

Received 03.06.2013
Reviewed 26.06.2013
Accepted 18.07.2013A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Spatial distribution of sediments in Suchedniów reservoir

Łukasz BĄK¹⁾ ABDEF, Szczepan Ludwik DĄBKOWSKI²⁾ ABDEF

¹⁾ University of Technology, Department of Geotechnics and Water Engineering, ul. Studencka 2, Energis Building, 25–314 Kielce, Poland; tel. 48 41 34-34-374, e-mail: L.Bak@tu.kielce.pl

²⁾ Institute of Technology and Life Sciences, Department of Water Engineering and Land Reclamation, al. Hrab-ska 3, Falenty, 05-090 Raszyn, Poland; phone: 48 22 73-57-543, e-mail: Sz.L.Dabkowski@itep.edu.pl

For citation: Bąk Ł., Dąbkowski Sz.L. 2013. Spatial distribution of sediments in Suchedniów reservoir. Journal of Water and Land Development. No. 19 p. 13–22

Abstract

The paper presents measurements of the amount, spatial distribution, grain size structure, density and the content of organic matter in sediments of Suchedniów reservoir. After 33 years of exploitation, the primary volume of the reservoir decreased by 78 thousand m³. Catchment area covered in 45% by forests is 83 km². Mean annual water flow is estimated at 0.63 m³·s⁻¹. Primary volume of the reservoir was 303 thousand m³ and its surface area – 21.4 ha. The greatest width of the reservoir is 490 m, distance from the river inlet to the dam is 655 m and the length along assumed water course is 740 m. Mean and maximum depths are 1.42 and 4 m, respectively.

The analyses of vertical and horizontal distribution of sediments revealed that in the deepest parts of the water body, where depth exceed 2.6 m, only 16% of sediment volume were deposited. In the inlet part of a relative volume of 0.2, 32% of sediment volume were deposited and in the outlet part – 16%. The reservoir accumulates material of a grain size <1.0 mm whose density varies between 2586 and 2758 kg·m⁻³. Percent of organic parts in sediments ranged from 0.24 to 18.97%.

The existing methods of description of sediment distribution in retention reservoirs do not allow for accurate predicting of this distribution. They do not account for many factors affecting the distribution of sediments in reservoirs and for the time of exploitation. None of the dimensionless curves of the Annandale's nomograph [ANNANDALE 1984] describes the distribution of sediments in Suchedniów Reservoir. The curve closest to the actual distribution curve corresponds to the value $dP/dx = 1.2$ while for Suchedniów Reservoir dP/dx is 0.0014 (P – wetted perimeter of the reservoir's cross section, x – distance from the dam).

Sediments in vertical profiles have laminar structure and bottom material in layers largely differs in grain size and colour which is an evidence of different conditions of sedimentation in different hydrological periods and exploitation conditions. In general, grain size of sediment particles tends to decrease along the water flow direction.

Key words: grain-size distribution, small water reservoir, silting of reservoir, spatial sediment distribution

INTRODUCTION

The intensity and course of silting in small dam reservoirs, also in these of agricultural catchments, is much higher than in large reservoirs [BEDNARCZYK,

MICHAŁEC 2002; DĄBKOWSKI *et al.* 1982; ŁAJCZAK 1995; MICHAŁEC 2008]. In many cases the effective time of exploitation of such an object does not exceed several dozen years. Sediments deposited in the reservoir decrease its volume, elevate its bottom, increase

and elongate the water lifting curve. Sedimentation is followed by overgrowing of the reservoir, by worsening its aesthetic values and by a decrease in the quality of stored water. Elevation of the water table in the upper part of the water lifting curve worsens anti-flood security in areas situated above the reservoir, bridges, footbridges and side dams. Understanding the distribution of sediments in the reservoir is important for water management and an ability to predict it, apart from assessing the amount of sediments, is helpful for designing proper location of facilities like spillways and intakes, bathing areas etc. This may also improve an assessment of the effectiveness of investment.

Published in the country and international literature [BRUK (ed.) 1986; MAJEWSKI, WALCZYKIEWICZ (eds.) 2012] results of field studies and numerical modelling [BANASIK *et al.* 1993] of the distribution of sediments pertain mainly to large water bodies. In Poland, such studies on small reservoirs were mainly carried out at universities [BANASIK *et al.* 1995a, b; 2012; BEDNARCZYK, MICHAŁEC 2002; MICHAŁEC 2008; GÓRSKI *et al.* 2011]. In the USA, studies on silting of small reservoirs of a volume between 2 thousand and 1170 thousand m³ and catchment area from 0.52 to 35 km² were performed at the Department of Agriculture and their results were presented by DENDY [1982]. It appears that – as in large reservoirs – the main factors decisive for sedimentation of solid particles and their distribution in a reservoir include: grain size of the river debris, exploitation conditions, shape of reservoir's basin affecting water velocity and retention time. In reservoirs studied by Dendy, fine-grained sediment of a diameter less than 0.08 mm was evenly distributed throughout the reservoir while particles larger than 0.75 mm settled in its upper part. However, due to different reasons their distribution may vary.

The aim of this study was to check spatial distribution of sediments in a small retention reservoir and to analyse methods describing this distribution based on data from Suchedniów Reservoir in Świętokrzyskie Province and to determine selected physical properties of sediments.

Studies were realised within the project N N305 299040 financed by the National Centre of Science, contract number 2990/B/P01/2011/40.

METHODS OF DESCRIPTION OF SEDIMENT DISTRIBUTION AND THE SPECIFICS OF SMALL RETENTION RESERVOIRS

Spatial distribution of sediments in reservoir's basin is being described by various methods. In an engineer's way, used in operational plans of water management, it is expressed as a shift of the actual curve of reservoir's volume with respect to the primary curve. Horizontal shift of a point on the curve actual for a given level of water lifting represents the volume of sediments deposited beneath this level.

This theoretical and very simplified method elaborated by CHRISTOFANO [1953] is known in English literature [BATUCA, JORDAAN 2002; RAHMANIAN, BANIHASHEMI 2012] as the Area-Increment Method (AIM). It belongs to the group of empirical methods based on the assumption that sedimentation takes place in the reservoir's dead volume. In the case of small reservoirs it is not a real assumption and, in general, it may pertain to reservoirs supplied mainly with suspended load.

Distribution of sediments in large reservoirs of a volume from 50 million m³ to 37 billion m³ was elaborated by BORLAND and MILLER [1958] who analysed results of measurements in reservoirs of the USA (in Polish literature this method is described in DĄBKOWSKI *et al.* [1982]).

In a method proposed by Rooseboom and Annandale [BATUCA, JORDAAN 2000] it is assumed that there is a relationship between horizontal distribution of sediments in a reservoir and the change of wetted perimeter in conditions of minimum stream power. Based on results of studies performed in 11 large and substantially silted water bodies of the Republic of South Africa, ANNANDALE [1984] elaborated graphical relationships between dimensionless cumulated sediment volume and the relative distance from the dam for various mean values of the gradient of wetted perimeter along the reservoir.

For small and shallow reservoirs without a large water level fluctuations, the methods mentioned above are, in authors' opinion, not justified since most sediments settle in the upper shallow zones of a reservoir as was shown in many analyses [BEDNARCZYK, MICHAŁEC 2002; BRUK (ed.) 1986; DENDY 1982; MICHAŁEC 2008]. From among country studies on small reservoirs, the richest set of data was collected by MICHAŁEC [2008]. He analysed 12 reservoirs in southern Poland, mainly on mountain rivers and streams, of various basin geometry, hydrology and of different regime of exploitation. Water flow through these reservoirs, periods of exploitation and the degree of siltation were also different. Measurements and results of studies on siltation in large reservoirs in the country are described in MAJEWSKI and WALCZYKIEWICZ (eds.) [2012]. No studies on siltation in reservoirs that play exclusively flood control role (called dry reservoirs) were found in the country literature. Due to their specific features, they differ in the transport of river debris during flood waves from the reservoirs permanently filled with water. Even if the latter are partly emptied to absorb flood waters, hydraulic processes operating there differ from those in dry reservoirs.

Sediment distribution certainly depends on the form of reservoir's basin since, irrespective of the water flow and the way of exploitation, forces that transport river material there depend on bottom slope, cross-section of the water stream and its variability along the flow. The proportion of reservoir's volume to the volume of inflowing water may also exert an

effect on sediment distribution. Small artificial water bodies are made in various ways. Their basins may be the natural depressions in river valleys but they may be dug or formed in a half-excavation or a half-dyke. Therefore, the variability of shapes and their elevation

is much greater in small than in large reservoirs. That is also why the transport of river debris operates there in a different way. When analysing the surface of reservoirs one may distinguish at least several characteristic schemes presented in Fig. 1.

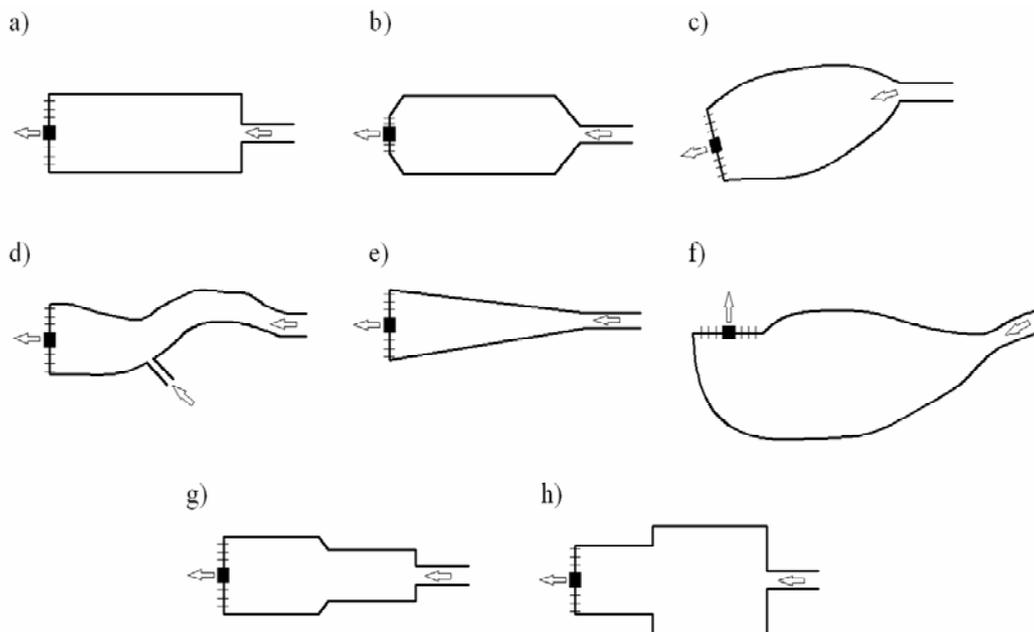


Fig. 1. Some examples of reservoirs' shape; source: own elaboration

In reservoirs of a circular shape as those in Fig. 1c and f, water velocity rapidly decreases from the river inlet. River debris settles in the upper part of the basin and is transferred closer to the dam along with its filling. In narrow and long reservoirs or such which smoothly widen towards the dam (Fig. 1a, b, d, e, g) water velocity decreases slower and river debris flows closer to the dam being sorted from coarser to finer at the same time. Shoreline roughness, meandering river channel in the natural valley and small depths result in varying flow velocities in various parts of the reservoir and accompanying increase of water turbulence. These flow features differentiate the conditions of river debris sedimentation and alter hydraulic conditions of transport. Another feature which does not manifest itself in large and deep reservoirs is the wave action which may cause resuspension of sediments and their relocation in the reservoir.

In all types of reservoirs, the distribution of sediments is affected by the way of throughflow of high waters and the location and type of spillways. In small reservoirs it may reach far upstream from the dam. In large reservoirs of controlled water management the effect may be magnified by marked lowering of water table when the reservoir is prepared to absorb and retain high waters. Described course of reservoir siltation is confirmed by both the studies of Borland and Miller and those of Murthy presented in the BRUK (ed.) [1986] publication. The latter author drawn the distribution of sediments in four reservoirs in India on the graphs of relative distribution given by Borland

and Millar. The graphs clearly show that the curves of distribution for shallow reservoirs are situated close to the curve I of Borland corresponding to reservoirs of a lake type. The reciprocal of the slope of reservoir volume curve presented in logarithmic scale (when depth is expressed in feet and volume in acre-feet) is an index of the reservoir type. For reservoirs of the type I the slope is 0.28–0.22 while reservoirs in river valleys are characterised by the slope of 1.0 to 0.67.

When comparing the distribution curves from measurements in 14 largely silted reservoirs with curves calculated with the Borland and Miller's method, ANNANDALE [1984] obtained the same number of the curve in only one case. Moreover, he failed to estimate the Borland and Miller's curve and to obtain sediment distribution as a function of the distance from dam for each of the reservoirs. He is of the opinion that better results in predicting sediment distribution brings the method of minimum moving force.

It should be underlined here, that the distribution of sediments in a reservoir is associated with the time of exploitation and the rate of sedimentation. It is known, that the last phase of reservoir's existence is a new river channel of dynamic equilibrium formed there. Sediments settled in a reservoir determine flow velocity and hence, the ability of a stream to transport and sort solid particles along its course. Based on published papers it is hard to find whether their authors considered time as a factor when evaluating the proposed methods of description of sediment distribution.

DENDY [1982] proposed a method to describe the spatial distribution of sediments in small retention reservoirs. The method presents in a dimensionless system the vertical (i. e. in distinguished layers of reservoir) and horizontal (i.e. along stretches of the reservoir's length) distribution of sediments. Vertical distribution of sediments depicts the relationship between their relative volume (S_v/S) and the relative reservoir's depth (D/D_{\max}). The relative volume of sediments should be understood as the ratio of their volume S_v settled beneath a given level v to the total volume of sediments S in a reservoir. Relative depth means the ratio of water depth D beneath a given level v to the maximum reservoir's depth D_{\max} . Horizontal distribution is presented as a relationship between the relative sediment volume (S_h/S) and the relative volume of a reservoir (V_h/V) providing that:

- the relative volume S_h/S means the ratio of sediment volume settled above a given cross-section of a reservoir S_h to their total volume S ,
- the relative volume of a reservoir V_h/V means the ratio of a volume of that part of a reservoir which is above a given cross-section V_h to its total volume V .

It seems that the method is more useful to describe actual sediment distribution rather than to predict it.

To sum up, one may state, that due to numerous factors affecting sedimentation of the river debris in small retention reservoirs and their translocation in various hydrological and exploitation conditions, we do not have sufficiently certain method for describing sediment distribution. Therefore, it is important to collect information on sediment distributions to enable sound analysis of this issue in the future.

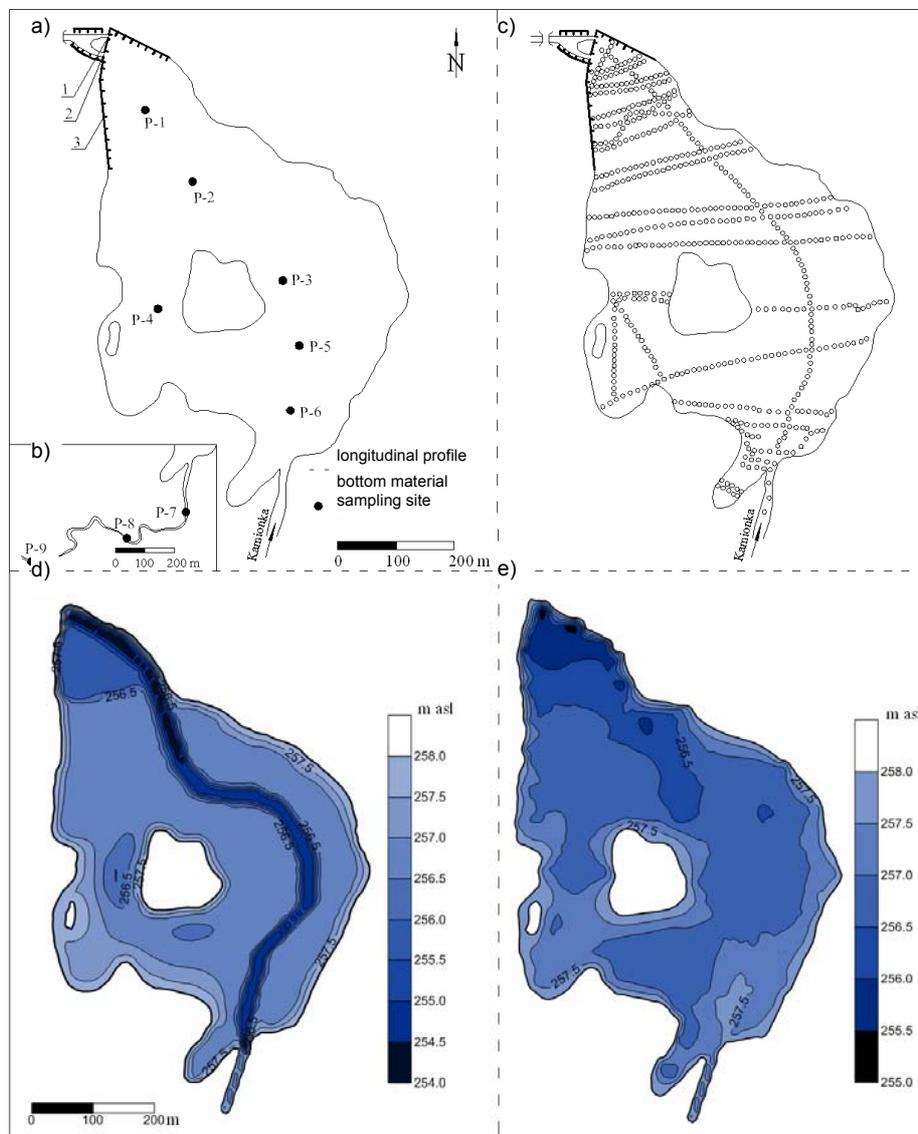


Fig. 3. Suchedniów Reservoir; a) plan of the reservoir and its technical facilities: P-1 to P-6 sites for sampling bottom sediments; b) plan of the inlet river section, P-7 to P-9 sites for sampling bottom sediments in the Kamionka River channel; c) routes of echosound during depth measurements; d) bathymetric map of Suchedniów Reservoir – designed state; e) bathymetric map of Suchedniów Reservoir – state of the year 2011; 1 – weir, 2 – relief spillway, 3 – earthen dam; source: own elaboration

CHARACTERISTICS OF THE STUDY OBJECT

The study object was a small reservoir in Suchedniów on the Kamionka River built in the years 1965–1974. The reservoir was made by damming the river in its 7+750 km course by a 320 m long earthen dam. Water surface and the location of the dam and spillways are presented in Figs 3a and 3b. There are two islands in the middle, widest part of reservoir. The smaller has an area of c. 1 ha, the larger branching the water course – 1.3 ha. The reservoir in its lower part smoothly narrows to the dam. Left shore of its upper part is developed into small promontories and bays. The reservoir is situated within the limits of Suchedniów and is used for recreational purposes.

Initial volume of the reservoir was 303 thousand m^3 (at normal water level = 258.00 m a.s.l.) and its surface area was 21.4 ha. The greatest width is 490 m, the distance from the dam to river inlet is 655 m and the length along the assumed water course – 740 m. Mean depth of the reservoir was 1.42 m and the maximum depth – 4 m (near the sluice). Measurements of the reservoir's volume were made twice: first in 2010 and the next in 2011. According to these measurements it was found that the initial reservoir's volume was reduced by ca. 78 thousand m^3 [BAK *et al.* 2011].

Land use structure of the catchment basin (of an area of 83 km^2) is dominated by forests which occupy more than 45% of the area. They form dense pine-fir complexes with an admixture of beech and spruce situated in south-eastern and south-western part of the catchment. Arable lands cover ca. 18% of the area and the crop structure is dominated by cereal plants. Remaining part of the catchment is covered by meadows, pastures and barren lands (32%) and built-up areas (5%). Soils are not fertile (IV, V and VI class of soil quality) and are represented by podzols made of weak loamy and loamy sands and loose gravel or of silt formations of water origin and by brown soils made of light and medium boulder loams.

Catchment basin of the Kamionka River is in the climatic region of the Świętokrzyskie Mountains where monthly mean precipitation achieves the highest values in July, June, August and May and the lowest are noted in October. Annual mean sum of precipitation is 750 mm [STACHY (ed.) 1987]. Annual mean water flow (SSQ) is $0.63 m^3 \cdot s^{-1}$ and other characteristic flows calculated with the hydrological analogue method are set up in Table 1. Flows for the analogue river (the Kamienna River, Wąchock cross-section) catchment were estimated from Atlas hydrologiczny for the years 1951–1971. Minimum acceptable flow Q_n was calculated with the method of Kostrzewa [KOSTRZEWA 1977].

Table 1. Characteristic flows of the Kamionka River in the Suchedniów cross-section, $m^3 \cdot s^{-1}$

NNQ	SNQ	SSQ	SWQ	WWQ	Q_n
0.05	0.14	0.63	10.50	43.40	0.18

Source: own study.

The reservoir is equipped with three outlets built in the earthen dam. Two of them include a two-span weir with vertically lifting gate and a concrete relief spillway. The third is a steel monk situated on the right side wall of the weir.

Normal water level of 258.00 m a.s.l. is maintained in spring, summer and autumn. In winter water table is lowered by 0.35 m. Operators have to manoeuvre the gates in a way to keep the normal water level even during the passage of flood waters. If, however, the inflow to the reservoir exceeds the output of the weir and open monk, waters spill over through the relief outlet and then, there are no possibilities of controlling water level in the reservoir. River debris flow in this situation from both upper and near-bottom water layers.

RANGE AND METHODS OF MEASUREMENTS

Sediment thickness in Suchedniów Reservoir was estimated from the difference of ordinates of primary bottom and those taken during water depth measurements at known ordinate of the water table. Depth was measured with a profiling flowmeter Sontek River Surveyor. It is equipped with a five-band ultrasonic transducer type S5 that enables measurements of both the depth and the distribution of velocity in measurement verticals. Measurement is based on Doppler's effect and is realised with 5 measurement bands: four bands of a frequency of 3 MHz each emitted at an angle of 25° from the vertical serve for velocity measurements and the fifth, 1 MHz vertical band is used to measure depth. The flowmeter is integrated with navigation module RTK GPS of an accuracy of ± 3 cm. All measured parameters are recorded continuously. Routes of echo sound during depth measurements are presented in Fig. 3c.

Echo sounding gives a set of points covering the reservoir's area where water is deeper than 0.2 m. Zones of smaller depths, not measured with the echosound were obtained by estimating the range of floods from plane images. So collected data served to evaluate a digital model of the present reservoir's basin. Primary shape of the reservoir was determined from archive data (post-construction cross-sections and plan of reservoir's basin). Both models were used to estimate the thickness, distribution and volume of deposited sediments. Collected data were analysed with the Surfer software. Bathymetric maps illustrating the primary and present shape of reservoir's bottom are shown in Fig. 3d and 3e.

Sediment samples were taken from a boat with Eijkelkamp sampler. It allows to take sediments to translucent cylinders of a length of 1.20 m and internal diameter of 43 mm pressed into the bottom. Samples have a form of a quasi-undisturbed core.

Mass of collected samples, depending on sediment thickness, varied between 0.50 and 1.10 kg. Location of sampling sites for sediment collection are marked in Fig. 3a. The entire core was divided into

layers differing in colour and composition as seen in Fig. 4. Grain size structure of sediments was determined for distinguished layers of a thickness from 0.10 to 0.25 m.

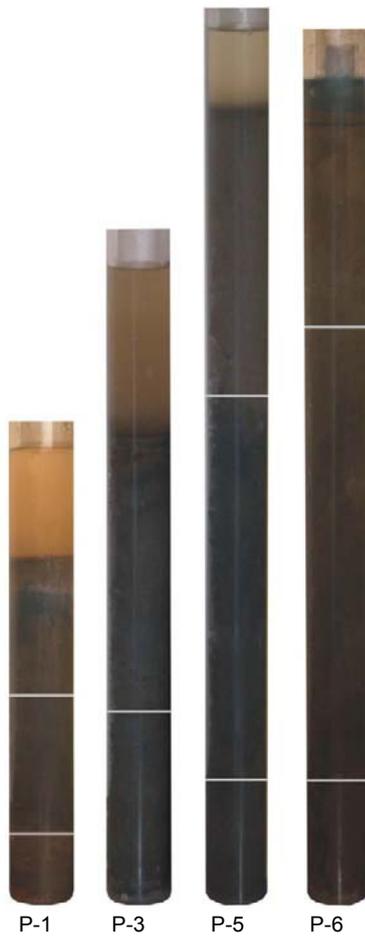


Fig. 4. Sediment core samples; sampling sites are shown in Fig. 3a and b; source: own elaboration

Granulometric composition was determined with the Cassagrande's method in Pruszyński's modification. 1.5 g of anhydrous sodium carbonate (Na_2CO_3) was added to sediment suspension as a de-flocculant. Sediment characteristics included:

- characteristic diameter of grains d_{50} which together with the smaller ones constitute 50% of mass of analysed sample,
- average diameter estimated as a weighed mean from the equation:

$$d_m = \frac{\sum[d_i \Delta p_i]}{\sum \Delta p_i} \quad (1)$$

where: d_i – mean grain diameter in a fraction of the content of Δp_i ,

- mean diameter d_s excluding the extreme fractions and expressed as:

$$d_s = \frac{d_{16} + d_{50} + d_{84}}{3} \quad (2)$$

- graphical mean diameter GSS :

$$GSS = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3} \quad (3)$$

- graphical standard deviation GSO :

$$GSO = \frac{\varphi_{84} - \varphi_{16}}{4} + \frac{\varphi_{95} - \varphi_5}{6.6} \quad (4)$$

where: in equations (3) and (4) $\varphi = -\log_2 d_i$, d_i – characteristic diameter, mm.

Scale φ proposed by KRUMBEIN [1934] is commonly used in sedimentology [GRADZIŃSKI *et al.* 1976]. Ranges of this scale correspond to logarithms at base 2 and the use of minus allows for using positive numbers for psammite and pelite sediments.

Sediment density was determined with the pycnometric method and percent of organic matter – as a loss on ignition. Noteworthy, in the river sediments (at a depth beneath 50 cm in P-9), material of a character of the rocky rubble was deposited. Fine-grained material of grain size as that given in graphs for P-8 originates from shore erosion or is delivered to the river channel as a product of surface erosion in the catchment.

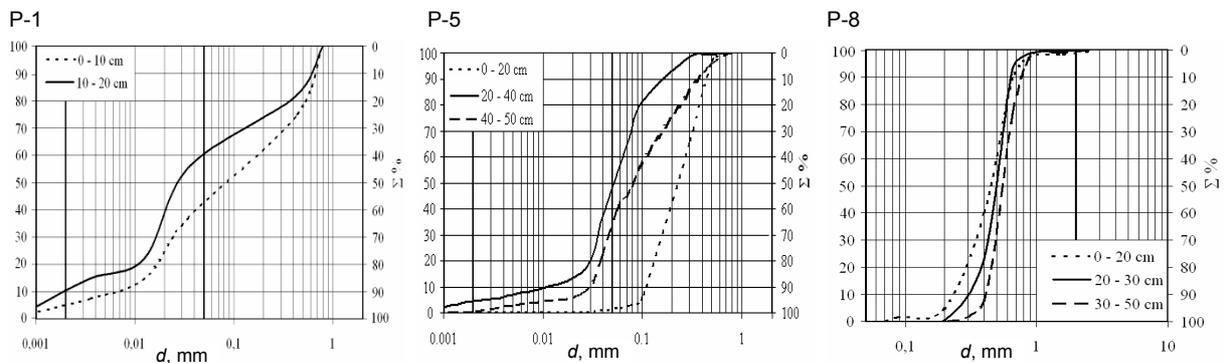


Fig. 5. Granulometric curves; location of sampling sites for sediments is presented in Fig. 3a and b; source: own elaboration

Table 2. Selected characteristics of bottom sediments in Suchedniów Reservoir

Sample	d_{50}	d_m	d_s	GSS	GSO	ρ kg·m ⁻³	Organic matter content %
	mm						
P-1	0.04–0.05	0.05–0.11	0.04–0.10	2.57–3.06	1.70–2.50	2586–2758	0.38–1.80
P-2	0.03–0.06	0.07–0.11	0.06–0.10	5.05–5.71	2.57–3.06		0.50–4.50
P-3	0.03–0.07	0.06–0.09	0.12–0.18	3.70–4.90	2.50–3.00		0.48–5.90
P-4	0.02–0.03	0.07–0.08	0.17–0.18	4.10–4.80	2.70–3.20		0.32–4.90
P-5	0.05–0.23	0.08–0.27	0.07–0.26	2.12–4.16	0.26–1.66		0.24–18.97
P-6	0.15–0.28	0.16–0.25	0.16–0.23	2.60–3.10	1.50–1.60		0.24–9.02
P-7	0.30–0.59	0.24–0.55	0.31–0.66	0.70–1.70	0.30–0.50		0.51–3.28
P-8	0.45–0.55	0.36–0.45	0.44–0.56	0.90–1.30	0.30–0.60		0.49–5.15
P-9	0.45	0.39	0.45	0.60	0.60		0.18

Source: own study

RESULTS AND THEIR ANALYSIS

Sediment distribution in Suchedniów Reservoir measured in 2011 i.e. after 33 years of its exploitation and prepared according to Dendy's method is shown in Fig. 6. Fig. 6a presents vertical distribution. It appears that in lower part of the water body of relative depth ≤ 0.35 , 16% sediments were deposited. At relative depth above 0.85 only 9% sediments were deposited. Seventy five percent of the total sediment volume settled at relative depth between 0.35 and 0.85. Sediments were evenly dispersed at the depth which was evidenced by a quasi-stable inclination of the fragment of dimensionless curve in this range (Fig. 6a). Clastic material deposited in this part of reservoir was in more than 50% composed of grains whose diameter was less than 0.08 mm.

The graph of horizontal sediment distribution (Fig. 6b) shows that after 33 years of exploitation 32% of the total sediment volume deposited in the inlet part of the reservoir (relative reservoir's volume ≤ 0.2). In the middle part (relative reservoir's volume from 0.2 to 0.8) sediment volume was 52% and in the outlet part (relative reservoir's volume ≥ 0.8) – 16% of the total volume.

Spatial distribution of sediments in Suchedniów Reservoir was compared with distributions in Zesławice [TARNAWSKI, SŁOWIK-OPOKA 2002] (after 2 and 17 years of exploitation) and Staw Górny [BANASIK *et al.* 1995b] (after 5 years of exploitation) reservoirs of similar volume and catchment basin (Fig. 7). The comparison showed that the vertical distribution of sediments in Suchedniów Reservoir was similar to that in Zesławice Reservoir after 17 years of its exploitation.

Small, less than several percent, differences in the distribution of clastic material pertain to the deepest and shallowest part of the water body, relative depth of which was 0.3 and 0.85, respectively. The two reservoirs have similar shape of the inlet and outlet parts but differ in the geometry of the middle part.

The curve of horizontal distribution of sediments in Suchedniów Reservoir is also similar to that in Zesławice Reservoir (Fig. 7b). Small differences may result from morphological differences and from time

that elapsed since the start of exploitation and the year of measurements. Dimensionless distributions of sediments in Suchedniów and Staw Górny reservoirs differ, however, remarkably and the reason may be sought in different shapes of their basins. The shape of Staw Górny is closer to a scheme *a* in Fig. 1 while that of Suchedniów Reservoir – to a scheme *f* in Fig. 1. The curve of sediment distribution in Suchedniów Reservoir from Fig. 8 is shown on Annandale's nomograph. Relative distance of the cross section from the dam is on abscissa and the relative sediment volume along a section of the length *L* from the dam – on the *Y* axis. V_{fsl} and L_{fsl} are the total sediment volume and total length of reservoir, respectively. None of dimensionless curves on this nomograph describes the distribution of sediments in Suchedniów Reservoir. The closest curve on the nomograph corresponds to

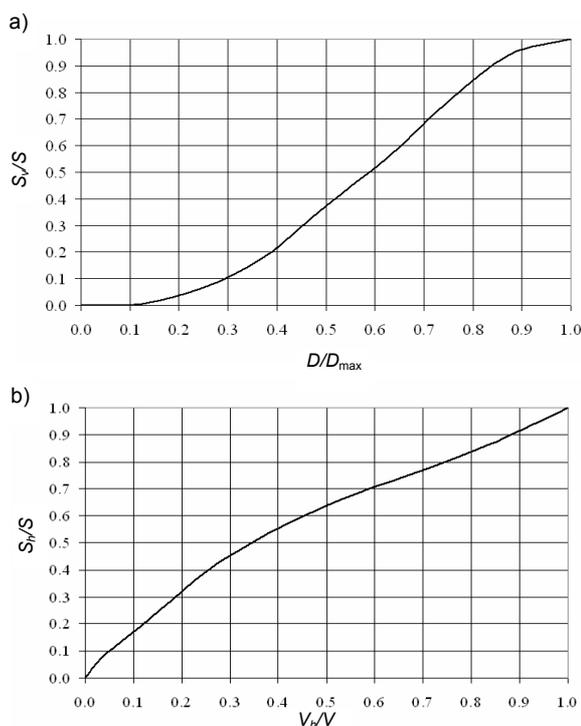


Fig. 6. Distribution of sediments in Suchedniów Reservoir: a) vertical, b) horizontal; source: own elaboration

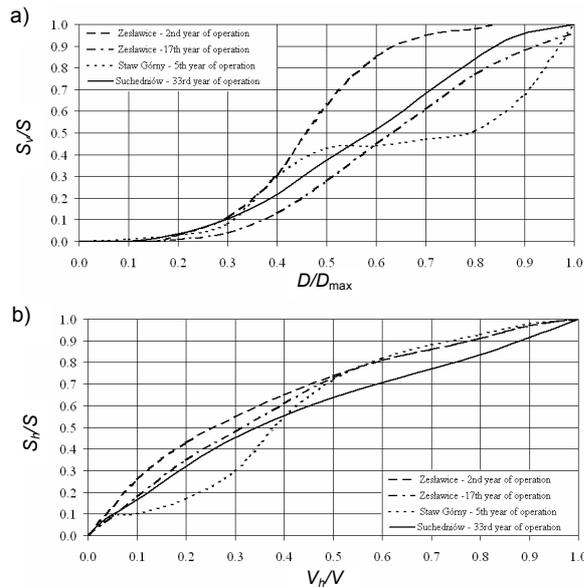


Fig. 7. Sediment distribution in small water reservoirs: a) vertical, b) horizontal; source: own study

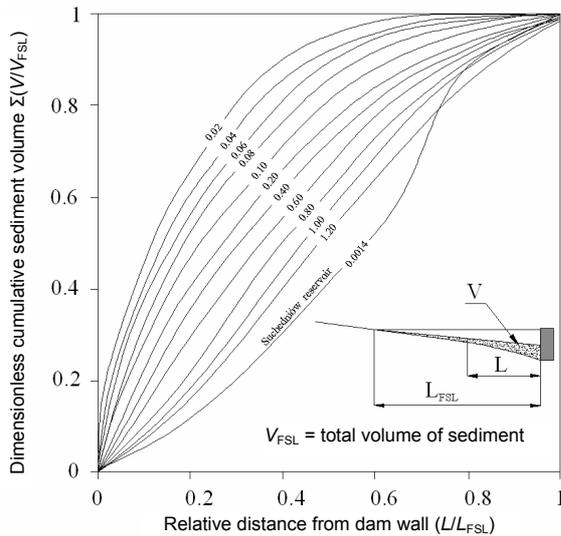


Fig. 8. Sediment distribution in Suchedniów Reservoir compared with the Annandale's nomograph

$dP/dx = 1.2$ while dP/dx for Suchedniów Reservoir is 0.0014, where P is wetted perimeter and x – distance along reservoir's axis.

Sediment characteristics

The analysis of grain size curves showed that sediments deposited in Suchedniów Reservoir contained mainly fine-grained material of grain diameter less than 1.0 mm (sandy, silt and clay fractions). According to country appendix to the norm PN-EN ISO 14688, bottom sediments of the reservoir qualify to the following ground categories: sample P-1 – silty loam (layer 0–10 cm and 10–20 cm), sandy silt (layer 20–25 cm), sample P-2 – clayey loam, samples P-3 and P-4 – silty loam, sample P-5 – sand (sediment layer 0–20 cm), sandy silt (sediments layer 20–40 cm and 40–50 cm), sample P-6 – silty sand, samples P-7, P-8 and P-9 – sand.

Material settling in the reservoir was badly or very badly sorted which was evidenced by the values of GSO above one, with the exception of an upper 20 cm thick sediment layer in sample P-5, for which graphical standard deviation was 0.26. So low GSO indicates very good sorting of the sediment. Bad sorting is a result of mixing the settled material deposited by currents of various strength, that appear in periods of variable water flow. Variable conditions and periodical character of the input of river debris are also evidenced by distinct granulometric differentiation in particular sediment layers (Fig. 5). Good sorting indicates the longevity of transport and settlement of a given fraction at constant water velocity along a given reservoir section. Such conditions may occur in backwater part of the reservoir and in the river channel outside the range of backwater. This may be confirmed by good sorting of samples P-7, P-8 and P-9 (Tab. 2). The GSO values for these samples were markedly smaller than one. When comparing grain sizes in P-3 and P-4, one may assume similar conditions of water flow and sedimentation in both branches divided by the island.

The analysis of diameters of d_{50} particles in the upper 10 cm sediment layer confirms the fact that it increases in cross sections more distant from the dam (Fig. 9) where moving force is stronger. Only for P-1 sample collected near spillways, this regularity was slightly disturbed which may be explained by narrowing the reservoir near dam and by an increase of flow velocity there. Similar variability of d_{50} diameter along the reservoir and similar values of d_{50} , d_m and d_s diameters were found by GÓRSKI *et al.* [2011] in Staw Górny, whose shape in its lower part is similar to the shape of Suchedniów Reservoir.

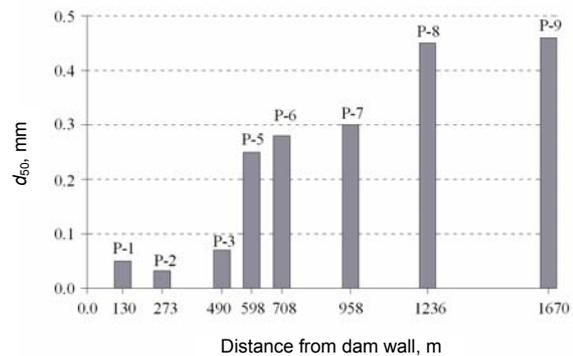


Fig. 9. Changes in d_{50} diameter of the upper 10 cm sediment layer; source: own elaboration

Organic matter content in analysed samples was from 0.18% to 18.97%. The highest content was found in an upper 3 cm sediment layer of samples P-5 (18.97%) and P-6 (9.02%) taken from the inlet part of the reservoir (Tab. 2). This could be an effect of several factors: sampling time (autumn – natural fallout of leaves and decomposition of aquatic vegetation and littoral plants) and hydrodynamic conditions (low flows facilitate sedimentation and accumulation of

inflowing organic material in the upper part of the reservoir).

In deeper sediment layers and in other samples the content of organic matter did not exceed 5.9%. Obtained results are comparable with those published by TARNAWSKI and MICHAŁEC [2006], MADEYSKI and TARNAWSKI [2007] and by MADEYSKI *et al.* [2008] for small reservoirs studied by these authors.

CONCLUSIONS

1. Existing methods for the description of sediment distribution in small retention reservoirs do not allow for accurate predicting this distribution.

2. Elaborated curves of sediment distribution in Suchedniów Reservoir show that 32% of sediments were deposited in its upper part whose relative volume was 0.2. In the middle part of the reservoir (relative volume from 0.2 to 0.8) 42% of sediments were deposited and in the outlet part – 16% of sediments. In the vertical sediment distribution we may distinguish two zones differing in the rate of sediment accumulation – the first to ca. 0.3 of its relative volume and the second – above 0.3. From the analysis of the curve of vertical sediment distribution it appears that in the deepest part of the reservoir (depth >2.6 m) 16% of the total sediment volume were deposited. In shallowest parts of the reservoir (depth <0.6 m) the volume of deposited sediments did not exceed 9%. The curves allow for distinguishing areas of various intensity of sediment settlement and for comparing their distribution with other reservoirs and after different periods of exploitation.

3. Fine-grained sediment of a diameter d_{50} in the range 0.03–0.28 mm, rather poorly sorted ($GSO > 1$), is mainly deposited in the reservoir.

4. Sediments in vertical profiles have a laminar structure and the layers differ in grain size and colour which is an evidence of different conditions of sedimentation in various periods.

5. Sediment density ranged from 2586 to 2758 $\text{kg}\cdot\text{m}^{-3}$ and the content of organic matter from 0.24% to more than 18%. Most organic particles were present in the upper 3 cm layer of sediments in the upper part of reservoir, where they settled from river water.

REFERENCES

- ANNANDALE G.W. 1984. Predicting the distribution of deposited sediment in southern African reservoir. Challenges in African Hydrology and Water Resources. Proceedings of the Harare Symposium, July 1984. IAHS Publ. No. 144.
- BANASIK K., GÓRSKI D., POPEK Z., HEJDUK L. 2012. Estimating the annual sediment yield of a small agricultural catchment in central Poland. In: Erosion and Sediment Yields in the Changing Environment [online]. Eds. A.E. Collins, V. Golosov, A.J. Horowitz, X.Ju.M. Stone, D.E. Walling, X. Zhang. IAHS Publ. 356. Wallingford, IAHS Press, p. 267–275. [Access 03.06.2013]. Available at: http://iahs.info/redooks/a356/abs_356_0267.pdf
- BANASIK K., GÓRSKI D., SKIBIŃSKI J., 1995a. Metodyka oceny intensywności erozji gleb w zlewni i akumulacji rumowiska w zbiornikach wodnych. W: Metodyka zagospodarowania zasobów wodnych w małych zlewniach rzecznych. [Methods for assessing soil erosion in the catchment and accumulation of debris in water reservoirs. In: Methods for water resources management in small river catchments]. Ed. A. Ciepielowski. Warszawa. Wydaw. SGGW p. 63–76.
- BANASIK K., GÓRSKI D., SKIBIŃSKI J. 1995b. Obliczenie akumulacji rumowiska w zbiorniku Staw Górny. W: Metodyka zagospodarowania zasobów wodnych w małych zlewniach rzecznych [Calculation of the accumulation of river debris in Staw Górny Reservoir. In: Methods for water resources management in small river catchments]. Ed. A. Ciepielowski. Warszawa. Wydaw. SGGW p. 136–143.
- BANASIK K., SKIBIŃSKI J., GÓRSKI D. 1993. Investigation on sediment deposition in a designed Carpathian reservoir. In: Sediment Problems: Strategies for Monitoring, Prediction and Control. Eds F. Hadley, Mizuyama. IAHS Publ. 217. Wallingford, IAHS Press, p. 101–108. http://iahs.info/redooks/a217/iahs_217_0101.pdf
- BATUCA G. D., JORDAAN M. J. 2000. Silting and desilting of reservoirs. Rotterdam, Netherlands. A.A. Balkema. ISBN 9789054104773 pp. 353.
- BAK Ł., DĄBKOWSKI SZ. L., GÓRSKI J. 2011. Metoda prognozowania zamulenia zbiornika wodnego na podstawie pomiaru pojemności [Method of predicting siltation of a water reservoir based on measurements of its capacity]. Woda-Środowisko-Obszary Wiejskie. T. 11. Z. 4(36) p. 19–29.
- BEDNARCZYK T., MICHAŁEC B. 2002. Ocena stopnia zamulenia małych zbiorników wodnych [An assessment of siltation of small water reservoirs]. Roczniki AR Poznań. Melioracje i Inżynieria Środowiska. T. 23 p. 3–11.
- BORLAND W., MILLER C.R. 1958. Distribution of sediments in large reservoirs. Journal of the Hydraulics Division ASCE. Vol. 84. No. HY2 p. 1–18.
- BRUK S. (ed.) 1986. Methodes de calcul de la sedimentations dans les lacs et resevoirs. Paris. UNESCO.
- CRISTOFANO E.A. 1953. Area-increment method for distributing sediment in a reservoir. Albuquerque. New Mexico. US Bureau of Reclamation.
- DĄBKOWSKI SZ. L., SKIBIŃSKI J., ŻBIKOWSKI A. 1982. Hydrauliczne podstawy projektów wodno-melioracyjnych [Hydraulic principles of water reclamation projects]. Warszawa. PWRiL. ISBN 8309004079 pp. 533.
- DENDY F.E. 1982. Distribution of sediment deposits in small reservoirs. Transactions of the ASAE. Vol. 25 p. 100–104.
- GÓRSKI D., POPEK Z., BANASIK K., HEJDUK L. 2011. Impact of small reservoir on reduction of solid transport. In: Prediction and reduction of diffuse pollution, solid emission and extreme flows from rural areas: case study of small agricultural catchments [online]. Eds. K. Banasik, L. Øygarden, L. Hejduk. Warszawa. Wydaw. SGGW p. 219–232. [Access 03.06.2013]. Available at: <http://ziw.sggw.pl/zaklad/monogra/rozdzal-14.pdf>
- GRADZIŃSKI R., KOSTECKA A., RADOMSKI A., UNRUG R. 1976. Sedymentologia [Sedimentology]. Warszawa. Wydaw. Geol. ISBN 83-220-0275-0 pp. 613.
- KOSTRZEWA H. 1977. Weryfikacja kryteriów i wielkości przepływu nienaruszalnego dla rzek Polski [Verification of the criteria and amounts of minimum acceptable flow for Polish rivers]. Materiały Badawcze IMGW. Ser. Gospodarka Wodna i Ochrona Wód. Warszawa. pp. 207.
- KRUMBEIN W.C. 1934. Size frequency distribution of sediments. Journal of Sedimentary Petrology. Vol. 4. No. 2 p. 65–77.

- ŁAJCZAK A. 1995. Studium nad zamulaniem wybranych zbiorników zaporowych w dorzeczu Wisły [A study on siltation in selected dam reservoirs in the Vistula catchment basin]. Monografie Komitetu Gospodarki Wodnej PAN. No. 8. Warszawa. PWN. ISSN 0867-7816 pp. 108.
- MADEYSKI M., MICHAŁEC B., TARNAWSKI M. 2008. Zamulanie małych zbiorników wodnych i jakość osadów dennych [Siltation of small water reservoirs and the quality of bottom sediments]. Infrastruktura i Ekologia Terenów Wiejskich. Seria Monografie. Nr 11. ISSN 1732-5587 pp. 76.
- MADEYSKI M., TARNAWSKI M. 2007. Wstępna ocena ilości i jakości osadów dennych wydzielonej części zbiornika wodnego „Besko” na rzece Wisłok [Preliminary assessment of the amount and quality of bottom sediments in a distinguished part of Resko Reservoir on the Wisłok River]. Infrastruktura i Ekologia Terenów Wiejskich. Nr 4/1 p. 101–110.
- MAJEWSKI W., WALCZYKIEWICZ T. (eds.). 2012. Wpływ zmian klimatu na środowisko, gospodarkę i społeczeństwo. T. 4. Zrównoważone gospodarowanie zasobami wodnymi oraz infrastrukturą hydrotechniczną w świetle prognozowanych zmian klimatycznych. Cz. 3. Zamulenie polskich zbiorników retencyjnych. Prognoza stanu i proponowane przeciwdziałania [The effect of climate change on the environment, economy and society. T. 4. Sustainable management of water resources and their hydro-technical infrastructure in view of predicted climate changes. Part 3. Siltation in Polish retention reservoirs. Prognosis of the state and proposed counteracting measures]. Warszawa. IMGW. ISBN 8361102647 pp. 240.
- MICHAŁEC B. 2008. Ocena intensywności procesu zamulania małych zbiorników wodnych w dorzeczu Górnej Wisły. [An assessment of siltation of small water reservoirs in the Upper Vistula River catchment]. Zeszyty Naukowe Uniwersytetu Rolniczego im. Hugona Kołłątaja w Krakowie. Rozprawy. Z. 328. ISSN 1899-3486 pp. 193.
- PN-EN ISO 14688-2. Badania geotechniczne oznaczanie i klasyfikowanie gruntów. Cz. 2. Zasady klasyfikowania. [Geo-technical studies, soil determination and classification. Part 2. Principles of classification].
- RAHMANIAN M.R., BANIHASHEMI M.A. 2012. Introduction of a new empirical reservoir shape function to define sediment distribution pattern in dam reservoirs. Iranian Journal of Science and Technology. Transactions of Civil Engineering. Vol. 36. No. 1 p. 79–92.
- STACHY J. (ed.) 1987. Atlas hydrologiczny Polski [Hydrological atlas of Poland] T. 1. Warszawa. Wydaw. Geol.
- TARNAWSKI M., MICHAŁEC B. 2006. Charakterystyka ilościowa i jakościowa osadów dennych zbiornika wodnego w Wilczej Woli [Quantitative and qualitative characteristics of bottom sediments in a reservoir in Wilcza Wola]. Infrastruktura i Ekologia Terenów Wiejskich. Nr 3/1 p. 31–43.
- TARNAWSKI M., SŁOWIK-OPOKA E. 2002. Rozkład materiału dennego w zbiorniku w Ześlavicach [Distribution of bottom material in a reservoir in Ześlawice]. Zeszyty Naukowe AR w Krakowie. Ser. Inżynieria Środowiska. Z. 23 p. 259–266.

Łukasz BAŁ, Szczepan Ludwik DĄBKOWSKI

Rozkład osadów w zbiorniku Suchedniów

STRESZCZENIE

Słowa kluczowe: mały zbiornik wodny, przestrzenny rozkład osadów, uziarnienie osadów, zamulanie zbiornika

W pracy przedstawiono przebieg pomiarów ilości osadów, ich przestrzenny rozkład i skład granulometryczny, ciężar właściwy i zawartość części organicznych w osadach w zbiorniku wodnym Suchedniów. Po 33 latach jego eksploatacji zmniejszenie pojemności pierwotnej zbiornika wyniosło ok. 78 tys. m³. Pole zlewni wynosi 83 km², a lasy zajmują 45% powierzchni. Średni roczny przepływ wody ocenia się na 0,63 m³·s⁻¹. Pierwotna pojemność zbiornika wynosiła 303 tys. m³, a powierzchnia lustra wody – 21,4 ha. Największa szerokość zalewu wynosi 435 m, długość w linii prostej od zapory do wlotu rzeki do zbiornika 655 m, zaś wzdłuż domniemanego nurtu – 740 m. Średnia głębokość akwenu to 1,42 m, a maksymalna – 4 m.

Na podstawie analizy pionowego i poziomego rozmieszczenia osadów stwierdzono, że w najgłębszych partiach akwenu, gdzie głębokość przekraczała 2,6 m, odłożyło się tylko 16% objętości osadów. W części wlotowej akwenu, o objętości względnej 0,2, zdeponowane zostało 32%, a w części wylotowej – 16% objętości namulów. W zbiorniku jest akumulowany materiał o średnicy ziaren <1,0 mm, którego gęstość właściwa zawierała się w przedziale od 2586 do 2758 kg·m⁻³. Udział części organicznych w namulach wahał się od 0,24 do 18,97%.

Istniejące metody opisu rozkładu osadów w zbiornikach retencyjnych nie dają możliwości trafnego prognozowania tego rozkładu. Nie uwzględniają wielu czynników kształtujących rozkład osadów w czaszy zbiornika i czasu eksploatacji. Żadna z krzywych bezwymiarowych nomogramu Annandala [ANNANDALE 1984] nie opisuje rozkładu osadów w zbiorniku Suchedniów. Krzywa nomogramu najbliższa w stosunku do rzeczywistej krzywej rozkładu odpowiada wartości $dP/dx = 1,2$ (P – obwód zwilżony przekroju poprzecznego zbiornika, x – odległość od zapory), a dla zbiornika Suchedniów $dP/dx = 0,0014$.

Osady mają w profilu pionowym budowę warstwową, a materiał denny w warstwach charakteryzuje się znacznym zróżnicowaniem uziarnienia i barwy, co świadczy o odmiennych warunkach jego sedymentacji w różnych okresach hydrologicznych i warunkach eksploatacji. Ogólnie widoczne jest zmniejszanie się średnicy ziaren osadu zgodnie z kierunkiem przepływu.