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CHANGES OF THE VISTULA RIVER CHANNEL PATTERN AND OVERBANK ACCUMULATION RATE IN THE CARPATHIAN FORELAND (SOUTH POLAND) UNDER HUMAN IMPACT

Abstract: The rate of overbank accumulation in the Vistula floodplain within the Carpathian Foreland has increased since at least the 16th century as a result of drainage basin deforestation (mainly in the Carpathian portion) and agricultural use of this area. However, since the 1850s, additional causes have included deepening of the Vistula channel and its tributaries (mainly the Carpathian ones) initiated by regulation works which delivered additional sediment for overbank accumulation within the inter-embankment zone. Since the 1950s, a rapid decrease in the overbank accumulation rate was noted. This resulted from the retention of the majority of the sediment by deep reservoirs on the Carpathian tributaries of the Vistula, reforestation of the Carpathian portion of the drainage basin, and the slowing down of the rate of deepening of the Vistula channel. An estimate was made of the differentiation of the rate of overbank accumulation within the inter-embankment zone in the longitudinal profile of the study section of the Vistula. The Author proposed a modified model of temporal change of the rate of overbank accumulation in section of the course of the Vistula studied, distinguishing a stage in which change was influenced by regulation works.

Keywords: overbank accumulation, floodplain, inter-embankment zone, inter-groyne basin, river regulation, River Vistula, Carpathian Foreland

INTRODUCTION

Accumulation of sediment transported by mountain rivers on floodplains in mountain forelands has occurred as a result of increasing human impact during the recent centuries (Wolman 1967; Gregory 1987; Starkel 1987a, 1994, 1995a, 2001b, 2005, 2014; Łajczak 1995a, 1999; Czajka 2000; Warowna 2003; Łajczak et al. 2006, 2008). The rate of overbank accumulation depends on the intensity of slope erosion in drainage basins and on the advancement of river control which results in channel deepening or shallowing. The intensity of accumulation effects on floodplains is also impacted by river regulation works, such as reducing geomorphologically active floodplain width to a narrow inter-embankment zone, deepening of the channel due to its shortening and narrowing, and a reduction in the rate of sediment transport as a result of the damming of rivers. For several centuries, human impact led to an increase in overbank accumulation, however, a trend to a decrease started to dominate in many areas in the 20th century. This change in the overbank accumulation trend has been noted for over 50 years (Wolman 1967; Becker, Mulhern 1975; Trimble 1981; Gregory 1987; Łajczak 1999; Starkel 2001b, 2014; Knox 2006; Macklin, Lewin 2010).

The rate of overbank accumulation has also been influenced by climatic fluctuations resulting in uneven distribution of large floods in time, especially in the clustering of these hydrological and geomorphological processes (Starkel 2001a, 2003). Therefore, the interpretation of changes in the rate of overbank accumulation is not univocal and requires particular caution in concluding the influence of human impact.

The floodplain of the River Vistula in the northern Carpathian Foreland has been the object of detailed geomorphological and palaeogeographical investigation for many years (Starkel (ed.) *Evolution of the Vistula river valley during the last 15,000 years*, parts I–VI, 1982a, 1987b, 1990, 1991, 1995b, 1996). However, there are not many works concerning human influence on the functioning of the channel and the floodplain / inter-embankment zone in this section of the river valley. There is still no answer to the question – what are determinants, course and rate of overbank accumulation on the floodplain in this section of the Vistula valley.

The aim of this work is an attempt to explain the following problems and to answer the following questions applying a quantitative approach: (1) explaining the evolution of the Vistula channel and floodplain in the 17th –19th centuries, (2) the scope of regulation works, geomorphological and hydrological consequences, (3) assessment of accumulation rates in the channel and on the floodplain since the beginning of regulation works, (4) drawing attention to overbank accumulation outside the flood control levees, (5) analysis of changes in the yield of suspended sediment in the years 1946–1995 with special regard to assessment of losses in the transport (multi-year trends, differentiation in the longitudinal profile of the river), (6) overbank accumulation versus inundation of the inter-embankment zone.

STUDY AREA

GENERAL INFORMATION

The Vistula starts in the Western Carpathians at an altitude of 1,107 m a.s.l., and between the 35th and 406th kilometre of its course (from Skoczów town to Annopol town), it flows within two mountain foreland basins (which represent the Subcarpathian Basins): the Oświęcim Basin and the Sandomierz Basin, which are divided by a 40 km long water gap called the Krakow Gate. To the north, the Vistula valley is adjacent to the edge of the Polish Uplands (Fig. 1A). In this 371 km long section, the Vistula receives many tributaries including six large Carpathian rivers (Soła, Skawa, Raba, Dunajec, Wisłoka, San) and two large upland rivers (Przemsza, Nida) (Fig. 1B). The area of the drainage basin down to the site which closes this section of the river course (Annopol town) is 51,518 km^2, and the absolute maximum and mean discharges are, respectively, 7700 and 450 $m^3 \cdot s^{-1}$. The absolute amplitude of water stages of the section of the Vistula studied varies among gauging stations between 600 and 900 cm. All the Carpathian tributaries held dominant shares in water inflow (80%) and in the supply of suspended sediment (90%) to the study section of the Vistula (Łajczak 1999). The 70 km long river section in the water gap across the Polish Uplands (with the Kamienna tributary) and the 5 km long river section in the adjacent part of the Polish Lowlands are also taken into consideration. The area of the drainage basin of the whole study section of the Vistula to the point where it flows out of the site (Puławy town) is 57,264 km^2.

Along the 441 km long section of the Vistula studied, the width of the floodplain at the Dunajec confluence is 15 km, and upstream it reaches 2–10 km (in the Kraków Gate the minimum width is 0.4 km). Downstream to the town of Annopol the width of the Vistula floodplain varies between 3 and 15 km. Within the water gap section across the Polish Uplands the minimum width of floodplain reaches 1.0 km (Fig. 1C). In all, 18 sections of floodplain (a–s) were distinguished with different widths and locations regarding the confluences of large Carpathian tributaries. In section “b”, there is the Goczałkowice Reservoir and its dam, and in sections “g–i” there are four shallow and narrow dams. The gradient of the mean water table α falls with the course of the river; downstream of the outflow of the Vistula from the Carpathians it is 1.5‰, in the Oświęcim Basin it falls to 0.5‰, in the Sandomierz Basin to 0.25‰ and at the outflow of the Vistula from the Polish Uplands it falls to 0.23‰ (Fig. 2) (Łajczak et al. 2006, 2008; Starkel 2014). These values increased in the 19th–20th centuries due to regulation works (shortening of the river course) (Trafas 1992). This resulted in a decrease in the sinuosity of the Vistula, which

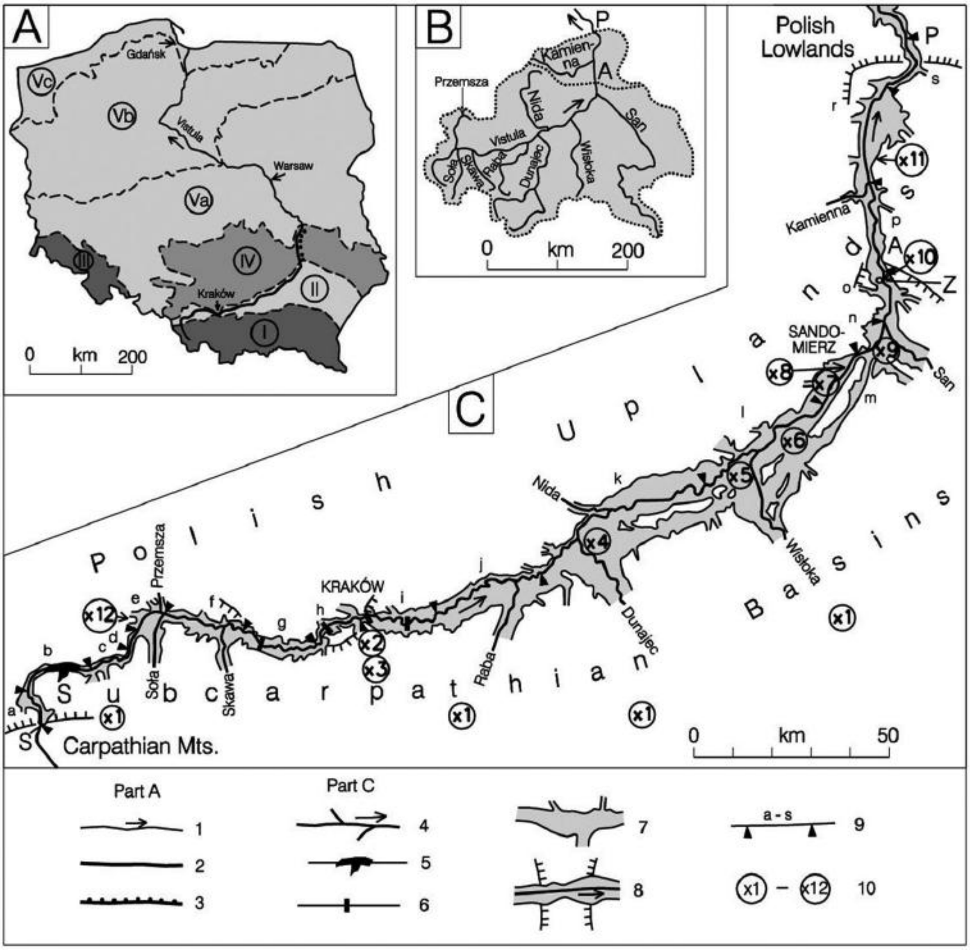

Fig. 1. Study area. A – the course of the Vistula in relation to the main geomorphological units in Poland (I – Carpathians, II – Subcarpathian Basins, III – Sudetes, IV – Polish Uplands, V – Polish Lowlands: Va – area with old-glacial relief, Vb – area with young-glacial relief, Vc – Baltic Coastlands); B – drainage basin of the Vistula course studied: A – to Annopol, P – to Puławy, main tributaries of the river; C – limit of the floodplain of the Vistula course which is the subject of this research. 1 – Vistula river, 2 – Vistula river within the Subcarpathian Basins, 3 – Vistula river within the water gap across the Polish Uplands, 4 – the Vistula and the lower sections of its main tributaries, 5 – Goczałkowice Reservoir and dam, 6 – shallow and narrow dams, 7 – limit of the floodplain (according to L. Starkel and E. Wiśniewski 1990), 8 – places where the Vistula crosses the boundaries between the Carpathians, Oświęcim Basin, Krakow Gate, Sandomierz Basin, Vistula Gorge (water gap across the Polish Uplands), Polish Lowlands, 9 – sections of the Vistula floodplain and their numbering, 10 – location of the areas described in detail in the text. Part C – location of the gauging stations discussed in the text: S – Skoczów, Z – Zawichost, A – Annopol, P– Puławy

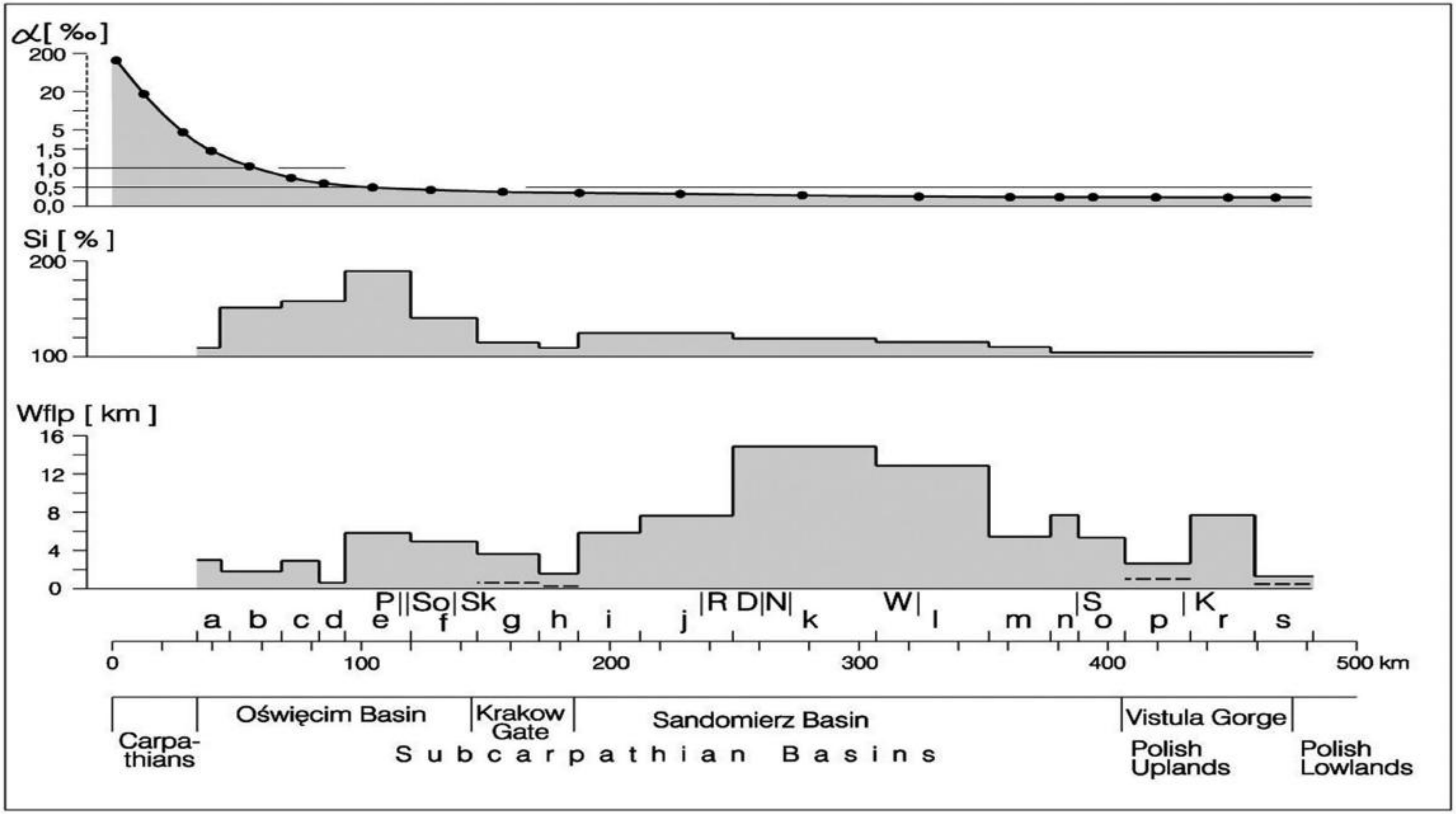

Fig. 2. Parameters of the channel and floodplain of the course of the Vistula that was the subject of this study. α– gradient of mean water table, Si – sinuosity, Wfpl – mean width of the floodplain (short broken lines show the narrowest stretches of floodplain). Limit of main geomorphological units and sections of the Vistula floodplain (a–s) as in Fig. 1. Confluences of the main tributaries of the Vistula: P – Przemsza, So – Soła, Sk – Skawa, R – Raba, D – Dunajec, N – Nida, W – Wisłoka, S – San, K – Kamienna

is still the largest in the Oświęcim Basin (up to 190%). In the river's lower course, the sinuosity decreases from 130% to 105%. The mean width of the floodplain in the sections "a–s" does not show any relationship with the sinuosity of the river channel (Author's research – unpublished data).

Despite the small river gradient, the hydrological regime of the Vistula in the Carpathian Foreland shows features of a mountainous river with a summer maximum of runoff and an increasing share of runoff during the spring thaw along the river course. The seasonal changeability of transport of suspended material shows a similar trend (Łajczak 1999). The Vistula is the second river in Central Europe (after the Danube) in terms of the frequency of occurrence of flood waves (Lambor 1962). Over the last 250 years, floods causing flooding of the floodplain occurred on average every 2.7 years, usually in summer. Such events occurred every 2 years in the period 1770–1830, every 3.3 years in the period 1860–1890 and every 2.9 years in the period 1900–1980 and since 1997 (Łajczak 1999). During catastrophic floods the Vistula floodplain on the Carpathian Foreland has been flooded with different intensities, for example in 1813 along the whole course of the river, in 1934 downstream of the Raba confluence (Lewakowski 1935) and in 1997 and 2010 smaller areas were flooded (Grela et al. 1999).

CHANGES IN LAND USE IN THE CARPATHIAN PART OF THE VISTULA DRAINAGE BASIN OVER THE LAST MILLENNIUM, CHANGES IN RIVER FUNCTIONING

L. Starkel (1988, 2014) showed changes in land use and land cover (tree cover, grassland, farmland and road density) which occurred in the Carpathian part of the Vistula drainage basin in the last millennium with a projection to the end of the 21st century (Fig. 3). This area, which is composed of flysch and where intensive erosion occurs, determines the flow of water and supply of sediment to the section of the Vistula course investigated. The replacement of forests by farmland and grassland and the increase in the density of dirt roads started in the 15–16th centuries and the maximum impact of these changes occurred in the first half of the 20th century (Soja, Prokop 1996; Kozak 2005; Kroczak 2010). Since that time, there has been a gradual increase of an opposite trend – such change is forecast to continue in the 21st century (Bucała, Starkel 2013). Deforestation of the Carpathians and the increase in the density of unsurfaced tracks caused an effect on the increase of flood frequency from a maximum in about 1800 resulting in rapid increase of the bed load and, most of all, an increase in the suspended load, the maximum of which was also at the turn of the 18th and the 19th centuries (Starkel 2014). These trends to change are confirmed in detailed studies in different areas of the Polish Carpathians (Soja, Prokop 1996; Kozak 2005; Kroczak 2010).

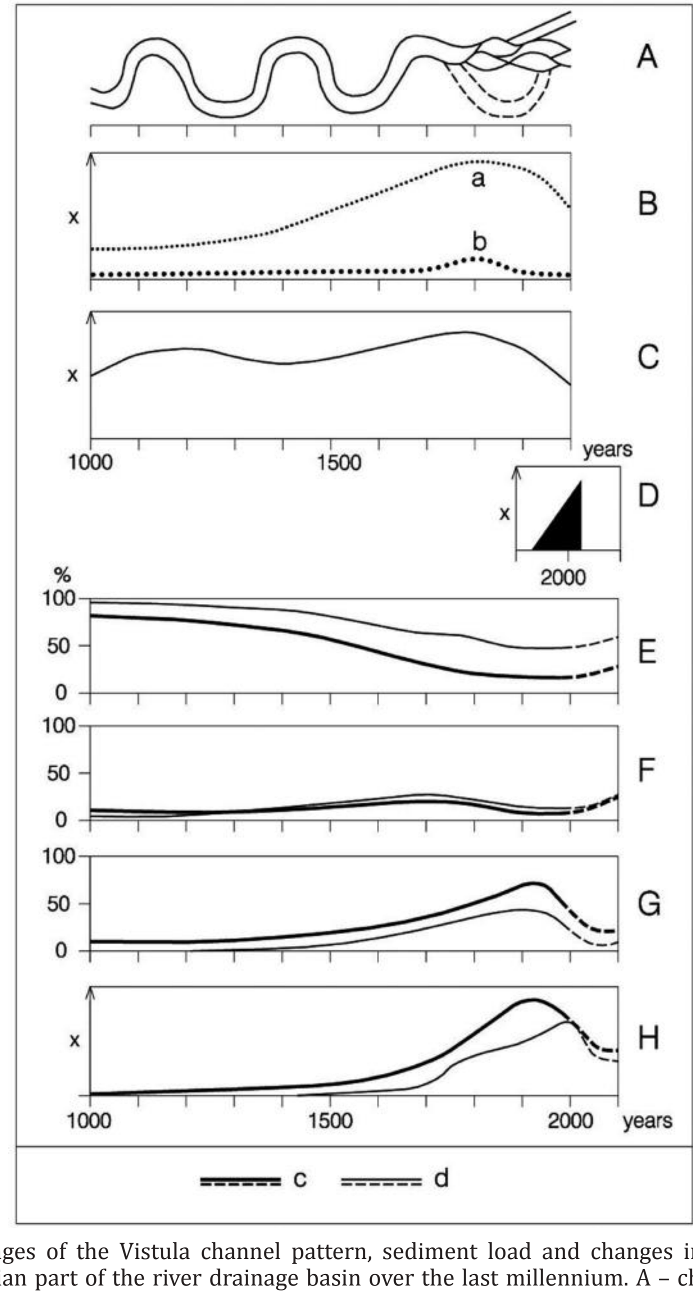

Fig. 3. Changes of the Vistula channel pattern, sediment load and changes in land use in the Carpathian part of the river drainage basin over the last millennium. A – changes of Vistula channel pattern, B – suspended load (a), bed load (b), C – flood frequency, D – increase in the number of dams (since 1932), E – forests, F – grassland, G – farmland, H – road density. Values E–H are related to: c – Carpathian Foothills, d – Beskidy Mts. x – non-expressed scale. Parts A–C and E–H based on L. Starkel (1988, 2014). Information on quantitative changes in the D and H parameters over time in the area analysed can be found in the following publications: R. Soja and P. Prokop (1996), A. Łajczak (1999), J. Kozak (2005), R. Kroczak (2010), A. Bucała and L. Starkel (2013)

Over that time, the Vistula river in the Carpathian Foreland downstream of the Dunajec confluence changed from a meandering river into a braided one (Author's research based on historical maps – unpublished data). The subsequent changes in land use resulted in a decrease in the rate of transport in the river, however, the main reason was the increasing number of dams built on the Carpathian tributaries which started in 1932 (Łajczak 1999).

Changes in the way the foreland course of the Vistula functioned during the last 300 years are shown in Figure 3 and are the basis of further research carried out by the Author, the results of which are shown in the following chapters.

MATERIALS AND METHODS

This paper was written on the basis of a broad spectrum of information: (1) archival maps (from the 18th century onwards), (2) hydrological data provided by the State Hydrological Survey (from the beginning of the 19th century to 2013, in the case of data on the transport of suspended sediment, over the years 1946–1995), (3) the results of geodetic measurements provided by the State Hydrological Survey (from the beginning of the 20th century onwards), (4) historical information concerning the Vistula valley, especially in the case of the oldest towns – Kraków and Sandomierz, (5) information from literature, (6) results of the Author's field work carried out since 1988, (7) data from aerial laser scanning LiDAR.

Based on maps from the years 1737, 1779–1782, 1785, 1804, 1810, 1809–1815, 1817, 1824, 1839, 1855, 1860–1866, 1882, 1890–1914, 1933, 1953, 1975, 1990 (see Łajczak 1995b) and also historical information (17th – 19th c.), changes in the course of the section of the Vistula being studied and the confluence sections of its tributaries were reconstructed, as well as the rate of decay of oxbow lakes and changes in channel width. Changes of the parameters of a channel in plan view (length, sinuosity) in defined sections of the river were related to the length of the axis of the meandering route of the river. As far as possible, historical information was used to determine the changes in the course of the Vistula near Sandomierz.

Based on hydrological data and the results of geodetic measurements of the State Hydrological Survey (SHS), the following elements were determined in 37 gauging stations on the Vistula river (for their distribution see Fig. 9C): (a) mean water table, which was the basis for determining the local gradient of the mean water table in individual sections of the river; (b) characteristic water stages at the Zawichost gauging station (for location see Fig. 1C). These data have been included to illustrate the vertical change of the Vistula channel and floodplain in the section of the valley floor with the greatest degree of overbank accumulation; (c) the size of channel deepening or shallowing since the beginning of regulation works was determined in each gauging station based on an analysis of multiannual changes of minimum annual water stages at each gauging station. These results were adjusted using the analysis of repeatable geodetic measurements carried out by SHS at each gauging station. The methodology of these calculation is presented in the publication: A. Łajczak (1995b); (d) taking into account information from the literature, the years were determined when regulation works (channel straightening, construction of flood control embankments, groynes and dams) started in individual sub-sections of the Vistula and when it finished. This was the basis for calculating parameters which describe the inundation of the inter-embankment zone: IN1 duration (mean number of days per year with these phenomena over the period 1946–2013), and IN2 (mean number of flood events per year which cause flooding of the inter-embankment zone over the same period); (e) the thickness of sediment fill in the inter-groyne basins at gauging stations was determined from geodetic data obtained from the SHS. The cross-section profile of the river channel, including in particular the height of the river banks, changes over time and these changes were taken into account in the calculation of IN1 and IN2 values. The years before 1946 with flood events occurring were determined from the literature (for example: 1813, 1934). Periods with a clustering of catastrophic floods were distinguished from about 1600 onwards, assuming that the duration of these periods was from several to a dozen or so years and the floods occurring in these periods repeated at least every 3 years (Łajczak 2009, 2012a). Information on the geomorphological effects of the largest floods and on changes of floodplain morphology was obtained from the literature (Szewczuk 1939); these places (X1–X12) are shown in Figure 1C. The latest information on this subject can be found in P. Gębica et al. (2019).

The thickness of the sediment infill in the inter-groyne basins along the study section of the Vistula was determined from the Author's field work. The structure of these sediments (bank outcrops, drillings) and changes in morphology of the "newly developed" floodplain zone was investigated at selected sites. Due to the limited length of this article, the detailed analysis of drilling results and exposures of sediments at individual research sites was abandoned, and attention was focused an analysis of the results obtained. Simultaneously, investigations were carried out concerning the thickness of sediment infill in 14 meanders cut off from the Vistula in the period 1780–1830 (the approximate year of the meander cut-off was determined from archival maps) along the whole section of the river investigated. At present these are located within the inter-embankment zone or beyond this zone.

The thickness and structure of sediments were determined by drilling (the results of these studies, taking into account the above-mentioned remarks, were also included in the article to a limited extent). Attention was also paid to the morphology of the strips of floodplain within the inter-embankment zone, from where the material was taken to build the flood control embankments.

The extent of such areas, which only cover some sections of the floodplain within the inter-embankment zone, is still visible on LiDAR images. LiDAR imagery was also used to determine the extent of the cut-off meanders of the river, which are largely filled with sediment, and of the inter-groyne basins.

The results obtained on the basis of the above-mentioned test methods are the only basis for the assessment of the relative differentiation of the rate of overbank accumulation in the course of the Vistula River and in the cross-section of the floodplain; this also applies to the current state of the river with a narrow inter-embankment zone.

A more detailed analysis of overbank accumulation rates along the section of the Vistula floodplain investigated (= inter-embankment zone) and the temporal changes in this process was carried out using the results of investigations of suspended sediment load in the river at 12 gauging stations over the period 1946–1995 (data obtained from SHS, for location the gauging stations see Fig. 10C). The application of the input-output method in succeeding balance sections of the river made it possible to determine the rate of loss in the transport of suspended sediment load (Łajczak 1999, 2003). In the section of the Vistula investigated, in which the deepening of the riverbed is predominant, losses in transport can be attributed to the accumulation of suspended sediment on the floodplain within the inter-embankment zone. These values are expressed in [tons$\cdot$ha$^{-1}\cdot$y^{-1}] and show the "potential" rate of overbank accumulation (Łajczak 1995a).

RESULTS

EVOLUTION OF THE STUDY SECTION OF THE VISTULA CHANNEL IN THE 17TH – 19TH CENTURIES VERSUS THE OVERBANK ACCUMULATION RATE

Analysis of archival maps indicates that until the 17th century, the Vistula was a meandering river in the Carpathian Foreland and the water gap across the Polish Uplands, which is confirmed by historical information concerning river sections near Krakow and Sandomierz and the further course of the river. The type of river channel pattern thus formed was studied by, among others, K. Trafas (1992). In the 18th century the Vistula started to transform from a meandering to a braided river downstream of the Dunajec confluence (Sokołowski 1987). A detailed analysis of the above-mentioned maps from the 18th and early 19th centuries shows that at that time, the braided sections of river channel first started to develop downstream of the confluences of the Dunajec, Wisłoka and San, and further from these confluences the river still kept its meandering course. The braided sections of the river were accompanied by natural cut-off meanders. In the 19th century, the process of channel braiding downstream of the Dunajec confluence intensified. The Vistula had a braided channel upstream of the San confluence and in its further course it was still braided but with a straighter alignment (Fig. 4A). The cut-off meanders were quickly filled with sediment during floods. The meandering course of the Vistula channel upstream of the Dunajec confluence, which has remained up until recent times, may be explained by smaller supplies of sediment from the Carpathian tributaries (the Soła, Skawa, Raba and several smaller ones) compared to the following large tributaries (the Dunajec, Wisłoka, and San), the drainage basins of which range more widely in the intensively eroded flysch Carpathians. It is interesting, that despite the large flood potential of the Soła, and also the Skawa and Raba rivers, the Vistula still keeps a meandering course upstream of the Dunajec confluence.

In the 17th – 19th centuries, the increasing supply of sediment to the Vistula from the more and more deforested Carpathians (which partly changed into farmland) led to changes in the pattern of the river system in the neighbourhood of the confluences of the largest Carpathian tributaries. The change of the Vistula channel from a meandering to a braided one at the Wisłoka confluence (site X5) was accompanied at the beginning of the 19th century by the development of an alluvial fan with a distributory channel system of this tributary within the wide river bed (Fig. 4B). On the other hand, the change of the Vistula channel in the 18th century from meandering to braided at the San confluence (sites X8, X9) was accompanied by increased overbank accumulation and levee development, which resulted in avulsion of the confluence section of the San. Another explanation for this process is that it was an autogenic process of aggradation on the San alluvial fan which caused channel avulsion during large floods. This, in turn, caused a shift of the junction of both rivers with the Vistula by 7 km downstream (Fig. 4C). These changes to the Vistula channel near the Wisłoka confluence are documented in the maps of period 1779–1839 (Fig. 5A), whereas the changes upstream of the San confluence at Sandomierz town and in the area of the Vistula and the San junction are documented in historical materials (since the 17th century) and maps of 1780 and of about 1840 (Fig. 5 B–C). To compare, the present course of these sections of the Vistula and its tributaries is also shown. These findings about the changes along the confluence section of the San river seem to be corroborated by the analysis by J.E. Piasecka (1976) of an archival Perthées map (dated approximately to 1780). Citing Perthées, she claims that the river`s

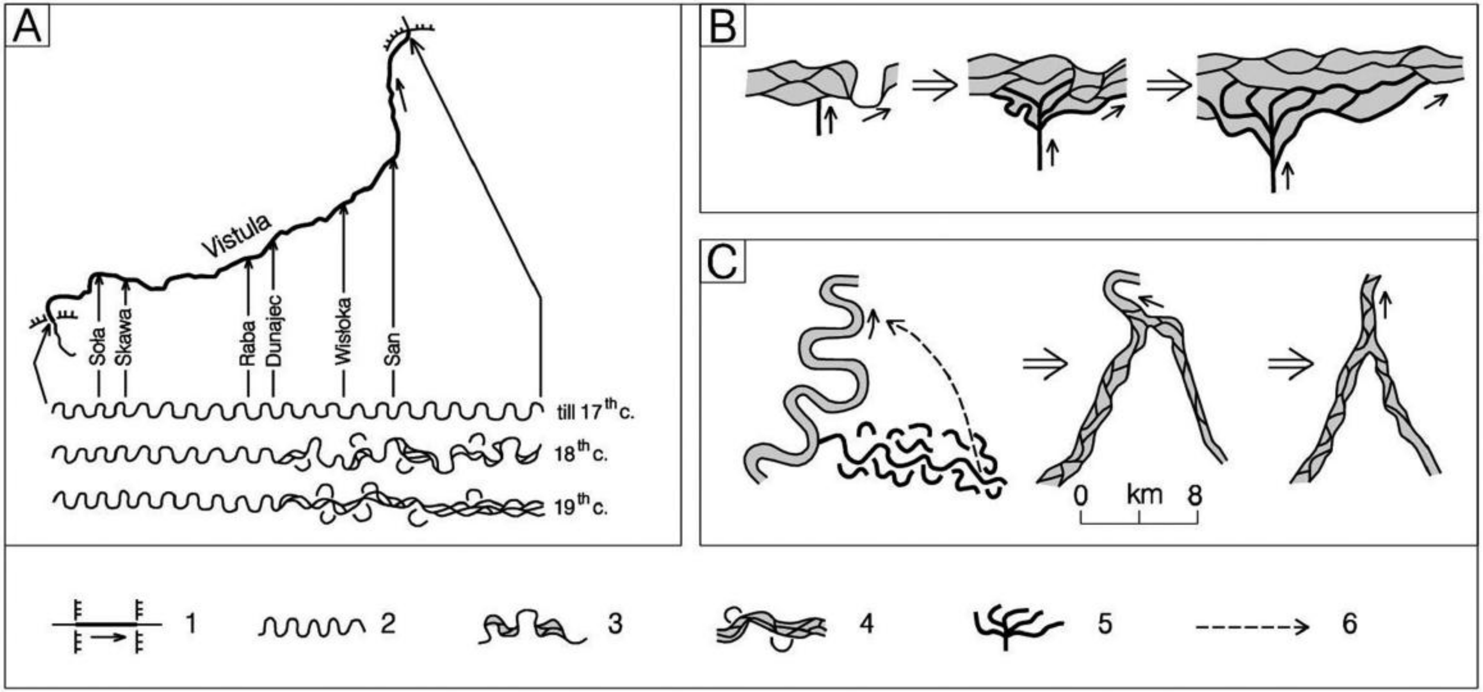

Fig. 4. Changes in the course of the study section of the Vistula from the 17th to 19th centuries. A – stages of changes in the river course, B – schematic diagram of the development of the Wisłoka alluvial fan with its distributory system of channels at the confluence with the Vistula at the beginning of the 19th century, C – changes in the courses of the Vistula and the San in the area of their confluence in the 18th century and the beginning of the 19th century. For more explanations see Fig. 5. 1 – Vistula section between its outflow from the Carpathians and its outflow from the Polish Uplands, 2 – meandering course of river, 3 – river course with meandering and braided sections, 4 – braided section of river with preserved cut-off meanders, 5 – the Wisłoka alluvial fan, 6 – avulsion of the confluence section of the San. Single arrow – river course, double arrow – transition from one phase to the next phase of river bed development

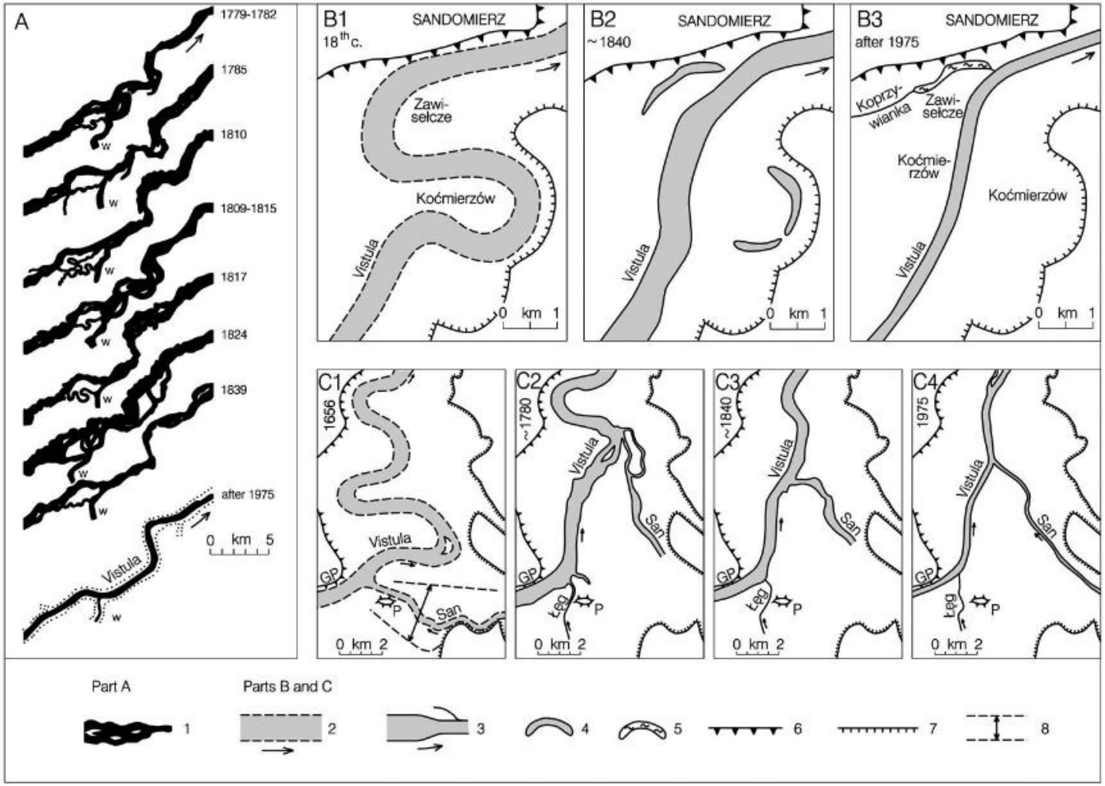

Fig. 5. Changes of the course of the Vistula since the 1650s at the Wisłoka confluence (A), near Sandomierz (B), at the San confluence (C). Part A: 1 – Vistula and Wisłoka channels (wide channel at the turn of 18th and 19th centuries, W – Wisłoka, source of material – maps analysed for the years indicated), Parts B and C: 2 – meandering channel of the Vistula, 3 – partly or totally braided channel of the Vistula, 4 – oxbow lakes, 5 – marshes, 6 – high escarpment of the Polish Uplands, 7 – edge of Pleistocene terrace, 8 – zone of the San which meandered until the 17th century. GP – Pepper Hills, P – Pączek Mound. Part B1 – interpretation of the author based on historical information. Parts B2 and B3 – based on archival maps, Part C1 – based on S. Pufendorf (1696), Parts C2-C4 – based on archival maps. Single arrow – river course

avulsion occurred between 1697 and 1733. The cut-off of the Vistula meanders near Sandomierz after large floods at the turn of the 18th and 19th centuries caused Koćmierzów village to be divided into two parts located on both sides of the river. Moreover, Zawisełcze village (which, looking from Sandomierz, means "beyond the Vistula" in Polish), started to be located in front of the Vistula, that is, on the left side of the river (Fig. 5B). During the avulsion of the confluence section of the San, one of the cut-off meanders of the Vistula was used by the San (Fig. 5C).

Since the 17th century, horizontal changes of the Vistula channel and channels of its Carpathian tributaries have been accompanied by their shallowing, especially after a series of large floods at the turn of the 18th and 19th centuries (for example in 1813), which is shown in historical materials (Adamczyk 1978, 1981). Aggradation in the channels of the Carpathian rivers led locally to a raising of the channel level, even above the floodplains, which caused the siltation of farmlands and orchards with flood sediments (site X1 in the Carpathian river valleys). The description of the consequences of the catastrophic flood of August 1813 (Szewczuk 1939) indicates flooding of the whole area of the Vistula floodplain (not only on the Carpathian Foreland), siltation of the Vistula meanders, the covering of the farmlands on the floodplain with a 1.5 m thick layer of flood sediments (downstream of the Dunajec confluence) and several months' stagnation of flood water on the floodplain (sites X2–X4, X6, X7). The most intensive accumulation on the Vistula floodplain occurred downstream of the San confluence (the largest Carpathian tributary), where the cut-off Vistula meanders were totally filled with flood deposits (Author's research – unpublished data). In the Vistula water gap across the Polish Uplands (site X11), the thickness of sediment layers accumulated on the floodplain (beyond the former meanders) from the 17th to the 19th century was estimated at 2.5 m (Maruszczak 1982). Other authors assert that the thickness of young overbank sediments in this section of the floodplain of the Vistula is smaller. For example, E. Falkowski (1982) gives the thickness of the sediments accumulated from the 17th century to 1963 as 2 m, and W. Pożaryski and T. Kalicki (1995) as 0.5–1.3 m thick (from medieval times).

Some historical facts can be used to estimate the scale of river channel aggradation and overbank accumulation of the Vistula at Zawichost town downstream of the San confluence (site X10) during the last 350 years. There used to be a castle located on an island in the channel of the Vistula from the 11th century onwards. This castle and its neighbourhood (March 26th 1656) is shown during the Polish-Swedish war (1655–1660) on Figure 6A (after Pufendorf 1696). The river channel at that time was so shallow (March usually had high river stages during thaws) that the soldiers crossed the river

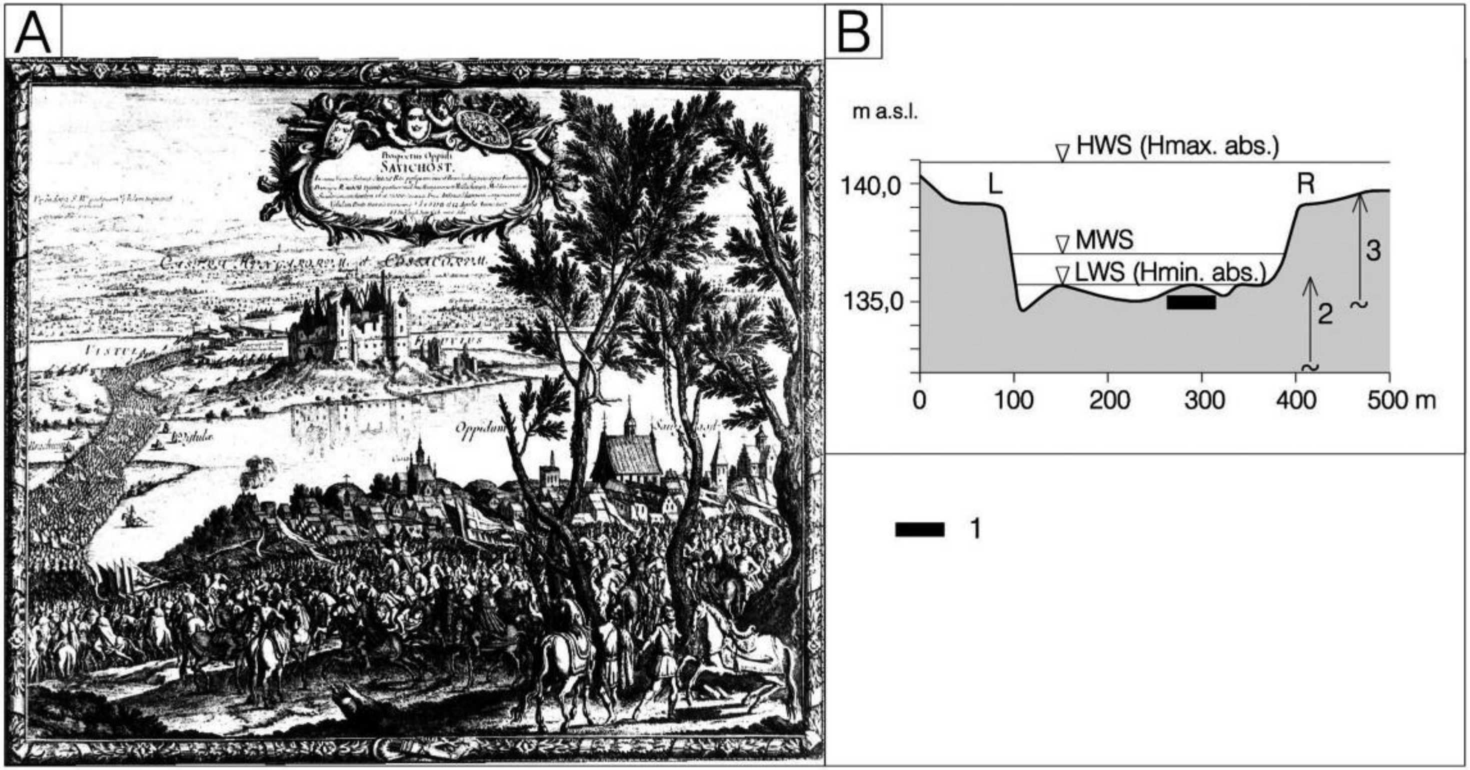

Fig. 6. Changes in the vertical location of the channel and floodplain of the Vistula river at Zawichost town since the 1650s. A – drawing showing the Vistula channel with the island and castle, March 1656 (by S. Pufendorf 1696), B – present profile of the Vistula channel in the location of the former castle. 1– foundations of the castle, 2 – probable increase in sediment in the river channel since the castle was destroyed, 3 – probable increase in sediment on the floodplain at the same time. Part B shows characteristic water stages measured at the water gauging station at Zawichost

on pontoon bridges and their commanders rode their horses. The foundations of the castle towered over the water level of the Vistula river. The shallowing of the Vistula channel, which gradually occurred over the years which followed, caused the island to wash away and castle to be destroyed during the large flood of 1813 (Kwiatkowski 1935). At present the foundations of the castle are found at a depth of 2 m below the mean river stage in the Vistula channel (on the route of the ferry) (Fig. 6B). This means that the river channel has probably shallowed by at least 3 m since the 1650s. The shallowing of the channel must have caused the floodplain to build up, possibly also by at least 3 m.

The overbank accumulation included the whole area of the Vistula floodplain until the second half of the 19th century. The process of overlaying of the convex meander banks (point bar development) of the Vistula occurred first as the accumulation of channel deposits and then as fine material accumulation, in effect forming scrolls. The levees were probably low and wide. Subsequent maps from the 19th century indicate a rapid decay of the oxbow lakes in the cut-off meanders, which evidences a rapid rate of filling of the meanders with flood sediments. Figure 7 shows the subsequent stages of filling with sediment of 14 meanders located along the river course studied which were cut off from the Vistula river in the period 1780–1830. The oxbow lakes located in these meanders were filled by sediments in the 19th century however flood deposits totally hid these meanders on the Vistula floodplain downstream of the confluences of the largest Carpathian tributaries. In the sediments filling the former meanders, one can distinguish paleochannel facies and levee facies (Fig. 7A2). For example, the channel deposits filling the cut-off meander of the Vistula south of Zawichost (the location of the meander below the San confluence is shown in Figure 5 C2–C3) are overlain by 4 m thick levee sediments. This fact confirms the comments in Figure 6B. Out of the 14 meanders cut off from the Vistula in 1780–1830 that were examined, 9 were located upstream the Dunajec river confluence, and the channel deposits are not yet covered by levee sediments. Downstream the confluence of this tributary, and especially downstream the confluences of the Wisłoka and San (the rivers providing the greatest amount of sediment to the Vistula), the paleomeanders of the Vistula investigated are completely masked by levee sediments (Fig. 7 A2–A3).

The intensity and range of overbank accumulation in the Vistula course studied started to change following the regulation works which commenced in the second half of the 19th century. This moment indicates the beginning of the subsequent phase in the geomorphological development of the Vistula channel and floodplain on the Carpathian Foreland.

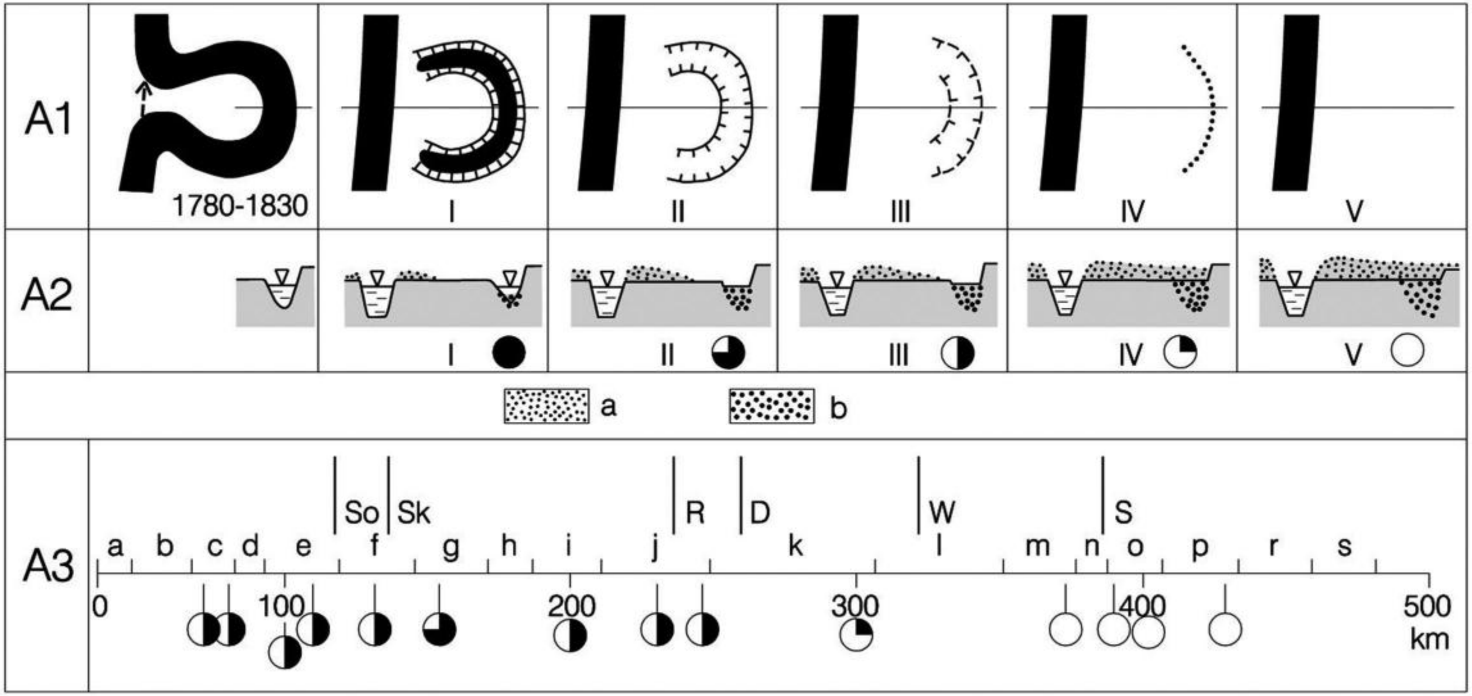

Fig. 7. Schematic diagram of the flood sediment infilling the meanders cut-off the Vistula in 1780–1830. A1 – gradual decay of meanders (stages I–V), A2 – increase of sediment disguising the meanders (the signatures show the progress of meander decay, 1 – levee facies, 2 – paleochannel facies), A3 – distribution of former meanders at a certain stage of decay along the Vistula section examined. Detailed sections of the Vistula floodplain with their numbers (a–s) are indicated as well as locations where the river joins with large Carpathian tributaries (see explanation to Figure 2)

THE SCOPE OF REGULATION WORKS. GEOMORPHOLOGICAL AND HYDROLOGICAL CONSEQUENCES

Regulation of the Vistula river upstream the San confluence started in the 1850s and intensified after 1884, but the lower river course was regulated as late as from the 1950s (Starkel 1982a). In the period 1920–1960, the extraction of alluvia from the Vistula channel occurred on a large scale (Starkel 2001b). Work on the regulation of the Vistula began to be phased out in the 1960s (Hennig 1991). The scope of the regulation works included: (a) the straightening of the channel by cutting off many meanders, mainly before 1900, (b) the construction of stone groynes on the river banks during the whole period of regulation works (downstream of the San confluence in the 20th century), (c) the construction of flood control embankments after 1884. Downstream of the San confluence the construction of embankments was completed in the 1970s, however locally this work continued later on a large scale, (d) the creation of a large retention reservoir on the Vistula river (1956) and four low and narrow dams (1949–1990) (Łajczak 1999), see Figure 1C.

To date, the length of the course of the Vistula in the study has decreased from 532.2 km to 446.0 km (by 16%). The intensity of changes was greatest in the highly meandering section of the river upstream of the Soła confluence, whereas a decreasing trend occurred in the lower course of the river (Fig. 8). This resulted in a decrease in the sinuosity of the course of the Vistula examined from 145% to 121% and an increase in the gradient of the water table at the mean water stage. This was most intensive in the river section upstream of the Soła confluence (from 0.62‰ to 0.89‰). The Vistula channel got narrower, mainly in the years 1855–1933; with the river course to the San confluence the absolute scale of these changes increases from 75 m to 200 m and later decreases to 100 m, whereas the relative scale of these changes decreases from 60% to 12%. The construction of flood control embankments drastically narrowed the flood zone, which is now reduced to the inter-embankment zone – its width gradually increasing along the course of the Vistula studied from 250 m to 1000 m. The width of this zone only covers 6–8% of the area up to the limit of the floodplain, however, in the water gap section of the valley within the Polish Uplands it covers up to 25%. As a consequence, the regulation works, are accompanied by a deepening of the Vistula channel along the majority of its length (Fig. 9C2) which has on average reached 2 m (maximum 4 m). The material from the deepened channel is transported far away; in the study section of the Vistula regular deposition on the channel bed only takes place upstream of the Soła confluence and in the water gap across the Polish Uplands (channel shallowing up to 1.5 m)

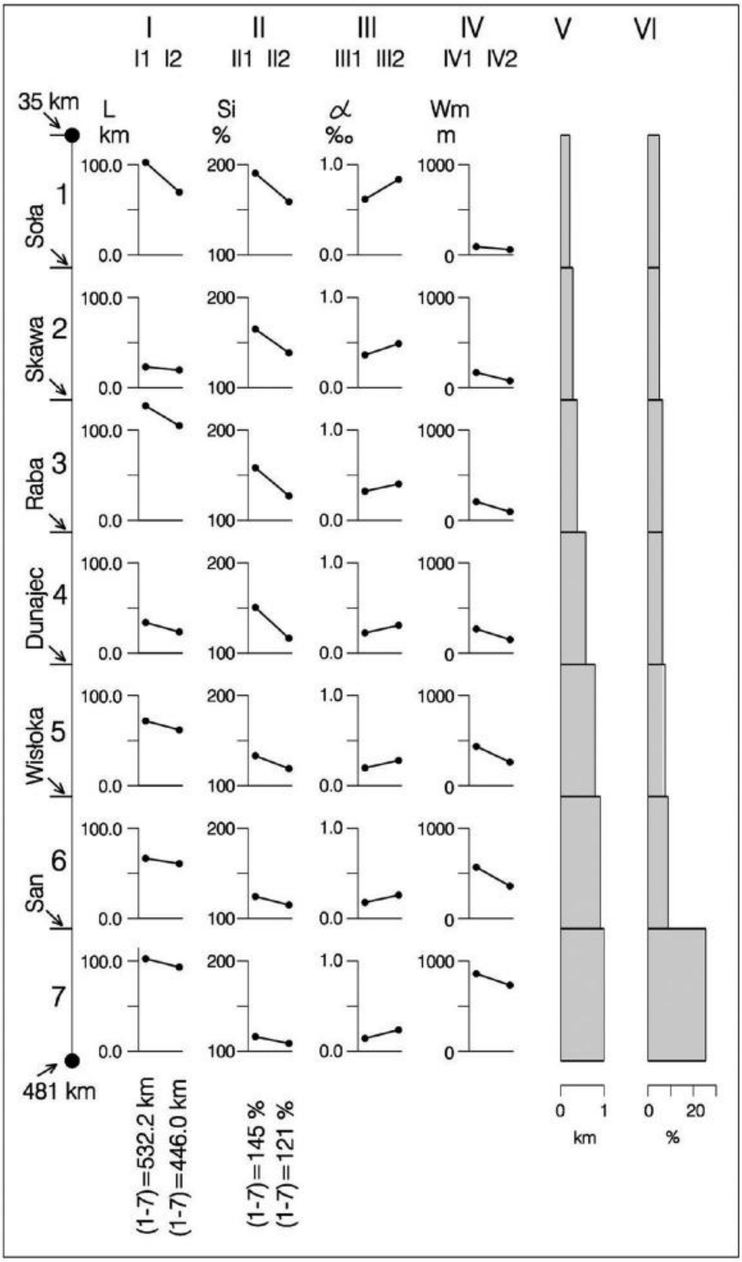

Fig. 8. Changes in the characteristics of the channel and the geomorphologically active zone of the Vistula floodplain in river sections (1–7) between the large Carpathian tributaries. I – river length L, II – river sinuosity Si, III– channel gradient measured as mean water stage α, IV – channel mean width Wm. I1, II1, III1, IV1 – characteristics of the channel before the beginning of regulation works. I2, II2, III2, IV2 – present characteristics of the channel. V – mean width of inter-embankment zone, VI – width of the inter-embankment zone in relation to the edge of the floodplain

(source: Author's own data). The formation of a narrow inter-embankment zone caused a twofold increase in the amplitude of the water stages in the river. The regulation of the Vistula caused an increase of river competence, an increase in the bedload and suspended load, which additionally is derived from

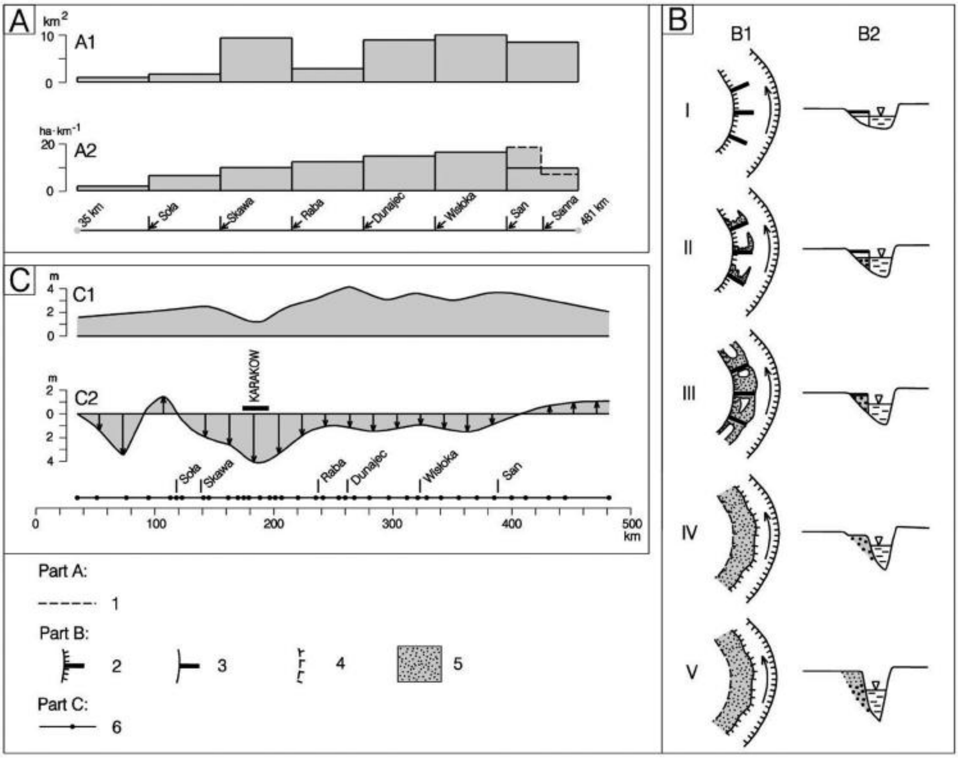

Fig. 9. Erosion and accumulation consequences of regulation works along the study section of the Vistula river. A – surface of the „new" floodplain which developed in river sections between the confluences of large Carpathian tributaries and expressed in: A1 – [km^2], A2 – [ha·km^{-1}]. Schematic presentation of the location of the confluences of the Carpathian tributaries. B – filling of the inter-groyne basins with sediment and changes in river channel geometry (5 stages: I–V, explanations in the text, B1 – channel plan, B2 – channel cross-profile). Horizontal and vertical scale in the section of the river studied. This shows great variation therefore Figures B1 and B2 are presented without dimensions. C1 – differentiation of mean thickness of sediments deposited in the inter-groyne basins, C2 – vertical changes in the channel (deepening, shallowing) in relation to the state before the beginning of regulation works along the section of the Vistula studied. Changes outside the channel have been omitted. Below parts C1 and C2 lie the locations of gauging stations in the longitudinal profile of the river which delivered data to prepare the diagrams. The locations of these gauging stations and the location of the confluences of the Carpathian tributaries reflect their real location along the course of the Vistula. 1 – value A2 in respect of the subsections of the Vistula: confluence of the San – confluence of the Sanna, and confluence of the Sanna – Puławy, 2 – the Vistula banks before the beginning of the regulation works, and after sediment infill in the zone with inter-groyne basins, 3 – groyne constructions, 4 – less and less visible convex edge of the meander overlain with sediments, 5 – sedimentsfilling the inter-groyne basins (for more information see Figure 7), 6 – location of hydrological gauging stations

the channel deepening (Łajczak 1999, 2003). The retention of sediment by the large shallow reservoir and by low dams on the Vistula is at a minimum throughout the period of their operation. The deepening of the Vistula channel has caused horizontal stabilisation of the river (Łajczak 1995b, 1999).

ACCUMULATION IN THE CHANNEL AND ON THE FLOODPLAIN SINCE THE BEGINNING OF REGULATION WORKS

The deepening of the channel of the course of the Vistula that was examined, which was initiated by regulation works, is connected with the sediment filling in inter-groyne basins along the river banks, which results in an increase of the floodplain area at the expense of a narrowing of the channel. The increase in floodplain area is shown in each section of the river between the confluences of the main Carpathian tributaries in [km^2], and also in hectares on each kilometre of the river course [$ha \cdot km^{-1}$] (Fig. 9 A1–A2). The latter of these two values shows the increasing area of "newly developed" floodplain along the river course, but only within the boundaries of the Subcarpathian Basins. In the water gap across the Polish Uplands, this value rapidly decreases. In the section of the course of the Vistula studied, the newly developed floodplain covers an area of 42.72 km^2, which means that for each 1 km of river course there is on average 9.6 ha of a "new" floodplain. In the section of the river from the San confluence to the beginning of the water gap (the Sanna river confluence), this value is twice as large.

Five stages in which sediment fills the inter-groyne basins (Fig. 9B) have been distinguished: in the stages 1–3 these basins are filled with channel deposits, stage 4 starts when groyne structures are covered with overbank sediments and stage 5 starts when the edge of the original channel bank becomes disguised by these sediments. The rate of filling of inter-groyne basins with these sediments depends on the rate of sediment transportation in the river. Indirectly, this process depends on the sediment supply from tributaries, and also on the amount of sediments originating from the deepening of the river channel. In turn, the rate at which sediment fills inter-groyne basins is also a function of time since the beginning of regulation works. Therefore the sediment thickness in these zones of the original channel is largest downstream of the confluences of the Carpathian tributaries, and also in the sections of the river where regulation works first started (it exceeds 2–3 m) (Fig. 9C1). The following regularity was noticed: the largest thickness of sediments in the inter-groyne basins was found in river sections located about 70 km downstream from the most deepened sections of the channel. The same situation occurs downstream of the Dunajec and Wisłoka confluences (Fig. 9 C1–C2). This value may indicate the maximum length of transport of large sediment loads, which in the conditions of an overloaded river accumulates in the bank zones of the channel and on the floodplain between the flood control embankments. Such regularity was not found in the Vistula downstream of the San confluence which may be explained by less intensive river regulation in the water gap across the Polish Uplands.

Accumulation of overbank sediments also takes place on the whole width of the floodplain within the inter-embankment zone. Two strips of depression at the base of the flood control embankment (from where material was taken to build the levees) were totally filled with sediments. Taking into account the increasing height of flood control embankment (along the course of the river) from 4 m to 7 m, the width of each of the depressions (with a depth of probably at least 0.5 m) must have been from about 80 m to 200 m. The total width of both depressions could have contributed from 25% to 80% of the total width of the floodplain within the inter-embankment zone. At present these depressions are filled with sediments up to the level of floodplain outside of the flood control embankments, or sometimes even higher (in isolated cases by up to 2 m, for example upstream of the confluence of the Soła with the Vistula).

Overbank sediments also build up natural levees which are usually not higher than 1 m and their width increases along the river course from about 50 m to 200 m; these forms enter the former depressions filled with sediments. Only in the Oświęcim Basin, upstream of the Soła confluence, 2 m high levees locally developed, which indicates that overbank sediments covered military constructions built in Summer 1944 on the left bank of the river (site X12 – at Nowy Bieruń, Łajczak 1999). The source of sediment which is building the levee is the deepened channel of the Vistula (before the creation of the Goczałkowice Reservoir). Such a large increase in the height of the levee is also conditioned by channel shallowing in sections "d–e" (see Fig. 9C2).

OVERBANK ACCUMULATION OUTSIDE THE FLOOD CONTROL EMBANKMENTS

Overbank accumulation outside the flood control embankments occurred quite frequently until the period 1930–1970 when the construction of embankments was completed. At that time large areas of the Vistula floodplain were flooded during catastrophic floods (for example in July 1934, 1960, 1970). Even in May and June 2010 such events occurred, but locally. The Vistula cut-off meanders that existed at the turn of the 18th and 19th centuries only became filled with the sediments in the 20th century to quite a small extent. On a very local scale, a large intensity of overbank accumulation occurred outside the flood control embankments when the structures were damaged by flood water (Gębica, Sokołowski 1999, 2001). In such places, the thickness of sediments in the oxbow-lakes exceeded 1 m.

CHANGES IN THE YIELD OF SUSPENDED SEDIMENT IN THE PERIOD 1946–1995

Since 1946 the rate of overbank accumulation within the inter-embankment zone of the fore-Carpathian course of the Vistula started to rapidly decrease as a result of beneficial changes in land use in the montane part of the drainage basin, an increase in the number of deep reservoirs retained behind dams on Carpathian tributaries which efficiently reduced the load of transported sediment, and also the decreased rate of channel deepening on the Vistula. At that time the supply of coal-dust from coal mines to the Vistula (upstream of the Soła confluence) started to decrease (Rutkowski 1986; Łajczak 2012b). The decreasing quantity of overbank accumulation is expressed in the size of losses of suspended sediment transport in successive 5-year periods in 1946–1995 in the individual balance stretches of the Vistula. These stretches of the river are delimited by successive gauging stations which monitor the suspended sediment concentration in the water. For comparative purposes the rate of decline in transport was shown in tons per kilometre of course of the river per year [tons$\cdot$km$^{-1}\cdot$y^{-1}] (Fig. 10A). The largest reduction in suspended sediment transport was found in a balance section of the Vistula with the largest Carpathian tributary – the San river. The trend of change (Fig. 10A) shows that the decrease in overbank accumulation rates within the inter-embankment zone of the Vistula has continued after 1995.

The mean values of losses in transport of suspended sediment in individual balance sections of the river in the period 1949–1995 related to the area of the floodplain within the inter-embankment zone and expressed in [tons$\cdot$ha$^{-1}\cdot$y^{-1}], reveals an increasing trend downstream as far as the beginning of the water gap across the Polish Uplands where it rapidly decreases (Fig. 10B). The rapid reduction in losses in the transport expressed in [tons$\cdot$ha$^{-1}\cdot$y^{-1}] in the gap section of the Vistula is attributable to the minimal supply of suspended sediment by tributaries compared to the upper reaches of the river. One notable stretch is the floodplain section directly downstream of the San confluence, where losses in suspended sediment transport are the greatest seen in the section of the Vistula examined. The trend indicated correlates with the rate of increase in area of the floodplain within the inter-embankment zone, expressed in [ha$\cdot$km^{-1}], which has occurred since the second half of the 19th century (see Fig. 9A2).

OVERBANK ACCUMULATION VERSUS INUNDATION OF THE INTER-EMBANKMENT ZONE

Values which describe the inundation of the inter-embankment zone, IN1 and IN2 (Fig. 11), partly explain the differentiation of the rates of overbank

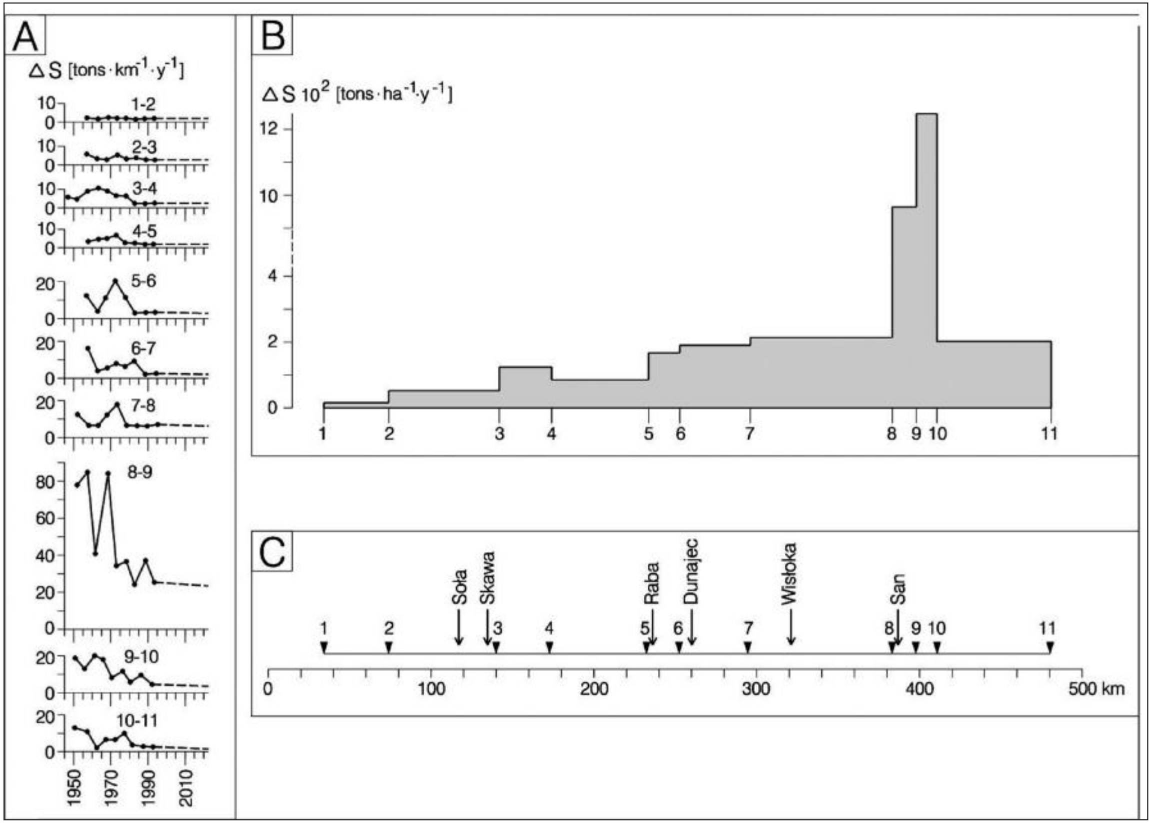

Fig. 10. Rates of accumulation of suspended sediment ΔS along the section of the Vistula analysed (in years 1946–1995). No data after 1995, the trend of changes in ΔS in years is indicated. A – mean 5-year rates of suspended sediment accumulation in the successive balance sections of the river (based on Łajczak 1999, 2003), B – mean rates of suspended sediment accumulation in the successive balance sections of the river, C – gauging stations with controlled concentration of suspended sediment. The gauging stations mark the balance stretches of the river. The locations of the confluences of the Carpathian tributaries are shown

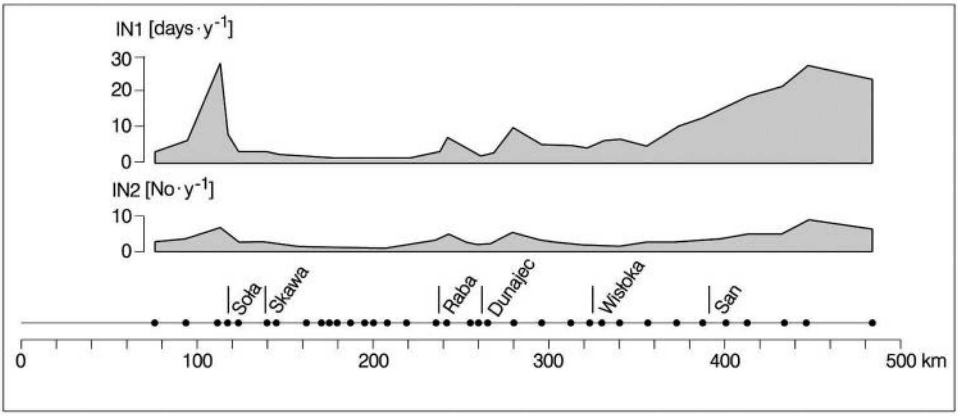

Fig. 11. Differentiation of the combined duration of the inundation of the inter-embankment zone (IN1) and the number of flooding events per year in the zone (IN2) along the section of the Vistula examined. The location of the gauging stations which delivered data for the calculations is shown as well as the location of the confluences of the Carpathian tributaries

accumulation in the longitudinal profile of the section of the Vistula floodplain examined (see Fig. 10B). The highest values of IN1 and IN2 were found in the sections of channel that had become shallowest and the lowest values occurred in the sections of channel which had been most deepened (compare Fig. 11 and Fig. 9C2). Carpathian tributaries only contribute to the increase of IN1 and IN2 values to a slight extent, but on the other hand they determine the rate of supply of suspended sediment load to the Vistula. That is to say, the rate of overbank accumulation within the inter-embankment zone of the Vistula is more influenced by the rate of supply of suspended sediment load by tributaries than the time when the whole inter-embankment zone is covered by flood waters. This relationship is particularly visible in the short section of the Vistula floodplain downstream of the San confluence (this tributary supplies the Vistula with the largest amounts of suspended sediment load) where the overbank accumulation reaches the highest value in all of the Vistula section studied (Fig. 10B). This remark may be confirmed by the information given in section "a. Evolution... ", according to which the cut-off meanders of the Vistula directly downstream the mouth of the San river get filled with sediment at the fastest rate. However, IN1 and IN2 reach their maximum value downstream in the water gap through the Polish Uplands (Łajczak 2007), which is explainable by the shallowing of the channel along this stretch of the Vistula (see Figs 9C2, 10B, 11).

DISCUSSION

As compared to similar works (Starkel 1987a, 2001b, 2014; Starkel et al. 1996; Łajczak 1999; Łajczak et al. 2006) the results of this investigation enable the Author to analyse in detail changes in the rate of overbank accumulation that have occurred in recent centuries in the section of the Vistula floodplain examined. Based on a broad spectrum of data from different sources as well as on the Author's long-term fieldwork it was possible to show a large differentiation of overbank accumulation (limited to the floodplain within the inter-embankment zone) along the course of the Vistula, especially between the confluences of large Carpathian tributaries (Figs 9A2, 10B).

The picture of changes in overbank accumulation rates in recent centuries (generalised for the whole section of the Vistula examined) includes elements of human impact which were not considered before. The course of overbank accumulation rates (OA) shown in Figure 12A covers two periods: an earlier one with a lower intensity of accumulation and concerning the entire area of the floodplain, and a still continuing period which started in the late 19th century, when works on flood control embankments commenced and were completed along the entire course of the Vistula examined in this study. For over 100 years, overbank accumulation has been limited to a narrow inter-embankment zone, therefore initially (until the mid-20th century) rates of overbank accumulation reached the highest values in the entire period analysed, which was caused, inter alia, by a large supply of material from the deepened channel. From the mid-20th century suspended sediment loads in the Vistula began to decline, which resulted in decreasing rates of overbank accumulation. Taking into account the effects of the Vistula regulation allows us to answer the question of why the course of overbank accumulation rates (OA) shown in Figure 12A can be considered as currently the most plausible one. However, the general trend of OA changes is convergent with the models previously presented.

So far, the increase in the rate of overbank accumulation which occurred over several centuries in the section of the Vistula floodplain being researched was explained by deforestation of the drainage basin (especially within the Carpathians) and agricultural use of this area. However, overbank accumulation intensified after the beginning of regulation works on the Vistula and its tributaries (especially the Carpathian ones) and reached its maximum in the 1930s–1940s (Fig. 12A). This is evidenced from comparative analysis of archival maps from the last 250 years. The same conclusion is also presented in other publications by the Author based on an analysis of repeated levelling measurements in gauging stations of the State Hydrological Survey which were carried out from the beginning of the 20th century (Łajczak

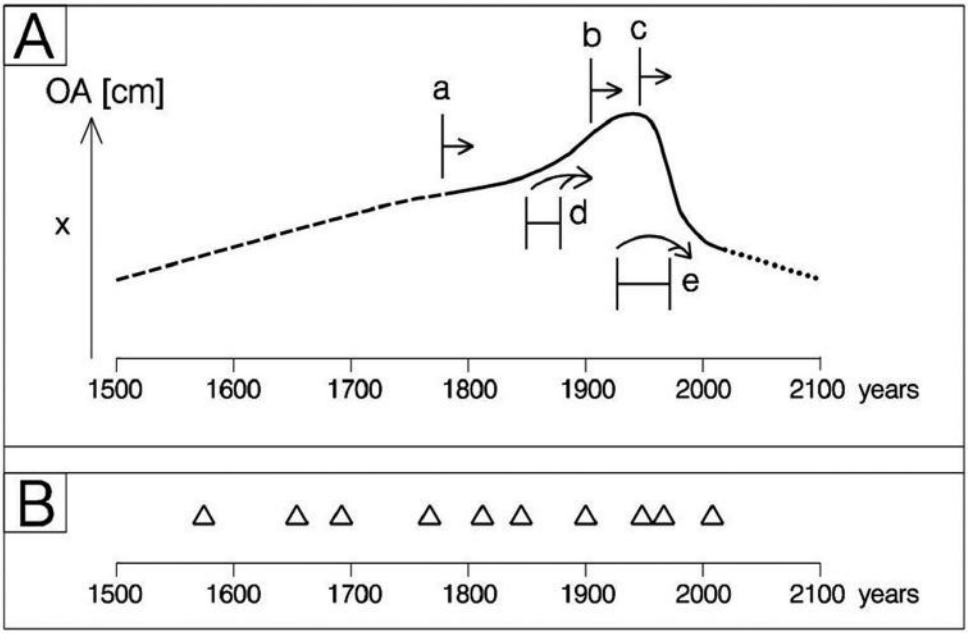

Fig. 12. Probable long-term changes in overbank accumulation rates, OA, within the section of the Vistula examined. A – relative changes of OA (proposed units: [cm], scale not quantified), B – periods when condensing occurred during catastrophic floods (clustering effect). The rules for determining periods with a clustering effect are explained in chapter – Materials and Methods. Non-continuous line – possible changes of OA, dotted line– prediction of OA changes, continuous line – changes of OA based on: a – maps, b – levelling measurements, c – balance of transport of suspended sediment. d – start of work on river embankments, e – end of work on river embankments. In the case of data b, the Author took into account information from previous publications (Łajczak 1995b, 1999)

1995b, 1999). These sources of information evidencing changes which occurred before and after regulation works include: changes in the course of the Vistula channel, changes of the rate of oxbow lake decay and their filling in with sediments, changes in the cross-section of the channel, and changes in the increase of overbank sediments. The acceleration of the overbank accumulation rate which has occurred since the second part of the 19th century resulted from the deepening of the Vistula channel and the lower sections of the Carpathian tributaries (as a consequence of river regulation). This resulted in the fact that more suspended sediment was delivered to rivers (Łajczak 1999, 2003). Another cause of the increased overbank accumulation was narrowing of the geomorphologically active floodplain into the inter-embankment zone.

Since the 1950s, a rapid decrease in the overbank accumulation rates (OA) on the floodplain has been recorded based on calculations of the transport balance of the suspended sediment load. Since the 1980s–1990s this decrease has been slowing down (Fig. 10A). The main causes of the decrease of OA rates include: (1) the retention of the majority of the suspended sediment load by deep reservoirs retained behind dams on the Carpathian tributaries of the Vistula, (2) beneficial changes in land use in the Carpathian part of the Vistula drainage basin (increase of reforestation, decrease of arable land and disuse of large sections of roads on slopes). The decrease of overbank accumulation rates which has occurred over the last 70 years is regarded as faster than the increase of its rates before the 1950s. In the coming years, a slower and slower decrease of OA rates is expected to take into account the lack of new deep reservoirs in the drainage basin, progressive stabilisation of land use, and a slowing down of the rate of deepening of the Vistula channel.

The scheme here presented shows relative changes of OA related to the whole section of the Vistula floodplain under study (which is why the vertical axis is not expressed). In the individual parts of the floodplain (within the Oświęcim Basin, Sandomierz Basin, water gap across the Polish Uplands), the course of changes of OA showed local variation. This is explainable by the fact that the effects of the regulation of the Vistula river and its tributaries, as well as the impacts of changes in land use in the basin, started to be conspicuous at different times.

The contemporary trend of decreasing rates of overbank accumulation is entirely determined by human impact because successive clusterings of catastrophic floods on the Vistula in the period since the end of the 18th century were separated by time spans of similar length: 20–40 years, 35 years on average (Łajczak 2009, 2012a) (Fig. 12B). It must be stressed that signatures in Figure 12B do not show individual large floods, but only the time intervals within which such events with the highest intensity are grouped. The findings are corroborated by those by A.K. Bielański (1984) on the history of floods (19th–20th c.) in the Upper Vistula catchment. If such a trend in the occurrence of clustering of floods is regarded as constant, considerably decreased overbank accumulation rates are expected in the coming decades in the section of the Vistula floodplain studied as compared to the rate of OA from the mid-20th century.

The course of changes in the overbank accumulation rates in the study section of the Vistula floodplain which is presented here is convergent with the results of research by S.W. Trimble (1981), K.J. Gregory (1987), C.J. Knox (2006) and M.G. Macklin and J.L. Lewin (2010) concerning the response of rivers of different sizes to urbanisation in a drainage basin, especially to channel regulation. As noted by M.G. Wolman (1967), the short-time period of increased transport and deposition of clastic material due to earth works in small rivers flowing across urbanised areas followed by the period with rapid decrease of its rate due to the building up of the area, may be recognised as analogous to changes documented in the Vistula valley over the last 170 years. Increasing of the overbank accumulation rates, as a result of the deforestation of the drainage catchment, are accompanied by an increase in the size of the sediment`s granularity (Klimek 1987; Pożaryski, Kalicki 1995; Kalicki 2006; Szmańda 2018). An increasing trend in potential overbank accumulation rates along the fore-montane course of the Vistula river, can be compared with other large Carpathian rivers – the Tisa and the Siret (Łajczak 1989). However, the rates of potential overbank accumulation in the inter-embankment zone of the Vistula are several times smaller than in the rivers indicated above.

CONCLUSIONS

Before the beginning of regulation works, the wide zone of the Vistula floodplain in the Carpathian Foreland acted as a place of accumulation of sediment transported in suspension and delivered to the Vistula mainly by its Carpathian tributaries. Including the vast alluvial fans of these tributaries, the width of this zone locally reached 20 km (Fig. 1C). From the end of the 19th century, due to building of flood control embankments and the development of the inter-embankment zone, the area of accumulation of sediment transported in suspension has narrowed to several hundred metres. Moreover, the rate of overbank accumulation expressed in [tons·ha^{-1}·y^{-1}] showed an increasing trend in the second part of the 20th century along the river course, but only up to a short stretch of floodplain downstream of the San confluence (the last Carpathian tributary), where the mean rate of suspended sediment accumulation reaches 1200 tons·ha^{-1}·y^{-1}. Downstream, along the water gap across the Polish Uplands, the rates of suspended sediment accumulation rapidly decrease to a level typical of the Vistula floodplain in the Sandomierz Basin (Fig. 10B). The lowest part of the floodplain of the Vistula within the Sandomierz Basin (directly below the mouth of the San river) was, both before and after the regulation of the river, the place of the highest intensity of overbank accumulation. This is evidenced by the most advanced filling of cut-off meanders in this section of the Vistula floodplain, as well as by the losses in suspended sediment transport being greatest in the present day.

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