Determination of conditions of suspended sediment transport in river and water reservoir

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Abstract: *Determination of conditions of suspended sediment transport in river and water reservoir*. The carried out measurement of waters flow and suspended sediment concentration in the river Wisłoka and the small water reservoir at Krempna constituted the basis of determination of conditions of suspended load transport at low water flow according to van Rijn's criteria (1984). The results of measurements carried out in the river and in the reservoir permitted elaboration of profiles of suspended sediment concentration C_a on the reference level "a". The reference level was established according to van Rijn's methods. In the river the reference level was adopted as 0.5 of the diameter of the biggest particle, and in the water reservoir 0.01 of elevation in a given hydrometric vertical. Measurement were performed at a flow equalling 0.89 $m^3 \cdot s^{-1}$. Concentration C_a in the river in five hydrometric verticals, determined from the concentration profile, ranged from 11.4 to 25.3 $g \cdot m^{-3}$. The concentration value, calculated according to van Rijn's formula was within the range 11.2–36.5 $g \cdot m^{-3}$ and the average it was over 26% higher than that determined from the concentration profile. In the water reservoir concentration measurements were performed in appointed verticals in eight cross-sections. At a flow 0.89 $m^3 \cdot s^{-1}$ in the water reservoir critical bed shear velocities causing movement of bottom material will not be exceeded. The calculated stage transport parameter (T) equaled from –0.9961 to –0.9996 in particular verticals of cross-sections. With regard to the negative values of the stage transport parameter (T) it proved impossible to calculate concentration C_a in the reservoir by use of the van Rijn's formula.

INTRODUCTION

Determination of the amount of suspended load transport is very important with regard to the problem of water reservoir silting. Suspended sediment constitutes about 90% of the total sediment transport. This kind of mineral material deposits in reservoirs, and accounts mainly for decrease in reservoir capacity. Recognition of river sediment transport, its kind intensity is indispensable in designing, execution, and operation of objects realized for needs of water economy. It is of great importance in water reservoir silting forecast.

Description of suspended sediment transport based on empiric investigation is connected with the necessity of introduction of hydraulic parameters describing water flow and parameters characterizing suspended sediment. Introduction of these parameters into description of water and sediment movement requires consideration of their reciprocate dynamic influence. Determination of water flow velocity, distribution in the river bed section, forces, and stresses acting on the bottom characterizing the beginning of

movement is also significant. Distribution of suspended sediment concentration, taking into regard its granulometric composition and fall velocity of particular grains, as well as hydraulic parameters, permit description of transport of the water-sediment mixture and determination of transportability of the sediment (Przedwojski et al. 1995). Theory of diffusion is most commonly applied in description of suspension and sediment transport. It corresponds with the conditions of turbulent flow with assumption of water masses and sediment particle exchange between particular layers of the current. In analysis of the movement of the two-phase medium two parameters characterizing movement of the sediment transport are used. These are such parameters as: particle diameter (D_*) and stage transport parameter (T) which were presented in a similar form by Ackers-White and Yalin, as well as by van Rijn (1984). Apart from the above mentioned parameters charactering sediment movement, special attention should be drawn to the published by Rouse in 1937 equation of concentration distribution in the vertical with assumption of logarithmic velocity distribution including the suspended parameter (Z), this parameter, according to the assumptions of the theory of sediment particle diffusion in water, expresses the influence of turbulence and gravity forces acting on a particle.

Among the many methods of mineral material transport determination which consider hydraulic parameters describing water and sediment flow the following methods can be mentioned among others: Acker-White's (1973), Young's or Engelund-Ferdsoe's method (after Batuca, Jordaan 2000) and also van Rijn's method (1984). Majority of methods serving at suspended sediment transport calculation base on equations describing the concentration profile and contain in their calculation procedures a significant parameter i.g. suspended sediment concentration (C_a) on the reference level "a" above the bottom. A correct result of sediment transport calculations depends, among others, on a proper determination of concentration C_a. The proposed by van Rijn empiric equation serving for calculation of this concentration takes into regard the basic parameters such as: particle diameter (D_*) and stage transport parameter (T). Application of van Rijn's method for suspended sediment transport in Polish rivers requires verification of possibilities of proper determination of sediment concentration C_a. Evaluation of applicability of this method in connected with determination of suspended sediment transport. On the basis of investigations carried out in river and a small waters reservoir, including measurements of water flow and suspended sediment conditions of sediment transport at low flow, were determined according to criteria given by van Rijn (1984) and on the basis of elaborated concentration profiles, suspended sediment concentration on the reference level "a" was calculated.

MATERIAL AND METHODS

Investigations of suspended sediment transport conditions in the river Wisłoka and water reservoir at Krempna were carried out. The water reservoir at Krempna was built in the years 1970–1972. This reservoir, of retention character, is located in the upper sector of the river

Wisłoka on the 145+023 km. The basic parameters of this reservoir are given in Table 1.

This reservoir undergoes quick silting and after 15 years of operation desiltation works were undertaken. In 1987 on the strength of the order of the local authorities of Krempna the reservoir was desilted and reconstructed. After its desilting and reconstruction its initial capacity equaled 112 thousand m^3.

The river Wisłoka belongs to the catchments basin of the upper river Vistula and comprises the area between three big physico-geographical units. These are the Carpathian Mts., Sub-Carpathian valley and the Little Poland Upland. The whole length of the river Wisłoka is 163.6 km and the surface area of its basin equals 4110.2 km^2. The river Wisłoka, from the springs to the reservoir at Krempna, of the length 18.6 km comprises a partial catchments area of 165.3 km^2. The water gauge profile at Krempna is located on the 145.0 km of the river course of the river Wisłoka.

A detailed description of the reservoir at catchments is given in Bednarczyk's et. al. (1997) and Bednarczyk, Michalec's (2002) publications.

Measurements of water flow velocity and suspended concentration sediment were performed at a flow equal 0.89 $m^3 \cdot s^{-1}$. Measurements were taken in appointed hydrometric verticals above the inlet into the reservoir and in the reservoir in cross--section corresponding with sections in the design. In every vertical of the section in appointed hydrometric verticals measurements of water flow velocity and suspended sediment concentration were made at various heights according to the methods given in the PIHM instruction and in the "Measurement Procedure" by IMGW (2002). Measurements of water flow velocity were performed by use of a current meter Nautilus C200 OTT Hydrometric, and concentration of suspended sediment was measured with a photo-optic instrument – Portable Suspended Solids and Turbidity Monitor System 770 of Partech make. During geodetic survey measurements of the cross-section of the river bed and cross--sections in the reservoir were made and water level decrease in the river and water reservoir was measured.

On the basis of the results of measurements of suspended sediment concentration profiles were elaborated and concentration on the reference level "a" above the bottom was determined at a previously established height of this level. With regard to the granulometric character of the mineral material forming the bottom in the river Wisłoka and in the water reservoir the reference level "a" was determined in agreement with

TABLE 1. Basic parameters of the water reservoir at Krempna

Parameter	Value
Ordinate of the normal elevation (NPP)	370.00 m.a.s.l.
Total capacity	119.1 thous. m^3
Surface area	3.2 ha
Average depth	3.72 ha
Length of the reservoir determined in terms of back-water reach	400 m

the methods given by van Rijn (1984). Concentration was also determined on the reference level according to the van Rijn's formula (1984) in form:

$$C_a = \frac{0.035}{\alpha_2} \cdot \frac{D_{50}}{a} \cdot \frac{T^{1.5}}{D_*^{0.3}} \qquad (1)$$

where:
α_2 – correction coefficient, which according to van Rijn equals 2.3,
D_{50} – median particle diameter of sediment [m],
a – reference level [m],
T – stage transport parameter [–],
D_* – particle diameter [–].

Van Rijn claims dependence of concentration C_a value on two parameters which were presented in a similar form by Ackers-White and Yalin (Van Rijn 1984). The stage transport parameter (T) and particle diameter (D_*) introduced by van Rijn are determined from the formulae in the following form:

$$T = \frac{(u_*)^2 - (u_{*cr})^2}{(u_{*cr})^2} \qquad (2)$$

where:
u_* – dynamic velocity dependent on sediment particles,
u_{*cr} – critical bed-shear velocity according to Shield's [m·s^{-1}].

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

where:
v – kinematic water viscosity [m^2·s^{-1}],
ρ_s – density of sediment particles [kg·m^{-3}],
ρ – water density [kg·m^{-3}],
g – acceleration of gravity [m·s^{-2}].

The reference level "a" should be determined considering the height of bottom or river bed forms (van Rijn 1984). In case of occurrence of bottom or river bed forms its height equals half of the height of these forms. If no bottom or river bed forms occur or their height is unknown the reference level is adopted as equal to absolute roughness (k_s) according to Nikuradse but keeping its minimal value equal 0.01 of water depth. Absolute roughness can be determined, among others, by use of following formulae: Kamphius' ($k_s = 2.5 \cdot D_{90}$), Hey's ($k_s = 3.5 \cdot D_{84}$), Mahmood's ($k_s = 5.1 \cdot D_{84}$) or Gładki's ($k_s = 2.3 \cdot D_{80}$) (van Rijn 1984).

The diameter D_{50} of the suspended material was determined from the granulation curve elaborated on the basis of the results of laboratory determination of granulometric composition of the suspended sediment and water solution sampled during pumping. Pumping was performed by use of a specially constructed system consisting of a suction piping, pump of garden's type 7000/3 2T driven by a combustion engine and an outlet piping. Measurements were performed in a hydrometric vertical on there levels above the bottom. The amount of reservoirs during pumping depended on the concentration value measured with a photo-optic apparatus Portable Suspended Solids and Turbidity Monitor System 770 of Partech make.

When the concentration equalled about 100 mg·dm^{-3} water was pumped with the suspended sediment to 20–30 containers, when the concentration was about 300 mg·dm^{-3} water with the suspended sediment was pumped to 7–10 containers.

RESULTS AND DISCUSSION

Measurements of water flow velocity and suspended sediment concentration in the river Wisłoka and in the reservoir at Krempna were performed on 6.06.2005. On the basis of measurements of water flow velocity in the river bed of the Wisłoka in the section located above the inlet into the reservoir mean water flow velocity was calculated and it was 0.70 m·s^{-1}. The calculated flow equal 0.89 m^3·s^{-1} is within the range of average low flows.

Taking into regard the mountainous character of the river Wisłoka whose bottom is covered with coarse grained mineral material the reference level "a" equaling half of the diameter of the particle of the bed material equal 0.06 m was adopted. The adopted height "a" is bigger than the value of absolute roughness determined according to the formulae by Kamphius, Hey, Mahmood and Gładki (Tab. 2).

Concentration of the suspended sediment C_a in the river, at the reference level equal 0.06 m above the bottom in every hydraulic vertical was determined from concentration profiles. Figure 1 presents suspended sediment concentration profiles elaborated on the basis of measurements in the river bed.

TABLE 2. Relative bed roughness k_s of the river Wisłoka calculated using empirical methods

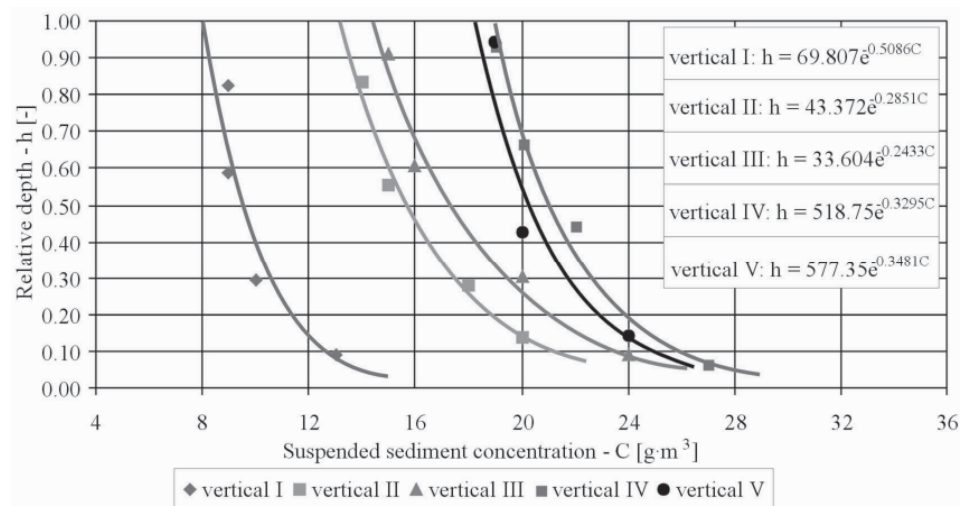| Equation acc. to	Particle diameter [mm]	Relative roughness k_s [mm]
Kamphius	$D_{90} = 110$	275.0
Hey	$D_{84} = 109$	381.5
Mahmood	$D_{84} = 109$	555.9
Gładki	$D_{80} = 105$	241.5

FIGURE 1. Profiles of suspended sediment concentration elaborated on the basis of measurements in hydrometric verticals in the river Wisłoka

The diameter D_{50} of the suspended sediment inflowing into the reservoir at Krempna is 0.074 mm. The mean proper sediment density (ρ_s) determined by Tarnawski (2003) equals 2.60 t·m^{-3}. Calculation results of parameters determining conditions of suspended sediment transport in the river Wisłoka, at flow rate equal 0.89 m^3·s^{-1} are given in Table 3.

Figure 2 presents cross-sections of the reservoir at Krempna with marked hydrometric vertical. Maximal values of velocity of each isotah permitted to draw an isoline of maximal water flow velocities in the reservoir (Fig. 2).

Calculation of concentration C_a the reservoir at Krempna requires determination of the bottom form height.

TABLE 3. Characteristics of suspended sediment transport in the river Wisłoka at flow 0.89 m^3·s^{-1}

|		Measurement verticals				
		I	II	III	IV	V
Distance from the left bank	L [m]	3.00	2.35	2.20	2.45	2.20
Water depth in vertical	h [m]	0.34	0.36	0.33	0.45	0.35
Mean flow velocity in vertical	$\bar{u}$ [m·s^{-1}]	0.329	0.343	0.365	0.378	0.371
Dynamic velocity	u_* [m·s^{-1}]	0.117	0.121	0.117	0.135	0.119
Dynamic velocity related to sediment particles	u_*^2 [m·s^{-1}]	0.016	0.017	0.019	0.019	0.019
Particle diameter	D_* [–]	1.79	1.79	1.79	1.79	1.79
Sediment concentration on reference level "a" according to measurements	C_a [g·m^{-3}]	11.4	14.2	21.4	25.3	22.8
Sediment concentration on reference level "a" according to formula (4.25) (α_2 = 2.3)	C_a [g·m^{-3}]	11.2	19.6	31.1	36.5	24.1
Difference in results of concentration C_a calculations according to measurements and formula (1)	Δ [%]	1.75	–38.03	–45.33	–44.27	–5.70
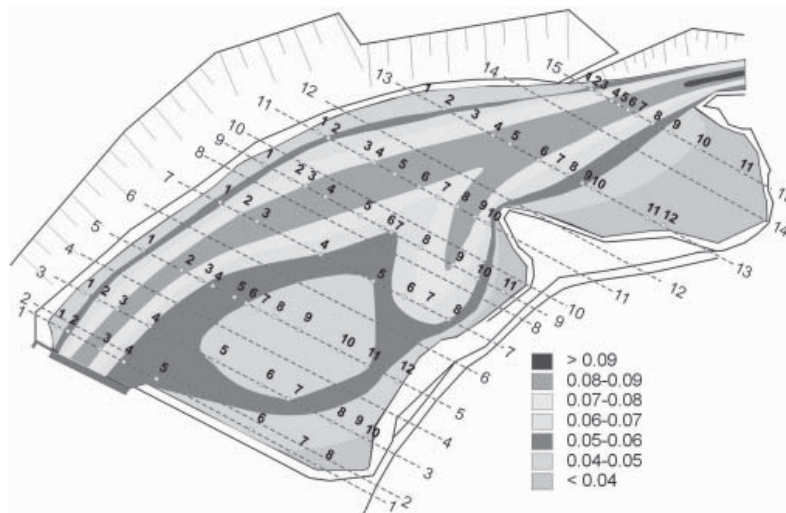
FIGURE 2. Location of hydrometric verticals and maximal water flow velocity distribution in the reservoir at Krempna at flow 0.89 m^3·s^{-1}

Underwater photos were taken in order to examine the morphological structure of the bottom and for determination of the height of bottom forms. Photos of the bottom were taken in the inlet part of the reservoir in cross-section 14-14 (Fig. 3) and in the part close to the dam in cross--section 3-3 of the reservoir at Krempna.

No bottom forms were found to occur. Only diversification of bottom configuration was stated in the reservoir. In the lateral part of the reservoir, characterized by small depths not exceeding 0.5 m, the bottom was covered with a layer of organic matter 3–5 mm thickness. Occurrence of gythia was also stated in the reservoir part close to the dam, whose bottom does not show great diversification of height. Determination of height diversification was possible by use of a matrix made of transparent Plexiglas with a graduated network of squares of a modulus equal 1.0 cm. In the inlet section of the reservoir differences in bottom forum height equaled about 2 cm (Fig. 3). Calculating

concentration C_a in the reservoir at Krempna the reference level equal 0.01 of water depth in the given hydrometric vertical was adopted.

In the performed investigations of determination of suspended sediment transport profiles of sediment concentration were elaborated and concentrations on the reference level were determined. Figure 4 shows profiles of maximal and minimal concentrations of suspended sediment in the inlet cross-section 15-15 and outlet cross-section 1-1 of the reservoir at Krempna. Minimal concentrations in the analysed verticals in the coastal zone of the reservoir both in the inlet and outlet part do not differ significantly form the values of close to the surface and close to the bottom concentrations (Fig. 4a). Minimal concentration C_a in the cross-section 15-15 and 1-1 equals $12\,g \cdot m^{-3}$. In verticals located in the main current of water flow, characterized by maximal flow velocity, maximal suspended sediment concentration on
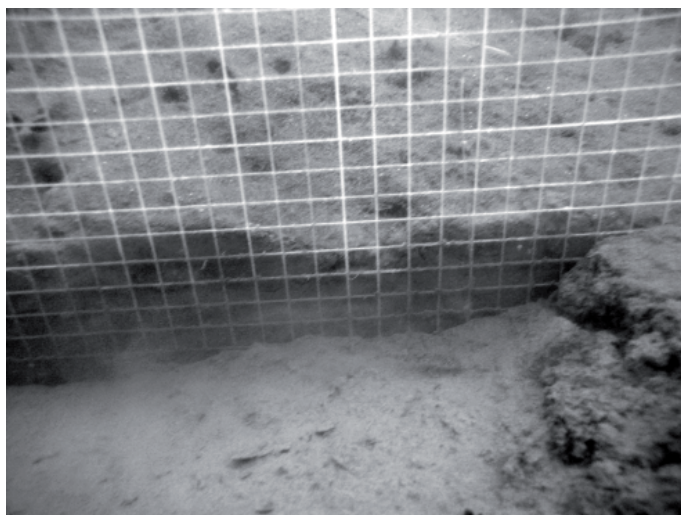

FIGURE 3. Profile of the bottom of the reservoir at Krempna in the inlet cross-section 14-14
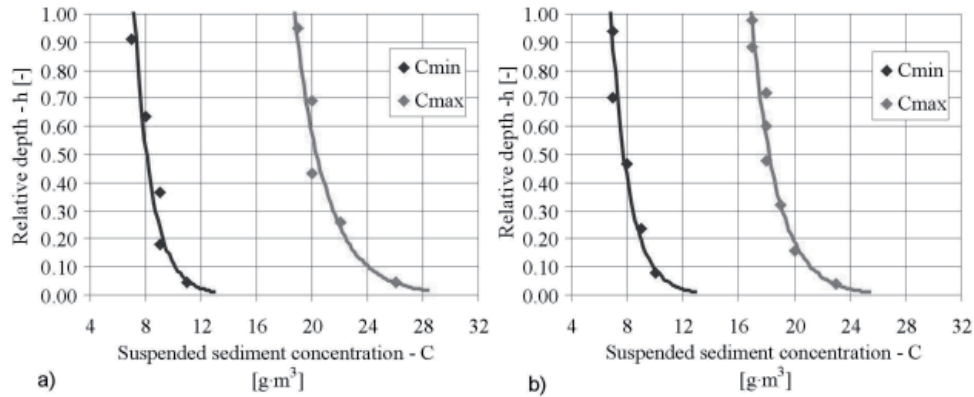
FIGURE 4. Profiles of maximal and minimal suspended sediment concentrations elaborated on the basis of measurements in hydrometric verticals in the inlet (a) and outlet (b) cross-sections of the reservoir at Krempna

the reference level was 28 $g \cdot m^{-3}$ and 25 $g \cdot m^{-3}$ in the section 15-15 and 1-1 respectively.

Calculation of C_a concentration according to van Rijn's formula requires determination of the coefficient of transport T. If the parameter of transport T reaches positive values the sediment particles can be displaced along the bottom or can perform more or less regular jumps. At increase in dynamic velocity exceeding the value of fall velocity of particular particles, their constant transport will take place values of the stage transport parameter T being higher and higher. In each of the verticals in the reservoir, from the inlet to the outlet section, critical bed-shear velocities (u_{*cr}), causing movement of the bottom material of this diameter will not be exceeded. In calculations performed for a particle diameter $D_{50} = 0.074$ mm negative values of the parameter of transport T within the range from 0.9961 to 0.9996 were obtained. The obtained results make calculation of C_a in a water reservoir possible by use of formula (1).

CONCLUSIONS

At an average low flow in the river Wisłoka concentration C_a of suspended sediment determined according to van Rijn's methods is on the average by 26% higher than that determined from profile concentrations. Concentration the reference level "a" determined from concentrations elaborated according to the data from five hydrometric verticals equaled 11.4 to 25.3 $g \cdot m^{-3}$. Highest concentrations were recorded in the main current of the river.

Determination of concentration C_a in a water reservoir at a flow 0.89 $m^3 \cdot s^{-1}$ according to van Rijn's formula is not possible since with regard the dominant hydrodynamic conditions critical bed--shear velocities (u_{*cr}), causing movement of mineral bottom material will not be exceeded. In each of the examined cross--sections of the reservoir diversification of values of velocity and concentration of sediment was stated. Highest suspended sediment concentrations in cross-sections were stated in verticals located in zones

of the reservoir characterized by maximal flow velocities. Greatest diversifications characterize maximal concentrations determined in vertical located in the main current in the reservoir. Reduction of maximal concentrations C_a was stated by comparing concentration profiles in the inlet and outlet part of the reservoir.

Application of van Rijn's method for determination of suspended sediment concentration requires further investigations including average and high flows.

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Streszczenie: *Określenie warunków transportu rumowiska unoszonego w rzece i w zbiorniku wodnym.* Określenie ilości rumowiska unoszonego transportowanego w rzekach jest istotne ze względu na zamulanie zbiorników wodnych. Opisanie warunków transportu rumowiska unoszonego na podstawie badań empirycznych wiąże się z koniecznością wprowadzenia parametrów hydraulicznych opisujących przepływ wody i parametrów charakteryzujących rumowisko unoszone.

Badania warunków transportu rumowiska unoszonego przeprowadzono w rzece Wisłoce i w zbiorniku wodnym w Krempnej na podstawie teorii podanej przez van Rijna [1984]. Zaproponowane przez van Rijna empiryczne równanie służące obliczeniu tej koncentracji uwzględnia podstawowe parametry, takie jak: parametr ziarnowy (D_*) i parametr transportu (T). Ocena możliwości zastosowania tej metody wiąże się z określeniem warunków transportu rumowiska unoszonego. Na podstawie przeprowadzonych badań w rzece i małym zbiorniku wodnym, obejmujących pomiary przepływu wody i koncentracji rumowiska unoszonego, określono warunki transportu rumowiska przy przepływie niskim według kryteriów podanych przez van Rijna [1984], a także na podstawie opracowanych profili koncentracji obliczono koncentrację na poziomie odniesienia „a".

Wykonane pomiary przepływu wody i koncentracji rumowiska unoszonego w rzece Wisłoce i małym zbiorniku wodnym w Krempnej stanowiły podstawę określenia warunków transportu rumowiska przy przepływie niskim, według kryteriów podanych przez van Rijna [1984]. Wyniki pomiarów w rzece i w zbiorniku umożliwiły opracowanie profili koncentracji i określenie koncentracji rumowiska unoszonego C_a na poziomie odniesienia „a". Poziom odniesienia ustalono według metodyki van Rijna. W rzece przyjęto poziom odniesienia równy 0,5 średnicy największego ziarna, a w zbiorniku równy 0,01 napełnienia w danym pionie hydrometrycznym. Pomiary wykonano przy przepływie wynoszącym 0,89 m^3·s^{-1}. Koncentracja C_a w pięciu pionach hydrometrycznych, określona z profili koncentracji, wynosiła od 11,4 do 25,3 g·m^{-3}. Obliczona wzorem van Rijna wartość koncentracji C_a mieściła się w przedziale 11,2–36,5 g·m^{-3} i była średnio ponad 26% wyższa od określonej z profili koncentracji. W zbiorniku wodnym przy przepływie 0,89 m^3·s^{-1} nie zostaną przekroczone krytyczne prędkości ścinające,

powodujące ruch materiału dennego. Obliczony parametr transportu (T) w poszczególnych pionach przekroi poprzecznych wynosił od –0,9961 do –0,9996. Ze względu na ujemne wartości parametru transportu (T) niemożliwe okazało się obliczenie koncentracji C_a w zbiorniku. Została ona ustalona z profili koncentracji.

Przy przepływie średnim niskim w rzece Wisłoce koncentracja C_a rumowiska unoszonego, określona według metodyki van Rijna jest średnio ponad 26% wyższa od określonej z profili koncentracji. Koncentracja na poziomie odniesienia „a" określona z profili koncentracji opracowanych według danych z pięciu pionów hydrometrycznych wynosiła od 11,4 do 25,3 g·m^{-3}. Najwyższe koncentracje odnotowano w głównym nurcie rzeki.

Określenie koncentracji C_a w zbiorniku wodnym przy przepływie 0,89 m^3·s^{-1} według wzoru van Rijna nie jest możliwe, gdyż ze względu na panujące warunki hydrodynamiczne nie zostają przekroczone krytyczne prędkości ścinające (u_{*cr}), powodujące ruch mineralnego materiału dennego.

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