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Morphology of the bottom of the Przekop Wisły canal

Morfologia dna Przekopu Wisły

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Abstract: Opened in 1895, the Przekop Wisły canal is a straight channel in the mouth of the Vistula River, which has been dug to adjust the hydrological situation in the Żuławy region. Recently, applying a multibeam echosounder has enabled the first comprehensive morphological registration and analysis of the bottom of the Przekop Wisły canal. The channel contains rapid, a side bar, a pool, and a front bar alongside sand dunes that have developed on the surface of these morphological units. The Przekop Wisły canal, in its current bathymetric situation, has been shown not to meet the conditions required for a free flow of water in case of considerable swelling, especially in case of an intense flow of drifting ice. No marine factors (naturally, apart from changes in sea level) were found to have a significant or direct effect on the morphology and sediments of the bottom of the Przekop Wisły canal.

Keywords: sand dunes, megaripples, straight river, Vistula River

Streszczenie: Uruchomiony w 1895 roku Przekop Wisły jest prostolinijnym fragmentem ujściowego odcinka Wisły wykonanym w celu uregulowania sytuacji hydrologicznej w rejonie Żuław. Zastosowanie echosondy wielowiązkowej umożliwiło przeprowadzenie pierwszej, dokładnej rejestracji rzeźby i analizy morfologicznej dna Przekopu Wisły. W obrębie koryta wyróżniono bystrze, odsyp boczny, ploso i odsyp środkowy wraz z rozwijającymi się na ich powierzchni falami piaszczystymi. Wykazano, że Przekop Wisły, w obecnej sytuacji batymetrycznej, nie spełnia w wystarczającym stopniu warunków do swobodnego spływu wód w przypadku dużych spiętrzeń, a szczególnie w sytuacji intensywnego spływu lodów dryfowych. Nie stwierdzono istotnych, bezpośrednich skutków wpływu czynników morskich (naturalnie oprócz zmian poziomu morza) na budowę dna przekopu i jego osadów.

Słowa kluczowe: fale piaszczyste, megariplemarki, rzeka prostolinijna, Wisła

Introduction

The Przekop Wisły canal (fig. 1) was dug between 1891 and 1895 (Szymański 1897). As planned, it constitutes an important flood control feature for the Żuławy region and Gdańsk. The channel has shortened the Vistula River by 10 km (Majewski 1969). The Gdańsk part of the river has been closed with locks and is now known as Martwa Wisła (in English, *Dead Vistula*) and Wisła Elbląska (Szkarpawa) (fig. 2). In 1915, Nogat, an eastern branch of Vistula, was closed off, blocking the discharge of water into the Vistula Lagoon through this river. Today, nearly all waters of the Vistula River are discharged through a single riverbed into the Gulf of Gdańsk.

Up-to-date information about the bottom of the Przekop Wisły canal is important for flood prevention in the Żuławy region. A detailed analysis of the bottom has recently been made possible, thanks to the application of a multibeam echosounder, which allows for a precise (to an accuracy of 1 cm) positioning of measurement profiles. A key advantage of this method is the high (decimetre-level) measurement resolution and its applicability in very shallow bodies of water (Lisimenka et al. 2013; Szefler et al. 2015).

Measurements with a multibeam echosounder were performed three times: in October 2013 and in March and June 2014. Detailed data about the bottom morphology in the mouth of the Przekop Wisły canal were obtained (fig. 3). Result analysis considered a concurrent, independent study, concerning the alluvial fan of the Vistula River (Wróblewski et al. 2015) and was performed regarding the effect of river,

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marine, and anthropogenic factors. The obtained results were used to determine the state of the bottom of the Przekop Wisły canal and the possibility to ensure a free flow of floodwater and drifting ice. The aim of this article is a precise determination of the current state of the Przekop Wisły canal, in its section stretching from the port in Świbno to the directional breakwaters in the river mouth in the Gulf of Gdańsk.

The Przekop Wisły canal is a gradually expanded, artificial riverbed with stabilized banks that run in a NNE line. A mouth section of the Przekop Wisły canal, 3.4 km in length (from the port in Świbno up to the river mouth in the Gulf of Gdańsk), was analysed. Within the section, the width of the channel ranges from 420 m at the port in Świbno to 450 m at the mouth, and its depth reaches 7 m. Despite the straight course of the Przekop Wisły canal, the Vistula River acts like a meandering river. Four primary morphological units have developed in the Przekop Wisły canal: a rapid, a side bar, a front bar, and a pool. On the surface of these morphological units, there emerge rhythmic forms, specifically, sand dunes with ripple-marks, including megaripples.

Material and methods

Research on the surface of the bottom was based on high-resolution measurements performed with a multibeam echosounder (MBES) Reson SeaBat 7101, 240 kHz, covering

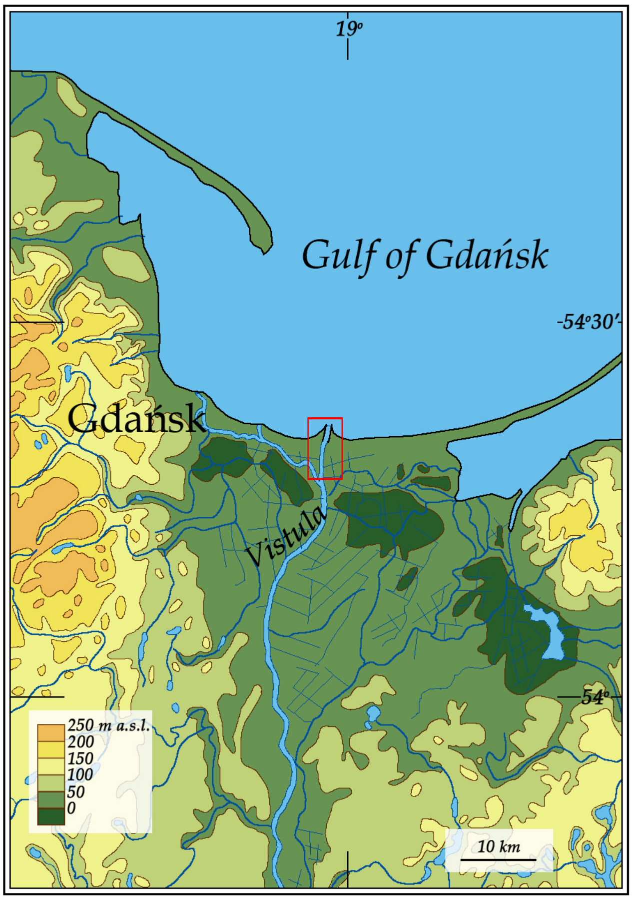

Fig. 1. Location of the research area. Hypsometric map acc. to Wróblewski et al. (2015).

Fig. 2. Research area on satellite photo (Google Inc. 2015).

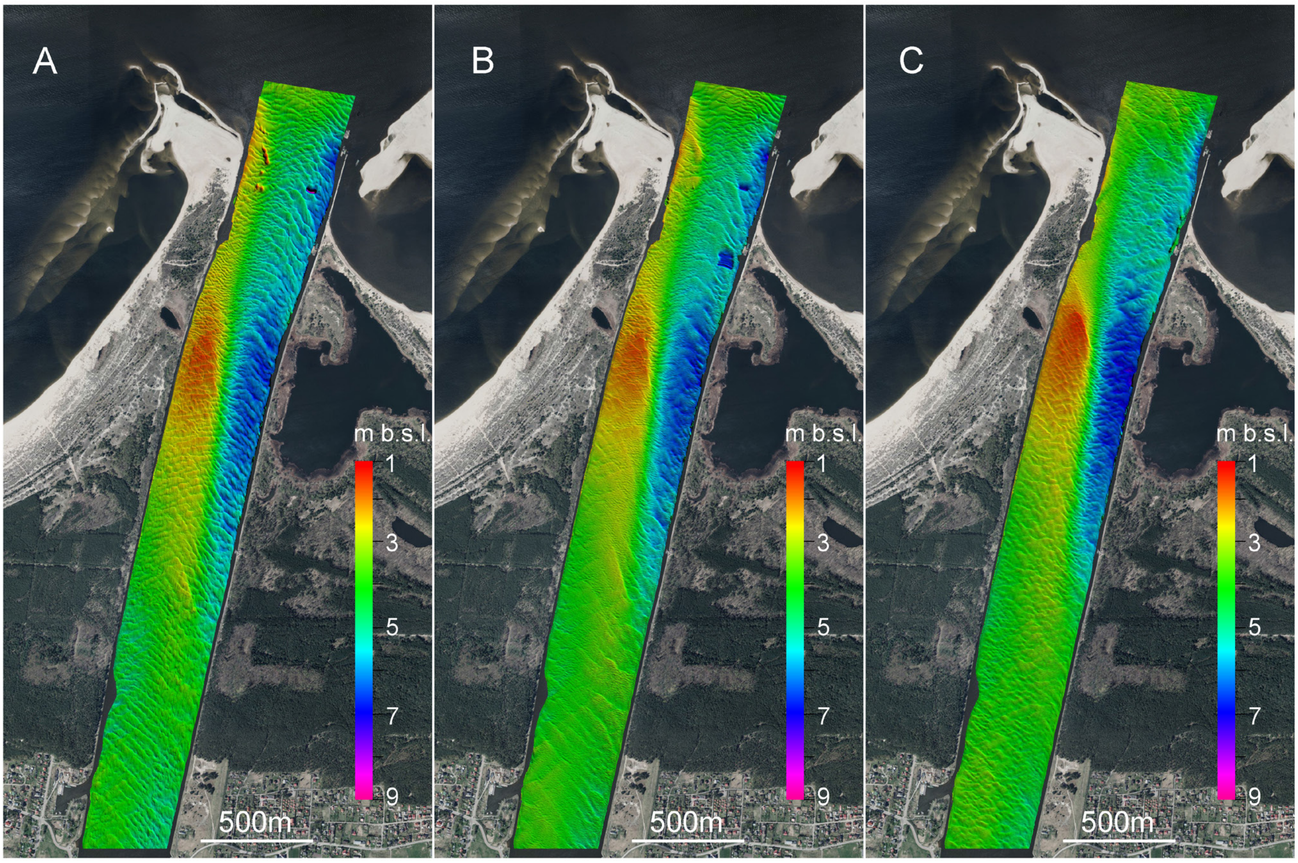

Fig. 3. The image of the bottom of The Przekop Wisły canal using multibeam echosounder. Bottom state current as of: A – October 2013, B – March 2014, C – June 2014.

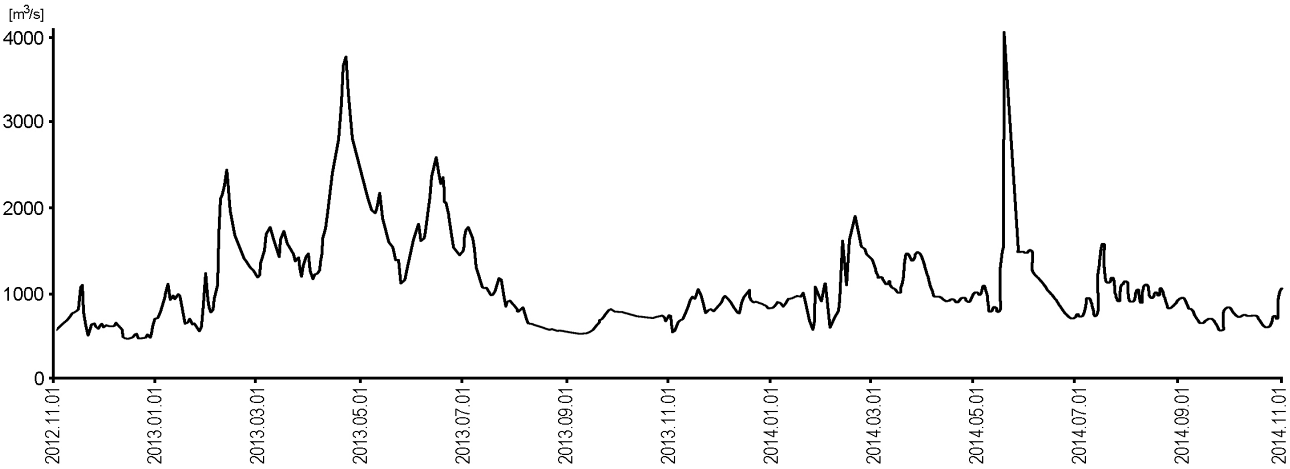

Fig. 4. Stream hydrograph for Vistula River, Stream Gaging Station in Tczew in the period of November 1st, 2012 – November 1st, 2014.

the area of research. The measurements were performed along the research profiles parallel to the axis of the channel at intervals of 10 m between the subsequent profiles. Sound propagation speed was measured using an FSI NXIC CTD meter. Measurement equipment was positioned using an RTK GPS receiver (Trimble SPS 851), adjusted for the EUPOS system and the Ixsea Hydrins Inertial Navigation System. The data were collected and analysed using the Qinsy 8.0 hydrographic system. Calculations on the WGS 84 ellipsoid were performed using the TRIMBLE GPSurvey 2.0 WAVE 2.20e software and Qinsy 8.0.

Data concerning the volume of water flow were collected from the website of the Polish Institute of Meteorology and Water Management (pogodynka.pl) for the gauging station in Tczew (fig. 4). Since the station covers 99.92% of the area of the Vistula River basin (Augustowski 1982), its registered flow volume was assumed to represent the entire mouth section of the Przekop Wisły canal.

A high-resolution (0.1 m x 0.1 m mapping grid) digital terrain model (DTM) was made for each measurement campaign. The obtained terrain data was used to conduct a morphological analysis of the bottom of the Przekop Wisły canal.

The individual elements of the channel and the forms located therein were isolated, based on various synthetic studies on rivers (Allen 1970; Chudzikiewicz et al. 1979; Coleman and Prior 1980; Gradziński et al. 1976; Lindner 1992; Reineck and Singh 1980; Zieliński 1998).

Most sediments within the Przekop Wisły canal constitute uniform coarse-grained and medium-grained sands (no fine-grained sands) with moderate sorting, negative skewness, and a leptokurtic distribution (Rudowski et al. 2017). The morpholithodynamic character of the sediments in the channel corresponds to the transport and deposition conditions for the upper level of lower hydrodynamic regime (Einsele 2000) at a flow speed of up to about 1 m/s.

Results

The bottom of the Przekop Wisły canal was characterised, based on a bathymetric map from October 2013 (fig. 5). Primary morphological units and mesoforms were distinguished. Changes that had occurred within these units in the bathymetric situations (October 2013, March 2014, and June 2014) were analysed. The units described here comprise a rapid, a side bar, a pool, and a front bar, on the surface of which rhythmical forms have developed, i.e., large subaqueous sand dunes (Ashley 1990) covered with ripple-marks, including megaripples (fig. 5, 6).

Rapid

In the southern part of the analysed section of the Przekop Wisły canal is the rapid (fig. 5). It spans the entire width of the channel and a length of about 1 km. The area is 3.4–5.4 m deep. A band of shallow water can clearly be seen within the rapid, running along the diameter of the section from SW to NE, or from the left bank to the right bank of the channel. The central part of the rapid is shallower, with a depth of 3.4–4.7 m, while closer to the banks, the rapid is 4.4–5.4 m deep. This part of the rapid arcs and transitions smoothly into the side bar.

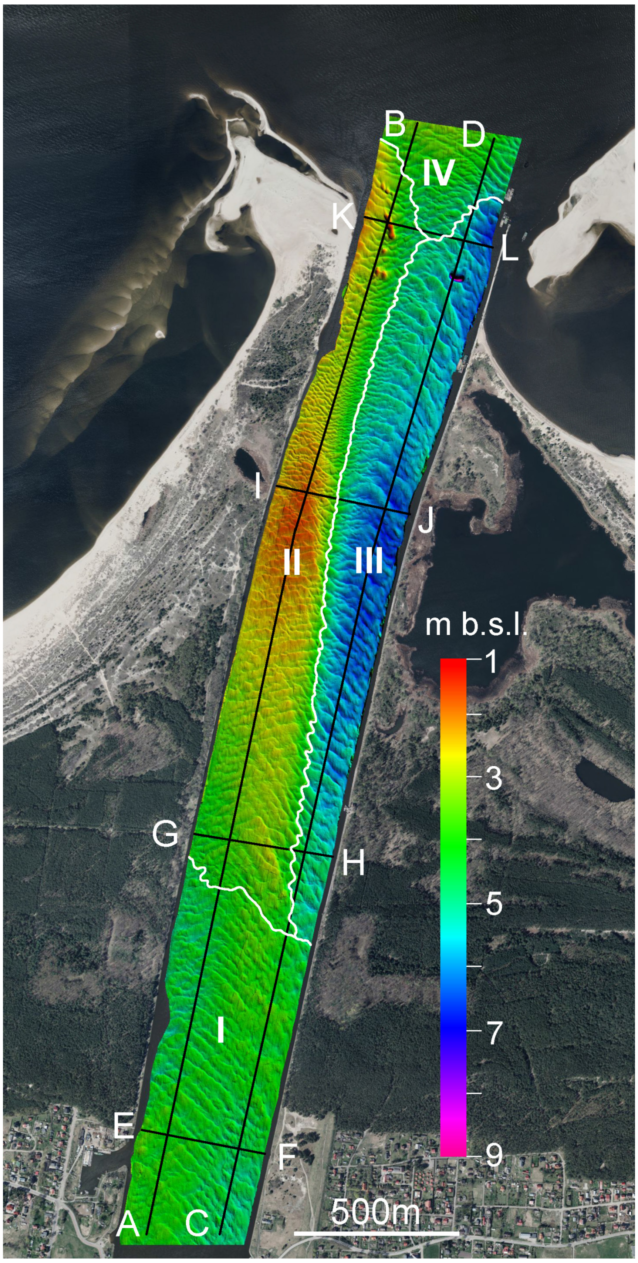

Fig. 5. The image of the bottom of the Przekop Wisły canal using multibeam echosounder (October 2013). The main bottom units were marked: I – rapid, II – side bar, III – pool, IV – front bar. Locations of bathymetric profiles (fig. 6) are shown.

Side bar

The side bar begins within the first kilometre of the analysed section of the Przekop Wisły canal, moves to the left bank, and continues for 2.3 km (fig. 5). The side bar gradually narrows towards the river mouth. It is about 380 meters wide in its southern part and 140 meters wide in its northern part, directly before the mouth. Depth within the side bar ranges from 1.5 m in its central part to 4.5–5.0 m on a slope, which divides it from the pool.

Pool

The right side of the channel is occupied by a pool, which runs from the 1 km point almost up to the river mouth (fig. 5). The pool is elongated in shape and widens gradually. It is 2.3 km long and up to 260 m wide, with a mean width of 170 m. The depth of the channel in the pool ranges from 4.5–5.0 m within the side bar to 7.0 m in the central and northern part of the pool. The depth curve within the pool is sinusoidal. The depth initially increases up to the central part, after which it decreases to 6.0 m, and increases again beyond that point to 7.0 m.

In the parallel parts of the bottom, within the side bar and the pool, the depth curves also change sinusoidally, but are out of phase (fig. 6). The shallowest parts of the side bar (about 2.0 m depth) correspond (within the same section of the channel) with the deepest parts of the pool (about 6.5-7.0 m depth),

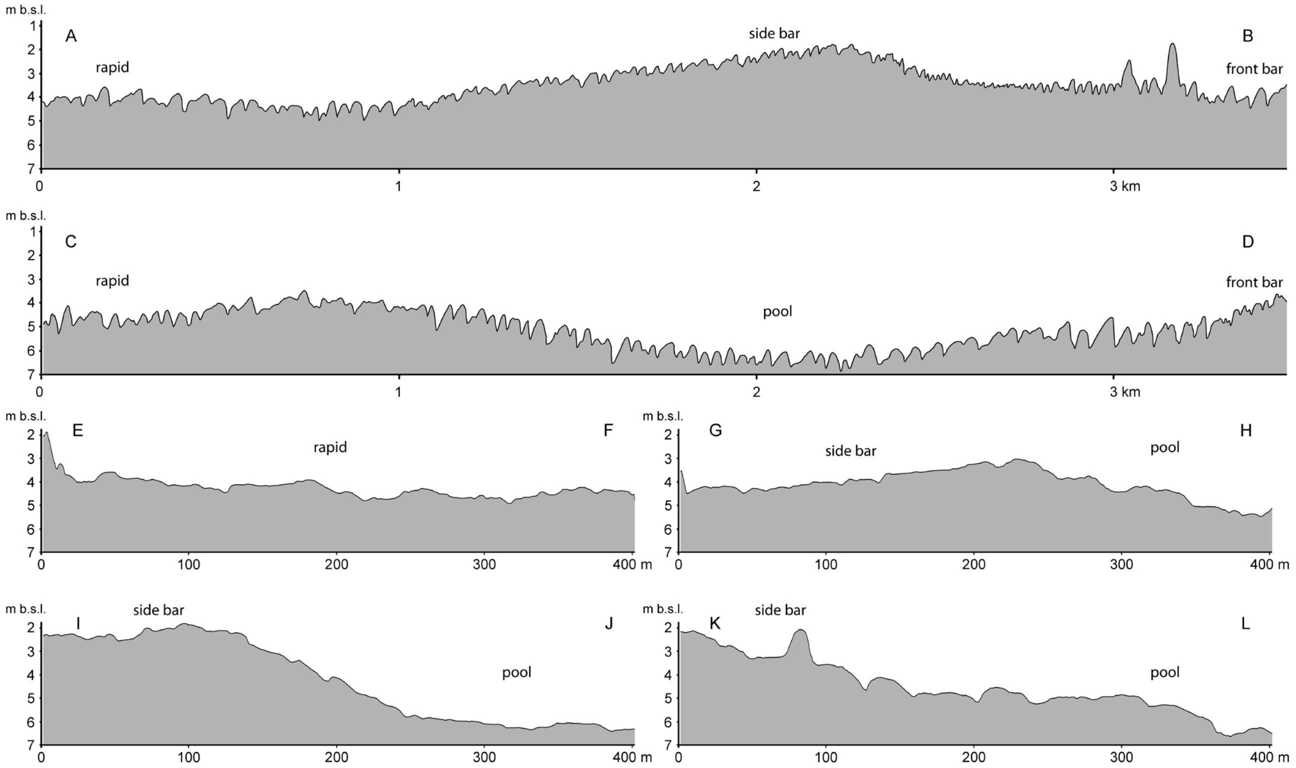

Fig. 6. Bathymetric profiles of the Przekop Wisły canal. Their locations are shown on fig. 5.

while the deepest parts of the bar (about 4.0 m depth) correspond to the shallowest parts of the pool (about 4.5-5.0 m depth). Depth within the side bar decreases toward the river mouth, reaching the lowest value in the central part of the bar, after which it gradually increases toward the mouth, where it decreases again by the left bank. Depth within the pool increases toward the mouth, reaching the highest value at the shallowest part of the side bar, after which it decreases up to the deepest part of the bar and increases again, reaching the maximum value at the shallow part of the bar, directly before the river mouth.

Front bar

Directly before the river mouth is the front bar, which has formed because of a decrease in the lift of the Vistula River, where it flows into the Gulf of Gdańsk (fig. 5). The front bar decreases the depth of the mouth section of the Przekop Wisły canal considerably and takes up the entire width of the channel in the river's final 150 meters. Depth within the front bar ranges from about 3 to 5 meters and decreases toward the river mouth. The bar is wedge-shaped, with the tip pointing upstream. Toward the mouth, it widens and makes the channel shallower.

Mesoforms

Series of sand dunes have developed on the surface of the morphological units in the Przekop Wisły canal. The dunes differ in size (Tab. I), distribution, and direction of movement (fig. 5, 6). Their proximal slopes in nearly the entire analysed area of the Przekop Wisły canal are slightly convex. The face angle visibly decreases with height, with a boundary between the different angles in many of the dunes. This is due to the crest of the preceding sand dune providing a shading effect.

Because the dunes overlap, measurement of their asymmetry (i.e., the ratio of proximal slope length and distal slope length) was only possible at isolated points. The dunes showed a similar asymmetry throughout the entire analysed section of the Przekop Wisły canal. Mean asymmetry amounted to 2.4, with the minimum value of 1.5 and the maximum value of 4.4.

The crests of sand dunes within the rapid are aligned perpendicularly to the axis of the shallow part of the bottom. Near the left bank, series of sand dunes have developed with crests aligned at an angle of 45° relative to the bank and 90° relative to the series of crests running along the axis of the rapid. In the central part of the analysed section, the overlapping crests of the sand dunes form a cross pattern, with the mean distance between the crests equal to 29 m and the maximum distance of 49 m. The dunes are from 0.22 to 0.80 m high (Tab. I). The inclination angle of their proximal slopes ranges from 0.6° to 3.0°, sometimes reaching 7.0°. The inclination angle of their distal slopes ranges from 1.5° to 8.0°, sometimes reaching 17.0°. The sand dunes on nearly the entire surface of the rapid are similar in size and course.

The crests of the dunes on the first 700 m of the bar form a herringbone pattern, with the arms running away from the axis of the bar (fig. 5) and tilted about 45° relative to the left and right side of the axis. Further on, the sand dunes are perpendicular

Tab. I. Parameters of sand dunes within the test measurement profiles (186 profiles).

	DISTANCE BETWEEN THE CRESTS [M]			HIGH [M]			PROXIMAL SLOPES [O]			DISTAL SLOPES [O]		
	average	max.	min.	average	max.	min.	average	max.	min.	average	max.	min.
Rapid	29	49	20	0.47	0.80	0.22	2.4	7	0.6	7.7	17	1.5
Side bar – southern part	23	36	13	0.38	0.48	0.26	1.9	3.3	0.7	8.2	18.7	2.4
Side bar – shallow central part	17.7	33	10	0.29	0.49	0.11	2.2	4.2	0.8	11.8	20.3	3
Side bar – deep central part	11.2	16.7	7	0.29	0.50	0.18	3.2	5	1.9	8.7	14.1	4
Side bar – northern part	20.5	28.5	14.5	0.42	0.57	0.22	2.3	2.6	2	10.9	16.2	4.5
Pool – southern part	28.6	42	24	0.58	0.90	0.21	2.9	5	1.2	8.5	23	2.7
Pool – shallow central part	32.1	60.5	16.2	0.74	1	0.47	2.5	2.8	1.4	11.1	16.9	5.8
Pool - northern part	21.8	25	17	0.64	1	0.35	2.9	4.1	2	14.6	24	12.7
Front bar	23.9	27.2	17.4	0.46	0.96	0.14	2.7	3.4	1.8	9.2	17.2	1.3

to the axis of the bar, with the mean distance between their crests equal to 23 m and a maximum distance of 49 m. The crests are 0.3–0.4 m high.

The height of the dunes within the bar decreases toward the river mouth, as does the distance between their crests. In the deepest part of the bar, beyond the shallow part, where the flow decreases due to the topography of the bottom, the sand dunes are the smallest among all identified in the analysed area. Within the shallows, in the end part of the bar, the height of the dune crests and the distance between them increase (Tab. I). In the deeper part of the bar, beyond the shallows, the sand dunes are more uniform in size and distance between the crests.

Dune crests within the pool are aligned slightly diagonally (at an angle of several degrees) to the axis of the pool toward the right bank (fig. 5). Distances between the dune crests initially decrease toward the deeper part of the pool, with a mean distance of 28.6 m, and increase in the shallower part, with a mean distance of 32.1 m and a maximum distance of 60.5 m. In the deeper part, toward the end of the pool, the distances increase again, with a mean distance of 21.8 m. The sand dunes within the pool are the highest within the analysed area. Their mean height is 0.74 m, and their maximum height is 1.0 m in the shallowest part of the pool. In the southern area of the deeper part, their mean height is 0.58 m, and in the northern part, 0.64 m.

The dune crests within the front bar are aligned perpendicular to the axis of the bar, pointing slightly outwards towards the riverbanks in a fan pattern. The dunes decrease in height and increase in width at the base toward the river mouth, and their slopes become gentler.

By October 2013, the end section of the channel bottom contained elements related to the construction and expansion of the directional breakwaters, particularly deposits of sandy material on the surface of the end section of the side bar and a nine-meter-deep depression in the end section of the pool.

Form variation

The location of the primary elements of bottom morphology is fairly stable, changing slowly over the years. An observable change in the bottom morphology of the Przekop Wisły canal occurred between October 2013 and March and June 2014 (fig.3). Within the rapid, the channel becomes uniform in depth. The northern border of the rapid moves with the river flow and enters the area of the pool and the side bar. The main, shallowest part of the side bar is transported toward the river mouth and expands toward the centre of the channel faster than it expands along the flow. The northern part of the side bar, which is visible on the map from October 2013, is being washed away, becoming narrower with time. The pool at the right bank of the channel is also transported toward the river mouth. From the south, the pool is being covered with material transported along the surface of the rapid. In its northern part, the pool widens and becomes shallower. The front bar increases its surface consistently, with its southern border moving upstream. The depth within the front bar decreases. Sand dunes appear on its surface that continue to grow larger and richer in rocky material. The distance between the crests of these dunes increases over time, as does their height.

The anthropogenic elements of bottom morphology that appear on the bathymetric map from October 2013 in the mouth section of the channel in bars and depressions do not appear on the map from June 2014.

Summary and conclusions

Modern systems for navigation and registration of bottom morphology were used to obtain material that corresponded in quality and accuracy to land topographic maps. A detailed analysis of the bottom morphology in the mouth of the Przekop Wisły canal was performed, based on this material.

The bottom of the Przekop Wisły canal is morphologically varied. The analysed section contains four primary morphological units of the bottom: a rapid, a side bar, a pool, and a front

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bar near the mouth. Well-developed, overlapping sand dunes are present on the surface of these units. This distribution of sand dunes results mainly from a large amount of material transported within the channel. The location of the primary elements of bottom morphology in the Przekop Wisły canal is fairly stable, undergoing slow changes over the years.

Bottom bed load is transported along the width of the channel, except in several-meter-wide zones by the banks, and takes the form of sand dunes with ripple-marks, including megaripples, on their surface.

The Przekop Wisły canal has the features of an aggradating river, i.e., one in which the material load is higher than the lift. Distributing morphological units on the bottom of the channel and their development indicate the sediment is too high for the channel to transport it to the alluvial cone. This causes the water to meander through the straight, profiled bed of the Przekop Wisły canal and the overlapping sand dunes to develop on the surface of the bottom of the channel.

No marine factors (naturally, apart from changes in sea level) were found to have a significant or direct effect on the morphology and sediments of the bottom of the Przekop Wisły canal. This is likely because the channel is shielded with a well-developed alluvial cone (Wróblewski et al. 2015), which also makes backflow less likely to occur due to landward wind and the effect of the waves (as the waves lose their energy on the banks of the deltaic plain, where barrier forms are created that shield the channel from the waves). The continuously expanding and shallowing deltaic plain hinders runoff, prevents the rocky bed load from being transported into the sea, and creates the risk of blockages.

The current state of the Przekop Wisły canal indicates large drifting ice floats will likely cause ice blockages in the region, regardless of the water level. The blockage may develop in the shallow parts of the channel bottom (side bar and front bar) and the shallow part of the deltaic plain within the alluvial cone of the Vistula River (Wróblewski et al. 2015). Should an obstruction occur, the Żuławy region and the Valley of the Lower Vistula will be at risk of flood. It may be impossible to respond to the threat by using ships to crush the ice, as access to the potential blockage site may be difficult due to the bathymetry of the channel and impossible from the sea.

The recommended method proposed to ensure the patency of the Przekop Wisły canal is to expand systematically the directional breakwaters in the mouth of the canal (Regional Water Management Authority, 2015). However, the expansion works conducted so far have been ineffective. While expanding the directional breakwaters was supposed to cause the mouth section of the channel to deepen, observations suggest it has had a small, practically imperceptible effect. The method would be effective in removing some of the accumulating sediments in the channel and the alluvial cone if the directional breakwaters were expanded to the very edge of the deltaic plain. Another effective method for preventing dangerous obstructions could be to deepen the channel bottom and expand it to the deltaic plain, up to its edge (the boundary with the front of the delta).

The channel cannot ensure a free water flow in case of large swelling, especially in case of an intense flow of drifting ice. Further research on the state of the channel and the alluvial cone is urgently needed to determine emergency conditions and methods for preventing obstructions.

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