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APPRAISAL OF METHODS OF DETERMINATION OF SEDIMENT QUANTITY SUPPLIED TO A SMALL WATER RESERVOIR

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Abstract: The paper present the results of calculations of sediment quantity supplied to a small water reservoir at the locality of Zesławice. A detailed elaboration of physiographic parameters of the catchment of the Dłubnia River resulted in determination of the sediment yields by use of the Reniger-Dębski's, of Brański's as well as DR-USLE and MUSLE methods. It was found that in the years 1966 to 1983 the mean annual inflow into the reservoir at Zesławice was 32 750 Mg according to the Reniger-Dębski's method, 43 620 Mg according to the Brański's method, 17 020 Mg according to the DR-USLE method and 28 470 Mg according to the MUSLE method and according to measurements – 16 000 Mg. Calculations of suspended load transport using of the van Rijn's method was based on two measurements performed at flow 0.98 $m^3 \cdot s^{-1}$ and 1.51 $m^3 \cdot s^{-1}$. The results of calculations obtained by use of the applied methods were compared with the results of silting quantity measurements in the reservoir at Zesławice.

INTRODUCTION

River sediment originating from surface erosion or from linear erosion of alluvial covers, constituting soils, as well as rocky sediment material originating from break offs, landslides, bank or river bed erosion is in its major part deposited in reservoir. Water reservoirs are a significant hindrance in carrying away the eroded alluvial covers and their rocky base beyond the catchment area. Carpathian reservoirs are supplied, first of all, with suspended sediments which in upper sections of Carpathian rivers may reach even 90–95% of the total sediment transport [8]. Bed-load enters the reservoirs mostly in the first years of exploitation up to the moment of formation of an armored bed within the reach of backwaters. Appraisal of the quantity of the sediment transported by a river based upon indirect methods may cause serious errors. This concerns mainly assessment of the quantity of transported suspended sediment. Quantity of the transported suspended sediments depends on intensity of erosive processes conditioned by a number of factors. One may mention here unchangeable factors, as e.g. geological structure and kind and depth of soil, inclination of slopes, arable land and seasonally changeable, e.g. level of vegetation, development of meteorological conditions of which the quantity and precipitation intensity are the most important factors. It is difficult to consider these factors especially in the case of big catchment areas. Consideration of factors in individual hydro-meteorological seasons may be helpful in taking into account seasonably changeable factors.

According to Łajczak [9] calculation of sediment transport by use of a direct method according to instruction of IMGW permits to obtain results approximate to the real values. The Reniger-Dębski's method is recommended by provisions concerning silting forecasts of water reservoir in Poland [18]. It enables determination of intensity of erosive processes in the catchment and is based on a nine degree scale of soil erodibility in the catchment of Polish rivers elaborated by Reniger [10] and quantitative indices of denudation corresponding to particular classes. The denudation indices were established by Dębski [5]. Brański [4], on the other hand, elaborated maps of denudation indices in the catchment of the Vistula River established on the basis of measurements of suspended load. On the mat eight types of catchments were distinguished according to the intensity of denudation process. Bed load transport was not considered there because of lack of measurements of dragging. One of the aims and criteria of elaboration of the map, adopted by Brański, was the possibility of comparing it with Reniger's map. With this aims in view Brański distinguished nine indices of erosion intensity. A comparison of these two maps shows discrepancy in appraisal of intensity of erosive processes in particular regions of Poland.

A more and more frequent practice is application of USLE method elaborated by Wischmeier and Smith [16, 17] based upon a statistical analysis of data obtained from long term experimental studies carried out in natural and laboratory conditions making also use of rain simulators. It enables calculation of the annual – from many years – mean of the mass of eroded soil from a surface unit. Williams [15] modified the USLE equation adapting it for calculations of the mass of sediment transported in the river during freshets. The MUSLE equation elaborated by Williams was modified and adopted by Banasik and Madeyski [1] to the conditions prevailing in Carpathian rivers.

The DR-USLE method of evaluation of the amount transported by the rivers takes into account the quantity of supply of products of erosion in the catchment by use of the USLE equation. In this method the quantity of supply of products of erosion in the catchment brought into the river bed is determined by establishing the parameter DR (delivery ratio) according to Roehl [11]. Appraisal of the usefulness of the DR-USLE method for qualification of suspended sediment transport in Carpathian rivers was carried out by Bednarczyk *et al.* [3].

The van Rijn's method [14] is based upon the theory of diffusion of solid particles in the water. It was elaborated in results of studies on concentration profiles in a hydraulic laboratory in Delft and verified, among others, for data from measurements in estuary sections of a river in Holland and from investigation results carried out by US Corps of Engineers as well as data from the Peterson and Howells base [14].

Proper appraisal of the sediment quantity transported by flows is of great importance in estimation of silting quantity of water reservoirs. In the case of big reservoirs located most frequently on streams under hydrological observations, the amount of inflowing sediment may be determined by the direct method. Small water reservoirs are usually located on streams not subjected to hydrological observations. Therefore, the amount of inflowing sediment is most frequently determined by indirect methods. The paper aims at assessment of applicability of some most commonly used methods at assessment of suspended sediment transported by the river. In the elaboration calculation the results obtained by use of Reniger-Dębski's, Brański's, DR-USLE and MUSLE methods were compared with calculation results obtained with the direct method, basing on bathymetric measurements. Preliminary studies determining the applicability of van Rijn's method were also carried out. In the carried out assessment of methods measurement results of silting quantity of the reservoir at Zesławice on the Dłubnia River, located below the investigation cross-section were referred to.

CHARACTERISTICS OF THE STUDY OBJECT

The Dłubnia River flows from its springs located on the Cracow Uplands across the Miechów Uplands, Proszowice Uplands down to its estuary in the Vistula Valley as a left bank tributary of the Vistula River at 89+400 km (Fig. 1). The total length of the river is 53.2 km and its catchment is 217.6 km^2.

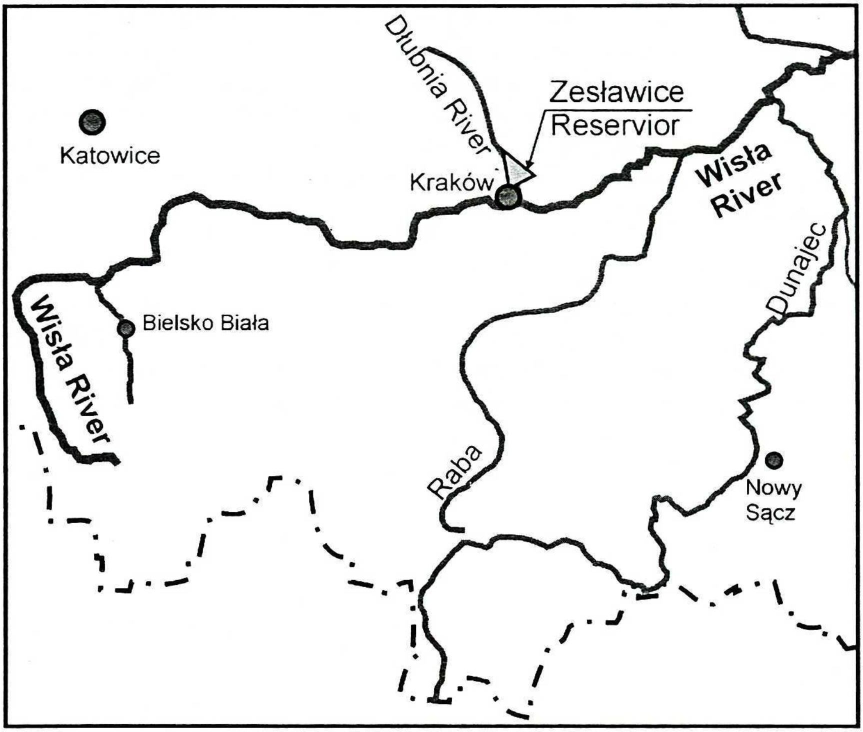

Fig. 1. The location of water reservoir at Zesławice

The water reservoir Zasławice is located at the 8.7 km of the river course of the Dłubnia. The catchment area to the profile Zesławice is 218.1 km^2.

The only water gauge controlling the whole catchment of the Dłubnia River, done away in the year 1992, was located at the 6+300 km of the river course. The catchment area to the water gauge profile was 264 km^2. The zero level of the water gauge was at the altitude 208.10 m a.s.l. according to Kronstadt. On the basis of the observation data from the years 1957–1991 the mean annual flow (SSQ) equal 1.17 m^3·s^{-1} was calculated. The values of the mean low flow for the examined period of many years was SNQ = 0.43 m^3·s^{-1}. The Dłubnia River makes the mean flow of the Vistula River increase by about 1%.

Characteristics of the catchment

The catchment area of the upper Dłubnia River spreads over an upland territory easily inclined in the south-eastern direction, including the Cracow Upland and Miechów Upland. The Miechów Upland in its southern part of the catchment ends with a threshold beyond which a large alluvial cone of the Dłubnia River is deposited. It is located below Zesławice and included in the valley of Sandomierz.

The most frequently encountered soils in the catchment of the Dłubnia are soils based on loess. The majority of them are loess soils with brown marks [13]. On slopes and top parts mainly unwashed loess of lower permeability occurs. Whereas in the lower parts of the slopes washed soils of bigger permeability occur [6]. Apart from loesses black soils occupy small areas. These are formed on chalky marls [12].

The surface area of the catchment is relatively poorly wooded. Bigger complex of mixed forests are found in the middle-western part of the catchment in the vicinity of the localities of Minoga and Tawnawa. However, wooded areas do not exert greater influence on hydraulic conditions in the catchment. In the area of the Dłubia catchment there occur sylvan habitats of thermophilic beech wood and various subgroups of upland forests growing on the dry ground. Forests occupy a relatively small area of only 7%. Meadows constitute about 90% of the catchment area [2].

Characteristics of the reservoir

The storage reservoir at Zesławice on the Dłubnia River (Fig. 2) was built in the years 1964–1966 and passed over for operation in 1966. Its destination is: industrial water supply for at that time functioning Lenin Steelworks, pipe water supply for Municipal Waterworks and Sewer Enterprise in Krakow and for flood control purposes. In the first years of operation already considerable silting of the reservoir was stated. In the year 1988 desilting activities of the main reservoir were undertaken. The earth dam of the reservoir is the elevating element and moveable weir functions as an outlet arrangement.

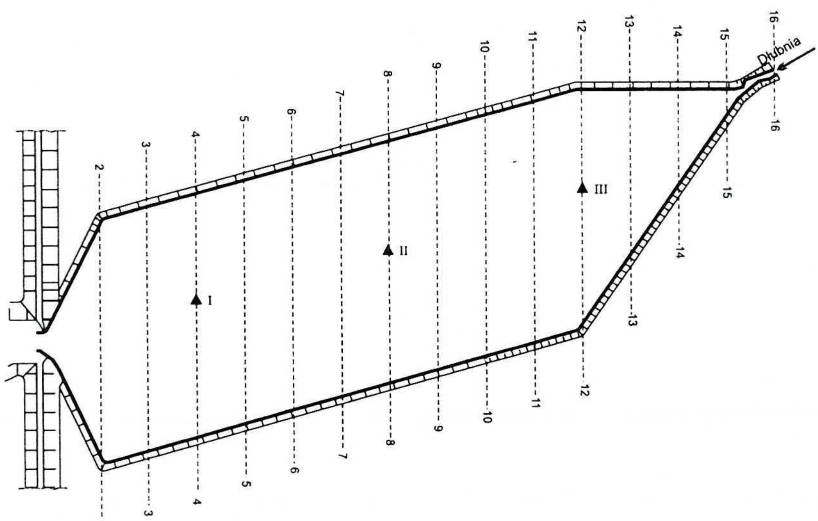

Fig. 2. Water reservoir at Zesławice; measuring cross sections marked and the places of collected bottom sediment (I–III)

Basic parameters of the reservoir:

- normal damming up level – 215 m a.s.l.,
- available storage capacity of the reservoir 228 000 m^3,
- mean depth of the reservoir 2.4 m,
- area at normal damming up 9.50 ha,
- length of the reservoir, measured in its axis 650 m.

Water management of the reservoir should ensure a permanent flow from the reservoir equal 0.48 $m^3 \cdot s^{-1}$.

METHODS

For direct method calculation of the real amount of sediment entering the reservoir at Zesławice hydrological data such as flow and corresponding with it concentration of suspended sediment must be available. Having from the Institute of Meteorology and Water Management gauging station at Zesławice a series of hydrological data on mean 24 hours' flows from the years 1966–1991, the mass of the transported sediment in particular years of this period was calculated. Calculations of transport were done according to the *Directions to elaboration of annual materials concerning suspended sediment* [7] and to the methods presented by Brański [4]. The missing data of turbidity were complemented using the elaborated relations of suspended sediment concentration in function of flow. On the basis of the obtained values of suspension U_i [$g \cdot s^{-1}$], which are the product of flow and sediment concentration, the 24 hours', the monthly, and the annual transport in the referred observation period was calculated. The genesis of meteorological phenomena influenced the changeability of the transportation of suspended sediment. The genetic inhomogeneity was eliminated by division of hydro-meteorological seasons. According to Bednarczyk [2] the intensity of erosive processes within the year to changeability makes possible emission of following seasons: spring snow melting, summer rains, autumn low discharges and winter. Such mentioned season is characterized by a typical course of hydrological and meteorological phenomena repeatable in the whole studied period. The drawn figures of relation N = f(Q) for each of these seasons will be used for estimation of the amount of suspended sediment in periods where bathymetric observations were carried out in the years 2000–2002 and 2005–2006 including measurements of sediment concentration in one point of the section. Measurements of mean 24 hours' water flow and corresponding with them suspended sediment concentrations in the cross-section above were preformed. The obtained results of 24 hours' flows and concentrations permitted calculations of suspended sediment transport entering the reservoir.

In calculations of suspended sediment transport based upon bathymetric data, sediment concentration in whole cross-section of the river was taken into account. Hence the measurements of sediment concentration were performed in the whole measurement cross-section of the river and corrective coefficient was established. This coefficient is a quotient of the mean concentration of suspended sediment in cross-section of river and suspended sediment concentration in the point of permanent water sampling.

In results of investigations of the MUSLE equations Banasik and Madeyski [1] established for the Carpathian rivers the coefficient α and β equal respectively 11.8 and 0.56. Calculations of sediment transport in the Dłubnia River were performed by use of the MUSLE equation in the form of:

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

in which: Y – mass of transported sediment in a given freshet wave,
V – total volume of the freshet,
Q_p – maximal flow of the freshet wave,
K – soil-erodibility factor,
LS – slope-length and slope-gradient factor,
C – cropping-management factor,
P – erosion-control practice factor.

Calculation of transport by use of the van Rijn's method [14] requires determination of concentration C_a on the reference level "a" above the bed, establishing the diameter D_{50}, transport stage parameter T, and particle diameter D_*. Basing upon the appointed profile of concentration, intensity of suspended load transport per unit can be calculated according to van Rijn's formula:

$$g_s = \frac{u_* \cdot C_a}{\kappa}\left[\frac{a}{h-a}\right]^Z \left[\int_a^{0.5h}\left(\frac{d-z}{z}\right)^Z \ln\left(\frac{z}{z_0}\right) + \int_{0.5h}^{h} \exp\left[-4Z\left(\frac{z}{h}-0.5\right)\right]\ln\left(\frac{z}{z_0}\right)dz\right] \tag{2}$$

in which: u_* – dynamic velocity,
C_a – reference level sediment concentration,
κ – von Kármán's constant,
a – reference level,
h – mean depth,
z – vertical coordinate,
z_0 – zero velocity level,
Z – suspended parameter.

Van Rijn elaborated a concentration equation on reference level "a" above the bed in the form:

$$C_a = 0.015 \cdot \frac{D_{50}}{a} \cdot \frac{T^{1.5}}{D_*^{0.3}} \tag{3}$$

where: D_{50} – diameter of the particle constituting with finer ones 50% of the weight content of the sample [m],
a – reference level [m],
T – sediment stage parameter [–],
D_* – particle diameter [–].

The sediment stage parameter T and the particle parameter D_* introduced by van Rijn are defined from the formulae (4) and (5) in the form:

$$T = \frac{(u'_*)^2 - (u_{*cr})^2}{(u_{*cr})^2} \tag{4}$$

where: u'_* – bed-shear velocity related to grains [$m \cdot s^{-1}$],
u_{*cr} – critical bed-shear velocity according to Shields [$m \cdot s^{-1}$].

$$D_* = D_{50}\left[\frac{(\rho_s - \rho) \cdot g}{\nu^2}\right]^{1/3} \tag{5}$$

where: ν – kinematic viscosity [$m^2 \cdot s^{-1}$],

ρ_s – density of sediment [kg·m^{-3}],
ρ – density of water[kg·m^{-3}],
g – acceleration of gravity [m·s^{-2}].
Practical application of this method permits to present the equation (2) in the form:

$$g_s = F \cdot \bar{u} \cdot h \cdot C_a \tag{6}$$

where: F – suspension coefficient calculated from the relation:

$$F = \frac{\left[\frac{a}{h}\right]^{Z'} - \left[\frac{a}{h}\right]^{1.2}}{\left[1 - \frac{a}{h}\right]^{Z'} [1.2 - Z']} \tag{7}$$

where: $\bar{u}$ – mean flow velocity [m·s^{-1}],
other denotations as in formula (2).

Calculations according to van Rijn's method were performed for the data obtained from measurements made in the river on 27th July 2005 and 11th July 2006. Measurements took place at different depths of the appointed hydrometric verticals in the measurement cross-section at Raciborowice located above the reservoir at Zesławice. Concentration of the suspended sediment was measured with photooptic instrument – Portable Suspended Solids and Turbidity Monitor System 770 Partech. For measurements of the water flow velocity a current meter Nautilus C2000 OTT Hydrometrie was used. The elaborated concentration profiles of the suspended sediment made it possible to determine the concentration on the level "a" above the bed. Sediment transport was calculated for the concentration value determined from the profile concentrations according to formula (3). The results of these calculations were compared with the results obtained using a different method.

Measurements of silting of the reservoir at Zesławice in its first operation stage, i.e. from 1966 to 1983 were made in the years 1968, 1969, 1970, 1971, 1974 and 1983 [2]. Consequent measurements, after desilting of the reservoir, were performed in years 1999, 2005 and 2006. Appraisal of the quantity of the sediment flowing into reservoir related to measurements of silting was preformed for the data concerning the period 1966–1983. An attempt of assessment of the van Rijn's method application was carried out on the basis of the data from two measurements. The results obtained by use of this method were compared with the calculation results obtained by use of the direct method.

A comparison of the calculated mass of the transported sediment with the measured volume of sediment deposits in the reservoir requires determination of bulk density of deposits. With this aims in view during silting measurements carried in years 1999, 2005 and 2006, samples of bottom deposits were taken. Samples were taken close to the dam, in the middle and in back water zones of reservoir. In each point samples were taken from the top (upper) deposits layer and from the depth of about 0.4 m below the deposits surface layer. By analyzing the results of 6 samples of bottom sediments, the arithmetic mean of volumetric density of the sediment trapped in the reservoir was determined.

CALCULATION RESULTS

The amount of suspended sediment transported by the Dłubnia River was determined on the basis on hydrological data from the gauging station of the Institute of Meteorology and Water Management. Disposing of a series of flows data for whole period of reservoir operation, the series was compared by reckoning the missing values of suspended sediment concentration to particular flows. For this purpose functional relations of mean 24 hours' flows and corresponding with them concentrations of the suspended sediment were elaborated. Figure 3 shows exemplary relations established for spring snow melting and for autumn low discharges seasons. These relations made possible to complement the missing data for analysis when concentration measurements were not performed.

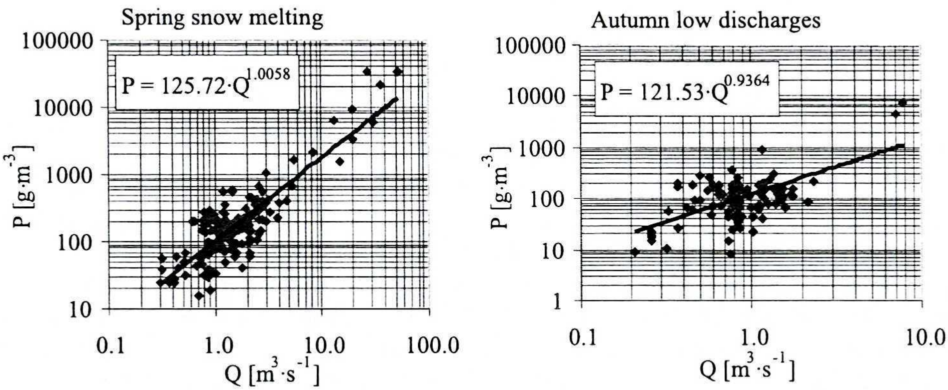

Fig. 3. Functional relations of mean 24 hours' flows and corresponding with them concentration of the suspended sediment in hydro-meteorological seasons

The ratios of mean 24 hours' flows and concentrations and the mean 24 hours' sediment transport were calculated. In calculations of suspended sediment transport in the whole cross-section of the river was considered. For these calculations corrections coefficient "k" was established; it was the quotient of mean concentration of suspended sediment in the cross-section of the river and concentration of suspended sediment in the appointed place of sampling. The coefficient "k" equal 1.065 was deduced from the regression equation with confidence range 95%.

Table 1 show the calculations results made by use of the direct method of amount of suspended sediment flowing into reservoir at Zesławice in the years 1969–1983. The determined volumetric density of sediment equaling 1.025 $Mg \cdot m^{-3}$ makes determination of the transported sediment possible. The mean annual sediment transport is 16004.5 $m^3 \cdot year^{-1}$, whereas, calculated by use of the MUSLE method, in consequence of exclusion of freshet waves in particular years of the period in question equals 8466.0 $m^3 \cdot year^{-1}$ (Tab. 1).

The denudation quantity from the Dłubnia River determined with Reniger-Dębski's method equals 32748.0 $Mg \cdot year^{-1}$ (Tab. 2). Partial areas of the basin were ascribed to respective classes of soil washability and to denudation indices basing upon map material in scale 1:25000.

Table 1. Annual suspended sediment transport in the Dłubnia River calculated by the direct method basing on bathymetric measurement results and MUSLE method

Year	Mean annual water flow SQ [$m^3 \cdot s^{-1}$]	Annual suspended sediment transport			
		The direct method [m^3]			The MUSLE method [m^3]
		The mass of sediment – in the appointed place of sampling [t]	The mass of sediment with the regard coefficient "k" [t]	The sediment volume [m^3]	
1966	1.28	14756.8	15716.0	15332.7	10240.7
1967	1.30	14385.2	15320.2	14946.6	14286.8
1968	1.09	9985.1	10634.1	10374.8	6891.6
1969	1.59	125010.1	133135.8	129888.5	40414.3
1970	1.06	9119.9	9712.7	9475.8	7482.1
1971	1.20	11006.8	11722.2	11436.3	11363.9
1972	0.90	5985.5	6374.5	6219.0	5777.5
1973	0.67	2809.7	2992.4	2919.4	820.7
1974	1.06	7409.3	7890.9	7698.5	2835.0
1975	1.27	11214.2	11943.1	11651.8	6645.5
1976	1.11	7655.8	8153.4	7954.5	4533.2
1977	1.25	15039.9	16017.5	15626.8	10483.8
1978	0.88	5029.4	5356.3	5225.7	3449.3
1979	1.44	17947.4	19114.0	18647.8	15183.7
1980	0.82	4040.6	4303.3	4198.3	1928.1
1981	0.97	5996.7	6386.5	6230.7	5310.5
1982	1.10	7271.8	7744.5	7555.6	2946.5
1983	0.71	2596.0	2764.8	2697.3	1794.2
The mean value:		15403.4	16404.6	16004.5	8465.9

Table 2. Denudation quantities in the Dłubnia River defined by Reniger-Dębski's method

Class according to Reniger	Catchment area corresponding to class [km^2]	Index of denudation according to Dębski [$Mg \cdot km^{2} \cdot year^{-1}$]	Denudation [$Mg \cdot year^{-1}$]
VI	197.60	123.0	24304.8
VIII	2.90	320.0	928.0
IX	17.60	427.0	7515.2
Total:	218.10	–	32748.0

According to Brański's method [4] the index of erosion intensity in the basin of the Dłubnia River is equal 3–4 and corresponds to the denudation value per unit equaling 200 $Mg \cdot km^{-2}$ determined from the map of denudation indices. The quantity of the denudation from the catchment area of 218.1 km^2 equals 43620 $Mg \cdot year^{-1}$.

The annual mean mass of the sediment drained by the river from the catchment closed by the dam calculated according to the DR-USLE equation is equal 17022.3 $Mg \cdot year^{-1}$. Table 3 includes the values of the equation parameters.

Table 3. Calculation results according to DR-USLE method

Equation parameter	Value
The rainfall factor – R [Je· year^{-1}]	86.994
The soil-erodibility factor – K [Mg·ha^{-1}·Je^{-1}]	0.539
The slope-length and slope-gradient factor – LS [–]	1.129
The cropping-management factor – C [–]	0.152
The erosion-control practice factor – P [–]	0.851
Annual average soil loss per unit area – E [Mg·km^{-2}·year^{-1}]	773.11
Annual average soil loss per cachment area [Mg·year^{-1}]	168537.13
Delivery ratio – DR [–]	0.101
Annual average amount of load [Mg·year^{-1}]	17022.3

Calculation of the amount of suspended sediment by use of the van Rijn's method [14] was made on the basis of two measurements performed on 27th July 2005 and 11th July 2006 at flows in the river equal respectively 1.51 m^3·s^{-1} and 0.98 m^3·s^{-1} and depths equal respectively 0.73 m and 0.59 m.

The performed measurements included determination of suspended sediment concentration in the cross-section of the river (Fig. 4) and appraisal of bed forms height. Measurements were performed in five hydraulic verticals in the cross-section of the river. Exemplary profiles with exponential equations, at flows 0.98 m^3·s^{-1} are presented in Figure 4.

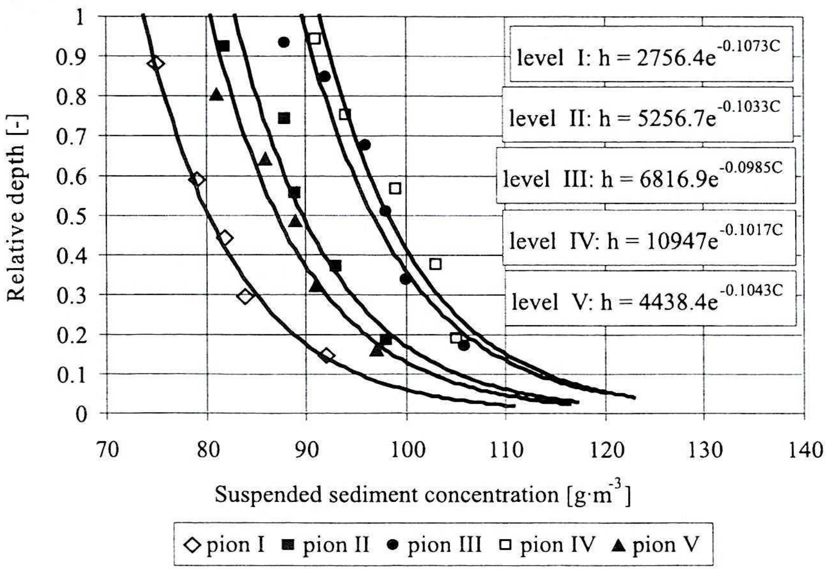

Fig. 4. Profile of suspended sediment concentration in cross-section of the Dłubnia River according to measurements from 11th July 2006 at flow 0.98 m^3·s^{-1}

The bed of the Dłubnia River in the cross-section above the reservoir, beyond the range of reservoir backwaters is covered with fine grained sediments of size D_{50} = 0.4 mm. Determination of the bed forms height is necessary for defining the reference level "a" and subsequently for estimation of suspended sediment concentration on this level.

The height of the ripples equaling about 0.01 m was defined. The reference level "a" above the bed defined as half height of the bed forms equals 0.005 m. According to van Rijn's criterion [14] the height "a" cannot be less than 0.01 of depth in the vertical profile. In the case of measurements carried out at a flow of 0.98 $m^3 \cdot s^{-1}$ the calculated value "a_{min}" equals 0.0031–0.0059 m and at a flow of 1.51 $m^3 \cdot s^{-1}$ it is ranged between 0.0045 m and 0.0073 m. Hence calculated values "a_{min}" were adopted and reference level of suspended sediment concentration C_a was determined on this level (Tab. 4). Calculation results of suspension of sediment transport, calculated according to van Rijn's formula and according to measurements, are presented in Table 4.

Table 4. Comparison of calculations results according to the van Rijn's method and the method based on measurement data

Parameter	Unit	Value of parameter according to measurement in year	
		2005	2006
Maximum suspended load concentration on reference level C_a according to equation (3)	$[g \cdot m^{-3}]$	777.5	469.2
Minimum suspended load concentration on reference level C_a according to equation (3)	$[g \cdot m^{-3}]$	428.3	265.6
Maximum suspended load concentration on reference level C_a according to measurements	$[g \cdot m^{-3}]$	246.3	139.0
Minimum suspended load concentration on reference level C_a according to measurements	$[g \cdot m^{-3}]$	203.7	115.5
Suspended load transport (g_s) according to van Rijn with C_a according to equation (3)	$[g \cdot s^{-1}]$	906.2	306.6
Suspended load transport (g_s) according to van Rijn with C_a according to measurements	$[g \cdot s^{-1}]$	323.7	100.6
Suspended load transport (g_s) according to measurements	$[g \cdot s^{-1}]$	246.3	81.88

Results of measurements of sediment volumes are given in Table 5. The volume of the sediment trapped in the reservoir was recalculated into mass taking into consideration the mean volumetric density of sediment evaluated on the basis of laboratory analysis of bottom material sampled from the reservoir. The established mean volumetric density of sediment is 1.03 $Mg \cdot m^{-3}$.

Table 5. Volume and mass of sediment deposited in the reservoir in consequent years of exploitation

Year	Years of operation	Volume of sediment deposited $[m^3]$	Mass of sediment deposited [Mg]
1968	2	26968	27642
1969	3	70425	72186
1970	4	75780	77675
1971	5	76251	78157
1974	8	86192	88347
1983	17	116091	118993
1999	14	56162	57566
2005	20	75315	77198
2006	21	77232	79163

A comparison of suspended sediment trapped in the reservoir in the years 1966 to 1983 and of sediment masses inflowing into the reservoir, obtained from calculation of transport by use of the Reniger-Dębski, Brański, DR-USLE, MUSLE and direct method is presented in Figure 5.

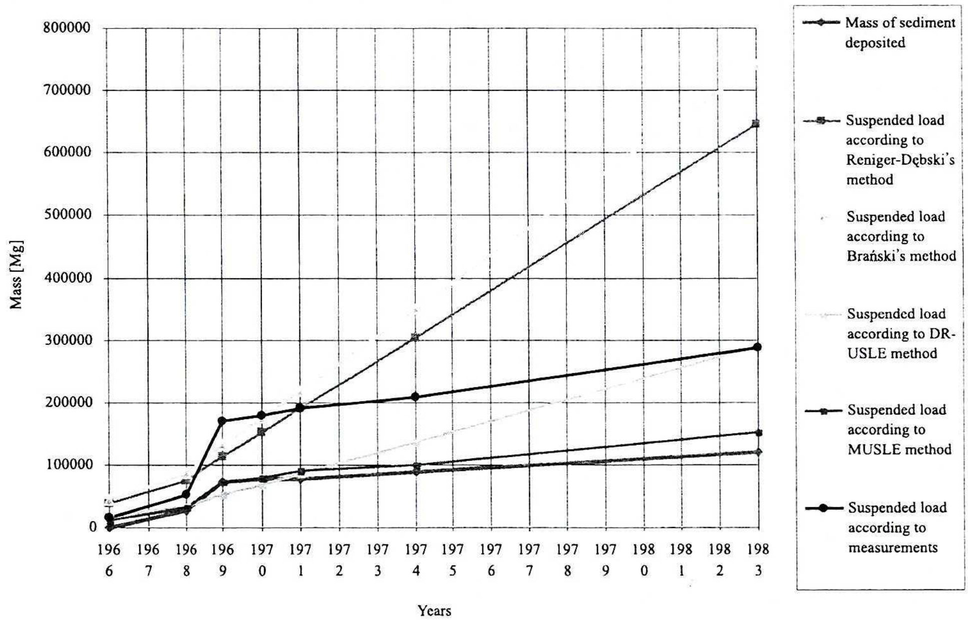

Fig. 5. Comparison of suspended sediment in the reservoir and sediment inflowing into reservoir at Zesławice in years 1966–1983, calculated by use of chosen methods

SUMMARY AND CONCLUSIONS

Historical methods, such as by Reniger-Dębski, or Brański, which treat intensity of erosive processes and sediment transport in macroregions of Poland in a global way, are only estimative method in calculations of transported sediment amount. Comparing the calculation results obtained by use of this method with the results by direct method it must be stated that for detailed analysis, it can not be applied. When analyzing the results of sediment transport calculated with directed method it was found that the results of calculations on the base of Reniger-Dębski's method are on the average 5 times overestimated. Whereas, the results of calculations performed according to Brański's method are on average 1.8 times higher than those obtained by direct method.

The DR-USLE method, based on consideration of the kind of soil, arable land utilization, slopes of the territory, anti-erosion activities, permits to obtain results approximate to the results of calculations preformed by use of measurements method. This however requires proper determination of the USLE equation parameters deciding about reliability of the obtained results. Applying the DR-USLE method a relatively smallest difference in results of sediment transport, contrary to Brański's or Reniger-Dębski's method was obtained. These points at possible applicability of the DR-USLE method in calculation of the amount of transported sediment in case hydrological data are missing. It should be underlined that the mentioned methods permit to determine the annual mean mass of the sediment passing through the studied cross-section of the channel. The MUSLE method permits to take into account the dynamics of the sediment flow. In this method it is, however, necessary to dispose of hydrograms of freshet waves. They can be used mainly in case of lack of bathymetric data. However, in the Dłubnia River the quantity of sediment transport calculated according to the MUSLE method is slightly higher than the mass of the sediment calculated by use of the direct method. Such an undervalued quantity of transport could suggest that over 78% of the total transport was trapped in the reservoir during seventeen years of operation. It is a much higher value than that obtained for data from direct measurements. Basing upon these measurements it was found that in the analyzed period of a couple of years over 41% was trapped in the reservoir. A similar value was obtained from the DR-USLE method. However, the amount of inflowing sediment calculated according to Brański's and Reniger-Dębski's methods as compared with measurements results of silting indicates that during seventeen years of reservoir operation respectively 16% and over 18% of the inflowing sediment was trapped.

The performed appraisal of van Rijn's method shows a possibility of adaptation of this method in calculations of suspended sediment transport. It requires, however, performance of calibration works what was shown by the results of transport calculation with concentration value C_a deduced from formula elaborated by van Rijn. The difference in results from calculations by use of this method and those obtained from directed measurements is significant. This may be caused by different conditions for which equations of parameters of this method were elaborated. Studies carried out on flows of differentiated regime of water and sediment flow may constitute the basis for elaboration of concentration on the reference level. Adaptation of van Rijn's method, based on its calibration in Polish rivers, will make calculation of sediment mass transport possible, may be without necessity of performing measurements of its concentration.

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OCENA METOD OKREŚLENIA ILOŚCI RUMOWISKA DOSTARCZANEGO DO ZBIORNIKA WODNEGO

W pracy przedstawiono wyniki obliczeń ilości rumowiska dostarczanego do małego zbiornika wodnego w Zesławicach. W wyniku szczegółowego opracowania parametrów fizjograficznych zlewni rzeki Dłubni określono wielkość denudacji odpływowej metodami Reniger-Dębskiego i Brańskiego oraz DR-USLE i MUSLE. Stwierdzono, że w okresie od 1966 do 1983 roku średni roczny dopływ rumowiska do zbiornika w Zesławicach wynosił odpowiednio: 32 750 Mg według metody Reniger-Dębskiego, 43 620 Mg według metody Brańskiego, 17 020 Mg według metody DR-USLE i 28 470 Mg według metody MUSLE, a według pomiarów – 16 000 Mg. Obliczenie ilości rumowiska unoszonego metodą van Rijna wykonano na podstawie dwóch pomiarów wykonanych przy przepływach wynoszących 0,98 $m^3 \cdot s^{-1}$ i 1,51 $m^3 \cdot s^{-1}$. Uzyskane wyniki obliczeń według zastosowanych metod porównano z wynikami pomiarów wielkości zamulenia zbiornika w Zesławicach.