Erosion and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium, July 1996). IAHS Publ. no. 236, 1996.

Reservoir sedimentation problems in the Vistula River basin, Poland

ADAM LAJCZAK
Institute of Nature Conservation, Polish Academy of Sciences, Lubicz str. 46, 31-512 Cracow, Poland

Abstract Existing knowledge of the geometric and hydrological characteristics of existing and planned dam reservoirs in the Vistula River basin, Poland, and of the spatial differentiation of suspended sediment and bed load transport in the area provides a basis for proposing appropriate locations for planned reservoirs in the river basin. If the location and the order of building of the planned dams conform to these proposals, this will result in slow silting of the reservoirs with advantages both for the use of the river as a waterway and for maximizing the useful life of the reservoirs.

INTRODUCTION

The correct planning of the development multipurpose reservoir systems in large river basins, where the rivers are characterized by different hydrological regimes and different suspended sediment loads and bed load yields, presents an important problem for fluvial sedimentology. Estimation of the useful lifetime of reservoirs of very different initial geometric and hydrological characteristics, when their functions are fulfilled, must be a prelude to the correct location of planned structures. This time period, which has been estimated for every reservoir studied according to the concept proposed, should not be shorter than the amortization time of the reservoir. The above procedure can be undertaken if the following information is available:

(a) the average annual suspended sediment load and bed load as measured at successive gauging stations on the river and its tributaries over a suitable period of time;
(b) the initial geometric and hydrological characteristics of existing and planned reservoirs; and
(c) the initial trap efficiency for the suspended sediment load of every reservoir studied.

The aims of the paper are:

(a) to establish the present-day degree of silting of existing reservoirs and their spatial distribution within the Vistula River basin and, later, to critically assess their locations; and
(b) to propose appropriate locations for new reservoirs in the river basin to achieve the minimum silting of the reservoirs for possible dam building scenarios. A plan for the location and order of building of different types of new reservoir along the Vistula and its Carpathian tributaries will be proposed. In this plan the maximum reduction of both silting in the reservoirs along the whole course of the Vistula River and of sediment supply by the river to the Baltic Sea will be achieved.

BRIEF DESCRIPTION OF THE RIVER, ITS BASIN AND THE RESERVOIRS

The Vistula River is 1047 km long, its catchment area extends to 194 424 km^2. The mean discharge at the mouth is 1250 m^3 s^{-1}. The river and its major tributaries flow through numerous morphological units with very varied suspended sediment yields (Fig. 1). The Vistula transports large amounts of terrigenic material. The suspended sediment load constitutes *c.* 60-70% of the sediment load transported by the main river and *c.* 50-90% of that transported by its tributaries. Suspended sediment concentrations are recorded daily at 16 gauging stations on the Vistula and at 69 gauging stations in its drainage basin. The records started before the dams in the area were constructed, i.e. during the 1930s-1950s. Specific sediment yields range from less than 2 to almost 1000 t km^{-2} year^{-1} within sub-catchments with an area of about 500-1000 km^2. Sediment yields reach maximum values in the lower deforested parts of the Carpathian Mountains. The highest values of bed load transport in the Vistula River network are found in the lowland reach of the river (Branski *et al.*, 1980; Lajczak & Jansson, 1993; Lajczak, 1996a).

The suspended sediment load of the Vistula varies markedly along its course and increases sharply along the piedmont reach of the river. This is caused by the large

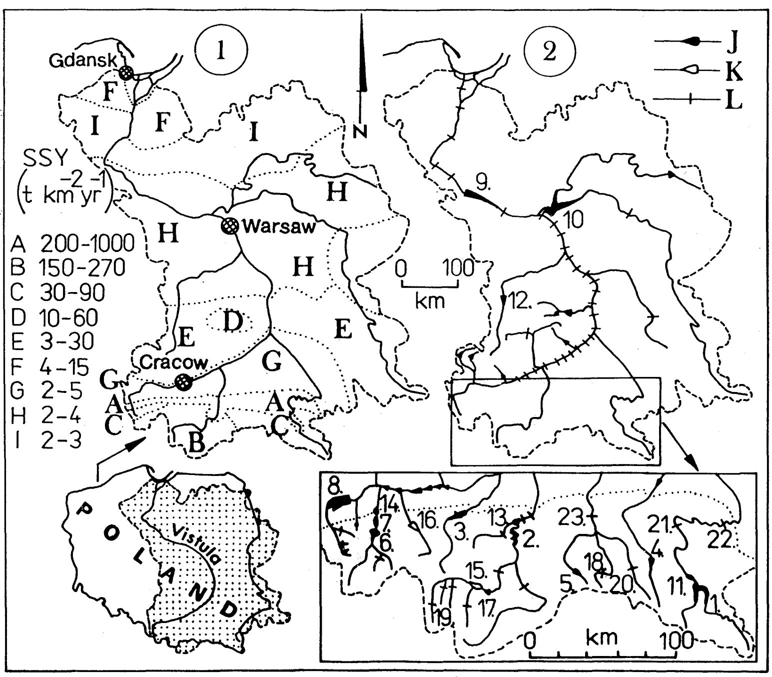

Fig. 1 Location map: 1 = typical values of suspended sediment yield, SSY, for the main morphological units within the Vistula River catchment basin (A, B, C = Carpathians; G = foreland of the Carpathians; D, E = middle Poland upland; F, H, I = Polish lowland); 2 = distribution of reservoirs in the river basin. Note the more detailed map for the Carpathian part of the river basin (reservoirs: J = existing, K = under construction, L = planned for the future). Numbered reservoirs are analysed in detail in the study.

supply of sediment from the Carpathian tributaries (Lajczak, 1995a). In the rivers studied, suspended sediment loads and bed load transport often decrease downstream of high dams as a result of the very intensive sedimentation processes operating in deep reservoirs with low water exchange (Branski, 1975, 1980; Lajczak, 1989, 1994).

The plans for the regulation of the Vistula and its tributaries have been changed many times since the beginning of the twentieth century. Different numbers of reservoirs with various geometric characteristics have been proposed in numerous programmes. The most recent programme, produced during the 1970s and named "The Vistula Program", now seems to be unrealizable and only some of the planned reservoirs will be finished during the next decades. Figure 1 shows the distribution of existing and planned reservoirs within the Vistula catchment basin. Most of the reservoirs are located on the Carpathian tributaries of the river. The reservoirs are multi-purpose and are used for flood protection, water retention and power generation (Jedrysik & Rusak, 1982).

Five types of reservoir can be identified within the study area:

(a) deep valley reservoirs in the Carpathians: permanently filled with water, with low water exchange:

(b) shallow valley reservoirs in the Carpathians: associated with deep valley reservoirs upstream (cascade system), occasionally flushed, with rapid water exchange;

(c) large and shallow lowland reservoirs: permanently filled with water, with rather low water exchange;

(d) shallow and narrow reservoirs along the Vistula: occasionally flushed, with very rapid water exchange; and

(e) small and shallow reservoirs and pools on numerous rivers and streams.

The reservoirs undergo silting by material supplied primarily by the rivers, especially suspended matter. Sandy material plays a more important role only in delta formation. The best conditions for suspended matter retention are in the deep reservoirs in the Carpathians. In contrast, the very rapid water exchange in the shallow reservoirs on the Vistula and the large Carpathian rivers reduces the effective sedimentation of suspended particles. The rate of water exchange in deep reservoirs increases with time as a result of the reservoirs becoming shallower. This trend is most pronounced in reservoirs receiving large amounts of terrigenic material (Lajczak, 1994, 1995b, 1996b).

BASIC DATA AND A LIST OF MAIN CHARACTERISTICS ANALYSED

The following basic data have been analysed in the area studied:

(a) the records of daily suspended sediment load transport from all the gauging stations in the Vistula catchment basin from 1946 to 1990;

(b) the daily water discharges (from the gauging stations) from the beginning of reservoir building activity until 1990;

(c) the daily water levels in the reservoirs from the above period;

(d) the results of repeated cross-section levelling of the reservoir; and

(e) the initial and current geometric characteristics of the reservoirs.

The following parameters have been computed for each reservoir studied:

(a) the mean rate of water exchange;

(b) the suspended sediment and total terrigenic matter input to, and output from, the reservoirs (including average values, mean monthly values and annual values during the reservoirs existence);

(c) the trap efficiency $\beta(\%)$ of reservoirs for suspended matter (calculated using Brune's (β_1), Drozd's (β_2) and Hartung's (β_3) formulae and by means of transport equations for the suspended load (β_4) and for the total terrigenic matter transport (β_5));

(d) the volume of deposited material in the reservoirs, over time (data concerning the initial capacity losses of the reservoirs are based on the β_5 values); and

(e) the useful lifetime of the reservoirs when their operation functions are fulfilled (Lajczak, 1996b). Later, the useful lifetime was compared with the half lifetime of the reservoirs (calculated according to Pitt and Thompson's methodology (Pitt & Thompson, 1984)).

Table 1 The average trap efficiency β values of selected reservoirs.

River	Dam reservoir		Number	β (%)				
				β_1	β_2	β_3	β_4	β_5
San	Solina	F	1	97	100	98	-	98
Dunajec	Roznow	F	2	84	86	90	93.3	98
Raba	Dobczyce	F	3	95	96	97	-	97
Wislok	Besko	F	4	95	96	97	-	96
Ropa	Klimkowka	F	5	95	96	97	-	96
Sola	Tresna	F	6	90	93	91	-	92
Sola	Porabka	F	7	77	80	82	-	82
Vistula	Goczalkowice	F	8	96	99	97	44.6	57
Vistula	Wloclawek	F	9	53	55	55	42.7	56
Narew	Debe	F	10	45	48	45	34.8	52
San	Myczkowce	F	11	47	48	53	-	50
Pilica	Sulejow	F	12	86	89	88	13.4	36
Dunajec	Czchow	F	13	25	0	30	21.8	23
Sola	Czaniec	F	14	0	0	0	-	0
Dunajec	Czorsztyn	UC	15	94	95	95	-	97
Skawa	Swinna-Poreba	UC	16	84	95	97	-	96
Dunajec	Sromowce Wyzne	UC	17	32	30	40	-	38
Wisloka	Krempna	P	18	97	98	98	-	98
Dunajec	Kojsowka	P	19	96	98	98	-	97
Jasiolka	Dukla	P	20	95	96	97	-	96
San	Niewistka	P	21	93	94	94	-	94
San	Krasiczyn	P	22	93	94	94	-	94
Wisloka	Kamienna	P	23	91	92	93	-	92

Reservoirs numbered as in Fig. 1; Reservoirs: F = functioning; UC = under construction; P = planned for the future; see the text for explanation of $\beta_1, \ldots, \beta_5$, values.

RESULTS

The trap efficiency of the reservoirs and its long-term change

Table 1 shows the average values of the trap efficiency for the whole functional life of the reservoirs and the estimated β values for both reservoirs under construction as well as planned. The greatest values of the β parameter are associated with reservoirs with a mean depth greater than 5-7 m. The further downstream the reservoir is located, the lower the value of β. The trap efficiency of deep reservoirs varies from 82 to 98%. For shallow reservoirs it always reduces to 0%.

The trap efficiency of a reservoir decreases over time as a result of a decrease in reservoir depth (Fig. 2). In the case of deep mountain reservoirs the β value decreases markedly only in the reservoirs receiving large amounts of terrigenic matter. This value decreases much more rapidly for shallow valley reservoirs and also for shallow lowland reservoirs. Since their construction, the shallow mountain reservoirs with an annual frequency of water exchange greater than 200 times per year have had a trap efficiency equal to 0%. Dredging activity in shallow lowland reservoirs, especially on the Vistula, cause an increase in the β parameter (Lajczak, 1995b).

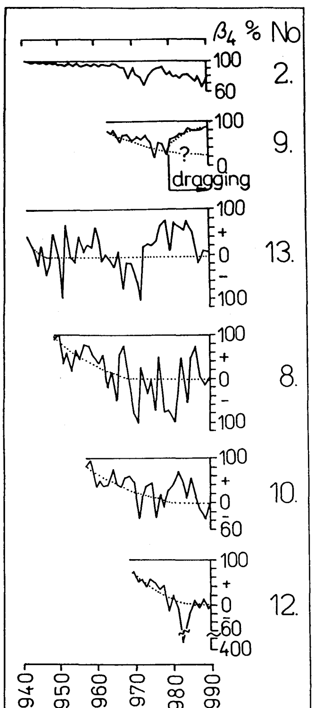

Fig. 2 The long-term course of the trap efficiency β_4 of six selected reservoirs. Reservoirs are numbered as in Fig. 1.

The current rates of reservoir silting

Up to 1990, different volumes of the reservoirs have been lost to siltation. The highest rates of silting, calculated as the percentage loss of the reservoir's initial capacity, are found in the first deep reservoirs constructed on the Carpathian rivers (Lajczak, 1994, 1995b). For example, the Rożnów Reservoir on the Dunajec River has lost 28% of its initial volume since 1941. Other younger deep reservoirs have lost no more than a few per cent of their initial volume. Reservoirs located downstream of deep reservoirs are silted much more slowly. Lowland shallow reservoirs have lost only a few per cent of their initial capacity. The construction of new deep reservoirs upstream, dredging activity and gravel extraction from reservoirs reduce the rate of silting. This trend will intensify in the future.

The long-term course of reservoir silting

Analysis of reservoir silting can identify two main phases (Lajczak, 1994, 1995b, 1996b). During the first phase, which can be identified as the useful lifetime of the reservoir, the coarser material can be totally trapped in the reservoir, and the percentage of suspended matter retained decreases to zero (Fig. 3). This phase of silting ends when the mean depth of the reservoir reaches a critical value, i.e. 5-7 m in reservoirs on the large Carpathian rivers, 3-4 m in large shallow lowland reservoirs and 2 m in small reservoirs. During the second phase of reservoir silting, only coarser material can be deposited in the reservoir for long time periods. If reservoirs are flushed, this material can pass through the dams. Detailed analysis of the balance of suspended matter transport provides evidence that the outflow of this material from heavily silted reservoirs (resulting from density currents and wave-induced resuspension of bottom deposits) over long periods is equal to the inflow (Lajczak, 1995b, 1996b). The deep reservoirs included in the study are at the beginning of the first phase of silting. The rest of the reservoirs studied are at the beginning of the second phase of that process.

The useful lifetime of reservoirs

The useful lifetime of initially deep reservoirs with seasonal water level fluctuations exceeding 10 m lasts until the useful storage capacity becomes completely silted. After this, a heavily silted reservoir on a mountain river no longer preserves its retentive role. Large lowland reservoirs may preserve the initial role for much longer periods. In contrast to deep mountain reservoirs, their useful lifetime extends not only through the first phase of sedimentation, but also through a large part of the second phase of sedimentation (Lajczak, 1995b).

The useful life of the deep reservoirs has been predicted using modified Orth's and Goncarov's formulae (Lajczak, 1995b). A limit rate to sedimentation V_{st} (which corresponds to 80% loss of the initial capacity) is still accepted in the literature. In this study, a real limit value specific to each reservoir studied was used. The limit is reached when the mean depth of the reservoir is reduced to the critical values mentioned and this was estimated separately for individual reservoirs using their initial $H-V$ relationships

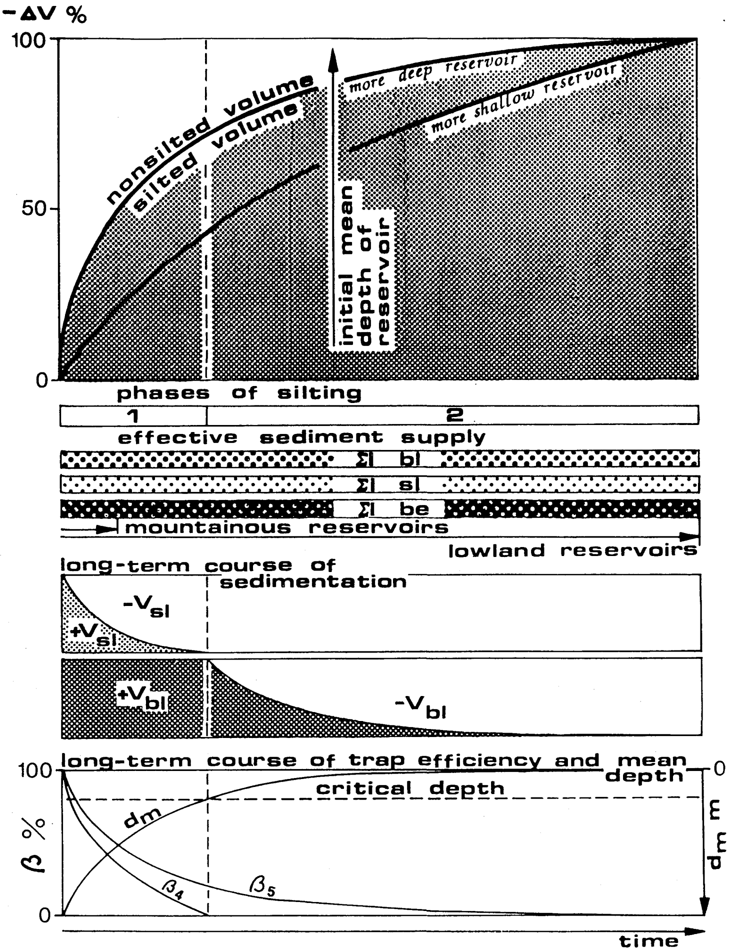

Fig. 3 Model illustrating the long-term course of reservoir silting: phases of silting: 1 = first, 2 = second; effective sediment supply: $\Sigma I\ bl$ = bed load; $\Sigma I\ sl$ = suspended load; $\Sigma I\ be$ = material from bank erosion; $+V_{sl}$ = retention of suspended matter; $-V_{sl}$ = outflow of suspended matter, $+V_{bl}$ = retention of bed load; $-V_{bl}$ = outflow of bed load; d_m = mean depth of reservoir. For explanations β_4 and β_5, see the text.

(Fig. 4). A preliminary V_{st}' value is derived from the $H-V$ relationship of the reservoir during the first year of its operation. In the reservoirs under construction and those planned for the future, the $H-V$ relationship has been calculated on the basis of the bathymetric plan of the reservoir and its planned depth. The limit for sedimentation, V_{st}, is not defined by the horizontal surface corresponding to the critical depth, but by the surface of the bottom sediments. Therefore, the estimated V_{st}' value must be reduced by the non-silted volume of the reservoir lying beneath the critical depth (V_{ns}), which is estimated from the probable bathymetric plan of the reservoir when the mean depth reaches the critical value. The V_{st}' value must also be increased by the volume of the periodically exposed deltaic deposits during low water levels in the reservoir (V_{eds}).

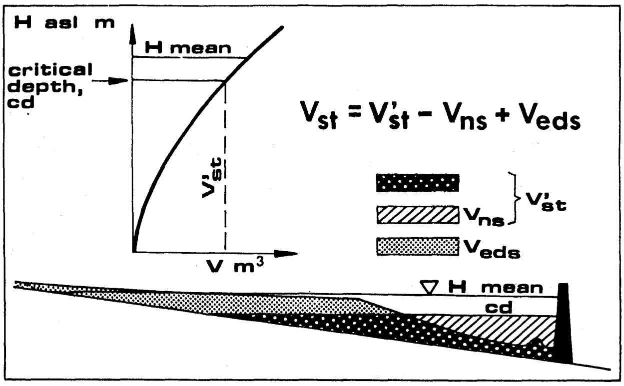

Fig. 4 Sketch showing how to predict the limit rate for reservoir silting, V_{st}. For explanations of the symbols (V_{st}, V_{st}', V_{ns}, V_{eds}), see the text.

In the calculations, two initial parameters were taken into account, namely, the long-term average annual sedimentation in each reservoir (based on the balance of transport) and the actual average loss of storage capacity of the reservoir (based on repeated surveys). The results are presented in Table 2. The useful lifetime of the deep reservoirs studied varies from 260 to 11 000 years. Taking into account the long useful lifetime of deep reservoirs, it is advisable to locate them in the upper densely-forested sections of the Carpathian valleys where there are low suspended sediment yields. The deep reservoirs located on the middle and lower stretches of the Carpathian tributaries

Table 2 The useful life, ULT, and the half life, HLT, of selected deep reservoirs.

River	Dam reservoir	Number	ULT (years)		HLT (years)
			ULT_1	ULT_2	
Ropa	Klimkowka	5	11 000	-	7000
Wisloka	Krempna	18	11 000	-	7000
Dunajec	Kojsowka	19	9600	-	8000
Jasiolka	Dukla	20	9600	-	8000
San	Solina	1	9700	9000	8500
Skawa	Swinna-Poreba	16	2500	-	1200
San	Niewistka	21	900	-	520
Wisloka	Kamienna	23	850	-	600
Dunajec	Czorsztyn	15	810	-	700
Sola	Tresna	6	680	620	520
Raba	Dobczyce	3	680	-	650
Dunajec	Roznow	2	320	260	230

Reservoirs numbered as in Fig. 1.; ULT values: ULT_1 = based on the balance of terrigenic matter transport; and ULT_2 = based on repeated storage capacity measurements on the reservoir.

of the Vistula and also on the Lower Vistula are silted much more quickly, but they effectively reduce the supply of terrigenic matter to the Baltic Sea. The useful lifetimes of the deepest reservoirs on the Vistula are very short and can be prolonged only by intensive dredging activity.

Table 2 provides data showing that the half life of the deep reservoirs investigated generally represents an earlier stage of their silting. It also shows that the difference between the useful life and the half life varies, roughly in proportion to the initial mean depth of the reservoir.

A critique of the location of existing reservoirs

The deep reservoirs in the Carpathian valleys should silt slowly and therefore retain their initial volume. From this point of view their location in the upper forested sections of the valleys is appropriate. Their theoretical useful life is over 9000 years. The deep reservoirs located in the middle and lower sections of the valleys are silted much more quickly and their useful life varies from 260 to 1300 years. From a practical point of view this time is sufficient for the water management of the reservoir. The Carpathian rivers transport large amounts of terrigenic material in their middle and lower reaches. The transport rates of this material are much reduced by the rapid siltation of the deep upstream reservoirs. The shallow reservoirs associated with deep reservoirs upstream, except for the initial years following their construction, do not reduce the rates of sediment transport in the rivers. The current rates of supply of terrigenic matter to the Vistula by the successive Carpathian rivers are reduced by between 10% and 90%. This means that on average the suspended sediment load in the piedmont reach of the Vistula has decreased two-fold (Lajczak, 1989, 1996a).

The decrease in the total supply of terrigenic matter to the Vistula by the upland tributaries (resulting from sedimentation in the reservoirs) has reached a few per cent. In the case of lowland tributaries discharging into the Vistula, this decrease is minimal because the large and shallow reservoirs have rapidly reached the second phase of siltation (Lajczak, 1995b).

To date only seven shallow and very narrow reservoirs and one large (wide) shallow reservoir have been built on the piedmont and lowland reaches of the Vistula. Very advanced sedimentation processes have been observed in the Włocławek Reservoir on the Lower Vistula. This reservoir causes a twofold reduction in the suspended sediment load of the river downstream. Expensive dredging work in the reservoir can be stopped if new dams are built along the river upstream (Lajczak, 1995b).

Broadly speaking, the silting of the reservoirs studied does not have any negative consequences for water management in the river basin.

Proposal for appropriate locations for planned reservoirs

The advantageous situation mentioned above will be prolonged for a very long period of time if the planned reservoirs are distributed in the Vistula basin as follows:

(a) The deep reservoirs should be located on the upper reaches of the Carpathian rivers to avoid rapid silting. This approach will allow the protection of the lower stretches of the Carpathian rivers from catastrophic floods. The retention of clear water in the reservoirs with the longest useful life will play a very important role in national water management for many centuries. The reservoirs will cause a negligible reduction in the supply of terrigenic material to the Vistula.

(b) The deep reservoirs located on the middle and lower stretches of the Carpathian tributaries of the Vistula will still be relatively quickly silted, despite the building of the new reservoirs mentioned above. The reservoirs located uppermost on each river will trap some terrigenic material and lead to a reduction in its transport in the river downstream. The deep reservoirs downstream will have a longer life and the supply of terrigenic matter to the Vistula could be reduced in successive rivers by as much as 100 times.

(c) The shallow reservoirs on the Carpathian rivers associated with the deep reservoirs upstream will not play an important role in the balance of material transport in the river basin.

(d) The role of upland and lowland tributaries of the Vistula in the supply of terrigenic matter to the river is minimal when compared to the Carpathian rivers. New and rather shallow reservoirs will have a long life on these rivers. In this case, the rates of material supply to the Vistula will be similar to the present-day state.

(e) Most of the shallow and narrow reservoirs along the Vistula will not reduce the amount of material outflow and only a few of them will be rapidly silted during the first decades of their existence. Later, the trap efficiency for suspended load will decrease to very low values.

Finally, the following order of building of the planned reservoirs is proposed:

(a) Firstly, the deep reservoirs on the middle stretches of the Carpathian tributaries of the Vistula should be completed to achieve a minimum rate of supply of terrigenic material from the Carpathian Mountains to the Vistula.

(b) Secondly, if the above programme is completed, the reservoirs on the Vistula should be built successively downstream from the stretch of the river near Cracow. If dredging activity in the reservoirs located along the piedmont course of the Vistula starts at the beginning of their operation, silting in the reservoirs located downstream will reach very low levels.

Building deep reservoirs on the upper reaches of the Carpathian rivers and also building new reservoirs on the upland and lowland rivers, are not going to play an important role in the silting of reservoirs on the Vistula.

CONCLUSIONS

The values provided for reservoir silting within the Vistula River catchment basin, and particularly for their useful life, are valid for present-day climatic conditions and land use in the area studied. In comparison to reservoirs in semiarid areas, siltation rates are rather low. However, the sedimentation rates for the reservoirs studied, expressed in m^3 km^{-2} $year^{-1}$ or mm $year^{-1}$, are about 10 times higher than for reservoirs located in old mountainous regions of Central Europe composed of more resistant rocks.

The presented method for calculating the useful life of the reservoirs studied can be adopted in other cases. The fixed value of 80% silting limit for each reservoir in these calculations (Hartung, 1959), should be replaced by a limit value specific to each reservoir studied.

Both the location of the planned reservoirs and the order of building of the planned dams proposed in the study should be seen as a means of effectively reducing sedimentation rates in the reservoirs. Dredging activity will prolong the useful life of the reservoirs on the Vistula. It must be stressed that flushing should not be used as it is a very aggressive practice for the river downstream.

Acknowledgements I wish to thank the Polish Hydrological Survey for providing the primary measurement data.

REFERENCES

Branski, J. (1975) Assessment of the Vistula catchment area denudation on the basis of suspended load transport measurement. *Prace IMGW* **6**, 5-58.

Branski, J. (1980) Sediment runoff from the catchment area of the Carpathian rivers. *Acta Hydrobiol.* **1**, 89-100.

Branski, J., Dabkowski, S. L. & Skibinski, J. (1980) Current knowledge of the fluvial transportation rates in the Upper Vistula with cascade system project. *Gosp. Wodna* **3**, 72-76.

Hartung, F. (1959) Ursache und Verhutung der Stauraumverlandung bei Talsperren. *Wasserwirtschaft* **1**, 3-13.

Jedrysik, M. & Rusak, M. (1982) The complex water management of the Vistula River. In: *The Monograph of the Vistula*, 1-250. Warsaw.

Lajczak, A. (1989) Differentiation of suspended material transportation in the Carpathian drainage basin of the Vistula. *Dokument. Geogr.* **5**, 1-85.

Lajczak, A. (1994) The rates of silting and the useful lifetime of dam reservoirs in the Polish Carpathians. *Z. Geomorphol.* **2**, 129-150.

Lajczak, A. (1995a) The impact of river regulation, 1850-1990, on the channel and floodplain of the upper Vistula River, southern Poland. In: *River Geomorphology* (ed. by E. J. Hickin), 209-233. Wiley, Chichester, UK.

Lajczak, A. (1995b) A study on silting of dam reservoirs in the Vistula River catchment basin. *The Monograph of the Water Resources Committee, P.A. of Sci.* **8**, 1-108.

Lajczak, A. (1996a) Potential rates of the present-day overbank sedimentation in the Vistula valley at the Carpathian foreland, southern Poland. *Quaest. Geogr.* (in press).

Lajczak, A. (1996b) Modelling the long-term course of non-flushed reservoir sedimentation and estimating the life of dams. *Earth Surf. Processes and Landforms* (in press).

Lajczak, A. & Jansson, M. B. (1993) Suspended sediment yield in the Baltic Sea drainage basin. *Nordic Hydrol.* **24**, 31-52.

Pitt, J. D. & Thompson, G. (1984) The impact of sedimentation on reservoir life. In: *Challenges in African Hydrology and Water Resources* (ed. by D. E. Walling, S. S. D. Foster & P. Wurzel) (Proc. Harare Symp., July 1984), 541-548. IAHS Publ. no. 144.