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DETERMINATION OF THE SILTING RATE OF THURINGIAN DAM RESERVOIRS ON THE EXAMPLE OF DACHWIG AND OHRA RESERVOIRS

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Summary

The silting process of reservoirs limits their use. Predicting this process is important for economic reasons. The paper assesses the possibility of using the methods of forecasting the silting process developed in studies of small Polish reservoirs to determine this process in reservoirs in other geographical regions. This analysis covers the Dachwig and Ohra reservoirs, located in Thuringia, Germany. The forecast of silting was developed using the Gončarov formula according to the guidelines in force in Poland and following the empirical formula used to calculate the average annual silting. It allowed determining the rate of silting. Based on the results of calculations using the Gončarov formula, it was found that the degree of silting after 100 years of operation of the Dachwig and Ohra reservoirs will be 2.45% and 0.001%, respectively. The average annual silting rate calculated from these data was found to be lower than that calculated using the empirical formula. The limitation of the empirical formula is also the reason for obtaining higher values of the average annual silting degree, which was developed in studies of reservoirs with capacities smaller than 3.86 million m^3. Thus, for the 2.1 million m^3 Dachwig reservoir, a difference of 43% in results was obtained, while for the much larger 17.5 million m^3 Ohra reservoir, results differing by as much as three times were obtained.

Keywords

silting degree • silting intensity • silting forecast

1. Introduction

The total capacity of dam reservoirs in Poland enables collecting about 5% of the annual outflow [Łajczak 1995], while water reservoirs located in the upper Vistula basin accumulate 6.7% of the annual outflow. These volumes are insufficient, both economically and in regard to flood protection. Also due to the shortage of water resources, it is becoming necessary to take measures to increase artificial water retention. This is particularly important in the foothill and mountain regions, as the average outflow from these areas is about $10\ l \cdot s^{-1} \cdot km^{-2}$ and is almost twice the average for Poland, amounting to $5.2\ l \cdot s^{-1} \cdot km^{-2}$. An increase in the retention for these areas was planned in the ‘Program for Rational Management of Water Resources of the Małopolska Voivodeship' ['Program małej retencji…' 2004 – 'Small retention program...' 2004]. The sites for 65 reservoirs and 4 polders have been planned. Their combined total capacity will enable the retention of approx. 38 hm^3 of water. Of the planned reservoirs, those in the following villages have been built: Piekary (reservoir No. 66 'Piekary' on the Szczyrzawy stream), Zielonki (reservoir No. 81 'Tonie' on the Sudół stream), Węgrzce (reservoir No. 80 'Węgrzce' on the Sudół Dominikański stream), Janowice (reservoir No. 68 'Janowice' on Wilga river) [Michalec and Cupak 2022]. The covered by the program small water reservoirs, with a capacity between 19 thou. m^3 and 1.77 million m^3, were located in the cross-sections enclosing the catchments between a few to several square kilometers. In the 'Small Retention Program...' [2004] it was stated that these reservoirs '... generally have not very favourable technical indicators, mainly as a result of the expected short duration of their silting...'. However, it was not specified after what time they will be silted. The forecast of the reduction of the dam reservoir capacity can be calculated with the Gončarov formula, which is recommended by the Instructional Guidelines, developed by Wiśniewski and Kutrowski [1973]. Determining the silting time requires detailed study work, including, among others, calculating the intensity of sediment transport, determining the characteristics of the sediment, and the sediment trap efficiency of the water reservoirs. The lack of hydrological data is a major obstacle in determining the silting intensity in the case of designed and existing small water reservoirs. This is due to the location of these reservoirs in small catchments with watercourses that are not hydrologically controlled. This makes it impossible to apply direct methods for determining the intensity of sediment transport, based on hydrometric data such as water flows and the corresponding concentration of suspended sediment.

It is therefore only indirect methods, i.e. calculation methods [Michalec 2009], allow to determine the transport rate of sediment flowing into small reservoirs. These methods determine the parameters describing the flow of water and sediment in a riverbed, or several factors connected to erosion in the catchment area and the volume of material supplied to a riverbed. These are most often empirical methods, which determine the volume of transported sediment on the basis of the established mass of eroded soil in the catchment and the volume of material supplied to a riverbed. In Poland, these are: the Reniger-Dębski method [Dębski 1959, Reniger 1959] based on the classification of denudation intensity, the Brański method [1975] based on the map of outflow denudation indicators, and the DR-USLE method [Wischmeier and Smith 1965], [Roehl 1962]. To these methods, one can add the MUSLE method [Williams 1975] and the RUSLE method [Renard et al. 1997], which are modifications of the universal equation of soil losses. These methods have been successfully applied in different regions of the world, and empirical and statistical models have been developed and refined from them to assess and quantify water erosion [e.g. Spalevic 1999, Amorim et al. 2010, Hazbavi et al. 2020].

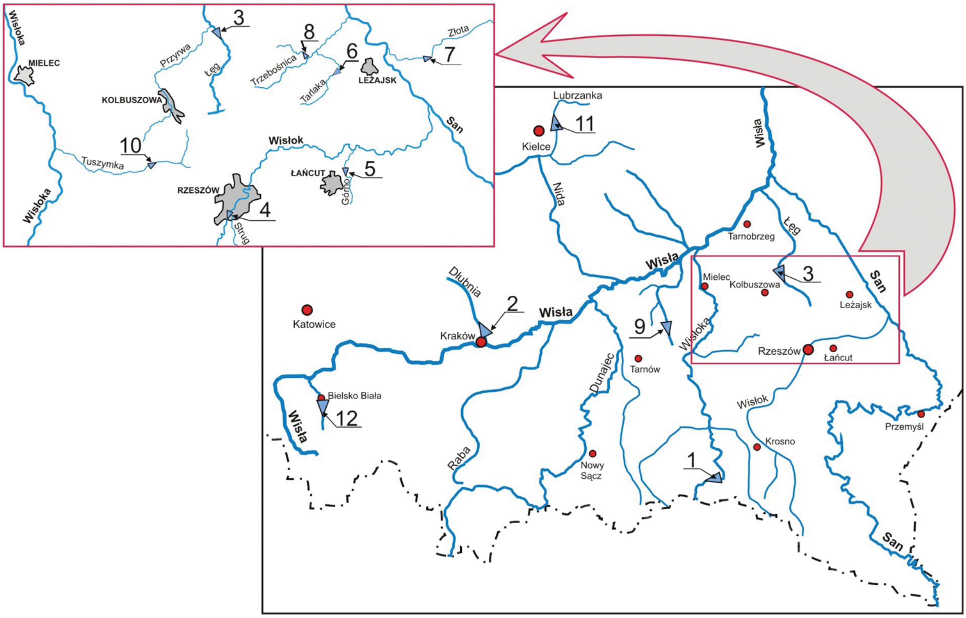
Among the methods for determining the volume of sediment transported in rivers and streams, which include parameters describing the flow of water and sediment in a riverbed, one can also mention the methods proposed by Bauer and Tille [1967], Van Rijn [1984], Bobrowitskaya and Zubkowa [1998]. Bauer and Tille [1967] developed a regional formula for determining the transport rate of sediment carried in the rivers of Thuringia, which takes into account hydraulic parameters such as average and maximum flow. Van Rijn [1984] developed a formula for determining the transport rate of a unit of sediment on the basis of a parametrised concentration profile of the suspended sediment and the calculated concentration of this sediment at the reference level above the bed, introducing into his analysis two parameters characterising the sediment movement, i.e. the grain parameter (D_*) and the transport parameter (T). Bobrowitskaja and Zubkowa [1998] proposed a method developed and tested for the Neva river, in which it is possible to determine the volume of suspended sediment flowing through the considered river cross-section on the basis of the developed dependence of the suspended sediment concentration on the flow velocity, depth and empirical coefficient depending on the magnitude of concentration, flow phases (high-water, low-pressure flow) and the shape of the hydrogram.

The volume of sediment flowing into water bodies, determined by the methods mentioned above, when there are no data on water flow rate and sediment concentration of the inflows or tributaries, allows to draw up a silting forecast. The study aims to determine the silting rate of two reservoirs located in Thuringia, Germany. The forecast of silting was developed using the Gončarov formula according to the guidelines in force in Poland and according to the empirical formula used to calculate the average annual silting. Both the elements of Gončarov's forecast, as well as the empirical formula were developed on the basis of research on the process of silting of small water bodies located in the upper Vistula basin. The analysis will make it possible to assess the applicability of the developed methods of siltation forecasting based on studies of small Polish reservoirs to the assessment of this process in reservoirs in other geographical regions. This analysis covers the Dachwig and Ohra reservoirs, located in Thuringia, Germany.

2. Characteristics of studied objects

The full characteristics of small reservoirs selected for the analysis (Fig. 1), regarding technical, hydrological, catchment parameters as well as those describing the transport of sediment and the silting process, were presented in Michalec [2008]. These reservoirs are: Krempna on the Wisłoka river, Zesławice on the Dłubnia river, Maziarnia on the Łęg river, and Rzeszów on the Wisłok river – these objects are located on rivers under hydrological observations. Other selected reservoirs are located on watercourses not covered by hydrological control, such as: Głuchów on the Graniczny stream, Brzóza Królewska on the Tarlak stream, Ożanna on the Złota river, Niedźwiadek on the Górno stream, Narożniki on the Dęba river, Cierpisz on the Tuszymka river, Cedzyna on the Lubrzanka river and Wapienica on the Wapienica river.

The capacities of the examined small reservoirs located in the upper Vistula river basin, as defined in the 'Agreement...' ['Porozumienie…' 1995] and 'Small Retention Program...' [2004], do not exceed 5 million m^3.



Source: Author's own study

Fig. 1. Location of small reservoirs: 1) Krempna, 2) Zesławice, 3) Maziarnia, 4) Rzeszów, 5) Głuchów, 6) Brzóza Królewska, 7) Ożanna, 8) Niedźwiadek, 9) Narożniki, 10) Cierpisz, 11) Cedzyna, 12) Wapienica [after Michalec 2008]

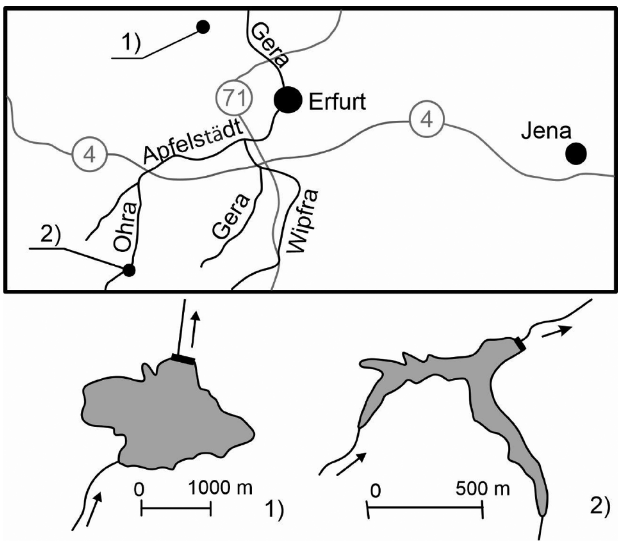


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Fig. 2. Location of small reservoirs: 1) Dachwig, 2) Ohra. Symbols: 4 and 71 – highways

The Dachwig and Ohra reservoirs are located in Thuringia, Germany (Fig. 2). The Dachwig reservoir is located about 20 km northwest of Erfurt, and the Ohra reservoir is about 40 km southwest of Erfurt.

The Dachwig reservoir (Fig. 2.1), which collects water from the Jordan stream, was constructed in 1974–1976. The Dachwig dam closes the catchment area of 27.70 km^2, and its capacity at normal water level (NWL) is 2.10 million m^3 (Table 1). The height of the dam is 11.3 m, and the reservoir area is 0.96 km^2. The largest measured flow in the Jordan stream was 13.8 $m^3 \cdot s^{-1}$, and the average annual flow of water in the Jordan stream, determined for the cross-section of the Dachwig reservoir dam, is 1.33 $m^3 \cdot s^{-1}$. The minimum guaranteed water intake was set at 38 $1 \cdot s^{-1}$.

The Ohra reservoir (Fig. 2.2), which accumulates and collects the water of the Ohra river, was commissioned in 1966 after six years of construction, and supplies the surrounding population with drinking water. Below the reservoir dam is the Luisenthal water treatment plant. Water intake allows supplying drinking water to 230 cities and municipalities, which inhabit approximately 700 000 inhabitants. The total capacity of the Ohra reservoir is 17.5 million m^3. The total catchment area of the Ohra dam reservoir is 91.9 km^2, and is the sum of the direct catchment area of the reservoir, amounting to 33.60 km^2, the catchment area of 34.70 km^2, which is the catchment area of the preliminary reservoir from which the water is channelled through the Gera water adit to the Ohra reservoir, and the catchment area of 26.70 km^2, which is the catchment area of the second preliminary reservoir from which the water is channelled through the Hassel water adit to the Ohra reservoir. The average annual flow in the cross-section of the Ohra reservoir dam is 0.78 $m^3 \cdot s^{-1}$.

3. Methodology

The volume of sediment entering the reservoirs located in the upper Vistula basin was determined by two methods. The transport of sediment entering the water reservoirs of Krempno, Zesławice, Maziarnia and Rzeszów was determined directly, i.e. based on bathymetric measurements [Michalec 2008]. The results of these measurements constituted the starting material for the calculation of the measures of suspended sediment transport, such as the second suspension U expressed in $kg \cdot s^{-1}$, annual transport R [$t \cdot year^{-1}$] and unit drain denudation d_o [$t \cdot km^{-2} \cdot year^{-1}$]. The calculation methodology was adopted in accordance with the 'Compilation of the results of the measurements of suspended sediment for annual publications' ['Opracowanie…' 1982]. The volume of sediment flowing into the remaining eight water bodies was calculated by the DR-USLE [Michalec 2008] method, which determines the volume of soil loss in a catchment using the Universal Soil Loss Equation (USLE) [Wischmeier and Smith 1965] and the delivery ratio (DR), which determines the volume of erosion products flowing out of the catchment. This indicator was determined from a functional relationship developed by Roehl [1962].

According to information obtained from Thueringer Fernwasserversorgung (Thuringian Long-Range Water Supply Plant), the concentration of suspended sediment of the tributaries to the Dachwig and Ohra reservoirs is not measured. The volume of sediment flowing into these water bodies was determined according to the Bauer and Tille method [1967]. According to Bauer and Tille [1967], measurements of the concentration of suspended sediment in Thuringia were started in 1960. The geological structure of Thuringia is closely connected to the type of soil, which is one of the most important factors influencing the intensity of erosion processes and the outflow of sediment from the catchment of the Thuringian watercourses [Bauer and Tille 1967]. In the proposed formula, aimed at determining the drainage denudation from the catchment, the authors took into account both precipitation, catchment area, and the parameters *m* and *log b*, determined on the basis of hydrological data from 11 measuring stations, established in the cross-sections of Thuringian rivers. This formula has the form:

$$\log A = \log b + (m - 1) \log F_N - m(3 - \log q) \quad (1)$$

where:

- A – outflow denudation of sediment $[g \cdot s^{-1} \cdot km^{-2}]$,
- m – a parameter which accounts for the bedrock in the catchment, determined by correlation tests, the average value m is 1.78,
- F_N – catchment area $[km^2]$,
- q – temporary unit precipitation in the catchment area $[l \cdot s^{-1} \cdot km^{-2}]$,
- $\log b$ – conversion parameter from flows expressed in $m \cdot s^{-1}$ to second suspension in $g \cdot s^{-1}$, which is determined from the formula:

$$\log b = 1.88 - 1.26 \log MQ \quad (2)$$

in which *MQ* is the maximum flow.

Based on regression analyses between the values of average flows (Q) and second suspension (Q_s), Bauer and Tille [1967] developed the following equation:

$$\log Q_s = \log b + m \log Q \quad (3)$$

with the designation of symbols as in the formula (1).

In Michalec [2008] it was shown that among the formulas and nomograms of Łopatin, Drozd, Karausev, Brune and Allen, Brune, Morris, Lisney, Ward, Brown, Gottschalk, Churchill, Chen, Borland, Łajczak and Yoon, only the Churchill method makes it possible for small water bodies to retain sediment (β) closest to the real value. Therefore, the sediment trap efficiency of the Dachwig and Ohra reservoirs was determined both according to the Churchill method and the Brune method, which was based on studies of small water bodies located in the United States and is one of the most commonly used methods [i.a. Vincent et al. 2001, Aspelund and Madsen 2004, Mulu and Dwarakish 2015, Tan at al. 2019]. The determined value of β made it possible to develop a forecast of siltforg of the Thuringian water bodies. The forecast was developed using the Gončarov formula [Wiśniewski and Kutrowski 1973]:

$$Z_t = V_p \left[1 - \left(1 - \frac{R_1}{V_p} \right)^t \right] \tag{4}$$

where:

Z_t – the volume of sediment deposits after t years [m^3],
V_p – initial capacity of the water reservoir [m^3],
t – years of operation,
R_1 – volume of sediment deposits after the first year of operation [m^3], according to the formula:

$$R_1 = \frac{\beta \cdot R_u}{\rho_0} \tag{5}$$

where:

R_u – annual mass of suspended sediment flowing into the reservoir [t],
β – the sediment trap efficiency of the reservoir [-],
ρ_0 – bulk density of sediments [$t \cdot m^{-3}$].

4. Results

The volume of sediment flowing to reservoirs located in the upper Vistula basin, according to Michalec [2008], is given in Table 1. It was compared with the volume of sediment flowing into the Dachwig and Ohra reservoirs, which was calculated using equation (3) of Bauer and Tille. The assumed maximum flow MQ for the calculation of log$b$ values (equation 2) was 13.8 and 75 $m^3 \cdot s^{-1}$ for the Dachwig and Ohra reservoirs, respectively. The average annual volume of sediment flowing into the Dachwig reservoir is 539 $t \cdot year^{-1}$, and to the Ohra reservoir only 1.4 $t \cdot year^{-1}$. The area of catchments of both water bodies is comparable, but the way they are developed is different. The Jordan stream, which feeds the Dachwig reservoir, flows through areas of intensive agricultural use, while the catchment area of the Ohra reservoir, located in the Black Forest, is covered with almost 100% forests. The calculations showing a small volume of sediment flowing into the Ohra reservoir according to the Bauer and Tille formula confirm the assumptions made in this formula that with increasing maximum flow MQ the value of unit suspension decreases (Q_s).

Due to the lack of data on silting measurements, it was not possible to determine the actual sediment trap efficiency (β_{rz}) of the Dachwig and Ohra reservoirs. The sediment trap efficiency of these reservoirs, determined according to Brune (β_B), is 76.8 and 96.2%, and is close to the value of β_{Ch} determined according to the Churchill method, which can be considered reliable according to the results of Michalec's research [2008] if it is not possible to determine the actual value of the β. Similarly, high values of β_B (Table 2, column 7), similar to the values of β_{Ch}, were obtained for the Maziarnia and Narożniki reservoirs, whose capacity ratios were 9.64 and 5.81%, respectively. This indicates that it is possible to correctly determine the value of the β_B according to Brune for reservoirs whose capacity ratio is at least several percent.

Table 1. Sediment trap efficiency of studied reservoirs

Reservoir	V_p [$10^3 \cdot m^3$]	R_u [t]	SQ [$m^3 \cdot s^{-1}$]	α [%]	β*rz* [%]	β*B* [%]	β*Ch* [%]
1	2	3	4	5	6	7	8
Krempna	119.1	3990.0	2.030	0.37	80.8	17.9	70.4
Zesławice	228.0	16400.0	1.090	0.66	82.4	32.1	84.4
Maziarnia	3860.0	97310.0	1.270	9.64	86.9	84.8	97.0
Rzeszów	1800.0	206110.0	18.650	0.31	89.0	13.8	52.1
Głuchów	22.6	872.0	0.567	0.13	91.8	2.3	58.6
Brzóza Królewska	49.0	308.0	0.224	0.69	94.5	33.3	86.9
Ożanna	252.0	1644.0	1.006	0.79	99.0	36.8	84.3
Niedźwiadek	124.5	737.0	0.166	2.38	98.1	63.7	96.0
Narożniki	283.8	720.0	0.155	5.81	79.0	78.9	97.5
Cierpisz	34.5	744.0	0.393	0.45	99.0	12.0	77.7
Cedzyna	1550.0	7092.0	1.105	0.28	93.7	75.0	95.6
Wapiennica	1100.0	919.0	0.120	2.91	95.6	67.7	100.0
Dachwig	2100.0	539.0	1.330	5.01	–	76.8	96.5
Ohra	17500.0	1.4	0.780	71.14	–	96.2	100

where: V_p – reservoir capacity, R_u – average annual mass of delivered sediment, SQ – average annual flow, α – capacity inflow ratio, β_{rz} – real sediment trap efficiency, β_B – sediment trap efficiency acc. to is Brune, β_{Ch} – sediment trap efficiency acc. to Churchill

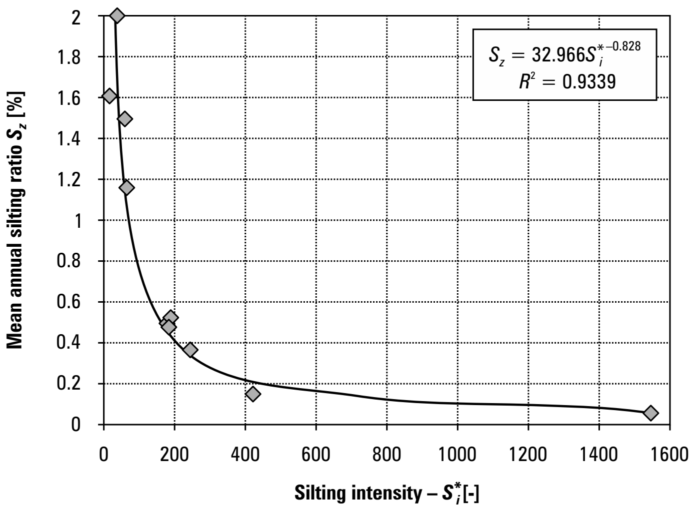
The silting forecast of the Dachwig and Ohra reservoirs was developed according to the Gončarov formula (equation 4), in which the volume of sediment deposits after the first year of operation (R_1) was calculated by taking into account the sediment trap efficiency of the water reservoirs determined according to Churchill (Table 1, column 8). Due to the lack of data on the physical properties of the sediment trap in the Dachwig and Ohra reservoirs, the volumetric density of the sediments was assumed to be equal to 1 $t \cdot m^{-3}$. The results of the calculation of the forecast volumes of sediment deposits in the Dachwig and Ohra reservoirs, 100 each since the beginning of the operation, are given in Table 2. The degree of silting of the Dachwig and Ohra reservoirs, which is the product of the forecasted volume of sedimented deposits and the initial capacity of a reservoir, was also calculated.

The obtained results (Table 2) indicate a very slow process of shallowing the two Thuringian reservoirs. The degree of silting after 100 years of operation is 2.45% for

Dachwig and 0.001% for Ohra. Due to the lack of data on the volume of sediment deposits accumulated in these reservoirs, there was an attempt to verify the obtained results, i.e. the calculated silting degree, which was compared with that determined from the relationship presented in Figure 3.

Table 2. Results of silting forecast of Dachwig and Ohra water reservoirs

Water reservoir	Years of operation	Year	Forecasted volume of sediment deposits [m^3]	Silting degree [%]
Dachwig	100	2076	51381	2,45
Ohra	100	2066	140	0,001



Source: Author's own study

Fig. 3. Regression dependence of the silting degree (S_z) and silting intensity (S^*_i) according to the Ŝamov equation

This dependence allows determining the average annual silting degree (S_z) based on the silting intensity (S^*_i), according to Ŝamov. The silting intensity, defined by Ŝamova [Michalec and Wałęga 2015], is defined as the ratio of the initial capacity of a reservoir (V_p) to the average annual volume of sediment flowing into a reservoir (R):

$$S_i^* = \frac{V_p}{R} \tag{6}$$

The dependency presented in Figure 3 was developed for twelve small water reservoirs of the upper Vistula basin [Michalec 2008].

On the basis of the calculated degree of silting of the analysed reservoirs after one hundred years of their operation (Table 2), the average annual degree of silting was calculated, which for the Dachwig and Ohra reservoirs is 0.0245 and 0.00001%, respectively. While the average annual silting degree (S_z) determined from the dependency in Figure 3 is 0.0351 and 0.00004%, respectively. These values were determined for silting intensity (S^*_i) calculated by the Ŝamova equation, amounting to 3896 for the Dachwig reservoir and 12500000 for the Ohra reservoir. The specified average annual silting degree of the Dachwig reservoir using the equation shown in Figure 3 is 43% higher than that given in Table 2, while the average annual silting degree of the Ohra reservoir is three times higher than that given in Table 4. The difference in results is mainly caused by general calculation assumptions, i.e. the assumed theoretical volumetric density of sediments, and lack of measurements of the sediment transport flowing to the analysed reservoirs. As it is not possible to determine the actual values for these parameters, the results obtained should be understood as estimates. The limitation of the empirical formula is also the reason for obtaining higher values of the average annual silting degree, which was developed in studies of reservoirs with capacities smaller than 3.86 million m^3. Thus, for the 2.1 million m^3 Dachwig reservoir, a difference in results of 43% was obtained, while for the much larger 17.5 million m^3 Ohra reservoir, results differing by as much as three times were obtained.

5. Conclusions

The basic criterion for the classification of water reservoirs is capacity. Under this classification criterion, in Poland, in accordance with the 'Small Retention Program...' [2004] small water reservoirs are classified as objects with a capacity between 200 thou. m^3 and 5 million m^3 and a damming height not smaller than 1.5 m. In Romania, the criterion of 5 million m^3 was also adopted as the maximum capacity of small water reservoirs [Batuca and Jordaan 2000]. In the United Kingdom, on the other hand, a small water reservoir is considered to be an object with a capacity of less than 1 million m^3, which closes catchment areas with an area smaller than 25 km^2 [White et al. 1996]. In Thuringia, a lower criterion for the size of water bodies introduced into the so-called 'management plans' (German: *der Bewirtschaftungsplan*) has been adopted. According to this criterion, reservoirs cannot have a smaller capacity than 100 thousand m^3 and the height of the dam cannot be lower than 5 m ['Gesetz- und Verordnungsblatt...' 2009]. Reservoirs with a smaller capacity than 100 thousand m^3 are classified as small water bodies [Bettzieche and Pohl 2012]. The analysed Dachwig and Ohra reservoirs, due to their capacity, are not classified as small dam reservoirs according to German criteria. According to the criteria used in Poland, the Dachwig reservoir is a small dam reservoir. These reservoirs have significant capacities in relation to the catchment area that is closed by their dams. Therefore, the calculated value of the capacity coefficient α is 5.01% for Dachwig and 71.14% for Ohra. These values correspond to Polish medium and large reservoirs, and on this basis, it can be expected that the silting rate will be slower than in small water bodies. This is confirmed by the results of the estimated silting forecast. The Dachwig and Ohra reservoirs are also characterized by favourable silting intensity values (S^*_i) determined according to Ŝamov, which is the ratio of the initial capacity of a water reservoir to the average annual volume of sediment flowing into a reservoir. The obtained values of S^*_i confirm the results of the silting forecast, indicating a very slow process of capacity reduction, especially for the Ohra reservoir. The above analysis showed that reservoirs with a relatively large capacity compared to the volume of incoming sediment have a low value of the average annual degree of silting, indicating a low silting intensity. This corresponds to high values of S^*_i, i.e. silting intensity.

The analysis of the silting process of the Dachwig and Ohra reservoirs showed the possibility of estimating their silting intensity both based on the results of the silting forecast developed by the Gončarov method as well as using the empirical formula. However, when using this formula, the capacity of an analysed water reservoir should be taken into account. The results of the forecast can be verified only after carrying out silting measurements.

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