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Granulometry of bottom sediments of the Przekop Wisły canal

Granulometria osadów dennych kanału Przekop Wisły

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Abstract: The Przekop Wisły (or the Vistula Cross-cut) is a canal created 120 years ago in the Vistula River mouth to prevent floods. In 2013/2014, 82 samples of canal sediments were collected in three sessions, which were next subjected to macroscopic descriptions and sieve analyses, including calculation of granulation indices expressed in the phi scale. Characteristics of granulation are presented in relation to forms of bottom relief, varied transport and storage conditions of individual sessions. Sediments in the canal are relatively even-sized, with coarse and/or medium-grained sands, quite well-sorted, with moderately negative skewness and a leptokurtic distribution. It was demonstrated that deposition of sediments in the canal is progressing, especially in its estuarial section, which impacts significantly on its patency. Hence, it is necessary to monitor sediments in the canal to establish its condition and identify trends related to risks and flood prevention. The Przekop Wisły canal constitutes a natural area of a straight channel river, and studies of its sediments may be an important model of fluvial processes.

Keywords: river sediments, straight channel river, grain size indices, transport conditions, canal patency, model

Streszczenie: Przekop Wisły to kanał utworzony 120 lat temu w ujściu Wisły dla zapobiegania powodziom. Z osadów kanału pobrano 82 próby w trzech sesjach 2013/2014 r. Wykonano opisy makroskopowe oraz analizę sitową prób z wyliczeniem wskaźników uziarnienia w skali phi. Przedstawiono charakter uziarnienia w relacji form rzeźby oraz zróżnicowanych warunków transportu i depozycji w poszczególnych sesjach. Osady kanału są względnie równoziarniste, z piaskami gruboziarnistymi i/lub średnioziarnistymi, umiarkowanie wysortowanymi, zwykle o skośności umiarkowanie ujemnej i o leptokurtycznym rozkładzie. Wykazano postępującą depozycję osadów w kanale zwłaszcza w jego ujściowej partii, co znacznie ogranicza jego drożność. Konieczne jest prowadzenie monitoringu osadów kanału dla ustalenia jego stanu i tendencji zmian w odniesieniu do zagrożeń i zapobiegania powodziom. Kanał Przekop Wisły stanowi swoisty naturalny poligon rzeki prostolinijnej i badania jego osadów mogą być traktowane jako ważny wzorzec procesów fluwialnych.

Słowa kluczowe: osady rzeczne, rzeka prostolinijna, wskaźniki uziarnienia, warunki transportu, drożność kanału, model

Introduction

The Przekop Wisły canal was created 120 years ago (Jasińska 2002, Graniczny et al. 2004, Wróblewski et al. 2015) to prevent floods in the Żuławy region and Gdańsk. Alongside a progressing accumulation of the mouth cone (the external delta), formed at the outlet of the canal, its successive extension conducted by increasing length of the directional breakwater, which outlines the canal, became necessary. At present (Fig. 1), the canal is about 3.5 km long and about 400 m wide. Geomorphologically speaking, the canal is a typical straight channel river (*sensu* Chorley et al. 1985).

The aim of this elaboration is to determine the features of granulometry of sediments at the mouth of the Vistula River, with particular consideration of the state of the Przekop Wisły canal as a significant element of hydrotechnical infrastructure preventing floods in the northern part of the Żuławy region and Gdańsk. The work constitutes the second in a series of publications on the Przekop Wisły canal assessment. The first elaboration in the series was concerned with relief of the canal bed (Wróblewski et al. 2016). The third publication (in progress) is devoted to structure of sediments in the canal bed as registered with the Sediment Echosounder (SES). The fourth publication will include an evaluation of the state of the canal and transformations of its bottom.

Sediments deposited on the canal bottom owe their form primarily to the river flows (usually not exceeding 1,000 m³/s, and reaching the level of 10,000 m³/s at maximum) (Koszka-Maroń & Jegliński 2009, Koszka-Maroń 2014, Wróblewski et al. 2016), combined with an indirect influence of wave motion and changes of sea level.

At the time of surveys performance, there was observed an exceptional situation involving passage of a substantial rain freshet with a flow up to 4,000 m³/s (Lisimenka et al. 2013, 2015).

Relief of the canal bottom is diverse (Wróblewski et al. 2016), with bars, rapid, and pool, covered with megaripples and sand waves.

Surveys of the Przekop Wisły canal, including bathymetric, granulometry, sediment structure, and hydrodynamic conditions measurements, have been conducted by the Maritime Institute in Gdańsk for many years, and since 2009, they have been performed with non-invasive methods and state-of-the-art instruments. The obtained results were pre-presented in speeches and posters at conferences, both domestically and abroad (e.g., Lisimenka et al. 2013), and in publications (Lisimenka et al. 2015, Wróblewski et al. 2015).

The aim of this work is to determine and characterise the granulometry of sediments in the canal bottom, based on analysis of 82 samples collected with a Van Veen grab sampler. The samples were taken in October of 2013 and in March and June of 2014 in the same (or nearly the same) places of distinctive character, selected based on a bottom relief analysis.

The elaboration refers to structure of the Vistula external delta (in the area adjusting to the canal), which is presented in a paper by D. Koszka-Maroń (2014).

Providing a skeleton of this work were materials from surveys conducted within the framework of the Applied Research Program no. PBS/A2/3/2012 managed by A. Lisimenka.

Materials and methods

Field studies were conducted by A. Lisimenka (Lisimenka et al. 2013, Lisimenka et al. 2015). Accurate positioning was ensured by an integrated navigation system. Sites of sample collection with a Van Veen grab sampler were selected based on a bottom relief analysis (Fig. 2). In the subsequent sessions, conducted in October of 2013 and in March and June of 2014, 82 samples were taken.

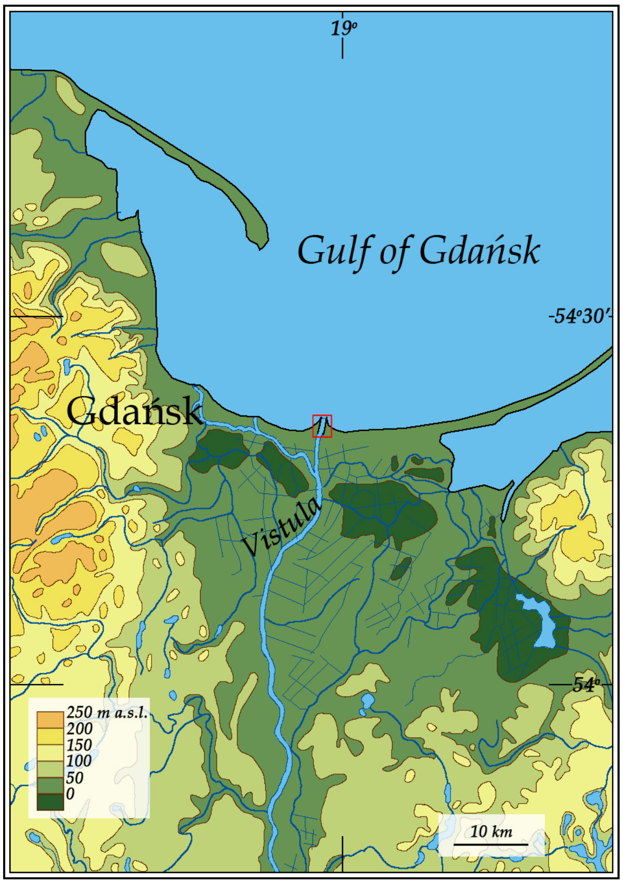

Fig. 1. Location of the research area. Hypsometric map acc. to Wróblewski et al. (2015)

The collected samples, which weighed about 0.5 kg, were next subjected to macroscopic description, including determination of the dominant fraction, sorting level, colour, reaction with HCl, content of admixtures, and other features (smell, shape, look of coarse grain components, occurrence of organisms and their remains). After drying at room temperature, the samples were reduced and subjected to a 24-hour drying time at the temperature of 105°C (Myślińska 2001).

Sieve analysis was conducted (Myślińska 2001, Łęczyński & Szymczak 2010) on the 150 g samples via the dry sieving, with sieves produced by the Fritsch company with the following mesh sizes (in mm): 8.0, 4.0, 2.0, 1.0, 0.5, 0.25, 0.125, 0.0625. Sieving time amounted to 12 minutes. Analytical scales with accuracy of up to 0.01 g were used.

Share of particular fractions of the sediments was expressed in weight percentages. Statistical parameters of grain size (granulometry) were calculated with application of the method of moments, and the Folk and Ward method (to enable comparison with results of other works calculated solely with the latter method). The Gradistat 5.11 program (a modified version) found application in the calculations. Values and descriptions of in-

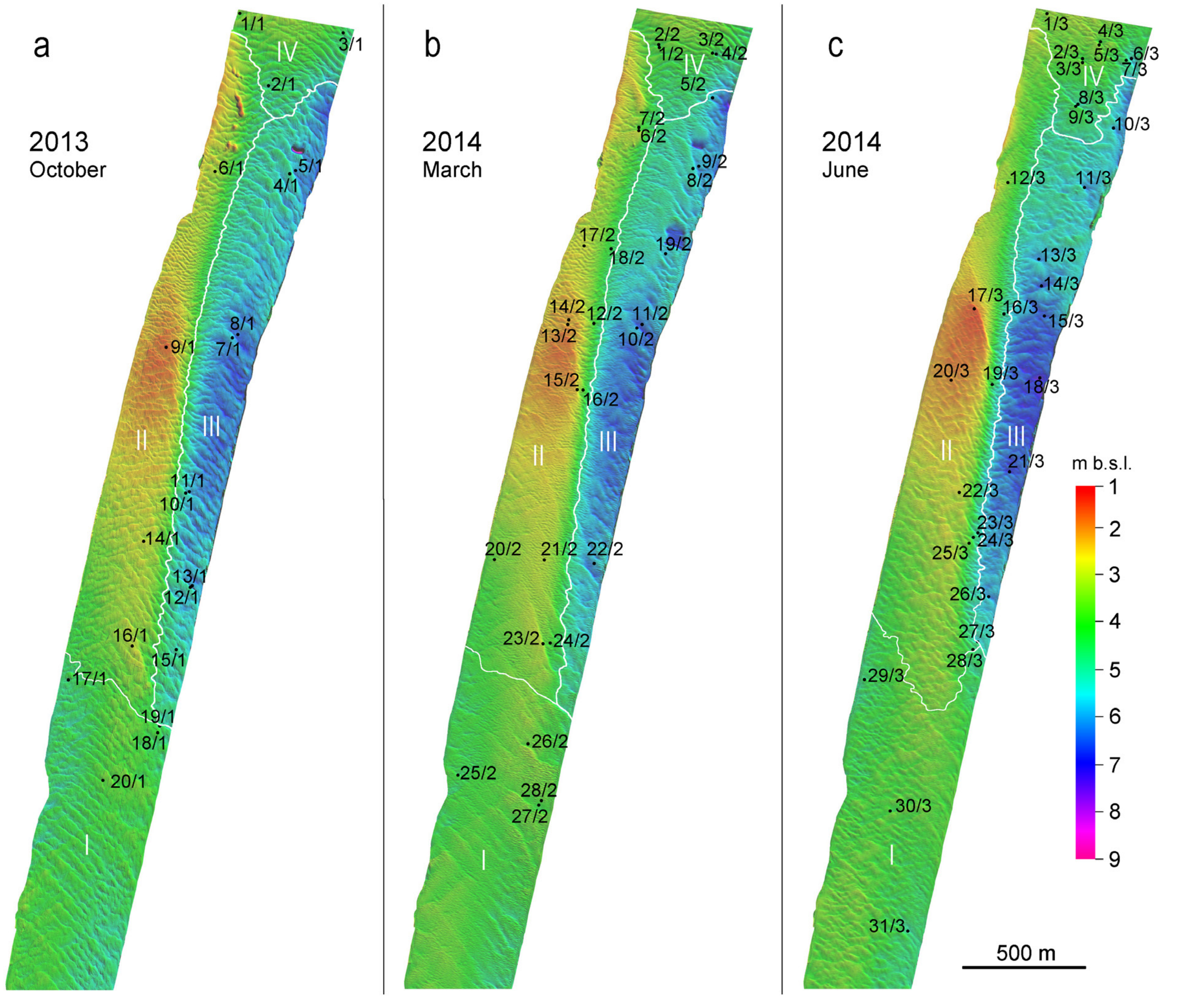

Fig. 2. The image of the bottom of The Przekop Wisły canal by using multibeam echosounder. The main bottom units were marked (acc. to Wróblewski i in. 2016): I – rapid, II – side bar, III – pool, IV – front bar. Sediments: coarse-grained sands in the area of the unit III, medium-grained sands in the area of the unit I, II and IV. The grab-sampling sites were marked. Bottom state current as of: a – October 2013, b – March 2014, c – June 2014.

Tab. I. Correlation of the grain size indices according to the Folk and Ward method (M_z, s_1, Sk_1, K_G) and the method of moments (M_1-M_4) for all the samples of session 1, 2 and 3

VALUE	MEAN DIAMETER		SORTING		SKEWNESS		KURTOSIS	
	M_z	M_1	S_1	M_2	SK_1	M_3	K_G	M_4
minimal	-0.134	-0.082	0.536	0.523	-0.394	-1.715	0.738	-0.153
medium	0.895	0.900	0.796	0.805	-0.077	-0.300	1.049	5.480
maximal	1.511	1.515	1.420	1.329	0.209	1.276	1.674	11.098

dices are conformed to the ones by E. Myślińska (2001) and L. Łęczyński and E. Szymczak (2010).

Samples taken in the first session were delivered to the laboratory frozen. Following thawing, they produced an intensive, pungent, unpleasant smell of excrements, and were rather clammy (although they contained no clay fraction). They were next tested for organic matter content via loss on ignition method at the temperature of 550°C (Myślińska 2001). Five selected samples were additionally subjected to specialised tests in the Laboratory of the Department of Environment Protection of Maritime Institute (Katarzyna Galer-Tatarowicz – Test report no. 281/13).The differentiated relief units are consistent with the system by R. Wróblewski et al. (2016). A comprehensive documentation (included in the Samples Files) is stored in the archive of the Department of Operational Oceanography of Maritime Institute in Gdańsk.

Results

On the bottom of the Przekop Wisły canal, there occurred (Tab. I) coarse and medium-grained sands (but no fine-grained ones), usually quite well-sorted, with negative skewness (Fig. 2, 3). Collective compilations of granulation indices in all sessions (Fig. 3) highlighted further small differences in their character, which are connected most probably with different flow conditions during the subsequent sessions. In the sediments, small, variable amounts of coarser fractions (of over 8 mm in diameter) also occurred. They were found mostly within the sediments deposited in the pool and, occasionally, in the furrows between sand waves and megaripples in the remaining part of the area. Sediments contained cobbles and crystalline rock debris, sandstone and bricks, concrete and other building materials. They constitute so-called "anthropogenic debris", connected most probably with construction and repair works and erosion of the canal bank's protection. In 2013-2014, intensive construction works aimed at extension of the eastern directional breakwater were conducted. These gravel-like admixtures might have been subjected to repetitive redeposition and spreading along the canal (when the flow was strong).

Moreover, fragments and entire shells of seawater and freshwater molluscs were found. Encountered especially often were big, complete shells of *Dreissena sp.* and occasionally those of *Anodonta sp.*, *Unio sp.* and *Pisidium sp*. Shells of seawater bivalves (*Mytilus sp.*) were found primarily in sediments collected in the 1st session, when they occurred in the sediments along the entire surface of the bottom. During the 2nd and 3rd sessions, there were found infrequent, complete seawater shells (*Mytilius sp.*, *Macoma sp*. and *Cerastoderma sp.*). No full analysis of malacofauna was performed (see Koszka-Maroń 2014). Only a preliminary identification was performed, which was limited to determination of big shells.

Particular units of bottom relief (Tab. II, Fig. 2) showed little diversity regarding the even-sized character of the sediments granulometry (Fig. 3) and referring to variable flow conditions of the subsequent measurement sessions (Tab. III, Fig. 2).

The basic differentiation is manifested in occurrence of coarse-grained sands, especially in the pool (Fig. 2). In the remaining area of the bottom (in the bar belt), there clearly predominated medium-grained sands. In the sediments of the bars, further slight differentiations of granulometry could be observed in the rapid, in the side bar, and the front bar (Fig. 4, Tab. II, III).

On the surface of the rapid, there were found mostly coarse-grained sands (in the sediments of the 2nd and 3rd sessions also with medium-grained sand clusters), moderately sorted, in leptokurtic distribution (Fig. 4a, Tab. II, III). Sediments taken in the 1st session demonstrated a slightly positive skewness, while in the 2nd and 3rd sessions, it was slightly negative. Characteristics of grain size distribution indicate conditions of redeposition accompanied by a highly energetic transportation (less intensive during the 1st session), and a relatively constant supply of debris.

Surface of the side bar comprised medium-grained sands, moderately well-sorted, with a negative skewness and leptokurtic distribution (Fig. 4b, Tab. II, III). At places, coarse-grained sands (near the shallower, ridge part of the bar) also occurred. Sediments were deposited near the upper level of the lower-regime flow where conditions of redeposition prevailed, and coarse fraction was intensively deposited in the top section of the bar.

Surface sediments of the pool consisted mostly of coarse-grained sands with a slightly diverse character in the subsequent measurement sessions. Sediments of the 1st session, clearly distinguished in the M_2 v. M_3 compilation (Fig. 4c, Tab. II, III), were moderately well-sorted and were of positive skewness. This corresponds with calm flow conditions with little sedimentation of finer sands,

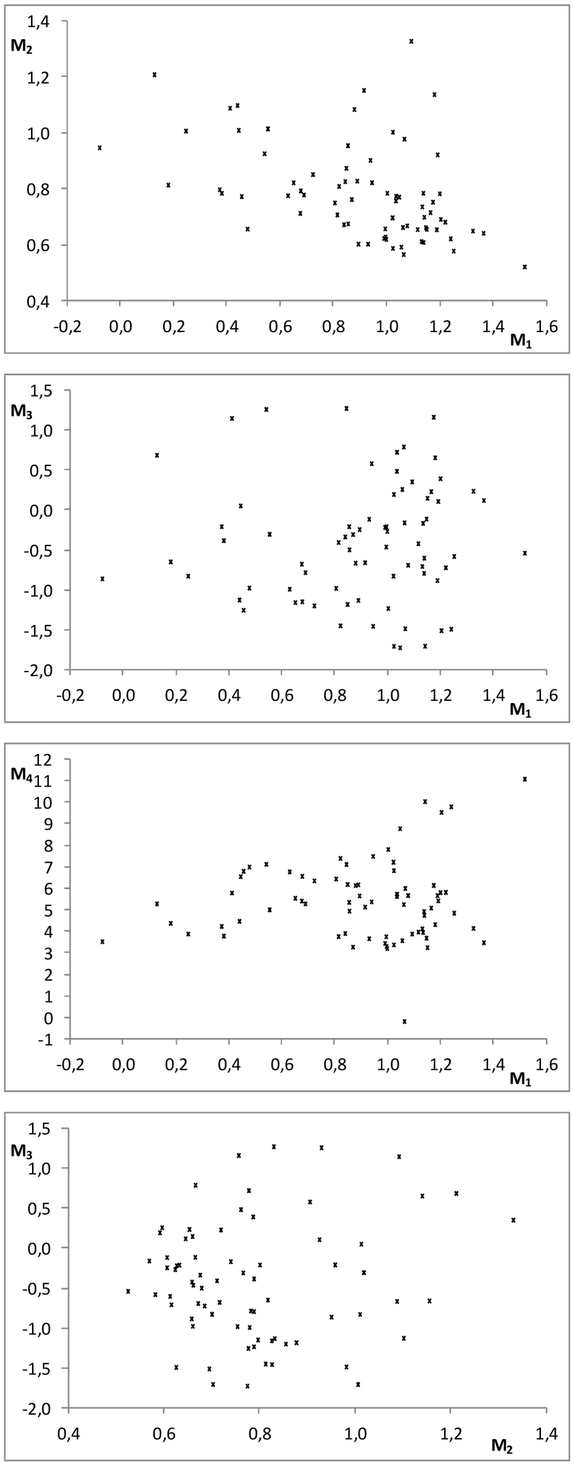

Fig. 3. Correlation diagrams of selected grain size indices for all the samples of session 1, 2 and 3

Tab. II. Correlation of the mean grain size indices (phi scale) (M_1-M_4) from the samples of all the sessions for the relief units I-IV

UNIT	M1	M2	M3	M4
I	0,93	0,94	0,10	4,51
II	1,07	0,71	-0,01	5,11
III	1,04	0,71	-0,69	6,31
IV	0,69	0,86	-0,48	5,77
ALL	0,90	0,81	-0,29	5,49

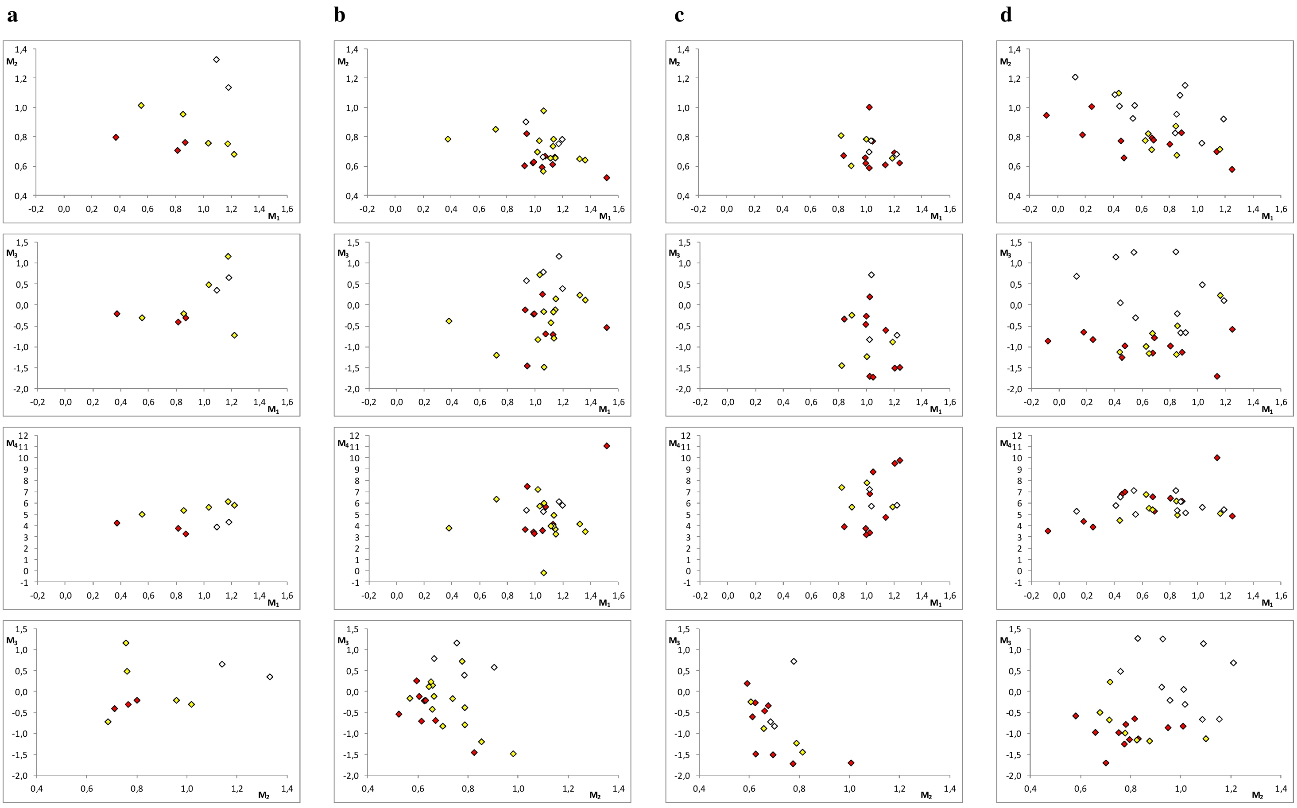

Fig. 4. Correlation diagrams of selected grain size indices for: a – rapid, b – side bar, c – pool, d – front bar; the samples of session 1 – white, session 2 – yellow, session 3 – red

Tab. III. Correlation of the mean grain size indices (phi scale) (M1-M4) for the relief units (I-IV) from session 1, 2 and 3

	SESSION 1					SESSION 2					SESSION 3				
	I	II	III	IV	ALL	I	II	III	IV	ALL	I	II	III	IV	ALL
M1	1,13	1,09	1,09	0,71	0,88	0,96	1,05	0,97	0,75	0,95	0,68	1,08	1,05	0,61	0,87
M2	1,23	0,78	0,72	1,00	0,93	0,83	0,73	0,71	0,81	0,76	0,76	0,64	0,69	0,79	0,72
M3	0,51	0,74	-0,27	0,29	0,32	0,09	-0,33	-0,94	-0,76	-0,45	-0,30	-0,45	-0,87	-0,98	-0,75
M4	4,12	5,66	6,28	5,89	5,73	5,61	4,36	6,65	5,51	5,17	3,78	5,32	6,01	5,92	5,59

which are primarily deposited in the hollows, between crests of the megaripples and/or sand waves. Sediments collected in the further sessions were characterised by a negative skewness and were well-sorted (better than in the 1st session). They correspond with conditions of redeposition from an intensive transport with a clear elevation of finer material. Admixtures of cobblestones and crumbs are connected, most probably, with the scouring of the deeper parts of sediments and the bed of the canal.

The front bar contained medium-grained sands, moderately well-sorted, with a negative skewness (Fig. 4d, Tab. II, III). Individual cases of coarse-grained sands occurrence (in the megaripples (furrows)) were also noticed. Hence, sediments of the front bar were formed under deposition conditions, which allowed supply, transport, and deposition of medium-grained sands and elevation of finer fractions. The front bar constitutes an obstruction, which hinders outflow of water and debris from the canal. Among the sediments taken from the pool, from the bottom at the depths mostly exceeding 5 m and reaching 9 m at maximum (a pit dug out for construction of the directional breakwater in 2013), admixtures of gravels and individual cobbles and fragments of debris (up to 5 cm in diameter) and, sometimes, small admixtures of fine sand were found more often than in other units. It is most probably connected with uncovering older erosional surfaces (during intensive flows) and subsequent gravitational deposition of finer fractions in other hollows.

Measurements of the 1st session were conducted after a relatively long period of low flow rates (not exceeding 1,000 m³/s). The last heavier flow (ca. 2,500 m³/s) had occurred three months before the measurement session. A distinct feature of sediments surveyed in this session was a greyish brown, clammy substance with a strong, hideous smell, which covered the sediment components. With the roasting method, the content of organic matter was determined, which turned out to be about 1% to 2%. It should be assumed that the substance comes from deeper layers of canal sediments from before 2003, when sewage from the Gdańsk-Wschód sewage treatment plant ran to the bay via the Przekop Wisły (Nowacki 2003). A new pit (9 m deep) was freshly dug near the outlet of the eastern directional breakwater, prepared for the planned extension; this can also relate to this issue. What is worth mentioning is that no similar organic matter content was found in the sediments collected during these sessions.

In the 2nd session, sediment samples were taken right after a relatively heavy flow, estimated at ca. 2,000 m³/s. Sampling of the 3rd session involved still heavier flow conditions. The samples were collected directly after a maximal, very heavy, and short-lived rainfall surge with a flow of over 4,000 m³/s (Wróblewski et al. 2016).

Therefore, the transportation and deposition conditions prevailing during the 1st session correspond to conditions of redeposition with a selective deposition of medium- and coarse-grained sands. During the 2nd session, the redeposition was combined with bottom scouring in the pool and deposition in the bar belt. During the 3rd session, there occurred an intensive redeposition with a selective deposition, which was visible, especially on the front bar, with a parallel erosion of the bottom in the pool, reaching deep into the bed of the canal sediments.

SUMMARY AND CONCLUSIONS

The characteristic features of granulometry of sediments in the bottom of the Przekop Wisły canal were identified. These are:

- a relatively even size of grains combined with occurrence of coarse-grained and/or medium-grained sands, but not fine-grained sands;
- mostly moderate sorting;
- usually negative values of the skewness index indicating a gain in number of coarser fractions and elimination of finer ones;
- leptokurtic distributions, indicating a debris shortfall.

Irrespective of the relatively even size of sediment grains with a grain-size diversity index of 2.250 (as calculated basing on 82 samples), certain small differences in granulometry of sediments taken from different bottom relief were noticed. Clearly, coarser grains with negative skewness occur mainly in the pool. In the remaining area of the bottom, in the bar belt, medium-grained sands were clearly predominant. Further differences were identified also in the rapid, the side bar, and the front bar.

Characteristics of the sediments granulometry (Gradziński et al. 1986, Racinowski et al. 2001) indicate prevalence of homogeneous dynamic conditions, combined with a powerful and variable energy of the environment, with debris subjected to intensive redeposition, and washing away of the finer material (*cf.* Mycielska-Dowgiałło 1998, Zieliński 1998, 2015).

The obtained results are important in assessing the condition of the canal and its capability to continue fulfilling of its functions effectively, i.e., to ensure a free flow of water of the Vistula River. There exists a credible risk that the water run-off may be hindered due to the progressing accumulation of sediments, especially their plugging the mouth of the canal. This may bear serious consequences, especially in conditions of an intense flow of drifting ice.

The conducted surveys may constitute an example of granulometry typical for river sediments of a channel facies of a straight channel river, which are deposited in the conditions of a substantial, constant supply of debris and a homogeneous alimentation (Babiński 1992, Zieliński 1998, 2015). The Przekop Wisły canal may be a peculiar, experimental canal used in studies of sediments and hydrodynamics.

Marine factors are, in this case, only of a limited impact, with changes in the sea level and wave motion in an extensive area of shallow waters of the delta plain (e.g., Koszka-Maroń & Jegliński 2009, Koszka-Maroń 2014).

In the survey period, the influence of anthropogenic factors connected with works on directional breakwater extension was significant. Digging of the canal bottom might have caused an increase in share of coarse fraction and seawater shells in the surface sediments, resulting from scouring of the located deeper, older layers of sediments in the bottom of the canal, and even its bed including sediments of deltaic and barrier facies.

So far, no granulometric surveys have been conducted over the entire length of the cross-cut. The surveys carried out by E. Szymczak (2015) were concerned with the area of the Vistula River estuary cone, with only the estuarial section of the canal considered. Sediments of this section were of similar character to the one determined in case of sediments of the front bar.

Granulometry of sediments of the Przekop Wisły canal resemble one of the sediments of the Y litofacies distinguished by D. Koszka-Maroń (2014) based on surveys conducted on the estuary cone outside the Przekop Wisły canal. This applies particularly to the Y_{II} subfacies, assumed by the author to be formed in the environment with a high level of energy connected with sediments of a distributary channel on the estuary cone.

A trial evaluation of the lithodynamic interpretation of the surveyed environment on the basis of granulometry indices (Fig. 3) indicates the surveyed sediments had been formed in a river environment at speeds requiring at least 50 cm/s to initiate transportation (acc. to A. Sundborg 1967; after J. Szmańda 2010). No further, more detailed deliberations, assessments, and interpretations of morphodynamic conditions with application of granulometry indices have been performed. Significant differences between the used methods, ranges of registration, and static compilations and interpretation constitute no basis to carry out objective comparisons of results (see Płoskonka 2010, Szmańda 2010). The obtained results are both of scientific importance, e.g., in determination of river flow character, and of practical ones, including assessment of transportation and supply of debris onto the cone and assessment of changes in environmental conditions with a particular consideration of a canal patency enabling unconstrained water and ice run-off. However, a full assessment of patency will be possible only if the surveys are continued in the form of monitoring of relief alterations and sediments and bottom structure of the Przekop Wisły canal. Proszę o wprowadzanie na końcu artykułu podziękowań:

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