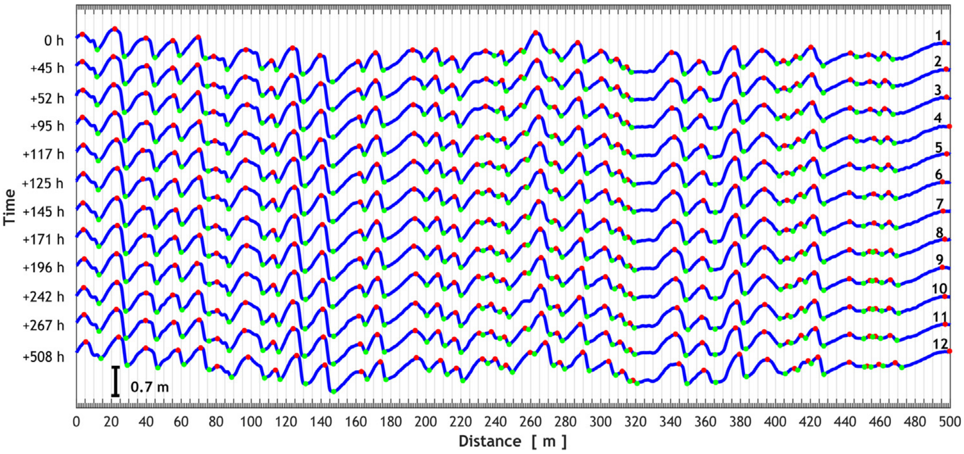

Figure 6 Depth elevation profiles along with "deep" segment of 500 m length for all successive days of echosounding. The appropriate time steps are in hours relative to the initial survey. Location of crests and troughs are depicted with red and green points, respectively. The height of the black vertical scale is 0.7 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

along two longitudinal segments (Fig. 4) indicated a distinct character of subaqueous bedforms — with dunes, in general, smaller in height and shorter in length at the "shallow" part of the investigated area (upstream of the submerged sandbar).

The number of individual dunes observed at the "shallow" segment (Fig. 5) reduced slightly in time from 48 at the beginning of the experiment (profile 1) to 44 bedforms 508 h later (profile 12). The mean and median values of dune heights η and lengths λ were derived from the statistics. Changes of these parameters revealed that both of them increased in time — from η_{mean} = 0.20 m, η_{median} = 0.18 m and λ_{mean} = 10.3 m, λ_{median} = 9.9 m to η_{mean} = 0.24 m, η_{median} = 0.22 m and λ_{mean} = 11.2 m, λ_{median} = 11.4 m in what can be interpreted as the amalgamation (merging) of a few small bedforms.

In turn, almost the same number of bedforms (34—36 individual dunes) was observed at the "deep" area (Fig. 6). Contrastingly to the "shallow" case, the mean values of dune heights and lengths remained almost without any changes — from η_{mean} = 0.33 m, η_{median} = 0.32 m and λ_{mean} = 14.5 m, λ_{median} = 13.6 m to η_{mean} = 0.32 m, η_{median} = 0.31 m and λ_{mean} = 13.7 m, λ_{median} = 13.9 m in the beginning (profile 1) and in the end (profile 12) of the experiment, respectively.

The most suitable probability density functions (with the smallest error estimated based on Eq. (1) in Van der Mark et al., 2008) were fitted to the appropriate distributions of the geometric variables (Figs. 7 and 8). Thus, it was found that the Gamma, Normal and Weibull distributions (blue, red and black curves respectively) yield the best approximation for bedform height and wavelength. It is in reliable agreement with the results of Van der Mark et al. (2008) as well as with the outcomes presented in Lisimenka and Kubicki (2017).

Calculation of the cross-covariance functions (Eq. (2)) for particular pairs of the bed elevation profiles (between the

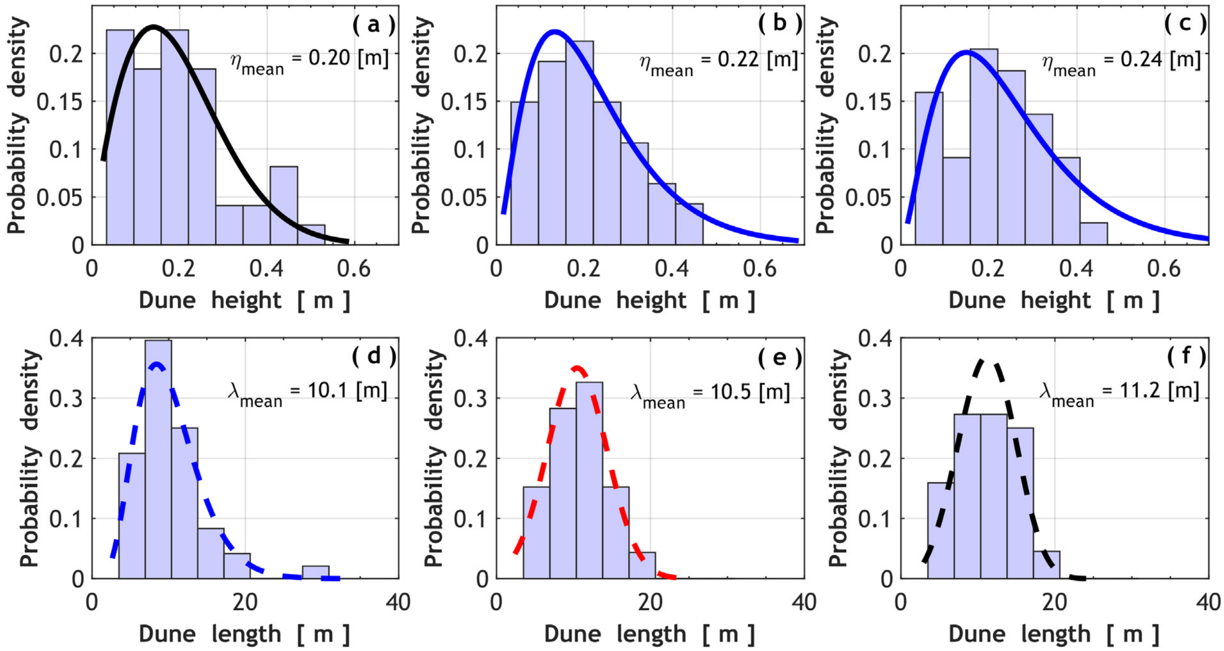

Figure 7 Histograms of dune height and length obtained, based on the measurements performed along the "shallow" segment at different moments of time — at 0 h (a, d), +267 h (b, e) and +508 h (c, f). The most suitable probability density functions are depicted by solid and dashed curves for dune height and length, respectively (blue — Gamma, red — Normal, black — Weibull). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

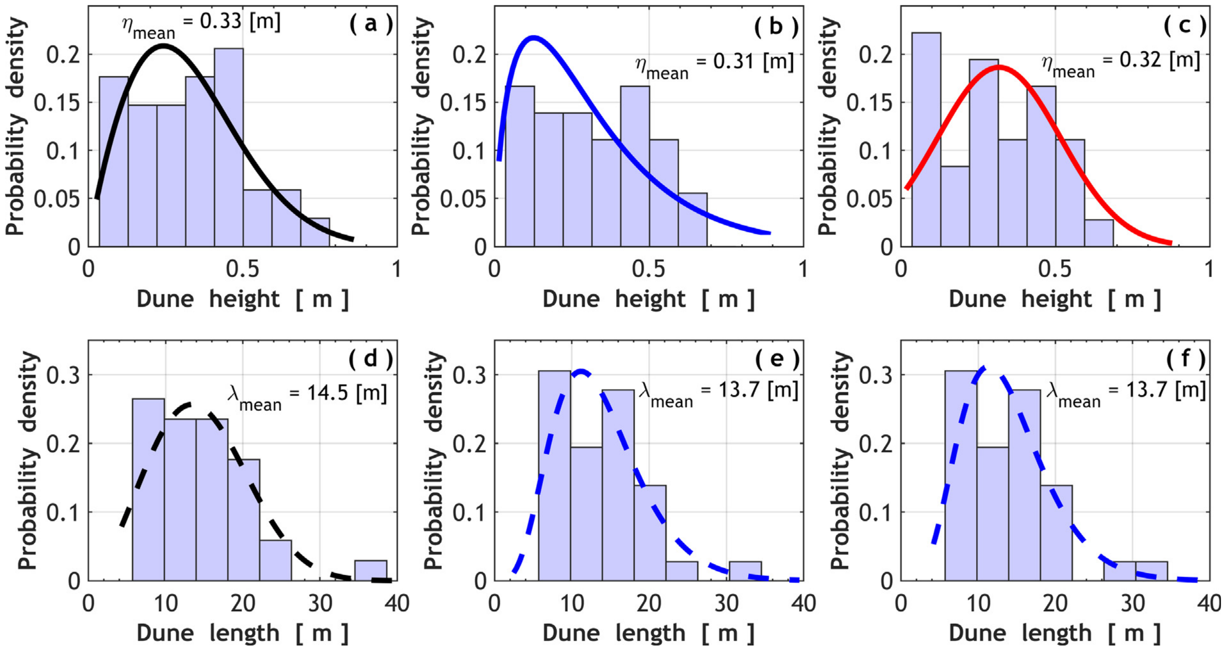

Figure 8 Histograms of dune height and length obtained, based on the measurements performed along the "deep" segment at different moments of time — at 0 h (a, d), +267 h (b, e) and +508 h (c, f). The most suitable probability density functions are depicted by solid and dashed curves for dune height and length, respectively (blue — Gamma, red — Normal, black — Weibull). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

initial one and the subsequently measured profiles) revealed distinct character of dunes migration at two different morphological parts of the river mouth. Progressive increasing of the spatial lag of the cross-covariance function maximums has got evidently "faster" character at the "shallow" segment in comparison with the "deep" one (Fig. 9). This can be explained by the difference in kinematics of the small-scale bedforms in comparison with the large ones (e.g. Bridge,

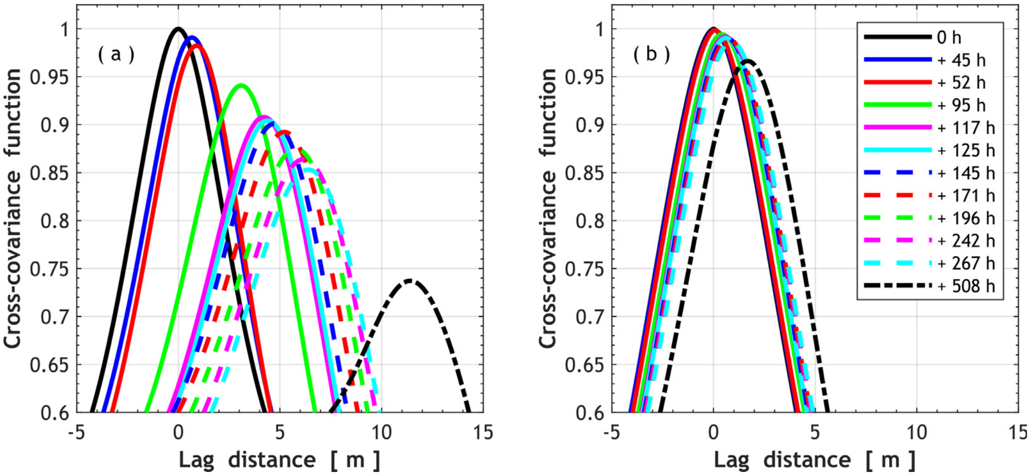

Figure 9 Cross-covariance functions (zoomed) calculated based on Eq. (2) for particular pairs of the bed elevation profiles (relative to the initial one) at the "shallow" (a) and the "deep" (b) segments.

2003). In addition, lag distance changes between successive time steps showed that dune migration rates were not constant in time (Table 1).

Overall downstream displacement of the "shallow" and "deep" ensembles of dunes (as a whole) for the entire period of the experiment (508 h) amounted to 11.4 m and 1.7 m, respectively. It means that, in general, dunes observed at the "shallow" area migrated 7 times faster in average than the "deep" dunes, with mean dune celerity equal to 0.022 m/h and 0.003 m/h, respectively.

Taking into account the average migration rates for the entire experiment together with mean dune heights (Table 1), as well as assuming that the porosity of the coarse sand bed equals to $p = 0.35$, an estimation of the volumetric bedload transport rate was calculated (Eq. (3)). The calculation revealed values of $q_{b\_shallow} = 4.25 \cdot 10^{-7}$ m^2/s and $q_{b\_deep} = 8.7 \cdot 10^{-8}$ m^2/s for the shallow and deep sections, respectively. Based on the assumption that the effective river channel width at the area of interest is about 420 m and the density of sand $\rho = 2650$ kg/m^3, it can be roughly estimated that the daily bedload transport amounts to 40.9 t/day and 8.4 t/day for the "shallow" and "deep" sections, respectively.

4. Discussion

In this study, estimation of bedload transport of Vistula River mouth into the Baltic Sea was approached over two dune fields. The calculation was done in the "shallow" part upstream from the submerged sandbar and in the "deep"

Table 1 Mean statistics in bedform geometry and migration of the "shallow" and "deep" ensembles of dunes for particular time steps.

#	Date/time of survey	Time step, Δt_i [h]	"shallow"/"deep"									
			Mean dune height, η_{mean} [m]		Mean dune length, λ_{mean} [m]		Mean dune steepness, $\eta_{mean}/\lambda_{mean}$		Distance travelled, Δx_i [m]		Mean dune celerity, $V_i = \Delta x_i/\Delta t_i$ [m/h]	
1	19 March 10:00	0	0.20	0.33	10.3	14.5	0.019	0.023	—	—	—	—
2	21 March 07:00	45	0.20	0.32	10.3	14.5	0.019	0.022	0.7	0.05	0.016	0.001
3	21 March 14:00	7	0.20	0.33	10.3	14.5	0.019	0.023	0.2	n/a	0.029	n/a
4	23 March 09:00	43	0.20	0.32	9.7	14.2	0.020	0.022	2.2	0.35	0.05	0.008
5	24 March 07:00	22	0.20	0.31	9.9	14.1	0.020	0.022	1.1	0.2	0.05	0.009
6	24 March 15:00	8	0.21	0.32	10.6	14.0	0.020	0.023	0.2	0.05	0.025	0.006
7	25 March 11:00	20	0.20	0.32	10.1	14.1	0.020	0.023	0.3	0.05	0.015	0.003
8	26 March 13:00	26	0.20	0.31	9.7	13.7	0.020	0.023	0.5	0.05	0.019	0.002
9	27 March 14:00	25	0.21	0.31	10.3	13.6	0.020	0.023	0.6	0.05	0.024	0.002
10	29 March 12:00	46	0.22	0.32	10.7	14.1	0.020	0.023	0.4	0.05	0.009	0.001
11	30 March 13:00	25	0.22	0.31	10.5	13.7	0.021	0.023	0.2	0.05	0.008	0.002
12	9 April 14:00	241	0.24	0.32	11.2	13.7	0.021	0.023	5.0	0.8	0.021	0.003
Total		*508*	*0.21*	*0.32*	*10.3*	*14.1*	*0.020*	*0.023*	*11.4*	*1.7*	*0.022*	*0.003*

part downstream from it (Fig. 4). Obtained values differ by a factor of 5 with much more bedload being transported upstream from the sandbar. This result may suggest that the sandbar intercepts ca. 78% of bedload coming from the upper part of the river during the average discharge of the river. The accumulated sediment is thus trapped at the sandbar, which supported findings of previous research (Wróblewski et al., 2015). The authors, using a cut-fill method, showed that the sandbar grew by nearly 1 m in height between 2009 and 2014. Further studies are needed to compare the accumulated volume with our calculations. It is however, unlikely that the entire bedload stays at the sandbar. Tarnowski (1995), using hydraulic models as well as analysis of bathymetric changes observed in the Vistula fan in the period between 1983 and 1990, speculated that bedload transport decays as a function of river discharge. Manthey and Gilewski (1980) observed that in the case of low water discharge of about 800—1100 m^3/s (similar to hydrological conditions during our measurement campaign), the bedload transport was not traceable at the river section located about 7—10 km upstream of the investigated area. In turn, Tarnowski (1995) postulated that, in the case of a river water discharge of about $Q \approx 1250\ m^3/s$, no bedload transport was observed about 3 km upstream of the area of interest.

Our results however, suggest constant dune migration all the way towards the river mouth even at average (low) hydrological conditions. Tarnowski (1995) estimated in his study that the riverbed material was mobilised only during river discharge larger than $Q \approx 3000\ m^3/s$. Although there is not enough data to support this claim, it is likely that accelerated currents during increased water discharge initiate erosional processes in the Vistula River mouth. We can therefore theorise that the sandbar is only temporarily intercepting riverine bedload, and that during more energetic conditions it is being eroded, and sediments are carried away towards the subaqueous river delta.

In such a case, the result obtained at the "shallow" section could be treated as the total quantity of bedload material reaching the outlet stretch from upstream parts of the river, whereas the outcome obtained at the "deep" section could be acknowledged as the bedload transport actually delivered to the subaqueous Vistula delta during the hydrological conditions of the experiment. The two aforementioned results should not be therefore averaged, but instead considered separately.

The application of high-resolution bathymetry gave a great overview of the river mouth relief. The investigated sections of the riverbed were chosen carefully, but due to the lack of riverine current speed data one is not certain which dune field is representative for the investigated hydrological conditions. High discrepancy of results for the studied "shallow" and "deep" sections proves that the applied method of bedload calculation is very sensitive to several factors of which the educated selection of tested dune field seems to be of highest importance.

Knowing that the experiment covered merely 21 days, and only during hydrological conditions close to the long-term mean annual water discharge, it is little justified that the annual bedload transport to the Baltic Sea would be calculated. However, by doing so, the results can be compared with previous studies on the bedload transport in the Vistula River mouth and delta. If extrapolated uniformly to the annual basis, our results reveal that the estimated volume of the annual bedload transport is of about 5900 m^3/year (at the "shallow" section of the investigated area). In turn, based on the data from the years 1895—1953 presented in Słomianko (1956), the mean annual bedload transport can be estimated at 24,100 m^3/year. This was however, the period before even the Włocławek Dam was constructed. Contrastingly, other investigators (Manthey and Gilewski, 1980) predicted the bedload transport at about $\sim$500,000 m^3/year, which is at least two orders more in comparison to the values obtained in our study. It is worth to note that their estimation was based on empirical equations applied for the Tczew cross-section (31.2 km upstream of the investigated area). Moreover, the authors conducted their calculations for the 1965 hydrological year, during which long-lasting intensive discharges (significantly higher than the mean annual water outflow) together with the flood wave up to $Q = 4520\ m^3/s$ were observed (confirmed based on data shared courtesy of IMGW-PIB). Manthey and Gilewski (1980) established also that, in spite of increased bedload caused by high water discharges, the Vistula River transports significantly more sediments in suspend during the spring. The authors estimated that the ratio of bedload to suspended load is the smallest (about 30%) at the beginning (March—April) of the spring season. Therefore, such a significant difference in bedload can be explained mainly by lack of energetic events during our experiment. Increased river discharge due to spring meltwaters and autumn rainfalls was not included in our approach, what probably resulted in underestimated volumes obtained in this study.

The great importance of sediment material transported by the river as a bedload was underlined by many investigators. Granulometry analysis of sediments forming of the Vistula alluvial fan (Wypych, 1968 as cited in Tarnowska and Zeidler, 1980) as well as its lithofacies model (Koszka-Maroń, 2016) show that the bedload transport powered by the riverine processes is the main source of sediments participating in the subaqueous delta development. Coarse and medium-grained sands, which are the main components of the bedload material supplied by the river into the sea (Rudowski et al., 2017), are deposited mainly on the alluvial fan. In turn, finer sediments are washed out by wave-bottom interaction and transported far away by wave currents.

Although, the accumulation processes in the alluvial fan are subjected primarily to the hydrological conditions in the river, the shape of the fan and its offshore edges is dependent also on the amplitude/directional characteristics of the wave-current field in the area. Due to the shield of a significant part of the Gulf of Gdańsk caused by the Hel Peninsula, the surface waves with the longest fetch from the east and north-east directions have the most powerful influence on the rebuilding of the fan. In general, the wind circulations induce the relatively low speed currents in the coastal area of the Gulf of Gdańsk (Pruszak and Szmytkiewicz, 2015) and so, wave currents generated by breaking waves have a crucial impact on hydrodynamics and in consequence on the bathymetry changes at the Vistula River mouth area, as well as influence on the longshore sediment transport processes. Results of numerical modelling obtained by Ostrowski et al. (2009) showed that the storm wave conditions should be lasted at least several hours in order to observe measurable erosion of the seabed. Such events, in principle, are caused by strong winds from the north and are very infrequent in the area of the Vistula River fan.

Besides, independently of the character of sediment transport in the river, there are two equivalent streams of longshore sediment transport in the coastal region enclosing the area of investigation. One of them flows from west to east, and the other one in the opposite direction, and are observed at the western and the eastern sides of the Vistula fan respectively. Based on a one-dimensional wave model, Pruszak and Skaja (2014) estimated that these streams are of about 20,000 m^3/year. However, in our opinion, this estimation is rather discussable (overestimated) at least in the case of the west-east stream, due to lack of significant sediment sources at the western part of the Gulf of Gdańsk which could supply this longshore stream. Nevertheless, it can be stated that the quantitative role of both these "sea" streams in sediment transport processes is essentially weaker in comparison with the amount of the sediments supplied by the Vistula River.

It is important to note that the influence of the storm surges in the Gulf of Gdańsk, or wave currents on the total balance of sediment transport in the area remains still unknown. It is common however, that the storm surge pushes marine waters into the Vistula River mouth (backwater phenomena). Such energetic events are likely to trigger erosion of the marine deltaic sediments, and part of these can be easily re-suspended and carried back into the investigated river mouth. There has been however, no safe method developed which would allow for the analysis of the marine influence on riverine sediment transport during storm surges. On the contrary, the period of storm surge has been avoided in our study in order to present undisturbed data obtained during the average riverine discharge period.

5. Conclusions

For the first time, based on the non-invasive hydroacoustic method, bedload sediment transport to the Baltic Sea has been estimated in the main Vistula River mouth (Przekop Wisły).

During a 21-day observation conducted in hydrological conditions close to that of the long-term mean annual water discharge, the bedload transport was found to take place constantly. The analysis of dune migration rates revealed the distinct character of sand dune migration at two different morphological parts of the Vistula outlet stretch. It has been found that the smaller in size dunes (mean dune height $\eta_{mean} = 0.21$ m and dune length $\lambda_{mean} = 10.3$ m) located upstream from the submerged sandbar that forms the last depositional barrier before the mouth, migrate 7 times faster than the larger ones ($\eta_{mean} = 0.32$ m and $\lambda_{mean} = 14.1$ m) located downstream from it. Average migration rates for the entire experiment revealed values of 0.022 m/h and 0.003 m/h and daily bedload sediment transport values of about 40.9 t/day and 8.4 t/day were obtained for "shallow" (upstream) and "deep" (downstream) sites, respectively. Such difference was attributed to sediment trapping by the submerged sandbar during the hydrological conditions of the experiment.

The presented method proved to be successful for estimation of the bedload transport but the approach should be repeated during high water discharges of the Vistula River to deliver better approximation of sediment volume to the subaqueous Vistula delta in the Baltic Sea.

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