THE EFFECT OF A SUSPENDED AND BED LOAD TRANSPORT BY TRIBUTARIES INTO WATER RESERVOIR ONTO THE SILTING PROCESS IN IT

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Abstract: There are many side tributaries flowing into water reservoirs in the Carpathian region. So far, no investigations were performed with regard to quantities of loads carried and brought by those side tributaries. In this paper, the authors present the most recent investigations made on the load transports delivered into two selected Carpathian water reservoirs: Myczkowce (its water storage-capacity equals 10.9 million m^3) in the San River, and another reservoir in the city of Rzeszów (its water storage-capacity equals 1.8 million m^3), in the Wisłok River. As for Myczkowce reservoir, the loads carried into it from the upper part of the river basin are rather limited because the San River bed has been 'partitioned' by a concrete dam of Solina, the largest water reservoir in Poland, constructed across the bed of the San River above the Myczkowce reservoir. The Solina reservoir water storage capacity is 497 million m^3. The water reservoir in Rzeszów, also investigated by the authors, is a flow-type reservoir fed by a main stream (Wisłok River) and a side tributary (Strug River); the latter one has a large basin area. The silt charge measurements in this flow-type water reservoir were performed, as well as the total quantity of the load carried into it by the Wisłok River. It is confirmed that the Strug River delivers a high quantity of loads. This is an indication that the side tributary essentially contributes to the silting process ensuing in this reservoir. A simulation of changes in the plant lining within the catchment basin was carried out and its results revealed a potentiality to reduce loads transportation into the reservoir executed by this side tributary.
Keywords: bed load, suspended load, side tributary, and water-reservoir, silting process

TRANSPORT VON SCHWEMMSTOFFEN IN WASSERBEHÄLTER DURCH NEBENFLÜSSE UND IHR BEITRAG ZU DEN PROZESSEN DER STAUMRAUMVERLANDUNG IN DIESEN BEHÄLTERN

***Zusammenfassung*:** Viele Nebenflüsse der Karpaten-Flüsse besorgen zahlreiche Wasserbehälter in Karpaten mit Wasser. Aber bis jetzt wurden keine Studien über die Mengen der durch diese Nebenflüsse transportierten Schwemmstoffe durchgeführt. Die Verfasser erforschten die Transporte von Schwemmstoffen in zwei gewählte Wasserbehälter in Karpaten: Myczkowce (Stauraum: 10.9 Mio. m^3) im San Fluss, und Rzeszów (Stauraum: 1.8 Mio. m^3) im Wisłok Fluss. Im ersten Wasserbehälter treffen beschränkte Mengen von Schwemmstoffen aus dem oberen Teil des Einzugsgebiets von San ein, weil der Flussbett von San über dem Wasserbehälter Myczkowce durch einen Betondamm gesperrt worden ist. Dieser Betondamm ist ein Teil von ‚Solina', einem der gröβten Wasserbehälter in Polen, dessen Stauraum 497 Mio. m^3 beträgt. Der zweite Wasserbehälter ist ein Durchlaufbehälter, der durch den Wisłok Fluss (als Hauptwasserstrom) und seinen Nebenfluss (Strug Fluss) mit Wasser versorgt wird. Das Einzugsgebiet beider Flüsse ist groβ. Im Rahmen der Untersuchungen wurde der Grad der Stauraumverlandung im Rzeszów Wasserbehälter bemessen und die Gesamtmenge der durch den Wisłok Fluss eingebrachten Schwemmstoffe berechnet. Die durch den Strug Fluss eingebrachte Menge der Schwemmstoffe deutet darauf hin, dass der Nebenfluss zum finalen Prozess der Stauraumverlandung wesentlich beiträgt. Die durchgeführte Simulation der Veränderungen im biologischen Bau des Einzugsgebiets zeigte, dass es möglich wäre, die Mengen der durch den Nebenfluss in diesen Wasserbehälter transportierten Schwemmstoffe zu reduzieren.

1. Introduction

Water reservoirs situated on the Carpathian, Vistula River's tributaries silt up to a high degree. A first, important reason is that suspended loads are carried into them. According to the investigations performed by Polish scientists, suspended loads constitute several percentage points of total loads transported into them [Mikulski, 1966]. Brański [1971] states on the basis of his research that the suspended load is 8% of the total load quantity transported, whereas Wiśniewski [1972] reports of a range between 8% and 12%. The hitherto investigations on the silting processes ensuing in water reservoirs allowed for the determination of load transports carried by main watercourses across which the reservoirs were situated. However, side tributaries feed many water reservoirs. Amounts of loads transported by them are often disregarded, or mere roughly estimated.

On the basis of the investigation results, the impact degree of a side tributary on the silting effect in the reservoir was identified and estimated. The authors calculated and verified quantities of load transported and carried into the two selected water reservoirs.

In the investigations, the authors focused on the Bereźnica Brook. Bed and suspended loads carried by this brook from its entire basin into the Myczkowce reservoir were investigated (Figure 1). The reservoir water-storage capacity is 1.9 million m^3. The load carried by the main feeder, the San River, was not determined because the only suppliers of this load were direct side tributaries flowing into the reservoir. The load transported by the San River was reduced because one of the Polish largest water reservoirs was constructed within the extent of the Myczkowce reservoir's backwater. Its name is Solina Reservoir and it was put into operation during the third year of the Myczkowce reservoir operation. This Solina reservoir traps the total bed load, and 98.7% of the suspended load [Sobczak, 1982]. 1965, the silting degree of this reservoir was measured. The records obtained showed that the cubic content of the silt deposited during a period from 1961 to 1965 was 640 thousand m^3 (Wiśniewski, 1967). 1982, the silting degree was tested again, and it was clear that the volume of the load deposited increased to 1400 thousand m^3.

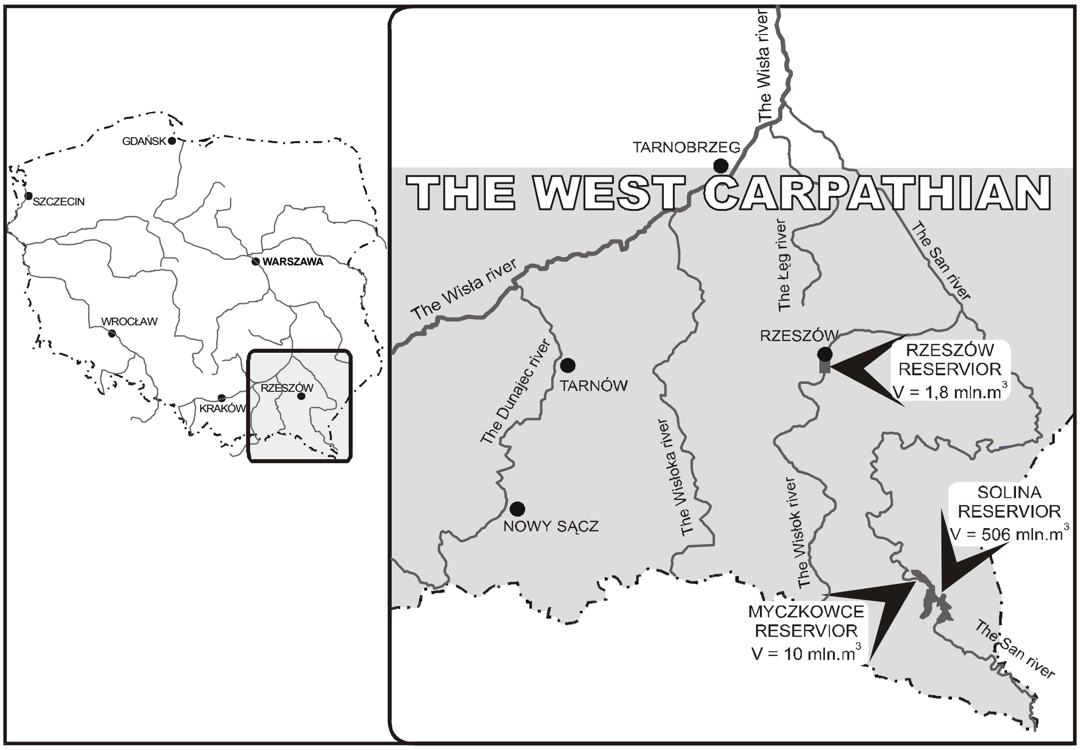

Figure 1 Location of the Myczkowce water-reservoir and the Rzeszów water reservoir

With regard to the water reservoir Rzeszów (its water-storage capacity is 1.8 million m^3), while determining the quantity of terrigenous materials carried into it, it is necessary to include both bed and suspended loads carried into it from the Strug River basin (Figure 1). The Strug

River flows directly into this reservoir. The quantity of loads carried into this reservoir by the Wisłok River was calculated using bathometric measurements, and it equaled 1900 thousand m^3 during a period from 1973 to 1986 [Bednarczyk and Michalec, 2001]. The calculations performed did not include loads brought from the Strug River basin. On the grounds of records taken in the year 1986 and pertaining to silt quantities, a 66% reduction in the reservoir water-storage capacity was stated. The volume of silt deposited in the Rzeszów reservoir was 119 thousand m^3 after the 13-year period of its operation.

2. Characteristic of the investigation objects

2.1. The Bereźnica Brook basin

This brook is a left-side tributary of the San River, and it flows into the Myczkowskie Lake (Figure 2). The Brook basis area is 24.3 km^2. It is situated in the Carpathian Mountain range, in its part known as External Carpathians or The Carpathian Flysch.

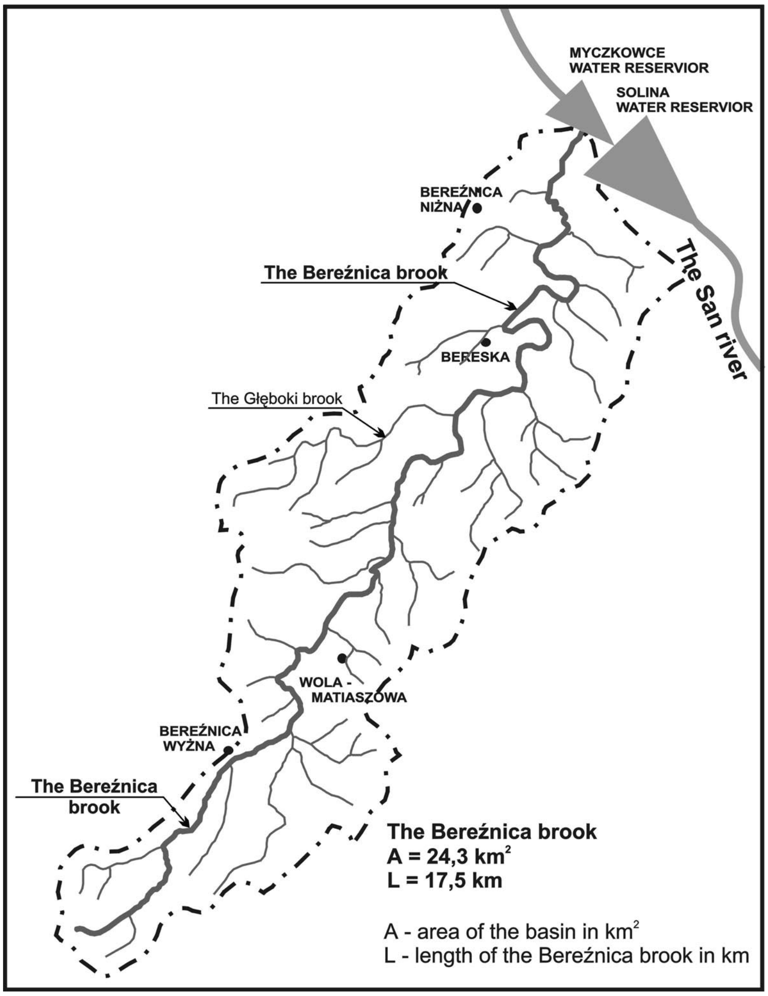

Figure 2. Location of the Myczkowce water-reservoir and the Bereźnica Brook

The Bereźnica Brook is 17.5 km long, and its course is tortuous. A mean longitudinal brook fall is 20%. In the narrowed, upper sections of the brook valleys, the brook bed width ranges from 1 to 2 m and there are numerous rock steps here. The brook fall along certain short sections is much bigger than the average slope (35% to 45%) [Galarowski, 1979]. Those sections are characterized by deep, down-cutting eroding processes. Below the rocky steps, eroding phenomena are even deeper. The soil cover is highly irregular and changing due to the differentiation of geological structure, as well as to natural or man-generated relief shaping processes.

Since the terrain of the Bereźnica Brook basin has a mountainous character, forests cover the majority of its surface and constitute about 60% of the total basin area. In the forests, wood harvest is the major industrial branch. So, a dense network of country roads and cart tracks is well developed. However, an intense, linear erosion process develops. Additionally, water flowing down the mountain slopes elevates soils, and the rocky subsoil is uncovered; furrows ruts are formed.

The agricultural land constitutes 24% of the total area. On the fields, farmers use neither special treatment against erosion nor crop rotation, and plough runs parallel to the slope. Quite frequently, shrubbery and bushes are rooted out, so, the ‘clean’ areas are ploughed and used as arable land. Other parts of land are often changed into grassland and grass is sown on valley-slopes, but even such measures do not solve the linear erosion problem. Pastures and other green land constitute only 16% of the total basin area, because there is no cattle farming on a large scale in this region.

2.2. The Strug River Brook basin

This river is a right-side tributary of the Wisłok River, and it flows into the water reservoir Rzeszów (Figure 3). The total river length is 34.1 km. Its 277.3 km^2 large basin is situated in the Province of The Western Carpathian Mountains.

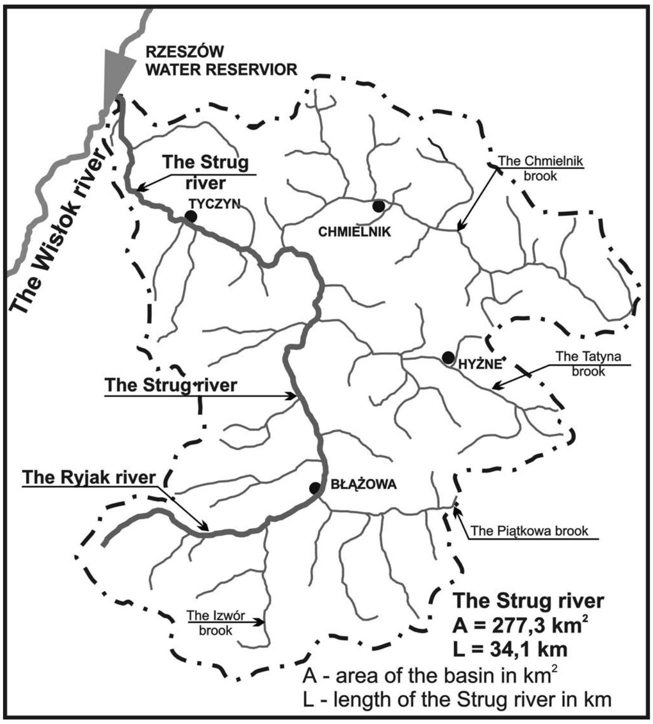

Figure 3. Location of the Rzeszów water reservoir and the Strug River

Mountainous and submontane surface features are characteristic of this basin. The land is made of heavy textured soils with the domination of silty soil. Arable fields prevail, and in several places, rural, densely built-up areas cut them. Forests cover a small area. The counter-perpendicular tillage predominates, so, the cropping runs along the slope and stimulates soil erosion phenomena. In some parts of the basin, terracing occurs.

3. Methodology of investigations

The quantity of the load transport can be determined using direct or indirect methods. The direct methods include measurements performed in the river, i.e. either the intensity rate of load transport is gauged or some other physical parameters that can be applied in calculating transport intensity rates.

The Bereźnica Brook and the Strug River are incorporated into hydrological investigation schemes. Consequently, no data on their flow rates exists with regard to periods prior to and after the erection of the water reservoir under investigation. In the end sections of the two streams, before their inlet into the reservoir, gauging stations were established to measure concentration rates of suspend loads. The stations have operated for one year. The records obtained, as well as mean daily flows gauged allowed of the determination of the quantity of suspended load transport. The calculated products were compared with outcomes obtained by an indirect method. The quantity of the suspended load transported was also computed using a DR-USLE method based on an Universal Soil Loss Equation (USLE). The said Equation was developed by Wischmeier and Smith, USA [1965, 1978] on the grounds of a statistical analysis of data obtained from multi-annual experimental studies that were performed in the natural environment and under laboratory conditions; rainfall simulators were utilized for the purposes of these studies, too. To calculate a perennial average of the eroded soil mass from an area unit, within a one-year period, the following equation was used:

$$E = R \cdot K \cdot L \cdot C \cdot S \cdot P \qquad (1)$$

where:

E – perennial average of the eroded soil mass from an area unit [$t \cdot ha^{-1} \cdot annum^{-1}$],

R – the rainfall factor, is the number of erosion-index units in a normal year's rain [area unit $\cdot$ $annum^{-1}$],

K – soil erodibility factor [$t \cdot ha^{-1} \cdot$ area $unit^{-1}$],

L – the slope-length factor,

C – the cropping-menagement factor,

S – the slope-length factor,

P – the erosion-control practice factor.

A DR parameter describes a quantity of erosion products obtained in a river basin that are carried into river-beds; this quantity is determined using the USLE software. This parameter was set by Roehl (1962).

The USLE was adjusted to the conditions and parameters of the river basins in Central Poland, and the adjustment outcome was satisfactory (Banasik, 1985), however, other scientists (Bednarczyk et al., 2000) critically evaluated the USLE adjustment with regard to submontane river basins.

Whilst calculating amounts of suspended load, computer software called DR-USLE, version 2.1, was applied.

Using a Meyer-Peter's and Mueller's method (equation 2) that was modified by a team of scientists – employees of the Department of Water Engineering, Agricultural University Cracow, the amount of bed load transported was calculated (Bartnik, 1992).

$$\gamma_w \cdot \frac{Q_d}{Q}\left[\frac{k_d}{k_r}\right]^{\frac{3}{2}} h \cdot I = 0{,}047(\gamma_r - \gamma_w)d + 0{,}25\left(\frac{\gamma_w}{\gamma}\right)^{\frac{1}{3}} \cdot q_r'^{\frac{2}{3}} \qquad (2)$$

where:

γ_w, γ_r – specific gravity of water and load [$N \cdot m^{-3}$],

Q – total water flow within a cross-section [$m^3 \cdot s^{-1}$],

Q_d – water flow at the width of the riverbed bottom provided that both the bed bottom and the walls show one and the same roughness [$m^3 \cdot s^{-1}$],

k_d – roughness coefficient of the river-bed bottom according to Strickler,

k_r - roughness coefficient of load grains at the river-bed bottom according to Strickler,

d – reliable diameter of loads at the river-bed bottom [mm],

I – hydraulic gradient of the stream,

q'_r – weight of the suspended loads per one unit of the river-bed width minus hydrostatic lift rate [$N \cdot s^{-1} \cdot m^{-1}$].

The calculations were performed with use of the 'TRANS' computer software (Bartnik, 1992).

4. Calculation results

The results of bathometric and hydrometric measurements allowed of the determination of the annual average amount of suspended loads carried out from the Bereźnica Brook and Strug River basins. The indicated results are respectively: load amounts carried out from the Bereźnica Brook basin: 6024.0 [$t \cdot annum^{-1}$], and from the Strug River basin: 13460.0 [$t \cdot annum^{-1}$].

On the grounds of the documented climatic, soil, and topographic records, as well as on the basis of data pertaining to the basin's land utilization systems, annual average masses of soils eroded from the entire area of each of the two basins were calculated.

The parameters referring to the Bereźnica Brook basin are: R = 99.0 [$Je \cdot annum^{-1}$], K = 0.126 [$t \cdot ha^{-1} \cdot Je^{-1}$], LS = 10.143 [-], C = 0.16 [-], P = 0.80 [-]. The calculated annual average of soil masses eroded from an area unit of the total river basin is: 1619.0 [$t \cdot km^{-2} \cdot annum^{-1}$], and the annual average soil mass eroded from the entire area of the Brook basin is: 39342.0 [$t \cdot annum^{-1}$]. The DR parameter equals 0.183 [-]. According to Roehl, the estimated load mass transported within the section closing the Brook basin is: 7199.0 [$t \cdot annum^{-1}$].

The fixed, Strug river basin parameters are: R = 103.9 [$Je \cdot annum^{-1}$], K = 0.48 [$t \cdot ha^{-1} \cdot Je^{-1}$], LS = 2.544 [-], C = 0.057 [-], P = 0.86 [-]. The calculated annual average mass of soils eroded from a basin area's unit equals: 621.9 [$t \cdot km^{-2} \cdot annum^{-1}$], and an annual average mass of soils eroded from the entire brook basin area amounts to: 161903.0 [$t \cdot annum^{-1}$]. The DR parameter, determined according to Roehl, is 0.096 [-], whereas the estimated load mass transported in a cross-section that closes the basin is: 15543.0 [$t \cdot annum^{-1}$].

Special geodetic survey was necessary to determine a quantity of the bed load transport. While performing the survey, the longitudinal slope of the brook bottom and cross-sections of the riverbed were measured. Load samples were taken from the Bereźnica Brook and Strug River, and on their grounds, the granulometric composition of the loads in the both streams was identified.

The water-table gradient in the Bereźnica Brook is 3.9 ‰. A TRANS software was applied to calculate it. Calculations were performed with regard to a medium bankful wave that lasted 5 days. The bed load transport carried along with the bankful wave, in the measuring section, was 0.35 [t].

The water-table gradient in the Strug River is 1.21 ‰. A TRANS software was applied to calculate it. Calculations were performed with regard to a medium bankful wave that lasted 7 days. The bed load transport carried along with the bankful wave, in the measuring section was 0.82 [t].

For the calculations of bed load amounts, it was assumed that two bankful waves occurred within one year, and the amounts of bed loads carried by the Bereźnica Brook and Strug River during one year were calculated. As next, it was computed an amount of bed loads delivered by the Bereźnica Brook during a period 1961-1982, and by the Strug River in a period 1973-1986 (Tab. 1).

Table 1. Amount of suspended and bed loads carried out from the river basins under investigations

Type of load (identified using method as the specified hereinafter)		*Amount of load carried out from the basin of the streams*			
		Bereźnica Brook period 1961-1982		*Strug River Period 1973-1986*	
		[thousand tonnes]	*[thousand m^3]*	*[thousand tonnes]*	*[thousand m^3]*
Suspended load	*DR-USLE*	151.18	111.98	202.06	142.30
	Bathometer	126.50	93.70	174.98	123.23
Bed load – MPM modified by the Department of Water Engineering, Agricultural University		1.47	0.60	2.13	0.84

The total load transport was determined with use of the calculation results obtained using indirect methods, i.e. DR-USLE and MPM, modified by the team of scientists from the Department of Water Engineering, Agricultural University Cracow. The amount of loads carried into the Myczkowce water reservoir by the Bereźnica Brook equalled 152,650 [t] in the period 1961-1982. The volume of the transported suspended and bed loads was calculated, it was 112.58 thousand [m^3]. While calculating the said volume, special bulk densities of both the suspended and bed loads were used; they equalled respectively: 1.35 [$t \cdot m^{-3}$] and 2.45 [$t \cdot m^{-3}$].

In the time period 1973-1986, the Strug River carried 204,190 tonnes of load into the Rzeszów water reservoir. While calculating the load, it was supposed that the bulk density of the suspended load was 1.42 [$t \cdot m^{-3}$], and the bulk density of the bed load equalled 2.53 [$t \cdot m^{-3}$]. They were computed using the study results obtained by the authors of this paper (Bednarczyk, Michalec, 1996). The computed volume of the transported load was 143.14 thousand m^3.

5. Conclusions

In Poland, the largest water reservoir in Solina traps the inflow of load into the Myczkowce reservoir almost completely. 1965, the volume of deposits in it was 640 thousand m^3, but since that year, a process of the reservoir's shallowing has slowly ensued. Four side-tributaries highly influence the silting process since they rather significantly contribute to the accumulation of loads in alluvial cones from which loads are transported into the reservoir. The Bereźnica Brook brings 112.58 thousand m^3 of load into the reservoir. If the other three side-tributaries carry similar amounts of loads, the quantity of the material delivered into the reservoir during its operation, i.e. until 1982, is 450 thousand tonnes. With regard to the water-storage capacity of this reservoir (10.9 million m^3), it is, in fact, negligible. However, if compared with loads trapped in the reservoir and determined in the year 1982, namely with 1.400 thousand m^3, it is already a significant amount.

In the studied period from 1973 to 1986, the Strug River carried approximately 7.5% of the total load delivery brought by the Wisłok River into Rzeszów reservoir. Although the Strug River only slightly contributes to the total load transport, its impact on the operational conditions of the Rzeszów reservoir is significant. The deposits of the loads carried from the Strug River basin disabled the proper operation of the 'Stara Stacja' water intake station supplying tap water into the pipeline system. 'Stara Stacja' is situated nearby the Rzeszów reservoir. Finally, the seriously silted inflows into the intake station caused the intake station shutdown. It had to be moved to a place above the reservoir.

Direct inflows into the reservoirs essentially influence their operational conditions, silting rate, and, thus, they should be taken into consideration while studying the silting processes ensuing in them, and also whilst forecasting such processes.

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