Transport of suspended sediment by the Vistula River basin upstream of Kraków, southern Poland, and the human impact during the second half of the 20th century

ADAM ŁAJCZAK

Jan Kochanowski University, Institute of Geography, ul. Świętokrzyska 15, 25-406 Kielce, Poland

alajczak@o2.pl

Abstract The upper part of the Vistula River basin, upstream of the city of Kraków (7524 km^2), southern Poland, represents an area where human activity has had a major impact on the rate and long-term trend of suspended sediment transport by rivers. During the 1950s and 1960s, the studied stretch of the Vistula River received increasing volumes of wastewater from industrialised and urbanised areas, primarily via its tributary the River Przemsza, which runs through the Upper Silesian Industrial Basin. These inputs subsequently reduced. At the same time, the transport of suspended sediment by other tributaries was declining due to reforestation and construction of new dams. Below the confluence of its three largest tributaries, the main river becomes overloaded with suspended sediment, largely of anthropogenic origin, and this rapidly accumulates within the embanked zone, especially along the two reaches where the river level is raised by several metres, due to impoundment.

Key words suspended sediment; sediment loads; human impact; Upper Vistula River basin; southern Poland

INTRODUCTION

The rate of suspended sediment transport may vary in similar river draining catchments with similar environmental characteristics, but affected by varying degrees of human impact. Changes in the degree of human impact can alter the suspended sediment loads of rivers quite significantly over the course of as little as a few years. Longer-term changes in suspended sediment transport in rivers affected by human impact reflect not only changes in hydrological and climatic conditions, but also changes in local land use. Research on the impact of human activity on the intensity of fluvial processes has been undertaken since the 1950s in many countries around the world (e.g. Wolman, 1967; Walling, 1974; Keown *et al*., 1986; Weiss, 1996; Łajczak, 1999, 2003). In Poland, the largest changes in suspended sediment transport due to human impact took place during the 20th century in the catchment of the Vistula River, upstream of the city of Kraków. This region of Poland is largely urban and industrial. However, the intensity of human impact varies significantly across the area and has changed substantially over the years. This has affected the suspended sediment transport regime of the rivers of this region. This conclusion is based on analysis of data on suspended solids concentrations provided by Poland's State Hydrological Survey. The data cover the second half of the 20th century. The purpose of this paper is to investigate suspended sediment transport in the Vistula upstream of Kraków. The paper looks at changes in the suspended sediment loads, both along the course of the river, as well as over time. The background for this paper is the transport of suspended sediment in tributaries flowing across the main morphological units of a study area with diverse land use.

STUDY AREA

The part of the catchment of the Vistula River which provides the focus of this study covers an area of 7524 km^2. This catchment area includes the Western Flysch Carpathians (Beskidy Mountains), the eastern part of the Silesian Upland, the Oświęcim Basin as well as some parts of the Carpathian Foreland and the Kraków Upland (Fig. 1). The elevation of the catchment ranges from 201 m to 1725 m. The Vistula River between its source and Kraków is 167 km long. The river is joined by two large mountain tributaries (the Soła and Skawa rivers) and by one large upland tributary (the Przemsza River). The mean discharge of the Vistula across the study area

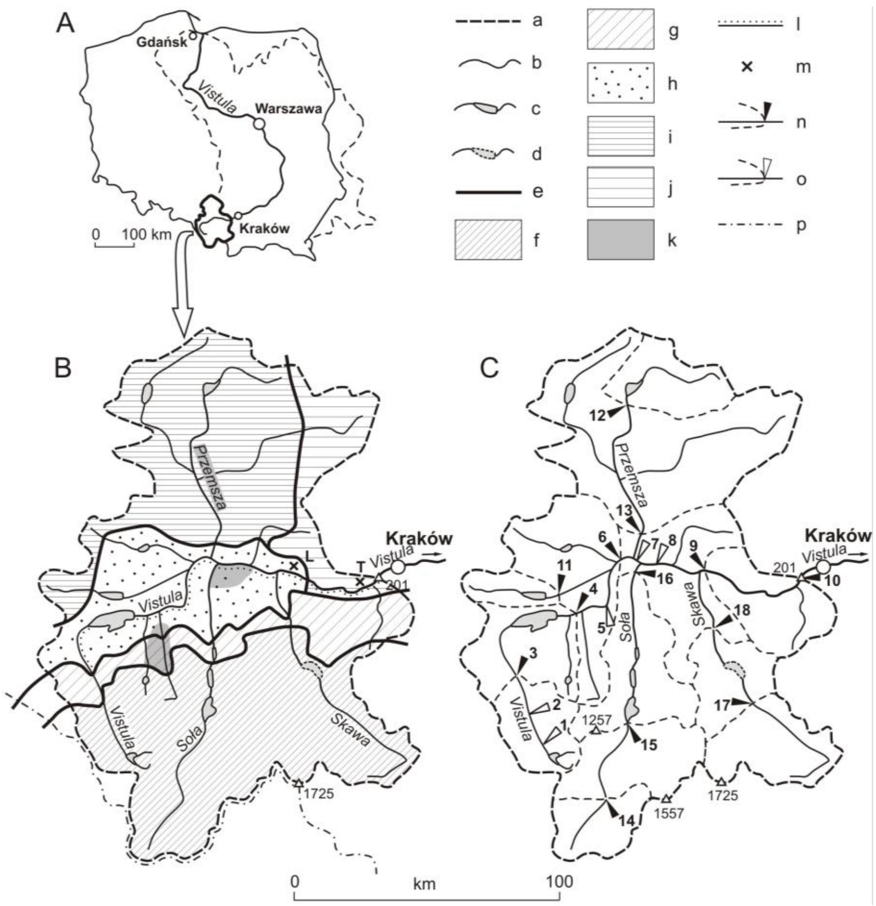

Fig. 1 The study area: A, the location of the Vistula drainage basin upstream of Kraków (marked by thick fat line) and the overall Vistula drainage basin; B, the geomorphological units; C, the location of suspended solids sampling sites. Key: a, boundary of the drainage basin; b, main rivers; c, operational reservoirs; d, reservoirs under construction; e, boundaries of geomorphological regions; f, Beskidy Mountains; g, Carpathian Foothills; h, Oświęcim Basin; i, Silesian Upland; j, Kraków Upland; k, mostly urban and industrial areas; l, deepened Vistula River channel just north of the Carpathian Mountains; m, largest weirs on the Vistula (Łączany, Tyniec); n, catchment area and suspended sediment sampling sites operated by the Polish State Hydrological Survey; o, other water measurement sites operated by the State Hydrological Survey; p, national border.

increases in a stepwise manner, reaching 100 $m^3 s^{-1}$ in Kraków. Within the study area, the most favourable conditions for the transport of fine weathered sediment in suspension are found in the Beskidy Mountains, the Carpathian Foreland and the loess uplands. The least favourable conditions are found in areas underlain by carbonate rocks and partially covered with Quaternary sands. The study area features a number of man-made lakes or reservoirs of varying size created in 1932–1973. These reservoirs affect the amount of suspended sediment flowing down the individual rivers and reduce the suspended sediment loads (Łajczak, 1999). Conversely, the input of suspended sediment into the Vistula from generally low-output sources such as the uplands underlain by carbonate rock has been increased by the addition of fine-grained waste products associated with coal mines, industrial facilities and municipal wastewater. This situation is primarily found in the Przemsza River, which drains the Silesian Upland region. This input of wastewater has been taking place since the 18th century, but it has declined since the 1970s. The quantity of wastewater entering the Vistula and its tributaries further declined, especially after 1990, when Poland's heavy industry began to restructure its operations (Łajczak, 1999). Another source of suspended sediment entering the Vistula is associated with the river channel regulation, which started in the late 19th and early 20th centuries (Łajczak, 1995). The deepening of the Vistula channel along some sections of the river in the Oświęcim Basin ceased by the 1970s. Some of the suspended sediment transported down the river is intercepted by dams and other man-made features. Large quantities of suspended sediment are trapped by the Goczałkowicki Reservoir Dam as well as upstream of weirs located at Łączany and Tyniec (Łajczak, 1995).

Measurements of suspended sediment concentration in the Vistula River within the study area were made by the Polish State Hydrological Survey between 1946 and the 1990s. Similar measurements were initiated in the tributaries of interest during the 1950s and 1960s. Measurements upstream of Kraków were made at five gauging stations. Measurements on the four largest tributaries were made at eight gauging stations (Fig. 1). In 1995 most of the gauging stations ceased to collect data on suspended sediment concentrations. The various sub-catchments where suspended sediment transport has been gauged, represent all of the geomorphological regions of the portion of the Vistula's catchment under investigation. Each sub-catchment also varies in terms of the degree of human impact.

CALCULATION METHODS

The paper is based on annual values of suspended sediment load *R* (t year^{-1}), estimated by the author on the basis of data obtained from the State Hydrological Survey. The following data were available for all suspended sediment sampling sites in the study area: instantaneous suspended solids concentration *P* (g m^{-3}) measured at 07:00 h daily during high and medium flows and every 3–5 days during low flows at the same point in the river, and the discharge *Q* (m^3 s^{-1}) at the time of sampling. By interpolating the concentration data obtained for periods of low flow, a continuous record of daily *P* values was reconstructed for each site. Values of annual sediment load were obtained by combining the records of daily *P* and *Q* values for each year. Summation and averaging of the annual load estimates provides an estimate of the mean annual load. An empirical correction factor *k* was used to take account of the difference between the suspended sediment concentration measured at the single sampling point and the mean concentration in the cross section. The *k* values were established by the State Hydrological Survey for each site, based on periodic field sampling.

RESULTS

Mean annual suspended sediment loads at gauging stations along the tributaries of the Vistula River

The mean annual suspended sediment loads *Rm* of the tributaries range from 2600 to 220 000 t year^{-1} (Fig. 2). On tributaries without dams, *Rm* increases downstream. On tributaries with dams, *Rm* decreases downstream of each dam. Maximum values of *Rm* are found in the middle reaches of the large mountain rivers such as the Soła and the Skawa. Further downstream, *Rm* decreases. This situation also occurs in the downstream section of the Przemsza River, which flows across industrial and urban areas. In contrast, the Vistula River transports six times less suspended sediment (35 000 t year^{-1}) within its Flysch Carpathian reach. The same is true of the Soła River downstream of three reservoirs (30 000 t year^{-1}).

Mean annual suspended sediment loads at gauging stations along the study reach of the Vistula River

A simplified representation of the mean annual suspended sediment loads for different gauging stations along the Vistula River up to the Kraków gauging station does not reflect the continuous downstream increase of catchment size and mean river discharge (Figs 2 and 3). This suggests that human impact is a key driver. The present day variation of the suspended sediment load along the study reach of the Vistula River can be explained in terms of: (a) increased runoff from partially deforested areas and agricultural areas primarily along the Soła and Skawa rivers, (b) input of man-made waste materials from urban and industrial areas primarily along the Przemsza River,

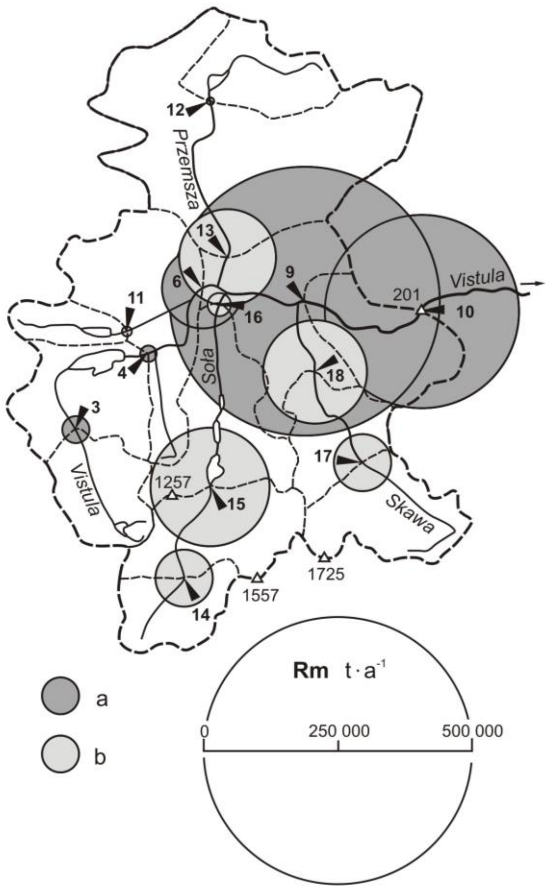

Fig. 2 Mean rate of suspended sediment transport *Rm* (t year^{-1}) at gauging stations in the study area: a, along the Vistula; b, along its tributaries. Gauging stations are numbered as in Fig. 1.

(c) input of suspended sediment due to ongoing dredging in the piedmont section of the Vistula River, (d) local reduction in suspended sediment supply to the Vistula River and its tributaries downstream of dams. The suspended sediment load reduces downstream of the small Wisła-Czarne Reservoir along the uppermost section of the Vistula River. However, this reduction is so small that it can be omitted from further analysis. Further downstream, the Vistula still flows through mountainous terrain and is joined by a number of tributaries. This leads to an increase in the suspended sediment load, which reaches 35 000 t year^{-1} near the town of Skoczów at the edge of the Carpathians. Further downstream, the large Goczałkowice Reservoir causes a major reduction in the rate of suspended sediment transport in the Vistula. The rate of transport increases again downstream, as large tributaries join the Vistula and deliver new inputs of suspended matter. Some of the new sediment comes from human impact in the Przemsza River catchment. The mean annual suspended sediment load increases from 35 000 t year^{-1} at Skoczów to about 500 000 t year^{-1} at Smolice. This is a distance of about 100 km. The main reason behind this spectacular increase in suspended sediment load is the influx of about 250 000 t year^{-1} of sediment from large mountain tributaries such as the Skawa (200 000 t year^{-1}) and another 180 000 t year^{-1} from the Przemsza River. The study period includes years when suspended sediment influx from the Soła River was reduced due to the construction of dams on the Soła.

The influx of suspended sediment supplied by the tributaries of the Vistula exceeds the suspended sediment load passing the Smolice gauging station by 20%, which suggests that a very large quantity is lost due to deposition across the floodplain. The mean annual suspended sediment load decreases by almost 30% further downstream and is 360 000 t year^{-1} at the Kraków gauging station. This suggests that sedimentation is taking place along this stretch of the Vistula. The

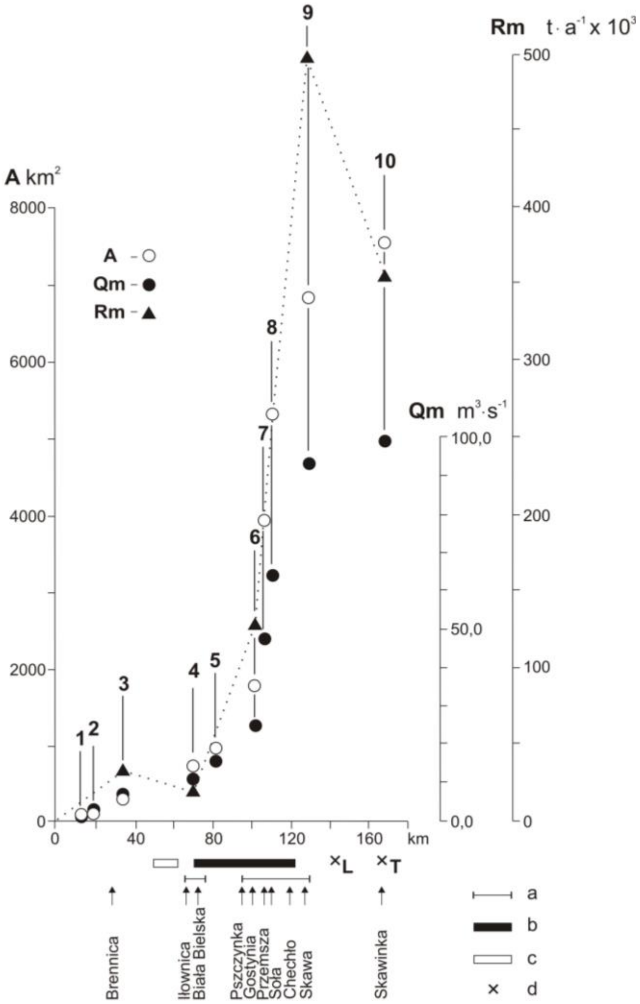

Fig. 3 Mean annual suspended sediment load *Rm*, mean discharge *Qm* and catchment area *A* at successive gauging stations along the study reach of the Vistula. The mouth of each large tributary is marked. Key: a, network nodes; b, section of river with the highest concentration of suspended sediment produced by human impact from industrial and urban areas; c, section of river with reverse water flow due to the Goczałkowice Reservoir; d, Łączany and Tyniec weirs. Gauging stations are numbered as in Fig. 1.

sedimentation largely takes place upstream of the Łączany weir, i.e. downstream of the confluence of the largest tributaries of the Vistula. Significant sedimentation is common all along the study reach of the Vistula and is mainly related to human impact.

Loss of suspended sediment along the study reach of the Vistula

The magnitude of the suspended sediment load recorded at a given gauging station on a river represents the difference between the total input of suspended sediment to the river by all tributaries and the quantity of suspended sediment deposited upstream of the given gauging station. The total quantity of suspended sediment entering a river can be represented by the sediment influx curve or hypothetical transport curve and is stair-shaped (Fig. 4). The actual curve of suspended sediment transport shows *Rm* (t year^{-1}) values for the study reach of the river (Fig. 4). The curve can be shown in simplified and adjusted forms (Łajczak, 2003). On the diagram, the area between the hypothetical transport curve and the adjusted actual transport curve represents the loss of sediment along the course of the river. Large scale losses can be observed downstream of the Goczałkowice Reservoir, and especially downstream of the Smolice gauging station. This large loss of suspended sediment is caused by human impact and results from increased sediment input

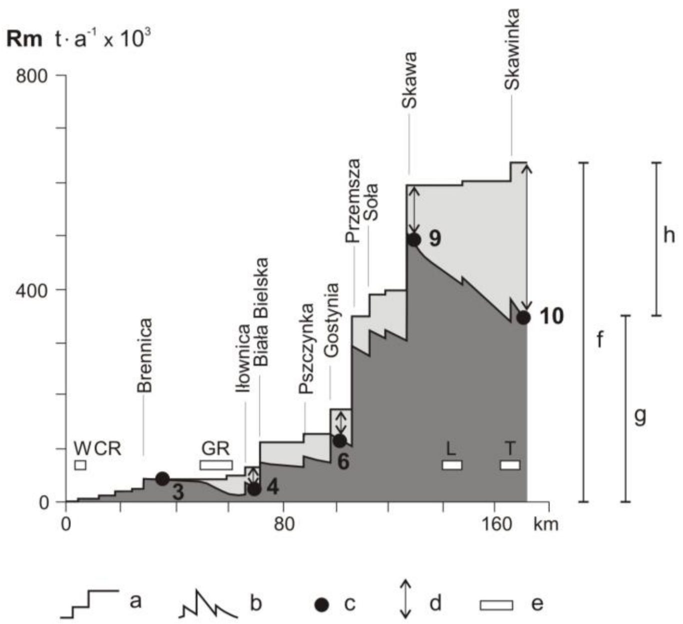

Fig. 4 Mean annual suspended sediment load and loss of suspended sediment along the study reach of the Vistula River. Key: a, sediment influx curve; b, adjusted form of actual curve of sediment transport; c, mean annual suspended sediment load at gauging stations (numbering as previously); d, difference between the potential and actual rates of suspended sediment transport at successive gauging stations; e, location of dams and weirs (WCR, Wisła-Czarne Reservoir; GR, Goczałkowice Reservoir; L, Łączany Weir; T, Tyniec Weir); f, mean annual total suspended sediment input by tributaries to the Vistula; g, suspended sediment load of the Vistula; h, total loss of suspended sediment upstream of Kraków.

from partially deforested mountain catchments and inflow of wastewater from urban and industrial areas and the trapping of suspended sediment by dams. The recent alluvium in the Vistula valley is highly polluted and contains large quantities of coal dust (Klimek, 1988).

Long-term changes in suspended sediment transport

The suspended sediment load for the most upstream reach of the Vistula as well as for the Soła and the Skawa rivers has tended to decrease since the 1950s. This is due to human impact (Fig. 5) and it reflects the situation throughout the Vistula drainage basin, where suspended sediment loads are decreasing independently of long-term fluctuations in river discharge (Łajczak, 1999). The main reasons for the decrease is the reduced input of suspended sediment from mountain tributaries of the Vistula where the forest cover is increasing, larger areas are covered by meadows, and arable cultivation is declining. At the same time, unmetalled roads on mountain slopes are being used less frequently. Unmetalled roads used to be a key source of fine-grained sediment that would be transferred to river channels.

The input of suspended sediment to the Vistula from its mountain tributaries decreased substantially after the construction of new reservoirs, especially the deeper ones. The cumulative effect of the two large dams on the Soła River was a 10-fold decrease in the suspended sediment input by this river to the Vistula River. As the amount of sediment deposited in the reservoirs increased, their trap efficiency was reduced, particularly during periods with frequent large floods (Łajczak, 1996, 1999).

Changes in suspended sediment transport by the Vistula River, downstream of its confluence with the Przemsza River, demonstrate a complex trend. The suspended sediment load was relatively low before 1955 and after 1980, as recorded by the Smolice and Kraków gauging stations. A general downward trend can be observed. However, the downward trend was reversed between 1955 and 1980, with the occurrence of a period of increased suspended sediment transport. The increase reached 300% and can be linked to the rapid industrialization and

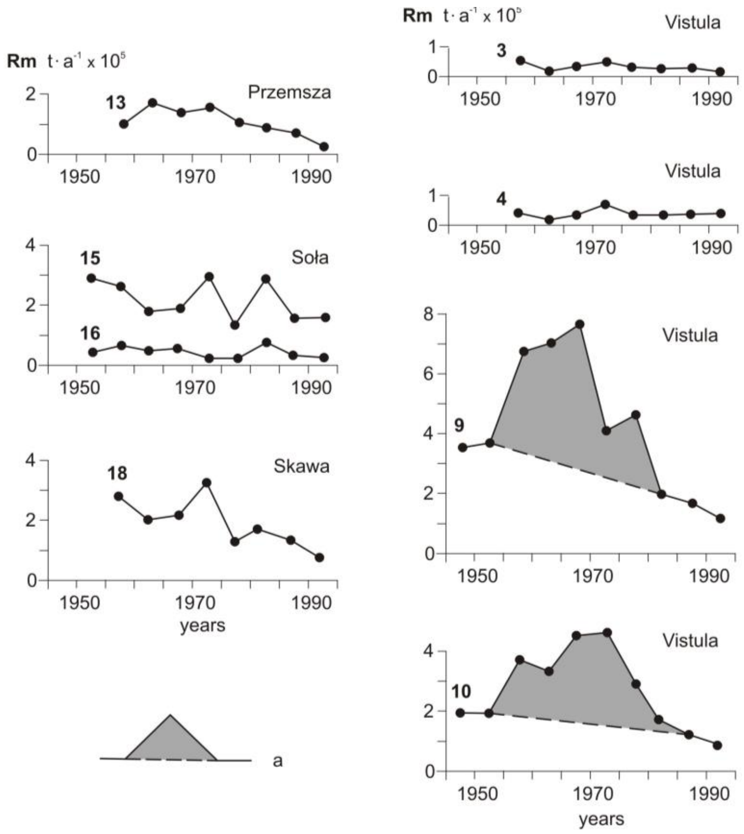

Fig. 5 Long-term changes in suspended sediment loads at selected gauging stations in the study area, as reflected by mean 5-year suspended sediment loads. The suspended sediment transport data collected at Smolice and Kraków has been used to estimate the sediment load associated with coal mine wastewater (a). Numbering system as previously.

urbanization of parts of the Vistula catchment in the Upper Silesian Industrial Region. The most important development in the region was the rapid expansion of the coal industry, which produced long-term changes in suspended sediment transport in the lower Przemsza River (Łajczak, 1999). Significant coal dust pollution has been detected in the Vistula via chemical analysis of 20th century alluvium (Klimek, 1988).

One of the key reasons for the decrease in the suspended sediment load at Smolice and Kraków before 1955 and after 1980 was the decrease in the rate of deepening of the channel of the Vistula River in the Oświęcim Basin, which had commenced in the 1940s. The decrease in suspended sediment transport was masked between 1955 and 1980 by the increased input of wastewater to the river. The Vistula channel deepening had begun in the late 19th and early 20th centuries as part of an overall effort to regulate the Vistula (Łajczak, 1995).

DISCUSSION AND CONCLUSIONS

In the period after the start of the Vistula River channelization, two phases, characterised by rapid changes in the suspended sediment load of the river, can be distinguished (Łajczak, 2003). An increase in the transport of suspended sediment in the Vistula River during the four decades after the initiation of the river regulation (1890s–1930s) was followed by a rapid decrease in suspended sediment loads, due primarily to the construction of dams and changes in land-use in the river basin. The suspended sediment loads of the mountain tributaries of the Vistula River in the study reach have decreased since the 1950s. Suspended sediment transport in the downstream section of the Przemsza River began to decline in the 1960s. The same was true of the Vistula River downstream of its confluence with the Przemsza, since about 1970. The rapid decrease of the suspended sediment load at Smolice and Kraków extended until the early 1980s. The decline subsequently continued, but at a slower pace and with fewer fluctuations (Łajczak, 1999). If this trend continues, the rate of sedimentation in reservoirs will decrease and the ecological state of the Vistula valley will improve. The sequence of changes shown by this study is similar to those reported by other studies of long-term changes in fluvial sediment transport and shown by the contemporary modelling of floodplains and river channels in other areas, particularly in response to the urbanization of catchments (e.g. Wolman, 1967; Walling, 1974). Similar causes for recent decreases in the suspended sediment loads of other rivers have been indicated by Winkley (1982), Keown *et al*. (1986), Kesel (1988), and Weiss (1996). The short period with increased suspended sediment load in rivers, as a result of construction work in the catchment area, identified by Wolman (1967), and the subsequent decrease in sediment load as a result of impoundments in the river basin, may be considered an analogue for the documented changes in sediment load documented in the study reach of the Vistula River, caused by human impact.

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