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Impact of small reservoir on reduction of solid transport

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Introduction

As a result of runoff from rainfall or snowmelt, soil particles are eroded from the surface of a watershed and transported through the processes of sheet, rill, and gully erosion to the streams. Once eroded, sediment particles are transported through a river system together with sediment produced by channel erosion. Impoundment of a river reach by construction of a dam always changes the stream's natural conditions. The reduction on the flow velocity causes gradual deposition of solids transported by water, resulting in the reservoir sedimentation. The amount of sediment deposited within a reservoir depends on the fall velocity of the various sediment particles, water flow rate and velocity distribution, which are determined mainly by the size, depth, shape and operation rules of the reservoir. It is commonly accepted that small reservoirs are more susceptible to quick sedimentation, simply because of their capacity. If the sediment inflow is large relative to the reservoir storage, then the useful life of the reservoir may be very short. On the other hand, sedimentation in the reservoir usually improves water quality of the downstream river due to the reduction of solid transport. All bedload sediment and part of the suspended load is deposited in the reservoir (reducing reservoir capacity) and upstream of the reservoir in reaches influenced by backwater.

Material and methods

The reservoir

The investigations were carried out for a small reservoir Staw Górny on Zagożdżonka river in the town of Pionki located about 100 km south of Warsaw. The reservoir was built in 1976, by design of a concrete main dam consisting of a rectangular weir structure equipped with two flap gates. The weir was flanked by an earth dam. The main purpose of the reservoir was to secure water demand of local chemical factory. The project of the new construction assumed two stages of investment – with reservoir volume V_0 = 252 000 m^3 in the first stage. After completion of the first stage construction in 1976, the rest of the project, assuming some land repurchase and lengthening of the flanking earth dam to the final volume of reservoir 990 000 m^3 (Banasik and Mordziński 1982), was not realized until now. In fact, because the both gates of the weir are still in their lowest position, the drop structure of reservoir acts as a fixed weir. At the normal impoundment water level NPP = 146,70 m a.s.l., the reservoir area is A_R = 14 ha, maximum water depth is about 2,60 m and total length of the reservoir is L_R = 900 m.

The reservoir watershed

The watershed area of the Zagożdżonka river to the dam of the reservoir is A_W = 91,4 km^2. Location of the reservoir and its watershed area are shown on schematic map on Figure 14.1. The dominant soil type in the watershed is constituted by sandy soils, developed mainly from poor clay sands (60,6%), clay sands (27,2%) and loose sands (about 0,1% of catchment area). The remaining 12,1% of the catchment area are organic soils, developed mainly in local depressions with no runoff. Reservoir water-

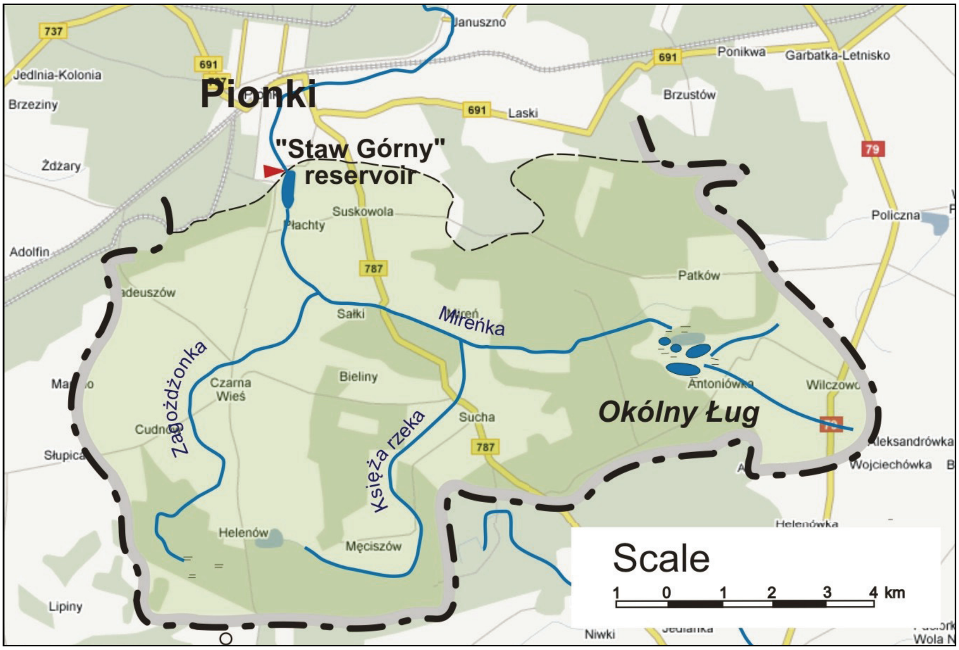

FIGURE 14.1. Location map of the Staw Górny reservoir and its watershed

shed is located in a typical agricultural region of central Poland. Arable land takes about 47,5% of the catchment area, pastures – 11,5%, forests – 40,5% and urban area – 0,5% (Banasik 1995). The catchment is of a lowland type – with the average slope of Zagożdżonka river at about 2,5‰ and the slopes of remaining streams not exceeding 3,5 ‰. Stream's channels are formed in medium and fine sands with the median particle diameter of bed material d_{50} in a range of 0,3–0,4 mm.

Field measurements

Reservoir surveys are the most reliable technique available for assessing sedimentation intensity, to update current storage characteristics of reservoir and to estimate sediment yield from the upstream hydrological basin (Strand and Pemberton 1982; Morris and Fan 1998). The first bed measurement of Staw Górny reservoir was conducted between November 1979 – February 1980 and in October 1980, using the range line method (Banasik and Mordziński 1982). A base line was established by fixing permanent markers along the left side of the reservoir and cross sections were referenced by distance and direction angles to the base line as shown on Figure 14.2. The same fixed range layout was used in successive surveys conducted in June 1991 and in September 2003. The last survey in August 2009 was carried out using contour line method. Measurements done in 2003 and in 2009 were conducted

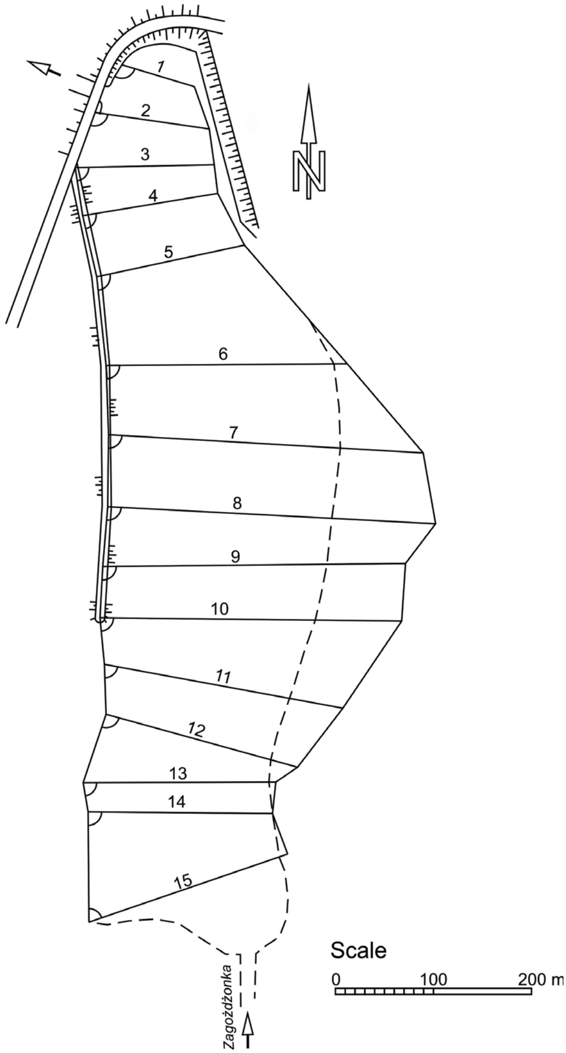

FIGURE 14.2. Scheme of the Staw Górny reservoir range layout

TABLE 14.1. Volume of sediment deposits in the Staw Górny reservoir

Period between measurements	Volume of sediment deposits (m³)	
	total	annual
1980–1991	14 650	1 330
1991–2003	11 620	968
2003–2009	4 900	817
1980–2009	31 189	1 075

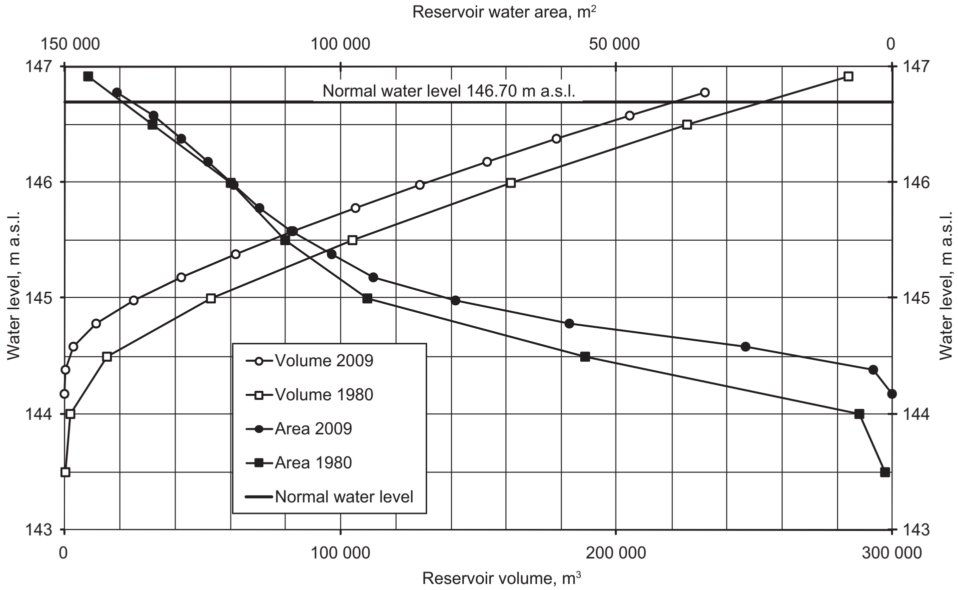

FIGURE 14.3. Area and capacity curves of the Staw Górny reservoir

using a survey vessel equipped with hydrographic system composed of an echo-sounder unit and a Global Positioning System (GPS) receiver. The 200 kHz echo sounder transducer makes it possible to survey depth of the water in the range 0,3–99,9 m with 0,01 m accuracy. The 8 channel GPS receiver allows determination of sounding point position with 1 m accuracy. All measured values of water depth together with the sounding position are then logged internally every two seconds. Results of sequential surveys of Staw Górny reservoir are given in Table 14.1. Area and capacity curves of the reservoir, calculated on the basis of surveys conducted in 1980 and 2009 are shown in Figure 14.3. In July 2010, bottom deposit samples were collected from the Staw Górny reservoir for the grain size distribution analyses. The grain size analyses of fine bottom sediments from reservoir deposits were carried out by laser diffraction method. Samples were taken using gravity corer of Kajak type, from a boat equipped with GPS receiver. Position of sampling point was recorded in the GPS receiver memory.

Reservoir trap efficiency

The trap efficiency β of a reservoir is defined as the ratio of the quantity of deposited sediment S_{dep} to the total sediment inflow S_{in}:

$$\beta = \frac{S_{dep}}{S_{in}} \tag{1}$$

The quantity of sediment deposits S_{dep} can be obtained on the basis of measured differences in reservoir capacity between successive surveys. To estimate the total sediment inflow S_{in}, suspended load transport and bedload transport are calculated separately, assuming that bedload consists of coarse material in the streambed which is mobilized by flowing water and suspended load depends on the rate of erosion in source areas and its delivery rate. Suspended sediment yield from reservoir catchment was estimated using the DR-USLE model, i.e. Universal Soil Loss Equation (Wischmeier and Smith 1978) with sediment delivery ratio – *DR*, and bedload transport rate was estimated using selected empirical formulas.

The Universal Soil Loss Equation (USLE) is a method most widely used around the world to predict long-term rates of soil erosion from field or farm size units subject to different management practices (Morris and Fan 1998). Wischmeier and Smith developed the USLE based on thousands of plot-years of data from experimental plots, and although the initial focus was oriented primarily to conditions in the middle and eastern United States, the USLE has been extended and applied worldwide. Application of the USLE formula to Polish conditions was explained in detail by Banasik (1994; Banasik et al. 1995):

$$E = R \cdot K \cdot LS \cdot C \cdot P \tag{2}$$

where:

E – annual soil loss per unit area ($Mg \cdot ha^{-1} \cdot year^{-1}$),
R – the rainfall and runoff factor ($JE \cdot year^{-1}$; $JE = (MJ \cdot ha^{-1}) \cdot (cm \cdot h^{-1})$ – the erosion index units),
K – soil erodibility factor ($Mg \cdot ha^{-1} \cdot JE^{-1}$),
LS – topographic factor (–),
C – cover and management factor (–),
P – support practice factor (–).

The USLE model is an empirical multiple-regression-type equation which determines erosion rates in particular area. Sediment delivery ratio *DR* represents the ratio of gross erosion within a watershed to the sediment yield during the same period. By using the USLE together with the sediment delivery ratio *DR* the annual amount of sediment yield from the reservoir watershed can be estimated as:

$$Y_r = DR \cdot E \cdot A_E \tag{3}$$

where:

Y_r – annual sediment yield from the catchment of the reservoir (Mg·year^{-1}),
DR – sediment delivery ratio (–),
A_E – active area of reservoir watershed (ha).

The parameters of equation (2) have been estimated for the catchment of Staw Górny reservoir in the Zagożdżonka river watershed (Banasik et al. 1995): DR = 0,13, A_E = 7180 ha, R = 77,1 JE·year^{-1}; K = 0,247 Mg·ha^{-1}·JE^{-1}; LS = 0,393; $C \cdot P$ = 0,08. That means that the annual sediment yield delivered to the reservoir from its catchment area is Y_r = 503 Mg·year^{-1}. Assuming the density of deposited suspended material in Staw Górny reservoir as equal to 0,7 Mg·m^{-3} (Banasik and Mordziński 1982), it gives a volume of suspended sediment deposits in the reservoir equal to 708 m^3·year^{-1}.

The mean annual bedload transport have been calculated from three different formulas:

a) Bedload transport formula for Zagożdżonka river, developed on the basis of field measurements records from sand-trap, localized upstream to the Staw Górny reservoir, at the experimental gauge station of Warsaw University of Life Sciences – SGGW (Popek 2006):

$$\frac{q_b}{\sqrt{(s-1)\,gd_{50}^3}} = \left[0{,}0792 + \frac{5{,}88 \cdot 10^{-5} q}{\sqrt{(s-1)\,gd_{50}^3}}\right]^2 \tag{4}$$

where:

q_b – specific bedload transport (m^3·s^{-1}·m^{-1}),
q – specific water discharge (m^3·s^{-1}·m^{-1}),
s – relative density of sediment ($s = \rho_s/\rho_w$ – sediment density/water density) (–),
g – the acceleration of gravity (m·s^{-2}),
d_{50} – the median particle diameter of bed material (m).

b) Skibiński formula, which was developed on the basis of bedload transport measurements for the Vistula river and its tributaries in central Poland (Banasik et al. 1995):

$$q_r = 61{,}8 \cdot 10^{-5} \cdot C_d^{0{,}134} \cdot h^{-0{,}223} v_s^{3{,}40} \tag{5}$$

where:

q_r – specific bedload transport intensity (m^3·s^{-1}·m^{-1}),
C_d – coefficient of grains uniformity according to Kollis, $C_d = \dfrac{d_{90} \cdot d_{10}}{d_{50}^2}$, (–),
h – water depth (m),
v_s – mean velocity (m^3·s^{-1}).

c) Meyer-Peter-Mueller formula (Banasik et al. 1995):

$$q_r = \frac{25{,}1}{(1-p)(s-1)}\left[\left(\frac{k_s}{k_r}\right)^{\frac{3}{2}} R_s \cdot J - 0{,}047(s-1)\cdot d_m\right]^{\frac{3}{2}} \tag{6}$$

where:
q_r – specific bedload transport intensity ($m^3 \cdot s^{-1} \cdot m^{-1}$),
p – porosity of deposited bedload sediment (–),
s – specific gravity of the sediment,
k_s – Strickler's coefficient of bed roughness ($m^{1/3} \cdot s^{-1}$),
k_r – the coefficient of particle roughness, equal to $26 / d_{90}^{1/6}$,
d_{90} – the particle size for which 90% of the bed mixture is finer (m),
R_s – the hydraulic radius of that part of the cross section apportioned to the bedload transport (m),
J – the energy gradient (–),
d_m – the effective diameter of bed-material mixture (m), $d_m = \sum_{i=1}^{n} d_i \Delta p_i$,
d_i – the mean grain diameter of the sediment in size fraction i (m),
Δp_i – the fraction, by weight, of bed material in a given size fraction (–).

Quantities of mean annual sediment transport delivered to Staw Górny reservoir, calculated as the sum of suspended sediment transport (from DR-USLE model) and bedload transport from formulas a) – c) are shown in Table 14.2. Mean annual bedload transport was estimated on the basis of daily discharge records from Zagożdżonka river from years 1970–1990.

TABLE 14.2. Mean annual sediment delivery to the Staw Górny reservoir

Formula used in calculation	Volume of sediment transport (m^3)			Trap efficiency
	suspended	bedload	total	
DR-USLE + a) Popek formula	708	398	1 106	0,97
DR-USLE + b) Skibiński formula	708	411	1 119	0,96
DR-USLE + c) MPM formula	708	515	1 223	0,88

Another way to estimate the reservoir's trap efficiency is to use empirical methods. There is a number of formulas to estimate the reservoir's trap efficiency, usually obtained for large or medium reservoirs and depending on the capacity-inflow ratio or capacity-watershed ratio (Brune 1953; Dendy 1974; Heinemann 1984; Morris and Fan 1998). For a small reservoir, such as Staw Górny reservoir, sediment trap efficiency value can be estimated using the Churchill method, developed for settling basins, small reservoirs, flood retarding structures, semi-dry reservoirs, and reservoirs that are frequently sluiced (Brune 1953; Carvalho et al. 2000; Madeyski et al. 2008). The Churchill formula can be written as:

$$\beta = 100 - \left[800 \cdot SI^{-0,2} - 12\right] \tag{7}$$

where:

β – sediment trap efficiency (%),

SI – reservoir sedimentation index, equivalent to the retention time divided by the reservoir average velocity of water flow ($ft^{-1} \cdot s^{2}$).

The same Churchill formula may by written as dimensionless expression (Strand and Pemberton 1982; Carvalho et al. 2000):

$$\beta = 100 - \left[1600 \cdot \left(SI \cdot g\right)^{-0,2} - 12\right] \tag{8}$$

where:

g – acceleration due to gravity ($ft \cdot s^{-2}$) when SI in ($ft^{-1} \cdot s^{2}$) or ($m \cdot s^{-2}$) when SI in ($m^{-1} \cdot s^{2}$),

The reservoir sedimentation index SI in ($m^{-1} \cdot s^{2}$) can be computed as:

$$SI = \frac{1}{L}\left(\frac{V_0}{SQ}\right)^2 \tag{9}$$

where:

V_0 – reservoir capacity at the mean operating pool elevation (m^3),

SQ – average daily inflow rate ($m^3 \cdot s^{-1}$),

L – reservoir length at the mean operating pool elevation (m).

Assuming for Staw Górny reservoir SQ = 0,342 $m^3 \cdot s^{-1}$ (value determined for dam cross-section) and L = 900 m, estimated sediment trap efficiency of the reservoir is equal to 94%.

Grain size distribution analysis of reservoir deposits

Grain size is the most fundamental property of sediment particles, affecting their erosion, transport and deposition. In order to compare different sediments, grain size distributions have most frequently been described by their deviation from a prescribed ideal distribution. Geometric scaling is usually employed to place equal emphasis on small differences in fine particles and larger differences in coarse particles. Most sedimentologists have adopted the logarithmic Udden-Wentworth grade scale, where the boundaries between successive size classes differ by a factor of two. In order to facilitate graphical presentation and statistical manipulation of grain size frequency data, Krumbein proposed that grade scale boundaries should be logarithmically transformed into phi (φ) values, using the expression:

$$\varphi = -\log_2 d \tag{10}$$

where d – the grain diameter (mm).

Distributions using these scales are termed 'log-normal', and are conventionally used by sedimentologists (Folk 1980; Blott and Pye 2001). The parameters used to describe a grain size distribution fall into four principal groups: those measuring (a) the average size, (b) the spread (sorting) of the sizes around the average, (c) the symmetry or preferential spread (skewness) to one side of the average, and (d) the degree of concentration of the grains relative to the average (kurtosis).

Grain size of fine sediments in Staw Górny reservoir deposits were analyzed using the laser diffraction method (Hejduk and Banasik 1999). Grain size distribution curves of sediments are shown on Figure 14.4. Parameters of grain size distribution of sediment deposits in Staw Górny reservoir, shown in the Table 14.3, were calculated using following formulas:

a) Arithmetic-mean diameter d_m (mm):

$$d_m = \frac{\sum d_i \cdot \Delta p_i}{\sum \Delta p_i} \tag{11}$$

where:
d_i – the mean grain diameter of the sediment in size fraction i (mm),
Δp_i – the fraction of bed material in a given size fraction (–),

b) Mean diameter S_S (mm):

$$S_S = \frac{d_{16} + d_{50} + d_{84}}{3} \tag{12}$$

where:
d_{16}, d_{50}, d_{84} – the grain diameter of a cumulative percentile value – i.e. the grain size at which a specified percentage (for ex. 16%, 50%, 84%) of the grains are coarser (mm),

c) Geometric mean diameter GS_S (φ-units):

$$GS_S = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3} \tag{13}$$

where:
$\varphi_{16}, \varphi_{50}, \varphi_{84}$ – the phi-value, calculated from formula (10), for the grain diameter of a cumulative percentile value – i.e. the grain size at which a specified percentage (for ex. 16%, 50%, 84%) of the grains are coarser (φ-units),

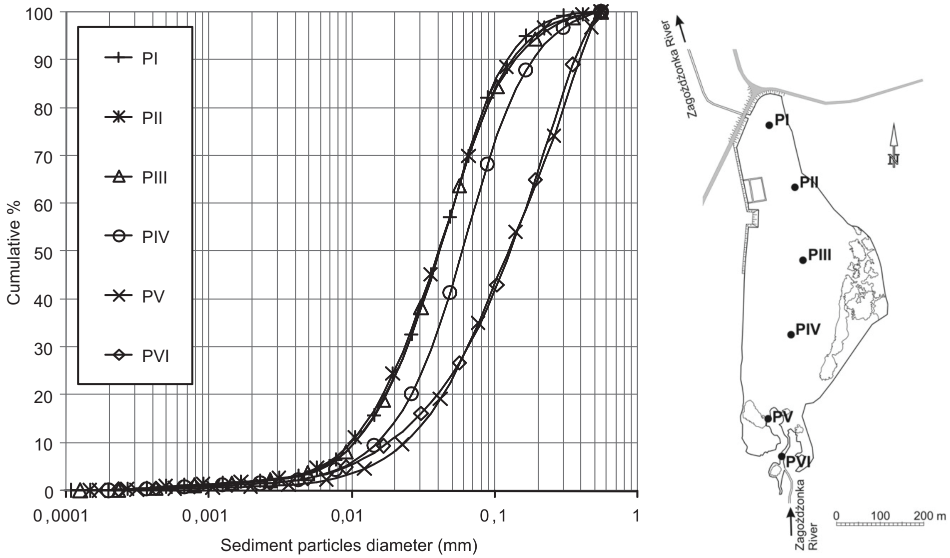

FIGURE 14.4. Grain-size distribution of sediment deposits in the Staw Górny reservoir

TABLE 14.3. Grain size distribution characteristics of sediment deposits in the Staw Górny reservoir

Profile	Modal diameter	Arithmetic-mean diameter	Mean diameter	Geometric mean diameter	Inclusive graphic standard deviation	Inclusive graphic skewness	Graphic kurtosis
	d_{50} (mm)	d_m (mm)	S_S (mm)	GS_S	σ_I	Sk_I	GK
I	0,041	0,057	0,050	4,71	1,39	0,122	0,896
II	0,040	0,060	0,051	4,71	1,47	0,095	0,902
III	0,041	0,062	0,052	4,67	1,46	0,065	0,948
IV	0,059	0,084	0,073	4,15	1,41	0,103	0,951
V	0,124	0,169	0,165	3,14	1,59	0,193	0,757
VI	0,128	0,162	0,155	3,24	1,68	0,307	0,835

d) Inclusive graphic standard deviation σ_I (φ-units):

$$\sigma_I = \frac{\varphi_{84} - \varphi_{16}}{4} + \frac{\varphi_{95} - \varphi_5}{6{,}6} \tag{14}$$

e) Inclusive graphic skewness Sk_I (–):

$$Sk_I = \frac{\varphi_{16} + \varphi_{84} - 2\varphi_{50}}{2(\varphi_{84} - \varphi_{16})} + \frac{\varphi_5 + \varphi_{95} - 2\varphi_{50}}{2(\varphi_{95} - \varphi_5)} \tag{15}$$

f) Kurtosis *GK* (–):

$$GK = \frac{\varphi_{95} - \varphi_5}{2,44\left(\varphi_{75} - \varphi_{25}\right)} \tag{16}$$

Results and discussion

The measured sediment accumulation in Staw Górny reservoir, between successive surveys was ranging from 1330 m^3 (in period 1980–1991) to 817 m^3 in the years 2003–2009 (Table 14.1). Mean annual sediment deposition in the whole period of investigation is equal to 1075 m^3 per year. It means the loss of 0,32% to 0,53% of the total reservoir capacity per year, and during the 29-year period of investigations, the total capacity loss of the Staw Górny reservoir reaches 12,4% of its volume, with mean annual value of 0,43%. Reservoir capacity curves in Figure 14.3 show, that sediment deposits are uniformly distributed in the reservoir – typically for reservoirs on a single stream with no major tributaries and operated at a nearly constant pool level (Morris and Fan 1998). Solid material which is deposited in the reservoir, is delivered by the Zagożdżonka river and consists of fine material from watershed erosion, transported as suspended sediment, and river bed material, transported as bedload. The calculated mean annual volume of sediment delivery to the reservoir (based on the analysis of reservoir's watershed area for suspended sediment yield estimation with DR-USLE and different formulas for bedload transport estimation, as shown in Table 14.2) allows to estimate the sediment trap efficiency of the Staw Górny reservoir in the range from 88% (using MPM formula for bedload transport calculation) to 96%–97% using formulas obtained from investigations carried out for Polish rivers. The highest value of reservoir trap efficiency (β = 97%) has been estimated using a formula obtained on the base of bedload transport investigations conducted in an experimental gauge station on Zagożdżonka river, upstream to the Staw Górny reservoir (Popek 2006). The trap efficiency of the reservoir estimated using empirical Churchill method is equal to 94%. It can be assumed that sedimentation processes in Staw Górny reservoir reduce transport of solid material in the Zagożdżonka river about 94%–97%.

The grain size analyses show that sediment deposits in Staw Górny reservoir contain mainly fine material i.e. fine sands and silt. As follows from the analysis of the grain size distribution curves on Figure 14.3, grain size of deposited material decreases along the reservoir. It is characteristic that the curves can be grouped in three parts of similar shapes: I–III in the lowest part of reservoir, IV in the middle part and V i VI at the reservoir entrance. According to the arithmetic mean diameter d_m in Table 14.3, the deposits in profiles I–III are classified as coarse silt, IV – very fine sands, and V, VI

– fine sands under the Udden-Wentworth classification. By using the geometric mean diameter GS_S in the Krumbein grade scale, deposits in profiles I–IV are classified as coarse silt and V–VI as very fine sands. Values of inclusive graphic standard deviation σ_I classify all of sediments deposited in the reservoir as poorly sorted.

Kurtosis measures the ratio between the sorting in the "tails" of the curve and the sorting in the central portion (Folk 1980). If the central portion is better sorted than the tails, the curve is said to be excessively peaked or leptokurtic; if the tails are better sorted than the central portion, the curve is deficiently or flat-peaked and platykurtic. According to graphic kurtosis *GK* in Table 14.3, the grain size distribution curves of sediment deposits in profiles II–IV are mesokurtic, when curves in profile I (closest to the dam) and V–VI (at the reservoir entry) are platykurtic.

Skewness measures the degree of asymmetry as well as the "sign" – i.e., whether a curve has an asymmetrical tail on the left or right. Symmetrical curves have $Sk_I = 0$; those with excess fine material (a tail to the right) have positive skewness and those with excess coarse material (a tail to the left) have negative skewness. The more the skewness value departs from 0, the greater the degree of asymmetry. According to the inclusive graphic skewness Sk_I values in the Table 14.3, grain size distribution curves in profiles II and III in the reservoir are symmetrical, when curves I, IV and V are fine skewed. The grain size distribution curve in profile VI (at the river inflow) is very fine skewed. The differences in calculated values of graphic kurtosis and inclusive graphic skewness between profiles located in the middle part of reservoir (II, III, IV) and close to the dam (I) as well as at the river inflow (V, VI) are the result of the fact that sediment is delivered to reservoir in pulses by large storms, separated by prolonged periods of low flows and smaller events. This is characteristic for small reservoir that the pulsed nature of sediment delivery may be recorded in deposits as alternating layers of coarse and fine sediments in different parts of reservoir and reported as poorly sorted material.

Conclusions

The Staw Górny reservoir reduces the sediment transport in the Zagożdżonka River at about 94%–97%. Successive reservoir surveys are an effective method of monitoring soil erosion processes intensity in the river catchment. Mean storage loss of the reservoir is equal to 0,43% per year. Fine grain size of sediments deposited in the reservoir – mainly fine sands and silt (d_{50} = 0,041 to 0,128 mm), indicates that most of the sediments are delivered from soil erosion in the watershed. Some of coarser material is deposited in the river channel upstream the reservoir. Sediment deposits are uniformly distributed in the reservoir and grain size of deposited material decreases in the dam direction – typically for reservoirs on a single stream and operated at a nearly constant pool level. Sediments are poorly sorted. Characteristics of grain size distribution of sediments shows that solid material is delivered to reservoir mainly by storms events. Continuation of reservoir Staw Górny surveys, will provide valuable data for further investigations on sediment transport and water quality processes in small lowland watershed.

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