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METHODS OF ANALYSIS THE RIVERBED EVOLUTION. A CASE STUDY OF TWO TRIBUTARIES OF THE UPPER VISTULA RIVER

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Summary

The analysis of variability of riverbed elevation recorded at five selected gauging cross-sections of Nida River, and at three gauging stations of Czarna Nida is presented in the paper. The studies concern the period of 60 – 80 years of observation. The trends of riverbed changes during the study period at the selected gauging stations were calculated based on the variability of observed minimal annual water stages. The reasons for the observed changes in the river course and channel geometry are given. These changes were caused by river regulation consisted of the shortening and narrowing of the river channel. Moreover, grain size distribution analysis in the selected gauging stations of Nida River and characteristic diameter variability of sediments along the river course examination are presented. These analyses were to evaluate the variability of characteristic diameters along the river course in connection with observed changes in cross-sections' geometry. Additionally, to confirm the process of erosion or deposition recognized in the examined river channels, hydrodynamic equilibrium was determined. Three methods were proposed and used: the mean velocity and critical velocity in the main river channel comparison, the stream power value calculation which defines the character of the river channel, and the WWK (index of cutting or shallowing of the river channel) index.

Key words: river channel, riverbed erosion, grain size distribution, hydrodynamic balance

INTRODUCTION

Human activity carried out over the decades, and even over centuries, in rivers and their valleys has led today to a variety of often irreversible effects.

Riverbed erosion observed in great number of river channels formed in alluvial, especially in their middle and lower courses, is caused mostly by river regulation resulting in the river channel shortening and narrowing, by hydraulic structures or sediment exploitation.

Riverbed erosion causes many problems, among which a significant decrease of alluvial aquifer, resulting in a loss of good quality drinking water resources, or riverbank vegetation change, degradation of habitats and destruction of natural spawning grounds. Human activity that changes width and length of river courses, embankments construction and banks protection, also contributes to permanent change of the morphodynamic processes in the channel and the valley and of the functioning of ecosystems dependent on the aquatic environment as well.

Understanding the dynamics of river channel is still a large area of research. Water flow in natural river channel is related to sediment movement. Sediment may come from processes of denudation occurring in the catchment area or may be a product of riverbed or bankfull erosion. Depending on the intensity of changes of water and sediment flow in space and in time, over decades we can observe the process of riverbed erosion or sediment deposition in the channel. The character of this process determines the correlation between the intensity of sediment flow and stream power capacity of sediment transport. In natural rivers, processes of erosion and accumulation in each part of river course vary. In consequence, the river channel tends to obtain the hydrodynamic balance (Chow1959, Mertens 1999). The main factors affecting the maintenance of this balance are: water flow, volume and type of sediment, stream longitudinal slope, bankfull vegetation. Hydrodynamic imbalance can be caused by anthropogenic factors as mentioned above (Łapuszek 2013).

Research (Punzet 1994, Bąk *et al.*, 2010) shows that the character of the river course can vary spatially and temporally with different intensity. In the period of 50-100 years, these changes may be slight, but a permanent change in the direction of the river channel can also be observed. This paper presents the studies on the trends of river channels changes during the decades on the selected tributaries of the upper Vistula River on the basis of the variability of annual low water stages observed during the long term. The results of grain size distribution in each gauging station and characteristic diameters variability of sediments along the river were analysed as well.

This assessment could be the first step to future research on trends in river channels and their valleys and could be helpful in future land-use development.

OBJECTIVE AND SCOPE OF THE STUDY

The aim of the paper is to present the studies on the river channel variability of Nida River and Czarna Nida during the 60-70 years (depending on data collecting) in selected gauging stations (Table 1). Moreover, grain size distribution in selected gauging station of Nida River was analyzed, and characteristic diameters variability of sediments along the river course was examined as well. This analysis was to evaluate these variability along the river course in connection with observed changes in cross-sections' geometry.

Table 1. Examined gauging stations

River	Tributary of	Gauging station	Km of river course	Object of analysis	
				Variability of river channel	Grain size distribution
Nida River	Vistula River	Mniszek	115.900	+	+
		Brzegi	97.800	+	+
		Motkowice	76.100	-	+
		Pińczów	56.800	+	+
		Wiślica	23.200	+	+
Czarna Nida	Nida River	Daleszyce	43.500	+	-
		Morawica	22.800	+	-
		Tokarnia	5.800	+	-

Nida River flows out from the Jędrzejowski Plateau. Nida River is formed with Biała Nida and Czarna Nida, which combine in the town of Brzegi. The catchment of Biała Nida is located on the Przedborska Upland. This area is characterized by sandy and muddy, less stony bottom of rivers and streams. The average longitudinal slope of the river is 2 ‰. The catchment of Biała Nida is covered in large part with pine forests and meadows (Cisak *et al*., 2008). The catchment of Czarna Nida is located on the Kielecka Upland, in Świętokrzyskie Mountains. In this area the rivers' and streams' channels are made of gravels and the average longitudinal slope of the rivers is from 4 ‰ to 7 ‰. Czarna Nida catchment area is covered largely with forests of fir and beech. After connecting Czarna Nida with Biała Nida, Nida River flows through the valley of Nida River. Is is typical upland area, called Niecka Niedziańska, river channel of Nida River is sandy, and average longitudinal slope of the channel is 2 ‰. The Nida valley in the lower reach is covered mostly by meadows; wetlands are also noticed. In this part of the river and its valley numerous of oxbow lakes can be observed where quagmires currently are formed. In some places are still well seen fragments of sandy terraces (Cisak, *et al*., 2008).

Czarna Nida is left side tributary of Nida River and flows out from the Kielecka Upland. The eastern part of the catchment area of Czarna Nida is located in Świętokrzyskie Mountains. In this region the river channel is formed by gravels. The average longitudinal slope of the rivers ranges from 4 ‰ to 7 ‰. The catchment of Czarna Nida is covered in most parts by coniferous forests (fir and beech) (Rzepa 1992). The catchment of Czarna Nida is mostly agricultural area, the only 1,5% of its total area is urbanized. However, in recent years, intensive pressure of investors associated with the recreational sector in this area is observed (Rzepa 1992).

METHODS

The studies on river channel evolution have shown that some modifications of the river channel as a result of human activity (river regulation or hydraulic structures construction) may often cause difficult to predict changes above or below these activities, particularly if these modifications concern the changes in flow regime. Therefore it is important to carry out research on riverine systems in the basin scale in order to identify their condition and to predict development trends. There are many proven methods which allow to study and analyse the structure of river channels (Krzemień K., 2006). Most of them are applicable in local scale, and they are all based on assessment of basic parameters on the riverbed forms.

In the paper, the analysis of the variability of riverbed changes was done on the assumption provided by Punzet [1994], and proven by Łapuszek (2003) the author, that minimal annual water stages correspond to the change of the riverbed level. The time series of minimal annual water stages of each studied gauging station is divided into time intervals. Then, in each time interval a function that describes the position of the bottom in a given year T is defined. The function $H_i(T)$, which describes the time course of the annual water stage observation in the i-th interval is written as follows (Łapuszek 2003):

$$H_i(T) = H_{min}(T) + \varepsilon \tag{1}$$

where:

ε – residual component;

$H_{av}(T)$ – regression function expressed by a linear function:

$$H_{av}(T) = E(H|T) = \alpha T + \beta \tag{2}$$

where:

T – year of observation;

α – the rate of the intensity of erosion or accumulation, cm·year–1;

β – constant, cm.

The value of parameter α indicates the average annual lowering or aggradations of the riverbed in year T. The symbol $E(H|T)$ is the conditional expected value of the minimal water stage in the minimum – T. The parameters a and b are estimated by the method of least squares.

The changes in the location of gauging station and the position of gauging station zero were taken into account in the calculations. The calculation results were verified by analysis of changes observed in the measured geometry of cross sections. The archived and current cross-sections of channel were used for the verification (IMGW 1934-82).

As mentioned above, one of the useful test for a full evaluation of river channel processes is to assess the sediment fractions. The grain size distribution in gauging stations of Nida River have been carrying out. The aim of the measurement was to evaluate the variability of characteristic diameters of sediment observed through the river course in connection with changes noticed in river channel caused by human activity.

Determination of type of sediment and estimation of particles diameters has been carried out in two steps. The samples of sediment has been collected in compliance with the relevant standard (ISO 4364: 2005). The tests were made using direct measurements by taking samples from the riverbed, and sandy material was collected directly into containers. Afterwards, the sandy samples were analysed in a laboratory. Weight of collected samples depending on the type and composition of sediment ranged from 5 kg (sand) to 50 kg (thick particles). In each gauging profile two or three samples were taken. The second step of the research were laboratory analysis according to the PKN-CEN ISO / TS 17892-4 standard. Based on the obtained results, the grain size distribution has been made for each gauging station, and the characteristic diameters sediments: d_{10}, d_{50}, and d_{90} were determined as well.

Additionally, to confirm the process of erosion or deposition recognized in the examined river channels, hydrodynamic equilibrium was determined. In the current study it was proposed and used three methods as follows:

- the mean velocity and critical velocity in the main river channel comparison,
- the stream power value calculation which defines the character of the river channel,
- the WWK (index of cutting or shallowing of the river channel) index calculation.

ANALYSIS OF THE RESULTS OF CALCULATIONS AND STUDIES

The variability of riverbed evolution observed in the long time (60-70 years) were carried out in four gauging stations of Nida River. In Mniszek the minimal annual water stages in the years 1961-2009 were analyzed. In the years 1962-1963 the river channel regulation near Mniszek was carried out. The objective of it was channel double-widening. The computation of riverbed lowering or aggradation was done by statistical model (equations: 1-2) and it was calculated, that due to river channel regulation the average annual lowering of the riverbed was 5.98 cm per year (Table 2). This process continued until 1970. Then the riverbed has been stabilizing and by the year 2000 a slight lowering of the bottom was observed (0.72 cm per year). Since 2001 the slow process of riverbed aggradation is observed (Table 2).

In Brzegi the riverbed evolution was analyzed on the base on the minimal annual water stages changes observed in the years 1939-2009. In the whole analyzed period of time in Brzegi the riverbed erosion occurred, but its intensity varied (Fig.1., Table 2). The most intensive erosion was in the years 1939-1955, when the average annual lowering of the bottom was 2.12 cm per year (Fig.1., Table 2). Due to river channel regulation on the section: Mniszek – Brzegi, the channel has been modified as trapezoid, and the river course has been changed as well. As a result of the work related to the shaping of a new river channel a process of riverbed erosion appeared there (2.12 cm per year). in the years 1956-1980 riverbed erosion was insignificant (0.2 cm per year). In the next years several procedures of river channel regulation have been taken close to Brzegi, which resulted again in the riverbed erosion process, which is still seen in the profile of Brzegi (Fig.1).

In Pińczów the minimal annual water stages in the years 1947-2009 were analyzed. Nida River in the middle course was meandering till 15th century. Then the expansionary agriculture started developing and the forest areas simultaneously decreased. Increasing amount of outflow of water and sediment from the catchment caused the instability of river channel, and finally changed meandering river channel into less winding, wider and shallow (RZGW 1934-82). This process lasted until the 19th century. The first river channel regulation was done close to Pińczów in the early 1950s. Until the 1970s deposition of sediment in the river channel was observed. The reason for this process was connected with systematic regulation of the tributaries of Nida River carried out in the years 1950-1980. These activities resulted in a quick drainage of rainwater from the upper part of the catchment, and it resulted in increasing of sediment transport to Nida River channel as well [RZGW – 1985]. In the years 1967-1973 another technical regulation of the river was carried out and new river channel was shaped. In the years 1984-1989 the aim of river regulation was the channel maintenance because it had trends to aggradation. However, since the 1990s. trends tendency to aggradation in the river channel have been appeared again (Table 2), therefore another river training in the area of Umianowice were re-started (RZGW 1985, Łajczak 2006). The problem of high sediment deposition in the river channel of Nida is strongly related to a large transport of sediment coming from its tributaries (Czarna Nida).

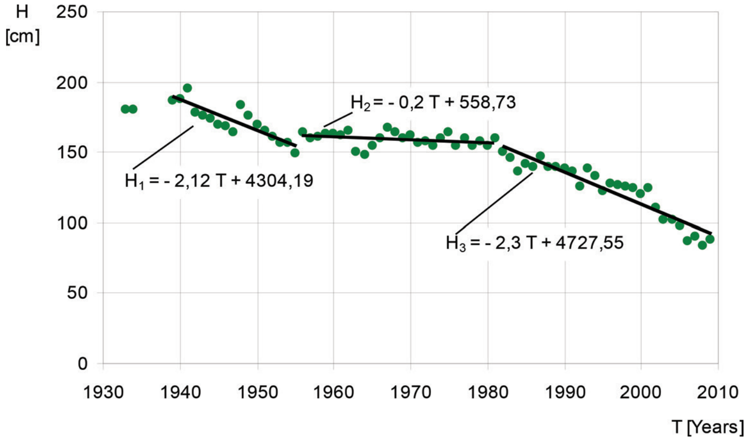

Figure 1. Variability of annual minimum water levels and estimated linear trends at the Brzegi cross-section on the Nida River.

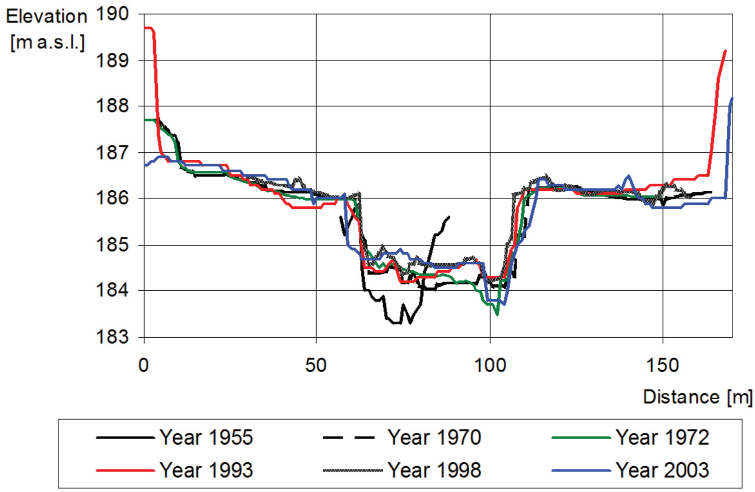

Figure 2. Changes in the geometry of the cross-section at the Pińczów gauging station.

In Wiślica the minimal annual water stages in the years 1940-1991 were analyzed. In this period of time process of continuous riverbed erosion was observed and it is due to river channel regulation and land use transformation in both close to Pińczów. Therefore this part of the river course was transformed into a accumulation zone. So there is a little supply of sediment to the lower reaches of Nida River where Wiślica gauging station is located, and sediment, as a product of riverbed erosion occurs through the river course downstream Wiślica.

The variability of riverbed evolution observed in the long time (60-70 years) were carried out in three gauging stations of Czarna Nida (Table 2). The results of calculations show that river channel of Czarna Nida in Daleszyce is stable. In the years 1971-1996 a slight accumulation of sediment in the riverbed is observed, while from 1997 to the present time a slight process of riverbed erosion can be noticed (Table 2). In Morawica the minimal annual water stages in the years 1949-2009 were analyzed. Throughout the considered period of time tendency of riverbed erosion is observed. However, the intensity of it varied in time (Table 2). The river channel on the examined course was regulated. The process of riverbed erosion is observed after each high flood event there (Bąk Ł *et al.,* 2010). Moreover, the banks of the channel are formed in the fine sand and clay which have tendency to reversing. Removal of the sandy bars due to river channel regulation caused that the bottom and the cut banks are the areas of strong erosion during flood events. Therefore, significant riverbed lowering in Morawica has been noticed. In Morawica the minimal annual water stages in the years 1948-2009 were analyzed. In the years 1948-1970 the riverbed of Czarna Nida was lowering by an average intensity of 1.71 cm per year (Table 2). Due to systematic removal of the sandy bars from the channel, the intensive process of sediment particles removing from the bottom occurred there, especially during the flood events. After 1971 year the river channel can be considered as stable (Fig.3).

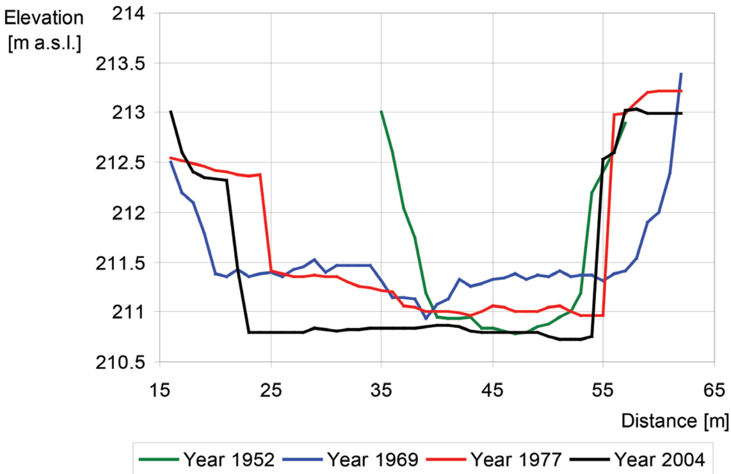

Figure 3. Changes in the geometry of the cross-section at the gauging station at Tokarnia.

Calculation results of the intensity of river bottom variability over the years are summarized in Table 2.

Table 2. Average annual lowering/increment of the river bottom at selected gauging stations of Nida River and Czarna Nida.

Time interval	The equation of intensity: lowering/increment	Index of: intensity: lowering/increment	
		equation of linear regression, cm	cross-sections
Nida River: MNISZEK gauging station			
1961 – 1970	H_1=-5.98T+11935.36	-5.98	– *
1971 – 2000	H_2=-0.72T+1573.93	-0.72	– *
2001 – 2009	H_3=2.83T–5535.72	2.83	– *
Nida River: BRZEGI gauging station			
1939 – 1955	H_1=-2.12T+4304.19	-2.12	– *
1956 – 1980	H_2=-0.2T+558.73	-0.2	-0.5
1981 – 2009	H_3=-2.3T+4727.55	-2.3	-1.0
Nida River: PIŃCZÓW gauging station			
1947 – 1970	H_1=1.06T–1931.62	1.06	– *
1971 – 1994	H_2=-0.004T+136.93	-0.004	0.0
1995 – 2001	H_3=5.61T–11050.4	5.61	– *
2002 – 2009	H_4=-3.012T+6150.43	-3.0	– *
Nida River: WIŚLICA gauging station			
1940 – 1960	H_1=-0.5T+1053.48	-0.5	-0.1
1961 – 1970	– *	– *	0.5
1971 – 1991	H_2=-1.24T+2507.47	-1.24	-1.8
Czarna Nida : DALESZYCE gauging station			
1971 – 1996	H_1=0.64T–1165.59	0.64	0.2
1997 – 2009	H_2=-0.89T+1907.36	-0.89	-0.4
Czarna Nida : MORAWICA gauging station			
1949 – 1967	H_1=-1.58T+3228.56	-1.58	– *
1968 – 1978	H_2=-4.35T+8719.24	-4.35	-3.8
1979 – 2009	H_3=-0.33T+783.94	-0.33	-0.1
Czarna Nida : TOKARNIA gauging station			
1948 – 1970	H_1=-1.71T+3528.75	-1.71	– *
1971 – 2009	H_2=-0.09T+320.21	-0.09	-0.18

* no data available

Examination of diameters characteristic of sediment particles variability along the Nida River shows that the diameters d_{10} are between 0.015 mm and 0.02 mm and do not vary along the river course (Figs. 4 and 5). Within the section from Mniszek to Brzegi the characteristic diameters d_{50} and d_{90} increase respectively: d_{50} from 0.15 mm to 0.23 mm and d_{90} from 0.41 mm to 0.43 mm. The observed trend of increasing characteristic diameter of d_{50} and d_{90} over the river course is related to the sediment supply by three tributaries of Nida River (Fig. 5). On the section from Brzegi to Motkowice the characteristic diameters d_{50} and d_{90} decrease slightly and are as follows: d_{50} = 0.17 – 0.23 mm and d_{90} = 0.41 – 0.43 mm. On the river course from Motkowice to Pinczów the characteristic diameters of d_{50} and d_{90} slightly increase over the length of the reach: d_{50} – from 0.18 mm to 0.20 mm, and the diameter d_{90} increased from 0.41mm to 0.43 mm. This section is supplied by the sediment transported from Mierzawa, the right tributary of Nida River. From Pinczów to Wiślica characteristic diameters d_{50} decrease to 0.15 mm Wiślica, and diameter d_{50} decreases to 0.41 mm (Fig. 5).

Due to field and laboratory measurements it was noticed that along the Nida River course the medium sand fraction (MSA), representing 50% in the profile of Brzegi for 66% of the profile of Wiślica, is dominating. The content of particles with a diameter greater than 0.5 mm (coarse sand fraction type – CSA) is insignificant and ranges from 3% in Mniszek to 0.5% in the other examined profiles. The content of particles with a diameter less than 0.02 mm, which is the fraction of coarse silt (CSI), ranges from 11% in Brzegi to 17% in Pinczów (Fig. 5).

The observed variation of characteristic diameters over the course of Nida River, and the analysis of grain size distribution of the gauging stations show that gradual decrease of grain size on the length of the river was slightly disrupted as a result of sediment supply by Nida tributaries.

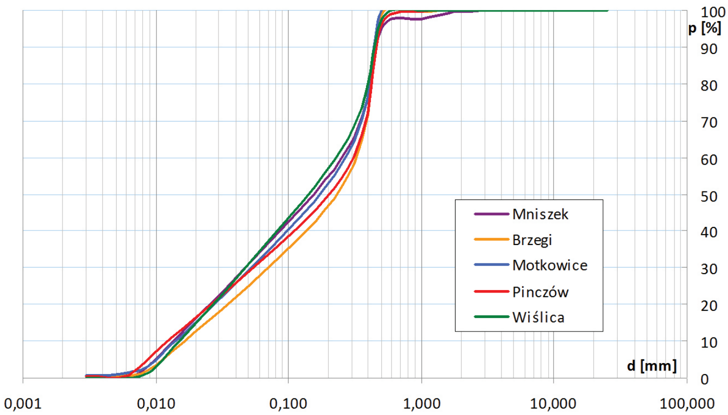

Figure 4. Grain size distributions in gauging stations of Nida River.

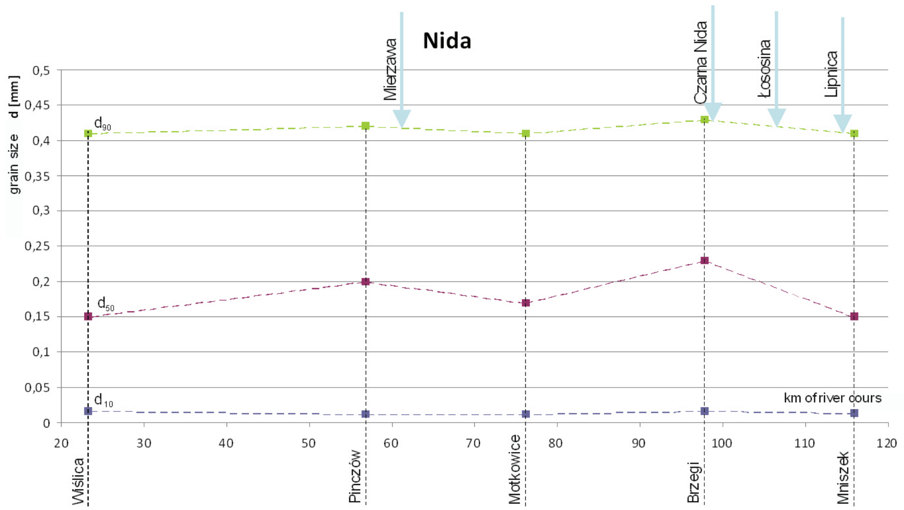

Figure 5. The variability of characteristic sediment diameters on the course of Nida River.

It is assumed that a natural river maintains the "dynamic equilibrium" or "quasi-equilibrium" (depending on the time interval adopted for the analysis of the process). The river adapts continuously its morphology (length, depth, longitudinal slope, sinuosity and meander arc length) in order to ensure optimal water flow and transported sediment. "Dynamic equilibrium" and "quasi-equilibrium" do not mean the total lack of physical changes observed in the channel, but on the contrary – its continuous adaptation to average conditions. The main problem is thus to determine a threshold beyond which the changes in the geometry are no longer the result of processes ensuring its equilibrium, but which indicates the beginning of excessive erosion or sedimentation in the river channel (Mertens W., 1999).

The study on hydrodynamic equilibrium for gauging stations of Nida River were made. Here below the results for Pińczów are shown. Calculations were made for the river parameters as follows: width of the bottom 40 m, the maximum depth of the channel 2.2 m, the mean slope of the water table 0.0002 – 0.0001, roughness by Stricler $\frac{1}{n} = \frac{21{,}1}{d_m^{1/6}}$ =0.013. For the future study another roughness depends on the dunes forms instead of grain size can be considered (Dąbkowski L. *et al*. 1982).

The mean velocity was calculated by the basic formula of Chézy-Manning, and compared with appropriates characteristic critical velocities by Szamow (Dąbkowski L. *et al*. 1982), dependent on the size of sediment diameter:

- velocity of beginning of movement: $v_1 = 4.4 \cdot d^{1/3} \cdot h^{1/6}$ [m/s]
- velocity of mass movement: $v_2 = 6 \cdot d^{1/3} \cdot h^{1/6}$ [m/s]
- velocity of the end of movement: $v_3 = 3.7 \cdot d^{1/3} \cdot h^{1/6}$ [m/s]
- permissible velocity for Nida by SGGW: $v_{per} = 0{,}52 \cdot h^{0{,}33}$ [m/s], (Dąbkowski L., *et al*., 1982).

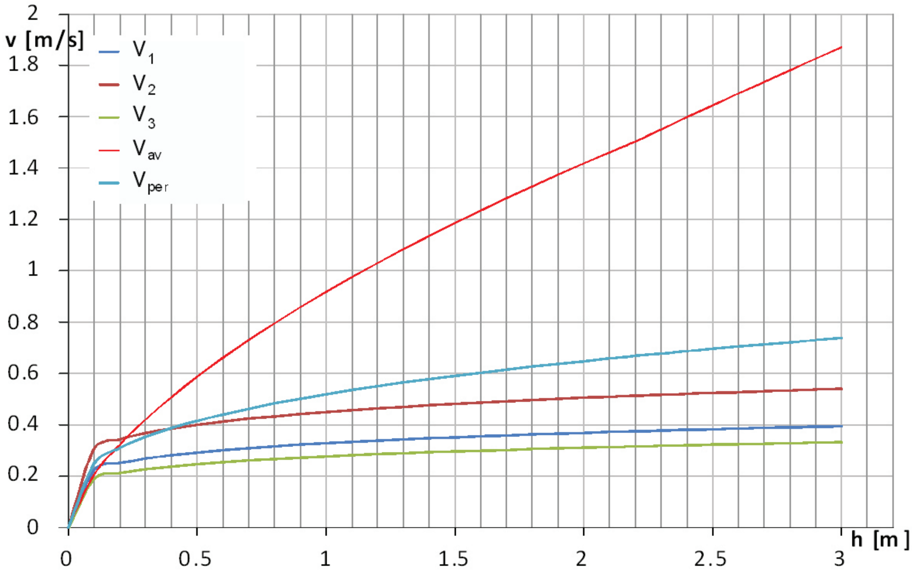

Figure 6. Mean velocity (v_{av}) and velocities v_1, v_2, v_3 by Szamow (Dąbkowski L. *et al*. 1982), v_{per} – by SGGW (Dąbkowski L. *et al*. 1982) calculated at the Pińczów gauging station.

The results on the graph show that even at low water levels the mean velocities exceeded the critical values by Szamow and SGGW formulas, and intensive sediment movement appears already at low flows sequences causing riverbed erosion. These calculations are confirmed by the observations previously described (Table 2). Unit stream power, the rate of energy dissipation against the riverbed and banks of a river per unit downstream length, was calculated due to formulae (Bojarski A. *et al*. 2005):: $\omega = \frac{\gamma_w \cdot g \cdot Q \cdot I}{w} \quad [W/m^2]$

where: ω – the stream power, γ_w – the density of water, kg/m^3, g – acceleration due to gravity (9.81 m/s^2), Q – discharge m^3/s, I – mean slope [-], w – the width of the river channel for flow of Q.

Unit stream power was calculated for a sequences of flows for Pińczów gauging station (Fig.7).

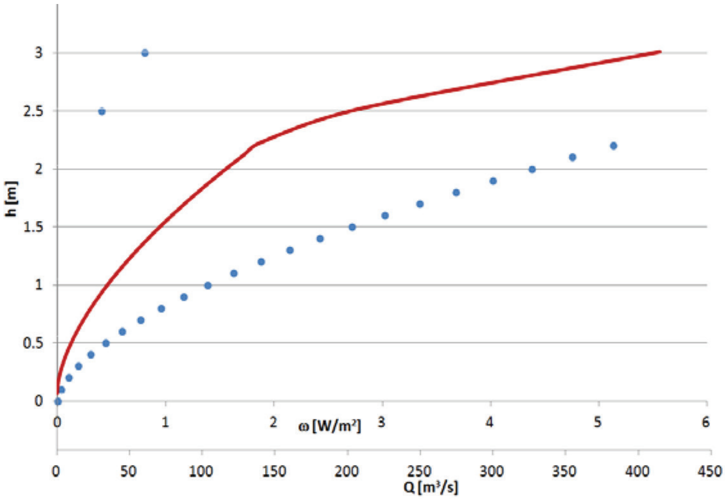

Figure 7. Unit stream power (blue points) and discharge curve (red line) at Pińczów gauging station.

Unit stream power value (ω = 0.02 ÷ 5.13) classifies Nida as a river with low energy stream power. With increasing water level in the channel unit stream power is increasing, reaching a maximum at a bankfull flow. Then it is rapidly decreasing while the high flow spills over the floodplain.

By an WWK indicator the river channel balance can be examined in a simplified way as well. WWK is index of cutting or shallowing of the river channel: WWK = Q_f/ $Q_{67\%}$, where: $Q_{67\%}$ – the bankfull flow, Q_f – the flow which fills completely the river channel; while it's value is greater than $Q_{67\%}$ – erosion appears, and while it is lower than $Q_{67\%}$ – the process of aggradation appears in the channel (Bojarski A., *et al*., 2005).

In Pińczów gauging station the maximum flow of exceedance probability of 50% ($Q_{50\%}$) is 91 m^3/s due to IMGW [IMGW – Kraków, 2010]. Calculations shows that: $Q_{67\%}$ < 91 m^3/s and Q_p = 139 m^3/s. It means, that the rate WWK > 1, and it indicates the trend of river channel in Pińczów towards erosion process. These results confirm the tendency to riverbed erosion in Pińczów identified and examined, as well, by using the other methods presented in the paper.

CONCLUSIONS

The studied river channels of Nida River and its tributary – Czarna Nida are transformed as a result of river training activities that were carried out mainly of the twentieth century. The most visible changes that were noticed in the studied rivers are: narrowing and deepening of the channels and relocating them into the new created, the river course modifications. Due to these changes in the vertical and horizontal direction the riverbeds tend to create a new profile in order to obtain a new hydrodynamic balance in disturbed conditions of fluvial system. The observations at the examined gauging stations show that intensity of these changes usually is very rapid immediately after river regulation, then weaken slowly, and the river channel reaches again the hydrodynamic equilibrium (in Mniszek and Brzegi on Nida River, in Tokarnia on Czarna Nida). The observed tendency to over-aggradation of some investigated river channels (e.g. Nida close to Pińczów) is due to the regulation works carried out systematically for decades on the tributaries. Those works consisted of the rivers' courses shortening. This resulted in a quick drainage of rainwater from the catchment with a large amounts of sediment into the recipient.

Based on the field measurements and calculations it can be concluded that the type and size of bed material, forming the river channel, are closely related to the local geology of the area; on Nida River predominant type is medium sand fraction (MSA) in all analyzed gauging stations. In all the analyzed profiles of Nida River variability of characteristic diameters d_{10} is insignificant, while the diameters d_{50} and d_{90} are varied along the river course. In sections where sediment, carried by its tributaries are supplied, increasing of d_{50} and d_{90} is noticed. The analysis of sediment transport conditions in selected gauging stations of Nida River allowed to establish time periods in which sediment movement can result in riverbed lowering.

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