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DETERMINATION OF SEDIMENT TRAP EFFICIENCY OF SMALL WATER RESERVOIR AT KREMPNA

Summary

The assessment of sediment amount transported by river based on indirect methods may lead to considerable errors. It particularly pertains to the assessment of transported suspended sediment quantity. In the paper methods are presented of determining the amount of load transported by the river and supplied to the water reservoir at Krempna on the Wisłoka river. The quantity of load flowing into the reservoir determined on the basis of field measurements was assumed reliable in the assessment of applied computational methods.

On the basis of results of the multi-annual investigations on the silting processes, the authors, set a value of β-parameter using the results of the silting volume measurements and load transport computations during the subsequent years of the reservoir's operational period.

The sediment trap efficiency of the reservoir determined on the basis of transported sediment mass computed according to bathometric measurements and silting surveys ranges between 65% in 1998 and 50% in 2005. The determined sediment trap efficiency on the basis of the results of calculations by the DR-USLE method is on about 30% larger than the sediment trap efficiency value calculated on the basis of bathometric measurements. The amount of sediment transport computed by the MUSLE method is much lower than the sediment mass trapped in the reservoir. Hence also the sediment trap efficiency appointed on the basis of the results of calculations by the MUSLE method is larger than 100%.

Key word: suspended load, silting, small water reservoir, sediment trap efficiency

INTRODUCTION

Suspended load originating form the surface or linear erosion of waste mantles constituting soils, as well as rock waste from rockfalls, landslides, erosion of river banks, river bed floor, is mostly deposited in water reservoirs.

Water reservoirs are considerable obstacles in carrying off the eroded waste mantles and their rock substratum to the outside of catchment boundaries. Suspended sediment load is primarily supplied to the Carpathian reservoirs and in the upper sections of Carpathian river courses it may constitute even between 90 and 95% of total load transport [Łajczak 1995]. Bed-load most frequently flows into reservoirs in the initial years of their operation, until bed armouring forms within the backwater range.

The assessment of sediment amount transported by river based on indirect methods may lead to considerable errors. It particularly pertains to the assessment of transported suspended sediment quantity. According to Łajczak [1989], computing sediment transport by the direct method, as recommended by The Institute of Meteorology and Water Management allows for obtaining results approximating real values.

The empirical methods of MUSLE, DR-USLE and the van Rijn method were chosen from among indirect methods to compute the volume of sediment transported by the Wisłoka river.

The USLE method was developed by Wischmeier and Smith [1965, 1978] on the basis of statistical analysis of data obtained from many year experimental research conducted on site and in laboratory conditions, using also rain simulators. It makes possible computing annual average soil loss per area unit. Williams [1975] modified USLE equation and adapted it for computing the mass of bedload transported by the river during high water stages. The MUSLE equation, elaborated by Williams was in Poland modified and adapted by Banasik and Madeyski [1989] to the conditions of the Carpathian rivers:

$$Y = \alpha \cdot (V \cdot Q_p)^{\beta} \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

where:

Y – mass, in tons, of sediment load transported in individual high water wave,

V – total high water volume in m^3,

Q_p – maximum flow in high water wave in $m^3 \cdot s^{-1}$,

α and β – coefficients established by Banasik and Madeyski; ($\alpha = 11.8$; $\beta = 0.56$),

K – soil erodibility factor,

LS – slope-length and slope gradient factor; [-],

C – cropping management factor; [-],

P – erosion control practice factor; [-].

The DR-USLE method allows to calculate the mean annual volume of the load transported by a river by considering the amount of catchment erosion products supply to the riverbed calculated using the USLE equation. In this method the amount of catchment erosion products supplied to riverbeds is determined through establishing the DR parameter according to Roehl [1962]. The DR-USLE method usefulness for determining suspended sediment load transport in the Carpathian rivers was evaluated by Bednarczyk *et al.* [2004].

The van Rijn method [1984] bases on the theory of solid particles diffusion in water. It requires determining the concentration on reference level C_a, reference level "a" above the bottom, determining diameter D_{50}, parameter of transport phase (T) and grain parameter (D_*). On the basis of the determined concentration profile it is possible to compute the unit intensity of suspended load transport according to the van Rijn formula:

$$s_s = \frac{u_* \cdot C_a}{\kappa}\left[\frac{a}{h-a}\right]^z \left[\int_a^{0,5h}\left(\frac{d-z}{z}\right)^z \ln\left(\frac{z}{z_0}\right) + \int_{0,5h}^{h} \exp\left[-4Z\left(\frac{z}{h}-0,5\right)\right]\ln\left(\frac{z}{z_0}\right)dz\right] \quad (2)$$

where:

u_* – bed-shear velocity in $m \cdot s^{-1}$,
C_a – reference concentration in $g \cdot s^{-3}$,
κ – constant of Von Karman for clear fluid; [-],
a – reference level in meters,
h – mean flow depth in meters,
z – vertical coordinate in meters,
z_0 – zero velocity level in meters,
Z – suspension number; [-].

In the paper the methods of determining the amount of load transported by a river and supplied to the water reservoir at Krempna on the Wisłoka river are presented. The quantity of load flowing into the reservoir, determined on the basis of field measurements was assumed to be reliable in the assessment of applied computational methods.

On the basis of data on silting rates of reservoir, and on load transportation rates into the reservoir, it is possible to determine the reservoir valid sediment trap efficiency (β-parameter). In this case, the β-parameter is the ratio of the total volume of suspended load retained in the water reservoir during the respective time period to the total amount of the suspended load conveyed into the reservoir during the same time period.

On the basis of the results of the multi-annual investigations on the silting processes, the authors set a value of the β-parameter using the results of the silting volume measurements and load transport computations over the subsequent years of the reservoir's operational period. Considering the measured amount of the sediment deposited in the reservoir, the assessment of obtained results of load transport was conducted.

CHARACTERISTICS OF THE STUDIED OBJECT

The Wisłoka river belongs to the upper Vistula Basin, covering the area within three large physical-geographical units. These comprise: the Carpathian Mts., sub-Carpathian Basins and the Małopolska Uplands. Total length of the Wisłoka is 163.6 km and the catchment area is 4110.2 km^2. The Wisłoka length to the dam profile is 18.6 km. The partial catchment area is 165.3 km^2. The Krempna river gauge profile is localized at the km 145.0 of the Wisłoka river course.

The contruction of the reservoir at Krempna (Fig. 1) was completed in 1972. This water reservoir, built for recreational purposes is localized in the upper course of the Wisłoka River section at the km 145.023. A project of the reservoir renovation was developed in 1988 on commission from the Communal Office at Krempna.

During the winter period, i.e. from November till May, the reservoir is emptied, to diminish its silting. Basic parameters of water reservoir are: normal water head in the reservoir – 369.80 m a.s.l, total capacity – 119.1 thousand m^3, after reconstruction in 1988 – 112 thousand m^3, area of inundation – 3.2 ha.

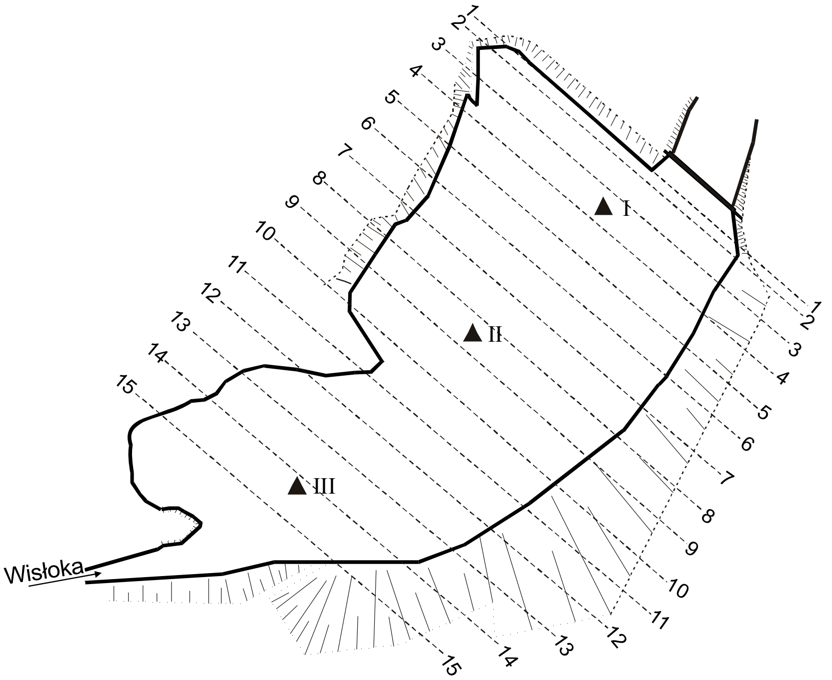

Figure 1. Water reservoir at Krempna after reconstruction completed in 1988. Measuring cross sections are marked

METHODS

Having obtained the sequence of hydrological data from the IMGW station at Krempna comprising mean daily flows for the 1972-2001 period, the mass of transported load was calculated for the individual years of this period. Computations of the transport were conducted according to Fall [1963] and methodology presented by Brański [1968]. Computations were made using so called normal method. The missing data on turbidity were supplemented using determined dependency of suspended sediment load concentration in the function of flow. On the basis of obtained suspension value U_i [kg·s^{-1}] which are the product of flow and load concentration, the daily, monthly and annual transport was calculated during the discussed period of observation. Bathometric observations were carried out in 1996-2005 and comprised the measurement of load concentration at a single point of the measurement cross-section. Measurements of mean daily water flows were made as well as the corresponding suspended sediment load concentrations in the cross-section of the gauging station. The obtained results of mean daily flows and concentrations made possible computing suspended sediment load transport inflowing to the reservoir in the May-November period [Bednarczyk and Michalec 2002]. Profiles of suspended sediment load concentrations were elaborated and the suspended sediment load concentration at the level "*a*" above the bottom was determined. The value of the suspended sediment load concentration was compared with the value obtained according to the empirical formula.

Computations using the van Rijn method were made for the data obtained from the measurements conducted in the river on 12 September 2005 and 18 September 2005. The measurements were performed on various depths of hydrometric verticals in the river gauge cross-section. The concentration of suspended sediment load was measured with Portable Suspended Solids and Turbidity Monitor System 770 (Partech). The measurements of flow velocity were made by a Nautilus C 2000 OTT Hydrometrie current meter.

Simultaneously with hydrometric measurements, the silting rate was determined in the cross-section upstream of the Krempna reservoir. The volume of sediment deposits were estimated on the basis of silting rate measurements conducted in years 1987, 1996, 1997, 1998, 1999, 2000, 2002, 2003 and 2005. The measurements were made from a boat using a sampling probe in the outlined cross-sections corresponding to the cross-sections in the reservoir construction design. The measured reservoir depth were marked on the construction scheme cross-sections.

Samples of bottom deposits were collected during silting measurement. The deposits were sampled near the dam, and in the central and backwater parts of the reservoirs. At each point a sample was taken form the deposit surface (upper layer) and from the depth of about 0.4 m under the deposit surface (lower layer). Arithmetic mean bulk density of bottom deposits was determined on the basis of six samples analyses.

RESULTS OF COMPUTATIONS

The data sequence at the authors' disposal, comprising flows for the whole period of the reservoir operation was supplemented and missing values of suspended sediment load concentrations were ascribed to respective flows. Products of mean daily flow and concentration were calculated and subsequently mean daily sediment load transport. Computations of suspended sediment transport considered sediment concentration in the whole river cross section. A correcting coefficient k was established as the ratio of the mean concentration of the suspended sediment load in the river cross-section to the concentration of the suspended sediment load at the point of permanent sampling. Coefficient k determined from regression equation with confidence interval 95% is 0.906. The regression relation determines interdependence between the average concentration levels of load suspended within the river's cross-profile and load suspended in a regular intake site of water samples.

The results of measurements of sediment volume flowing into the reservoir at Krempna in 1972-2003 were given in Figure 2. Because of the reservoir emptying in the Winter-Spring period, i.e. from November to May, the specification of sediment transport for the May-November period of each year of operation was given. The results of computations for each half-year will enable to compare the sediment transport amount with the magnitude of reservoir silting.

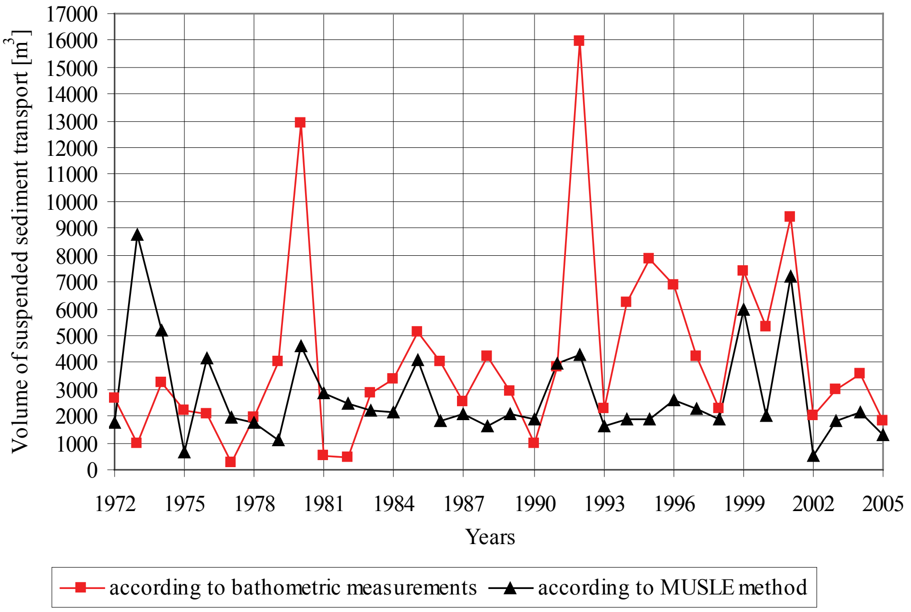

Figure 2. Annual transport of suspended sediment computed on the basis of bathometric measurements and by the MUSLE method

The mean annual mass of the sediment carried away by the river from the catchment closed by the dam, computed by the DR-USLE equation is 8234.06 [t·year^{-1}]. The values of equation parameters were compiled in Table 1. The amount of sediment inflowing in the analyzed half-year period is 4.12 thousand tons.

Table 1. Results of computations of DR-USLE parameters and annual average amount of sediment load by the DR-USLE method

Equation parameter	Value
the rainfall factor – R [Je· year^{-1}]	103.900
the soil-erodibility factor – K [t·ha^{-1}·Je^{-1}]	0.820
the slope-length and slope-gradient factor – LS [-]	7.263
the cropping-management factor – C [-]	0.007
the erosion-control practice factor – P [-]	1.0
annual average soil loss per unit area – E [t·km^{-2}· year^{-1}]	433.15
annual average soil loss per cachment area [t· year^{-1}]	71600.55
delivery ratio – DR [-]	0.115
annual average amount of sediment load [t· year $^{-1}$]	8234.06

Figure 2 shows the amount of suspended sediment transport in individual years computed using the MUSLE method for the May-November period of each year of the operation. Average annual sediment transport calculated using MUSLE is 2850.1 t·year^{-1}.

Computing the amount of suspended sediment by the van Rijn method was done on the basis of two measurements conducted with the river flows: 0.43 m^3·s^{-1} with water depth: 0.46 m, and 0.74 m^3·s^{-1} with water depth: 0.60 m.

The conducted measurements involved determining suspended sediment concentration in the river cross-section and determining the height of bottom forms. The bottom of the Wisłoka river in its mountain course is covered with coarse grained sediment of diameter D_{50}=37 mm. Average height of bottom forms of 0.12 m enabled determining the reference level *a* and then suspended sediment concentration on this level. The reference level, according to van Rijn's method [1984] is assumed to be equal to half the bed-form height, or the equivalent roughness height. The reference level *a* above the bottom is 0.06 m and suspended sediment concentration (C_a) on this level is 15.4 g·m^{-3} according to the first measurement done on 11 June 1999 and 28.9 g·m^{-3} according to the data from the second measurement conducted on 9 September 2000. The results of computations of equation (2) parameters were presented in the paper by Bednarczyk *et al.* [2004]. Table 2 contains results of computations of inflowing sediment amount conducted using van Rijn formula and by the IMGW method based on bathometric measurements.

Table 2. Computation results according to the method presented by van Rijn and method based on measurement data

Parameter	Unit	Measurement on 12.08.2005	Measurement on 18.08.2005
transport stage parameter (T)	[-]	3.16	6.72
fall velocity of suspended sediment (w_s)	[$m \cdot s^{-1}$]	0.00452	0.00452
overall bed-shear velocity (u_*)	[$m \cdot s^{-1}$]	0.15976	0.18989
correction factor for suspended load (F)	[-]	0.70376	0.76696
suspended load transport (q_s) according to van Rijn	[$g \cdot s^{-1} \cdot m^{-1}$]	36.48	397.75
suspended load transport (q_s) according to measurements	[$g \cdot s^{-1} \cdot m^{-1}$]	35.95	376.58

The results of measurements of sediment volume were compiled in Table 3. The volume of sediment trapped in the reservoir was converted into mass considering mean bulk density of the sediment determined on the basis of laboratory analysis of bottom deposits sampled from the reservoir. The established mean bulk density of the sediment is 1.23 t $\cdot m^{-3}$.

Table 3. Volume and mass of sediment deposited in reservoir in subsequent years of operation and sediment trap efficiency β established on the basis of the mass of sediment transport calculated according to bathometric measurements (β_1), DR-USLE method (β_2) and MUSLE method (β_3)

Year	Volume of sediment deposited [m^3]	Mass of sediment deposited [t]	Sum of delivered sediment calculated using according to			Sediment trap efficiency		
			bathometric measurements [t]	DR-USLE method [t]	MUSLE method [t]	β_1 [%]	β_2 [%]	β_3 [%]
1996	27041	33260	57148	37053	25651	58.2	89.8	129.7
1997	30464	37471	62555	41170	28501	59.9	91.0	131.5
1998	34637	42604	65342	45287	31351	65.2	94.1	135.9
1999	38002	46742	75392	49404	34201	62.0	94.6	136.7
2000	40144	49377	82296	53521	37051	60.0	92.3	133.3
2002	44200	54366	97780	61755	42752	55.6	88.0	127.2
2003	44901	55228	103423	65872	45602	53.4	83.8	121.1
2005	45810	56346	112919	74106	51302	49.9	76.0	109.8

The results of sediment trap efficiency calculations (Table 3) show the incorrect qualification of the quantity of transported sediments to the reservoir according to methods DR-USLE and MUSLE. The sediment transport determined by these methods is understated in the comparison with that calculated according to bathometric measurements. Determined sediment trap efficiency

(β_2) on the basis of the results of calculations by the DR-USLE method is on average about 30% larger than the value determined sediment trap efficiency (β_1) calculated on the basis of bathometric measurements. However, the sediment trap efficiency (β_3), appointed on the basis of the results of calculations by the MUSLE method, is larger than 100%. This shows that the sum of the mass of sediments incoming to the reservoir during analyzed period is smaller than the mass of sediment deposited in the in the same period.

CONCLUSIONS

Type of soils, agronomic use, land slopes, share of forest areas in the catchment cover and their distribution determine to a great extent the intensity of erosion processes in the catchment. The proper determination of the USLE equation parameters decides about the reliability of obtained computation results. The MUSLE method is an extension of the USLE method whose application requires hydrographs of high water stages.

The mass of sediment transport calculated by the DR-USLE and MUSLE methods is lower than the results of computations by bathometric method. This is confirmed by the results of calculations of the sediment trap efficiency. The sediment trap efficiency of the reservoir determined on the basis of transported sediment mass computed according to bathometric measurements and silting surveys ranges between 65% in 1998 and 50% in 2005. The sediment trap efficiency of the Krempna reservoir is undergoing a much stronger reduction.

The determined sediment trap efficiency on the basis of the results of calculations by the DR-USLE method is on average about 30% larger than the value of the sediment trap efficiency calculated on the basis of bathometric measurements. The amount of sediment transport computed by the MUSLE method is much lower than the sediment mass trapped in the reservoir. Hence also the sediment trap efficiency appointed on the basis of the results of calculations by the MUSLE method is larger than 100%.

Conducted calculations showed the possibility of the use of the van Rijn's method to compute suspended sediment load transport revealed the potential of this method application in the conditions of mountain rivers. The calculated sediment transport per unit width by the van Rijn method is negligibly lower than the sediment transport per unit width defined by the bathometric method. The difference in the results of the computed suspended load transport per unit width, by the method based on measurement data and method suggested by van Rijn is 1.5% and 5.3%, respectively. The quantification of the possibility of the use of this method in the calculations of the transportation of sediment and also to reckon the sediment trap efficiency requires for more investigations.

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