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Impact of Floods on Sediment Trap Efficiency of a Small Shallow Reservoir—A Case Study

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Abstract: Silting is the main factor limiting the ability to perform the tasks that small reservoirs are intended for. Therefore, the change in sediment trap efficiency was studied for a small shallow reservoir, Krempna, which, due to high silting intensity, was desilted twice (2005, 2018). Siltation measurements were performed in two periods (1987–2005, 2006–2018) after the reservoir was desludged. It was found that the sediments were composed of fine-fraction sediment; therefore, a series of measurements of suspended sediment transport were performed. These data allowed us to calculate the daily sediment transport flowing into and out of the reservoir and water-level measurements. Then, the sediment trap efficiency was calculated. The aim of this study was: (1) to determine the impact of flood flows on the sediment trap efficiency (STE) of a small shallow reservoir, (2) to determine changes in the value of the sediment trap efficiency of a small shallow reservoir in two different periods of its operation, and (3) to demonstrate whether it is possible to determine the value of the initial sediment trap efficiency and changes in the STE values during operation using empirical formulas. Finally, during flood flows, the amount of sediment retained in the studied reservoir was several times lower than during freshets with a much smaller flow. It is these small freshets that reduce the capacity of the reservoir. A correlation relationship was developed for 18 data—flood flows (Q) and sediment trap efficiency (STE).

Keywords: flood; suspended-load sediment; physical modeling; field studies; reservoir

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1. Introduction

Small reservoirs fulfill economic, agricultural, energy, natural, and recreational functions and improve water balance [1]. They are also used for tourism-related purposes, including fishing, swimming, and water sports; they also increase the aesthetic value of areas on which they are built [2,3]. Small reservoirs have a limited effect on flood protection and reduce the risk of flooding. Small reservoirs are widely used to store water, especially for irrigation [4]. However, their particular significance is based on functions, such as accumulating water for irrigation, improving water relations in river valleys and forest areas, direct water supply to farms and villages, fire protection, providing watering places for farm animals, protection against water erosion, or improving ecological conditions. Small reservoirs do not significantly impact flood protection due to their small capacity and lack of flood capacity. These are reservoirs mainly with uncontrolled water management. According to a literature review by Habets et al. [5], the cumulative impacts of small reservoirs on hydrology are most often estimated from the annual discharge, low flows, and floods. According to some authors [6–8], sets of small reservoirs lead to a reduction in flood peaks of up to 45%.

Silting is the main factor limiting the ability to perform the tasks that reservoirs are intended for. In large reservoirs, the storage capacity is reduced much more slowly than in small reservoirs. According to Hu et al. [9], the annual average silting-related storage capacity loss rate of large reservoirs in the world is 0.5–1% and varies significantly depending on the region; for example, in China, it is 2.3%, and in Europe, it is 0.17–0.2%. According to data presented by Thakkar and Bhattacharyya [10], the annual average loss of the storage capacity of 23 reservoirs with capacities of 3,800,000 to 7,165,800,000 m^3 is 0.03–1.87%. A study on 23 small reservoirs in Morocco, conducted by Alahiane et al. [11], shows that reservoirs with a capacity of 1680 to 578,850 m^3 were characterized by the values of an annual average loss of storage capacity from 0.58% to 11.11%. Rădoane and Rădoane [12] report that reservoirs with a capacity of 220,000 to 4,800,000 m^3 are characterized by quick silting, and the annual average loss of storage capacity of these reservoirs ranges from 1.13% to 14.17%. Michalec and Wałega [13] report that small reservoirs in the Upper Vistula Basin, whose capacity ranges from 34,500 to 3,860,000 m^3, are characterized by a mean annual silting ratio of 0.06% to 5.08%.

Such a significant intensity of silting means that small reservoirs, in a short time, of several to several dozen years, are silted to such a large extent that they cannot perform the functions they were designed for. The restoration of their function requires the removal of sediments. Unremoved sediment deposits contribute to the accumulation of flood flows. Therefore, it is important to understand the operating conditions of the existing small reservoirs, especially with respect to their silting process. The results of research on this process may contribute to the development of methods of forecasting the viability of small reservoirs, developing methods of their optimal location in the catchment area, so as to minimize the negative effects of river sediment transport. The main research gap is the lack of methods for determining the sediment trap efficiency (STE) of small reservoirs. The methods presented in the world literature have been developed based on sediment yield and silting of medium and large reservoirs. As mentioned above, small bodies of water are characterized by a short and fast silting process in which a significant reduction in STE can be observed. The research challenge is, therefore, to develop a method for determining STE for small reservoirs. It may be innovative to develop a method of forecasting silting of small reservoirs, considering the change in STE. In order to perform this, it is necessary to examine the conditions of sediment flow through the reservoir and to determine the sediment trap efficiency—its initial value and changes during operation. For this purpose, using historical hydrological data and measurements of sediment concentration flowing into and out of the reservoir, as well as the siltation measurements made during the reservoir's operation, the following research objectives were adopted: (1) determination of the impact of flood flows on the sediment trap efficiency of a small shallow reservoir, (2) determination of changes in the value of the sediment trap efficiency of a small shallow reservoir in two periods of its operation, and (3) verification of empirical formulas to determine the initial value of the sediment trap efficiency (STE) and its changes during operation.

2. Materials and Methods

2.1. Characteristics of the Research Object

The small reservoir Krempna is located in the upper reaches of the Wisłoka River (Figure 1), 145.0 km from its mouth to the Vistula. The Wisłoka River from its sources to the reservoir in Krempna is 18.6 km long and covers a subcatchment area of 165.3 km^2. The total length of the Wisłoka River is 163.6 km, and its catchment area is 4110.2 km^2. The Wisłoka River belongs to the Upper Vistula Basin, which covers an area within three great physical-geographical units, that is, the Carpathians, Subcarpathian Basins, and Lesser Poland Uplands.

The catchment area, mostly due to its mountainous character, is largely (i.e., in 80%) covered with forests. The bottom part of the catchment and its flat slopes are small agricultural areas, making only 4% of the catchment covered with arable land. Only about 2% of the catchment consists of road and building infrastructure, while grasslands occupy 14% of the area [14].

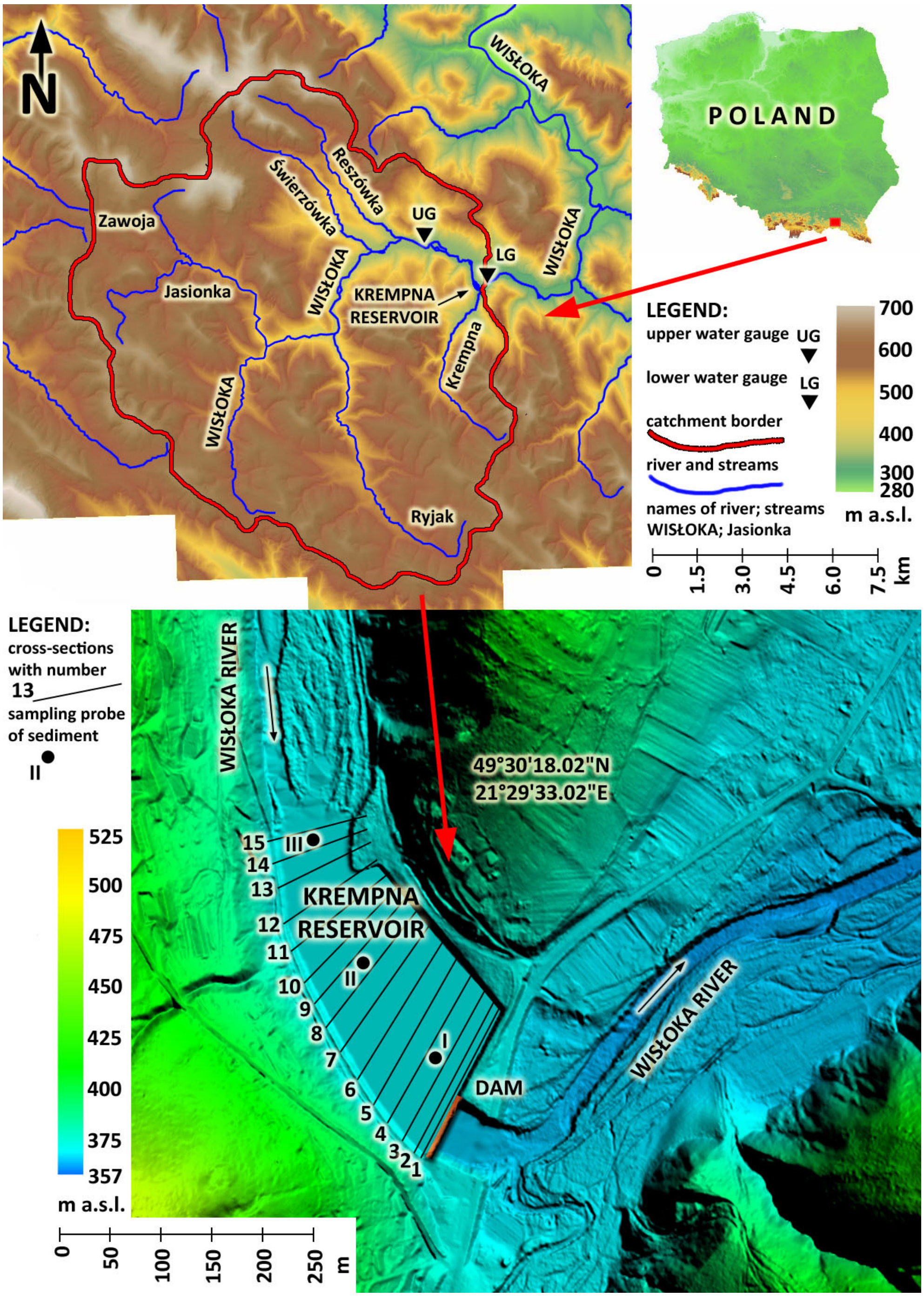

Figure 1. Location of the small reservoir Krempna.

The Krempna reservoir (Figure 1), with a designed capacity of 119,000 m^3, an area of 3.72 ha, and a length of 400 m, was constructed in 1970–1972. Due to its siltation, its functions, that is, water intake for irrigation and recreational function, have been limited. For this reason, it was desilted for the first time in 1987. As a result of desilting, the depth and width of the reservoir were reduced, which reduced its capacity to 112,000 m^3. In 2005, after 18 years of operation, the reservoir was desilted again due to a siltation of over 40%. As a result of the conducted work, in which part of the extracted sediment was deposited on the left bank of the reservoir, a new slope was created, reducing the width of this reservoir. This resulted in a reduction of its capacity to 96,350 m^3. In order to reduce the intensity of silting, which is particularly high during the spring thaw, the Krempna reservoir is emptied in late autumn (in the last days of November or the first days of December) and refilled in late spring (in the last days of May or the first days of June).

There are water gauges upstream and downstream of the reservoir. The upper water gauge (UG) is located at a distance of 2.827 km from the dam axis, and the lower water gauge (LG) is located 65 m from the dam axis. The upper water gauge belongs to the national hydrometeorological network supervised by the Institute of Meteorology and Water Management (IMWM). The highest observed flow was 205.99 $m^3 \cdot s^{-1}$, the average flow from the multiyear period of 1973–2005 was 2.03 $m^3 \cdot s^{-1}$, and from the multiyear period of 2006–2018, it was 2.68 $m^3 \cdot s^{-1}$. The lowest observed flow was 0.13 $m^3 \cdot s^{-1}$.

2.2. Method of Suspended Sediment Transport Calculation

Suspended sediment transport in the two Wisłoka water gauge sections, that is, in cross section of the upper water gauge (UG) and in cross section of the lower water gauge (LG), was calculated based on hydrological data. These data included the mean daily flows (Q) and the corresponding suspended sediment concentrations (C). Daily flow hydrographs were available for each operational period (1997–2005 and 2006–2018). Water level data strings on the upper water gauge (UG) are recorded by the Institute of Meteorology and Water Management (IMWM), and the flows with the rating curve were determined for these levels. IMWM does not carry out measurements of suspended sediment. The sediment concentration was measured in research projects carried out in 1995–2007. During these studies, the point sediment measurements were conducted by the employed workers who collected samples of water with the suspended sediment into 10 dcm^3 containers. The samples were collected every 2–3 days in the periods between freshets and every day during freshets. The water samples with the sediment were filtered on-site, and the filters were delivered to the laboratory, where the suspended sediment concentration collected at the cross-sectional point of the river (C_p) was measured. The collected data allowed for the development of the relationships of C_p = f(Q), which made it possible to supplement the flow hydrographs with the missing values of the suspended sediment concentration collected at the cross-sectional point of the river. The relationships C_p = f(Q) were developed for the upper water gauge (UG) and lower water gauge (LG) by separating hydrological and meteorological seasons. According to Bednarczyk [15], the separation of these seasons allows for the diversification of the hydraulic conditions of water flow in the watercourse and the variability of the intensity of erosion processes during the year. The following hydrological and meteorological seasons were distinguished: spring thaws, summer torrential rains, autumn low flows, and winter. The resulting transported sediment balance included two seasons of summer torrential rains and autumn low flows, because the reservoir collects water during these seasons. During winter and spring, the reservoir remains empty.

The transport calculations were carried out according to the "guidelines for elaborating annual reports on suspended sediment load" [16]. The values of the second load of suspension U_i ($g \cdot s^{-1}$) were calculated as the product of the daily concentration values C_p ($g \cdot m^{-3}$) and daily flows Q ($m^3 \cdot s^{-1}$). Then, taking into account the number of seconds in a day, the daily suspended sediment transport was calculated, which allowed for determining the suspended sediment transport (SST_m) during each month of each of the reservoir's operating periods.

The calculated values of the daily and monthly suspended sediment transport were corrected with the correction factor k. This factor is the quotient of the average suspended sediment concentration in the river's transverse profile (C_{cs}) and the suspended sediment concentration at the constant sampling site (C_p). In order to determine this coefficient, a series of suspended sediment concentration measurements at the sampling point and in the entire cross section of the river were performed using the Partech Portable Suspended Solids and Turbidity Monitor System 770 photo-optical device. The resulting suspended sediment transport in the entire cross section of the river, calculated for water gauge cross sections, made it possible to obtain a balance of the sediment flowing into and out of the reservoir along with the sediment retained within the reservoir.

Flood waves with a flow greater than flows with a 50% probability of exceedance were selected from the hydrographs. The suspended transport sediment was calculated for the designated waves in the cross section of the upper water gauge (UG) and in the cross section of the lower water gauge (LG), for which then separate relationships of sediment concentration measured at a given point as a function of average daily flow (C_p = f(Q)) were developed. After the sediment transport calculations were corrected by the correction factor k, it was possible to develop the balance of the suspended sediment flowing into and out of the examined reservoir.

2.3. Method of Silting Measurement and Determination of Sediment Trap Efficiency

The amount of sediment retained in the Krempna reservoir was calculated on the basis of the results of bathymetric measurements made from a boat using a stick probe, on which a 20 × 20 cm foot was mounted at its lower end. The measurements were conducted in cross sections and by the scattered point method. The results of the depth measurements in the reservoirs were plotted on the as-built cross sections, the locations of which are shown in Figure 1. Then, the deposit areas in the cross sections were determined, and having the distances between successive cross sections, the deposit volumes in the reservoir were determined. During the siltation measurements, samples of bottom sediments were collected in the dam zone (I), middle zone (II), and backwater zone (III) of the reservoir (Figure 1). At each point, three samples were taken from the sediment surface (upper layer) and from a depth of about 0.4 m below the sediment surface (bottom layer). Based on the analysis of 18 samples, the particle size distribution and the arithmetic mean volume density of bottom sediments were determined.

The real sediment trap efficiency (STE_R) value was determined as the product of the sediment volume retained in the reservoir and the sediment volume flowing into the reservoir. Silting measurements were not performed in the first year of operation after desilting; therefore, the initial STE_R value was determined approximately. For the assumed volume of sediment after the first year of operation (V_1), the forecasted siltation was calculated from Gončarov's Equation (1), and the obtained value was equal to the measured siltation volume in the last measurement of the operation period. Then, the STE value was calculated from the transformed Equation (2), knowing the volume density of sediments (ρ_0) and the mass of suspended sediment transport (SST_1), which flowed into the reservoir in the first year of operation. Gončarov's Equation (1) is recommended by the Polish guidelines for siltation forecasting [17] to calculate the volume of sediment deposition in a reservoir (V_t) after t years, knowing the reservoir's initial capacity (V_p):

$$V_t = V_p \left[1 - \left(1 - \frac{V_1}{V_p} \right)^t \right] \tag{1}$$

The volume of sediment depositions after the first year of operation (V_1) is calculated according to the following formula:

$$V_1 = \frac{\mathrm{STE} \cdot \mathrm{SST}_1}{\rho_0} \tag{2}$$

where STE is the sediment trap efficiency of the reservoir (-), and ρ_0 the sediment bulk density ($t{\cdot}\mathrm{m}^{-3}$).

Using Formula (1) to forecast the time of silting, the STE value is determined from empirical formulas or nomograms. These methods were developed as empirical dependencies of STE on various parameters. The most frequently used parameter is the capacity–inflow ratio (C–I), which is the quotient of the reservoir's capacity and the sum of the average annual water supply. The C–I ratio was used in the methods of Łopatin [17] (Figure 2a) and Drozd [18] (Figure 2b) and in the most frequently used method of Brune [19].

Brune's method is most often used in engineering practice, as well as in scientific studies (Table 1). This method was modified by, among others, Morris [20] and Linsley et al. [21] and Ward [22] (Table 1). Brown [23] (Table 1), Brune and Allen [24] (Figure 2c), and Gottschalk [25] (Figure 2d) developed dependencies of the STE on the capacity–watershed ratio (C–W), which is the quotient of the reservoir's capacity and the reservoir's catchment area. A different approach was used by Churchill [24] (Table 1), who developed the relationship between STE and the sedimentation index (SI—the proportion of time of water retention in a reservoir (s) and mean flow velocity in a reservoir (ft·s^{-1})).

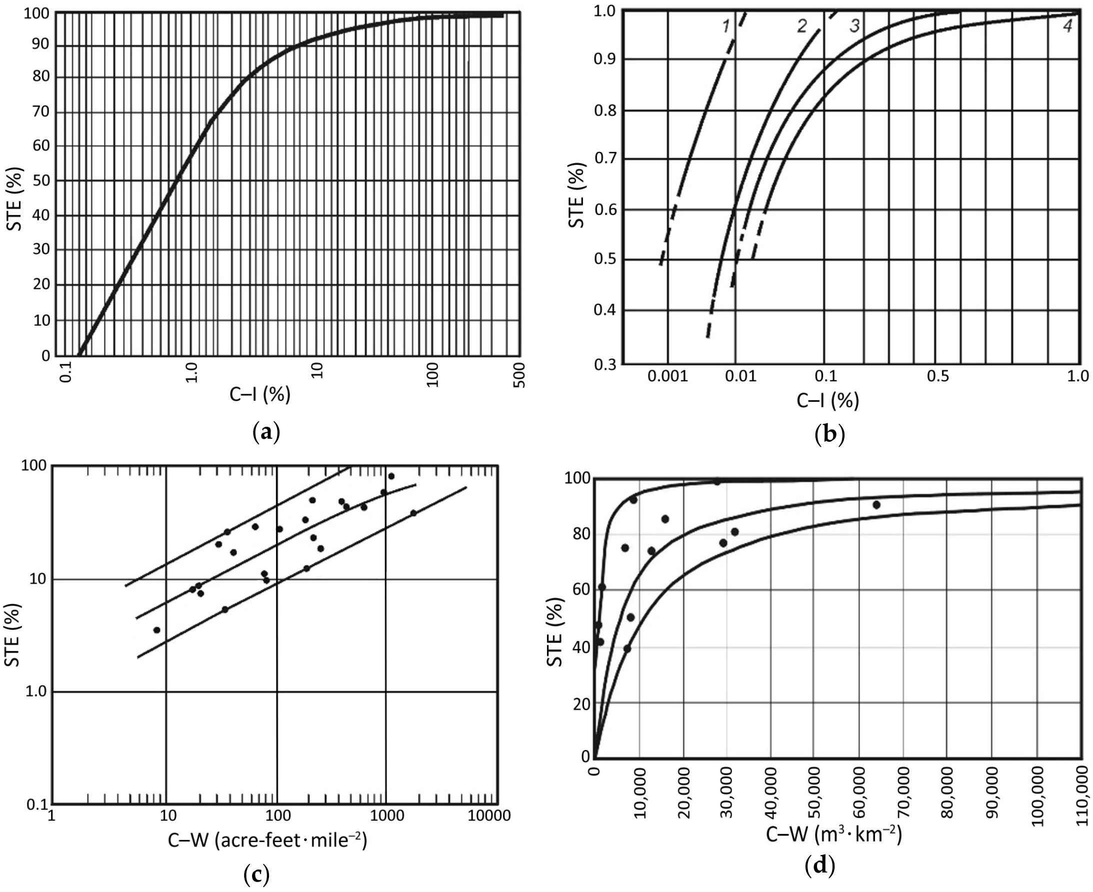

Figure 2. Sediment trap efficiency according to: (**a**) Łopatin [17]; (**b**) Drozd: 1—coarse-grained sands, 2—fine-grained sands, 3—dusts, 4—clay [18]; (**c**) Brune and Allen [24]; (**d**) Gottschalk [24].

Table 1. Methods for determining sediment trap efficiency (STE).

Author/s of Method	Equation
Brune [19]	$STE = 100 \cdot \left(0.97^{0.19^{\log C\text{–}I}}\right)$; *)
Morris and Wiggert [20]	$STE = 100 \cdot \left(\frac{C\text{–}I}{0.012+1.02 \cdot C\text{–}I}\right)$
Linsley et al. [21]	$STE = 100 \cdot \left(1 - \frac{1}{1+a \cdot C\text{–}I}\right)^{n}$, a = 65–130, n = 2–10
Ward [22]	$STE = 1 - \left(\frac{0.05}{C\text{–}I^{0.5}}\right)$
Brown [23]	$STE = 100 \cdot \left(1 - \frac{1}{1+K \cdot C\text{–}W}\right)$, K = 0.046–1.0; *)
Churchill [24]	$STE = 100 – \left(800 \cdot SI^{-0.2} - 12\right)$; *)

C–I—capacity–inflow ratio; C–W—capacity–watershed ratio; SI—sedimentation index; *)—the method is also presented in the form of a nomogram.

For the parameters of the examined reservoir, calculated by the above-listed methods, the initial STE value was determined, that is, the one from the beginning of a given operating period. It is then compared with the initial STE_R value determined from the sediment balance. Verifying these methods in this way makes it possible to indicate which of them enable the correct determination of the STE for the small reservoir, such as Krempna.

The obtained results of silting measurements carried out in two operational periods, together with the calculated suspended sediment transport from the beginning of operation in a given period to the year of silting measurement, allowed for calculating the STE_R value in subsequent years, in which the siltation measurement was performed.

The STE_R value is also calculated in the analysis of the suspended sediment transport carried in the separated flood waves as the ratio of the difference in the mass of sediment flowing in and out to the mass of sediment flowing into the reservoir.

3. Results

3.1. Impact of Flood Waves on the Sediment Trap Efficiency

The hydrographs for the 1987–2005 and 2006–2018 multiannual periods were developed for the time intervals from the beginning of June to the end of November of each year—they cover 3294 days (Figure 3) and 2196 days (Figure 4), respectively. A red horizontal line on hydrographs shows the flow with a probability of exceedance of 50% = 26.14 $m^3 \cdot s^{-1}$. This flow was interpolated from flows with the probability of exceedance $Q_{0.1\%}$ = 509 $m^3 \cdot s^{-1}$, $Q_{0.2\%}$ = 383 $m^3 \cdot s^{-1}$, $Q_{1\%}$ = 290 $m^3 \cdot s^{-1}$, and $Q_{10\%}$ = 156 $m^3 \cdot s^{-1}$, included in the "report on the implementation of flood hazard maps and risk maps" (2013), and flow $Q_{100\%}$ = 0.13 $m^3 \cdot s^{-1}$ [26].

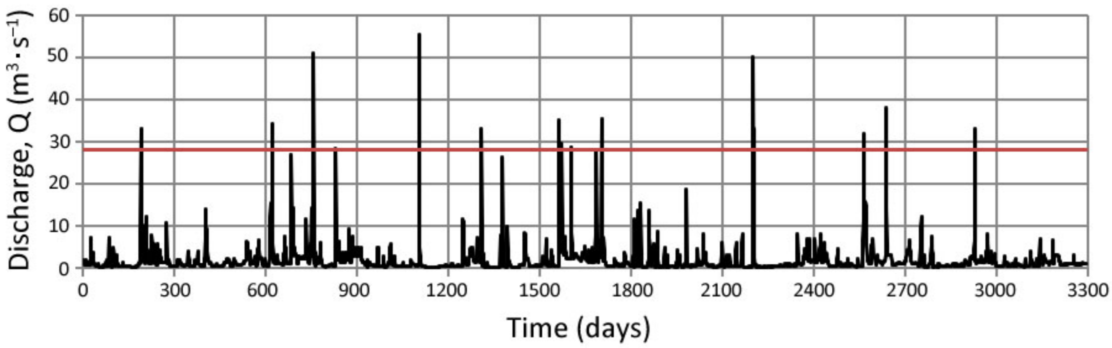

Figure 3. Hydrograph for the multiyear period of 1987–2005 with 15 waves with a probable flow greater than 50% = 26.14 $m^3 \cdot s^{-1}$ (red line).

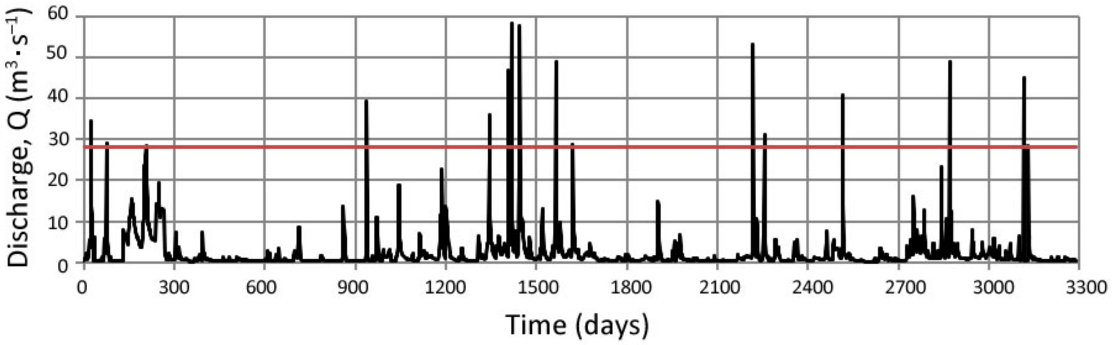

Figure 4. Hydrograph for the multiyear period of 2006–2018 with 16 waves with a probable flow greater than 50% = 26.14 $m^3 \cdot s^{-1}$ (red line).

Figure 4 shows the developed dependencies of the suspended sediment concentration collected at the cross-section point of the Wisłoka River on the daily flow for summer heavy rainfalls. Figure 5a shows the relationship developed for the upper water gauge (UG), and

Figure 5b for the lower water gauge (LG). As a result of supplementing the hydrological data sequences with the missing suspended sediment concentrations, the transport was calculated both in the entire two operating periods and in the selected flood waves with a peak flow greater than $Q_{50\%}$. The calculations consider the correction factors k, which are 0.906 for the upper water gauge (UG) and 1.08 for the cross section of the lower water gauge (LG) cross section.

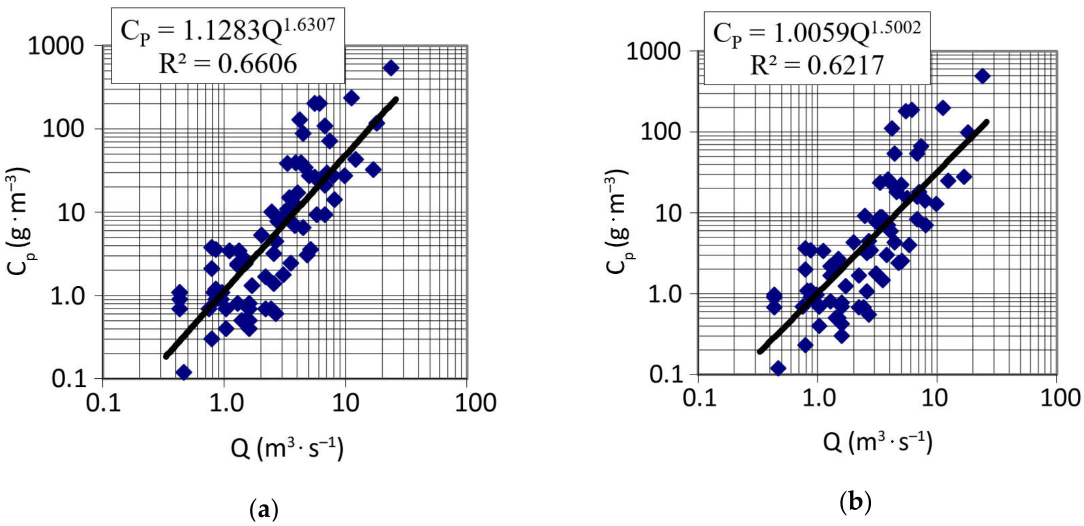

Figure 5. Relationship between the suspended sediment concentration measured in the point of cross section (C_P) of a water gauge and mean 24 h flows (Q) established for: (**a**) cross section of the upper water gauge and (**b**) cross section of the lower water gauge season: summer heavy rainfalls.

Table 2 presents the results of the calculations of suspended sediment transport flowing into and out of the Krempna reservoir in the separated flood waves, as well as the real sediment trap efficiency (STE_R) calculated for the reservoir in the flow conditions of these waves. The total suspended sediment transport in the selected flood waves constitutes 47.1% of the total suspended sediment transport in the operational period of 1987–2005. On the other hand, in the period of 2006–2018, it accounted for 48.0% of the total suspended sediment transport.

The correlation relationships between STE and Q were established for each of the two operating periods. The developed regression equations have the form of: STE = 4360.72 $Q^{-1.585}$ for the 1987–2005 period (R^2 = 0.5379, significance level = 0.05) and STE = 5150.42 $Q^{-1.689}$ for the 2006–2018 period (R^2 = 0.6890, significance level = 0.05). Figure 6 shows the correlation relationship developed for two operating periods. The developed relationship is significant at the level of 0.05.

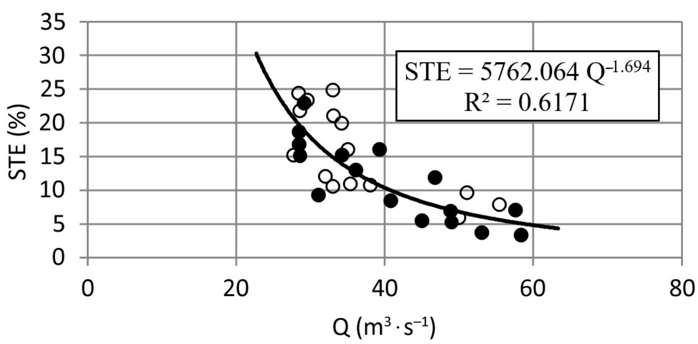

Figure 6. Relationship between sediment trap efficiency (STE) and mean 24 h flows (Q) established for data of two operation periods (empty points are for the period 1987–2005).

Table 2. Suspended sediment transport and sediment trap efficiency (STE_R) for the selected flood waves.

No.	Period 1987–2005				Period 2006–2018			
	Q_{max} ($m^3 \cdot s^{-1}$)	SST in Cross Section [t] UG	SST in Cross Section [t] LG	STE_R (%)	Q_{max} ($m^3 \cdot s^{-1}$)	SST in Cross Section [t] UG	SST in Cross Section [t] LG	STE_R (%)
1	33.00	2258	1809	24.8	34.35	839	728	15.2
2	34.20	1589	1324	20.0	29.13	1244	1012	22.9
3	51.00	4736	4321	9.6	28.50	2869	2418	18.7
4	28.40	520	418	24.4	39.34	1522	1312	16.0
5	55.50	6235	5778	7.9	36.10	1846	1634	13.0
6	33.10	2368	1956	21.1	46.80	547	489	11.9
7	35.03	2137	1842	16.0	58.40	2113	2045	3.3
8	29.60	785	636	23.4	57.60	5591	5223	7.0
9	28.60	604	496	21.8	48.90	1941	1815	7.0
10	27.70	3351	2909	15.2	28.60	978	849	15.2
11	35.40	2463	2219	11.0	53.10	1346	1298	3.68
12	50.02	4843	4572	5.9	31.10	1341	1227	9.3
13	32.01	2425	2166	12.0	40.86	2920	2693	8.4
14	38.06	3062	2765	10.7	49.00	3409	3239	5.2
15	33.50	6677	6035	10.6	45.00	1662	1576	5.5
16	-	-	-	-	28.50	914	783	16.8

Figure 7 compares the results of the STE calculations using the equation shown in Figure 6 with the STE_R values determined based on the balance of suspended sediment transported in the separated flood waves. The predictive efficiency of the developed model was statistically assessed using the following measures: root mean square error (RMSE) = (Σ(xp − xm)2/N)0.5 and mean absolute error (MAE) = Σ∣xp − xm∣/N, where xp is the predicted STE value, xm is the STE_R value calculated based on the measured results, and N is the number of data.

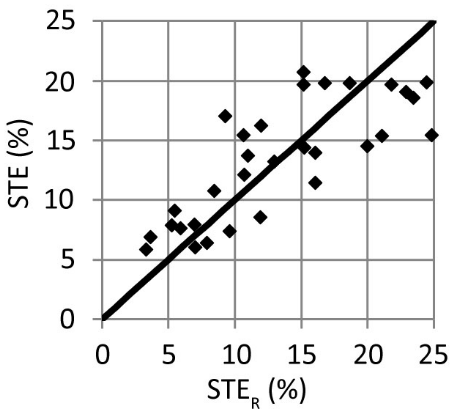

Figure 7. Comparison of the calculated STE according to the equation shown in Figure 6 and the established STE_R value according to sediment balance in flood waves.

The calculated RMSE is 3.94, which means that the STE values predicted using the model (Figure 6) deviate on average by 3.94% from the STE_R value. The error determined by means of MAE is 3.36, and the difference in the MAE and RMSE values (Δ) of 14.6%

is not significant. It does not indicate the occurrence of errors with huge values in the forecast period.

3.2. Sediment Trap Efficiency Changes during Operation

The results of the Krempna reservoir silting measurements are presented in Table 3. The silting ratio (SR) calculated based on the measured volume of the deposited sediment (V_t) increases by several percent in the following years (Table 3, column 4). Silting ratio (SR), as the ratio of the volume of sediment load deposits collected in the given operation period and the total volume of the reservoir, after 18 years of operation in the period of 1987–2005 reaches 40.9%, while after 12 years of operation in the period of 2006–2018 indicates 31.1% of silting (Table 3, column 4).

Table 3. Sediment trap efficiency of the Krempna reservoir established from silting measurements and estimated volume of delivered suspended sediment transport.

Year	Years of Operation	Volume of Sediment Deposits V_t (m^3)	Silting Ratio SR (%)	Total Volume of Suspended Sediment Transport SST (m^3)	Capacity–Inflow Ratio C–I (%)	Sediment trap Efficiency STE_R (%)	Mean Annual Sediment Trap Efficiency STE* (%)
1	2	3	4	5	6	7	8
Period 1987–2005							
1996	9	27,041	24.1	46,462	0.265	58.2	6.47
1997	10	30,464	27.2	50,858	0.255	59.9	5.99
1998	11	34,637	30.9	53,124	0.242	65.2	5.93
1999	12	38,002	33.9	61,294	0.231	62.0	5.17
2000	13	40,144	35.8	66,907	0.224	60.0	4.62
2002	15	44,200	39.5	79,496	0.212	55.6	3.71
2003	16	44,901	40.1	84,084	0.210	53.4	3.34
2005	18	45,810	40.9	91,804	0.207	49.9	2.77
Period 2006–2018							
2009	3	6710	7.0	11,932	0.212	56.2	18.75
2011	5	15,133	15.7	26,321	0.192	57.5	11.50
2012	6	18,242	18.9	33,122	0.185	55.1	9.18
2017	11	26,055	27.0	55,679	0.166	46.8	4.25
2018	12	29,943	31.1	64,108	0.157	46.7	3.89

The total volume of suspended sediment transport presented in Table 3 (column 5) was recalculated from the weight of the transported sediment. For this purpose, the average bulk density of bottom sediments was used, amounting to $\rho_0 = 1.23\ t{\cdot}m^3$. The sediment trap efficiency (STE_R) was calculated for each of the measurements of the sediment deposition volume (V_t) and the calculated volume of sediment delivered to the reservoir (SST) (Table 3, column 7). In the first of the analyzed operating periods, that is, 1987–2005, the STE_R value decreased from 58.2% (1996) to 49.9% (2005), and in the period 2006–2018, it decreased from 56.5% (2009) to 46.7% (2018). The tendency to increase the sediment outflow from the reservoir in subsequent years of operation is well represented by the mean annual sediment trap efficiency (STE*) (Table 3, column 8). It was calculated as the quotient of STE and years of operation.

The calculated initial STE_R value, that is, for the beginning of the Krempna reservoir's operation, is 77.1% in 1987 and 63.1% in 2006. These values enable the verification of empirical formulas for the determination of the initial value of sediment trap efficiency

(STE) and its changes during operation. For this purpose, the capacity–inflow ratio (C–I) was also determined not only for the initial value of STE_R, but also for the one determined in the subsequent years in which the silting measurements were performed (Table 3, column 5). The C–I value for the period of 1987–2005 was calculated for the average annual flow amounting to 2.03 $m^3 \cdot s^{-1}$, and for the period of 2006–2018 for the average annual flow amounting to 2.68 $m^3 \cdot s^{-1}$.

3.3. Verification of Methods for the STE Determination

The capacity–inflow ratio (C–I) of the Krempna reservoir, calculated for the reservoir's initial capacity, that is, after its desilting, is 0.350% and 0.228% for the periods of 1987–2005 and 2006–2018, respectively. However, the initial values of the capacity–watershed ratio (C–W) are 1.42 and 1.22 acre-feet·mile^2 (678 and 583 $m^3 \cdot km^{-2}$). Therefore, the calculated sediment index (SI) proposed by Churchill is: $2.362 \cdot 10^6$ and $9.83 \cdot 10^5$ $s^2 \cdot feet^{-1}$, respectively, for the two analyzed periods. For these parameters, the projected STE values of the Krempna reservoir were determined at the beginning of operation in each period (Table 4).

Table 4. Forecasted STE according to verified methods for determining sediment trap efficiency.

No.	Method/Parameter	Period	
		1987–2005	2006–2018
1	Łopatin [17]	22.0	10.0
2	Drozd [18]	–	–
3	Brune [19]	16.5	8.9
4	Morris and Wiggert [20]	22.5	15.9
5	Linsley et al. [21]	9.8	5.2
6	Ward [22]	15.0	−5.0
7	Brown [23]	12.5	10.9
8	Brune and Allen [24]	99.9	99.8
9	Gotshalk [25]	–	–
10	Churchill [26]	69.3	61.4

The projected initial value of STE from the Łopatin nomogram (Figure 2a) is several times lower than that determined from the sediment balance. It amounts only to 22% and 10% (Table 4) for the first and second operation periods, respectively. Obtaining the STE value from these nomograms that is close to the actual STE_R value (the one determined from the balance of retained and inflowing sediment, i.e., 77.1% and 63.1%) would be possible for the C–I value of 1.8%–3.5%.

It is not possible to determine the STE from the Drozd nomogram, as the tested small reservoir has C–I values of 0.350% and 0.228%, which are outside the lower range of the curve no. 3 (dust sediment) in this nomogram (Figure 2b), amounting to approximately 1%.

Brune's method and its modifications by Morris and Wiggert [20] and Linsley et al. [21] and Ward [22], in which the STE value is estimated for the C–I ratio, do not give satisfactory results—the predicted STE values are several times lower than the real STE_R (Table 4), similar to those obtained from the Łopatin nomogram. The initial STE forecasted for the second period using Ward's formula proved to be negative (Table 4).

The methods of Brown, Brune and Allen, and Gotshalk's method, in which the STE is presented in relation to the C–W ratio, also do not give the expected values—Brown's method gives significantly underestimated values, while Brune's and Allen's methods overestimate them significantly, as they are close to the STE value of 100%. On the other hand, determining the STE value from the Gotshalk nomogram is impossible because the C–W values on the abscissa (horizontal) axis are given in thousands of $m^3 \cdot km^{-2}$ (Figure 2d).

Thus, as a result of an attempt to estimate the Krempna reservoir STE values, they would be of about 1–2% from this nomogram.

While looking at the obtained results of the forecasted STE, only Churchill's method allows for obtaining the forecasted STE values close to those determined on the basis of the balance of retained and inflowing sediment. The forecasted initial STE value for the period of 1987–2005, amounting to 69.3% (Table 4), differs by 10.1% from the actual initial value of STE_R = 77.1%, and the forecasted initial STE value for the period of 2006–2018, amounting to 61.4% (Table 4) differs by 2.7% from the actual initial value of STE_R = 63.1%.

3.4. Reduction of the STE Value and Its Forecasting

The STE values projected at the beginning of the reservoir operation in the 1987–2005 and 2006–2018 periods, presented in point 3.3, indicate that among the developed STE calculation methods, only Churchill's method allows for estimating the STE of the small Krempna reservoir. Churchill proposed the original SI parameter in 1948, concerning the reservoir sedimentation index to percent of incoming sediment passing through a reservoir. Brune [19] implemented the C–I ratio developed in 1914 by Hazen [24]. The C–I ratio proved to be the most frequently used parameter in empirical relationships with STE. Based on Brune's nomogram [19], the obtained initial STE_R values were presented for both operation periods (Figure 8), as well as the STE_R values determined from the sediment balance calculations (Table 3, column 7). Based on the data in both Table 3 and Figure 7, a reduction in the STE_R value depending on the decreasing C–I ratio can be observed. For each measurement period, separate regression curves were developed, for the 1987–2005 period (Figure 8, line 1) in the form:

$$STE = 42.145 \cdot \ln(C\text{–}I) + 120.138 \quad (3)$$

and for the period 2006–2018 (Figure 8, line 2) in the form:

$$STE = 42.852 \cdot \ln(C\text{–}I) + 125.73 \quad (4)$$

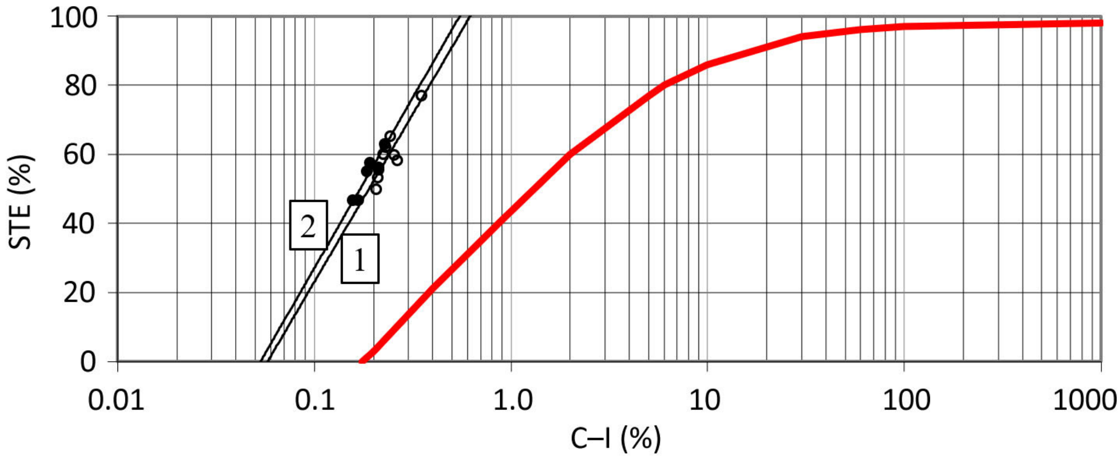

Figure 8. Sediment trap efficiency (STE) related to the C–I ratio for the Krempna reservoir compared with Brune's curve (red): 1—STE regression line for the period 1987–2005 (empty points); 2—STE regression line for the period 2006–2018 (points filled with black).

The developed equations are statistically significant at the significance level of 0.05, and the coefficients of determination for these equations are: R^2 = 0.7847 for Equation (3) and R^2 = 0.8884 for Equation (4). Tables 5 and 6 present the results of the STE values forecasted using the developed correlation equations along with measures of their predictive efficiency. The calculated RMSE and MAE are 7.83 and 5.43 for Equation (3) (Table 5) and 3.54 and 2.40 for Equation (4) (Table 6), respectively. A significant difference in the values between

MAE and RMSE (Δ), of 30% (Table 5) and 32.3% (Table 6), indicates the occurrence of large values of errors in the forecast period.

Table 5. Results of the forecasted STE according to established models (correlation equations) for the period of 1987–2005.

Year	Years of Operation	STE_R (%)	STE Acc. to Equation (3) Line 1 on Figure 6 (%)	Churchill's Method		
				SI ($s^2 \cdot feet^{-1}$)	STE Acc. to Churchill (%)	STE Acc. to Equation (5) Line 1 on Figure 7 (%)
1	2	3	4	5	6	7
1987	0	77.1	63.5	$2.3 \cdot 10^6$	69.3	69.5
1996	9	58.2	75.9	$1.3 \cdot 10^6$	64.3	64.2
1997	10	59.9	64.2	$1.2 \cdot 10^6$	63.5	63.4
1998	11	65.2	62.6	$1.1 \cdot 10^6$	62.5	62.4
1999	12	62.0	60.3	$1.0 \cdot 10^6$	61.5	61.5
2000	13	60.0	58.4	$9.4 \cdot 10^5$	60.9	60.9
2002	15	55.6	57.1	$8.4 \cdot 10^5$	59.7	59.8
2003	16	53.4	54.8	$8.2 \cdot 10^5$	59.5	59.5
2005	18	49.9	54.4	$7.9 \cdot 10^5$	59.1	59.3
	RMSE		7.83	–	5.36	0.11
	MAE		5.43	–	4.56	0.10
	Δ (%)		30.8	–	14.9	7.2

Table 6. Results of the forecasted STE according to established models (correlation equations) for the period of 2006–2018.

Year	Years of Operation	STE_R (%)	STE Acc. to Equation (4) Line 1 on Figure 6 (%)	Churchill's Method		
				SI ($s^2 \cdot feet^{-1}$)	STE Acc. to Churchill (%)	STE Acc. to Equation (6) Line 1 on Figure 7 (%)
1	2	3	4	5	6	7
2006	0	63.0	58.2	$1.0 \cdot 10^6$	61.7	61.6
2009	3	56.2	62.4	$8.8 \cdot 10^5$	60.3	60.0
2011	5	57.5	59.3	$7.2 \cdot 10^5$	58.1	57.8
2012	6	55.1	55.1	$6.7 \cdot 10^5$	57.3	57.0
2017	11	46.8	53.4	$5.4 \cdot 10^5$	54.9	54.6
2018	12	46.7	48.9	$4.8 \cdot 10^5$	53.5	53.4
	RMSE		3.54	–	3.87	0.20
	MAE		2.40	–	2.56	0.16
	Δ (%)		32.3	–	33.9	21.0

The STE_R values determined from the sediment balance calculations (Table 3, column 7) together with the initial STE_R values for both operating periods plotted on the Churchill nomogram [24] (Figure 9) are located close to the Churchill curve (red line). The data presented in Table 3 show the reduction of the STE_R value, and it is also visible in Figure 9, where the decreasing STE_R values determined from the sediment balance correspond to the decreasing SI values. For the SI range calculated for the Krempna reservoir, the calculated projected reduced STE values together with those calculated from the sediment balance are presented in Tables 5 and 6. For each measurement period, separate regression curves were develop, for the period 1987–2005 (Figure 9, line 1) in the form of:

$$STE = 9.547 \cdot \ln(SI) - 70.432 \quad (5)$$

and for the period 2006–2018 (Figure 9, line 2) in the form of:

$$STE = 10.855 \cdot \ln(SI) - 88.619 \quad (6)$$

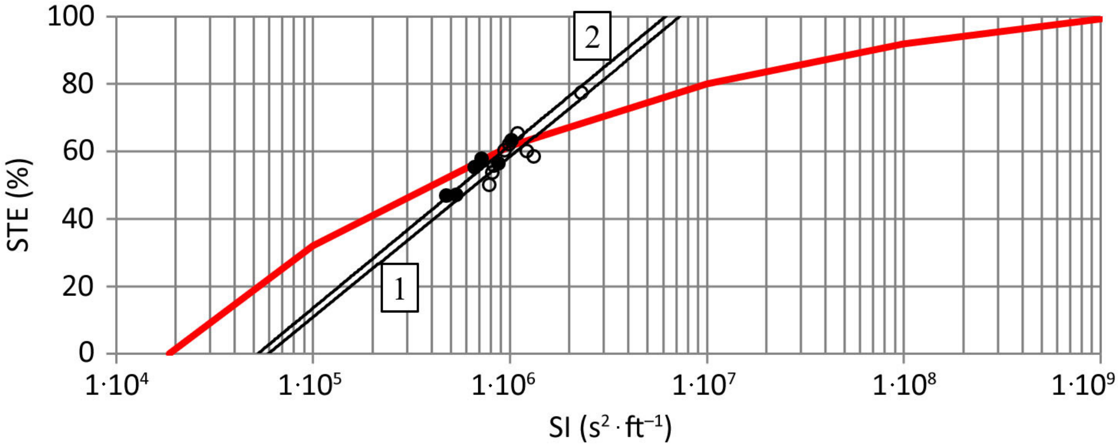

Figure 9. Sediment trap efficiency (STE) related to the SI ratio for the Krempna reservoir compared with Churchill's curve (red): 1—STE regression line for the period of 1987–2005 (empty points); 2—STE regression line for the period of 2006–2018 (points filled with black).

The developed equations are statistically significant at the significance level of 0.05, and the coefficients of determination for these equations are: R^2 = 0.9988 for Equation (5) and R^2 = 0.9995 for Equation (6). The calculated RMSE and MAE are 0.11 and 0.11 for Equation (5) (Table 5), and for Equation (6), 0.20 and 0.16, respectively. The STE value forecasted with these equations differs on average by only several hundredths from the STE_R value. A very small difference in the values between MAE and RMSE (Δ), of only 7.2% (Table 5) for Equation (5) indicates that errors with large values do not occur in the forecast period. A greater difference between MAE and RMSE (Δ) was obtained for Equation (6). It amounts to 21% and indicates the occurrence of errors in the forecast period.

Extrapolation of the curves described by the developed correlation Equations (5) and (6) shows their significant deviation from Churchill's curve. This means that in conditions of progressive silting, resulting in a decrease in capacity and a decrease in SI, the STE forecasted by Churchill's method will differ increasingly from the real values.

4. Discussion

The analysis of the flood waves' flow through the reservoir showed that in the conditions of extreme flood flows, a small shallow reservoir retains only a few percent of the suspended sediment transport. The developed model presented in Figure 5 allows for estimating the STE value of the examined reservoir under the conditions of flood flow with a flow rate greater than the one with a probability of exceedance of 50%. The scatter of the points in Figure 6 is uniform along the 1:1 line for the STE range from 0% to 10%, showing relatively good agreement of the measured values with the predicted ones, as compared with the scatter of points above the value of 10%. The reason for obtaining such significant dispersion of points in relation to the 1:1 line may be the impact of the measurement method, that is, the measurement carried out at daily intervals, without the concentration of measurements during freshets consisting in measuring, for example, every hour. This is important in the case of sudden floods with a high peak wave and of a very short duration, as in the case of the Krempna reservoir. These largest flood waves were recorded as 24 h events. When the largest flood waves flow through a very small reservoir, the entire wave with the suspended sediment flows through the reservoir without the retention effect, causing almost all sediment transport to be carried through the reservoir. In the case of smaller waves, the flood flow retention effect may, to a small extent, contribute to the retention of a larger part of the sediment than during extreme floods. Extreme flood events may fundamentally impact sediment dynamics and morphology in terms of their tremendous ability to carry sediment load and reshape the estuarine morphology [27]. Łajczak [28] claims that in the case of large reservoirs, as opposed to shallow ones, the greatest size of sedimentation occurs in years with high floods.

The calculated total suspended sediment transport in flood waves in relation to the total transport was 47.1% and 48.0%. De Girolamo et al. [29] report that the share of sediment transport during the high flow regime was 94%. This value was determined on the basis of 12-month studies in the Celone River and did not take into account the multiyear variability. A large share of suspended sediment transport in flood waves in relation to the total transport was also demonstrated by Oeurng et al. [30]. Research carried out over 2 years showed 85% of annual load transport during floods for 16% of the annual duration (in 2007) and 95% of annual load transport during floods for 20% of the annual duration (in 2007). Based on the 10-year period, Tena et al. [31] reported results similar to those obtained for the Wisłok River, which flows through the Krempna reservoir. These studies show that the contribution of such events (i.e., floods, including both natural and flushing flows) represents 39% of the total suspended sediment load. Tena et al. [31] report that natural floods transported up to 65% of the annual load in some years.

It was demonstrated that flood waves with the highest flow rate cause the flow of almost all of the transported sediment—the STE_R values for these waves amount to several percent (Table 2). The reduction of STE can also be observed by analyzing flood waves of a similar flow rate, which occur in the following years. The waves from the period of 1987–2005, presented in Table 2 in rows 1, 2, 6, 7, 14, and 15, can be shown as examples of such a situation. The STE_R values for these waves are from 20.0% to 24.8% in rows 1 and 2, that is, at the beginning of the operational period to 10.6–10.7% in rows 14 and 15, which is the end of that period. A similar observation was made by Lee et al. [32] in waves from 2004 to 2016. These authors report total desilting efficiency values ranging from 12.7% to 20.9%. The desilting efficiency in a flood event is defined as the ratio of sediment volume outflow to sediment volume inflow [32]. Thus, 100% minus desilting efficiency results in STE, which means that in the following years, an increasing amount of sediment flows out of the reservoir, whose initial storage capacity was 310,000,000 m^3, and STE is reduced from 87.3% to 79.1% over 12 years.

The small, shallow reservoir in Krempna silts rapidly. After 18 years of operation, the silting ratio is over 40%, and after 12 years of operation, the silting ratio is 31%. Such a significant rate of silting allows for tracking changes in the parameters describing this process, including the silting degree, capacity–inflow ratio, capacity–watershed ratio, and sediment trap efficiency. A reduction in C–I, C–W, and STE is not presented in the scientific literature due to the fact that the presented silting problems mainly concern large reservoirs, and the reduction of STE in large reservoirs reaches only a few percent during several or several dozen years of operation [23,33].

The initial STE_R value, determined based on the balance of sediment retained in and flowing out of the Krempna reservoir, was 77.1% in 1987 and 63.1% in 2006. These are values that fall within the STE range defined for small reservoirs by Brune in 1953 [34]. According to Brune, the trapping efficiency for smaller dams ranges between 10% and 90%. According to Williams and Wolman [35] and Graf [36], larger STE values, close to 99%, are achieved by large reservoirs (volume of 107 m^3). An attempt to estimate the initial values by means of empirical methods showed that only Churchill's method makes it possible to determine the initial STE value close to the STE_R value. The methods of Łopatin, Brune, Morris, and Linsley et al., as well as of Ward and Brown, give the predicted values of sediment trap efficiency several times lower than the value determined from the balance of sediment retained in and flowing into the reservoir (STE_R). The Krempna reservoir has a capacity–inflow ratio (C–I) for an initial storage capacity of 0.350% and 0.228%. Without the balance of sediment retained in and flowing into the reservoir, the assumption of the forecasted STE value from these nomograms could be considered a correct value. This was performed by Juško et al. [37], when determining the STE values for the Hnusno reservoir by Brown's, USDA forest service's, and Brune's methods, obtaining STE values of 45.6%, 42.2%, and 40.0%, respectively (while for the C–I of this reservoir, of 0.529%, the STE value from Brune's method should amount to 26.3%, instead of 40%). The changes in erosion processes in a small catchment in the western Carpathians' mountain landscape and related modifications in the siltation intensity of the small reservoir situated in the catchment were determined for the averaged STE value. Are the adopted STE values for the Hnusno reservoir underestimated, as in the case of the tested Krempna reservoir? No suspended sediment transport results were available. The STE of the Hnusno reservoir (total volume of 55,000 m^3) determined by Churchill's method is 86.1%. This indicates great caution in determining the STE of small reservoirs using methods available in the literature as well as the need to verify these methods, and to develop a method for determining STE dedicated to small reservoirs.

Small reservoirs are characterized by a rapid change in the STE value. The change in the STE value during the operation of the reservoirs is confirmed by the observations of many researchers who state that the ability of reservoirs to retain sediments is not a constant value over time [33,38,39]. The verified methods cannot be used to demonstrate the STE reduction. Most of these methods were developed based on the data collected for reservoirs of various capacities, for which the volume of sediments was determined at various times of their operation. An example is a study by Brune [19], who developed a nomogram for reservoirs, for which the calculations were made for the period from 1 to 72 years of operation. On the other hand, capacities of reservoirs determined for a given measurement ranged from 3000 m^3 (this is the capacity of Lake Halbert after 69 years of operation) to 31,720,000,000 m^3 (this is the capacity of Lake Mead after 13 years of operation—this is the reservoir formed by the Hoover Dam!). Despite the widespread and uncritical use of Brune's method, as well as other methods that did not give satisfactory results in this work, there are reports in the scientific literature pointing to the problematic use of these methods even for large water bodies. Lewis et al. [40], reporting the results of the Burdekin Falls Dam reservoir (volume of 1,860,000,000 m^3), found that the measured TE of the reservoir ranged between 50% and 85% and was considerably less than the estimates using the Brune and Churchill curves over the 5-year study period.

The reason for the inability to correctly determine the STE of the Krempna reservoir using the methods of Łopatin, Drozd, Brune, Morris and Wiggert, Linsley et al., Ward, Brown, Brune and Allen, and Gottschalk is mainly that these methods were developed for reservoirs with different capacities and in different years of operation. The limitation results from the lower value range of the described (independent) variable, adopted in the developed method, for which the STE values are close to zero. Brune obtained the lower nomogram range for C–I of 0.29% and 0.41% and STE values of 23% and 5.8%, respectively, for the two reservoirs—Lake Halbert 1 and Lake Halbert 2—after 69 years of operation. Based on their study, if the authors of this paper had determined the STE values of the Krempna reservoir after 69 years, they would have obtained similar, or even lower, STE values. What would the median curve have been if the Brune method had STE values for these reservoirs in the first year of operation? Would such data be removed as outliers? The authors of this study point out that it is necessary to determine the STE values in the first years of operation of water reservoirs characterized by low values of the descriptor (independent). This is the reason why the STE of the Krempna reservoir cannot be determined correctly.

Verstraeten and Poesen [41] stated that no correct empirical formula has been developed so far to determine the sediment retention capacity of small reservoirs and ponds. The demonstrated reduction in the STE of the Krempna reservoir in two operating periods may constitute the basis for an attempt to develop a method dedicated to small reservoirs. The developed dependencies indicate the possibility of their development, assuming both C–I and SI as describing (independent) variables. Although they underestimate the initial STE value of the Krempna reservoir, they also allow forecasting the change in the STE. The developed models (3) and (4, describing the dependence of STE in the function of C–W, provide a more understated initial estimated STE value. However, they better forecast the STE in the later years of operation (column 4 in Tables 5 and 6). The STE predicted by the SI-based models, that is, (5) and (6), differs in decimal values (column 7 in Tables 5 and 6) from the STE determined by Churchill's method (column 6 in Tables 5 and 6). This consistency of the results covers the SI range determined for the Krempna reservoir. The extrapolated predicted STE values outside this SI range will increasingly deviate from the STE estimated by Churchill's method (Figure 9). Adaptation of Churchill's method to predict the STE reduction may result from the genesis of this method. Churchill developed his method based on tests carried out in 1935–1938 on two reservoirs, Hales Bar and Wilson, taking quarterly measurements. A correlation curve was developed for the 18 measurement data obtained, and the measurement data from the following quarters of the 4-year measurement period, presented in the Churchill nomogram, show a trend of STE reduction. This was, however, not defined by Churchill. Despite the fact that Churchill's curve was developed for reservoirs with a capacity of over 174,000,000 m^3 (Hales Bar) and less than 300,000,000 m^3 (Wilson), it can also be applied to forecast the STE of small reservoirs. This means that SI seems to be a better estimator than C–I. The authors point out that this observation is limited to the investigated small reservoir Krempna and may apply to other small reservoirs with a C–I smaller than 1%. However, this requires the study of a larger number of small reservoirs. The relationship between STE and flood discharges also has a limited application. This relationship applies to small reservoirs. A study of more small reservoirs is required. The relationship of STE to the flow rate of flood waves is also of limited use. This relationship applies to small reservoirs. For large reservoirs, applying the proposed approach is possible with caveats. However, it should be taken into account that the siltation process for large reservoirs is much slower than for small ones. The slower rate of capacity reduction contributes to small reductions in C–I over the comparable lifetime of small reservoirs, which means slight reductions in STE.

5. Conclusions

1. In the 31 flood waves separated from the two operational periods of the Krempna reservoir, the flow rate of which is greater than the flow with the probability of exceedance of 50% and amounting to 26.14 $m^3 \cdot s^{-1}$, the suspended sediment transport amounts to 47–48% of the total sediment transport in the analyzed operation periods. The sediment trap efficiency, determined from the balance of sediment flowing in and out of the reservoir in the separated flood waves, is from over 3% to less than 25%. The lowest STE values were observed for the waves with the highest flow rate.
2. The initial STE value determined for the initial storage capacity of the reservoir in Krempna using the methods of Łopatin, Brune, Morris and Linsley et al., Ward, and Brown proved to be several times lower than the value determined from the balance of sediment retained in and flowing into the reservoir (STE_R). This is due to very low values of the capacity–inflow and capacity–watershed ratios of the analyzed reservoir, which belong to the lower range of the STE values of the verified methods, or, as in the case of the Drozd's method, they are lower than its lower range, making it impossible to determine the STE. In contrast, Brune and Allen's method provided the STE values of more than 99%. Only Churchill's method allows for determining the initial STE value close to the STE_R value. Therefore, it is not possible to determine the STE reduction of the examined reservoir using the above-mentioned methods, except for Churchill's method.
3. The small shallow reservoir in Krempna is characterized by a rapid STE reduction of 27.2% over 18 years of operation (period of 1987–2005) and 16.4% over 12 years

of operation (period of 2006–2018). In a small reservoir, the effect of reducing its capacity can be observed in a relatively short period of operation due to rapid silting. With the average flow for this period, it is possible to demonstrate the relationship between the decreasing C–I value and the reduction of STE, C–W, or SI with STE. The developed model of STE reduction in the function of the C–I ratio proved to be burdened with greater error compared with the model of STE reduction in the function of the sedimentation index proposed by Churchill.

4. The presented approach on the example of the Krempna reservoir in two operating periods indicates the possibility of developing a method for forecasting the STE value and its reduction during operation. However, it is necessary to have a larger number of small reservoirs examined. Expanding this model based on the obtained results of studies on silting of small reservoirs may contribute to developing a method dedicated to such reservoirs.

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Notations

C–I	capacity–inflow ratio
C–W	capacity–watershed ratio
C_{cs}	average suspended sediment concentration
C_p	suspended sediment concentration
Δ	difference in the MAE and RMSE values
k	correction factors
LG	lower water gauge
MAE	mean absolute error
N	number of data
Q	discharge
RMSE	root mean square error
R^2	determination coefficient
SI	sedimentation index
SR	silting ratio
STE	sediment trap efficiency
SST_m	suspended sediment transport
SST_1	mass of suspended sediment transport, which flowed into the reservoir in the first year of operation
STE	sediment trap efficiency of the reservoir
STE_R	real sediment trap efficiency
STE*	mean annual sediment trap efficiency
U_i	load of suspension
UG	upper water gauge
V_p	reservoir's initial capacity
V_t	volume of sediment deposition in a reservoir (V_t) after t years
V_1	assumed volume of sediment after the first year of operation
xp	predicted STE value
xm	STE_R value calculated based on the measured results
ρ_0	the volume density of sediments

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