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Changes in flood risk impacted by river training – case study of piedmont section of the Vistula river

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Abstract: *Changes in flood risk impacted by river training – case study of piedmont section of the Vistula river*. Main problems concerning the flood risk in piedmont section of the Vistula, Southern Poland, are discussed. This stretch of the river is channelized since the middle of the 19th century. It is part of the mainstream discussion of the effectiveness of existing river channelization methods. The following problems are analysed: (1) current state of flood risk, (2) the rate of river flow, (3) changes in flood risk since the start of channelization efforts with respect to changing channel geometry and changing rates of river flow reflecting the effects of channelization work. Substantially increased bankfull discharge in a channelized river may be considered as a stable hydrologic feature of the river stretch analysed. This means that the river is effectively reducing the quantity of water available for flooding the inter-embankment zone. This statement is the basis for analysis of changes in flood risk in the river studied. An assessment of changes in flood risk for the piedmont section of the Vistula cannot be categorical. Some changes in discharge help reduce flood risk, while others increase it. The paper is based mainly on the State Hydrological Survey data over more than the last 100 years, a large-scale maps over the last 230 years, and fieldwork conducted by the author.

Key words: flood, river training, channel geometry, embankment, inter-embankment zone, inundation, piedmont Vistula, Southern Poland

INTRODUCTION

Flood risk is the possibility of a river inundating a settled flood plain. The magnitude of flood risk depends on the duration of overbankfull water stages, the height of the water stages and the resulting extent of flooding across a flood plain. Well-planned human activity across valley floors and in river channels can lead to a reduction in flood risk. One form of human activity that has not yet been fully evaluated with respect to flood risk is river channelization (Kajak and Okruszko, 1990, Andrews and Burgess, 1991, Finlayson, 1991, Angelstam and Arnold, 1993, Gilvear, 1999, Wyżga, 2001, Łajczak, 2007, 2012). The construction of embankments makes the inundation zone much more narrow, increases high water stages in rivers during major floods and increases the rate of floodwater flow (Soja and Mrozek, 1990, Osuch, 1991, Punzet, 1991, Łajczak, 2012). The acceleration of the flood wave is one of the stated goals of river channelization, which is designed to reduce flood risk. Channelization efforts systematically make the river channel deeper and more narrow along shortened sections with a bigger gradient, although downstream sections with a smaller gradient become more shallow and wider (Brookes, 1990, Hey, 1996, Thorne et al., 1997, Łajczak, 2007, 2012). This results in flood waves that concentrate more quickly and move faster (Punzet, 1991, Wyżga, 1993, Łajczak, 2012). In addition, the extent of the flood is different as is the height of the peak wave. Increasingly deeper river channels are characterized by ever shorter durations of overbankfull water stages. Shallower downstream sections of river channels with to narrow inter-embankment zone experience increased flood risk (Punzet, 1991, Łajczak, 2007, 2012) due to higher upstream flood wave intensities and larger fluctuations in water stages.

Existing river channelization methods have becoming objects of scrutiny in recent years. Some researchers argue that channelization does not really decrease flood risk (Kajak and Okruszko, 1990, Andrews and Burges, 1991, Finlayson, 1991, Angelstam and Arnold, 1993, Pinter and Heine, 2005), which actually increases along shallow sections of river (Cooper et al., 1987, Howard, 1992, Kajak, 1993, Łajczak, 2007, 2012).

The piedmont section of the Vistula in southern Poland is an example of a river channelized since the middle of the 19th century (Fig. 1). This section of the Vistula is 411 km long and flows across the Subcarpathian Basins and the Polish Uplands (between gauging sites at Skoczów and Puławy). Drainage basin area up to Puławy is 57 264 km^2. The hydrological regime of the piedmont section of the Vistula is shaped by mountain tributaries where summer rainfall floods dominate. Most economic losses from floods along this stretch of the Vistula are noted from May to October, usually in July. It is only downstream of the last mountain tributary, the San river, that large floods are also noted during snowmelt season (Punzet, 1991). Mean discharge in the piedmont section of the Vistula increases in steps and exceeds 500 m^3·s^{-1} downstream of the San tributary. Maximum discharge in the same place of the river reaches 7,700 m^3·s^{-1}.

The channelization efforts taking place along the piedmont section of the Vistula since the 19th century have altered the river's channel. Work started in the 1840s and accelerated following the great flood of 1884. In order to produce the desired river channel and help prevent future floods, the following steps were taken: the river channel was made shorter by cutting off selected meanders in the late 1800s, stone groynes were constructed perpendicular to the banks to produce a more narrow river channel since the 1840s, embankments were constructed to limit flooding since the 1890s (Łajczak, 1995). The most extensive channelization work along the Vistula was done between 1890 and 1960. Selected sections of tributaries, mainly mountainous, were channelized to some extent as well (Wyżga, 1993, Łajczak, 2007).

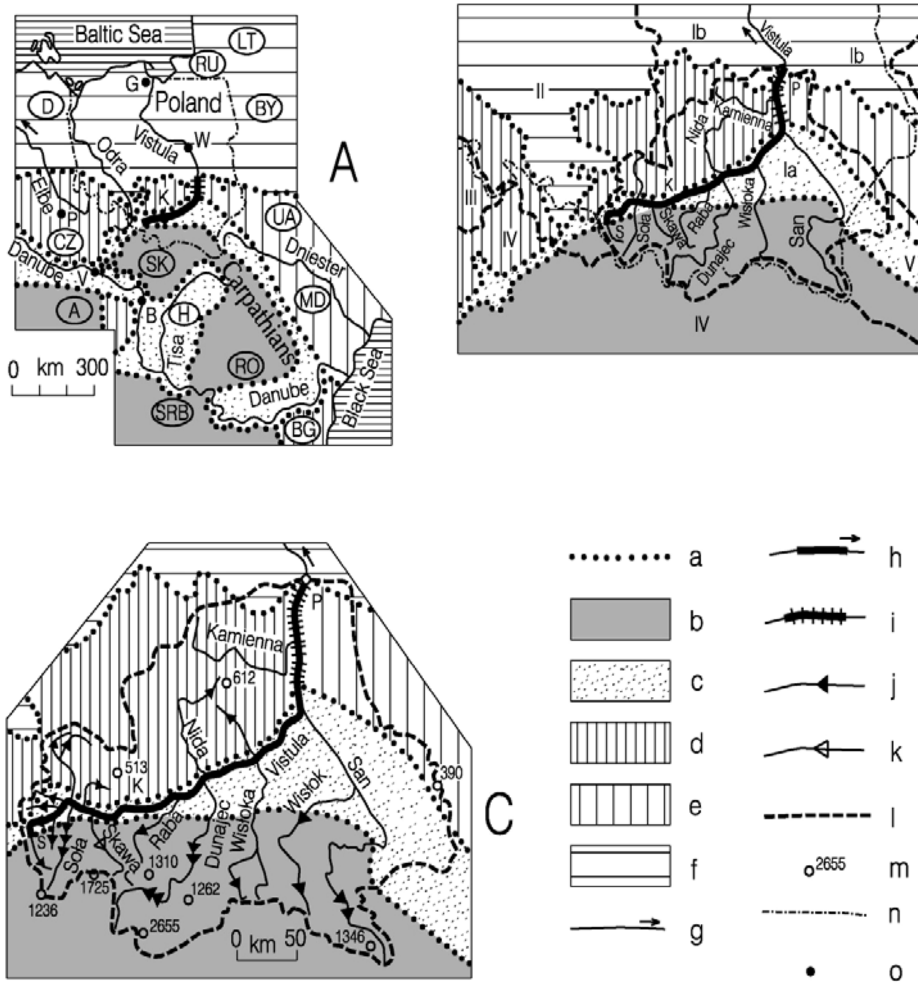

FIGURE 1. Study area: A – location of the piedmont section of the Vistula on a geomorphological sketch of Central Europe, B and C – boundary of the piedmont drainage basin of the Vistula, a – limit of main geomorphological units, b – alpine mountain systems, c – foreland basins and lowlands, d – Paleozoic and Mesozoic mountains and uplands, e – Tertiary uplands, f – Central European lowlands, g – main rivers, h – piedmont section of the Vistula, i – gap section of the Vistula valley through the Polish Upland, j – dams, k – dams under construction, l – boundaries of drainage basins, Ia – piedmont section of the Vistula, Ib – downstream section of the Vistula, II – the Odra, III – the Elbe, IV – the Danube, V– the Dnister, m – major peaks, n – Polish national border, o – selected cities: K – Kraków, W– Warszawa, G – Gdańsk, B – Budapest, V – Vienna, P – Prague. S, P – gauging sites marking the boundaries of the piedmont section of the Vistula: S – Skoczów, P– Puławy

MATERIAL AND METHODS

The paper is based on an analysis of hydrological data (daily water stages and discharges) recorded by 40 gauging sites operated by the State Hydrological Survey and located roughly every 11 km on the Vistula stretch analysed. Hydrological data have been collected for the Vistula since the 19th century, which is also when efforts began to reduce flood risk in the Vistula valley. The progress in river training can be observed on topographic maps produced every 14 years, on average, over the course of the last 230 years. The results of engineering efforts can also be analysed using hydrological data from successive gauging sites one the river strech analysed (till 2010), and results of measurements of the river channel geometry made by the State Hydrological Survey every a few years since the early 20th century. Results of fieldwork conducted by the author, information from the research literature and information from the Regional Water Management Office in Kraków are also analysed.

Maps at a scale of 1 : 100 000 or greater were used to establish changes in length, width and sinuosity for the Vistula river. Mean channel parameters representing the pre-channelization period were deduced using the oldest maps (prior to 1850). The current state of the channel was determined using the newest maps (after 1990). The width of inter-embankment zone along the river stretch analysed was also deduced from the latest maps. Repeated measurements of the channel cross profile at successive gauging sites is the basic source of readily available data concerning the channel width and depth related to mean water stages in the river. Field data were used to establish the current height of the riverbanks above a mean water stage in numerous places between successive gauging sites. Finally, the extent to which the river substretch became deeper or more shallow was assessed. The data were also used to determine changes in mean channel depth (D_m) between the upper edge of the riverbank and the mean location of the river channel bottom. Mean width of the channel (W_m) was determined in the same manner. The W_m/D_m is an indicator just how compact the river channel is at a given measurement site. An analysis of minimum annual water stages (WS_{min}) at gauging sites for a long period of time is the basis for a better evaluation of vertical changes in the river channel. This includes stabilization as well as increases and decreases in channel depth (Łajczak, 1995, 2012).

Increases in riverbank height and corresponding bankfull stages were determined first. That information was used to calculate the number of days with flooding the inter-embankment zone for each year at every gauging site. This information was used to establish the total inundation time of the inter-embankment zone at each gauging site (IN_1) [day·yr^{-1}], for a series of years. The number of flood events (IN_2)

[no·yr^{-1}], featuring this type of hydrological situation was also determined for the same series of years. When flooding occurs, river discharge is greater than bankfull discharge (Q_{bf}). The following characteristic discharge magnitudes [m^3·s^{-1}] were computed for all gauging sites: mean discharge (Q_m), mean high discharge (Q_{mh}), channel-forming discharge (Q_{chf}), and bankfull discharge (Q_{bf}). Q_m, Q_{mh} and Q_{bf} magnitudes of discharge were computed based on State Hydrological Survey data starting from 1931. Each magnitude of discharge was calculated for every section of river between large mountain tributaries. The calculations were based on at least two gauging sites located preferably close to the endpoints of each river section. The channel forming discharge (Q_{chf}), was estimated using the Inglis formula (1941): $L = 29.6\sqrt{Q_{chf}}$, where L stands for the mean length [m] of meanders prior to river channelization. Pre-1850 maps were used for this purpose (Łajczak, 1995). The mean high discharge (Q_{mh}) was calculated as a mean value from maximum discharges observed in 12 consecutive months for successive years over a 80 years period (1931–2010). Characteristic discharge magnitudes: Q_m and Q_{mh}, fluctuate over the long term and bankfull discharge (Q_{bf}) increases in rivers with deepened channels since river channelization (Łajczak, 1995, 2012).

The research literature suggests that changes in river channel geometry initiated by channelization efforts affect flood risk in river valleys (Punzet, 1991, Wyżga, 1993, Gilvear, 1999, Łajczak, 2007, 2012). Hence, the following approach was designed to attempt to explain changes in flood risk in the river stretch studied since the onset of channelization work. The source materials cited were used to assess changes in river channel geometry and to show which changes exert the greatest impact on river discharge. Next, changes in discharge conditions were assessed. Changes that increase fluctuations in water stages were identified. Changes that increase or decrease the frequency and duration of overbank water stages were also identified. These long-term changes are presented in light of climate-driven fluctuations and constitute the basis for flood risk forecasting in the near future.

RESULTS AND DISCUSSION

Due to the channelization works the Vistula stretch analysed became 15% shorter compared to the late 18th century and now measures 411 km. The sinuosity of the river channel decreased from 1.6 before channelization work to 1.2. When the Vistula channel became shorter, its gradient became steeper. This resulted in increased flow velocity and initiated the deepening of the river channel. Another factor that accelerated channel deepening processes was the construction of stone groynes perpendicular to riverbanks at a number of locations. The structures were designed to focus the current. The extraction of alluvial material had the same basic effect and lasted until the 1960s. The deepening of the channel started during the middle of the 19th century in the Kraków region. By the second half of the 19th century, deepening of the Vistula channel had been expanded along the entire length of the river between the Soła and the Dunajec tributaries. The Vistula upstream of the Soła was quickly deepened in the first half of the 20th century. Channel deepening of the Vistula downstream of the Dunajec started in the second half of the 20th century. However, the river channel becomes shallow downstream of the deepened stretches (Fig. 2). The gradient of the shallow channel is gentler than that of the dredged channel. This trend is especially clear downstream of gauging site at Goczałkowice and even more so along the gap section of the river within Polish Upland. The tendency for the piedmont section of the Vistula to become deeper or shallower has been confirmed by river channel height measurements made by the State Hydrological Survey since the beginning of the 20th century (Łajczak, 1995, 2012).

An analysis of changes in channel geometry of the Vistula piedmont section focuses also on sub-sections of the river between major mountain tributaries (Fig. 3). The first sub-section of the Vistula to the Soła has become deeper by as much as 1.5 m on average. The mean increase in depth further downstream between the next mountain tributaries ranges from 1.3 to 3.0 m. The largest mean increase has been noted between the Skawa and the Raba rivers. The Vistula channel tends to become shallower between the last mountain tributary (San) and the gauging site at the Puławy. The average loss in depth is 0.4 m. The magnitude of vertical changes (channel level changes – CH.L.CH.) caused by channelization work, increases along the length of the piedmont section of the Vistula until its confluence with the Raba, at which point it begins to decrease. The mean depth of piedmont section of the Vistula channel varies depending on location. Mean channel depth tends to increase downstream of the river to the channel sub-section between the Skawa and the Raba rivers (7.2 m) and then tends to decrease towards the gap through the Polish Upland (4.8 m). The mean depth of the piedmont Vistula channel was between two and three times smaller prior to channelization than it is today and its increase is a product of both a lower river floor and higher riverbanks. In past its depth was also much more homogeneous than it is today. The mean width of the river channel increases in steps along the length of the river section of interest. Today, the width of the river channel increases from about 25 m in the first sub-section of interest to 750 m in the last sub-section of interest. The width of the river channel has decreased in the first three sub-sections of interest by up to 70%, while in the last sub-section of interest by over 10%. Greater compactness of the channel (low

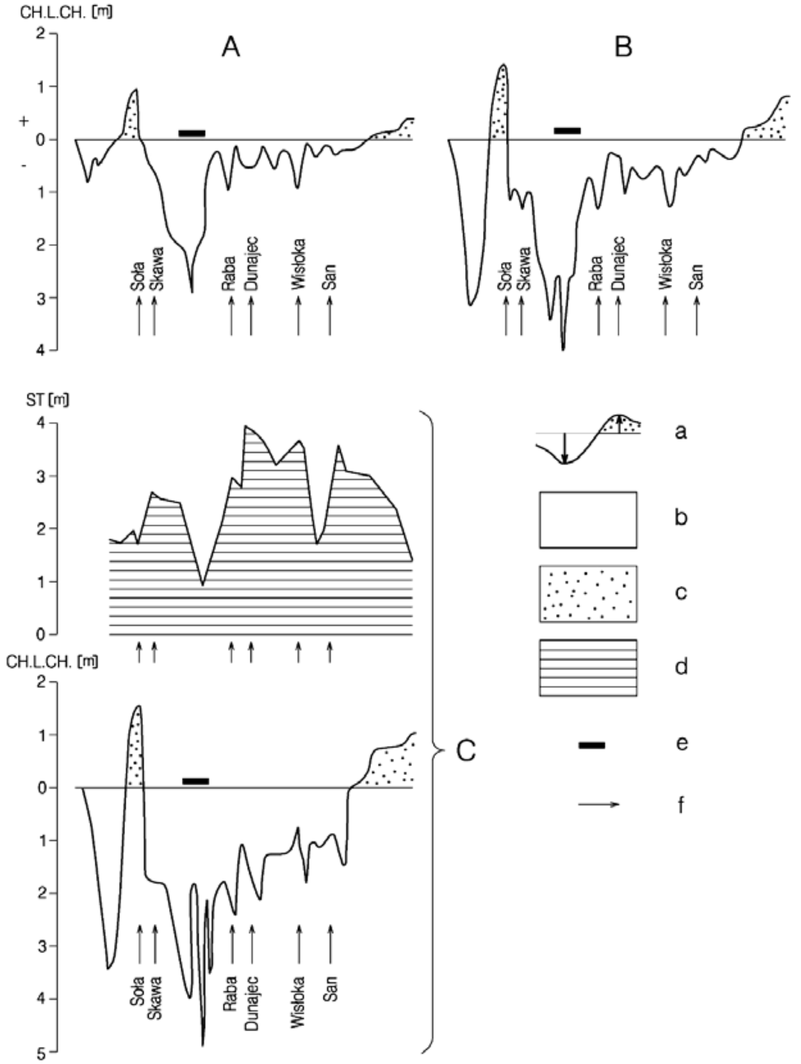

FIGURE 2. Increases and decreases in river channel depth (channel level changes), CH.L.CH. [m] for piedmont section of the Vistula since start of channelization work up to 1930 (A), up to 1960 (B) and until 2010 (C). Part C of figure shows differences in sediment thickness, *ST* [m] for sediments accumulated along riverbanks. Lines showing vertical changes in the channel and sediment thickness for the river's longitudinal cross-section are given for all gauging sites. Designations: a – point of reference used to establish changes in depth or the height of the river channel at the beginning of water stage measurements at gauging sites, b – increase in channel depth, c – decrease in channel depth, d – thickness of riverbank sediments, e – the Vistula in the city of Kraków, f – points of confluence with major mountain tributaries. Analysed river section is located between S and P points (see Fig. 1)

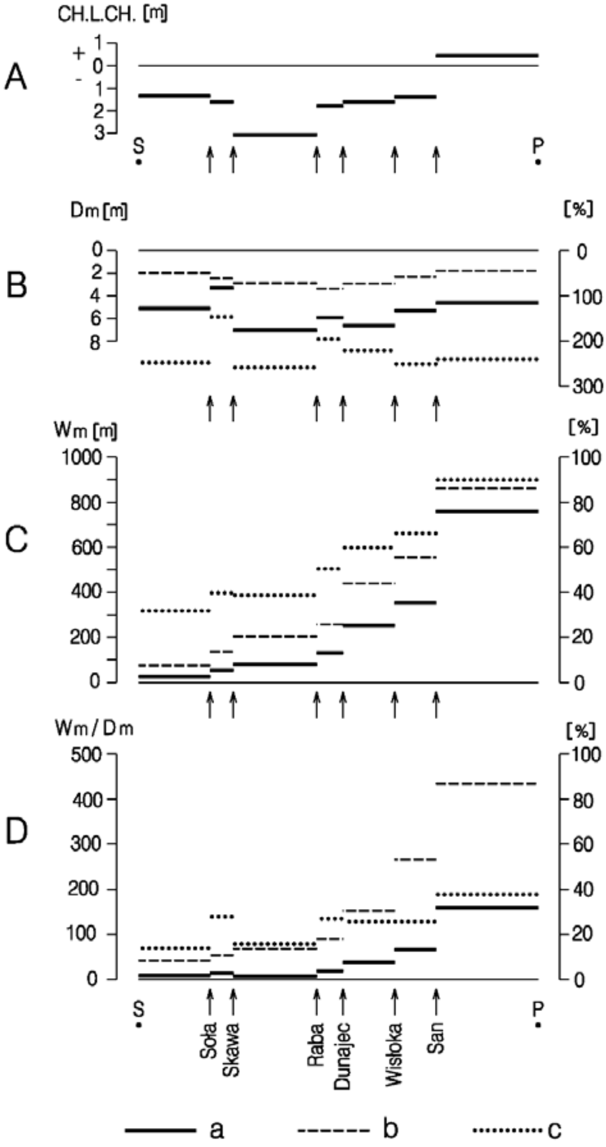

FIGURE 3. Mean geometric parameters of channel of piedmont section of the Vistula for consecutive sub-sections of river between major mountain tributaries. Designations: a – current values, b – pre-channelization values, c – values a as a percentage of b values [%]; A – changes in vertical position of river channel bottom (CH.L.CH.), B – changes in mean channel depth (D_m), C – changes in mean channel width (W_m), D – changes in compactness ratio (W_m/D_m). Points of confluence with major mountain tributaries are marked. S, P – as explained in Figure 1

value of the W_m/D_m) results in faster flow velocity. Prior to channelization work the W_m/D_m increased with each consecutive sub-section of the river from 40 to over 400, but today varies between 5 and 156. Thus the ratio decreased by 63–88% in sub-sections of river due to channelization. The largest changes were noted along the meandering section of the Vistula upstream of the Raba (in the vicinity of Kraków city). The piedmont section of the Vistula channel has become more and more compact over the last 100 years but only as far as to the outlet of the last mountain tributary (Fig. 4). This is shown by a systematic decrease in the W_m/D_m at selected gauging sites. Further downstream the W_m/D_m increased until the second half of the 20th century and for the last 40 years the ratio has been decreasing.

Prior to construction of embankments the piedmont section of the Vistula valley used to be flooded over 20 km wide at some locations during major floods (Łajczak 2012). The construction of the embankments reduced 10-fold on average and over 50-fold at some locations the width of the inundation zone. Now the width of the inter-embankment zone increases downstream of the river in its successive sub-sections between the major mountain tributaries from about 300 to 1,100 m (Fig. 5). It means that the inter-embankemnt zone is only between 12 and 1.5 times wider, respectively, than the river channel in successive sub-sections of the river. The construction of embankments close to the channel of the Vistula resulted in greater fluctuations (up to 9 m) in the water stages, especially after 1920 (Soja and Mrozek, 1990, Osuch, 1991,

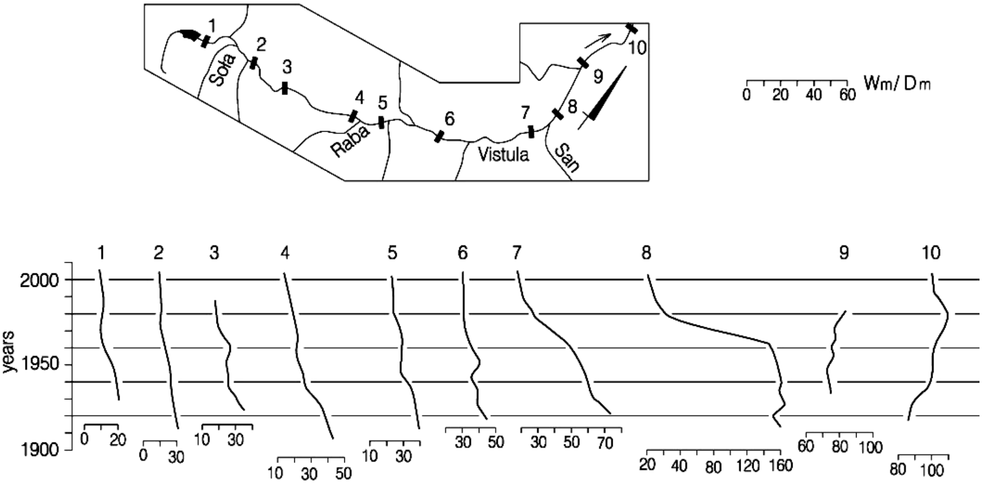

FIGURE 4. Changes in compactness ratio (W_m/D_m) for piedmont section of the Vistula at selected gauging sites: 1 – Goczałkowice, 2 – Smolice, 3 – Kraków –Tyniec, 4 – Sierosławice, 5 – Jagodniki, 6 – Szczucin, 7 – Dzików, 8 – Zawichost, 9 – Solec, 10 – Puławy

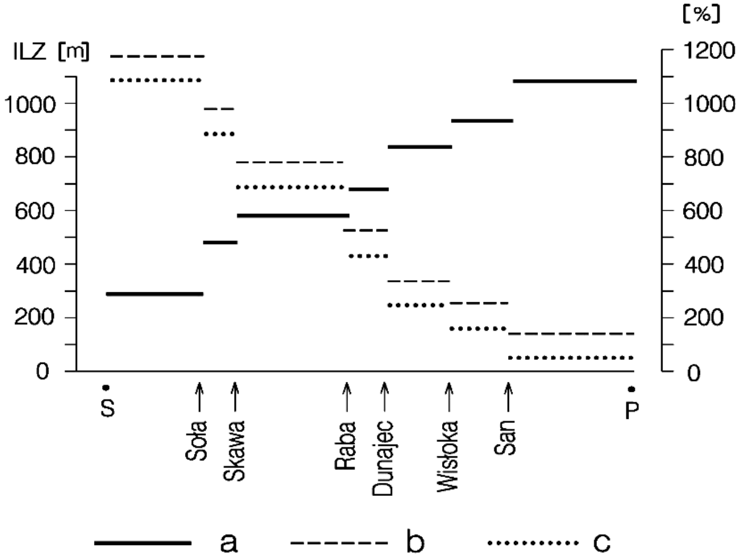

FIGURE 5. Key parameters for inter-embankment zone for sub-sections of the Vistula between major mountain tributaries. Designations: a – mean width of inter-embankment zone ILZ [m], b – width of inter-embankment zone expressed as a percentage of width of river channel, c – width of inter-embankment zone (without channel) expressed as a percentage of width of river channel. Points of confluence with major mountain tributaries are marked. S, P – as explained in Figure 1

Punzet, 1991). Increasing maximum water stages in the river during major floods resulted in the breaching of embankments at a number of locations. For example, during the great floods of May 2010 and May 2014, embankments were breached along the shallow channel of the Vistula. Flooded areas included during these events areas upstream of the Soła, near the Vistula's confluence with the San and upstream of gauging site at Puławy.

State Hydrological Survey data indicate increasing current velocity accompanied by a decreasing values of the W_m/D_m for the piedmont Vistula (Łajczak, 2012). For the years after 1970 changes in the W_m/D_m correspond to an increase in current velocity. In the years 1931–1970 the changes in current velocity reached even higher rates. The shallow channel of the Vistula downstream of the San did not experience these types of changes after 1970. A somewhat larger increase, even double, in current velocity was recorded during bankfull discharges (Q_{bf}). This increase in current velocity downstream of the San was no more than 20% or did not take place at all after 1970. The current velocity in the piedmont section of the Vistula increased on a greater scale as a result of changing channel geometry. The increase in current velocity typical for characteristic magnitudes of discharge (Q_m, Q_{mh}, Q_{bf}) was correspondingly larger, becoming

4-old for bankfull discharge. The current velocity in the piedmont section of the Vistula increased the most during the first few decades following the start of channelization work (Łajczak, 2012). Punzet (1991) indicates an increase in the rate of flood wave travel along the Vistula what reflects changes in the channel geometry and too narrow the inter-embankment zone.

One of the most important results of the author's investigations is an explanation of tendency for bankfull discharge (Q_{bf}) to increase in the piedmont section of the Vistula. It can be explained as the result of increasing current velocity in the Vistula following increasing channel gradient and a decreasing values of the W_m/D_m. This tendency began during channelization work on the river (Fig. 6). Increases in Q_{bf} have been precisely recorded since 1950. A reverse extrapolation of this trend shows that Q_{bf} was similar to mean high discharge (Q_{mh}) until the year when deepening of the channel began. The magnitudes of Q_{mh} and Q_{bf} can be considered similar for the era prior to Vistula channelization (Łajczak, 2012). Later bankfull discharge (Q_{bf}) increased more slowly in shallow sub-sections of the river. Q_{bf} values increased during the course of the 20th century for each designated sub-section of the piedmont Vistula as follows: about 3-fold for the sub-section upstream of the Raba, 2.7-fold for the sub-section between the Raba and the Dunajec, 2.2-fold for the sub-section between the Dunajec and the Wisłoka, 2-fold for the sub-section between the Wisłoka and the San, and 1.45-fold for the sub-section running through the Polish Upland (see the ratio Q_{bf1}/Q_{bf2} on Figure 7, where Q_{bf1} is the current value of Q_{bf} and Q_{bf2} is value of Q_{bf} at the beginning of the 20th century).

Channel-forming discharge (Q_{chf}), calculated for the pre-channelization period was about 20% smaller than bankfull discharge for the meandering section of the Vistula upstream of the Dunajec (Fig. 6). Channel-forming discharge was as much as 25% higher than bankfull discharge for the braided channel section of the Vistula further downstream. The calculated Q_{chf} values are smaller than current bankfull discharge Q_{bf} for the entire piedmont section of the Vistula. The calculated Q_{chf} values are between 5 and 1.2 times smaller, respectively, than bankfull discharge for consecutive sub--sections of the Vistula between major mountain tributaries. If channel-forming discharge produces the greatest changes in river channel geometry, then bankfull discharge should be able to make these changes permanent, as it is much higher today. For this reason, substantially increased discharge in a channelized river may be considered as a stable feature. This means that the river is effectively reducing the quantity of water available for flooding the inter-embankment zone. This statement is the basis for further analysis of changes in flood risk in the piedmont section of the Vistula today.

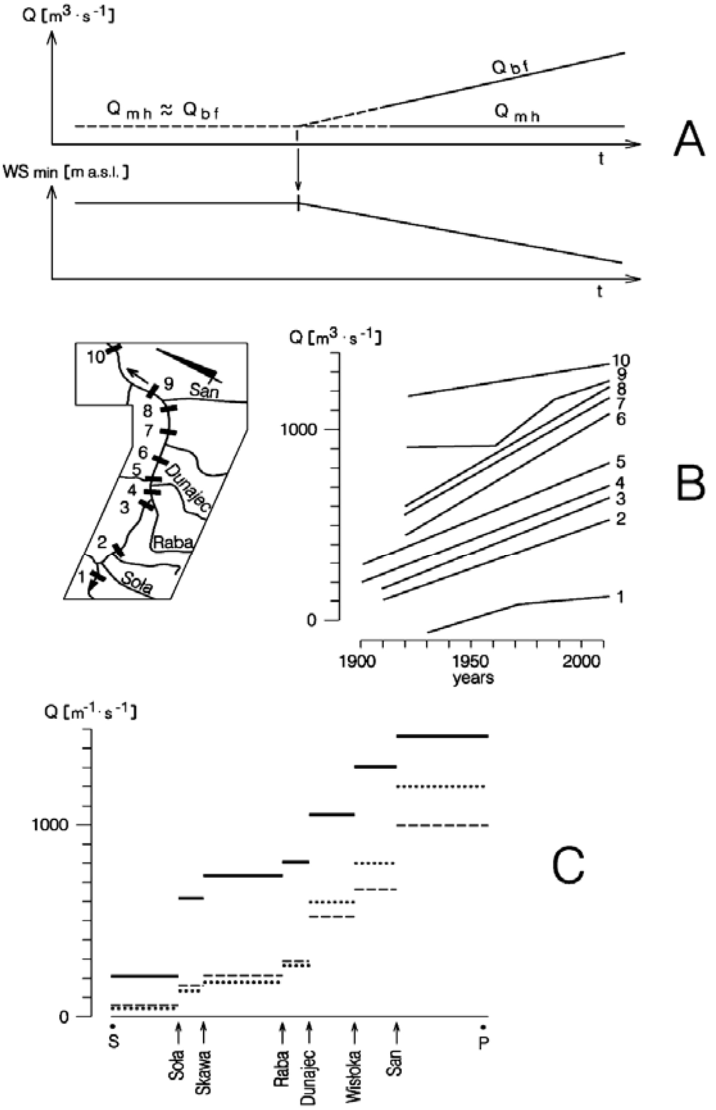

FIGURE 6. Changes in bankfull discharge (Q_{bf}) for the piedmont section of the Vistula since the start of channelization. A – scheme illustrating increasing Q_{bf} relative to mean high discharge (Q_{mh}). The increase in Q_{bf} began with the systematic deepening of the river channel. WS_{min} – trends in minimum annual water stages in the Vistula. B – increase in Q_{bf} at selected gauging sites for the entire study period. Marked locations of gauging sites: 1 – Goczałkowice, 2 – Smolice, 3 – Sierosławice, 4 – Jagodniki, 5 – Karsy, 6 – Szczucin, 7 – Koło, 8 – Sandomierz, 9 – Zawichost, 10 – Puławy. C – estimated increase in bankfull discharge (Q_{bf}) for each sub-section of the Vistula between major mountain tributaries since the start of channelization. Current Q_{bf} values are marked with a continuous line while pre-channelization Q_{bf} values with a broken line. Channel-forming discharge (Q_{chf}) is marked with a dotted line. Points of confluence with major mountain tributaries are marked. S, P – as explained in Figure 1

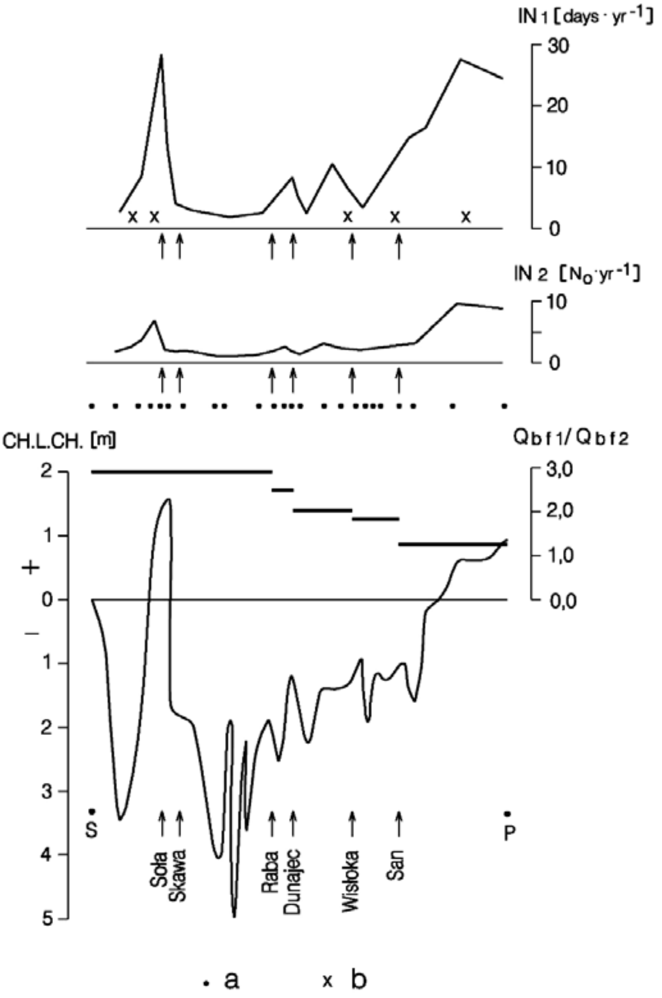

FIGURE 7. Mean inundation time (IN_1) for the inter-embankment zone of the piedmont section of the Vistula versus mean number of flood events (IN_2). Post-channelization vertical changes in the river channel CH.L.CH. and Q_{bf1}/Q_{bf2} have also been marked, where Q_{bf1} is the current value of Q_{bf} and Q_{bf2} is value of Q_{bf} at the beginning of the 20th century. Designations: a – location of gauging sites along the Vistula for which IN_1 and IN_2 have been noted, b – approximate location of embankment breaches during great flood of May 2010. Points of confluence with major mountain tributaries are marked. S, P – as explained in Figure 1

The mean flood duration (IN_1) for the inter-embankment zone along the piedmont section of the Vistula is between 2 and 28 days per year (Fig. 7). The IN_1 values are smaller for sub-sections of river that have been deepened the most and have experienced the largest increase in bankfull discharge. For this reason, it is possible for flooding to take place in the inter-embankment zone for less than

10 days a year along a deepened sub-sections of the Vistula with a Q_{bf} that has doubled or tripled. In two sub-sections of the piedmont Vistula the channel becomes shallower and in gap sub-section of the valley through the Polish Upland the bankfull discharge increased negligibly. There flooding in the inter-embankment zone is longer than 10 days a year. Breaches in embankments occur most frequently in areas with long-duration flooding of the inter-embankment zone, what is well illustrated by the floods in May 2010 and May 2014. Flood waves contained by deepened river channel can inundate the inter-embankment zone further downstream, where the river channel is shallower. For this reason, the number of flood events (IN_2) with inter-embankment zone flooding varies along the course of a river and mirrors (IN_1). The most deepened sub-sections of river experience inter-embankment zone flooding only once or twice a year, with each event lasting only 2 or 3 days. Shallow sub-sections of river experience inter-embankment zone flooding even 10 times a year. Inter-embankment zone flooding may last more than a week during major flood events.

Flood waves along the piedmont section of the Vistula caused by the melting of snow last longer and have lower peaks than summer flood waves (Soja and Mrozek, 1990, Osuch, 1991). Snowmelt flood waves are contained by the deepened river channel and lead to flooding only along shallow sections of river channel. Inter-embankment zone flooding occurs along all the piedmont section of the Vistula only from May to October. Flooding must have occurred more frequently prior to the channelization of the piedmont section of the Vistula. This must have also been true of snowmelt floods. Floods must have also lasted longer, as evidenced by notes on the Great Flood of August 1813 (Łajczak, 1999). The aforesaid changes in river channel geometry and discharge conditions lead to shorter inter-embankment zone flooding times and the elimination of flood risk in the spring season.

The piedmont section of the Vistula has been experiencing shorter duration of overbank water stages since at least the 1930. This trend is independent of long-term discharge fluctuations and is the result of channel deepening (Fig. 8). The shortening in duration of these water stages must have been significant during the second half of the 19th century and up to the 1930, when channel deepening was at its most intense. Beyond the confluence of the Vistula and the San, the tendency to shorten overbank water stage duration is not significant due to the late onset of channelization work.

One result of the channelization of the piedmont section of the Vistula is the concentration of flood waves expressed in the form of shorter duration and increased height. This is the direct result of increased current velocity at high water stages and indirectly points to the increasing compactness of the

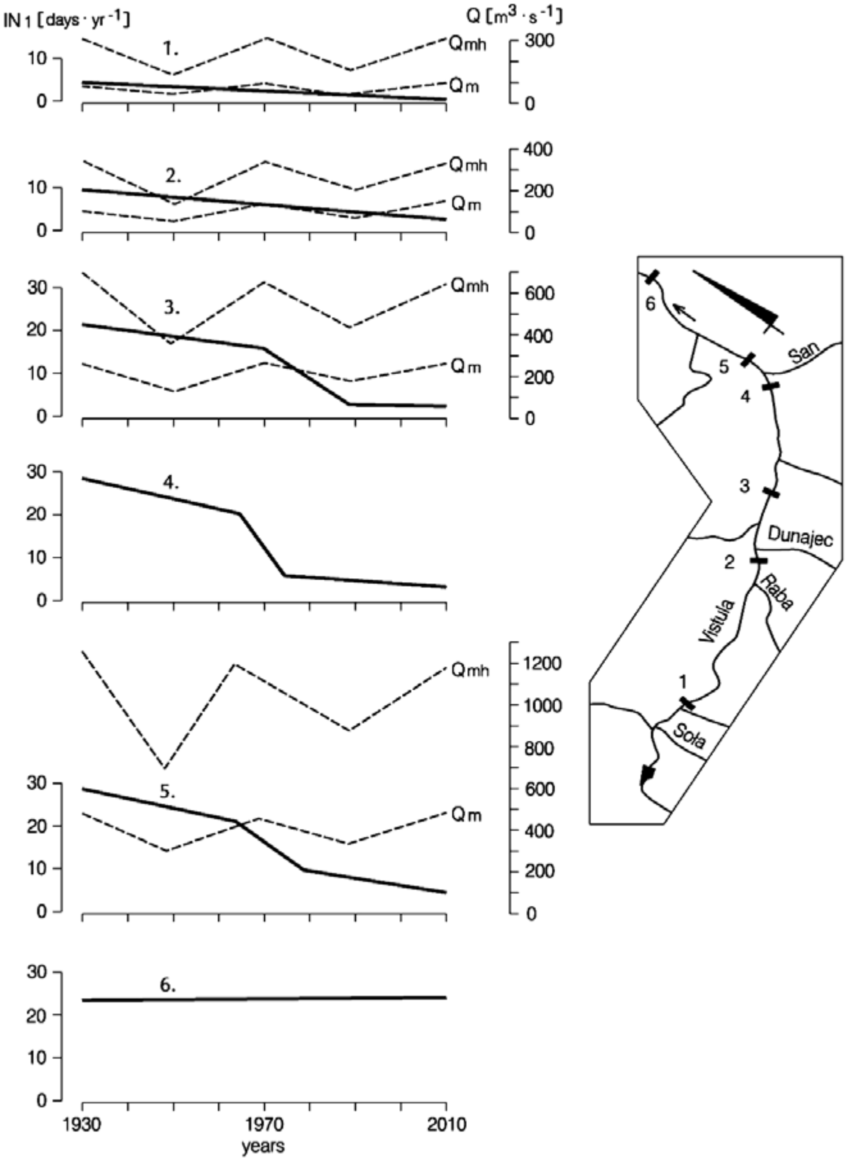

FIGURE 8. Trends in overbank water stage duration (IN_1) at selected gauging sites along the piedmont section of the Vistula after 1930 (continuous line) versus trends in mean discharge – Q_m and mean high discharge – Q_{mh} (broken line). Marked locations of gauging sites: 1 – Smolice, 2 – Jagodniki, 3 – Szczucin, 4 – Sandomierz, 5 – Zawichost, 6 – Puławy

river channel (Osuch, 1991, Punzet, 1991, Łajczak, 1995, 2012). Shorter flood wave duration and increased height were key characteristics of flood events along the Vistula in the vicinity of Kraków during the 20th century. Extremely high peak flood stages also became more common. In effect, flood wave travel times became shortened. Flood wave travel times along the Vistula became 33% shorter during the last 100 years between Goczałkowice (upstream of the Soła) and Zawichost (downstream of the San). Flood wave travel times along the Vistula became over 50% shorter between Smolice (downstream of the Skawa) and Sierosławice (vicinity of the Raba). This section of river has the deepest channel. Increasingly concentrated flood waves in the downstream stretches of mountain tributaries help accelerate flood waves in the piedmont section of the Vistula (Punzet, 1991). Increased concentration of flood waves in this section of the Vistula leads to the reduction of flood wave volume (Punzet, 1991). One of the most important reasons for this is bankfull discharge, which has been increasing since the onset of channelization (Łajczak, 2007, 2012). The increase in Q_{bf} discharge must occur along with a decrease in the volume of the upper part of the flood wave – above the bankfull water stage.

An assessment of changes in flood risk for the piedmont section of the Vistula cannot be categorical. Some changes in discharge help reduce flood risk, while others increase it. This article is part of the mainstream discussion of the effectiveness of existing river channelization methods. These methods are currently perceived as controversial and even counterproductive (Brookes, 1990, Kajak and Okruszko, 1990, Andrews and Burgess, 1991, Finlayson, 1991, Angelstam and Arnold, 1993, Hey, 1996, Thorne et al., 1997, Łajczak, 2007, 2012). This article, basing on the piedmont section of the Vistula, has proven the hypothesis formulated by Cooper et al. (1987), Howard (1992) and Kajak (1993) about other rivers where shallow channels tend to increase flood risk. The gap section of the Vistula valley through the Polish Upland stands out in terms of flood risk with respect to the entire length of the river.

CONCLUSIONS

The following facts support decreased flood risk in the piedmont section of the Vistula valley: (1) drastic narrowing of the flood plain to within the limits of the inter-embankment zone, (2) ongoing shortening of overbank water stage duration in deepened sections of river channel, (3) increased rate of flood wave travel and consequently reduced flood wave duration, which reduces the likelihood of an embankment breach, (4) no overbank water stages in deepened sections of river channel during minor summer floods and all snowmelt floods. Increased flood risk in the valley is the result of: (1) presence of shallow sections of river channel, which lengthen overbank water stage duration, (2) increased fluctuations in floodwater stages following the construction of embankments. In effect, maximum water stages tend to increase during consecutive floods, while flood duration tends to decrease. Excessively high water stages in the inter-embankment zone may lead to a breach in the upper part of the embankments. Another reason for increased flood risk in the piedmont section of the Vistula valley is an increased rate of flood wave travel resulting in more peak water stages in the inter-embankment zone in a shorter period of time. In effect, flood emergency responders have less time to secure embankments.

An assessment of current flood risk and long-term trends in flood risk depends on the location along the river and flood characteristics. Two opposing trends need to be considered: (1) decreasing flood risk due to decreasing flood duration and decreasing geographic extent, (2) increasing flood risk due to higher floodwater stages. This situation is typical of long deepened sections of the Vistula channel. Areas outside the inter-embankment zone are generally safe from flooding. The exception is areas close to breached embankments. In light of the different aspects of flood risk associated with the piedmont section of the Vistula, the changes that have taken place over the last 100 years may be considered positive. Contrary to the views of Andrews and Burges (1991), Finlayson (1991), as well as Angelstam and Arnold (1993), the author believes that it is still reasonable to employ existing channelization methods in large rivers. Inter-embankment zones need to be widened and polders need to be created that would help flatten flood waves (Łajczak, 2007, 2012).

No new flood protection measures may be expected in the near future. No large-scale channelization efforts are planned. Only one new dam is being built in the piedmont drainage basin of the Vistula. No other new dams are planned. Appropriate discharge management in dam reservoirs makes it possible to influence the travel of flood waves resulting in flatter flood waves and altered flood wave arrival times (Punzet, 1973, 1991). An exceptional situation occurs when excess floodwaters collect behind a dam and need to be released from the reservoir resulting in a higher flood wave (Łajczak, 2012). Dams help manage flood waves more effectively in the mountain tributaries of the Vistula than in the Vistula itself.

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Streszczenie: *Zmiany w zagrożeniu powodziowych powodowane przez regulację rzeki na przykładzie przedgórskiego odcinka Wisły*. W pracy zanalizowano główne problemy związane z zagrożeniem powodziowym w dolinie przedgórskiego odcinka Wisły (południowa Polska). Ten odcinek rzeki podlega pracom regulacyjnym od połowy XIX wieku. Omówiono wiele problemów wpisujących się w główny nurt dyskusji na temat efektywności stosowanych metod regulacji rzek. Główną uwagę zwrócono na: (1) aktualny stan zagrożenia powodziowego, (2) wielkość odpływu rzeki, (3) zmiany w zagrożeniu powodziowym od początku prac regulacyjnych z uwzględnieniem zmian w geometrii koryta i zmian w wielkości odpływu rzeki odzwierciedlających efekty prac regulacyjnych. Za główną cechę hydrologiczną badanego odcinka Wisły należy uznać znaczny od zapoczątkowania prac regulacyjnych wzrost wielkości przepływu pełnokorytowego, który trwa nadal. Oznacza to, że zmniejsza się ilość wody w rzece, która podczas stanów wyższych od stanu pełnokorytowego może zatapiać strefę międzywala. Tą uwagę uznano za podstawę analizy zmian w zagrożeniu powodziowym w przedgórskim odcinku Wisły. Ocenę tych zmian w badanym odcinku rzeki nie można jednak uznać za jednoznaczną, gdyż niektóre zmiany w warunkach odpływu przyczyniają się do zmniejszenia ryzyka powodzi, podczas gdy inne są odpowiedzialne za jego zwiększenie. W pracy wykorzystano dane z ponad 100-letniego okresu udostępnione przez Państwową Służbę Hydrologiczną, uwzględniono również mapy opublikowane w dużej skali w ostatnich 230 latach, a także wyniki badań terenowych autora.

Słowa kluczowe: powódź, regulacja rzek, geometria koryta, wał przeciwpowodziowy, międzywale, zatapianie powodziowe, przedgórski odcinek Wisły, południowa Polska

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