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THE INFLUENCE OF SMALL WATER RESERVOIR OPERATIONAL CHANGES ON CAPACITY REDUCTION

The impact of operational changes of small reservoirs on the coefficient of capacity and silting ratio was described. The dependence of the mean annual silting ratio on the capacity-inflow ratio α, which was approximated by an exponent function, was established based on silting investigations carried out by STANOWSKI [9] for five large dam reservoirs, i.e. Solina, Goczałkowice, Tresna, Porąbka and Rożnów. The reservoirs are located in the catchment area of the upper Vistula. The silting intensity was described by the mean annual silting ratio. The silting investigations of these dam water reservoirs permitted the determination of changes in the silting ratio in consecutive years of the reservoir operation.

Two small water reservoirs (Krempna on the River Wisłok and Zesławice on the River Dłubnia) helped prove that reservoir operational changes due to reconstruction influence the capacity-inflow ratio with this value significantly affecting silting intensity and the intensity of capacity reduction.

1. INTRODUCTION

Small water reservoirs become intensively silted. Currently, there have been only a small number of studies conducted on small reservoir siltation, while parameters describing the capacity reduction intensity of such reservoirs are lacking. The following parameters are needed to predict small water reservoir silting: mean annual silting ratio, silting intensity, volume of sediment trapping in the first year of operation, and the bulk density of sediment. When the silting process is understood, the quantity of reservoir water retention can be predicted in subsequent years of operation.

According to Hartung (from BATUCA and JORDAAN [1]), the mean annual silting ratios of large, medium, and small water reservoirs are 0.25%, 0.50% and 0.30%, respectively; however, Hartung does not present the criterion of reservoir capacity. Polish publications mainly describe medium and large water reservoirs [4], [5], [10]. Large water reservoirs are mostly characterized by a high capacity-inflow ratio α [9], which is the quotient of the initial capacity of the reservoir by the sum of the mean

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annual water inflow. A characteristic feature of small water reservoirs is quick water exchange as determined by the coefficient of exchange ($1/\alpha$).

While investigating large water reservoirs in southern Poland, STONAWSKI [9] proved a relation between the mean annual silting ratio and the capacity-inflow ratio. According to Stanowski, large water reservoirs are characterized by a high capacity-inflow ratio of the range of 4.6–12.1% and a mean annual silting ratio of 0.81–0.87%. The mean annual silting ratio was determined by STONAWSKI [9] using the sediment parameter introduced by PARTL [8]. Partl investigated water reservoirs in the Alps and proved a similar relation between the sediment parameter and the capacity-inflow ratio.

The mean annual silting ratio and capacity-inflow ratio may be helpful for predicting small water reservoir silting. This paper attempts to show how operational changes influence the conditions of small water reservoirs in terms of the capacity-inflow ratio and the silting ratio. It also seeks to describe a functional relationship between these parameters.

2. CHARACTERISTICS OF THE RESERVOIRS STUDIED

The reservoirs at Krempna, Zesławice, Cierpisz, Maziarnia, Rzeszów, Ożanna, Niedźwiadek, Narożniki, Cedzyna and Wapienia are located in the upper Vistula River basin. These reservoirs are built in catchments with different geomorphology, geology, and hydrology. They also vary in terms of their design and operation. A detailed description of the reservoirs investigated and catchment areas is given by BEDNARCZYK and MICHALEC [2], [3] and MICHALEC [6], [7]. The basic technical parameters of these water reservoirs are listed in table 1.

Table 1

Basic parameters of water reservoirs

Reservoir/ water-course	Reservoir capacity (1000 m^3)	Reservoir area (ha)	Mean annual flow ($m^3 \cdot s^{-1}$)	Capacity-inflow ratio α (%)	Catchment area (km^2)
Krempna/Wisłoka	119.1/112.0*	3.20	2.030	0.372/0.350*	165.30
Zesławice/Dłubnia	228.0	9.50	1.090/0.709**	0.663/1.018**	218.00
Rzeszów/Wisłok	1 800.0	68.20	18.650	0.306	2060.70
Maziarnia/Łęg	3 860.0	160.00	1.270	9.638	233.00
Ożanna/Złota	252.0	18.00	1.006	0.791	136.30
Niedźwiadek/Górno	124.5	8.10	0.166	2.378	18.75
Narożniki/Dęba	283.0	28.00	0.155	5.810	25.00
Cierpisz/Tuszymka	34.5	2.30	0.393	0.278	54.50
Cedzyna/Lubrzanka	1 554.0	64.00	1.105	4.448	140.00
Wapienia/Wapienica	1 100.0	17.50	0.120	2.907	55.53

* – Capacity of Krempna water reservoir before and after desilting and reconstruction in 1987.

** – Change of operational conditions resulting in partial water flow to the side water reservoir at Zesławice.

The general characteristics of the two chosen water reservoirs, i.e. at Zesławice and Krempna, are presented.

The retention reservoir at Zesławice on the Dłubnia River was built in 1964–1966 and began operation in October 1966. The effective storage capacity of the reservoir is 228 thousand m^3, its area is 9.5 ha, and average depth is 2.4 m. In 1983, after seventeen years of operation, siltation was found to be over 50%. Before desilting, a side reservoir was built. Its construction began in 1986 and in 1987 it began operating. The task of the side reservoir was to take the function of the main reservoir while it was being desilted. As a consequence of directing a part of the flow to the side reservoir, the mean annual inflow to the main reservoir decreased. The mean annual flow in 1987 before reconstruction was 1.09 $m^3 \cdot s^{-1}$, while after reconstruction it was 0.71 $m^3 \cdot s^{-1}$ (table 1).

The retention water reservoir at Krempna was built in 1970–1972. This water reservoir, well suited for recreation, is located in the upper part of the Wisłoka River at 145+0.23 km. After fifteen years of operation, the water reservoir at Krempna reached 30% siltation. In 1987, i.e. in the sixteenth year of operation, it was desilted and reconstructed. Prior to reconstruction, the capacity of the reservoir was $119.1 \cdot 10^3$ m^3 and the reservoir area was 3.2 ha with an average depth of 3.72 m. Reconstruction reduced the reservoir capacity to $112 \cdot 10^3$ m^3.

Two stages of operation were distinguished for the reservoirs. The stages were characterized by a different value of the capacity-inflow ratio with the reservoirs labelled before silting, i.e. Krempna-1 and Zesławice-1, and after desilting Krempna-2 and Zesławice-2.

3. METHODS

The mean annual silting ratio of the small water reservoirs studied was determined from direct silting measurements. The measurements of silting at Krempna, Zesławice, Maziarnia, Ożanna, Niedźwiadek, Narożniki and Cierpisz were performed by using a rod probe operated from a boat. Silting measurements at Wapienica and Cedzyna, as the depth exceeded 4.0 m, were carried out with an echo sounder Humming Bird 1000. Measurements were performed in cross-sections using the scattered point method. Measurement accuracy of the bottom height was ±3 cm corresponding to the rod probe foot thickness which prevented penetration of the rod probe into the sediment. Depth measurements were plotted on post performance cross-sections. Subsequently, the surface areas of deposits were determined in cross-sections and the reservoir volumes were calculated. Silting of the reservoir “Rzeszów” was determined by the Subcarpathian Board of Drainage and Water Appliances in Rzeszów.

The mean annual silting ratio was determined by the quotient of the mean annual silting volume by the original reservoir capacity. STONAWSKI [9], using the method similar to that of PARTL [8], determined the mean annual silting ratio in terms of the sediment parameter. The results of silting studies in the five large water reservoirs at Solina, Goczałkowice, Tresna, Porąbka, and Rożnów conducted by Stonawski were used for the determination of the mean annual silting ratio and the capacity-inflow ratio α.

The influence of a different capacity-inflow ratio α due to reservoir renovation on silting intensity was investigated for two retention reservoirs, i.e., Zesławice and Krempna. In the analysis conducted, neither the intensity of erosive processes in the catchment area and consequent sediment transport nor extreme hydrological phenomena were taken into consideration. The analysis was based on silting measurements and hydrological data. The capacity-inflow ratio of the reservoirs was determined for the change in operational conditions. Relative capacity was calculated as the difference between 100% reservoir capacity and the silting ratio.

4. RESULTS AND DISCUSSION

The mean annual silting ratio ($S_{z,m}$) was determined from measurements of small water reservoir silting and the silting ratio for the given years (S_z). The results are shown in table 2.

Table 2

Volume of the sediment deposited and the silting degree of small water reservoirs

Reservoir/water-course	Year	Years of operation	Volume of sediment (m^3)	Silting ratio S_z (%)	Mean annual silting ratio $S_{z.m}$ (%)
Krempna-1 / Wisłoka	1986	15	35665	29.95	2.00
Krempna-2 / Wisłoka	2005	18	45810	40.90	2.27
Zesławice-1 / Dłubnia	1983	17	116091	50.92	3.00
Zesławice-2 / Dłubnia	2006	21	77232	33.87	1.61
Rzeszów / Wisłok	1986	13	1188000	66.00	5.08
Maziarnia / Łęg	2003	14	625300	16.20	1.21
Ożanna / Złota	2003	25	30206	11.99	0.48
Niedźwiadek / Górno	2003	5	3214	2.58	0.52
Narożniki / Dęba	2005	4	1646	0.58	0.14
Cierpisz / Tuszymka	1990	34	15000	43.48	1.28
	2003	13	6745	19.55	1.50
Cedzyna / Lubrzanka	2003	30	168500	10.87	0.36
Wapienica / Wapienica	2003	71	46800	4.25	0.06

Figure 1 shows the dependence of the mean annual silting ratio ($S_{z,m}$) on the capacity-inflow ratio (α). Capacity-inflow ratios and mean annual silting ratios of five big water reservoirs determined by STONAWSKI [9] were: α = 78.30% and $S_{z,m}$ = 0.018% for Solina; α = 53.85% and $S_{z,m}$ = 0.052% for Goczałkowice; α = 12.08% and $S_{z,m}$ = 0.39% for Tresna; α = 4.57% and $S_{z,m}$ = 0.812% for Porąbka; α = 9.51% and $S_{z,m}$ = 0.877% for Rożnów.

Water reservoirs with very low capacity-inflow ratios are characterized by a considerable reduction of capacity due to intensive silting. From the relation presented in figure 1 it is evident that the capacity of the reservoirs with a capacity-inflow ratio lower than 0.58% is reduced by over 1.5%. Such a low capacity-inflow ratio indicates a short period of water retention and is characteristic of small water reservoirs. Figure 1 shows that a change in capacity occurs when the water inflow changes in small water reservoirs with a capacity-inflow ratio lower than 3–4%. This frequently occurs during the periods of reconstruction for desilting. The reconstruction alters the capacity-inflow ratio which affects silting conditions and thus the mean annual silting ratio and the intensity of capacity reduction.

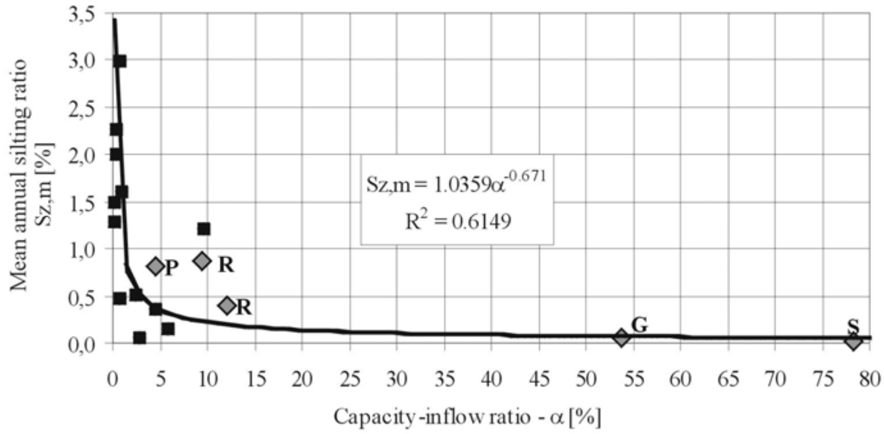

Fig. 1. Dependence of mean annual silting ratio ($S_{z,m}$) on capacity-inflow ratio (α): S – Solina, G – Goczałkowice, T – Tresna, P – Porąbka, and R – Rożnów

The analysis of silting measurements of two small water reservoirs at Krempna and Zesławice helped verify this statement. Measurements of silting are given in table 3.

Silting ratios of the reservoirs studied are presented in figure 2. A continuous line represents the silting ratio of the reservoirs before desilting and reconstruction (Krempna (α = 0.372%) and Zesławice (α = 0.663%)) and after desilting and reconstruction (Krempna-2 (α = 0.350%) and Zesławice-2 (α = 1.018%)).

Table 3

Volume of the sediments deposited in the reservoirs studied

Reservoir	Year of measurements	Year of operation	Volume of sediment deposits (m^3)
Krempna-1	1986	15	35665
Krempna-2	1996	9	27041
	1997	10	30464
	1998	11	34637
	1999	12	38002
	2000	13	40144
	2002	15	44200
	2003	16	44901
	2005	18	45810
Zesławice-1	1968	2	26968
	1969	3	70425
	1970	4	75780
	1971	5	76251
	1974	8	86192
	1983	17	116091
Zesławice-2	1999	14	56162
	2005	20	75315
	2006	21	77232

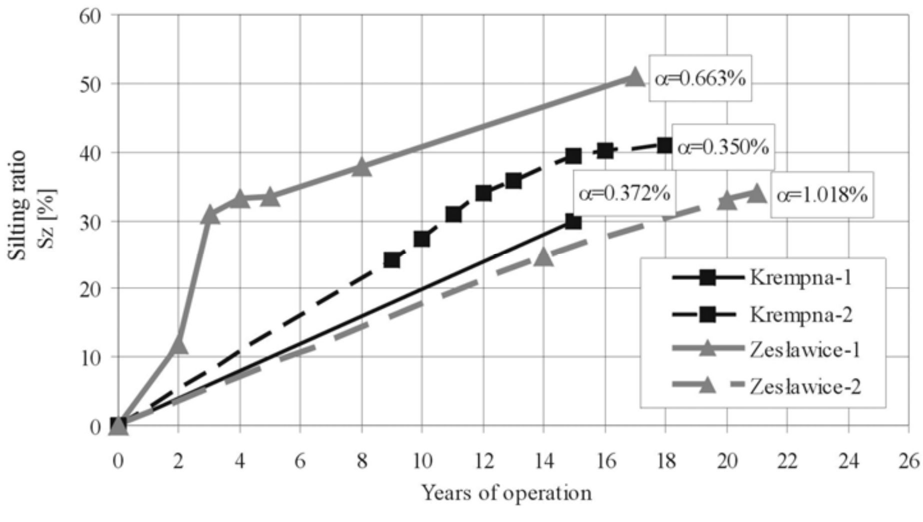

Fig. 2. Silting ratios of reservoirs Krempna-1, Krempna-2 and Zesławice-1, Zesławice-2

With a change in the capacity-inflow ratio, a change in silting conditions in the reservoirs occurred. After reconstruction of the reservoir at Krempna, the capacity-

-inflow ratio decreased, while the amount of sediment being trapped in the reservoir during a comparable period of operation increased. In the fifteenth year of operation before reconstruction, the silting ratio was 29.95% (Krempna-1) and after reconstruction in the same year of operation it reached 39.46% (Krempna-2). In the case of the reservoir at Zesławice, silting in the initial period of operation proceeded more intensively in relation to the period after reconstruction and the change of water inflow conditions. In the seventeenth year of operation, the silting ratio was 50.92% (Zesławice-1). As a consequence of dividing the water inflow stream to the main reservoir and the side reservoir, associated with the capacity-inflow ratio in a comparable seventeen year period of operation, the silting ratio of the main water reservoir (Zesławice-2) equalled 29%.

The relative capacity of the reservoir at Krempna in the fifteenth year of operation before reconstruction was 68% ($\alpha = 0.372\%$). A decrease in the capacity-inflow ratio due to the reservoir reconstruction contributed to an increase in silting intensity. This caused a reduction in the relative reservoir capacity to 63% compared with a comparable fifteen-year operation period. In the reservoir at Zesławice, prior to the change of water flow conditions and an increase in the capacity-inflow ratio, a relative capacity was 49% in the seventeenth year of operation. In a comparable period in the seventeenth year of operation, when the capacity-inflow ratio increased and thus silting intensity decreased, the relative reservoir capacity approached 71%.

5. CONCLUSIONS

Small water reservoirs are characterized by intensive silting which quickly reduces their capacity. The derived relation $S_z = 1.0359 \cdot \alpha^{-0.671}$ permits the determination of the mean silting ratio, depending on the capacity-inflow ratio. According to this relation, the capacity of water reservoirs with a capacity-inflow ratio less than 0.58% is reduced, on average, by 1.5% annually. Low values of the capacity-inflow ratio, in the order of just a few per cent, are characteristic of small water reservoirs.

The silting ratios calculated based on reservoir bottom measurements at Krempna and Zesławice before and after desilting showed the changes in silting intensity with a concomitant change in the capacity-inflow ratio. The reduction of the reservoir capacity at Krempna caused a decrease in the capacity-inflow ratio thereby influencing an increase in the silting intensity. As a consequence of diminished water inflow into the Zesławice reservoir, the capacity-inflow ratio increased. This reduced sedimentation intensity. Changes in the operational conditions of small water reservoirs and in the design capacity due to renovation influence both silting conditions and the intensity of capacity reduction.

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WPŁYW ZMIANY WARUNKÓW EKSPLOATACJI MAŁYCH ZBIORNIKÓW WODNYCH NA REDUKCJĘ POJEMNOŚCI

Podjęto próbę wykazania wpływu zmiany warunków eksploatacji małych zbiorników wodnych na wartość współczynnika pojemności i stopnia zamulania. Wykorzystując wyniki badań STANOWSKIEGO [9] nad zamulaniem pięciu dużych zbiorników zaporowych w dorzeczu górnej Wisły, tj. Soliny, Goczałkowic, Tresnej, Porąbki i Rożnowa, ustalono zależność średniego rocznego stopnia zamulenia w funkcji współczynnika pojemności α, którą aproksymowano funkcją potęgową. Intensywność zamulania scharakteryzowano za pomocą średniego rocznego stopnia zamulenia. Uzyskane wyniki badań zamulania dziesięciu małych oraz pięciu dużych zbiorników retencyjnych w dorzeczu górnej Wisły umożliwiły określenie zmiany stopnia zamulenia w kolejnych latach eksploatacji.

Na przykładzie dwóch małych zbiorników wodnych (Krempna na rzece Wisłoce i Zesławice na rzece Dłubni) wykazano, że zmiana warunków eksploatacyjnych, wynikająca z ich przebudowy, wpłynęła w sposób istotny na zmianę współczynnika pojemności, intensywność zamulania i redukcję pojemności.