ANALYSIS OF SEDIMENT TRAP EFFICIENCY OF SMALL WATER RESERVOIRS

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Abstract: Analysis of silting of small water reservoirs was conducted at Krempna, Zesławice, Rzeszów, Mazarnia, Wapiennica, Cedzyna, Ożanna and Niedźwiadek reservoirs, of capacities ranging between 112 thous m^3 to 3860 thous m^3. Transport of sediment supplied to studied reservoirs was determined using DR-USLE method. Measurements of suspended load transport conducted in the river cross sections above the reservoirs made possible calculating sediment transport. Sediment trap efficiency of studied reservoirs was determined according to Łopatin's, Brune's, Drozd's, Karaušev's, Brune & Allen's, Brown's and Chruchill's nomograms. No possibility of the nomograms application for small water reservoirs was found. Results of measurements of silting and calculations of sediment transport allowed to determine the reservoir sediment trap efficiency over the successive years of reservoir operation. On the basis of long term research on small water reservoirs a considerable rate of their sediment trap efficiency reduction was revealed. The finding was supported by established values of the reservoir trap efficiency in subsequent years of their operation.

Keywords: small water reservoir, sediment transport, sediment trap efficiency

DIE KLÄRWIRKUNGANALYSE DES KLEINES WASSERBECKEN

Zussamenfassung: Die Stauraumverlandung wurde im kleinen Wasserbecken Krempna, Zesławice, Rzeszów, Mazarnia, Wapiennica, Cedzyna, Ożanna i Niedźwiadek bemessen. Die Ursprünglicher Inhalt des kleines Wasserbecken enhaten von 112 Taus. m^3 bis 3860 Taus. m^3. Der Schwemmstoffefracht, der zu den forchenden Wasserbecken liefern ist, wurde zufolge DR-USLE Methode bezeichnen. Die durchgeführte Messungen vom Schwemmstoffkonzentrationen im Querschnitt des Flussen unten den Wasserbecken ermöglichen die Transporte vom Schwemmstoff zu berechnen. Die Klärwirkung des Wasserbecken würden nach die Kurven von Łopatin, Brune, Drozd, Karaušev, Brune und Allen, Brown und Churchill bestimmt. Vestgestellt wurde, das keine möglichkeiten für Klärwirkung des kleines Wasserbecken nach diesen Methoden waren. Nach die Messungergebnise vor Stauraumverlandung und nach berechnungen die Transporte vom Schwemmstoff würden die Klärwirkung des Wasserbecken in folgenden Jahren beziehnet.

Das wurde aufgeziegen, das das Tempo der Klarwirkungreduzierung des kleines Wasserrbecken gross ist. Die Grundlagen für diese Festellung sind die Klärwirkungren, die in folgenden Jahren beziehnet sind.

Schlüsselworte: das klein Wasserbecken, der Schwemmstoffefracht, die Klarwirkung

1. Introduction

Silting of water reservoirs is among the main factors limiting their correct operation. While projecting a water reservoir, one should consider its silting process. Reservoir silting remains an actual problem of research works. During many years of a big water reservoir operation its sediment trap efficiency diminished only slightly. On this basis a value of determined reservoir sediment trap efficiency, invariable over a several year period, is assumed. This approach is right only for big water reservoirs, in which reduction of this value is slight, reaching only several percent.

Sediment trap efficiency was determined for several small water reservoirs using Łopatin's, Brune's, Drozd's, Karaušev's (Dąbkowski et al., 1982), Brune & Allen's, Brown's and Chruchill's (Batuca and Jordan, 2000) nomograms.

Obtained results were compared with actual sediment trap efficiency of selected reservoirs. Farther in their work the Authors denoted reservoir sediment trap efficiency as

STE. Determining the actual value of STE requires establishing volume of bedload trapped in a reservoir and quantity of sediment flowing into a reservoir. The Authors of presented article have attempted at developing a nomogram of small water reservoir sediment trap efficiency at the same time seeking a criterion to precisely define “small water reservoir”.

2. Selection of research object

Small water reservoirs at Krempna, Zesławice, Rzeszów, Mazarnia, Wapiennica, Cedzyna, Ożanna and Niedźwiadek are situated on the upper Vistula tributaries (fig.1).

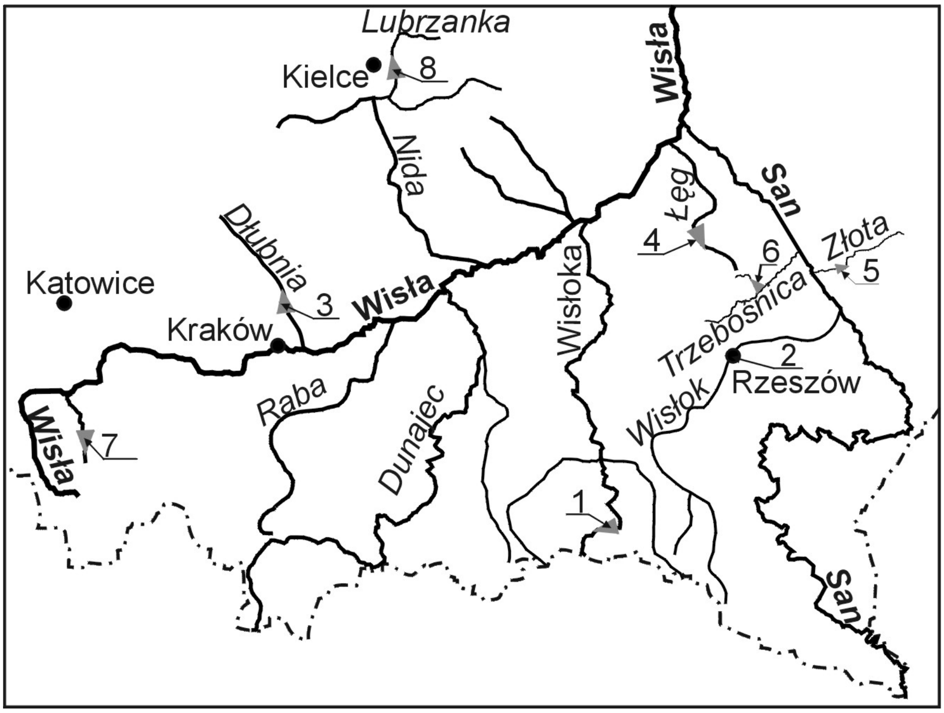

Fig.1. Location of studied water reservoirs: 1-Krempna, 2-Rzeszów, 3-Zesławice, 4-Mazarnia, 5-Ożanna, 6-Niedźwiadek, 7-Wapiennica, 8-Cedzyna

Krempna water reservoir on the Wisłoka river was constructed in 1972. Initially the reservoir had 119 thous m^3 capacity. In 1987 it was desilted and its capacity diminished to 112 thous m^3. From its source to the reservoir at Krempna the Wisłoka river is 18.6 km long and covers a partial catchment with the area of 165.3 km^2.

Zesławice water reservoir on the Dłubnia river was constructed in 1966. The reservoir with 228 thous m^3 capacity was desilted in 1983. From its source to the reservoir at Zeławice, the Dłubnia river covers the catchment area of 218 km^2.

Rzeszów water reservoir (1800 thous m^3 capacity) on the Wisłoka river was put into operation in 1973. It was rebuilt in 1994-1995 and its width was decreased owing to construction of longitudinal dams. At present it is a flow reservoir, with the area of 2060.7 km^2.

Maziarnia water reservoir on the Łęg river was put into operation in 1989. Its capacity is 3860 thous m^3. Staff gauges have been installed above and below the reservoir. The catchment area to the dam cross section is 233 km^2.

Wapiennica water reservoir was put into operation in 1932. The reservoir has never been desilted. The Wapiennica river catchment area to the dam profile is 11 km^2.

Cedzyna water reservoir on the Lubrzanka river was built in 1973. Its capacity is 1554 thous m^3. The Lubrzanka stream catchment area until water-gauge at Cedzyna is 140.7 km^2.

Ożanna water reservoir on the Złota river was constructed in 1878. Its capacity is 252 thous m^3. The reservoir was desilted in 1988 and 26 thous m^3 of sediment was removed. The Złota river catchment to the reservoir at Ożanna covers the area of 136.3 km^2.

Niedźwiadek water reservoir on the Górno River was put into operation in 1998. The reservoir capacity is 124.5 thous m^3. The catchment area to the reservoir dam at Niedźwiadek is 18.75 km^2.

All the reservoirs, except Ożanna and Niedźwiadek, are situated on watercourses included in hydrometric measurements. Detailed description of the investigated reservoirs may be found in papers by Bednarczyk (1994), Bednarczyk and Michalec (1996, 1997) and Michalec (2003).

3. Methods

Determining actual sediment trap efficiency requires establishing the quantity of load supplied and deposited in the reservoirs.

3.1. Methods of determining sediment volume flowing into reservoirs

Volume of suspended sediment transported by rivers was determined on the basis of hydrological measurements of mean daily water discharge (Q) and corresponding concentrations of suspended sediment (P). Discharge values were supplied by measuring points of the Institute of Meteorology and Water Management. Measurements of suspended sediment concentrations in measuring profiles situated above the reservoirs were conducted using a Portable Suspend Solids and Turbidity Monitor System 770 (Partech). Available data sequences concerned water discharges for the whole period of individual reservoirs operation. Accessible data sequences of concentration values comprised shorter and random periods. Hydrological data sequences on discharge and concentrations were supplemented. For this reason function dependencies – P= f(Q) – of mean daily discharges (Q) and corresponding concentrations of suspended load (P) were developed. The dependencies made possible supplementing the missing data for days omitted in the concentration measurements. Ratios of mean daily discharges to concentration were calculated and subsequently a mean daily sediment transport. Computations of sediment transport considered sediment concentration over the whole river cross section. The volume of suspended load carried into each water reservoir was calculated for periods from the day of reservoir putting into operation till the day when the last measurement of silting was conducted. Methods of calculations were described in the article by Bednarczyk and Michalec (1996).

Volume of bedload influx to the reservoirs was determined on the basis of computations done according to Meyer-Peter and Mueller's equation modified by the research team of the Department of Hydraulic Engineering of the Agricultural University of Krakow, using TRANS computer programme (Bartnik 1992). Calculations of bedload transport using TRANS computer programme require the following data: bed sediment texture, channel cross section, water surface slope, hydrogram of computational cross section. Texture and bulk density of the sediment were determined basing on bedload samples collected.

Two from among the analysed reservoirs, Ożanna and Niedźwiadek, are situated on watercourses which have not been included in many-year measurements of water discharge. Therefore, it is impossible to determine the transport of suspended load and bedload. The volume of transported sediment was measured by DR-USLE method. The method is based on Universal Soil Loss Equation (Wischmeier, Smith 1965, 1978) and delivery ratio (DR) parameter. DR parameter describes the volume of catchment erosion product supply to riverbeds determined on the basis of USLE equation. DR Parameter was calculated according to Roehl (1962). DR-USLE v 2.1 computer programme was used to calculate sediment volume. In order to compare the results of computations of suspended load transport according to hydrological data, calculations of sediment flowing into the other reservoirs were conducted by DR-USLE method.

3.2. Methods of measuring silting of water reservoirs

Volume of trapped sediment was determined on the basis of silting measurements. The measurements were carried out from a boat using a rod probe in delineated cross sections corresponding to reservoir transects in the construction project. Additionally, in order to supplement the measuring materials the measurements were carried out with scattered plot method. Results of depth measurements in reservoirs were plotted on the cross sections drawn in the construction project. Subsequently, the deposit areas in cross sections were determined and the volume of deposits in a reservoir was computed.

During measuring of silting, bed deposits were sampled near the dam, at the middle section and at the inlet. At each point a sample was collected from the deposit surface (top layer) and from the depth of about 0.4 m under the deposit surface (bottom layer). Arithmetic mean volume density of bottom deposits was determined on the basis of results of analysis conducted on six samples.

4. Results of research and calculations

4.1. Volume of sediment flowing into reservoirs

Mean annual mass of sediment carried away by individual rivers from catchment, computed on the basis of hydrological measurements was compared with results of calculations conducted by DR-USLE method (Table 1). On the basis of a slight difference of computation results DR-USLE method was applied for computing suspended load transport carried to Ożanna and Złota reservoirs situated on the untrained rivers. The volume of sediment flowing into the Rzeszów reservoir was not computed by DR-USLE method. The Wisłoka catchment area closed with a profile of reservoir dam has a catchment area of 2060.7 km^2. Obtaining a correct result of computations requires precise and thorough recognition of physiographic and soil characteristics of the catchment, its utilisation and applied anti erosion measures.

Table 1. Mean annual transport of sediment supplied to reservoirs

River (water reservoir)	*Mean annual mass of sediment carried away from catchment by a river (thous t ·year $^{-1}$)*		*Difference in results (%)*
	Calculated from hydrological measurements	*Computed by DR-USLE method*	
Wisłoka (Krempna)	4.41	4.12	-6.6
Dłubnia (Zesławice)	16.40	17.02	3.8
Wisłok (Rzeszów)	205.7	-	-
Łęg (Mazarnia)	67.70	74.67	10.3
Wapiennica (Wapiennica)	0.87	0.919	6.2
Lubrzanka (Cedzyna)	6.84	7.09	3.7
Złota (Ożanna)	-	1.644	-
Górno (Niedźwiadek)	-	0.74	-

Calculations of bedload transport were conducted for selected high water waves from hydrogram. It necessitated calculating a limit depth at which critical stress is exceeded and bedload movement starts.

It was found that 4.3% of total load transport in the Wisłoka river is made up of bedload. It is a mean value calculated on the basis of data for the years 1972-1998. Bedload carried into the water reservoir at Zesławice in the 1966-1983 period constitutes 6.7% of the total load transport. However, the Wisłoka river carries only 4.7% of total load supply to the reservoir in Rzeszów. In the Łęg, Wapiennica and Lubrzanka rivers, bedload makes up respectively 6.9%, 4.8% and 5.2%. Therefore, it was assumed that the volume of bedload flowing into the Ożanna and Niedźwiadek reservoirs constitutes 5% of the total load transport. It may be assumed that this assessment is correct, especially when a similar estimation has been reported by researchers studying Polish Carpathian rivers. Brański (1971) stated, that the proportion of bedload makes up 8% of the total transport, whereas Wiśniewski (1972) states that bedload makes up between 8 and 12% of the total transport. Mikulski (1966) estimates the share of bedload for several percent of the total sediment transport.

Mean arithmetic volume density of bed deposits was established on the basis of analysis carried out on six samples collected in the reservoirs (Table 2).

Water reservoir	*Water-storage capacity (thous.m^3)*	*Year*	*Year of operation*	*Volume of sediments (thous. m^3)*	*Annual discharge ($m^3\cdot s^{-1}$)*	*Capacity -inflow ratio (%)*	*STE (%)*
Krempna	119.1	1973	1	2.15	2.03	0.372	80.8
		1986	15	35.67		0.261	66.1
	112.0	1989	1	3.27		0.350	77.1
		1996	9	27.04		0.265	58.2
		1997	10	30.46		0.255	59.9
		1998	11	34.643		0.242	65.2
		1999	12	38.00		0.231	62.0
		2000	13	40.14		0.224	60.0
		2002	15	44.20		0.212	55.6
		2003	16	44.90		0.210	53.9
Rzeszów	1800.0	1974	1	81.52	18.65	0.306	89.0
		1986	13	1188.00		0.104	52.1
Zesławice	228.0	1967	1	12.64	1.09	0.663	82.4
		1968	2	26.97		0.585	66.7
		1969	3	70.43		0.458	37.7
		1970	4	75.78		0.443	38.5
		1971	5	76.25		0.441	36.2
		1974	8	86.19		0.413	37.5
		1983	17	116.09		0.326	35.2
		1984	1	—		0.663	—
		1999	16	101.51		0.368	36.4
Maziarnia	3860.0	1990	1	49.99	1.27	9.638	86.9
		1999	10	504.88		8.377	74.4
		2002	13	609.60		8.116	70.7
		2003	14	640.50		8.039	69.9
Wapiennica	1100.0	1933	1	6.47	1.2	2.907	99.0
		1967	36	24.25		2.843	94.6
		2003	71	46.80		2.783	92.6
Cedzyna	1550.0	1974	1	5.78	1.105	4.448	98.0
		1999	26	145.00		4.032	88.1
		2003	30	168.50		3.964	88.7
Ożanna	252.0	1979	1	1.23	1.01	0.791	97.0
		1998	20	26.00		0.710	94.1
		2003	25	30.21		0.696	87.4
Niedźwiadek	124.5	1999	1	0.61	0.166	2.378	98.0
		2003	5	3.21		2.317	96.9

Table 2. The bulk density of sediments in investigated water reservoirs

Water reservoir	*The bulk density of sediments sampled in selected parts of reservoir ρ_{OSL} ($t\cdot m^{-3}$)*						
	Near the dam		*Middle part of reservoir*		*Inlet of reservoir*		*Arithmetic mean value*
	top layer	*bottom layer*	*top layer*	*bottom layer*	*top layer*	*bottom layer*	
Krempna	1.16	1.17	1.16	1.32	1.31	1.28	1.23
Rzeszów	1.19	1.47	1.22	1.46	1.42	1.47	1.37
Zesławice	0.68	1.30	0.80	1.16	0.78	1.43	1.03
Maziarnia	1.59	1.67	1.62	1.71	1.59	1.67	1.64

Wapiennica	1.22	1.27	1.24	1.33	1.30	1.36	1.29
Cedzyna	1.06	1.11	1.09	1.14	1.14	1.17	1.12
Ożanna	1.14	1.17	1.17	1.22	1.18	1.24	1.19
Niedźwiadek	1.08	1.13	1.1	1.09	1.12	1.16	1.11

4.2. Results of measurements of water reservoir silting and actual sediment trap efficiency (STE)

Results of measurements of the studied reservoir silting and years when the measurement were conducted were presented in Table 3. The table also gives the values of mean discharges computed from sequences of hydrological data. Mean annual discharges in the Złota (Ożanna reservoir) and Górno (Niedźwiadek reservoir) rivers were computed according to a regional Iszkowski's formula (Dąbkowski et al. 1982). Knowing determined volume of sediments deposited in a reservoir (V) and suspended load (SL) calculated from hydrological data, and bedload (BL), actual sediment trap efficiency (STE) of the reservoirs was computed for subsequent years of their operation (Table 3). The computations comprised arithmetic mean bulk density of bed deposits (ρ_{OSL}) and bulk density of bedload. Actual sediment trap efficiency was established from the following formula:

$$STE = \frac{V - \dfrac{BL}{\rho_{OBL}}}{\dfrac{SL}{\rho_{OSL}}} \cdot 100\ \% \qquad (1)$$

According to Wiśniewski and Kutrowski (1973), the calculations assumed that the total volume of bedload flowing into the reservoirs would be trapped there. The crest of sill in the analysed reservoirs was placed at least 1.0 above the reservoir bottom.

Decreasing values of capacity-inflow ratio of individual reservoirs (Table 3) were determined for subsequent years as a ratio of a difference in inflow capacity and volume of sediments to the sum of mean annual water inflow to a reservoir.

Table 3. Silting and actual sediment trap efficiency (STE) of analysed reservoirs in subsequent years of operation and corresponding capacity-inflow ratios

Real value of STE of the analysed water reservoirs after the first year of operation was compared with suspended sediment trap efficiency determined according to Łopatin, Brune, Drozd, Karaušev, Brune & Allen's, Brown's and Chruchill (Table 4). Sediment trap efficiency of suspended load established using Łoptain's, Brune's, Drozd, Brune & Allen's method is much lower than the value obtained from measurements.

Table 4. Sediment trap efficiency in first year of operation

Water reservoir	*Sediment trap efficiency in first year of operation according to*							
	measurement	*Łopatin*	*Brune*	*Drozd*	*Karaušev*	*Brune & Allen*	*Brown*	*Churchill*
Krempna	80.8	24.0	20.0	-	10.1	2.2	18.0	73.0
Rzeszów	89.0	20	18.0	-	39.4	3.1	19.0	52.0
Zesławice	82.4	41.0	35.0	-	27.6	3.0	21.0	90.0

Maziarnia	86.9	91	90.0	-	-	11.0	79.0	99.0
Wapiennica	99.0	77.0	67.0	75.0	100.0	31.0	95.0	100.0
Cedzyna	98.0	81.0	75.0	81.0	100.0	9.5	69.0	98.0
Ożanna	97.0	47.0	38.0	-	99.9	3.6	20.5	86.0
Niedźwiadek	98.0	75.0	64.0	70.0	99.9	8.5	55.0	97.0

Drozd'd method has considerable applicability limitations due to STE determination being dependent on capacity-inflow ratio and size of sediment grains carried into the reservoir. Application of this nomogram proved impossible for Krempna, Rzeszów, Zesławice, Maziarnia and Ożanna reservoirs. Empirical dependence given by Drozd and developed on the basis of lake type reservoirs in the Ukrainian plains, has been commonly used for project designs concerning reservoirs localised on the territory of Poland.

The highest compatibility of results of determined STE values with real suspended sediment trap efficiency was obtained by Churchill method. Only in case of Rzeszów reservoir STE value obtained using Churchill method differs considerably from the value.

Attention should be paid to results pertaining to Maziarnia reservoir. STE value determined both according to Łopatin's, Brown's and Churchill's nomogram approximates real STE value. It results from the initial value of capacity-inflow ratio in this reservoir equalling 9.6%. A problem with precise STE determinations for other reservoirs is due to limit value of capacity-inflow ratio on nomograms subjected to verification. For example it is 1.% for Łopatin's nomogram and 1.6% for Brune's nomogram. Therefore, the existing nomograms are perfect for determining STE in medium-sized and large water reservoirs. So, what is the criterion distinguishing small and medium-sized reservoirs due to their capacity-inflow ratio? Let us first visualise the obtained results calculated real sediment trap efficiency in the researched reservoirs. In order to do this, correlation relationships between actual sediment trap efficiency values in individual water reservoirs given in Table 3 and corresponding capacity-inflow ratios were determined. A logarithmic function was assumed to describe correlation relationship of STE and capacity-inflow ratio of each reservoir. The relationships were given in Figure 2. While seeking answer to the posed question, it should be mentioned that in world literature on the subject (Batuca, Jordan, 2000, Heineman, 1984, Wiśniewski 1972) reservoir sediment trap efficiency is treated as constant. This statement is right for medium-sized and large water reservoirs, However, as demonstrated by the computations, real sediment trap efficiency of small reservoirs is reduced during a relatively short period of time. Also, analysing the rate of sediment deposition it may be stated that silting rate and at the same time the rate of reduction of parameter β is considerable in small water reservoirs. Developed curves range between 0.01 and 10%. Considering the above facts it may be initially assumed that the value, which distinguishes small and medium-sized reservoirs due to capacity -inflow ratio is value 10%.

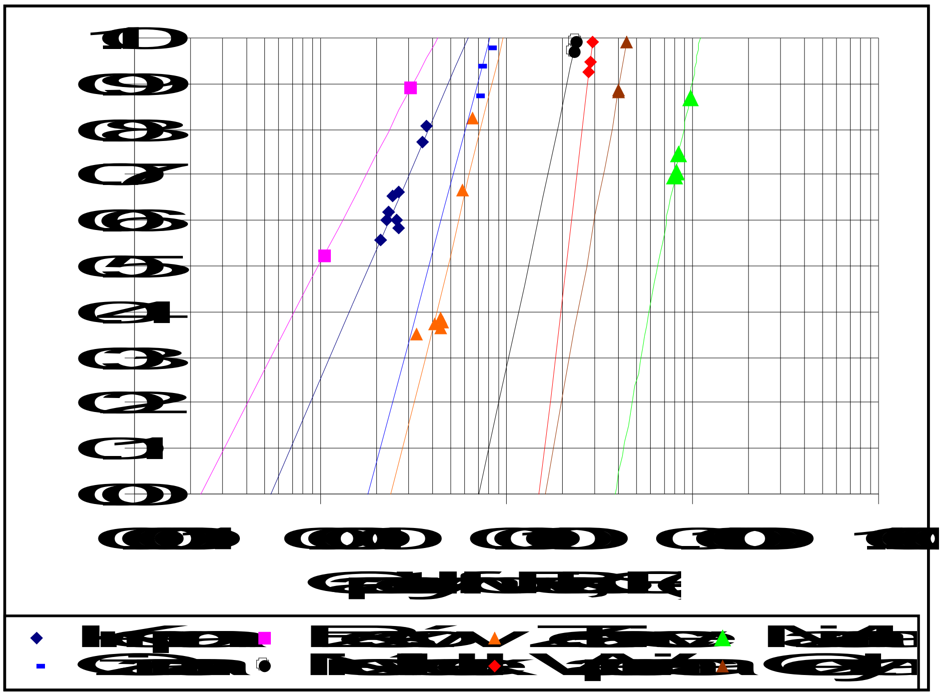

Fig.2. Dependence of sediment trap efficiency (STE) on capacity-inflow ratio (CIR)

5. Conclusions

Suspended load plays a dominant role in mineral material transport in rivers. It was found that bedload volume constitutes several percent of total bedload transport in rivers.

Silting measurements conducted on selected water reservoirs made possible determination of their actual sediment trap efficiency in subsequent years of operation. Obtained results were compared with STE values established from Łopatin's, Brune's, Drozd's, Karaušev's, Brune & Allen's, Brown's and Chruchill's nomograms. Application of these nomograms for small water reservoir is limited and obtained results may considerably differ from real values. Churchill's method enabled to reach the highest compatibility of determined STE values.

Small water reservoirs are characterised by a great rate of sediment deposition and rate of STE value reduction. Developed curves of reduction of sediment trap efficiency in small water reservoirs range from 0.01 to 10%. Therefore on the basis of conducted analyses it may be initially assumed that the value distinguishing small and medium sized water reservoirs due to capacity-inflow ratio is 10%.

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