IMPACT OF THE WŁOCŁAWEK RESERVOIR ON THE CONDITIONS FOR THE TRANSPORT OF SUSPENDED LOAD

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The article presents the conditions for the spatial diversity of the concentration of suspended load in the Włocławek Reservoir. The main components of suspended load, namely the mineral and the organic ones, as well as the grain size of mineral suspension were characterized. Moreover, the mechanism of water turbidity connected with the hydrodynamics of the reservoir and the diversity of the sources of the suspended load supply was analysed. The research results show that the course of water turbidity in the upper, i.e. the river part of the reservoir depends on the conditions of the suspended load delivery by the river. In the lower part of the reservoir, i.e. the lake one, the concentration of the suspended load and its features heavily depend on the hydrodynamic and sedimentation processes in the reservoir.

Key words: dam reservoir, course of water turbidity, concentration of suspended load, composition of suspended load, grain size of suspended load

INTRODUCTION

One of the main consequences of river damming is the change in the conditions of river runoff. It is estimated that the average retention time in large dam reservoirs in the world is 0.21 year, while in the case of smaller reservoirs it is 0.011 year (VÖRÖSMARTY et al. 2003). Thanks to their retention abilities, large dam reservoirs periodically hold about 40 % of the world river runoff (VÖRÖSMARTY et al. 2003). Naturally, the changes of the flow conditions influence fluvial transport. Both quantity and quality of the dissolved, suspended and bed load get transformed. The transport conditions for the suspended load play a significant role, because as much as 72 % of the world river matter is transported in this way (SYVITSKI 2003). As the water flow velocity decreases towards the dam, intensive sedimentation processes of clastic material take place in dam reservoirs. It is estimated that globally large dam reservoirs (circa 45 000) have accumulated 4 to 5 Gt of river clastic material, which makes up 25 to 30 % of the entire matter transported to the oceans by rivers (VÖRÖSMARTY et al. 2003). These data indicate that dam reservoirs play a key role in the exchange of matter between lands and oceans, as well as in the biogeochemical cycle of elements.

Sedimentation of suspended load in dam reservoirs results in changes in its concentration as well as its composition and grain size. Both suspended load delivery and the conditions for its sedimentation in dam reservoirs influence the rate of siltation, as well as the quality of the water environment, including their eutrophication and pollution. Sedimentation of the suspended load increases water transparency, which improves the conditions for the development of phytoplankton and, as a result, changes the concentration of biogenic substances (GIERSZEWSKI 2005). The environmental significance of the suspended load is also expressed by chemical reactivity of clay minerals, which are an important component. Large adsorption capacity of clay minerals results in the decrease in many substances' concentration in the solution, including phosphorus, heavy metals and organic pollutants. These substances, compound with the adsorbent, are cumulated in bottom sediments (ONGLEY 1982). Such an amount of cumulated biogenic and toxic substances is a potential source of secondary pollution of the reservoir's water.

As the examples quoted above indicate, explaining the reasons for the diversity of both concentration of the suspended load and its composition and grain size is crucial for the explanation of the mechanisms of functioning of the dam reservoir geosystem.

STUDY AREA, AIM AND METHODS OF RESEARCH

The Włocławek Reservoir takes the first place in terms of the area (70 km^2) and the se-

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cond in terms of the capacity (present capacity: 376 mil. m^3) among all the dam reservoirs in Poland. It was constructed in 1970 at the lower section of the Vistula River by damming the river channel in Włocławek. This reservoir is a typical example of a lowland dam reservoir of the valley type. Low depths (maximum 13 m, average 5.5 m) and a significant elongation of the reservoir (length of 55 km) mean this is a polymictic water body. Its characteristic feature is a rapid water exchange; the average water retention time is 5.2 days. Significant throughflow, as well as intensive wind mixing, result in the large dynamics of the water environment in the Włocławek Reservoir (GIERSZEWSKI 2006). At the times of high discharges, transport and accumulation of clastic material is predominantly dependant on the speed of the Vistula River throughflow current. At the times of average inflow to the reservoir (1000 $m^3\ s^{-1}$) the flow velocity decreases, and amounts from 0.7 m s^{-1} at the limit of the back-

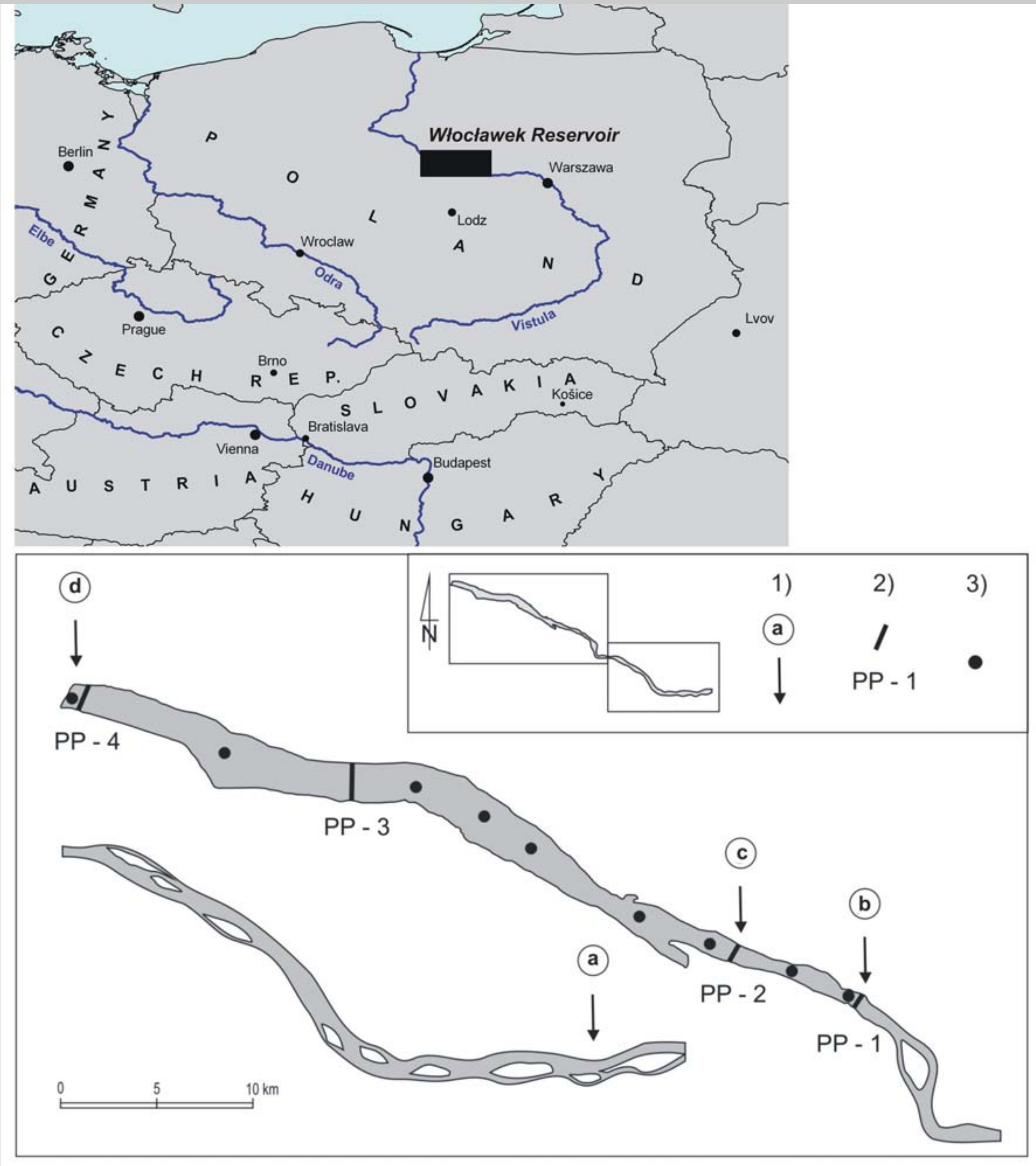

Fig. 1 Location of the Włocławek Reservoir and position of suspension sampling sites (data source: (c) ESRI Data)

1 — RIEP sampling points (a — Wyszogród, b — Płock, c — Brwilno, d — dam of the reservoir), 2 — cross section profiles, 3 — sampling points along the longitudinal axis in the reservoir

flow to < 0.1 m s^{-1} near the dam. At the times of the low water discharges the importance of the throughflow current decreases in favour of wind-driven current circulation.

As the results of the studies carried out so far indicate, the main source of suspended load in the Włocławek Reservoir is the material transported by the Vistula River. According to BANACH (1994) the share of this source amounts up to 96 %. The remaining part is delivered from the reservoir's banks. Other studies show that the Włocławek Reservoir trapped about 40 – 50 % of the suspended load delivered by the Vistula River (BABIŃSKI 1994 or ŁAJCZAK 1999).

Large dynamics of the water masses in the reservoir brings instability to the deposition environment. As the sedimentological analyses of the bottom deposits prove, the material accumulated in the reservoir is a subject to a process of periodical resuspension and redeposition, while the areas of good conditions for sustainable accumulation are found only in the deepest parts of the reservoir's bottom (GIERSZEWSKI and SZMAŃDA 2007).

The main aim of this paper is to explain the mechanism of concentration and transportation of the suspended load in the Włocławek Reservoir. Special attention will be paid to the significance of the suspended matter delivery from the autochtonic sources (bank abrasion and resuspension of the bottom material) on the course of turbidity.

The reasons for the spatial diversity as well as multi-annual and seasonal diversity in the concentration of the suspended load in the reservoir will be presented. Moreover, the diversity in both composition and grain size of the suspended load as a response to hydrological conditions and diversifying sources of supply of the clastic material will be discussed. Investigation into the changes in the conditions of transport of suspended load in the Włocławek Reservoir is crucial in relation to the Vistula's role as the main source of the suspended load delivered into the Baltic Sea. The Vistula's share in this process is estimated to be 28 % (ŁAJCZAK 2005).

The regularities of both multi-annual and seasonal course of the turbidity in the Włocławek Reservoir have been based on the results of total suspended solids analysis, which were carried out by the Regional Inspectorates of Environmental Protection at four measurement sites. Concentration of suspended load in the water samples was measured once or twice a month. A total number of 1 400 measurement results from the years 1982 – 2006 were taken into consideration; in the case of a measurement point below the dam itself the data from the years 1977 – 2006 were included. The location of the measurement points reflects the diversity of the hydrological conditions in the Włocławek Reservoir (**Fig. 1**). The measurement point in Wyszogród (a) shows the features of the freely flowing river, the one in Płock (b) is located in the upper-lotic section of the reservoir, the one in Brwilno (c) is in the transit section of the reservoir, while the one located below the dam (d) represents the limnic section.

The analyses of the contribution and the quantity of the main components of the suspended load, i.e. the mineral and the organic ones, as well as grain size of the suspended mineral load were based on 12 measurement series undertaken between 2003 and 2006. The individual measurement series were undertaken at a large range of the Vistula's discharges: from 253 to 2319 m^3 s^{-1}. Concentration of the suspended load was determined in 5 – dm^3 water samples which were collected using a batho-meter from the depth of 1 meter below the water surface. The samples were taken along four cross-sections located at the river, transit and limnic sections of the reservoir (**Fig. 1**). Three samples were taken from each profile. They represented the zone of the old river thalweg and the former channel of the Vistula River, as well as the inundated part of the reservoir. Additionally, nine samples were taken during a flood wave along the long profile of the reservoir (**Fig. 1**). Concentration of the suspended load was measured with the use of the weight method (BRAŃSKI 1968), and hard filters. The measurement of the contents of organic material in the suspended load was based on the loss by a roasting method at the temperature of 550ºC. Grain size of the mineral components in the suspended load was measured with the use of a laser particle size analyser Analysette 22. The main and the secondary fractions were determined according to the Udden-Wenthworth grain-size scale, while statistical parameters of grain size were based on the FOLK and WARD'S equation (1957).

RESEARCH RESULTS AND DISCUSSION

THE COURSE OF TURBIDITY IN THE YEARS 1982-2006

Changes in the concentration of suspended load in the measurement sites show a natural tendency to decrease their value towards the dam (**Tab. 1**). The difference in the concentration of suspended load between the sample point at Wyszogród and the Włocławek dam is

	Wyszogród (1)	**Płock (2)**	**Brwilno (3)**	**Dam (4)**	**Dam (4)**
	1982 – 2006				1977 – 2006
arithmetic mean	29,0	25,0	30,0	20,0	25,0
geometric mean	23,0	22,0	23,0	11,0	13,0
minimum	2,0	3,0	3,0	0,0	0,0
maximum	128,0	76,0	295,0	511,0	511,0
variation coefficient (%)	68,0	52,0	99,0	187,0	170,0
asymmetry coefficient	1,6	0,8	4,2	7,7	5,5
curtosis	3,4	0,3	27,3	81,2	45,2

Tab. 1 Statistical characteristics of the suspended load concentration

	Wyszogród (1)	**Płock (2)**	**Brwilno (3)**	**Dam (4)**
Wyszogród (1)	x	**0,66**	**0,33**	0,13
Płock (2)		x	**0,46**	0,03
Brwilno (3)			x	0,01
Dam (4)				x

Tab. 2 Correlation between suspended load concentration in following sampling points (bold: statistically significant)

about 30 % if presented as an arithmetical average from the multi-annual period, or 52 % if expressed as a geometrical average. Large values of the asymmetry coefficient at the transit (3) and the lower (4) sections of the Włocławek Reservoir indicate the dominance of the periods of low values of turbidity as well as of significant distortion of the arithmetical average. The reason for this significant distortion is rare cases of extreme values of the suspended load's concentration. The level of the influence of the extreme values of the suspended loads' concentration over the mean value of water turbidity is expressed by the variation coefficients. In accordance with them, the largest variation of turbidity (187 %) was shown at the measurement site located at the dam.

Both strong correlation between the individual values of the concentration of suspended load (**Tab. 2**), and the variability of the annual values of the total concentration of suspended load (**Fig. 2**), indicate a similar course of turbidity both in the Vistula River and in the upper section of the Włocławek Reservoir. A weaker correlation of the course of the water turbidity in Brwilno with the measurement sites located up-stream is the result of higher concentrations of suspended loads in the years 1982 – 1983 and 2004 – 2006. The increase of water turbidity in these years resulted from intensification of the river dredging and the river gravel mining below Płock. The quantity and the concentration variability of suspended load in the lower, i.e. limnic part of the reservoir does not show any correlation with the course of the water turbidity at the upper-located measurement sites (**Tab. 2**). If compared to a quite aligned course of the average annual values of the suspended load's concentration in Wyszogród, Płock and Brwilno, which show irregular fluctuations ranging from 20 to 35 mg dm^{-3}, the multi-annual concentration of suspended load in the limnic section of the reservoir shows much larger variability (**Fig. 2**). Three periods of diverse course of the water turbidity can be distinguished in this section of the reservoir. In the first one, between 1977 and 1986, the values of the concentration of the suspended load were significantly higher. Moreover, at that time two maximums appeared; the first one lasted for three years with one culmination in 1980 (68.3 mg dm^{-3}) and another one, a bit lower, in 1986 (27 mg dm^{-3}). The second period lasted from 1987 until 1995, and showed a much lower level of water turbidity; at first it showed an increase in the suspended load's concentration in 1992 (20 mg dm^{-3}), which was followed by a significant decrease down to 13 mg dm^{-3}. During the last period, which started in 1996, an aligned course of water turbidity was recorded with much lower average levels of suspended load's concentration of below 10 mg dm^{-3}. High concentrations of the suspended load in this section of the reservoir, which were recorded in the earlier half of the multi-annual period of time, result from a periodical input of clastic material from the banks of the reservoir. Culminations of water turbidity, which were recorded at that time,

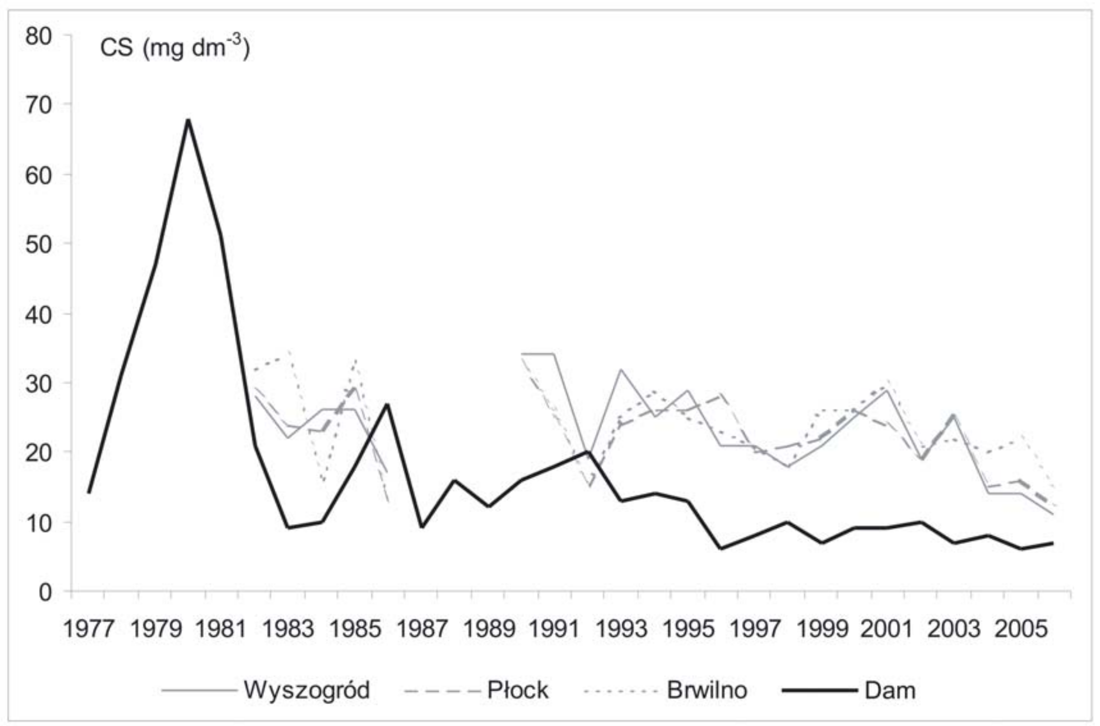

Fig. 2 Mean annual values (geometric mean) of suspended load concentration

correspond with the periods described by BANACH (1994) during which increased activity of mass movements appeared at the high shores of the reservoir as well as intensive abrasion of the shore zone (**Fig. 3**). Both increased input of material from the shores of the reservoir, and resuspension of the bottom sediments are the reasons for a pe-riodical positive balance of the concentration of suspended load in the Włocławek Reservoir. Such a situation was reflected in the 25 % of the measurement series, mainly, although not exclusively, in the

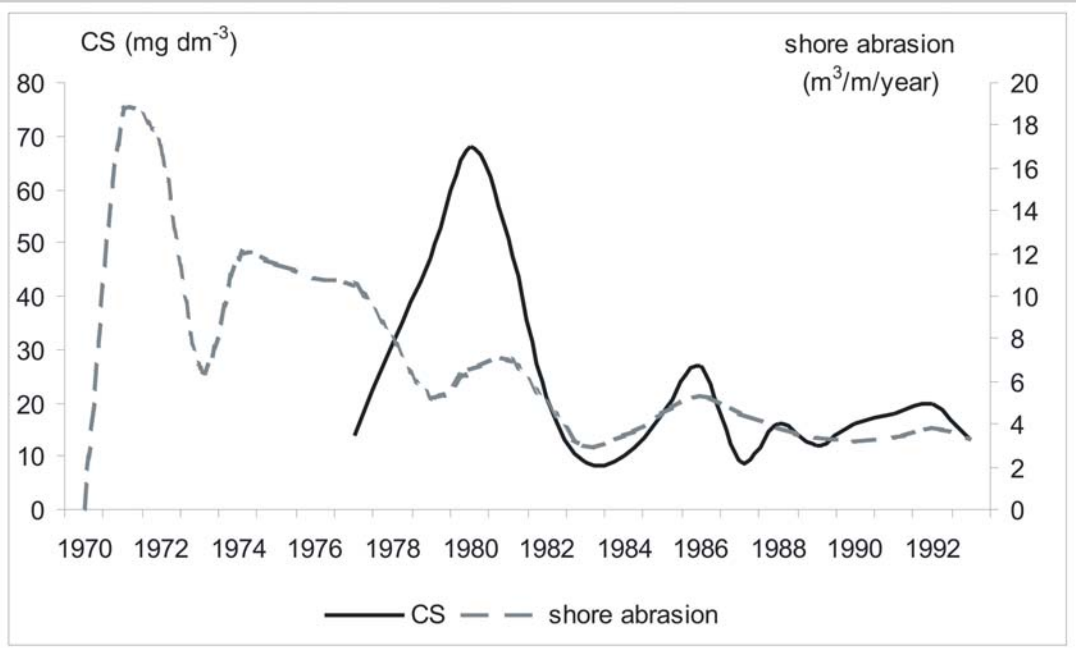

Fig. 3 Course of the suspended load concentration in the sample point below the dam on the background of intensity abrasion of the shoreline (after BANACH 1994, changed)

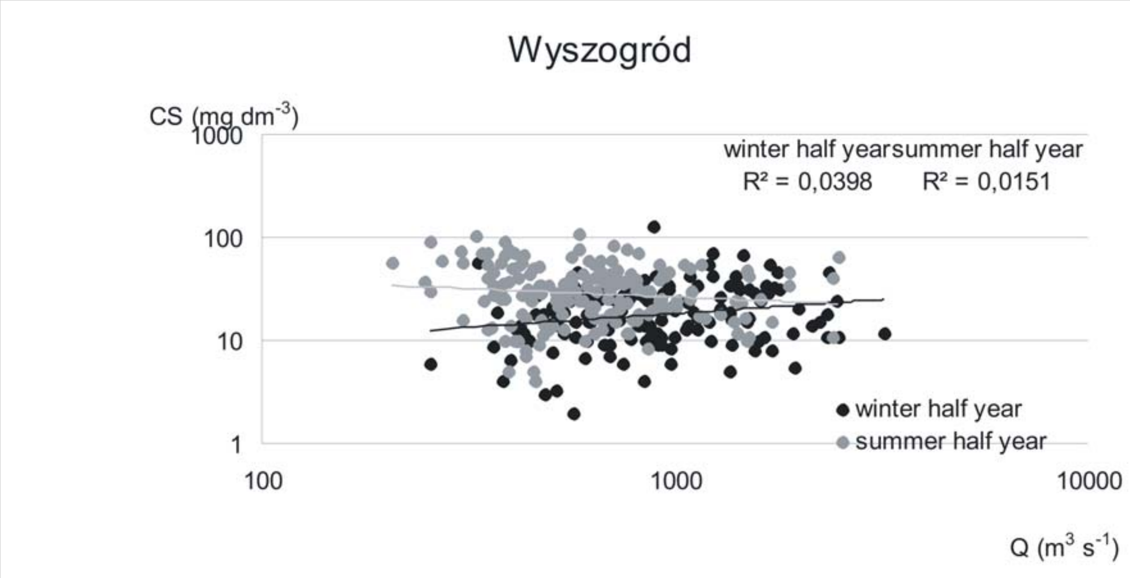

Fig. 4 Relationship between discharge (Q) and suspended load concentrations (CS) in the sample points Wyszogród (freely flowing river)

earlier half of the multi-annual period of 1982 – 2006.

Concentration variability of the suspended load at various times scales depends on changeability and size of the input of clastic material from the catchment area and from the river channel. The correlation of the processes responsible for the input of the material with the processes shaping the river runoff is reflected by a strong relation between the concentration of suspended load and water discharge. In case of a single flood event the relation between the discharge and the concentration of the suspended load is complex and takes the shape of a hysteresis loop (WALLING 1974, FROEHLICH 1975 or WILLIAMS 1989). According to the analysis of the multi-annual measurement series, a usual situation shows a positive correlation between the discharge and the suspended load's concentration. This stems from the fact that during the highest values of the discharge, the mass of the deposits transported in suspension is larger (AL-ANSARI et al. 1988, WALLING and WEBB 1992 or ASSELMAN 1999). The best mathematical approximation of the correlation between the concentration of the suspended load and the discharge is a power function (WALLING 1974). In the

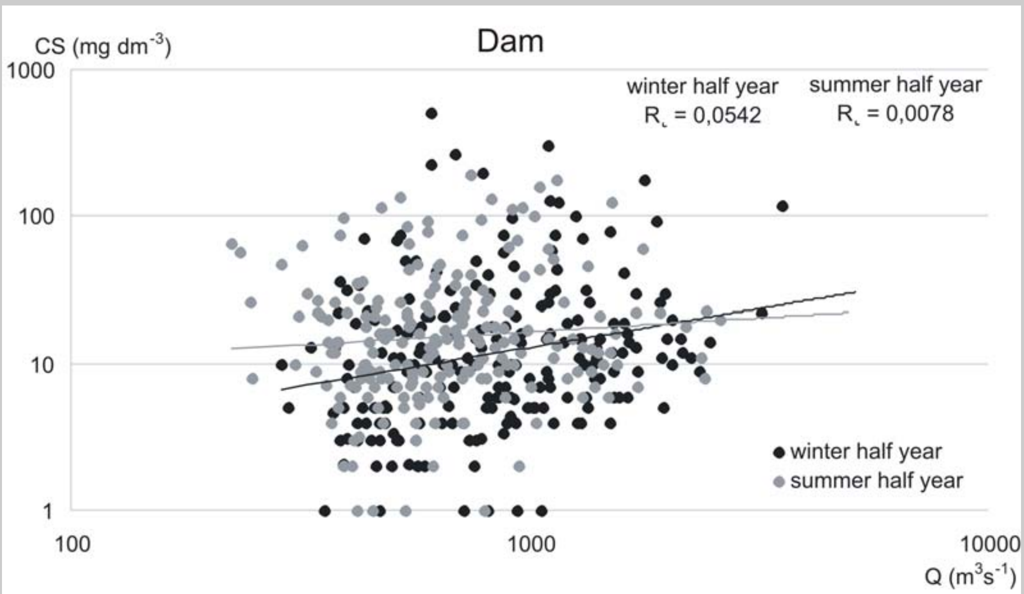

Fig. 5 Relationship between discharge (Q) and suspended load concentrations (CS) in the sample points below the dam

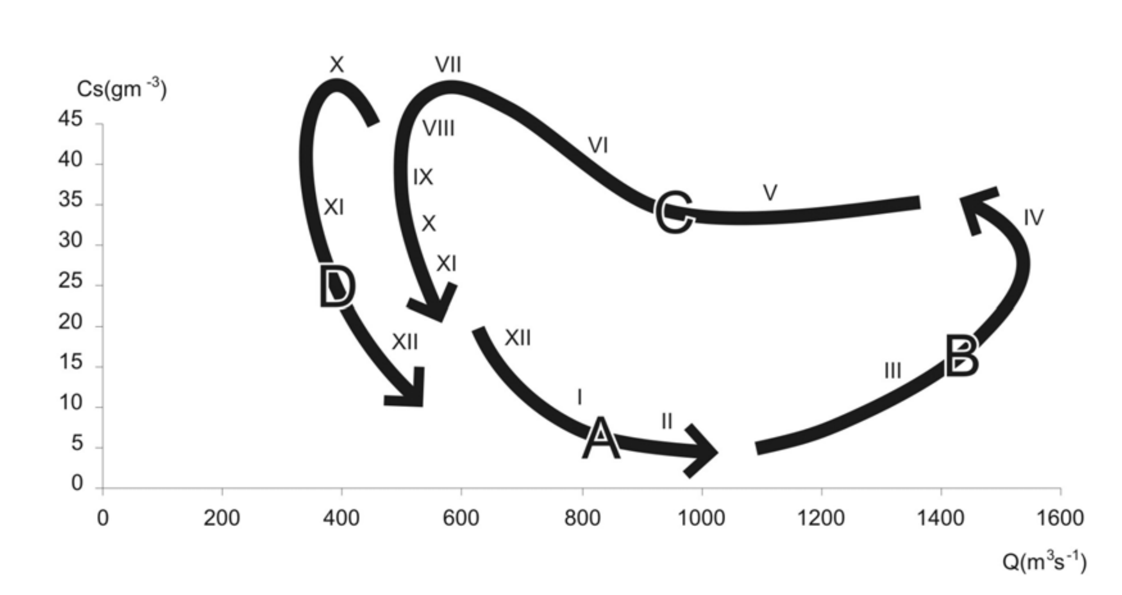

Fig. 6 Scheme of suspension concentration (CS) changes in relation to water discharge(Q) in the average hydrological year (1982-2006); A-D turbidity course cycle described in paper

case of large river systems, a statistical power of this correlation decreases downstream. It is expressed by a smaller inclination of the regression curve drawn for the power function. This is the result of a large amount of loose deposits, which may be transported at both low and high discharges (ASSELMAN 2000). Similar conditions were found at the analysed section of the Vistula River. At all the measurement sites the correlation between the concentration of the suspended load and the discharge shows a positive character and a low power, which is expressed by a slight slope of the regression line (**Fig. 4** and **Fig. 5**). This indicates the input of the suspended load into the Vistula River channel and the reservoir is independent from hydrological conditions.

The analysis of the average annual variation of the suspended load's concentration has enabled the author to distinguish three or, in the case of the limnic part of the reservoir, four characteristic phases of the water turbidity (**Fig. 6**). The first one (A), the winter phase, is recorded when the discharge increases but does not reach the average value, and the delivery of the suspended load is controlled by the course of the ice phenomena. At the time when shore ice appears, the input of material from the river banks gets limited and, as a result, the concentration of suspended load decreases. The March-April phase (B) is connected with the spring meltwater floods. At that time the concentration of the suspended load increases, although it does not reach the maximum values. A major source of suspended load is the matter delivered from the channel banks and the transit suspended load. The third phase (C) is correlated with the seasonal cycle of the development of phytoplankton, the maximum of which is recorded between May and June/July. At the measurement sites the influence of the summer maximum of the development of phytoplankton is concordant with the high concentrations of the total suspended load in June and July. The last phase (D) is recorded only in the central and lower section of the reservoir. The increase in the water turbidity, at the insignificant variations of the discharges, results from the delivery of the matter from the shores of the reservoir during autumnal storms.

COMPOSITION VARIABILITY OF THE TOTAL SUSPENDED LOAD

The suspended load, which is deposited in the Włocławek Reservoir, contains various proportions of organic and mineral matter (bioseston and abioseston). As the results of the research carried out in the years 2003 – 2006 indicate, the suspended load in both the upper and the lower sections of the reservoir predominantly contain mineral elements. In the upper section of the reservoir (Płock) an average share of the mineral suspended load amounted to 85 % and fluctuated within the small range of 65 – 96 %. At the dam this share was a bit lower, 76 %, but the range of these values was larger, i.e. 25 – 95 %. Larger values of concentration of both total suspended load and of its main fractions were mainly recorded in the upper section of the reservoir. A relatively strong correlation between the concentration of the mineral suspended load with the discharge at the upper section of the reservoir (R = 0.67) indicates that this level of water turbidity is controlled by the river flow. Lack of similar correlation in the lower section of the reservoir (R = -0.11) shows the input of the material from the allochthonous sources, such as abrasion of the reservoir shores and resuspension of the deposits, is unconditioned by the discharge. A strong correlation between the supply and transportation of mineral suspended load and the hydrology of the river in the upper section of the reservoir is also shown by a larger concentration variability of the suspended load (cv = 61 %) if compared to the lower section of the reservoir (cv = 33 %). A larger variability of the organic suspension in the limnic section of the reservoir (cv = 212 %) reflects the influence of the periodic resuspension of the organic matter from the bottom of the reservoir as well as a seasonally changing biomass of bioseston, especially phytoplankton. The analysis of a series of samples collected during a flood discharge (Q = 2319 m^3 s^{-1}) shows clearly a decrease in concentration of suspended load by about 80% towards the dam. High water turbidity (51 – 36 mg dm^{-3}) was recorded along the section of over 20 km of upper and middle part of the reservoir. A significant decrease in the concentration of suspended load first down to 23 mg dm^{-3}, and later even to about 10 mg dm^{-3}, was recorded at the distance of 16 and 9 km from the dam, respectively. Concentration of suspended load at the level of 10 mg dm^{-3} reflects a medium level of the water turbidity in the lake part of the reservoir. During the flood flows the transported suspended load mainly contains mineral material, the average share of which amounts to 91 %. As the results of the studies indicate, even during the flood flows this highly through-flow reservoir has a limnic zone, which proves against the widespread opinion this reservoir shows a highly rheolimnic character (GIZIŃSKI and FALKOWSKA 2003).

Lower than along the axis of the reservoir, but also significant concentration variability of the suspended load was recorded at the cross-sections located in the characteristic sections of the reservoir. The cross-section located at the upper part of the reservoir (Płock) larger concentration of both suspended mineral and organic matter, and also total turbidity, was recorded mainly on the right, i.e. the midstream side, of the cross-section. A dissimilar situation, i.e. the increase in the concentration of suspended load out of midstream, was recorded during low water discharges. At this profile, the average differences in concentration of suspended mineral and organic matter were 36 and 53 %, respectively. The midstream part of the cross-section also showed a much larger concentration variability of both types of suspended load (91 – 83 %) then the out of midstream part (60 – 49 %). Such a character of water turbidity in the upper section of the reservoir significantly stresses the role of the former Vistula River channel as the preferential route of both streamflow and delivery of the mineral matter to the reservoir. A similar character of turbidity variability was recorded along the Brwilno cross-section, which represents the transition zone of the reservoir. This profile is located 10 km below Płock, where the course of water turbidity and the composition of suspended load is also influenced by the

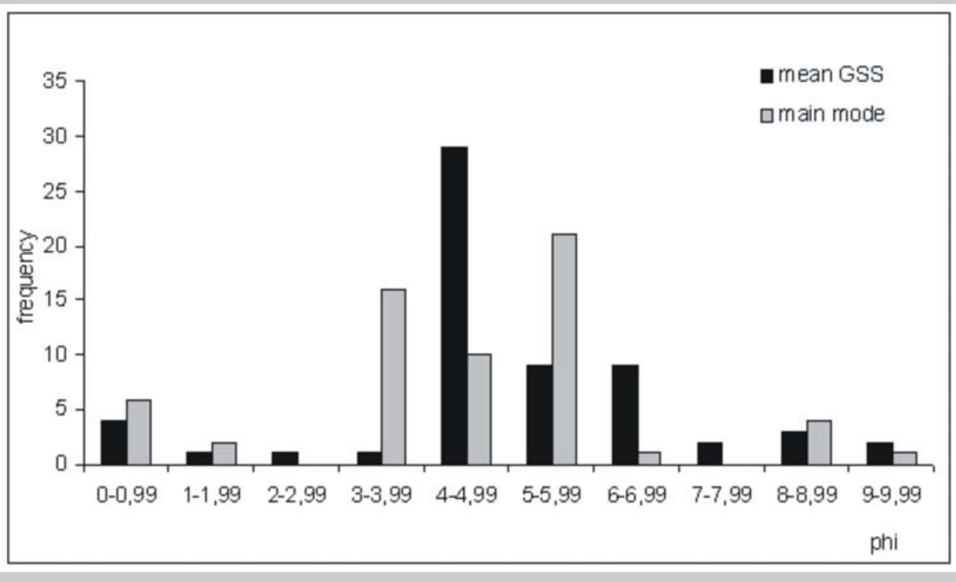

Fig. 7 Frequency distribution of mean grain size and main modal value in suspension samples

discharge in the former Vistula River channel, although this influence is smaller. A diverse character of concentration variability of the suspended load is presented in the profiles located at the limnic part of the reservoir (Dobrzyń and the dam), at 13 and 0.2 km from the very dam, respectively. If compared to the upper and transition zone of the reservoir, concentration of suspended mineral load is lower. Similarly, its share in the total water turbidity is lower (65 – 71 %) and the variability along the cross-sections is also less significant (25 %). It is also characteristic that the variability in concentration of organic suspended load out of midstream sections of the profiles is larger. Lack of correlation of concentration of suspended load with the discharge, lower variability of both total suspended matter and its elements in the midstream sections of the profiles indicates a large influence of the reservoir's water circulation, independent from the river discharge, on the course of water turbidity in the limnic part of the reservoir.

GRAIN SIZE OF THE SUSPENDED LOAD

It is accepted that the suspended load mainly contains grains of silt fraction, which is smaller than 0.063 mm (4 φ) in diameter (KNIGHTON 1998, SZMAŃDA and KRZEMIEŃ 2008). The collected samples of suspended matter included a diverse share of grains smaller than 0.063 mm in diameter, and amounted from 2.9 do 100 %. However, in the case of as many as 64 % of samples, the share of this fraction was over 80 %. The average diameter of grains (GSS) ranged from 0.06 to 9.89 φ, the mean value being 5.06 φ. The dominant (47 %) were the samples where the GSS ranged from 4 to 4.99 φ. As the modal values indicate the majority of samples are dominated by the fraction of coarse silts (5 – 5.99 φ). A large share is also taken by very fine sands (3 – 3.99 φ) and very coarse silts (4 – 4.99 φ) (**Fig. 7**). These results indicate the suspended load transported along the Włocłwek Reservoir shows a coarse silt character. The domination of coarse silts and very fine sand fractions in the suspended load is also proved by the experimental studies (SENGUPTA 1979). In accordance with them, irrespectively of the grain character of the source material, the composition of the suspended load will always be dominated by fractions between coarse silts and medium sands. An increase in the discharge would only mean the modal value of the grain size of the suspended load will move towards a coarser fraction. The distribution of the grain size of suspended load does not change so much, as the increase in the concentration of coarse and fine fractions is marginal. One of the reasons for such a situation is the fact that grains of the above diameters are more resistant to erosion. In the case of coarser grains, their resistance is conditioned by their weight, while in the case of finer grains by their cohesiveness. The muddy cha-racter of the studied suspended load is well expressed by the average share of the main grain fractions. The muddy fraction makes up 71.6 % of the grains in an average sample of suspended load, while the sandy one 22.8 %, and the silty one only 5.6 %. In most of the analyzed samples a very positive (51 %) or positive (33 %) skewness of the grain size distribution was recorded. Positive values of the skewness of grain size frequency distributions curves of the suspended load transported along the Włocławek Reservoir indicate its relative richness in finer fractions. It is the result of selective deposition of coarser grains during the transportation downstream the river and floodplain deposition. Such conditions are characteristic for lower sections of rivers of large fluvial systems (WALLING 1983). The level of sorting of the analysed suspended load is poor or very poor. Such features were shown by as much as 74 % of the analysed samples. The remaining samples showed medium level of sorting. Even worse sorting was recorded in the samples collected in the upper, river section of the reservoir.

As the results of the studies on grain size of the samples of suspended load show, the basic indicators are highly diverse. Undoubtedly, the factor responsible for this situation is the change in the hydraulic conditions of the discharge caused by the damming of the river and, as a result, new sources of material. The presented mean values of the grain size (GSS) show a slightly larger average grain diameter in the suspended load in the lower section of the reservoir (4.9 φ) than in the upper section (5.4 φ). These values correspond with the medium and coarse mud, respectively. A finer character of the suspended load in the upper section of the reservoir is also proved by the fact that in 20 % of samples the values of average grain size corresponded with the silt fraction, while in the limnic section no samples showed such features.

Both hydro - and lithodynamic diversity of transport conditions of suspended load in the river and limnic part of the reservoir is illustrated by the correlation between the average grain size and the discharge (**Fig. 8**). Changes in the GSS values along the cross-section in the river part of the reservoir show well the tendency for the average grain size to increase with the decreasing discharge (**Fig. 8a**). This tendency is especially well visible in the former channel part of the reservoir (right and

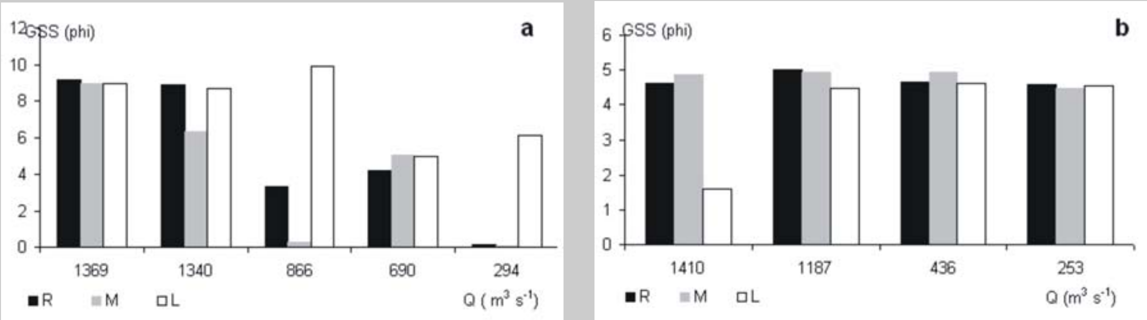

Fig. 8 Average grain size (GSS) of suspended solids in cross section Płock (river part of the reservoir) and Dobrzyń (limnic part of the reservoir) at different discharge. R, M, L – measuring points adequately in right, middle and left side of the cross section

central part of the cross-section). Low values of GSS in this part of the profile suggest there is a possibility for the coarse sands of the river channel facies to be included in the suspended load during low discharge periods. At higher discharges the grain size of suspended load is similar along the entire profile. In the limnic part of the reservoir the grain size of suspended load is, irrespectively of size of water inflow, similar and amounts to about 4.7 φ (coarse silt) (**Fig. 8b**). In the case of strong wind mixing of the reservoir waters, however, even sandy fractions of the bottom material can get suspended.

The analysis of the samples collected on the 1 April at Q = 2319 m^3 s^{-1} shows that during a flood discharge grain size of the suspended load along the entire reservoir is relatively homogenous. Irregular changes in the average grain size are insignificant (5.7 – 7.6 φ) and in terms of their fraction they correspond with medium and very fine silts. The suspended load was poorly sorted as well as a very coarse skewed grain size distribution, which reflects a significant inclusion of grains finer that the average ones. In the upper, i.e. river and transit parts of the reservoir the distribution of grain size in the analysed samples of suspended load showed unimodal character, while in the limnic part, bimodal. The value of the second mode (8.2 – 8.4 φ) corresponds with the clay fraction. Significant domination of fine silt fraction and, at the same time, relatively high homogeneity of the granulometric composition of the suspended load during flood discharges stems from the grain size character of the source material. The source of the material during flood discharges periods is mainly the so called ‘clay alluvial soil’, which makes up the lower section of the flood deposits found in the structure of the floodplain. An increased inclusion of clayey fraction in the lower section of the reservoir must be connected with the local delivery of the material, especially from the right shore of the reservoir where in numerous places clay and silty Miocene and Pliocene deposits are uncovered. Activation of this source of the material, especially at intensive waving, is favoured by high water level in the reservoir

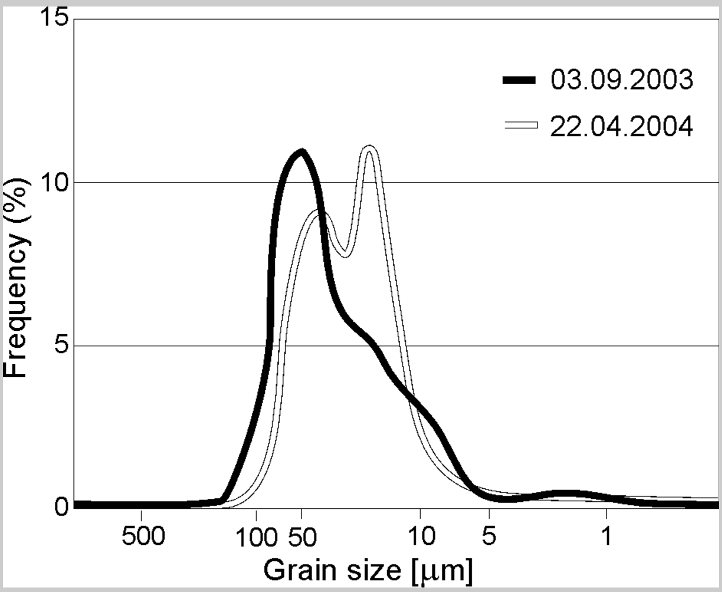

Fig. 9 Average frequency curves of suspension grain size

during flood discharges. The increase of energy of the current environment also activates the cohesive fine-grained fraction from the bottom deposits of the reservoir. It must be stressed that in the conditions of a river streamflow some finest mineral elements of those transported in suspension are susceptible to aggregation (WALLING and KANE 1984). Dispersion of these aggregates in the measurement equipment gives lower values of this fraction than in reality. This can be the explanation of a significant decrease in concentration of suspended load towards the dam despite a similar grain size of the suspended load along the entire reservoir.

Differences in grain size of the suspended load during high and low discharges are well illustrated by the examples of mean curves of grain size frequency for the samples taken in the central and lower part of the reservoir. The samples collected during a low water discharge ($Q = 253\ m^3\ s^{-1}$) on 3 September 2003 show unimodal distribution of grain size (**Fig. 9**).

Although clayey fraction dominates (58.3 % on average) a significant share is taken by the sand fraction (39.4 % on average). The grain size of the suspended load in the sample taken during a high water discharge ($Q = 1187\ m^3\ s^{-1}$) on 22 April 2004 shows a diverse character. The distribution of grain size is bimodal (**Fig. 9**). The first mode is found within the coarse clayey fraction of the average frequency of 9 %. The second mode, of a higher frequency, is found within the fine clayey fraction of the average frequency of 11 %. The samples collected during high water discharges show increased clayey fraction (up to 76.2 % on average) while the sandy fraction decreases (down to 22 % on average). The comparison between the grain size distribution of suspended load and bottom deposits shows that the suspended load contains basically grains of coarse clayey fraction, while the bottom deposits show shortage of them. It is possible, thus, that an important source of coarse clayey fraction in the suspended load is the product of the erosion of the bottom of the reservoir. The fine clayey fraction in the samples of the suspended load is connected either with the erosion of the shores or the increase in the erosion of the bottom deposits in the reservoir during highly energetic discharges. The increase in energy of water currents during flood discharges results in intensification of the erosion of the bottom of the reservoir, and thus the grains of the fine clayey fraction, which pose the main element of the reservoir's depositions (GIERSZEWSKI and SZMAŃDA 2005) get included into the suspended load.

Hydrodynamic diversity of the transportation environment of both the river and the lake part of the reservoir is explained by the correlation of the average grain size diameter (GSS) with the sorting measure (GSO). In the river part of the reservoir the dominant is the situation in which the increase in the average grain size diameter means the level of sorting out of the material decreases, while in the lake part of the reservoir the opposite situation is more typical (**Fig. 10**). The observed correlations pose the basis for general conclusions on the hydrodynamic conditions of transportation of suspended load and on the source of the material transported in suspension. The 'A' type of cor-

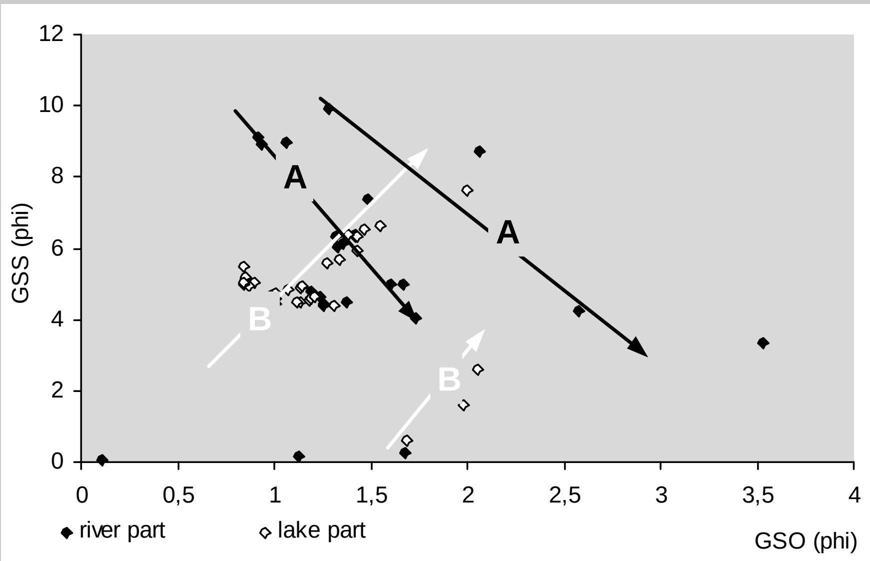

Fig. 10 Mineral suspension samples distribution on the scater diagram of mean grain size (GSS) and sorting measure (GSO); A, B – types of dependencies described in the paper

relations found in the upper part of the reservoir also indicates the conditions for variable dynamics of both erosion and transport of clastic material in the Vistula River channel. The coarser, better-sorted material typical for river channel deposits gets activated during lower dynamic of water motion. The flow velocities in the upper part of the reservoir, even during very low discharges (250 m^3 s^{-1}), are higher (25 – 30 cm s^{-1}) then the critical scour velocities needed for detachment and transportation in suspension of sandy fractions (GIERSZEWSKI 2006). Transportation of finer material dominates during higher discharges in the Vistula River. High water stages, and lateral erosion of the river channel correlated with them, favours the delivery of a bit better-sorted material, which builds the floodplain. In the case of the 'B' correlation found in the limnic part of the reservoir, the decrease in the average grain size diameter means the level of sorting also lowers. During low and medium discharges the suspended load contains a better-sorted material in which clayey fraction, mainly the coarse one, dominates. In such conditions the suspended load loses sandy fraction and aggregated silty particles. In such a situation, the source of the medium sorted coarse and medium silts are bottom deposits of the reservoir. This situation is favoured by intensive mixing of the reservoir waters, which cause resuspension of the bottom material followed by its transportation by circulation currents. The idea of the large scale of resuspension processes in the Włocławek Reservoir is supported by the dominance of lithodynamic environments of redeposition and transportation character, which is recorded in the bottom deposits in the reservoir (GIERSZEWSKI and SZMAŃDA 2007). Poorly sorted fine particles are recorded in large quantities in the suspended load during the flood discharges.

CONCLUSION

It is commonly believed that dam reservoirs of the valley type with short retention time do not pose large influence over the transformation of river water, including suspended load (STAŠKRABA and TUNDISI 1999). Besides the retention time, the potential ability to trap the transported suspended load also depends on other factors, such as grain size of the suspended matter (which decides about its weight), hydrological regime of the river and morphological features of the reservoir (VERSTRAETEN and POESEN 2000). Changes in concentration and composition of suspended load in reservoirs result from complex and dynamic relations between the input of the river and autochthonic material, and resuspension, scouring and sedimentation (MALMAEUS and HÅKANSON 2003). Thanks to these processes the course of both transportation and deposition of suspended load, even in the strong throughflow reservoirs, are independent from hydrological regime of the river. Such a situation is recorded in the case of the Włocławek Reservoir. The features of the suspended load and the conditions for its transportation, described above, indicate that this reservoir has both a river and a limnic section. Such a dual division of the reservoir is observed even during smaller flood discharges. The course of the turbidity in the upper, river part of the reservoir depends on the conditions of the delivery of the river suspended load to the reservoir. In the lower, lake part of the reservoir the level of the water turbidity and the features of the suspended load depend, most of all, on the course of the hydrodynamic and sedimentation processes taking place in the water mass of the reservoir. They also depend on the delivery of the mineral material from new sources, such as the shores of the reservoir (abrasion), the bottom of the reservoir (resuspension) and a larger share of the bioseston in the transported suspended load.

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