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CHANGES IN MORPHOLOGY OF SELECTED SEGMENTS OF THE VISTULA RIVER BED

Abstract: The paper presents a reconstruction and an analysis of the Vistula river bed changes in the 19th and 20th centuries, performed on the basis of topographic maps. The analysis took into account both natural (floods, changes in rock-debris supply) and anthropogenic (e.g., river regulation, construction of water reservoirs) causes, which resulted in significant changes of the morphology of the Vistula river bed. To estimate the river bed changes the author used such parameters as: the length of the banks and changes of their location, the width of the river bed, and the surface of the river bed forms and their share in the river bed surface area.

Key words: morphology of the Vistula river bed, historical topographic maps.

INTRODUCTION

The main cause of river bed formation is the interaction between water flow and sediment transport. In particular, during a peak flow, erosion and accretion processes are intense. As a result the rock-debris transported has an impact on the formation of the river beds and floodplains (Żelazo, Popek, 2002; Babiński, 1991, 1992). In the last two centuries, humans have had a significant impact on the shape of river beds, by regulating rivers to improve their navigability and to decrease the flood hazard. The purpose of this paper is to analyse these transformations on the example of the changes of the Vistula river bed geometry in the 19th and 20th centuries, in two selected river segments.

2. CHARACTERISTICS OF THE STUDY AREA

For analysis, two segments of the Vistula rivers have been chosen: km 531-550 and km 605-632 of the river course (Fig. 1). There are no large

confluents in these segments, and hydrological observations are available for them, from the measurement stations at Warsaw and Kępa Polska.

Fig. 1. Location of the segments selected

The mean flow in the period 1951-1990 in the first segment (measurement station Warsaw) is $573 \text{ m}^3/\text{s}$, the mean width of the river bed is 623 m, and the gradient of the river is 0.30‰. In the second segment (measurement station Kępa Polska), mean flow and width are larger: $936 \text{ m}^3/\text{s}$ and approx. 832 m, resp. The river gradient is smaller (0.10‰) (Table 1).

Table 1. Characteristics of the segments selected

length [m]	mean width [m]	gradient [‰]	NNQ [m^3/s]	SSQ [m^3/s]	WWQ [m^3/s]
first segment	622,7	0,30	108	573	5650
second segment	832,0	0,11	162	936	6900

Source: *Przepływy charakterystyczne ...* 2000

The main cause of the changes in river bed morphology are changes of water level and related changes of flow intensity. The analysis of the two characteristics has been based on hydrological data from the measurement station in Warsaw, which has the largest measurement series.

The highest levels of the Vistula river at Warsaw (863 cm) was recorded during the flood of 27 July 1844. The lowest stage (68 cm) occurred in 1992. The absolute amplitude is 795 cm (Fal, Dąbrowski, 2001).

Snowmelt and precipitation floods occur on the Vistula river at Warsaw. This results from the mixed type of catchment alimentation. The flood of 1813, which covered the largest area, caused the flooding of the lower-located Warsaw districts and suburbs from Wilanów to Kuzuń (Fal, Dąbrowski, 2001). The flood of 1844 reached the highest level; it was a precipitation flood which lasted 28 days.

Among the snowmelt floods, the flood of March and April 1924 caused serious damages. It was caused by the significant thickness of the snow cover and a large water content of snow, as well as by an ice jam. The snowmelt flood of 1947 was also very large: its magnitude was even increased by ice jams. In 1960 and 1962 precipitation floods occurred which, however, did not cause large material damage, but the water level approached the top of the flood walls (Fal, Dąbrowski, 2001).

The course of the annual flow changes in the Vistula river in 1921-2000 does not show a marked periodicity or a tendency to it. It does exhibit, however, consecutive oscillations of several years duration. The deviations of the annual discharge from the mean are random. In recent years one can, however, observe an increase in duration of the sequence of dry and humid years. The largest sequence of humid years, with mean annual discharge higher than the mean from the multi-annual period, lasted eight years: from 1974 to 1981, inclusive. It was succeeded by a multi-year period of flows lower than the mean flow, which lasted until 1994, with an interruption in 1989. In 1996 a new period of higher flow began (Fal, Dąbrowski, 2001) (Fig. 2).

Fig. 2. Yearly characteristic flow in 1921-2000 (Fal, Dąbrowski, 2001)

For the Vistula river at Warsaw, frequent changes of daily flow are characteristic: high-water occurs several times a year, alternating with low-flow periods. 15 low-flow periods have been distinguished, most of them occurred in summer and summer/autumn.

The intensity of changes in river bed morphology is impacted also by the amount of the rock-debris transported. Babiński (1999) calculated that in the period 1971-1990 in the profile Kępa Polska, 715,000 t of rock-debris suspended and 2,330,000 t of rock-debris dragged was transported - together 3,045,000 t of clastic rock-debris.

The river bed segments studied were under the Russian rule during the partitions of Poland and therefore no comprehensive regulation works had been performed on them. Only local flood defences and local attempts at river bed stabilisation were made. In the first segment, dredging works began as late as in 1923. The works aimed at improving the navigability during low-flow periods. In 1925 Ingarden and then Rybczyński and Matakiewicz made plans of comprehensive regulation of the Vistula river, its utilisation and of utilisation of its valley. These plans had not been realised, since the the Polish state was not able at that time to finance such an undertaking. As a result, only occasional regulation works were performed, mainly channel deepening, and flood protection walls were built.

In 1957, the "Vistula Programme" was established. Its essential element was the construction of a cascade (stepped falls) which would also fulfil the role of retention reservoirs. The programme was being modified during 25 years and, finally, approved in 1978 – but not realised. Regulation works built a long time ago below Warsaw, up to the confluence of the Narew river, were mostly destroyed, and new regulation works on larger scale were not made. Nowadays, there are many islets, sandbars, shoals, and chute bars in the river bed; the segment is not regulated. Built-up area takes up 8%. Nowadays there are 19 regulation works there, most of them constructed in 1960-1965, from km 537 to km 540 and from km 549 to km 550.

In the second segment there are now 34 regulation works, built at the turn of 1980s and 1990s. From 1970, the lower part of this segment has been impacted by the drop at Włocławek. The remaining part of the Vistula river bed is not regulated and is characterised by a large number of small river islands (islets) and sandbars. Its has a braided or anastomosed layout.

3. METHODOLOGY

The research method applied is based on a cartographic analysis of archival and modern topographic maps. The following maps have been used: the *Karta Topograficzna...* (scale 1:126 000), the *Novaya Topografitjeskaya Karta Zapadnoi...* (1:84 000), topographic maps published by the Military Institute for Geodesy (scale 1:25 000), military topographic maps (scale 1:25 000), topographic maps published by the Main Office for Geodesy and Cartography (scales 1:25 000 and 1:50 000). Maps have been calibrated by means of the software package Super EditPro, so as to reduce them all to one reference system (system 1992) and one scale. Thanks to that it was possible to track the changes of the river bed in the individual periods and

4. RESULTS

Table 2. Banks length and their location changes in 19th and 20th centuries

year	shoreline length [km]		changes of shoreline length Δl [km]		mean change in shore location [m/year]			B/z _{sr} B – riverbed width
	right bank	left bank	right bank	left bank	right P	left L	Z _{sr} (P+L)	
first segment								
1843	28,6	23,4	6,6	3,7	3,2	2,5	5,7	127,3
1913	22,0	19,7						
1930	19,3	23,2	2,7	-3,5	8,5	8,2	16,7	44,6
			-2,3	4,6	2,6	4,9	7,5	106,4
1956	21,7	18,6	-5,0	-0,8	8,4	1,5	9,9	59,3
1977	26,7	19,4	5,4	0,1	2,4	1,9	4,3	145,5
1992	21,2	19,3						
second segment								
1843	31,9	30,6	-3,8	-1,1	2,5	4,9	7,4	147,7
1914	35,7	31,7						
1935	30,0	28,1	5,7	3,6	8,1	8,9	17,0	56,9
1955	32,7	34,8	-2,7	-6,7	4,8	4,1	8,9	109,0
			-2,7	-1,6	1,7	2,7	4,4	226,6
1977	35,4	36,4	-2,4	3,3	9,0	3,1	12,1	68,7
1991	37,8	33,1						

The above causes - impacting the shape of the Vistula river bed - are visible also when analysing the changes of shore location along the river's course. The greatest changes of the shoreline location occurred in the right shore, in 1956-1977 (approx. 40 m/year at the km 541) in the first segment and in 1977-1991 (approx. 60 m/year at the km 619) in the second segment. The years 1892-1935 are also marked in this respect: at that time the changes in shoreline location were approx. 15 m/year in the first segment (km 540) and 25 m/year in the second second segment (km 613), resp. The left bank exhibited a greater stability. In the last period studied the shoreline location changes were fairly small.

The mean width of the Vistula river bed in the segments studied was greatest in mid-20th century and was equal approx. 800 m and 1110 m, resp. In the second half of the 20th century the river bed became narrower. This was probably influenced by smaller intensity of rock debris transportation observed in the Vistula river (Łajczak, 2005). Regulation works began as late as 1960s; they could not, therefore, impact the river bed width changes. In 1970s, in the second segment, a small increase of the mean width of the river bed was observed (approx. 994 m in 1977). This was caused by the construction of a drop in Włocławek. In the consecutive years, a narrowing of the river bed occurred again. This was a result of the local regulation works by means of groynes and dams, which caused some of the sandbars and islets to connect to the banks, forming peninsulas and bays. Next, accretion occurred in the area regulated, causing the fluvial landforms to join the banks entirely. As a result, the shoreline became straightened out, and therefore the river bed became narrower. Moreover, the analysis of the multi-annual data on water level and flow in the Vistula river showed that the period from 1982 was exceptionally arid, almost without high-water (Bajkiewicz-Grabowska, 1996). Water flow was low, which was related to smaller intensity of the dragged and suspended rock-debris transportation (Babiński 1992).

In the 20th century, the Vistula river achieved the largest width (over 1.5 km) at the km 542. A similar width, at the same km, was measured in 1930. The smallest width was at the km 538: approx. 273 m in 1991 and approx. 289 m in 1977 (Fig. 3).

In the 19th century, the Vistula river achieved the largest width (over 2 km) at the km 614, while the smallest (approx. 464 m) near the islet Liszyno. In 1991 the river bed was widest (approx. 1988 m) near the islet Kępa Ośnicka, and the narrowest (approx. 484 m), near the islet Liszyno, as in the 19th century (Fig. 3).

In 1839, the first segment of the Vistula river was characterised by a large number of sandbars, shoals, islets, and chutes (40), taking up approx. 23.2% of the river bed area. Their total area surface was approx. 3.1 km². In 1892, there were fewer fluvial landforms in the Vistula river bed (19), but with a greater total area (4.3 km²). Over the next 40 year the shape of the river bed had changed significantly. In the river bed, large-area sandbars and

Fig. 3. River bed width changes (km 631-650 and km 605-632)

islets dominated, taking up approx. one-third of the river bed area. Their number also increased (34), and the total area was approx. 4.9 km²). In the next period, the surface area of islets, sandbars, and chutes decreased (4.0 km²). A few large landforms were created, some of which have been

joined with the river banks as a result of accretion. The next 30 years (1956-1977) brought a decrease (by half) of both the number of sandbars and islets (36) and their surface area (approx. 2.5 km²), as well as the percentage of the river bed area (23.8%). In the last period (1977-1992), the smallest number of them (21) occurs in the river bed, with the area 2.0 km². Also, the percentage of the river bed taken by them is smallest (approx. 18.6%) (Tables 3 and 4).

In the second segment a large area was taken up by the fluvial landforms at the beginning of the 19th century: approx. 7.5 km², which amounted to 26.8% of the river bed area. In the following years the area of sandbars and islets increased to approx. 8.0 km² (approx. 29.5% of the river bed area), and decreased to approx. 5.5 km² (approx. 22.8% of the river bed area) in 1955. In the period 1955-1972, the surface area of the fluvial landforms increased to a value close to that of 1839. A decrease of the area to approx. 3.7 km² was observed next (Table 3). This was probably due to non-occurrence of long-lasting flood-water flows in 1984-1990 which cause an increase in rock-debris transportation and an increase in accretion within fluvial landforms (Babiński, 1992); another cause was probably the joining of the Kępa Liszyno islet to the Vistula river bank.

Table 3. Area of the sandbars and islets in the segments of the Vistula river bed studied in 1839-2002 (author's own study)

Year	Surface area of sandbars and islets [km ²]	Surface area of sandbars and islets / surface area of the river bed [%]
First segment: Warszawa-Modlin (km 530.000÷549.000)		
1839	3,1	23,2
1892	4,3	31,7
1932	4,9	35,7
1956	4,0	28,9
1977	2,5	23,8
1992	2,0	18,6
Second segment: Kępa Polska-Płock (km 607.000÷632.100)		
1839	7,5	26,8
1902	8,0	29,5
1935	6,2	25,6
1955	5,5	22,8
1972	7,2	28,3
1991	3,7	17,7

The number of sandbars and islets exhibited a large variability in the second segment in the period studied. In the early 19th century there were 56 of them. Next, their number decreased to 29. This value persisted at this level until as late as 1970s, when it increased two-fold. At the end

of the 20th century their number fell to the level of mid-20th century (Table 4).

Żelazo et al. (2002) obtained similar results, studying a segment of the Vistula river between Warsaw and Plock, using topographic maps in the scale 1:100 000, 1:126 000 and 1:84 000.

Table 4. Number of islets and sandbars in the Vistula river bed segments studied in 1839-2002 (author's own study)

Year	Number of islets and sandbars
First segment: Warszawa-Modlin (km 530.000÷549.000)	
1839	40
1892	19
1932	34
1956	70
1977	36
1992	21
Second segment: Kępa Polska-Plock (km 607.000÷632.100)	
1839	56
1902	29
1935	33
1955	38
1972	80
1991	41

5. CONCLUSIONS

The 19th century was a period of intensive transformation of the Vistula river bed morphology, caused mainly by changes in water level and in flow intensity. The changes were particularly significant during high-water periods. The second half of the 20th century was a period when human activities, above all regulation works, had a significant effect on the changes in river bed morphology. At the end of the 20th century, the works in the first segment were not very significant, due to their poor condition. In this period, small changes in the Vistula river bed shaping occurred.

REFERENCES

- Babiński Z., 1991, Morfodynamika koryta dolnej Wisły w okresie holocenu [Morphodynamics of the lower Vistula river bed in Holocene], *Czasopismo Geograficzne*, 4, 260-285.
 Babiński Z., 1992, *Współczesne procesy korytowe dolnej Wisły* [Contemporary river bed processes of the lower Vistula river], *Prace Geograficzne*, 157, Warszawa.
 Babiński Z., 1999, Zmiany transportu rumowiska klastycznego dolnej Wisły w wyniku prac

- hydrotechnicznych [Changes of clastic rock-debris transportation in the lower Vistula river as a result of water regulation works], *Acta Universitatis Nicolai Copernici*, Geografia XXIX, Nauki Matematyczno-Przyrodnicze, Toruń, 103, 327-335.
- Bajkiewicz-Grabowska E., 1996, Wezbrania Wisły w Kotlinie Płockiej [High water in the Vistula river in the Płock Basin], [in:] Mikulski Z., Bajkiewicz-Grabowska E. (eds), *Ekologiczne podstawy zagospodarowania dolin rzecznych (na przykładzie Wisły pod Płockiem)* [Ecological foundations of river valley management (on the example of the Vistula river near Płock)], 39-50, Towarzystwo Naukowe Warszawskie, RetroArt, Warszawa.
- Fal B., Dąbrowski P., 2001, Dwieście lat obserwacji i pomiarów hydrologicznych Wisły w Warszawie. Obserwacje stanów wody [Two hundred years of hydrological observations and measurements of the Vistula river in Warsaw. Observations of river stage], *Gospodarka Wodna*, 11, 461-467.
- Fal B., Dąbrowski P., 2001a, Dwieście lat obserwacji i pomiarów hydrologicznych Wisły w Warszawie. Przepływy Wisły w Warszawie [Two hundred years of hydrological observations and measurements of the Vistula river in Warsaw. The Vistula river flows in Warsaw], *Gospodarka Wodna*, 12, 503-510.
- Fal B., 2007, Nizówki na górnej i środkowej Wiśle [Low-water in the upper and middle Vistula river], *Gospodarka Wodna*, 2, 72-81.
- Łajczak A., 2005, Dostawa materiału unoszonego do Bałtyku przez rzeki, ze szczególnym uwzględnieniem roli Wisły i Odry [Supply of suspended matter to the Baltic Sea by rivers, with particular emphasis on the role of the Vistula and Oder rivers], *Czasopismo Geograficzne*, 4, 265-293.
- Przepływy charakterystyczne głównych rzek polskich w latach 1951-1995* [Characteristic flows of major rivers in Poland in 1951-1995], 2000, Materiały Badawcze, Seria: Hydrologia i Oceanologia – 26, IMGW.
- Żelazo J., Popek Z., 2002, *Podstawy renaturyzacji rzek* [Fundamentals of river renaturation], Wydawnictwo SGGW, Warszawa.
- Żelazo J., Kowalska A., Okruszko T., Popek Z., 2002, The morphological changes of river bed on the Vistula River reach in 19th and 20th century, *Materiały pokonferencyjne* [post-conference materials] IAHR, AIRH, 16-21 września, 1-11.
- Cartographic materials:
- Karta Topograficzna Królestwa Polskiego* [Topographic Map of the Kingdom of Poland], 1:126 000, 1843, Kwatermistrzostwo Generalne, Korpus Topografów Wojskowych.
- Novaya Topografitskaya Karta Zapadnoy Rossii* [New Topographic Map of Western Russia], 1:84 000, 1913-1914.
- Mapy topograficzne* [Topographic maps], 1:25 000, 1933-1939, Wojskowy Instytut Geograficzny.
- Wojskowa mapa topograficzna* [Military topographic map], 1:25 000, 1956-1958, Oddział (Zarząd) Topograficzny Sztabu Generalnego Wojska Polskiego.
- Mapa topograficzna Polski* [Topographic map of Poland], 1:25 000, 1981 – 1982, Główny Urząd Geodezji i Kartografii.
- Mapa topograficzna Polski* [Topographic map of Poland], 1: 50 000, 1995, 2004, Główny Urząd Geodezji i Kartografii.

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